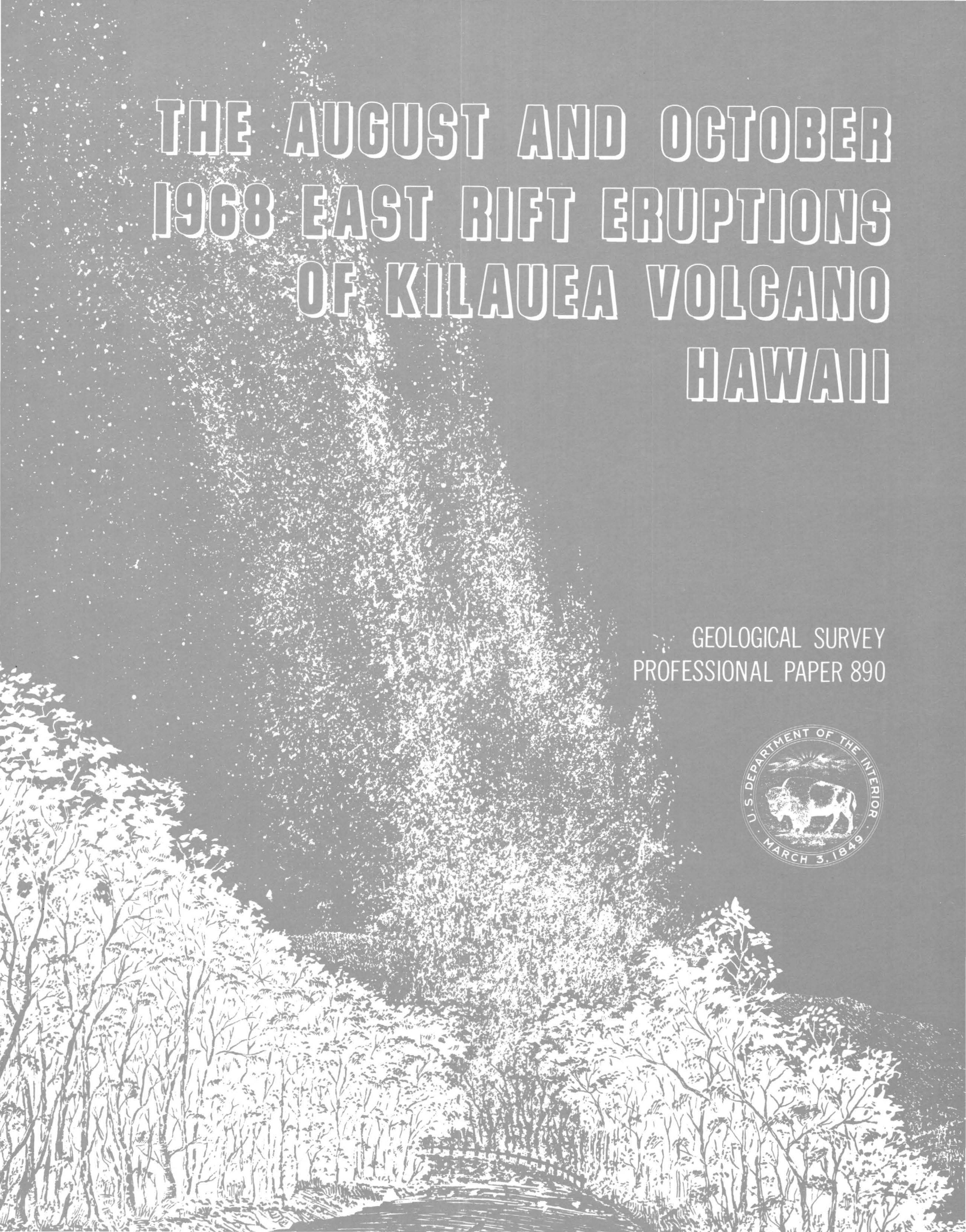
THE AUGUST AND OCTOBER 1968 EAST RIFT ERUPTIONS OF KILAUEA VOLCANO HAWAII



GEOLOGICAL SURVEY
PROFESSIONAL PAPER 890

The August and October 1968 East Rift Eruptions of Kilauea Volcano, Hawaii

By DALLAS B. JACKSON, DONALD A. SWANSON, ROBERT Y. KOYANAGI,
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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

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By DALLAS B. JACKSON, DONALD A. SWANSON, ROBERT Y. KOYANAGI, and THOMAS L. WRIGHT

ABSTRACT

The eruption of August 22–26, 1968, began in Hiiaka Crater, on Kilauea's east rift zone. In 3 days, the activity migrated 20 km down the northern margin of the active part of the rift zone, venting in six different places. A 27-m-deep pool containing $8.9\times10^4 m^3$ of lava formed in Hiiaka; only about 3.5×10^3 m^3 remained after drainback into the eruptive fissure. The total volume of lava remaining on the surface, about 13.5×10^3 m^3, is the smallest net output of lava in a historic Kilauea eruption. The August lava is the chemical equivalent of one of the early variants of the 1969–71 eruption mixed with a lesser amount of 1967–68 summit lava and olivine. Systematic enrichment in phenocrysts of plagioclase and clinopyroxene downrift suggests the lava cooled about 65°C during shallow underground transport.

Following 6 weeks of rapid reinflation of the summit area, another east rift eruption began on October 7 along a more or less continuous, 6.5-km-long line of vents northeast of Makaopuhi Crater. The eruption lasted until at least October 22, and spattering of uncertain origin was observed as late as November 11. Napau Crater was flooded by a lava lake 5 m deep and 6.3×10^5 m^2 in area. The net volume of lava remaining above ground, about $7.5\pm2.2\times10^6$ m^3, is perhaps 25 percent less than the total volume of erupted lava, because of voluminous drainback. Some of the October lava is a differentiate, chemically equivalent to 1961 summit lava from which some olivine, clinopyroxene, and plagioclase have been removed. Other October lava can be explained as a mixture of 1 part differentiate and 3 parts lava of 1967–68 summit composition.

The August and October eruptions were accompanied by severe ground deformation at the summit and along the rift zone near the sites of eruption. The summit region subsided, tilted inward, and contracted as magma was withdrawn from a reservoir and moved into the rift zone. Maximum vertical displacement at the summit was about 20 cm, maximum measured horizontal displacement about 16 cm. Frequent tilt measurements made during the eruptions indicate multiple centers of deformation that shifted location with time. The center of net deformation for both eruptions, as defined by vertical and horizontal displacements, ground tilt, and dilatational strain, was about 1.5 km southeast of Halemaumau Crater. By using a point-source elastic model, the vertical displacement and tilt data give the best solutions for a focal depth of 3.2 km for the August eruption. The October deformation data are inadequate for modeling purposes.

Parts of the east rift zone adjacent to the eruptive fissures were uplifted during eruptions, at least 35 cm in August and 20 cm in October. A subsidence trough, probably a keystone graben, formed along the August fissures. Trilateration stations on the rift zone were displaced as much as 63 cm away from the new fissures. Finite-element modeling and geologic evidence suggest that the August dikes are vertical or dip steeply southward.

Seismicity was concentrated in the summit and eruption areas during each eruption. Earthquakes and harmonic tremor at the summit were probably related both to the mechanics of subsidence and the transfer of magma. Earthquakes in the eruption area were mainly associated with ground rupture as magma forced its way to the surface; once dikes were emplaced, earthquakes gave way to tremor, caused by both subsurface transfer of magma and surface fountaining.

The presence of a magma reservoir on the east rift zone in the vicinity of Makaopuhi Crater is inferred from seismic, petrographic, and chemical evidence.

INTRODUCTION

A swarm of shallow earthquakes shook Kilauea Volcano early in the morning of August 22, 1968, followed about 3 hours later by eruption of tholeiitic basalt in Hiiaka Crater[1] (fig. 1). Small outbreaks of lava occurred progressively downrift for 20 km until all eruptive activity ceased on August 26. During the next 6 weeks seismicity was normal as the summit rapidly reinflated. In October another east rift eruption began on the east flank of Kane Nui o Hamo. Eruptive activity quickly spread downrift for 5 km and eventually centered near Napau Crater, where it continued until late October or early November. These two small eruptions, similar in many ways, followed closely the 1967–68 summit eruption in Halemaumau Crater (Kinoshita and others, 1969) and were the first two in a series of four east rift eruptions that took place before the next summit eruption in August 1971.

This paper presents a chronological narrative of the two 1968 east rift eruptions and summarized deformation and seismic data and the petrography of the erupted lavas. We emphasize the results of the study of ground deformation during and between the two eruptions, because these results are more detailed than those of any previous flank eruption at Kilauea. Vertical ground displacement was determined by leveling, horizontal displacement and dilatational strain by trilateration with a Model 6 geodimeter, and ground tilt

[1]Called Heake Crater on some maps.

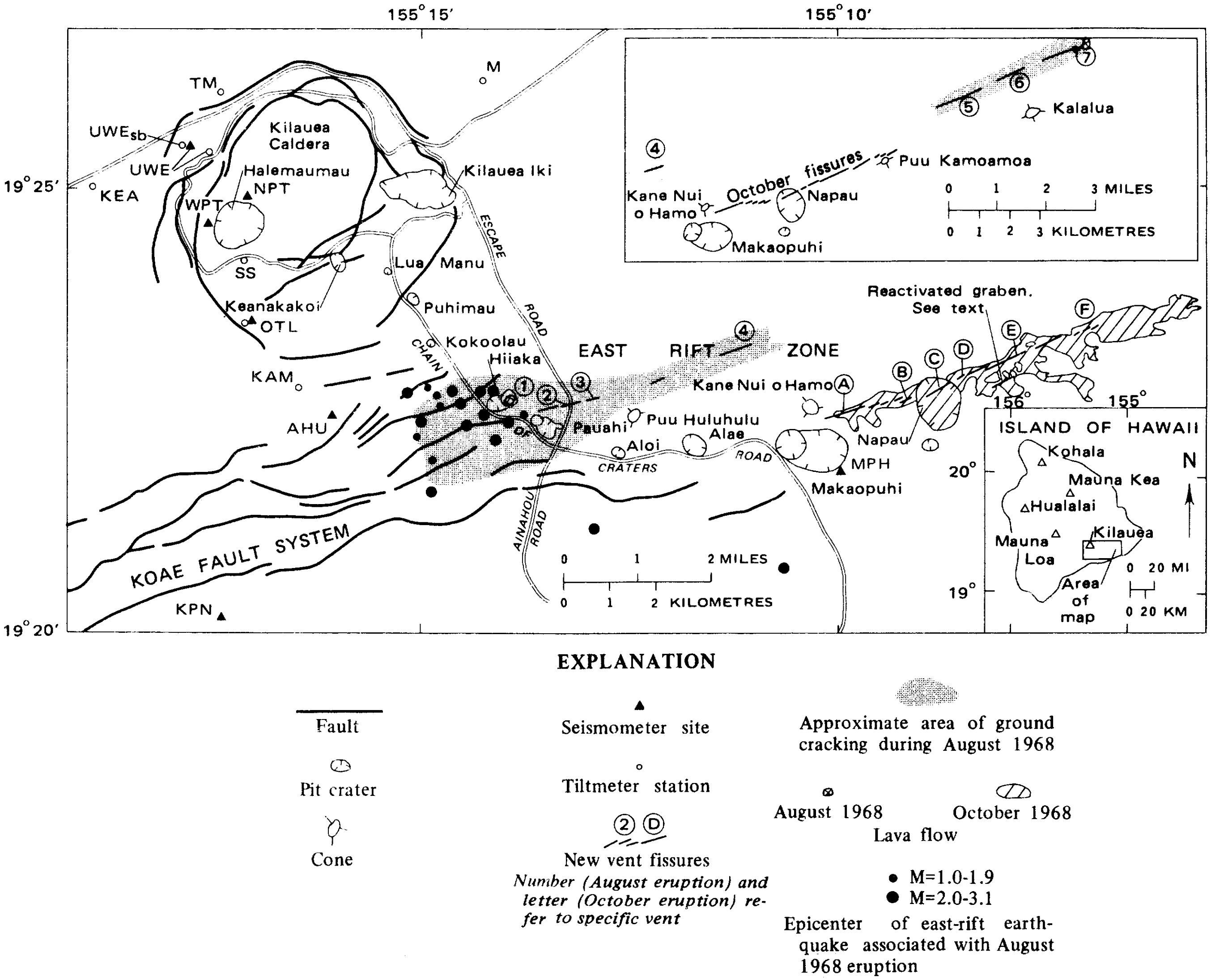


FIGURE 1.—Summit area of Kilauea Volcano and parts of the east right zone and Koae fault system, showing vents and lava flows of the August and October 1968 east rift eruptions and epicenters of earthquakes associated with August 1968 eruption. Location of easternmost vents of the August 1968 eruption shown in large inset. Tiltmeter stations: UWE, Uwekahuna; UWEsb, Uwekahuna short base; SS, Sandspit; OTL, Outlet Vault; KAM, Ahua; M, Mehana; KEA, Keamoku; TM, Tree Molds. Seismometer stations: UWE, Uwekahuna; NPT, North Pit, WPT, West Pit; OTL, Outlet; AHU, Ahua; MPH, Makaopuhi; KPN, Kipuka Nene.

by a continuously recording mercury tiltmeter and several water-tube tiltmeters. The techniques and precision of instruments used in the ground deformation study are described in detail by Kinoshita, Swanson, and Jackson (1974) and Fiske and Kinoshita (1969a). A description of the seismic network and instrumentation is given by Koyanagi (1968).

ACKNOWLEDGMENTS

The entire staff of the Hawaiian Volcano Observatory contributed significantly to this paper. J. B. Judd provided many observations and accompanied Swanson on difficult forays to vents 4 and D through F. Our knowledge of the eruptions downrift from Napau is dependent almost entirely on the generosity and skill of the Hilo-based Civil Air Patrol, which provided overflights for observatory staff members and made numerous independent observations, especially at night. Personnel of the Kilauea Job Corps Center formed part of our survey crews. The National Park Service cooperated in many ways with our efforts. The California Institute of Technology loaned us a recording tiltmeter used during the October eruption. W. T. Kinoshita, who had recently left the Observatory staff, returned during the August eruption and offered advice and help with the surveying. J. H. Dieterich kindly supplied displacement curves

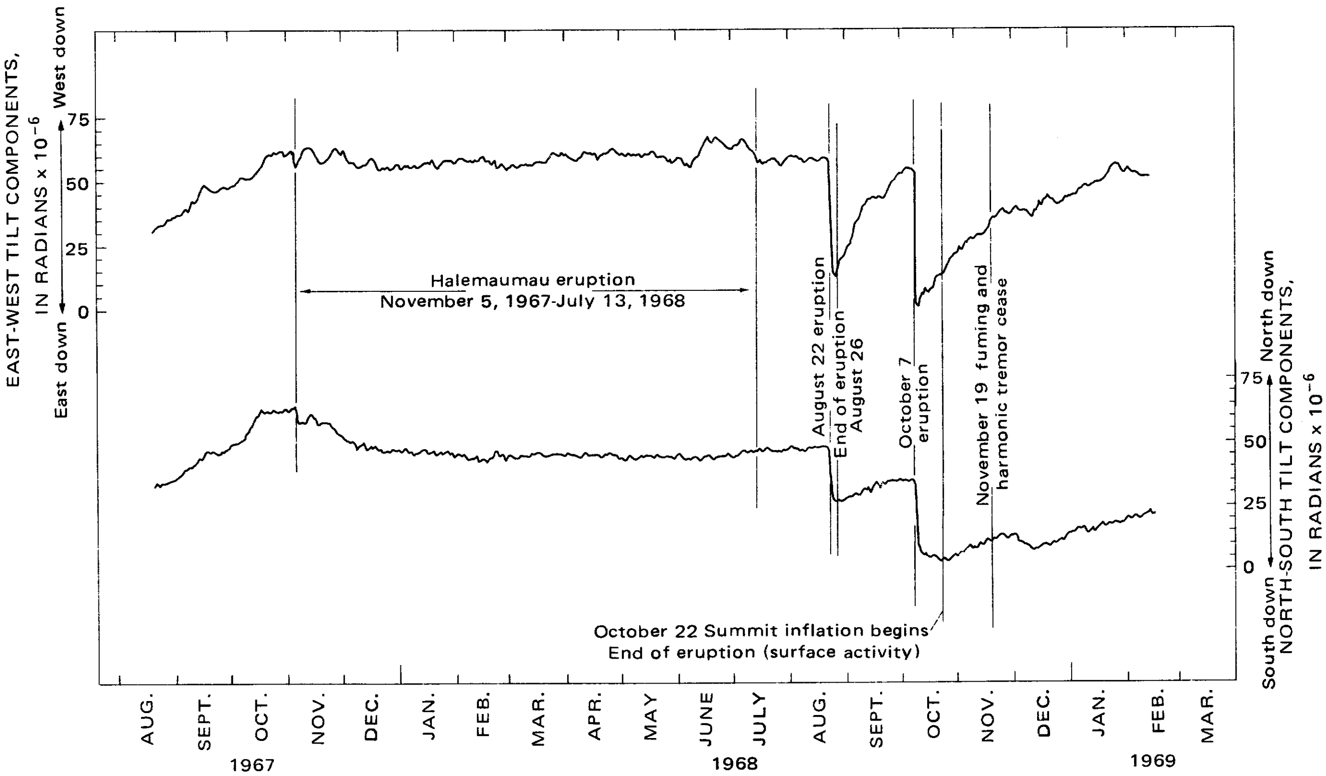


FIGURE 2.—Record of the north-south and east-west components of tilt measured by the Uwekahuna short-base water-tube tiltmeters from August 1967 to February 1969. These tiltmeters are read once daily or more frequently when required by rapid tilting. All measurements are relative to a datum established prior to August 1967.

based on the finite-element method for aid in interpreting the east rift deformation. R. L. Christiansen and W. A. Duffield reviewed and improved the manuscript. We thank all of these individuals and organizations for their invaluable assistance.

EVENTS PRECEDING THE AUGUST 1968 ERUPTION

The summit area of Kilauea was highly inflated just before the August 1968 eruption. The volcano began swelling soon after the major deflation associated with the December 1965 east rift eruption (Fiske and Koyanagi, 1968) and continued almost uninterruptedly through the 1967–68 summit eruption (Fiske and Kinoshita, 1969a; Kinoshita and others, 1969; figs. 2 and 3 of this paper). Thus Kilauea was in a highly distended state at the end of the 1967–68 summit eruption, ready to erupt again.

A map of altitude and tilt changes between June 4–6 and July 15, 1968—the last month and a half of the summit eruption—shows uplift of more than 25 mm centered about 1 km south of Keanakakoi Crater (fig. 4). This area may have undergone even further, though slight, uplift before the August eruption began, for the record of the short-base water-tube tiltmeter at Uwekahuna vault (figs. 1 and 2) indicates very slight summit tumescence between July 15 and August 22. The area of subsidence centered near Halemaumau Crater (fig. 4) may be related to loading of the earth's crust by lava ponded in Halemaumau during the 1967–68 summit eruption, as suggested by Kinoshita, Koyanagi, Wright, and Fiske (1969, p. 467). The upper east rift zone between Pauahi and Alae Craters also shows subsidence (fig. 4), but we do not know if this area continued to subside until the August eruption began, as no leveling surveys were run between July 15 and August 22.

The number of earthquakes beneath the upper east rift zone and adjacent areas increased between mid-June and the start of the flank eruption. Nearby seismographs commonly recorded 40 to 70 earthquakes per day during this period. These earthquakes may have resulted from increasing stresses created by magma that, as the summit eruption waned, continued to enter and become stored in high-level parts of Kilauea's reservoir system within the upper east rift zone.

AUGUST 1968 ERUPTION

SETTING

The August 1968 eruption began from a fissure on the floor of Hiiaka Crater (fig. 1), which lies in the area where the east rift zone and the Koae fault system merge. Northwest of Hiiaka, the east rift zone is radial to Kilauea Caldera. Southeast of Hiiaka, the rift zone gradually changes direction, until near Aloi Crater it has an east-northeast trend similar to that of the Koae fault system. The east-northeast trend continues to beyond Cape Kumukahi, the easternmost tip of the island (Moore, 1971). Fissures for a given eruption tend to be arranged in a right-offset en echelon pattern east of Hiiaka (Moore and Koyanagi, 1969, p. 4; fig. 1), and in a left-offset en echelon pattern in and west of the crater (Duffield, 1975, fig. 8).

The outbreak in Hiiaka was, at the time, the westernmost historic east rift eruption; later, in May 1973, vents opened as far as 1.6 km west of Hiiaka. Eruptive activity so far west is apparently infrequent, for only two prehistoric vents can be documented uprift of Hiia-

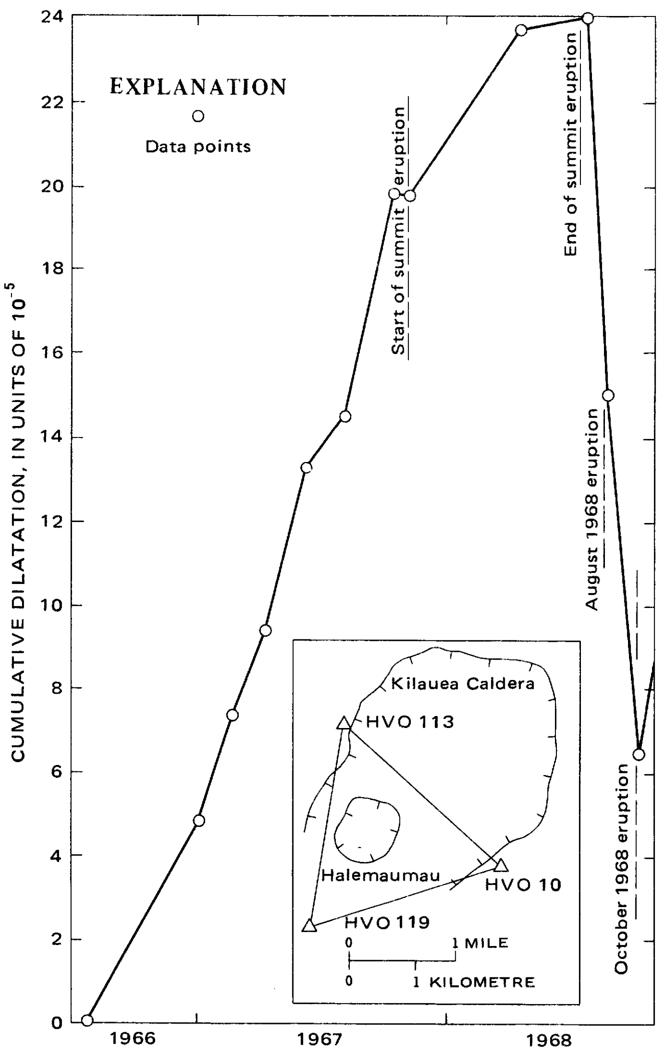


FIGURE 3.—Cumulative dilatation (change in area divided by old area) between July 1966 and October 1968 for a survey triangle across main part of Kilauea Caldera. Strain of zero arbitrarily assigned to first measurement.

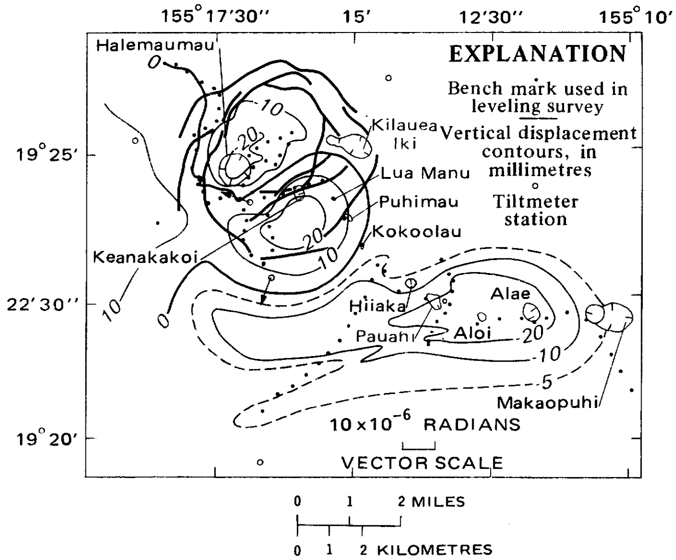


FIGURE 4.—Tilt (vectors) and vertical ground displacements (contours) for the period June 4–6 to July 15, 1968. Dashed −5 mm contour, approximately located. Heavy lines, faults.

ka. One of these is marked by a spatter cone at Kokoolau Crater (fig. 1), 2 km northwest of Hiiaka, the other by a spatter cone along the Chain of Craters Road 600 m west of Hiiaka. In contrast, hundreds of eruptions, including more than 20 historic ones, have occurred on the rift zone east of Hiiaka.

Vents 1 through 4 (fig. 1) are at least 1.5 km north of all other pre-1973 historic east rift fissures and 100 to 200 m north of the May 1973 fissure system. Vents 5 through 7 are 100 to 300 m north of the line of 1840 fissures, the previously northernmost set of historic vents (Moore and Koyanagi, 1969, pl. 1).

NARRATIVE OF THE ERUPTION

The first indication of an impending eruption came at about 1500 August 21, when a flurry of several hundred small earthquakes began on the east rift zone near Makaopuhi Crater (fig. 1). At 0248 August 22, residents of the summit area felt an earthquake of 1.9 Richter magnitude that occurred about 2 km south of Makaopuhi, and soon after numerous earthquakes centered near Hiiaka Crater began to be recorded. At approximately 0330 August 22, the recording tiltmeter in Uwekahuna vault began to register summit deflation, and sometime between 0607 and 0635, the flank eruption started in Hiiaka Crater (vent 1). Table 1 and figure 5 summarize many of the events accompanying the eruption.

A pool of lava 60–75 m in diameter and 18 m deep had already formed by 0700, when observers reached the rim of Hiiaka. Fountains averaging 20 m high, with spurts to 45 m, played from an east-northeast-trending

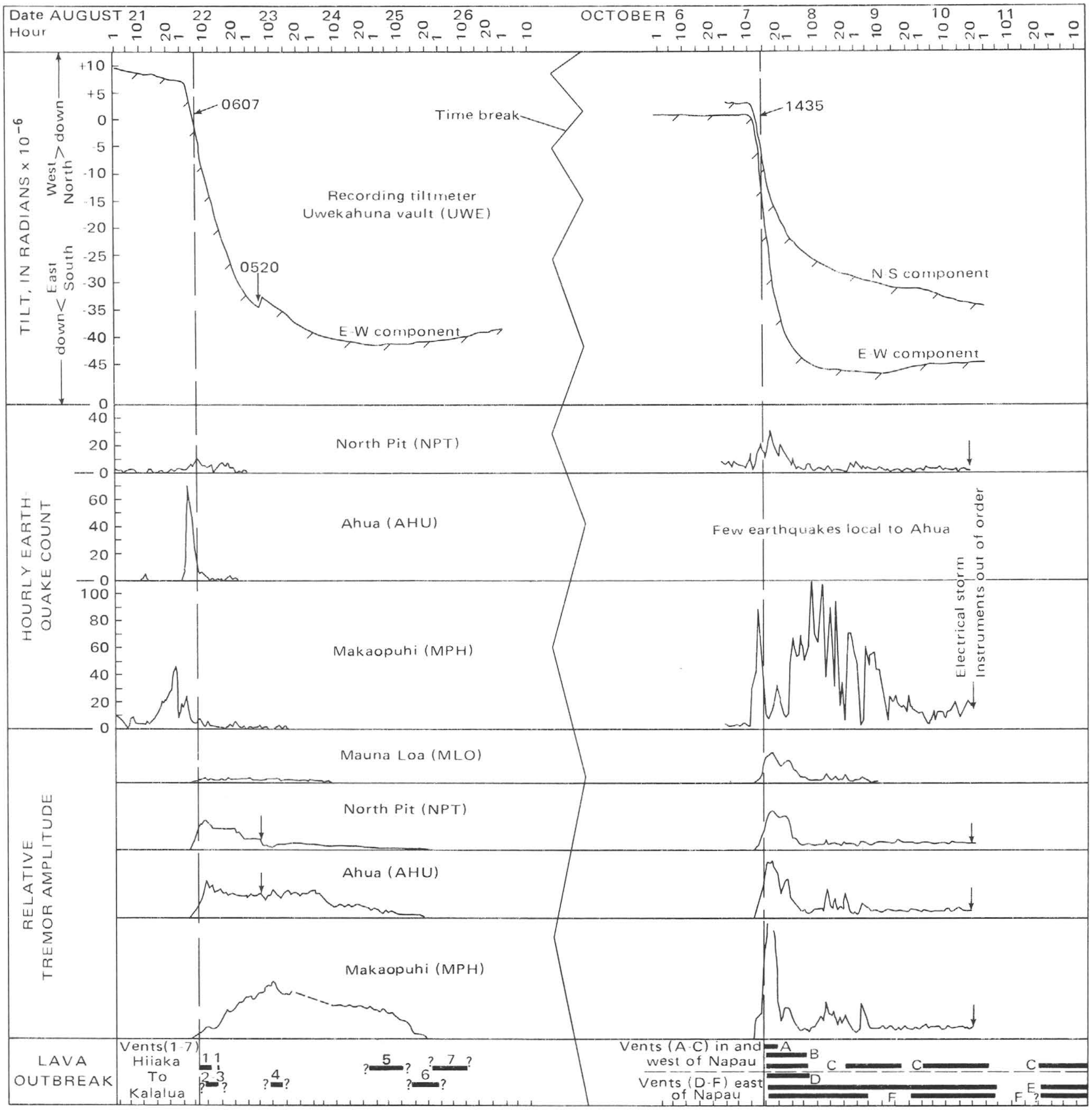


FIGURE 5.—Summary of seismicity and tilt associated with the August eruption and first 6 days of the October flank eruption. Broken lines at 0607 on August 22 and 1435 on October 7, the earliest reported sighting of fume for each eruption. The north-south component of tilt during the October eruption was recorded at Uwekahuna vault with a mercury-tube tiltmeter. Location of vents from which lava outbreaks occurred shown on figure 1.

fissure that cut the eastern wall of the crater. Two segments of the fissure were active: a vent on the wall about 30 m above the drowned floor of the crater and a line of vents beneath the south-central part of the lava pool. At 0713, a short fissure, offset 30 m south of the extension of the main fissure, began fountaining on the southwest wall of the crater, feeding a small flow of viscous lava; activity ceased abruptly at 0840 with a 5-minute blast of hot gas that caused vegetation 30 m upslope to flash into flame.

Fountaining from the main fissure reached its peak at about 0830, then slowly decreased until 1130, when

TABLE 1.—*Time of eruption and drainback, and volume and rate of lava extruded, from the seven major vent areas of the August 1968 eruption*

Vent	Distance from Hiiaka (km)	Time (approx.)	Volume in m^3 (approx.)	Maximum rate of extrusion (m^3/hr)	Sample No. (analysis in table 2)
1 Hiiaka Crater	------	0620–1130; 1312–1325, Aug. 22	8.9×10^4	30,000	Hi68–2 Hi68–3
	------	0915 to evening of Aug. 22	-8.55×10^4 (drainback)	?	
2	1	0900(?)–1300(?) Aug. 22	<10	?	
3	1.5	0900(?)–1300(?) Aug. 22	5×10^3	1,250	
4	4.5	0900(?)–1300(?) Aug. 23	5×10^2	?	Hi68–12
5	16 (approx.)	Night of Aug. 24 and morning of Aug. 25	$\sim10^3$	?	
6	18 (approx.)	Afternoon and evening of Aug. 25	$\sim1.5\times10^3$	?	
7	20 (approx.)	Evening of Aug. 25 and morning of Aug. 26	$\sim2\times10^3$	?	Hi68–14
		Total volume remaining on ground surface =	$\sim1.35\times10^4$		

eruptive activity temporarily ceased. As fountaining declined, the lake developed a solid crust (fig. 6), and sluggish lava flows advanced across it from the fountains. Weak fountaining resumed at 1312 but stopped again 13 minutes later.

The pool of lava reached its maximum depth of 27 m and surface size of 98 m by 124 m at about 0915. At this time, some lava drained back into inactive parts of the drowned fissure, although fountaining was still strong locally, and by 1000 the lake level had dropped 1.5 m. During the next hour drainback was rapid, and by 1100 the still sinking lake surface was about 12 m below the high-lava mark (fig. 7). Continued drainback at a reduced rate eventually lowered the lake surface to its final level of about 18 m below the high-lava mark. Of the $8.9\times10^4 m^3$ lava erupted into the crater, only about $3.5\times10^3 m^3$ remained. The preeruption slopes of the crater reappeared beneath a thin plaster of solidified lake crust as the lake receded (fig. 8).

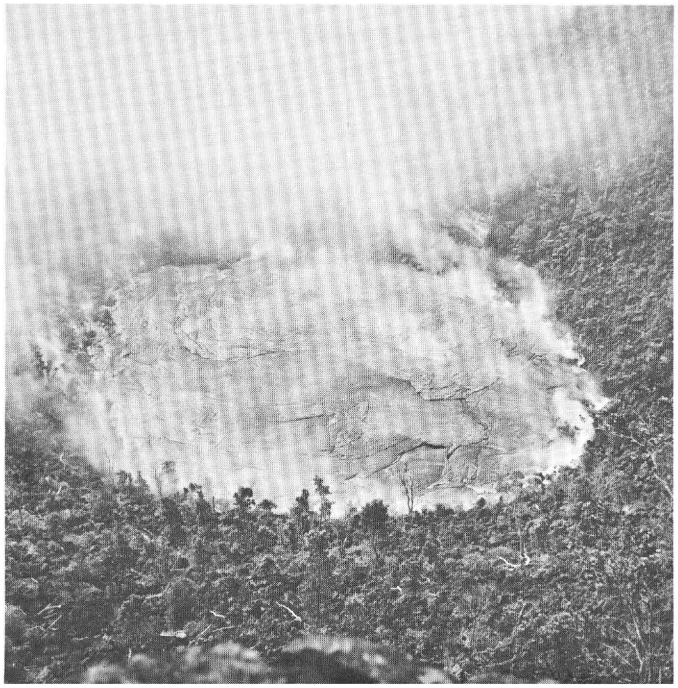


FIGURE 6.—Lava lake in Hiiaka Crater at 0840 August 22, 1968. View from west rim of crater. Active lava flow fed from the low fountains playing in the southeast part of the lake is slowly advancing across a thin solidified crust. Note the alinement of fountains, which have heights of 5–10 m above the lake surface. Diameter of lake is about 100 m.

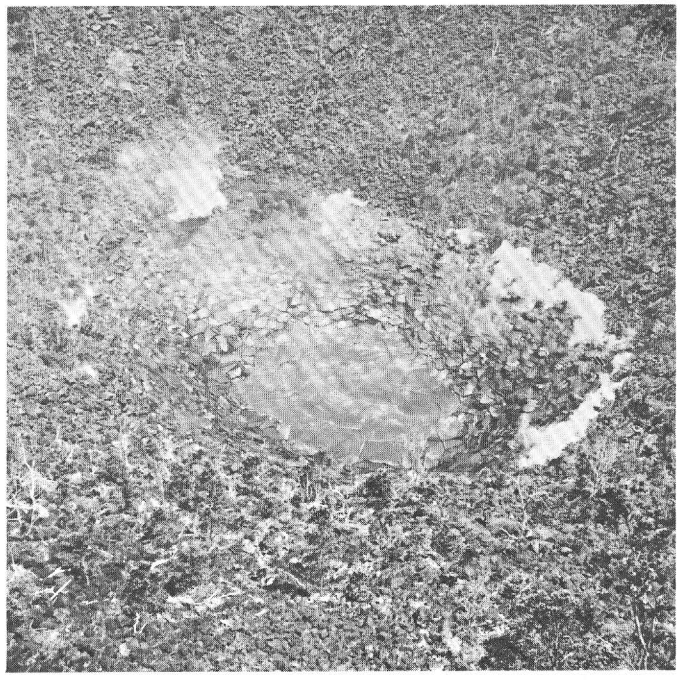


FIGURE 7.—Nearly drained lava lake in Hiiaka Crater at 1400 August 22, 1968. View from approximately the same location as figure 6. The slopes of the crater below the high stand of the lake are plastered with slabs of crust left by the receding lake. Steam which partly encircles the lake results from heating of ground water. The level of the lake lowered several metres after this picture was taken. By the morning of August 23, the crust on the molten pool had overturned, destroying the smooth surface. Note the spatter ramparts projecting above the high stand of the lake along the eastern shore.

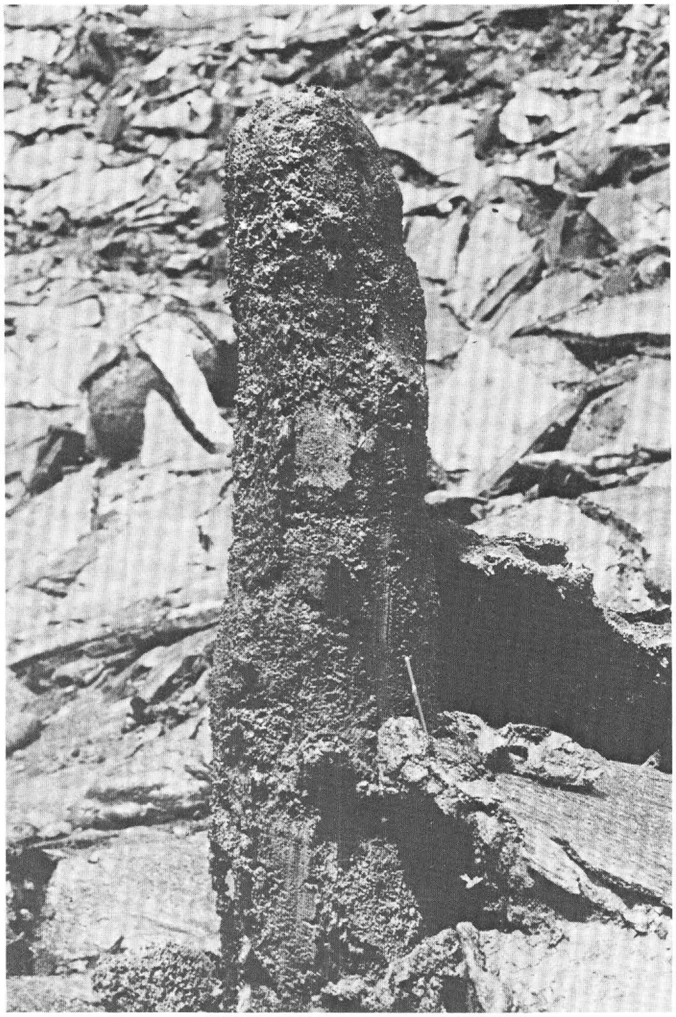


FIGURE 8.—Tree mold and lava-coated talus boulders (background) protruding above the lava plaster left on the slope of Hiiaka Crater after draining of the lava lake. Tree mold approximately 40 cm in diameter.

Before fountaining ceased in Hiiaka, weak spattering began at two fissures about 1 km to the east (vents 2 and 3, fig. 1). These fissures, and a third fissure closer to Hiiaka that emitted only gas, were arranged in a right-offset en echelon pattern (fig. 9). At vent 3, lava sprayed a few metres into the air (fig. 10) and fell to feed a flow less than 1 m thick that covered an area about $5\times10^3 m^2$. Vent 2 erupted only minor amounts of spatter and a small flow of $10 m^2$. By 1400 August 22, all eruptive activity from these two vents had ceased.

At 0900 August 23, fume was observed billowing above the dense jungle northwest of Makaopuhi Crater (vent 4, fig. 1), but no lava was seen during an overflight later in the day. Ground examination a month later, however, revealed a thin flow and associated spatter covering about $10^3 m^2$ along a new fissure 310 m long

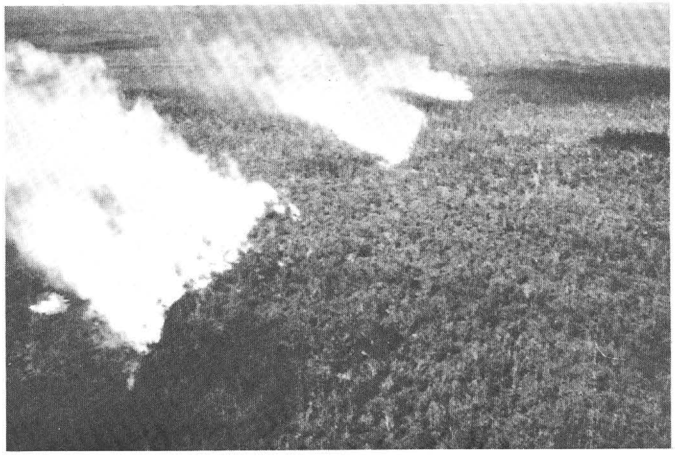


FIGURE 9.—Sulfurous fume issuing from vents 3 (foreground) and 2 and an unnumbered fissure (background) at 0830 August 23, 1968. Note right-offset en echelon arrangement of fissures. Hiiaka Crater off the upper right edge of the photograph.

FIGURE 10.—Spatter-draped branches of a denuded ohia tree at site of vent 3. Such spatter drapery helps locate vents buried by younger flows.

FIGURE 11.—Narrow fissure largely covered by a thin mantle of welded spatter in jungle at vent 4, September 28, 1968. Sulfurous fume issues from several points along fissure.

and 0.5–1 m wide (fig. 11). This lava was probably erupted on the morning of August 23 but was not identifiable from the air because heavy fume and a dense canopy of tree ferns obscured the area.

Aerial reconaissance at about 1700 the next day, August 24, revealed new fuming cracks 2 to 2.5 km west-northwest of Kalalua cone, but no fresh lava was seen. At 0845 the next morning, a Civil Air Patrol overflight found a low fountain feeding a small flow at vent 5 (fig. 1), and new fuming cracks, offset en echelon to the right, extending discontinuously downrift to a point due north of Kalalua (vent 6). At 1700 August 25, vent 5 was quiet, but new fuming cracks were observed 3 km east-northeast of Kalalua and viscous lava was issuing from vent 6. By 0630 August 26, the line of fuming fissures had extended about 200 m downrift from its position of the previous evening, and weak fountaining was confined to one vent (vent 7) at the east end of the line, where a small mound of viscous lava about 8 m high was being built. Vent 7, about 200 m north of the easternmost occurrence of October 1963 lava (Moore and Koyanagi, 1969, pl. 1), is the easternmost vent of the August eruption. Overflights were continued twice daily through August; no further eruptive activity or new cracks were seen anywhere along the rift zone, although fume and steam continued to issue from the new fissures for several weeks.

By the time the eruption was over, about $9.9\times10^4 m^3$ of lava had been erupted, 90 percent of it in Hiiaka Crater. About $8.55\times10^4 m^3$ had drained back into a fissure cutting the floor of Hiiaka, leaving only about $1.35\times10^4 m^3$ of lava on the surface (table 1). These relatively small volumes of lava represent the smallest output of any historic Kilauea eruption.

GROUND CRACKING

Ground cracking was extensive despite the small output of lava. Nine sets of vertical or nearly vertical cracks opened across the Chain of Craters Road between the Hilina Pali and Escape Roads, and others cut the Escape Road northeast of Pauahi Crater (fig. 12). The cracks were easily recognized where they crossed roads but were largely obscured by dense jungle elsewhere. The area of cracking may extend downrift along the projected trend of the eruptive fissures, rather than being restricted to the immediate areas of fissure zones themselves (fig. 1). Uprift, the cracks die out quickly west of the Chain of Craters Road.

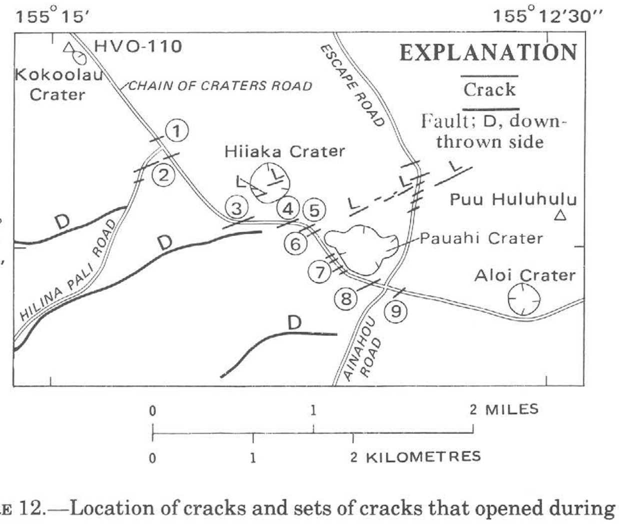


FIGURE 12.—Location of cracks and sets of cracks that opened during the August 1968 eruption in the vicinity of Hiiaka Crater. Numbers refer to crack or sets of cracks discussed in text. L, erupted lava; G, emitted gas only. Heavy lines, preexisting faults, downdropped side (D) indicated. HVO 110 and Puu Huluhulu are trilateration stations. Base map traces from vertical aerial photograph EKL-12CC-188; scale is uncorrected for distortion.

Most of the cracks had extensional displacements of 1 cm or less, but three in sets 1, 2, and 8 (fig. 12) opened 3.3, 6.6, and 5.1 cm, respectively, as detected at existing crack-measuring stations. The total dilation caused by cracking along the Chain of Craters Road was probably less than 25 cm in a N.20° W. direction. A few cracks opened with a small component of right-lateral displacement. The maximum amount of right-lateral displacement, 1.8 cm, was measured at set 1, where the amount of opening normal to the crack was 3.3 cm. The road near crack 3 southwest of Hiiaka Crater was buckled upward several centimetres.

Vertical displacement along most small cracks was negligible, but a releveling across five of the larger cracks showed vertical offsets of 1.5 to 3.4 cm. The south side was relatively uplifted on three cracks and downdropped on two cracks. The largest vertical displacements were across cracks 7 and 8.

Six open and several incipient fractures split the Escape Road between vents 2 and 3. These cracks showed extensional opening of 5 to 10 cm with minor vertical displacement. The eruptive fissures east and west of the Escape Road opened 25 to 60 cm and showed vertical displacements of several centimetres, with north side up in places and down in others.

Most cracks south and east of Hiiaka Crater, as well as the eruptive fissures (fig. 9), were arranged in a right-offset (left lateral) en echelon pattern, whereas most cracks between Hiiaka and the Hilina Pali Road showed a left-offset (right lateral) en echelon pattern. The presence of both right and left en echelon patterns is common throughout the Koae fault system (fig. 1), where short cracks are arranged in right- and left-offset senses on opposing limbs of arcuate master faults of tensional origin (Duffield, 1975).

The ground cracks opened or continued to widen at different times during the August eruption. Observations showed that most cracks across the Chain of Craters Road had reached their final width by 0610 August 22 (3 minutes after the first fume was sighted) and had probably opened during the seismic flurry early that morning (fig. 5). The cracks at site 8 (fig. 12), however, were small when crossed at 0645 but had grown so large by afternoon that road repairs were necessary. Cracks along the Escape Road widened 50 to 100 percent between 1430 August 22 and 1215 August 23. Cracking near the Hilina Pali Road was not observed until about 0830 August 23, despite heavy traffic on the road the previous afternoon. Two distances measured with a geodimeter across the zone of cracking each lengthened 4 cm between the afternoon of August 23 and September 4, probably in part reflecting continued cracking even though eruptive activity in that area had ended by midafternoon on August 22. Earthquake activity near the area of ground cracking (see following section and fig. 5) decreased shortly before the eruption began and remained at a low level thereafter, despite the continued opening and widening of some cracks.

SEISMICITY

Several hundred earthquakes were recorded by the Makaopuhi seismograph between 1500 August 21 and 0300 August 22 (figs. 1 and 5). The magnitudes of these quakes were so small and the epicenters so local to Makaopuhi that Ahua and North Pit stations, 10 and 14 km away, respectively, failed to record most of the quakes. Soon after the felt earthquake at 0248 August 22, high seismicity directly associated with summit deflation and magma intrusion began. Most of these earthquakes were centered beneath the eastern part of the Koae fault system and the upper east rift zone near Hiiaka Crater, at depths of 5 km or less (fig. 1). The seismic swarm was most intense between 0300 and 0600, when several hundred earthquakes in the Hiiaka area were recorded, but decreased rapidly when the eruption began. These quakes were apparently associated with dilation of the rift zone as dikes wedged their way upward toward the surface. When the surface was breached and the conduits widened, the number of earthquakes decreased. By 0700 August 22, earthquake activity on the rift zone had returned to a nearly normal level although the eruption had just begun. Shallow earthquakes beneath Kilauea Caldera increased as the summit slowly collapsed (fig. 5).

Traces of weak harmonic tremor, typically associated with shallow subsurface movement of magma at Kilauea, and local earthquakes appeared on the Makaopuhi seismogram between 2100 and 2300 August 21. By 0300 August 22, tremor was being recorded by most of the seismographs (fig. 5). Tremor amplitude increased rapidly at Ahua, and to a lesser degree at North Pit, at about 0630, shortly after east rift earthquake activity had declined and eruption in Hiiaka Crater began. The seismometer at Ahua was apparently close enough to Hiiaka to respond conspicuously to ground shaking caused by fountaining in the crater. In fact, tremor recorded at Ahua closely tracked the course of fountaining in Hiiaka, reaching maximum amplitude when lava fountains played at maximum heights and decreasing somewhat as fountaining subsided. In contrast, the intensity of tremor at the Makaopuhi seismometer continued to build up, apparently as a dike intruded downrift from Hiiaka. Peak tremor amplitudes were reached a day later, at about the time that eruption began at vent 4 (fig. 5). After 1000 August 23, tremor amplitude at Makaopuhi decreased, probably because the leading edge of the intruding dike moved downrift away from the station. Tremor declined at all stations for the next day and a half and had virtually ceased by 2300 August 25, though some eruptive activity continued at vent 7.

Throughout the eruption, a portable seismic unit was operated in several of the areas along the central and lower east rift zones that are poorly covered by permanent installations of the Hawaiian Volcano Observatory seismic net. Comparison of tremor amplitudes from all records shows that subsurface movement of magma was confined to zones beneath the summit area and along the upper and central ceast rift zone, terminating near vent 7 (fig. 1).

SUMMIT DEFORMATION

During the eruption, the summit area subsided and contracted substantially, presumably in response to withdrawal of magma from the central conduit system and intrusion into the east rift zone. Such a deformation pattern is typical of Kilauea flank eruptions.

TILT AND VERTICAL DISPLACEMENTS

The presence of a bowl-shaped area of subsidence in the summit region was determined by leveling surveys between July 15 and August 28, an interval that spans the eruption. The bowl was elongate in a northwest direction and centered 1–1.5 km southeast of Halemaumau (fig. 13). This subsidence took place during the August eruption, as deformation was slight and in the opposite sense prior to the eruption (fig. 2). The maximum measured vertical displacement of −19 cm is relative to a datum point 9.5 km northeast of the center of subsidence. The maximum subsidence that actually took place during deflation was probably somewhat

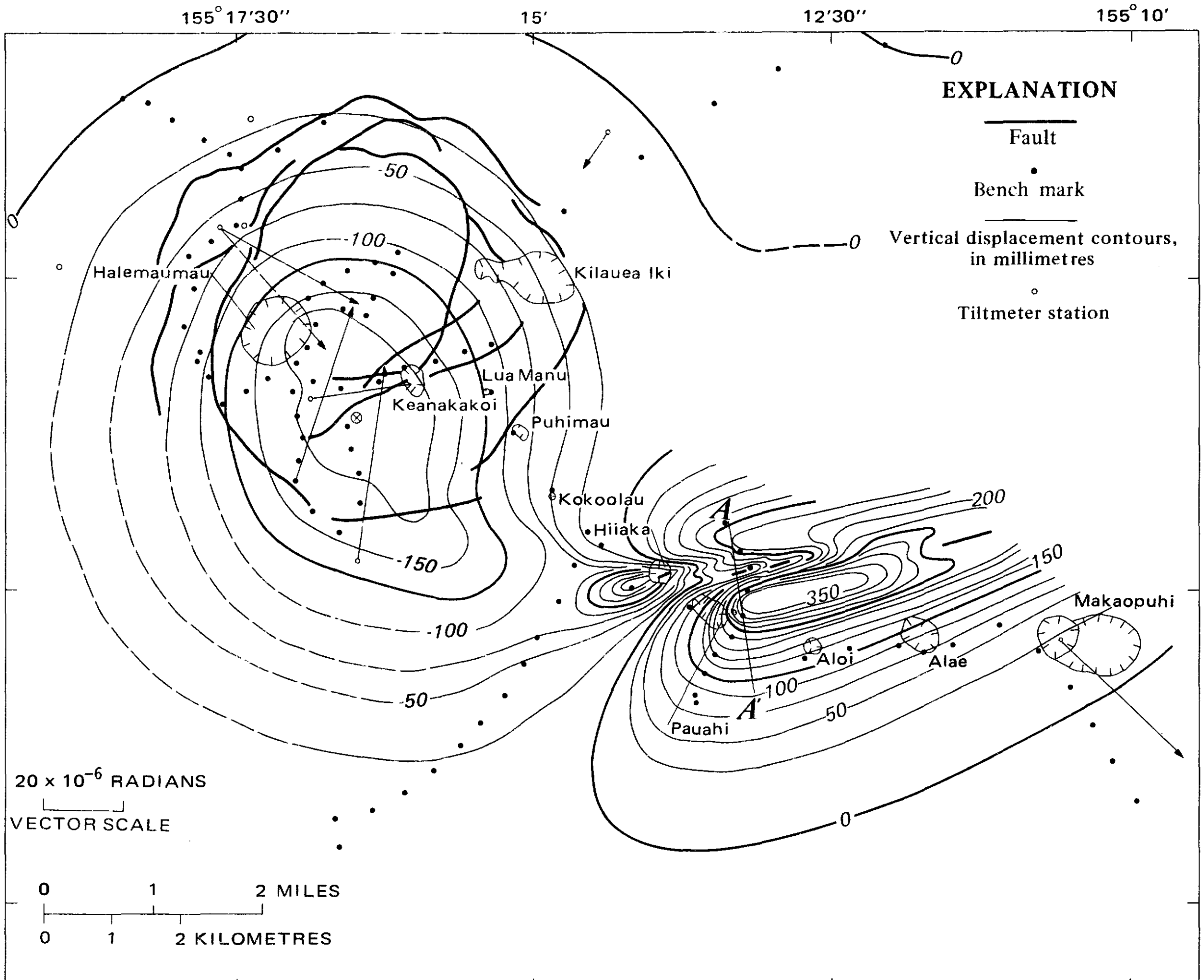


FIGURE 13.—Ground tilt (vectors) and vertical ground displacement (contours) for the period July 15 to August 28, 1968, which spans the August eruption. Dashed arrow at Uwekahuna short-base tilt station (northwest of Halemaumau) represents preferred empirical 20° adjustment of observed tilt (solid arrow). The tilt at Makaopuhi Crater was determined by releveling a grid of bench marks on the crust of the 1965 lava lake (Wright and others, 1968). Datum point for the leveling surveys is a bench mark 6 km northeast of Kilauea Iki. *A–A'*, line of the vertical displacement profile shown in figure 24.

greater, because the datum point also may have subsided a small amount and surveying was not completed until after the summit had already begun to reinflate (fig. 5).

Most tilt vectors for the interval that spans the eruption agree closely with the leveling data (fig. 13) and point toward the zone of maximum subsidence. An empirical clockwise adjustment of 20° applied to the Uwekahuna short-base vector brings it into agreement with the overall pattern. This adjustment seems to be valid for the episodes of rapid summit deflation connected with the August and October 1968 eruptions (see figs. 14 and 31) and with the rapid summit deflation accompanying the February 1969 east rift eruption (Swanson and others, 1975). Kinoshita, Swanson, and Jackson (1974, fig. 13) describe a similar perturbation of the Uwekahuna short-base tilt vector during the first 15 hours of the 1967–68 summit eruption.

The rate of east-west ground tilting at Uwekahuna vault can be calculated from the record of the continuously recording tiltmeter there (fig. 5). Tilting was rapid throughout the morning of August 22, about 4 microradians per hour during the first 12 hours of deflation, began to slow in the afternoon, and, with the exception of one reversal between 0520 and 0630 August 23, continually decreased until the morning of August 25, when summit reinflation began.

The sharp, 70-minute-long tilt reversal on August 23 coincides exactly in time with a small but abrupt decrease of tremor amplitude at the North Pit and Ahua seismic stations (arrows in fig. 5). This suggests a temporary blockage or constriction in the conduit system between the summit and the east rift zone. At 0630 the recording tiltmeter once again began registering deflation, although at a slower rate than before the reversal, and tremor amplitude increased at Ahua to about its former level. The tremor amplitude at North Pit did not increase, perhaps because blockage continued in the conduit very near the North Pit station.

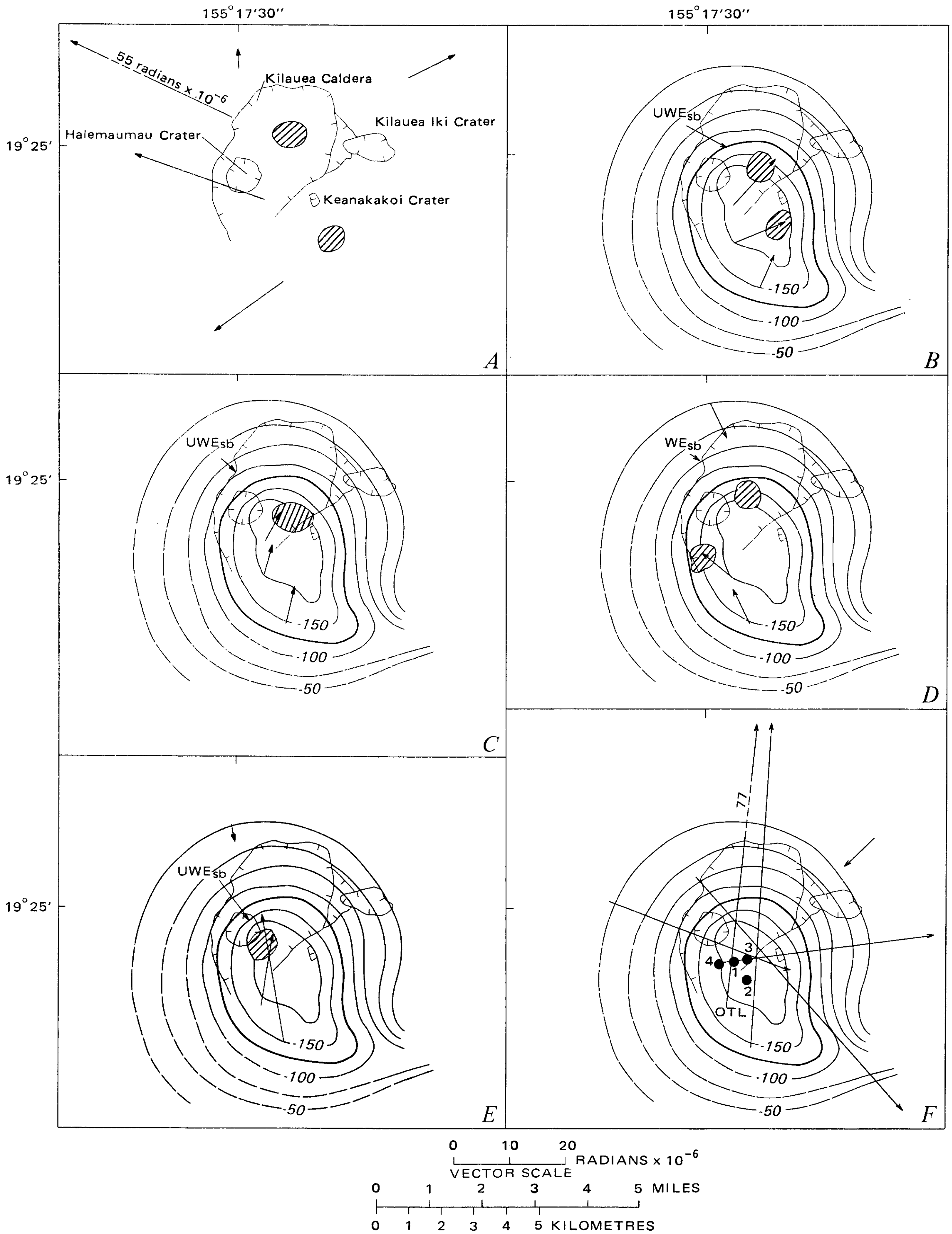
Several water-tube tilt stations in the summit region were occupied periodically between the morning of August 22 and August 25 to help trace the development of the subsidence bowl. The resulting tilt vectors (fig. 14) record a migration of the centers of subsidence between a time early in the eruption, when the deflation rate was rapid and all eruptive activity was centered near Hiiaka, and a time late in the eruption, when the deflation rate had slowed markedly and all eruptive activity was located farther downrift.

Deflation early in the eruption, from 1130 to 1630 August 22, was centered in nearly the same areas where preeruption inflation had been localized (compare figs. 14*A* and *B*). The two centers of deflation in figure 14*B* were probably active concurrently, because the period of tilting was only 5 hours long. Between 1630 and 2300 August 22 (fig. 14*C*), the southern deflation center had become largely inactive, and subsidence was concentrated east of Halemaumau. From 2300 August 22 to 1100 August 23 (fig. 14*D*), a center of deflation appeared in the southwest part of the caldera south of Halemaumau, although the northern center remained active. The activity of the southwestern center was short-lived, and subsidence became focused southeast of Halemaumau sometime between 1100 August 23 and 1200 of August 25 (fig. 14*E*), by which time summit inflation had resumed.

Several distinct centers of deflation were active at various times during the eruption, but the composite effect of their deflation over the entire eruption (figs. 13 and 14*F*) is that of a single broad zone of maximum subsidence centered about 1.5 km southeast of Halemaumau. This zone is virtually coextensive with those associated with previous east rift eruptions (fig. 14*F*). Perhaps each of the net deflation centers for previous flank eruptions was a composite of several distinct centers similar to those delineated in figure 14 for the August 1968 eruption.

Although similar detailed data are not available for earlier deflations, the migration of preeruption inflation centers was studied by Fiske and Kinoshita (1969a, fig. 5), who used tilt and leveling surveys to trace the summit deformation during the 22 months prior to the 1967–68 summit eruption. They found that the center of inflation migrated with time. The earliest center was about 1 km east of Halemaumau. The center then moved to a position 1.5 km northeast of Halemaumau, quickly shifted to a location about 2 km southeast of Halemaumau, and then oscillated in a 3-km-wide, west-trending zone 1–1.5 km south of Halemaumau until the eruption began.

All of the centers of vertical deformation just before and during the August 1968 eruption lie within the zone of uplift delineated by Fiske and Kinoshita (1969a). However, the migration sequence of subsidence centers during the 1968 deflation was not the reverse of the sequence during the inflation, as might be expected if the deformation were caused by movement of magma in a system of simply interconnected chambers. Possibly this lack of correspondence is related to the great difference in duration of inflation and deflation. The filling of the reservoir before the 1967 outbreak took place over 22 months, whereas the 1968 emptying took place in 3 days, a time difference of two orders of magnitude. It is perhaps too much to expect of the chamber plexus, whatever its geometry and nature, to respond in the same manner under such different rates of strain.


155°17'30"
155°17'30"
19°25'
19°25'
19°25'
55 radians x 10⁻⁶
Kilauea Caldera
Kilauea Iki Crater
Halemaumau Crater
Keanakakoi Crater
A
UWEsb
-150
-100
-50
B
UWEsb
-150
-100
-50
C
WEsb
-150
-100
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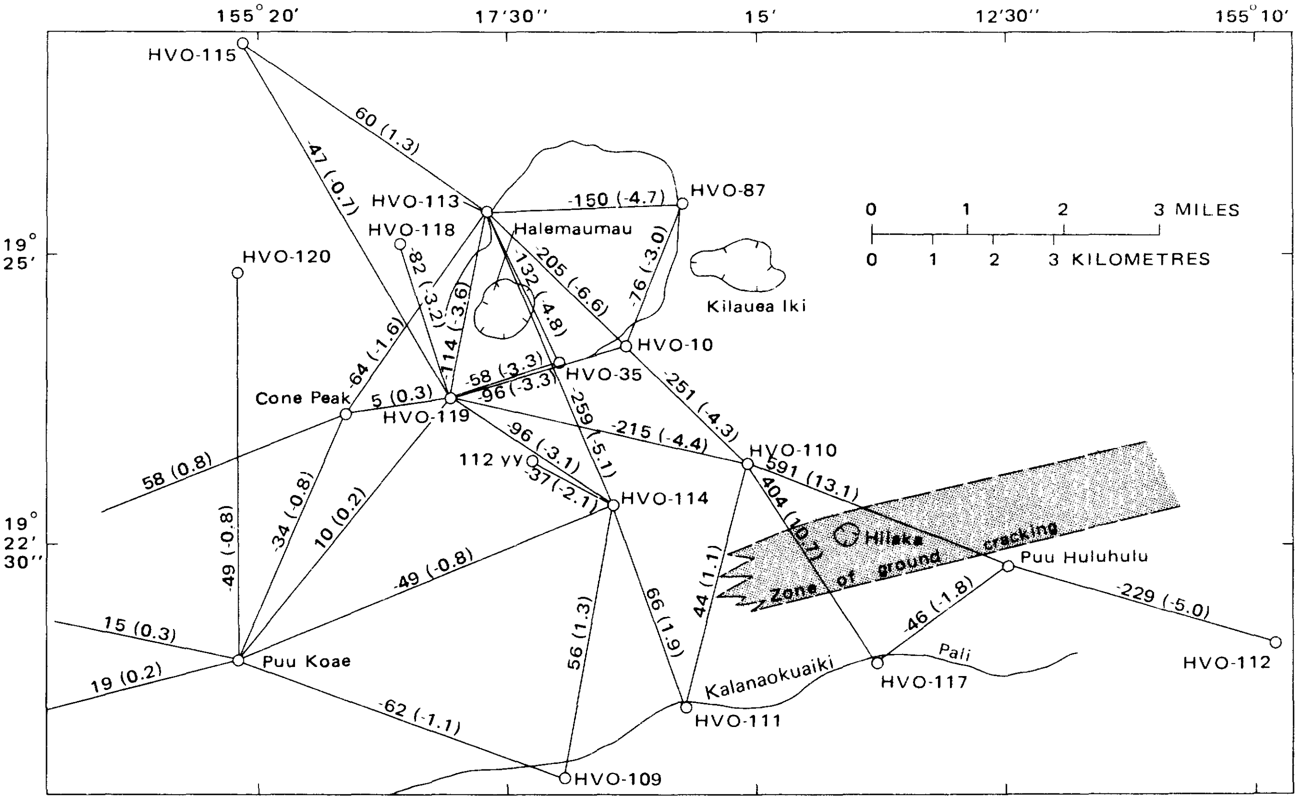

FIGURE 15.—Change in length (in mm) of geodimeter lines in Kilauea Volcano summit area for August 1968 eruption. Extensional strains (change in length divided by length) are plotted in units of 10^{-5} (cm/km) and shown in parentheses. Survey period is July 22–24 to August 23–24 except for distances involving Puu Koae and the distance west of Cone Peak, measured on September 3.

HORIZONTAL DISPLACEMENT AND STRAINS

The results of trilateration surveys conducted on July 22–24 and August 23–24, 1968, plotted in figure 15, show that nearly all measured linear strains are negative in the summit area, reaching values as high as -6.6×10^{-5}. Measured distances across the center of deformation contracted more than other distances. The data clearly show that the summit area contracted as well as subsided.

Horizontal displacements were derived by graphic means (Kinoshita and others, 1974) relative to a 4.4-km baseline west of Puu Koae (fig. 16). For the first time at Kilauea, the horizontal control network of the Hawaiian Volcano Observatory was tied to a baseline that could be considered fixed throughout the eruption. However, the distances involving Puu Koae and one of the baseline stations were not measured until September 3 (see fig. 15), whereas the rest of the network was surveyed on August 23 and 24. During this 10-day delay, substantial tilting occurred as the summit reinflated (fig. 2); the distance data, then, must be adjusted before displacements can be determined. The displacements in figure 16 were obtained by adjusting the distances measured on September 3 for a 25-microradian inflationary tilt centered 0.5 km northeast of Halemaumau, using a 3-km, point-source elastic model (see section "A Vertical Displacement and Tilt Model for the Summit"). The location and magnitude of the tilt were taken from the north-south and east-west components of the Uwekahuna short-base tiltmeter adjusted for a 20° error in azimuth (see section "Tilt and Vertical Displacement"). The derived displacements are not sufficiently reliable for detailed interpretation, but they

FIGURE 14.—Changes in ground tilt at the summit area of Kilauea before and during the August 1968 eruption. *A*, mid-February to mid-June 1968; *B*, 1130 to 1630 August 22; *C*, 1630 to 2300 August 22; *D*, 2300 August 22 to 1100 August 23; *E*, 1100 August 23 to 1200 August 25; *F*, mid-June to August 28, 1968. Tilt vector at Uwekahuna short-base water-tube tilt station, UWE_{sb}, has been adjusted by 20° clockwise rotation (*B* through *E*), an empirical adjustment that appears valid during times of rapid summit deflation. Numbered solid circles in *F*, approximate centers of subsidence for four previous east rift eruptions: 1, Eaton (1962); 2, Fiske and Koyanagi (1968); 3, Wright, Kinoshita and Peck (1968); 4, Moore and Krivoy (1964). Subsidence contours *B* through *E* are from figure 13. Hachured areas are centers of deformation. In *F*, the tilt at Outlet (OTL) is 77 microradians.

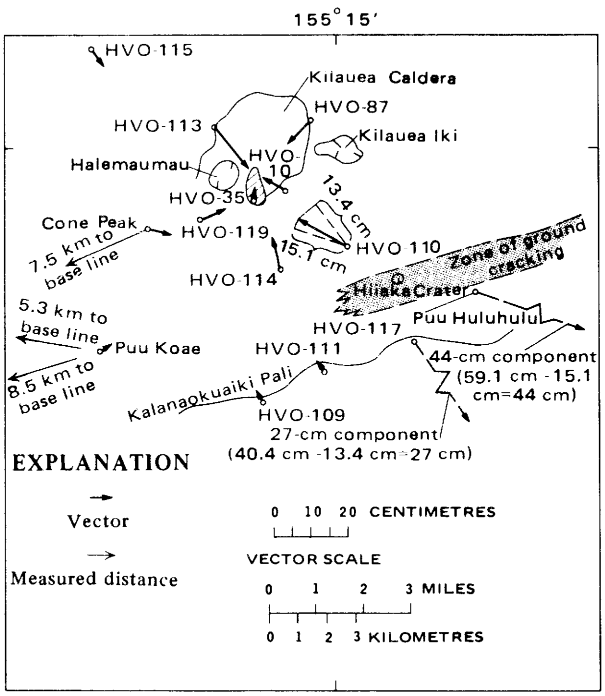

FIGURE 16.—Horizontal ground displacement (vectors) between July 22–24 and August 23–25, 1968, a period that spans the August eruption. See text for assumptions used in deriving the displacements. Lined area shows general focus of displacements. Displacements cannot be determined for HVO 117 and Puu Huluhulu, not tied into two or more stations in the trilateration network (see fig. 15). However, distances from HVO 110 to both HVO 117 and Puu Huluhulu were measured, and the component of displacement away from HVO 110 and the way it was determined are shown.

provide a qualitative picture of the horizontal deformation during the eruption.

Bench marks in the summit region were displaced as much as 15 cm toward an elongate area remarkably similar to that defined by the leveling survey (compare figs. 13 and 16). Only the displacement at Cone Peak departs significantly from this pattern; data obtained for subsequent east rift eruptions indicate that this departure is common, possibly because Cone Peak lies within the highly fractured southwest rift zone. The center of horizontal deformation is slightly north of the center of vertical deformation (fig. 13). This offset may be the result of poor data or the timing of the summit horizontal survey, which was made while subsidence was still underway and the locus of deformation was migrating southward (fig. 14).

Dilatational strain for selected survey triangles in the summit area, contoured in figure 17, was computed from the adjusted data. Most of the dilatational strains are negative, with a maximum value of about -10^{-4}. The zone of maximum dilatation agrees well with the center of net deformation defined by other means. Dilatational strain in the Koae fault system, on the southern fringe of the summit area, was positive, possibly in part because of slight widening of cracks within the Koae (Duffield, 1975).

DEFORMATION OF THE UPPER EAST RIFT ZONE

Contours of equal vertical ground displacement (fig. 13) define an area of uplift on the upper east rift zone extending eastward from Pauahi Crater. There are too few bench marks to completely define the shape of the area of uplift, but it seems reasonable that the uplift should more or less parallel the fissures and ground cracks and it is so portrayed. The uplift extended at least as far east as Makaopuhi Crater, where a southeastward tilt of 50×10^{-6} radians was recorded over the eruption. The uplift is apparently asymmetric, if the displacement profile measured along the line of bench marks just east of Pauahi Crater is typical. Maximum displacement is 33 cm south of vent 2 but only 12 cm at a comparable distance north of vent 2.

A trough of relative subsidence is superimposed on the crest of the uplift. Subsidence is a maximum of 20 cm at a bench mark 300 m southwest of Hiiaka Crater and decreases eastward (fig. 13). A bench mark just east of Pauahi lies in the trough but was actually uplifted 4 cm relative to the survey datum. The subsidence trough probably developed as a keystone graben along the crest of the uplift.

Two geodimeter lines, HVO 110–HVO 117 and HVO 110–Puu Huluhulu, cross the zone of cracking; both lengthened appreciably between July 22 and August 23 (fig. 15), indicating eruption-related dilation of the rift

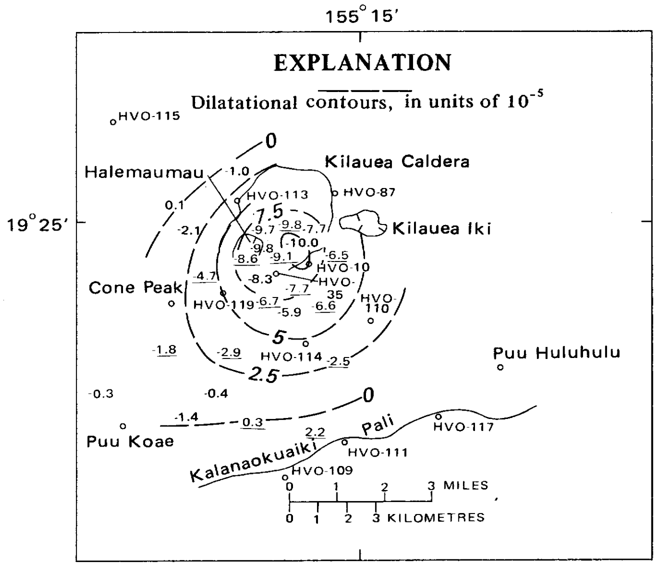

FIGURE 17.—Dilatational strain (change in area divided by area) for the August 1968 eruption. Data points plotted at center of gravity of each strain triangle for which dilatation was computed. Underlined values considered most reliable because of triangle shape and size.

zone. Each line then lengthened 4 cm between the afternoons of August 23 and September 4. This extension probably is the net result of continued subsidence of the summit region and continued dilation within the zone of ground cracking. Both lines south of the zone of cracking, HVO 117–Puu Huluhulu and Puu Huluhulu–HVO 112, shortened, probably as a result of areal contraction and closing of existing cracks.

Horizontal displacements at HVO 117, Puu Huluhulu, and HVO 112 cannot be determined directly from the existing trilateration network (fig. 15) but can be estimated by assuming that displacements at HVO 117 and HVO 112 were oriented perpendicular to the average trend of the cracks and eruptive fissures. This assumption is reasonable, based on the observed direction of opening of cracks and subsequent observations of ground displacement on the rift zone (Swanson and others, 1976). If this assumption and the measured components of displacement away from HVO 110 at HVO 117 and Puu Huluhulu are used (fig. 16), displacements can be derived and shown graphically (fig. 18). The azimuth of displacement at Puu Huluhulu was derived, not assumed to be perpendicular to the fissures, and is therefore a good check on its reasonableness. The indicated displacement at Puu Huluhulu, the station nearest the zone of cracking, is about 63 cm, approximately equal to the amount of opening of the nearest eruptive fissure but probably less than the total amount of dilation in the zone of ground cracking.

The horizontal displacement at station HVO 110 is of special interest (fig. 16). This station is only 2 km northwest of Hiiaka Crater, yet both the direction and magnitude of its displacement appear to chiefly reflect the summit deformation, not the effects of ground rupture near the site of eruption. In contrast, the horizontal displacement of HVO 117, a comparable distance south of Hiiaka, must be at least 12 cm more than that of HVO 110 (fig. 16) and is probably oriented perpendicular to the zone of cracking. Several investigators (Fiske and Kinoshita, 1969b; Swanson and others, 1976; Koyanagi and others, 1972) have proposed that the north flank of Kilauea (that portion north of the east rift zone) is comparatively unaffected by intrusion of magma into the rift zone, whereas the south flank is displaced southeastward away from the rift zone, as magma dilates it. The contrast between the displacements at HVO 110 and HVO 117 is consistent with this proposal.

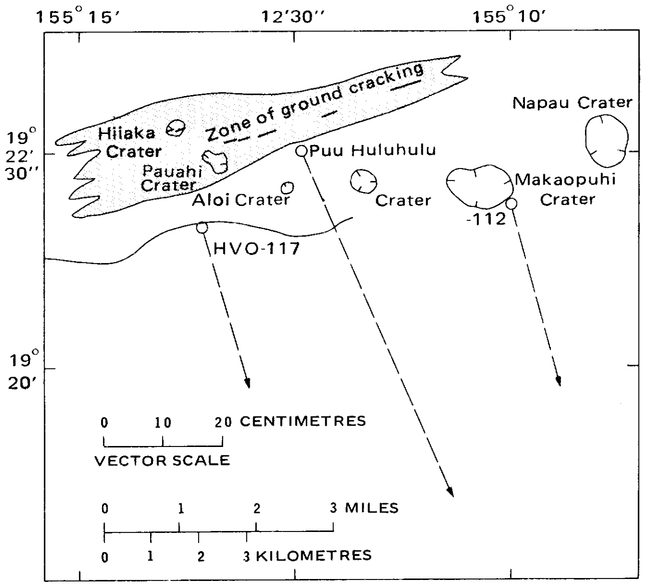

FIGURE 18.—Possible horizontal displacement (dashed vectors) near site of August 1968 eruption, July 22–24 to August 23–24, 1968. Displacements for HVO 117 and HVO 112 assumed to be perpendicular to new cracks. See text for explanation. Heavy lines within area of ground cracking are eruptive fissures.

A VERTICAL DISPLACEMENT AND TILT MODEL FOR THE SUMMIT

Although the summit deflation during the August eruption was complex, the net result approximates a single center of subsidence, and the tilt and vertical displacement data fit a point-source elastic model remarkably well, as Mogi (1958), Eaton (1962), and Fiske and Kinoshita (1969a) found for earlier Kilauea eruptions. The horizontal displacement data cannot be used in model studies of this eruption, because of their relatively poor quality. For model comparison of vertical displacements, all bench marks near the summit were used except those on the upper east rift zone near the site of local uplift and the five adjacent to the east side of Halemaumau, which were substantially affected by crustal loading during the 1967–68 Halemaumau eruption (Kinoshita and others, 1969) and probably continued to subside throughout the July 15 to August 28 survey period.

The observed vertical displacement data best match theoretical curves plotted from Mogi's equations (1958) for a focal depth of 3.2 km (fig. 19). This depth agrees with those commonly obtained at Kilauea (Fiske and Kinoshita, 1969a; Hawaiian Volcano Observatory, unpub. data, 1969). The vertical displacements measured at distances farther than 4 km from the center of subsidence, however, diverge markedly from the theoretical curve.

The maximum theoretical value of tilt Tm, which occurs at distance $f/2$ from the center of deformation, can be computed from the vertical displacement curve in figure 19 to be 55×10^{-6} radians, by using the relation derived by Eaton (1962):

$$\Delta ho = -1.16\, fTm,^{2} \qquad (1)$$

[2]This equation is incorrectly given as $\Delta ho = -0.83 fTm$ in Eaton (1962).

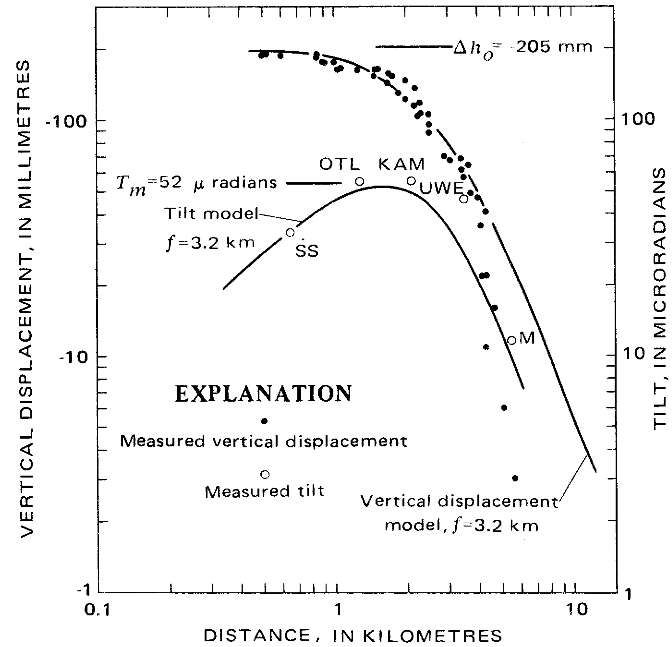

FIGURE 19.—Measured vertical ground displacement and tilt, compared with displacement and tilt curves for mathematical model with a spherical source depth of 3.2 km relative to the horizontal distance (d) from the center of deformation to the data point, (Mogi, 1958). Tm and Δho, theoretical maximum tilt and vertical displacement, respectively; f, the vertical distance (depth) from the center of the buried source to the ground surface. Bench marks not shown because of positive or zero values, arranged in order of d and Δh: 5.6, 2; 5.8, 1; 7.0, 1; 8.0, 5; 9.5, 0. Tilt stations labeled as in figure 1.

where Δho is the maximum theoretical vertical displacement (205 mm in fig. 19) and f is the focal depth (3.2 km in fig. 19). By plotting the theoretical curve for this Tm and $f=3.2$, a reasonable fit to the observed tilt data is obtained (fig. 19). If Tm is increased to 60×10^{-6} radians the fit is improved (fig. 20). If equation (1) is used to find the equivalent Δho of 223 mm, a better fit is obtained for the vertical displacement data (fig. 20). The indicated 18 mm increase in value of Δho between figures 19 and 20, if significant, could be explained if the survey datum point had been displaced 18 mm downward or if cumulative survey errors total -18 mm. Almost certainly, however, the inability of Kilauea to respond with perfect elasticity, and the oversimplification of the complex magma reservoir into a small sphere, contribute significantly to the departures from the theoretical curves.

Two other elastic deformation models for the summit region of Kilauea have been recently proposed. One, by Walsh and Decker (1971), assumed a vertical line source of dilatation. The other, by Yokoyama (1971), employs a small, spherical thrust-pressure source rather than the small, spherical, constant displacement source of Mogi (1958). Both models are here compared with the observed vertical displacement data used in the Mogi model calculations.

A comparison of the model for a vertical line source to the summit tilt data (fig. 21) shows that the best match to the tilt data is for a model of 2.5 km depth to the top of the line source. As the tilt data need not be referenced to a stable datum point outside the area of deformation, we can compute an equivalent vertical displacement model that will fit the survey data if we have chosen the correct model and there are no survey errors. From the relation $\Delta ho=2.6 f\, Tm$, the maximum vertical displacement Δho for a 2.5-km-deep line source is -364 mm (J. B. Walsh, written commun., 1972). The discrepancy between the maximum measured vertical displacement, -196 mm, and the predicted maximum vertical displacement, -364 mm, is far too great to be considered a survey error. It seems, then, that for the August 1968 eruption, the summit vertical displacement and tilt data are not compatible with data for a vertical line source of dilatation. Walsh and Decker (1971, p. 3299) point out, however, that the displacement field produced by a small change in length of a vertical line source will be the same as that for a change in intensity of a point source. The fit obtained for a Mogi-type model would apply equally well to a vertical column of magma that decreases slightly in length during eruption, a reasonable possibility.

In figure 22, the vertical displacement data from

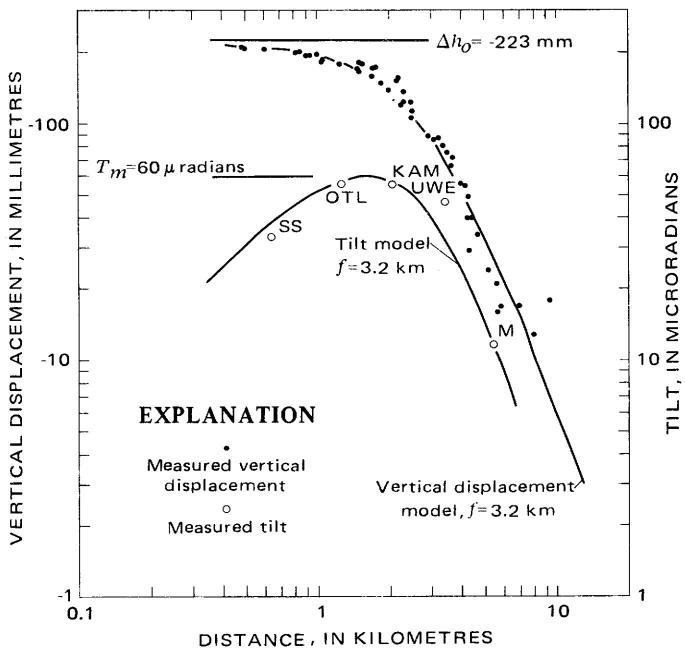

FIGURE 20.—Observed tilt data from figure 19 fitted to a theoretical tilt curve (Mogi, 1958) having a theoretical maximum tilt (Tm) of 60 microradians. The measured vertical displacement data have been changed by -18 mm, using the relation $\Delta ho= -1.16\ Tm$ (Eaton, 1962), and refitted to a theoretical vertical displacement curve having a Δho of -223 mm. The model curves for tilt and vertical displacements are for a spherical source depth of 3.2 km, as in figure 19. All symbols as in figure 19. Vertical displacement and tilt data plotted relative to distance (d) from center of subsidence.

figure 19 are compared with a model curve for a small spherical source of the thrust-pressure type from Yokoyama (1971). As Yokoyama gives no tilt models, only models for the leveling data are treated here. Model curves for source depths of 2.5 km and 3 km fit the observed data reasonably well to a distance of about 2.5 km from the center of subsidence, and are very similar to the 3.2 km fit for the Mogi model (fig. 19). Beyond 2.5 km, however, the field data depart sharply from the model curves, and at $d=5.7$ km the departure is 32 mm. From later leveling surveys in which carefully calibrated rods were used (Hawaiian Volcano Observatory, unpub. data, 1971), it appears that a 32-mm vertical discrepancy at 5.7 km from the epicenter of the postulated source is larger than would be expected from either rod or datum errors. The model of Yokoyama, therefore, does not seem to explain the summit deformation accompanying the August eruption.

A VERTICAL DISPLACEMENT DIKE MODEL FOR THE UPPER EAST RIFT ZONE

Several lines of evidence indicate that magma is injected into Kilauea's east rift zone as dikes, but the attitude of these dikes is not known. Most dikes exposed in deeply eroded rift zones of older volcanoes in Hawaii are nearly vertical. Estimates for Kilauea's unexposed

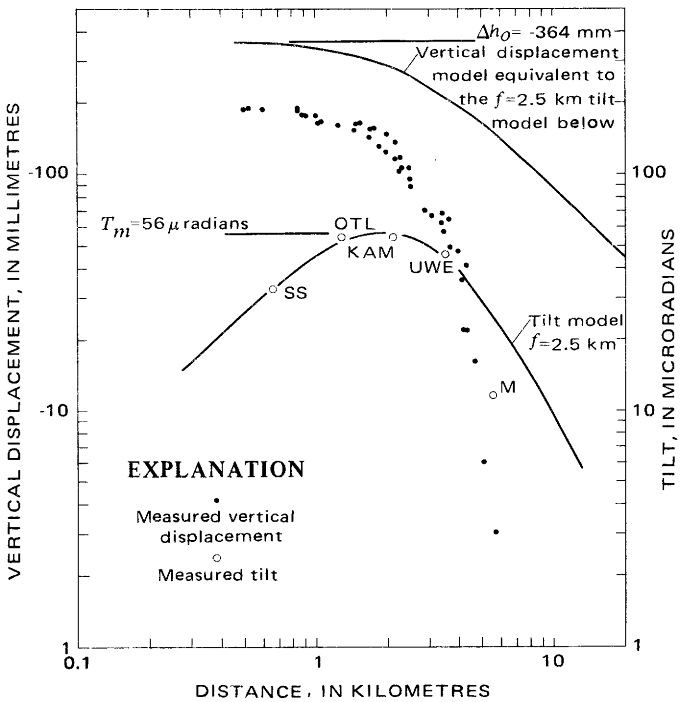

FIGURE 21.—Measured tilt and vertical ground displacement for August 1968 eruption compared with model curves for a vertical line source (Walsh and Decker, 1971) whose top is at 2.5 km depth. Bench marks not shown because of positive or zero values, arranged in order of d and Δh: 5.6, 2; 5.8, 1; 7.0, 1; 8.0, 5; 9.5, 0. All vertical displacement and tilt data plotted relative to distance (d) from center of subsidence.

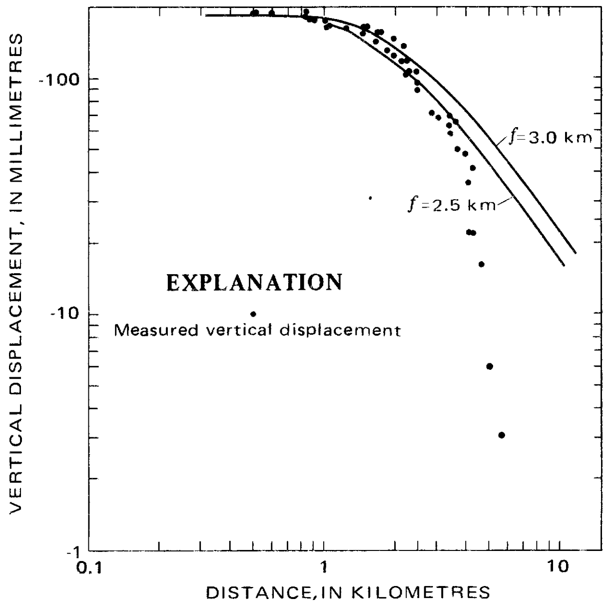

FIGURE 22.—Measured vertical displacement data for the August 1968 eruption compared with models for a small spherical thrust-pressure source (Yokoyama, 1971) at depths (f) of 2.5 and 3.0 km relative to distance (d) from center of subsidence. Bench marks not shown because of positive or zero values, arranged in order of d and Δh: 5.6, 2; 5.8, 1; 7.0, 1; 8.0, 5; 9.5, 0.

dikes range from north-dipping (Ryall and Bennett, 1968) to nearly vertical (Hill, 1969; Fiske and Kinoshita, 1969b) to south-dipping (Moore and Krivoy, 1964); most recent workers (for example, Swanson and others, 1976; Fiske and Jackson, 1972) favor nearly vertical.

A vertical displacement profile (A–A', fig. 13) across an active part of the rift zone, obtained along the Escape and Ainahou Roads during the August 1968 eruption, provides an opportunity to compare these displacements with theoretical displacements resulting from dikes of different attitudes injected into a perfectly elastic medium. The results of this comparison are not conclusive, because of probable structural complications related to dike injection, but they suggest that the August 1968 dikes are steeply south-dipping to nearly vertical.

Theoretical vertical displacement curves, calculated by J. H. Dieterich (U.S. Geol. Survey, written commun., 1972) using the finite-element method[3] for constant pressure dikes dipping 60°, 75°, and 90° embedded in a perfectly elastic, homogeneous half space, are shown in figure 23. All model dikes have a strike length of infinity, a dip length of $4f$, and a thickness of $9.25\times10^{-4} f$, where f equals the depth from the ground surface to the top of the dike dipping at an angle θ.

Inspection of the curves in figure 23 shows that vertical displacements over nonvertical dikes exhibit

[3]Information on finite-element methods of modeling and calculation may be found in Clough (1965) and Dieterich and Onat (1969).

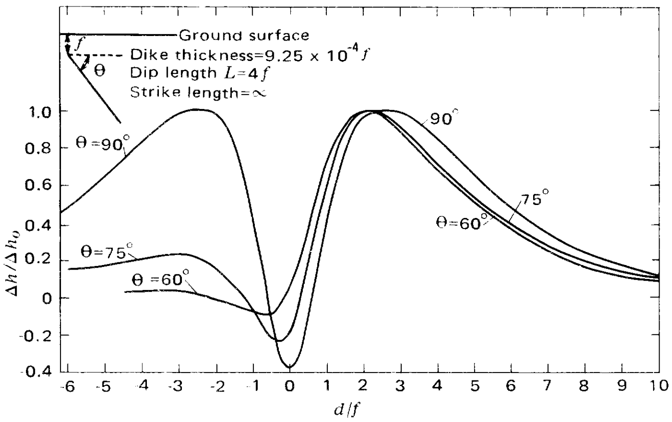

FIGURE 23.—Theoretical vertical displacement curves calculated by the finite-element method by J. H. Dieterich (written commun., 1972) for three dikes of infinite length dipping 60°, 75°, and 90° respectively. θ, dip angle; f, distance from ground surface to top of dike; d, horizontal distance from epicentral position of top of dike to bench mark. $\Delta h/\Delta ho$, ratio of observed displacement to maximum displacement.

marked transverse asymmetry and that the portions of the theoretical curves away from the zero point in the updip direction are more sensitive to dip variations than the portions in the downdip direction.

Comparison of the observed displacement data, projected into profile *A–A′* (fig. 13), with the theoretical curves suggests that the August dike dips steeply southward and has its top about 140 m below the surface (fig. 24*A*); actually, of course, the dike reached the surface along the active fissures. The center of the subsidence trough on profile *A–A′* (fig. 13) coincides with the area of negative displacements on the theoretical curves, and the projection of the location of vent 2 (the nearest vent to the profile) into the cross section coincides closely with the minimum in the 75° theoretical curve.

The largest discrepancy between the observed and theoretical displacements occurs south of the dike at distances greater than 0.5 km. Part of this discrepancy can be resolved by applying the −18 mm adjustment suggested by the vertical displacement and tilt models at the summit (figs. 19–20). When the adjusted field data are matched to theoretical curves for dikes dipping 75° to 90° (fig. 24*B*), the fit is improved, and the depth f is increased only slightly. A nearly perfect bracket of the field data (fig. 24*C*) by the 75° and 90° curves may be obtained if an additional −35 mm adjustment is made to all the data; this adjustment, however, cannot be justified by any observations or independent theoretical considerations.

The dike model in figure 23, the only finite-element model now available, assumes a dike thickness of $9.25\times10^{-4} f$, or 0.15 m for the match in figure 24*C*. Probable fits for other combinations of dike thickness and depth could be made if theoretical curves were available. The observed width of the fissure opening at vent 2 was about 0.6 m, that at vent 4 between 0.5 and 1 m. These widths may be more realistic values for the dike thickness at depth than that derived from the model.

It should be kept in mind that profile *A–A′* crosses an area of preexisting faults, some of which moved and ruptured the ground surface during the eruption. Therefore, the measured ground displacements do not reflect entirely elastic behavior. We examined ways in which the elastic model could be combined with field observations of ground rupture to give a satisfactory explanation for the ground displacements.

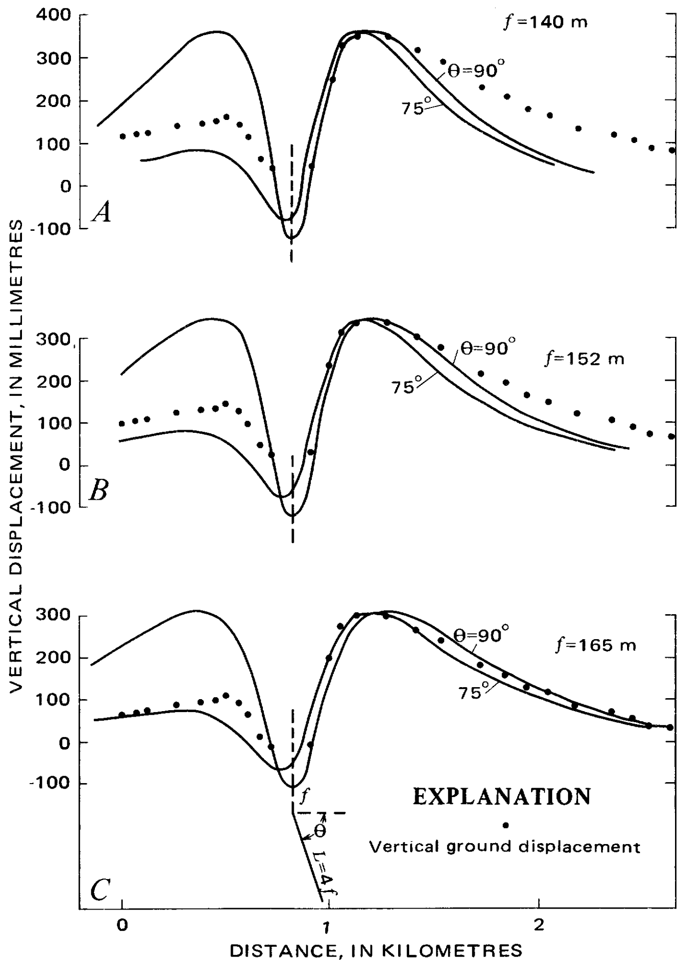

FIGURE 24.—Finite-element model curves for dikes dipping 75° and 90° matched to vertical ground displacements measured along the Escape and Ainahou Roads projected to profile *A–A′* (fig. 13). Data plotted relative to distance from northernmost bench mark. *A*, field data matched to model curves for f=140 m; *B*, data points from *A* minus 18 mm and rematched to curves for f=152 m; *C*, data points from *B* minus 35 mm and rematched to model curves for f=165 m. All plots suggest a dip between 75° and 90°. Symbols as in figure 23.

Geologic relations suggest that the asymmetry of the observed displacement profile can be at least partly explained in a way other than simple diking—by uplift and tilting of fault blocks south of the dike, rather than by intrusion of nonvertical dikes into an elastic medium. Fault blocks in the Koae fault system (Duffield, 1975; Duffield and Nakamura, 1973) are generally uplifted along normal faults bounding the north side of the block and are tilted southward. Uplift and tilting of such blocks, observed and measured during the December 1965 eruption, were interpreted by Fiske and Koyanagi (1968) to result from elastic rebound of accumulated strain during episodes of faulting. The Koae fault system intersects the east rift zone near Hiiaka, and similar tilted fault blocks probably occur within the rift zone, although they are largely buried by flows from frequent eruptions.

Uplift and tilting of fault blocks south of the dike, owing to elastic rebound during opening of the eruptive fissure and other cracks, superimposed on a symmetrical uplift caused by injection of a vertical dike, could have produced the observed asymmetric displacement profile along the Escape and Ainahou Roads. Figure 25 is a model for such a situation, where net vertical displacements are a combination of nonelastic tilting of the block south of the zone of fissures and symmetrical elastic deformation on both sides of the zone of ground cracking due to emplacement of a vertical dike. By subtracting the vertical displacements caused by a vertical dike (fig. 23) with *f* equaling 162 m from the adjusted vertical displacements (fig. 24*B*), a residual curve is obtained that could approximate a number of straight-line segments bounded by normal faults. The placement of the normal faults shown in figure 25 is conjectural, although zones of ground cracks do exist in those areas.

In summary, the observed displacement data, interpreted solely in terms of an ideal dike intruding a perfectly elastic medium, suggest a steep southward dip greater than 75° but less than 90°. If the possibility of uplifted and tilted fault blocks south of the eruptive fissure is considered, it seems likely that the dip of the dike could be nearly vertical.

PETROGRAPHY AND CHEMISTRY OF THE AUGUST 1968 LAVA

Four chemical analyses (table 2, columns 1–4) indicate that the August 1968 lava is tholeiitic olivine basalt. The differences in composition among the four analyses can be explained solely in terms of addition or subtraction of olivine (Fo_{84}). The lava is unusually magnesian for lava erupted along the east rift zone, and the two spatter samples from Hiiaka Crater contain more MgO than any other analyzed lava from a historic east rift eruption except for some 1840 lava erupted low

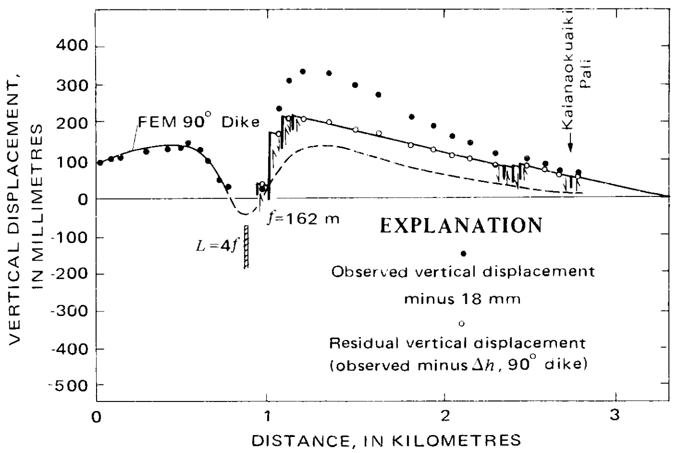

FIGURE 25.—Residual vertical displacement across east rift zone (profile *A–A′*, fig. 13) derived by subtracting vertical displacements calculated for finite-element method (FEM) vertical dike of *f* equal to 162 m (fig. 23) from adjusted data points of figure 24*B*, plotted relative to distance from northernmost bench mark. Straight-line segments of residual curve suggest asymmetric profile of vertical displacements could result from uplift and tilting of blocks south of fissure zone combined with uplift above a vertical dike beneath fissure zone. Symbols as in figure 23.

on the rift zone (Wright and Fiske, 1971, table 4a). The August 1968 analyses are examined in detail by Wright, Swanson, and Duffield (1975), who find that the August lava is chemically equivalent to a mixture of some of the first lava erupted during the 1969–71 eruption with lesser amounts of 1967–68 summit lava and olivine.

Spatter from the main vent in Hiiaka contains olivine and trace amounts of spinel as the only crystalline phases (table 3), which indicates a high temperature of eruption. This is consistent with temperatures within fountains measured by optical pyrometer from the rim of the crater, 150–200 m away. The measured temperatures were consistently 1145°C; because of the distance, these should be corrected to at least 1180°C (Wright and others, 1968, table 5). The corrected temperature is near the temperature at which plagioclase and pyroxene start to crystallize in Kilauean lava.

The phenocryst assemblages of the August lava change systematically downrift. Spatter erupted at vents 2 and 3 is similar to that from the Hiiaka main vent, containing phenocrysts of olivine and spinel only; spatter at vent 4 carries, in addition, trace amounts of small plagioclase and clinopyroxene phenocrysts (table 3). The only sample of spatter analyzed from farther downrift, at vent 5, contains significant amounts of plagioclase and clinopyroxene phenocrysts; this spatter was erupted from very low weak fountains. No true spatter or pumice was erupted from vents 6 and 7; rather, viscous lava slowly issued to the surface with

TABLE 2.—*Chemical analyses of lava from the August and October 1968 eruptions of Kilauea Volcano*

[Analyzed in the laboratory of the U.S. Geological Survey, Denver, under the direction of L. C. Peck using methods described by Peck (1964). Analysts: Hi68-2, Hi68-3, N68-8, N68-14—G. O. Riddle; Hi68-12, Hi68-14, N68-4, and N68-11—E. L. Munson. Figures are percentages]

Date	August				October			
	22	22	23	26	7	13	14	14
Sample No.	Hi68-2	Hi68-3	Hi68-12	Hi68-14	N68-14	N68-4	N68-8	N68-11
SiO_2	47.84	[1]48.06	49.31	48.90	50.38	50.33	50.39	50.11
Al_2O_3	11.00	[1]11.32	12.49	12.06	14.22	13.67	14.35	13.63
Fe_2O_3	1.02	1.06	1.08	1.73	1.56	1.44	1.35	1.22
FeO	10.98	10.92	10.48	9.99	9.81	9.88	10.08	10.10
MgO	15.44	15.09	11.04	12.27	6.76	7.71	6.52	8.22
CaO	8.97	9.08	10.21	9.86	10.95	10.89	10.74	10.87
Na_2O	1.81	1.81	2.12	1.99	2.42	2.30	2.47	2.32
K_2O	.41	.41	.47	.45	.55	.51	.59	.52
H_2O+	.07	.06	.07	.00	.07	.04	.05	.05
H_2O-	.00	.00	.00	.01	.00	.00	.01	.02
TiO_2	2.01	2.05	2.37	2.29	2.77	2.66	2.91	2.57
P_2O_5	.32	.20	.24	.23	.27	.27	.28	.26
MnO	.18	.18	.17	.17	.17	.17	.17	.17
CO_2	.01	.01	.01	.01	.01	.02	.01	.01
Cl	.01	.01	.02	.01	.01	.02	.01	.02
F	.03	.03	.03	.04	.04	.04	.05	.04
Subtotal	100.10	100.29	100.11	100.01	99.99	99.95	99.98	100.13
Less	.01	.01	.01	.02	.02	.02	.02	.02
Total	100.09	100.28	100.10	99.99	99.97	99.93	99.96	100.11

August 1968:

Hi68-2: Spatter erupted on August 22 from main vent in Hiiaka Crater.

Hi68-3: Spatter erupted on August 22 from short-lived vent on the southwest wall of Hiiaka Crater.

Hi68-12: Spatter erupted on August 23 from vent 4 northwest of Makaopuhi Crater.

Hi68-14: Glassy flow crust erupted on August 26 from easternmost vent (7) of eruption.

October 1968:

N68-14: Spatter erupted on October 7 from westernmost vent (A) on Kane Nui o Hamo.

N68-4: Spatter erupted at 1553 October 13 from vent B, 0.5 km west of Napau Crater.

N68-8: Spatter erupted on October 14 from easternmost vent (F) of eruption.

N68-11: Spatter on October 14 from vent D, 0.5 km east of Napau Crater.

[1]These values are corrected from initially reported erroneous values.

only occasional bursts of gas blasting the lava into pasty clots.

A sample of glassy skin from one of the flows at vent 7, approximately equivalent to the clots in degree of crystallinity, contains large amounts of plagioclase and clinopyroxene phenocrysts (table 3) in a clear glass containing a few quench silicates.

The increased number of plagioclase and clinopyroxene phenocrysts (table 3) and decreased vigor of eruption downrift suggest that the lava cooled and degassed during subsurface transport from the site of initial eruption at Hiiaka. This suggestion is supported by the low water content of the sample from vent 7 (table 2), a reflection of the degree of degassing (Swanson and Fabbi, 1973). The depth of magma transport required for such rapid subsurface degassing and cooling is probably no more than several hundred metres.

The temperature probably decreased several tens of degrees between vents 1 and 7, judged by comparison with lava lake studies at Kilauea (Peck and others, 1966; Wright and others, 1968). An estimate of the amount of cooling can be made from the iron-magnesium ratios of the glassy portion of analyzed samples by using the curve in Thompson and Tilley

TABLE 3.—*Modal analyses of spatter and glassy flow skins of August 1968 eruption*

[Analyses in volume percent; 1,000 points counted for each sample. Plus and minus values indicate the total range of two counts of 500 points each. Tr, trace]

Vent	1(main)	1(subsidiary)	2	3	4	5	7
Sample	Hi68-2	Hi68-3	Hi68-5	Hi68-4	Hi68-12	HI68-15	HI68-14
Glass + quench[1]	76±4	74±1.2	75±4	84±6	83±0	78.7±0.7	71.8±4.7
Phenocrysts							
Olivine + spinel	24±4	16.6±1.2	25±4	16±6	17±0	13.9± .7	12.1±4.7
Clinopyroxene	----	6.4	----	----	Tr	4.1	9.0
Plagioclase	----	3.0	----	----	Tr	3.3	7.1

[1]Quench products include crystallites and oxidized glass.

HI68-5. Spatter from vent 2; erupted August 22.
HI68-4. Spatter from vent 3; erupted August 22.
HI68-15. Spatter from vent 5; erupted August 24-25.

HI68-2, HI68-3, HI68-12, HI68-14 } see table 2.

(1969, p. 471). Whole rock iron-magnesium ratios were adjusted for phenocryst content (tables 2 and 3) in order to obtain the iron-magnesium ratio of the glass. For this calculation, the ratio $\frac{MgO+FeO+Fe_2O_3}{FeO+Fe_2O_3}$ was assumed to be 0.200 for olivine (Fo_{84}), 0.352 for pyroxene (1963 Alae augite), and 0 for plagioclase. Calculated ratios for the glass suggest temperatures of about 1250°C at Hiiaka (Hi68–2, 0.511), 1200°C at vent 4 (Hi68–12, 0.575), and 1185°C at vent 7 (Hi68–14, 0.603). From these figures, the lava cooled about 65°C between vents 1 and 7. The absolute values of these temperatures are in doubt for two reasons: (1) errors in modal analysis of olivine could be large; (2) the curve of Thompson and Tilley (1969) is based on melting experiments under anhydrous conditions and probably indicates higher temperatures than those during eruption. Nonetheless, a temperature difference of 65°C seems reasonable. This value cannot be verified because differences in bulk composition make curves relating modal compositions to temperatures for previous Kilauea eruptions, such as the March 1965 eruption (Wright and others, 1968, figs. 12 and 15), not strictly applicable.

Despite the evidence for subsurface cooling and crystallization during transport, there is not chemical evidence of pyroxene removal, such as occurred during the March 1965 eruption (Wright and others, 1968). The chemistry and modal data do suggest a general olivine depletion at downrift vents, however. If olivine depletion during subsurface transport was common during prehistoric eruptions, accumulation of this olivine in the rift conduit system would help account for the positive gravity anomaly (Kinoshita and others, 1963) and high seismic P-wave velocities (Hill, 1969) along the east rift zone.

Lava erupted from the short-lived vent on the southwest wall of Hiiaka Crater was more crystalline and therefore cooler than lava erupted simultaneously from the main vent on the northeast wall (Hi68–2 and Hi68–3, table 3). This lava had not degassed significantly, as it fountained vigorously from the vent. The clinopyroxene and plagioclase crystals are much smaller than those in spatter from the downrift vents, probably good evidence for a shorter period of cooling, especially when the fluxing effect of the dissolved volatiles is considered.

VOLUME OF DEFORMATION RELATIVE TO VOLUME OF ERUPTED LAVA

The volume of subsidence in Kilauea's summit area during the eruption is about $6.4 \times 10^6 m^3$, calculated from the contoured vertical displacements (fig. 13) by using the U.S. Geological Survey computer program C628 written by P. C. Doherty. The volume of erupted lava before drainback is estimated to have been much smaller, about $9.9 \times 10^4 m^3$ (table 1). If we assume that the volume of subsidence should equal the volume of magma withdrawn from the storage reservoir beneath the summit, there is a discrepancy of about $6.3 \times 10^6 m^3$ to be explained. Most of this excess volume must be accounted for by magma stored within the east rift zone.

The volume of uplift for that part of the east rift zone covered by our leveling survey or extrapolated from it is about $1.8 \times 10^6 m^3$, but as control is poor, this figure could easily be revised by 50 percent. If the volume per unit length is assumed to remain the same to the easternmost vent, 20 km from Hiiaka, the total volume of uplift is about $4.0 \times 10^6 m^3$. If this value is 50 percent too low and the volume of uplift is considered to reflect an approximately equal volume of stored magma, then the missing volume of magma is accounted for.

A dike 20 km long, 0.6 m wide, and 500 m from top to bottom contains a volume of about $6.0 \times 10^6 m^3$, approximately equivalent to the missing volume of magma. The length of 20 km for the dike is reasonable based on the observed locations of vents, information obtained from portable seismic units, and the fact that geodimeter measurements (Hawaiian Volcano Observatory, unpub. data, 1968) indicated no deformation had occurred in an area 6 to 8 km farther downrift than vent 7 (fig. 1). The width of 0.6 m is reasonable, judged by the widths of observed August eruptive fissures and other Hawaiian dikes. The vertical thickness of 500 m seems very small, but all characteristics of the eruption downrift from Napau—weak harmonic tremor, sluggish extrusion of relatively cool, largely degassed lava, and virtual absence of earthquakes detected by seismometers only a few kilometres away—suggest that intrusion was shallow, perhaps similar to that which has taken place in Kilauea's southwest rift zone in historic time (Duffield, 1972).

It appears reasonable that most of the magma that vacated the summit reservoir complex was either erupted onto the surface or remained beneath the surface at a shallow depth between Hiiaka Crater and the easternmost vent, 20 km distant.

RATE OF MAGMA TRANSFER

A direct connection between Kilauea's east rift zone and summit reservoir system was inferred as early as 1960 from the rapidity with which the summit deflated during flank eruptions (Richter and Eaton, 1960). The presence of such a connection was indicated again during the August 1968 eruption by the short interval (3 hours) between the start of deflation at the summit and the onset of eruption on the east rift zone (fig. 5). If this interval reflects simply the time necessary for subsurface transfer of magma from the summit chamber to the eruption site, then the velocity of transfer was about 1.7

km/hr, in close agreement with values of 1.36 and 1.41 km/hr reported[4] by Moore and Krivoy (1964). The mechanism of transfer of magma is not always simple, however, and the magma actually erupted may have originally entered the rift zone during a previous episode of intrusion (see Wright and Fiske, 1971, p. 8). The lack of phenocrysts other than olivine in the earliest erupted lava is evidence that the velocity we calculated represents a true rate of subsurface magma transfer, and suggests derivation directly from the summit reservoir system. However, the erupted lavas may be mixtures of two different magmas. Mixing of magmas commonly occurs in the rift zone (Wright and Fiske, 1971) but is rarely recognized to take place in the summit area (Wright, 1973). The significance of the calculated magma transfer rate is, therefore, open to some doubt.

Subsurface magma transfer from Hiiaka Crater to vent 7 was probably much slower than that from the summit reservoir to Hiiaka. The average rate was about 250 m/hr, assuming a time of 3½ days for the 20 km distance (table 1). The average rate is very close to the progressive rate of migration of vents down the southwest rift zone during the early part of the September 1971 eruption, when the depth of magma transport was considered roughly as shallow as that in August 1968 (Hawaiian Volcano Observatory, unpub. data, 1971). It is somewhat greater (by a factor of 1.5 to 3) than velocities inferred for the 1955 and 1960 east rift eruptions, when the transport distance was much greater (Wright and Fiske, 1971, p. 50).

Transfer from the summit reservoir into the rift zone took place through a relatively open conduit system, whereas transfer farther downrift involved shallow rupturing of wallrock, a process made increasingly more difficult because progressive degassing would cause loss of driving force. The seismicity during the eruption is consistent with this interpretation; few earthquakes were recorded from the area between the summit and Hiiaka, whereas many quakes occurred along the rift zone as the dike advanced toward vent 7.

EVENTS BETWEEN THE AUGUST AND OCTOBER 1968 ERUPTIONS

Even during the August eruption, Kilauea began to prepare for another outbreak. By midmorning of August 25, inflation of the summit had resumed, and by midday the rate of tilting at Uwekahuna vault had accelerated to an average of 1.2 microradians per day, a rate that held throughout the rest of August and September. Coincident with resumption of inflation, the seismic activity in the summit area decreased to a normal level, although sporadic deep earthquakes and tremor bursts indicated continued movement of magma at depth. From mid-September to early October, the daily number of shallow caldera earthquakes increased at a fluctuating rate as the summit area became more highly strained.

The rapid summit inflation ended abruptly on October 2, by which time 80 percent of the tilt lost at Uwekahuna during the August deflation had been recovered. The summit had apparently become stabilized and no further inflation took place between October 2 and the afternoon of October 7, when the eruption began. This eruption proved to be the second in a nearly continuous sequence of eruptions that lasted through 1974.

The vertical and horizontal control networks were not reoccupied during the post-August inflation, as our schedule called for surveying to begin on October 8. Details concerning the summit and possible east rift deformation before the October eruption are therefore not available.

OCTOBER 1968 ERUPTION

SETTING

The vents of the October 1968 eruption are located along a line of en echelon fissures about 6.5 km long between the east flank of Kane Nui o Hamo, a prehistoric lava shield, and a point about 4 km east-northeast of Napau Crater (fig. 1). These fissures are within the part of the east rift zone that has been more frequently active during historic time than any other section of comparable length. Before 1968, five historic eruptions (in 1840, 1922, 1961, October 1963, and March 1965) took place in this area along a narrow zone less than 300 m wide (Moore and Koyanagi, 1969, plate 1). The October 1968 fissures occur along the northern margin of this zone, 50–100 m north of the March 1965 fissures. Narrow grabens are common along this part of the rift zone; an especially large one located 400 m south of vent E (fig. 1) subsided during the eruption. The October fissures occur south of a gap in the line of August fissures, between vents 4 and 5 (fig. 1). If the two eruptions are considered together, lava was erupted along almost the entire 20 km between Hiiaka Crater and vent 7 of the August eruption during a period of 1½ months.

NARRATIVE OF THE ERUPTION

A seismic prelude to the eruption began unexpectedly at 1037 October 7, when seismographs began recording harmonic tremor and a swarm of shallow earthquakes in the summit and upper east rift areas. Tremor amplitude increased steadily into the afternoon, and numerous earthquakes triggered rock falls from the walls of

[4]Moore and Krivoy calculated these two flow rates using the onset of harmonic tremor for the starting time, because no continuously recording tiltmeter was available.

Makaopuhi Crater (fig. 1), where seismic intensity was strongest and many quakes were felt.

At 1435, an observation party anxiously waiting at Makaopuhi sighted a fume cloud just starting to rise from the east slope of Kane Nui o Hamo (fig. 1). Seen from Makaopuhi, the cloud appeared to issue from a point source, but within 20 minutes its base had widened a kilometre or more as fissures opened downrift. A roaring sound indicated vigorous fountaining as the turbulent fume column rose more than 1,000 m high.

Between 1615 and 1635, Wright flew over the eruption area in a Civil Air Patrol plane. The earliest fountains, those at vent A (fig. 1), had already died out, but a nearly continuous line of fountains extended about 5 km downrift from near vent A to a point between vents E and F northeast of Napau Crater. The fountains rose 70 or more metres above several en echelon segments of the fissure system, each segment offset in a right-offset (left-lateral) sense. The floor of Napau Crater was flooded by lava cascading over its east and west walls and issuing from fissures cutting the northern part of its floor. A gassy fluid flow fed from several vents east of

FIGURE 26.—Tree molds about 500 m west of vent B, formed during first 2 hours of October 1968 eruption. Tree mold in foreground is about 1.5 m in diameter. Molds formed as lava chilled around trunk of tree (similar in size to those in background); upper part of tree burned off at top level of flow, toppled onto flow, and was carried away. As lava supply rate decreased, lava level dropped, exposing mold of trunk. An inclined, tapered ledge about 60 cm below top of mold formed during a pause in lowering of lava level. The inclination of such ledges and related striations on tree molds are good criteria for determining direction of flow. In photograph, direction of flow is to left.

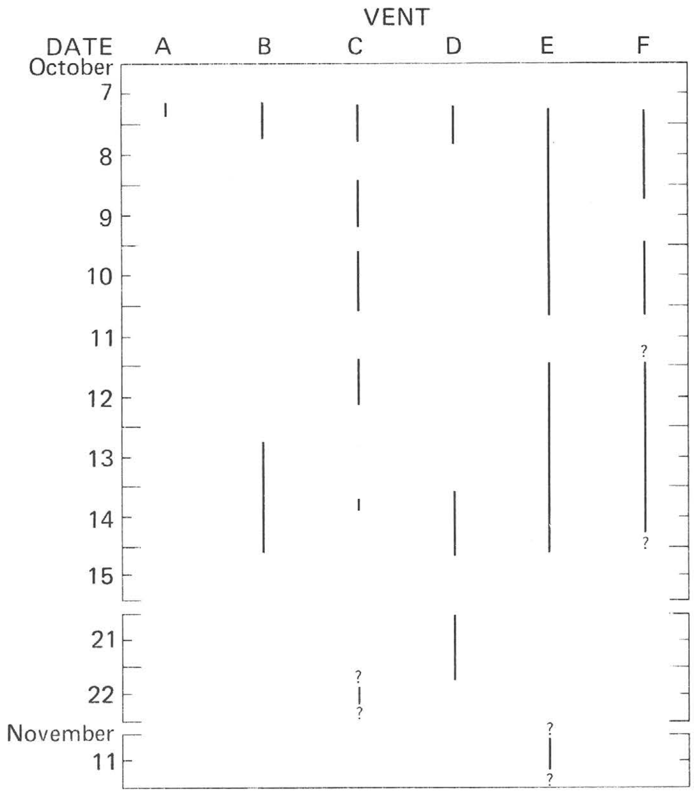

FIGURE 27.—Approximate periods of activity, selected vents of October 1968 eruption. See figure 1 for location. Question mark signifies uncertainty as to exact time.

vent A had already partly drained downslope into Napau as the eruption rate decreased, leaving tree molds standing as high as 8 m above the subsided surface of the flow (fig. 26). One lobe of this flow advanced southward, covering a part of the foot trail to Napau with slab pahoehoe.

By 0645 October 8, fountaining had died out in and west of Napau Crater but still continued at vents E and F (fig. 27). The highest fountains (at vent F) sprayed lava 45 m above a 50- to 60-m-long fissure, and fountains at vent E were active along a 100-m-long fissure. These fountains were feeding flows confined in narrow channels that crossed the new pahoehoe erupted the previous night. Already much of the March 1965 lava in this area was covered. Flows from both vents emptied into new cracks that cut the solidified but still hot pahoehoe, and lava from vent E flowed 200 m downrift before pouring into the extension of the same fissure from which it had erupted. Only a small fraction of the total volume of lava erupted remained above ground.

By October 9, the only active flows were within Napau Crater, although fountains played at a low level at vent E. Fifteen- to thirty-m-high fountains were active at vent C in Napau, feeding small flows that spread for short distances across the languidly overturning lake crust. Fountaining at vent C had ceased by 1730 October 9, but low spatter activity continued sporadically at vent E. A new crack about 65 m long, just downrift from vent F, emitted fume but never erupted lava.

From October 10 through 13, fountaining moved back and forth along the line of fissures between vents B and F. During the night of October 11–12, Civil Air Patrol observers discovered that Napau Crater was once more being flooded, and fountains up to 100 m high were playing along the rift zone between vents E and F. By midday on October 12, the lava lake in Napau had reached its highest level of the eruption, within 2 m of the high lava mark left by the March 1965 eruption (Wright and others, 1968).

Vigorous fountaining resumed between vents D and E at about 0030 October 14, with renewed sporadic activity near vent F. Throughout the day, lava cascaded 30–40 m from vent D into Napau, creating a lava pool, ponded by its own natural levees, about 150 m in diameter on the crust of the larger Napau lava lake. Much of the lava overflowed the levees, advanced about 300 m across the surface, then drained back underground along a segment of the eruptive fissure just east of vent C (fig. 28).

By October 15 all surface activity along the rift zone had ceased (fig. 27), and only weak harmonic tremor was being recorded at the Makaopuhi seismometer. Renewed eruption occurred on October 21, when weak spattering and a small sluggish flow were generated at vent D near the east lip of Napau Crater. The last verified activity took place on October 22, when small showers of spatter periodically burst from a cone at vent C on the floor of Napau.

Barely perceptible tremor from a shallow source continued to be detected by the Makaopuhi seismometer after October 22. On November 11, an observatory party examined the remote area between vents B and F to investigate the cause of the tremor. Weak spatter activity was seen through two small holes in the side of a roofed-over spatter cone near vent E. Judged by the sloshing sounds, a pool of lava was contained at a shallow depth beneath the cone. This feeble spattering possibly signified only degassing of stagnant lava stored in the fissure after the October activity and technically may not indicate continued eruption. By November 19, all fuming from the cone and associated harmonic tremor had ceased.

AREA AND VOLUME ESTIMATES

The eruption added about $3.15 \times 10^6 m^3$ of new lava to Napau Crater, forming a lava lake $6.3 \times 10^5 m^2$ in area and 5 m deep. Estimates of the volume of lava remaining on the surface outside of Napau are subject to errors, because flow thickness must be assumed. Examination of several flows suggests an average thickness of 1.5 m

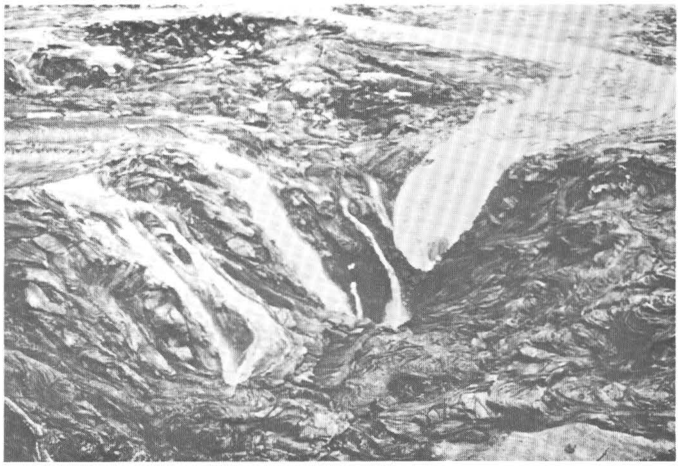

FIGURE 28.—Lava pouring underground along segment of eruptive fissure just east of vent C in Napau Crater, October 14, 1968. Largest tongue of flow is 2–3 m wide. Lava is draining out of a pool (upper left) perched behind a natural levee on crust of Napau lava lake. Depth to which lava is pouring not known; petrographic evidence suggests some lava was reerupted to the surface after storage for several days at shallow depth.

over an area of $2.9 \times 10^6 m^2$, giving a volume of $4.35 \times 10^6 m^3$; this estimate may be in error by as much as 50 percent. The total volume of lava remaining on the surface is probably about $7.5 \pm 2.2 \times 10^6 m^3$.

The total volume of erupted lava was much greater than that remaining on the surface, owing to extensive drainback into large cracks in Napau and at several places father downrift. The volume of drainback is impossible to estimate reliably but is possibly as much as 25 percent of the volume remaining on the surface.

GROUND CRACKING

The ground in and near the zone of vent fissures cracked repeatedly throughout the first several days of the eruption. Some cracks cut newly erupted pahoehoe east of Napau, then served as drainback fissures during later eruptive activity. Several of the cracks opened 1–2 m, but most are less than 50 cm wide. The cracks parallel the trend of the rift zone and are commonly arranged in a right-offset en echelon fashion, like the eruptive fissures themselves. The cracks are vertical and exhibit dilation normal to their trend. Inaccessibility and dense jungle cover precluded mapping most of the new cracks.

The Chain of Craters Road was cut by two sets of right-offset en echelon cracks about 300 m south of the tourist overlook at Makaopuhi Crater. The cracks were a maximum of 1.3 cm wide, opened in a direction normal to the cracks, and displayed no vertical displacement. They formed sometime before October 10, probably during the waning stages of major earthquake activity near the Makaopuhi seismometer (fig. 5).

A narrow graben about 400 m south of vent E (shown on pl. 1 of Swanson and others, 1975) had an especially informative history (fig. 29). Before the eruption, the graben was 30–40 m deep, 10–15 m wide, and 300 m long. Lava erupted from near vent E on October 7 cascaded into the graben, which eventually filled and overflowed to the south. After the lava flow had stopped, probably on October 8, the graben subsided along its preexisting bounding faults. Subsidence had started before the new lava was completely solidified, and cool, sticky lava dribbled down the newly formed walls of the graben. Continued subsidence lowered the October 7 lava fill by 60–70 m. Several days later, a small volume of aa from renewed activity at vent E trickled into part of the graben.

SEISMICITY

Seismic activity increased sharply at 1037 October 7, 4 hours before the start of the eruption, with a swarm of upper east rift and shallow caldera earthquakes accompanied by harmonic tremor (fig. 5). A relatively high level of seismicity continued until early November but was highest during the first 4 days of the eruption. On October 7 and 8 the earthquakes, which had focal depths of 6 km or less, were concentrated in the summit area and along the east rift zone from near Alae to about 3 km east of Napau. On October 9, the final day of strong east rift seismicity, earthquake epicenters began to migrate

FIGURE 29.—Lava flow south of vent E cut by a wide graben. The graben, present before the eruption, was filled with newly erupted lava on October 7, 1968, then underwent renewed subsidence, probably on October 8. View south from above vent E. Flow approximately 200 m wide along graben.

TABLE 4.—*Locations of key seismic stations used in establishing the epicenter and hypocenter locations in figure 30*

Station	Symbol	Location by map coordinate	
Mauna Loa	MLO	19°29.8′N.	155°23.3′W.
Mauna Loa 2	MLX	19°27.6′	155°20.7′
Ahua	AHU	19°22.4′	155°15.9′
Outlet	OTL	19°23.4′	155°16.8′
Desert	DES	19°20.2′	155°23.3′
North Pit	NPT	19°24.9′	155°17.0′
West Pit	WPT	19°24.7′	155°17.5′
Makaopuhi	MPH	19°21.8′	155°10.0′
Kealakomo	KMO	19°18.5′	155°09.6′
Kipuka Nene	KPN	19°20.1′	155°17.4′
Cone Peak	CPK	19°23.7′	155°19.7′
Glenwood	GLN	19°29.0′	155°09.9′
Pahoa	PAX	19°29.1′	154°55.8′
Waiohinu	WAO	19°03.6′	155°36.6′
Uwekahuna	UWE	19°25.4′	155°17.6′
Hilo	HIL	19°43.2′	155°05.3′

southward across the south flank of the volcano, and the hypocenters deepened by several kilometres.

Despite high tremor levels and frequent overlap of earthquake traces on seismographs during the early days of eruption, more than 300 earthquakes of magnitude 0.5 to 3.3 were read and located by using data from some or all of the 16 seismograph stations listed in table 4. Earthquake arrival times and daily counts were obtained from Develocorder 16-mm strip film recordings; tremor amplitudes were measured from smoked-drum records; earthquake magnitudes were determined mainly from photographic recordings of short-period Sprengnether seismographs located at Uwekahuna vault. Owing to the existing seismometric coverage and the complex seismic wave velocities within the volcanic edifice, errors in location of at least a kilometre for earthquakes in the summit area and several kilometres for earthquakes along the east rift zone and south flank of Kilauea should be expected (Ward and Gregersen, 1973). Individual station differences, together with frequent gain changes during peak periods to accommodate the relatively narrow dynamic range of the recording system, force the measurement of tremor amplitude, and hence the tremor intensity, to be qualitative.

The seismicity during the October eruption can be divided into four stages, roughly defined by the changes in pattern of eruption, earthquake occurrence, and tremor intensity (fig. 30):

Stage I, 1037 to 1435 October 7, was characterized by a marked increase in the number of shallow earthquakes in both the summit region and on the east rift zone between Alae and Napau Craters (figs. 5 and 30*A*). The summit earthquakes were concentrated beneath the south-central part of Kilauea Caldera at shallow depths and probably resulted from strain release accompanying summit detumescence. Epicenters of the rift earthquakes fall in a zone elongate along the trend of the rift zone and roughly centered on the area near

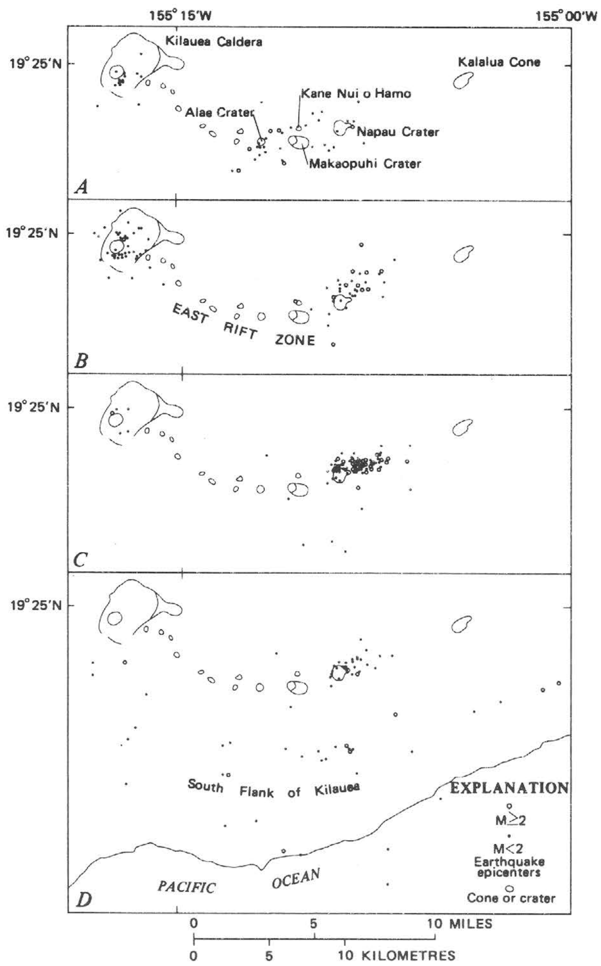

FIGURE 30.—Epicentral distribution of selected earthquakes for four stages of activity before and during the October 1968 eruption. *A*, Stage I. 1037 to 1435 October 7. Marked increased in number of shallow earthquakes in summit area and east rift zone between Alae and Napau Craters. *B*, Stage II. 1435 to 2355 October 7. Strong harmonic tremor and increased number of caldera earthquakes. *C*, Stage III. October 8. High seismicity local to Makaopuhi as ground cracking and fountaining continued in eruption area. *D*, Stage IV. October 9 to November 20. Low-level tremor gradually declined in intensity with decreased fountaining. Determination of earthquake epicenters based on seismic velocities in Model B of Eaton (1962).

Kane Nui o Hamo, where the eruption later began. The elongation of the epicentral area may result partly from limited seimometric control east of Makaopuhi Crater. These rift earthquakes were shallow and apparently related to intrusion of magma as it worked its way toward the surface. No earthquakes were generated between the summit and Alae Crater during this or any subsequent seismic stages.

Harmonic tremor began at 1037 and increased in intensity throughout the preeruption stage (fig. 5). The tremor started at about the same time as deflation of the summit region, yet the amplitude of the early tremor was largest at Makaopuhi and progressively decreased toward the summit region (fig. 5). This suggests that the source of the early tremor was near Makaopuhi.

Stage II, 1435 to 2355 October 7, was characterized by strong harmonic tremor and increase in number of caldera earthquakes (figs. 5 and 30*B*). Earthquakes west of Kane Nui o Hamo virtually ceased as the eruption spread downrift; many quakes were centered east-northeast of Napau Crater. Only the largest of these quakes were recorded at the Makaopuhi seismometer. The intensity of harmonic tremor sharply increased soon after the eruption began and was very strong at the Makaopuhi seismometer between about 1430 to 1900, coincident with the most vigorous fountaining in the eruption area. Tremor amplitude decreased rapidly at about 1730. A subsequent rise in tremor from 2100 to 2400 was recorded most strongly at Ahua (AHU in fig. 1), possibly suggesting a surge of magma or partial blockage of a conduit near Ahua.

Stage III, on October 8 (figs. 5 and 30*C*), was a period of high seismicity local to the Makaopuhi seismometer, as ground cracking and lava fountaining continued in the eruption area. Epicenters of east rift quakes were concentrated in a zone outlining the vent area downrift from Napau Crater. Tremor intensity fluctuated in response to vigor of fountaining. The frequency of caldera earthquakes declined as summit deflation slowed.

Stage IV, from October 9 to November 20 (fig. 30*D*), was characterized by low-level tremor that gradually declined in intensity with decreased fountaining. This gradual decline was interrupted by a 7-hour burst of fluctuating strong tremor recorded at the Makaopuhi seismometer on October 13 and 14, coincident with increased vigor of fountaining at vents E and F. From October 9, the last day of the major part of the seismic swarm along the rift, earthquake activity began to scatter to the south and to greater depths, in accordance with the model of Koyanagi, Swanson, and Endo (1972) which relates diking in the rift zone to the southward migration of earthquakes and the seaward displacement of the south flank of Kilauea.

SUMMIT DEFORMATION

The October 1968 eruption was more voluminous and lasted longer than the August eruption, yet we know less about the accompanying ground deformation because all of the October eruptive activity took place east of the geodetic networks in a remote, jungle-covered area. Furthermore, the timing of the geodetic surveys relative to eruptive activity was poor, so that they indicated relatively small changes even though substantial tumescence and subsidence occurred between surveys. Selected measurements made during the eruption provide some clues as to what happened.

Several of the summit tilt stations were periodically reoccupied during the rapid deflation between October 7 and October 10 (fig. 31). The migration of deflation centers with time was less complex than during the August eruption. Subsidence was initially centered about 1 km east of Halemaumau Crater and remained near there until the evening of October 7 (fig. 31*A–C*). During the night of October 7–8, the subsidence center began to shift southward (fig. 31*D*); it finally stabilized in an area about 1.4 km west-southwest of Keanakakoi Crater. By the morning of October 10 (fig. 31*E, F*), deformation was nearly complete. The net center of deflation over the period October 1 to 1000 October 10 falls within the group of overall deformation centers for previous flank eruptions and is coincident with center 3 in figure 14*F*.

No tilt surveys were run after October 10. The plot of daily tilt (fig. 2) suggests that slight deflation continued south and southwest of Uwekahuna vault until about October 22, the time of the last definite eruptive activity. Thereafter, the Uwekahuna tiltmeters once more registered summit inflation.

The altitude and tilt changes in the summit area between the start of preeruption inflation and the end of major deflation (fig. 32) show a pattern of subsidence similar to that accompanying the August eruption (fig. 13). The center of subsidence is somewhat farther south in October than in August, and the amplitude is smaller, largely if not entirely because of the timing of the surveys. Experience from other eruptions suggests that the datum point for the leveling surveys (fig. 32) was displaced no more than 10 percent, or 1.5 cm, of the maximum subsidence.

Net horizontal ground displacements for the period covering both the preeruption inflation and the October deflation are surprisingly large, considering the timing of the surveys (fig. 33). Actually the horizontal displacements resulting from the October eruption must have been still greater than those shown in figure 33 and were almost certainly equal to, or somewhat greater than, those associated with the August eruption (fig. 16).

Most of the horizontal displacements indicate a center of deformation for the October eruption 1–2 km southeast of Halemaumau. The center is south of the center of horizontal deformation for the August 1968 eruption (fig. 16) and near the center defined by vertical displacements and ground tilt (figs. 31*F* and 32). Contours of equal dilatation (fig. 34) define about the same locus of deformation as the other data. Maximum dilatation is somewhat greater than that over the August eruption (fig. 17) and is consistent with the relative magnitudes of displacement during the two eruptions.

DEFORMATION OF THE UPPER EAST RIFT ZONE BETWEEN AUGUST AND OCTOBER

Vertical displacements define a shallow (less than 4 cm) trough near Hiiaka Crater (fig. 32), in the general area of vents 1, 2, and 3 of the August eruption. This trough may reflect continued subsidence related to the August events, possibly caused by final subsurface migration of stored magma, contraction of cooling intrusive bodies at shallow depth, or final adjustments along the newly opened and reactivated ground cracks. The trough does not appear to be related to the events of the October eruption because the closest October vents are near Kane Nui o Hamo, 7 km farther east.

Events almost certainly related in some way to the October eruption are the uplift of at least 21 cm centered south of Makaopuhi Crater and the associated tilting of 250 microradians measured in Makaopuhi. No event capable of causing such substantial deformation took place before the eruption, although some of it may be related to the inferred filling of a magma reservoir in the Makaopuhi area (discussed below). Leveling on October 10 showed that the uplift was already present, and subsequent resurveys on October 14 and 25 indicated no change. The area was probably elevated between October 7 and 10, the time of principal earthquake activity near Makaopuhi Crater (fig. 5).

Geodimeter measurements suggest that virtually all of the deformation near Makaopuhi took place during the early part of the eruption, probably on October 7 and 8. The distance between Puu Huluhulu and HVO 112 (figs. 15 and 18) was measured five times during the eruption, on October 8, 13, 15, 16, and 25. No significant change in length was noted, whereas the distance had extended 16 cm between August 23 and the afternoon of October 8. From this, we believe that most of the horizontal deformation near Makaopuhi took place on October 7 or during the morning of October 8.

The deformation data taken together do not adequately define the shape of the uplift near Makaopuhi. The elongate ridge projected in figure 32 is reasonable, but there are other interpretations. The line of bench marks across the uplift (fig. 32) gives a vertical displacement profile that resembles the displacement profile expected from the intrusion of either vertical or south-dipping dikes that would reach the surface near the line of October vents (see fig. 23). Lacking data north of the fissures, we cannot evaluate this resemblance, nor can we evaluate the role played by the magma reservoir inferred (in a later section) to be located near Makaopuhi Crater.

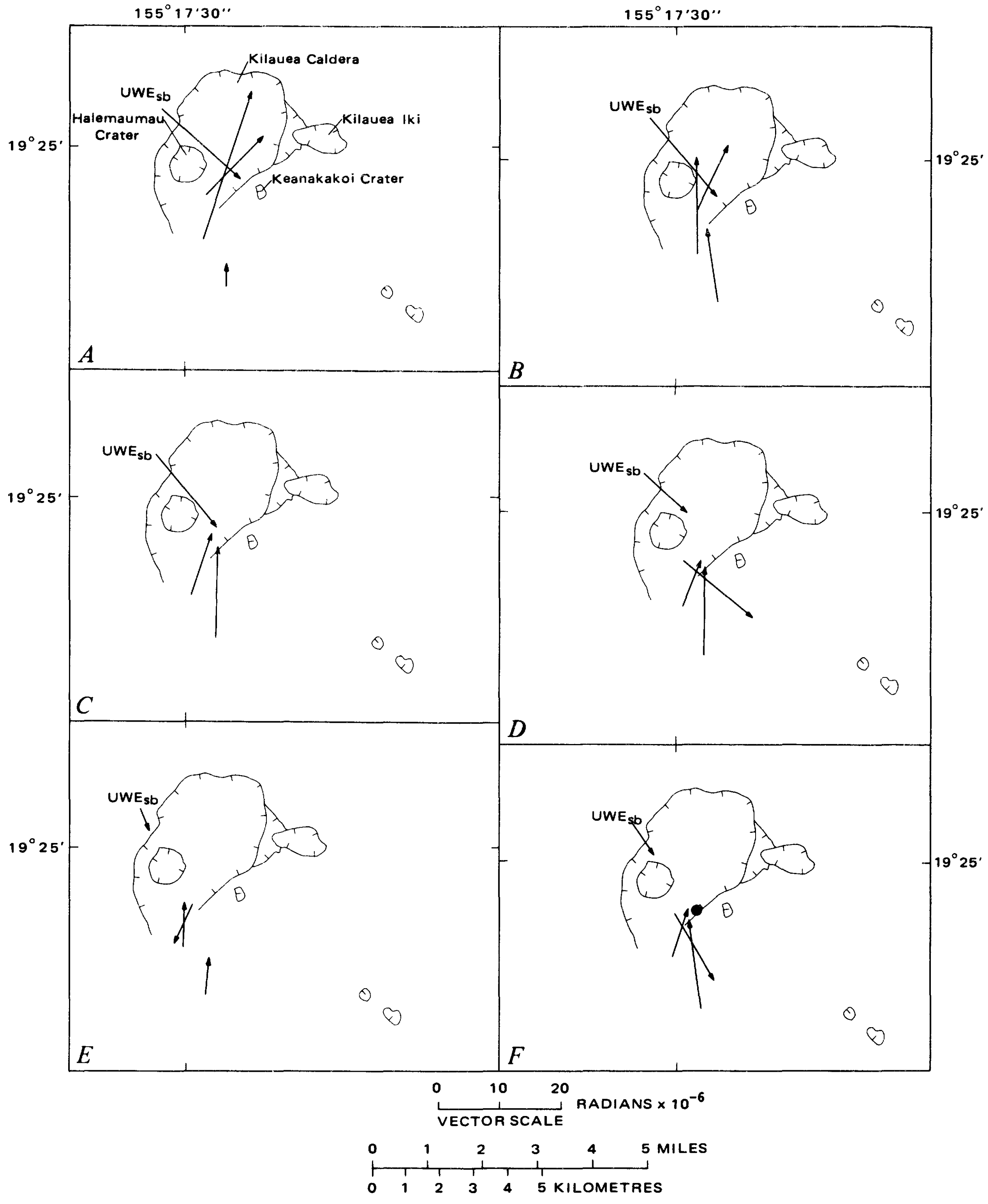

FIGURE 31.—Ground tilt changes at the summit of Kilauea during the October 1968 eruption. *A*, October 1 to 1400 October 7. No measurable deformation occurred between October 1 and the onset of deflation at 1040 October 7; *B*, 1400 to 1700 October 7; *C*, 1700 to 2230 October 7; *D*, 2230 October 7 to 0930 October 8; *E*, 0930 to 2130 October i; *F*, 2130 October 8 to 1000 October 10. Solid circle in *F*, net center of deformation for August 1968 eruption (see fig. 14 *F*), shown for comparison. Uwekahuna short base (UWEsb) vectors are adjusted as explained in figure 14.

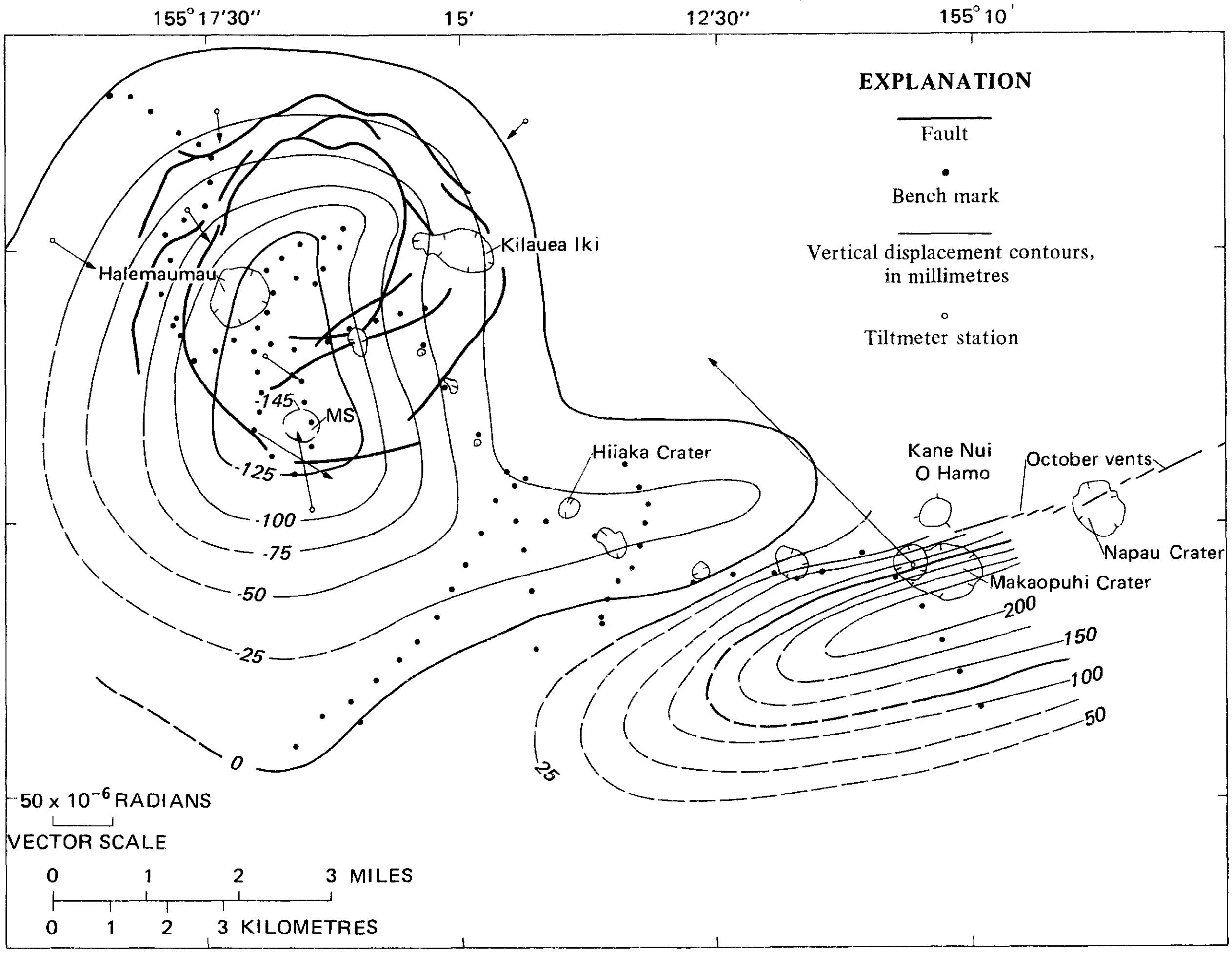

FIGURE 32.—Vertical ground displacement (contours) and tilt (vectors) from August 26–29 to October 9–10, 1968, the period that spans the inflation and deflation associated with the October eruption. Supplementary −145-mm contour south of Halemaumau delineates area of maximum subsidence (MS) in summit region. Northwesternmost bench mark is the datum point for the two leveling surveys.

PETROGRAPHY AND CHEMISTRY OF THE OCTOBER 1968 LAVA

Modal analyses (table 5, excluding samples N68–4 and N68–12) show that the October lava was less than 10 percent crystalline when erupted. Olivine and minor spinel phenocrysts make up less than 4 percent of solidified spatter, and small but significant amounts of plagioclase and clinopyroxene, some in intergrown clots and some in single phenocrysts, occur in every specimen. In contrast, the initial August 1968 lava contained 16 to 25 percent olivine plus spinel, and no plagioclase or clinopyroxene (table 3, samples Hi68–2, Hi68–4, and Hi68–5).

Direct measurements of lava temperature were not made during the eruption. The presence of plagioclase and clinopyroxene probably implies temperatures between 1150°C to 1170°C, based on the studies of Wright and Weiblen (1968). Temperatures inferred from iron-magnesium ratios in glass corrected for crystal content are 1165°C to 1195°C (Thompson and Tilley, 1969). The iron-magnesium ratios were computed for samples N68–8 (0.655), N68–11 (0.589), and N68–14 (0.632) by using chemistry from table 2, modes from table 5, and $\frac{MgO+FeO+Fe_2O_3}{FeO+Fe_2O_3}$ ratios of 0.200 for olivine plus spinel, 0.352 for clinopyroxene, and 0 for plagioclase. The temperatures estimated from the chemical data are probably somewhat too high, because the melting experiments were anhydrous (Thompson and Tilley, 1969). Nonetheless, these temperatures, as well as those estimated from the modal data, are clearly lower than the 1250°C estimated from iron-magnesium ratios at early vents of the August eruption.

Chemical analyses of the October lava are given in table 2. Detailed study of these analyses by Wright, Swanson, and Duffield (1975; see also Wright and Doherty, 1970, p. 2004, and table 5) suggest that spatter samples N68–8 and N68–14 are differentiates formed by

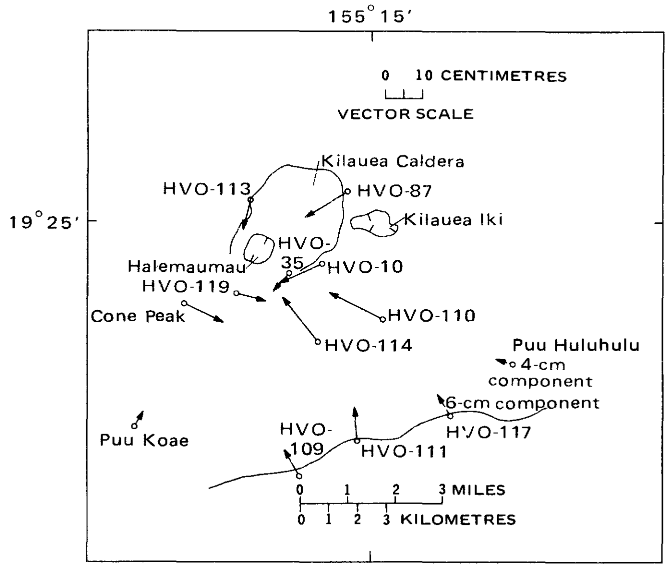

FIGURE 33.—Horizontal ground displacement (vectors) between August 23–24 and October 10–15, 1968 relative to a baseline several kilometres west of Puu Koae (fig. 16). August survey adjusted as explained in text. Components of displacement toward HVO 110 shown for HVO 117 and Puu Huluhulu. See figure 16 for explanation.

removal of about 0.9 percent olivine, 8.2 percent clinopyroxene, and 1.3 percent plagioclase from a magma having a composition equivalent to that of the 1961 summit eruption. Samples N68–4 and N68–11 are hybrid lavas resulting from mixing of three parts of magma of 1967–68 summit composition with one part of a differentiate similar in composition to N68–8 and N68–14. Pyroxene removal requires cooling to or below the temperature of pyroxene appearance, and magma mixing suggests a chamber containing a circulating melt. Both conditions are consistent with the inferred presence of a magma reservoir located in the Makaopuhi area (see following section).

Samples N68–4 and N68–12 are more crystalline than other October spatter; significantly, both samples are of spatter erupted from fissures that had served as sites of voluminous drainback a few days earlier. The contrast in crystallinity is especially apparent in samples N68–4 and N68–5, both of which were erupted from vent B at different times (table 5). The modal data suggest that the crystalline spatter is reerupted lava that had cooled and partly crystallized during its first eruption before draining into a shallow storage reservoir, where additional cooling caused further crystallization before final eruption. This series of events apparently had little effect on the bulk chemistry, because sample N68–4, for example, has a composition compatible with the other samples. Its water content is slightly lower, however, possibly because of degassing following initial eruption. No significant differences in phenocryst mineralogy or texture corresponding to primary or reerupted spatter were recognized.

MAGMA RESERVOIR IN THE MAKAOPUHI AREA

Several convergent lines of evidence suggest that magma was stored in a shallow subsurface reservoir in the Makaopuhi Crater area before it was erupted in October 1968. The best evidence is the pattern of harmonic tremor and shallow earthquakes during the 4 hours preceding the eruption. This seismicity, which presumably indicates forceful injection of magma by hydraulic fracturing, was recorded most strongly by the Makaopuhi seismograph, and weakened progressively uprift toward the summit (figs. 1 and 5). These relations imply the subsurface presence of magma before the eruption closer to Makaopuhi than to other seismometer sites. The intervals between arrivals of S and P waves for the larger earthquakes recorded by the Makaopuhi seismograph during this time are small and suggestive of nearby origin.

The petrography and chemistry also suggest preeruption storage of magma. The presence of numerous phenocrysts and intergrown clots of plagioclase and clinopyroxene indicate significant cooling, and the hy-

TABLE 5.—*Modal analyses in volume percent of spatter samples from the October 1968 eruption*
[Plus and minus values indicate the total range of two counts of 500 points each]

Vent	A	B	B	C	C	D	E	E	F
Sample No.	N68–14	N68–5	N68–4	N68–13	N68–12	N68–11	N68–10	N68–9	N68–8
Glass + quench[1]	98	100	77±0.1	94.3±0.1	83.8±0.8	97.0	95.5±0.3	91.4±1.6	96.1±0.3
Phenocrysts									
Olivine + spinel	Tr	Tr	3.2± .2	2.5± .3	3.8± .6	.8	1.3± .7	.3±.3	.4±0
Plagioclase	Tr	Tr	7.6± .6	1.3± .1	4.4±0	.2	1.3± .5	3.7± .7	1.7± .3
Clinopyroxene	2	Tr	12.1± .9	1.9± .5	8.0± .2	2.0	1.9± .1	4.6±1.7	1.8±0
Sum	100	100	100	100	100	100	100	100	100
Number of points counted	878	1,000	1,000	1,000	1,000	575	1,000	1,000	1,000

[1]Quench includes crystallites and oxidized glass.
N68–4, N68–8, N68–11, N68–14: Chemically analyzed samples; see table 2 for location.
N68–5. Erupted on October 7 from vent B.
N68–9. Erupted at unknown date from cone fuming on November 11 (see text).
N68–10. Erupted on October 13 or 14 from vent E.
N68–12. Erupted after October in Napau Crater from the site of extensive drainback on the afternoon of October 14 (see text and fig. 28).
N68–13. Erupted on October 12 or 14 from vent C.

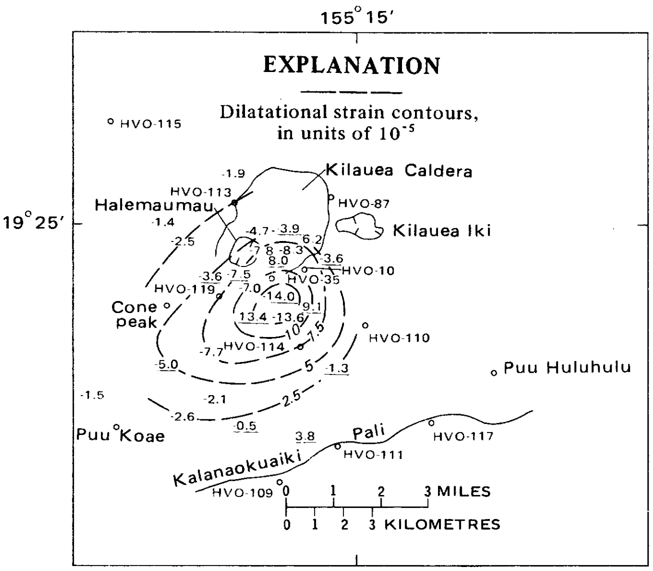

FIGURE 34.—Dilatational strain between August 23–24 and October 10–15, 1968. Data derived from adjusted displacements in figure 33 and plotted at center of gravity of each strain triangle. Underlined values are those considered most reliable because of triangle size and shape.

brid nature of the lavas requires room for mixing; both processes imply storage for some time within the rift zone (tables 2 and 5; Wright and Fiske, 1971). On the basis of this and the seismic evidence, a storage reservoir near Makaopuhi is reasonable.

The following sequence of events is consistent with what is known about the October 1968 eruption. At least several million cubic metres of magma were stored in a shallow reservoir in the Makaopuhi area, possibly beneath the site of vent A, for a time long enough to permit cooling of several tens of degrees and consequent crystallization of plagioclase and clinopyroxene. A continuous fluid connection probably existed between the summit conduit system and the Makaopuhi reservoir, as earthquakes in that area were few. At about 1035 October 7, magma began forceful intrusion upward from the reservoir, possibly in response to either increasing volatile pressure or influx of new magma from the summit system. Four hours later, as this magma first reached the surface, the eruption started. Some of the stored magma became depleted in clinopyroxene because of flow differentiation during its subsurface intrusion, and finally erupted as lava-like samples N68–8 and N68–14. As magma from the summit system flooded the emptying Makaopuhi reservoir, it mixed with the stored magma. The resulting hybrid entered the eruption conduits, lost pyroxene by flow differentiation, and erupted as lavalike sample N68–11. Possibly the eruption continued until most of the stored magma was mixed with new magma and flushed from the rift zone, its place taken by fresh magma not yet ready to erupt because of insufficient volatile pressure. A similar concept of "eruptibility" was developed for summit eruptions by Wright and Fiske (1971).

When did magma become stored in the Makaopuhi reservoir? It may be significant that several leveling surveys between 1966 and 1969 showed repeated deformation, principally uplift, along the Chain of Craters Road near Makaopuhi (Hawaiian Volcano Observatory, unpub. data, 1969), seemingly independent of summit deformation. Possibly magma entered the Makaopuhi system one or more times during this period. This interpretation is consistent with fractionation calculations of Wright, Swanson, and Duffield (1975) showing that the best parent magma for the October 1968 lava is the 1961 magma and the next best parent the 1967–68 magma, both of which are inferred to have been injected into the rift zone before 1968 (Wright and Fiske, 1971).

NET GROUND DEFORMATION, JULY TO OCTOBER 1968

Net ground displacements and tilt over both the August and October 1968 eruptions, illustrated in figures 35–37, show that part of the summit of Kilauea subsided a net amount of 33 cm during the two eruptions, and that some points on opposite sides of the caldera, such as HVO 113 and HVO 114, moved toward each other by more than 45 cm. Roughly concentric patterns of subsidence and contraction were centered about 1 km southeast of Halemaumau, and contours of equal degree of deformation are remarkably concentric to this area (see also Kinoshita and others, 1974, fig. 14). The volume of subsidence was about $1.06 \times 10^7 m^3$; the decrease in surface area from contraction, obtained by summing the change in areas of adjacent triangles in the survey network, was more than $4 \times 10^3 m^2$.

As a result of this subsidence and contraction, the summit region was less highly strained than at any time after early 1967. For example, one survey triangle across part of the caldera had lost about 75 percent of the dilatational strain acquired since mid-1966 (fig. 3). Most summit elevations were lower than at any time since later February 1967. Yet some net uplift and positive residual strains relative to the February 1967 datum remained, especially in the south caldera region, perhaps because of intrusions fed from the central conduit system. Such residual strain in the summit area after flank eruptions has been characteristic during at least the last 10 years, and it may slowly accumulate, eventually weaken the structure of the volcano, and lead to major eruptions and summit collapses (Swanson and Okamura, 1972).

Despite the significant strain release over the August and October eruptions, Kilauea did not long remain

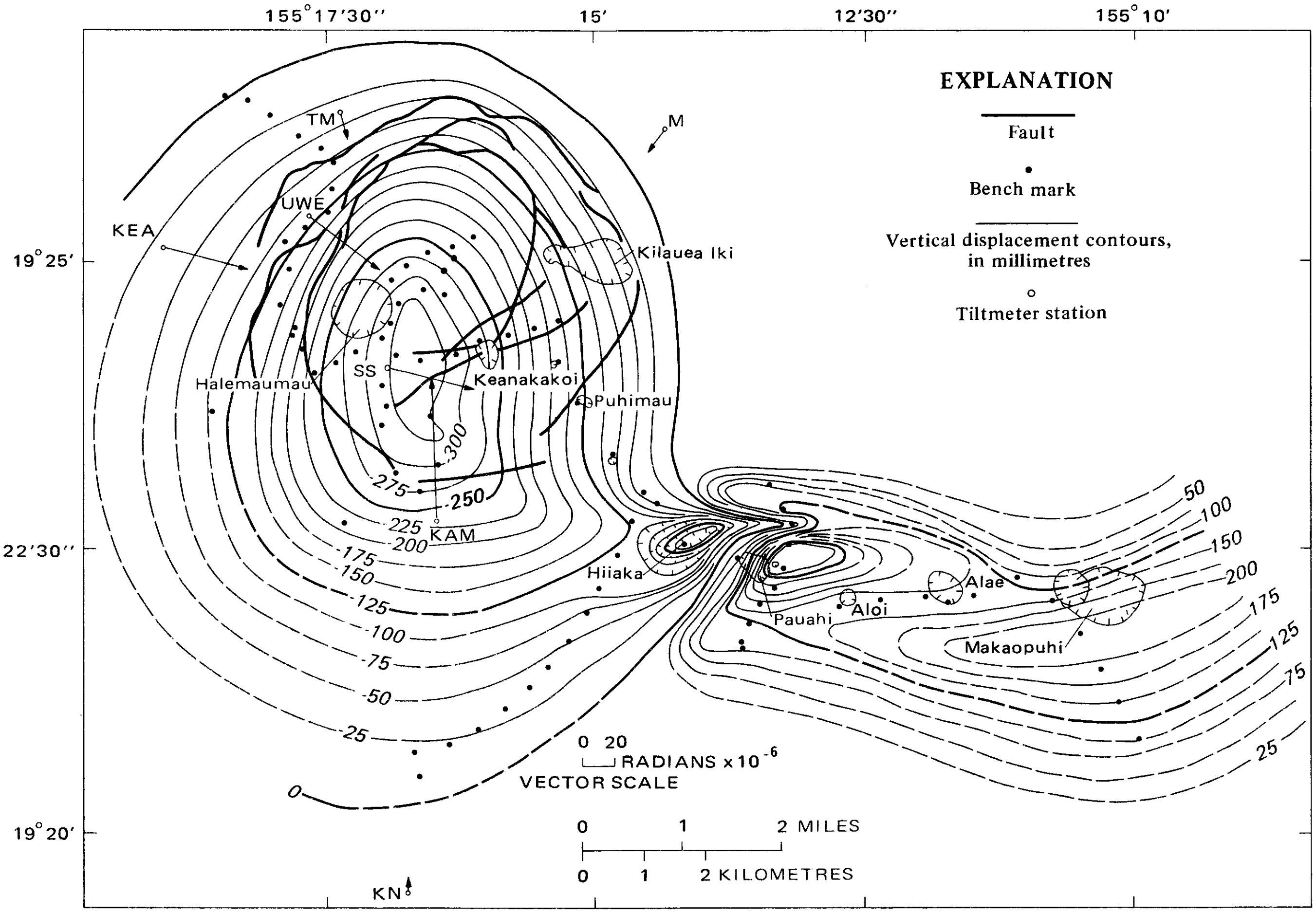

FIGURE 35.—Vertical ground displacement (contours) and ground tilt (vectors) between July 15 and October 9–10, 1968. Datum point for leveling surveys is northwesternmost bench mark. Tilt stations: TM, Tree Molds; M, Mehana; KEA, Keamoku; UWE, Uwekahuna; SS, Sandspit; KAM, Ahua; and KN, Kipuka Nene. Contours of vertical displacement are dashed where uncertain.

inactive, erupting in February 1969 (Swanson and others, 1975) and again in May 1969, when the largest eruption in Kilauea's recorded history, the 1969–71 Mauna Ulu eruption, began (Swanson and others, 1971).

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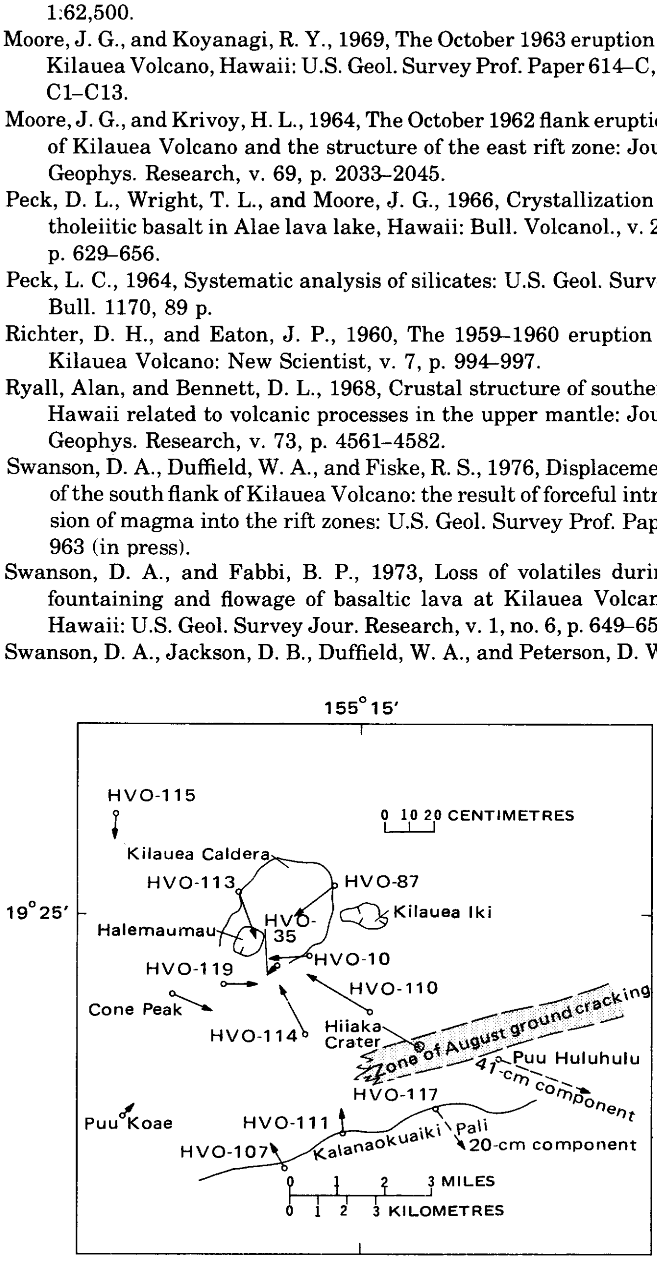

FIGURE 36.—Horizontal displacement (vectors) between July 22–24 and October 10–15, 1968. Displacement computed relative to baseline several kilemetres west of Puu Koae (see fig. 16). Components of displacement away from HVO 110 at Puu Huluhulu and HVO 117 were determined as shown in figure 16.

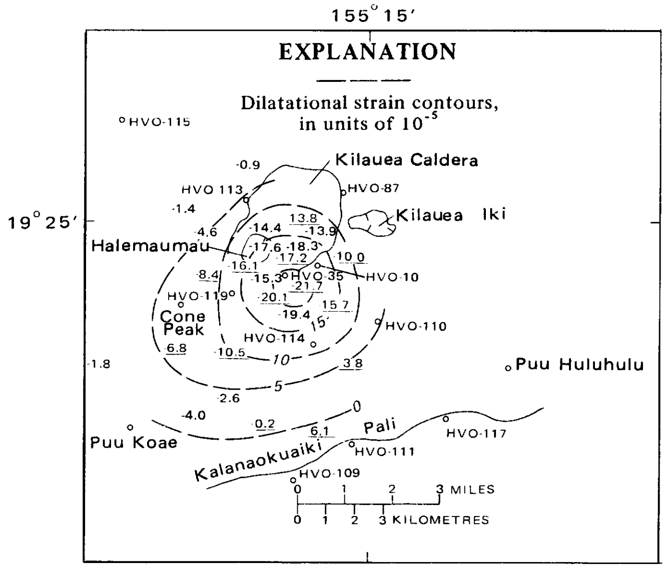

FIGURE 37.—Dilatational strain (contours) between July 22–24 and October 10–15, 1968. Data are derived from displacements in figure 36 and plotted at the center of gravity of each strain triangle. Underlined values considered most reliable from triangle size and shape.

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