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Kilauea Volcano: The 1967-68 Summit Eruption

Classic lava-lake activity returned for 250 days to Kilauea's summit crater, Halemaumau.

Willie T. Kinoshita, Robert Y. Koyanagi, Thomas L. Wright, Richard S. Fiske

On 5 November 1967 Kilauea volcano began erupting lava from vents on the floor of its summit pit crater, Halemaumau, 170 meters deep. This eruption ended nearly 2 years of quiescence that followed a short-lived eruption on the east rift zone of Kilauea in December 1965 (*1*). The 1967–68 eruption was the first activity in Halemaumau since July 1961 (*2*). The eruption ceased on 13 July 1968 following 31 separate phases of fountaining separated by short periods of quiescence. Six weeks after the end of the summit eruption, a short eruption occurred on the upper east rift zone of Kilauea. As this article goes to press there have been four eruptions, all on the upper east rift zone. The last of the four began in May 1969 and has just completed its seventh phase.

This article summarizes the eruption in Halemaumau and complements an article by Fiske and Kinoshita on the deformation that preceded the eruption (*3*). The methods of study and the instrumentation used during the eruption are the same as those discussed in the earlier article. The locations of all seismographs, tiltmeter stations, and bench marks are shown in Fig. 1.

The authors are all either past or present staff members of the U.S. Geological Survey's Hawaiian Volcano Observatory. Mr. Kinoshita is now with the Survey in Menlo Park, California; Dr. Fiske, in Washington, D.C.

History of Kilauean Activity

Kilauea is a shield volcano lying on the flank of Mauna Loa, its 13,680-foot (4,100-meter) sister volcano (Fig. 1). Both volcanoes have erupted relatively uniform tholeiitic basalt throughout the exposed part of the shield.

Table 1 summarizes the 200-year "historic" record of activity at Kilauea. During most of the 19th century and the early 20th century there was nearly constant eruption in the summit caldera —at times in many active lakes, at times in a single one that occupied the site of the present Halemaumau. Broadly, the pattern of historic activity has consisted of several years of caldera or pit-crater filling followed by discharge of lava through a flank eruption that resulted in collapse of the caldera or crater, often leaving a huge empty pit in the summit.

1967–68 Eruption from Halemaumau Crater

The 1967–68 Halemaumau eruption began with fountaining in Halemaumau crater at 0232 on 5 November 1967, along a line of vents oriented in a north-south direction across the crater floor. There were 31 separate episodes of eruption, here termed "phases," separated by periods of quiescence. These phases can conveniently be divided into five groups, on the basis of similarities in the manner of eruption, in tremor, or in tilt pattern as recorded at Uwekahuna (Table 2 and Fig. 2). The pattern of filling of Halemaumau crater is shown in Fig. 3.

Shallow harmonic tremor with a predominant period of about 0.5 second preceded the eruption by about 1 hour and accompanied all the eruptive phases. The highest tremor amplitudes were recorded early in the eruption; the lower tremor amplitudes were associated with the later phases. Gross variations in the pattern of the eruption over any short period of time were most conveniently deduced from seismograms recorded at moderate distances up to 5 kilometers from the site of the eruption. The rapid decrease in the amplitude of tremor with increasthe epicentral distance between 1 kilometer and 15 kilometers resembled the pattern of amplitude decay for Kilauea caldera earthquakes having focal depths of 3 to 4 kilometers, an indication that the source of tremor was also shallow.

During phases 1 to 23, high rates of lava extrusion were accompanied by high tremor amplitude and by an eastward tilt at Uwekahuna (deflation). Conversely, low or no output of lava was accompanied by low or no tremor and by a westward tilt (inflation). During phases 24 to 31, the lava output remained almost constant, but the tremor and tilt patterns showed minor fluctuations. Because the recording tiltmeter records only the east-west component, we do not know whether it responds to an inflation-deflation of a single center or to the migration of a center. We believe, however, that during any one group of related phases the tiltmeter is sensing the input or output from a single reservoir. The tilt pattern is so monotonously repetitious that the "ups" and "downs" of the tilt curve during a group of related phases must be derived from the volume change of one and not several reservoirs or subreservoirs.

Phase 1

In the 23 hours of vigorous fountaining during phase 1, Halemaumau was partly filled by a lake of lava 32 meters deep. Most of the filling took place in the first 8 hours, after which the rate of extrusion decreased markedly (Fig. 2 and Table 2). The early line of fountains degenerated within the first few hours to a semicircular zone of fountains centered over the site of a collapse pit associated with the aftermath of the 1960 flank eruption (Fig. 3). The sites of fountaining remained in the same area for the rest of the eruption. The stable, central location of the fountains contrasted with fountain locations for previous eruptions of Halemaumau in 1952, 1954, and 1961, which were either on the wall or in various changing positions on the floor during the eruption.

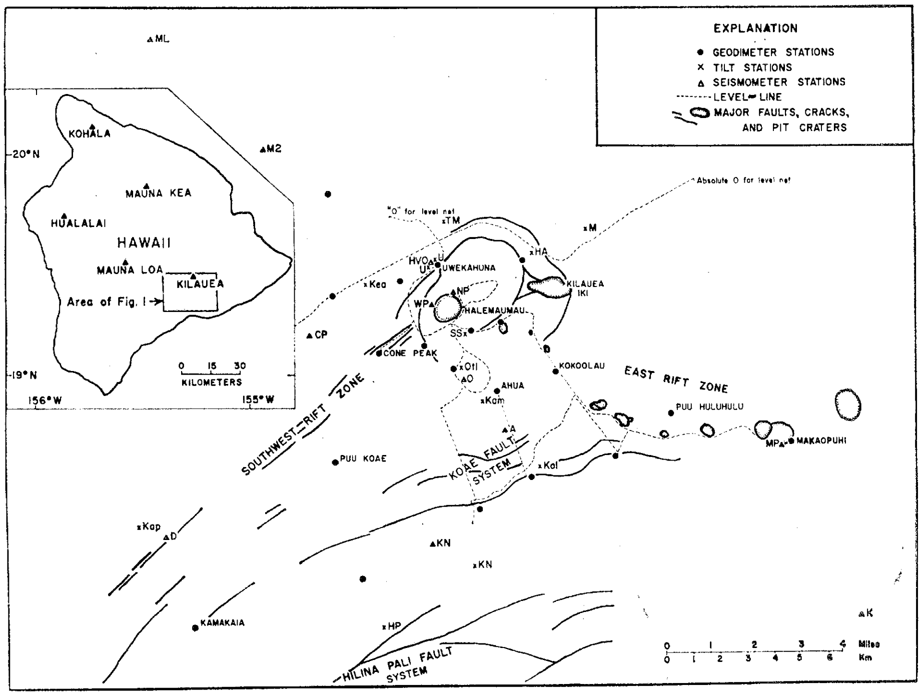


Fig. 1. Index map showing location of geodimeter, tilt, and seismometer stations. The bench marks along the level-lines are spaced about 0.5 kilometer apart.

Table 1. Summary of historic summit activity at Kilauea.

Date	Type of activity	Collapse: volume (10^6 m^3)	Eruption: volume (10^6 m^3)
1790	Phreatic explosions	Major collapse	
1790–1823	Caldera flooded		543
1823, Spring	Southwest-rift eruption	535	
1823–1832	Caldera flooded		672
1832, January	Byron Ledge flow	580	
1832–1840	Caldera flooded		627
1840, June	East-rift eruption	214	
1840–1849	Infill with piston uplift		153
1849–1851	Inactive, fuming		
1851–1866	Infill with piston uplift		153
1866–1868	Caldera flooded		76
1868, April	Byron Ledge and southwest-rift eruptions	191	
1868–1870	Inactive fuming		
1870–1886	Caldera flooded		268
1886, March		38	
1892–1894	Infill, in Halemaumau area only		38
1894, July		9	
1894–1904	Mostly inactive, return of lava lake to Halemaumau	9	
1904–1918	Active lava lake, Halemaumau		
1918–1924	Southwest-rift eruption to form Mauna Iki in 1920; caldera floor flooded in 1918–1921		
1924	Phreatic explosions	203	
1924–1934	Seven short eruptions in Halemaumau		28
1952–1954	Two short eruptions in Halemaumau and caldera floor		55
1955	East-rift eruption	92	
1959	Summit eruption at Kilauea Iki crater		39
1960	East rift	118	
1961	Three short eruptions at Halemaumau and one on east rift	16	
1962–1965	Five short east-rift eruptions	27	
1967–1968	Halemaumau eruption		84

During the first phase, the tremor amplitude was so high that meaningful measurement of relative amplitude had to be made on the record obtained from the Mauna Loa seismometer, located about 15 kilometers from the site of the eruption. Figure 4A shows the spectacular record of tilt and tremor recorded at Uwekahuna. Note the abrupt change from deflation to inflation following the end of fountaining. The sequence of events in the first phase is as follows.

5 November 1967

0133. Tremor begins.
0145. Rapid westward (inflation?) tilt.
0204. The first of three felt (Richter magnitude, 2.8), shallow (depth, 4 to 5 kilometers) earthquakes about ½ kilometer southwest of Halemaumau.
0220. The second felt (Richter magnitude, 3.4), shallow (depth, 4 to 5 kilometers) earthquake slightly east of the first quake.
0232. First sighting of eruption in Halemaumau.
0245. Westward tilting ends.
0257. Third and last felt (Richter magnitude, 2.8), shallow (depth, 4 to 5 kilometers) earthquake about ½ kilometer south of the second quake.
0315. Maximum tremor amplitude reached, followed by rapid decrease in amplitude.
0400. Beginning of rapid eastward (deflation) tilt.
1030. Decrease observed in rate of extrusion.

6 November 1967

0015. Beginning of rapid decrease of tremor amplitude.
0100. End of first phase.
0130. Tilt reverses direction to westward (inflation) tilt.
0315. Tremor amplitude fades to imperceptibility.

From about 0200 on 5 November to 0030 on 6 November, the short-base water-tube tiltmeters at Uwekahuna showed a tilt direction of S45°E. On the basis of the direction of S45°E and of the tilt of 8×10^{-6} radian registered on the tiltmeter recording east-west tilt, a calculated value of 11.2×10^{-6} radian was obtained for the total deflation at Uwekahuna during the first phase. This agrees with the value of 12.0×10^{-6} radian measured on the short-base water-tube tiltmeters and indicates an average tilting rate of about 0.5×10^{-6} radian per hour.

The first phase of the eruption ended abruptly at 0100 on 6 November, and the lake level was lowered 14 meters by drainback within the next 48 hours, about 7.6 million cubic meters of lava being left in the pit.

Phases 2 to 7

The next 2 days, 7 and 8 November, were marked by local overturning of the crust of the newly formed lava lake and by very weak spatter action above one or two vents. On the morning of 9 November, continuous harmonic tremor was recorded again, and a pad of new lava, fed by very small bubbling fountains, was observed in the center of the lake. The increase in tremor amplitude and in lava output was so gradual that it is not clear when phase 2 actually began, but we have arbitrarily placed its beginning at 00 hours on 9 November (Fig. 2). Over the next few days tremor built up to amplitudes about half those recorded during the first phase, and the fountains became steady at a height of 20 to 30 meters. For 2 days, tremor was at a maximum, and the surface of the new lake was rising at a rate of 3 meters per day. The daily rise for the remainder of the second phase was 2 meters, and the depth at the center of the lake reached about 35 meters, exceeding the maximum depth reached by the first phase. During the second phase, a central pool of active lava around the fountains was contained by a low levee of ever-increasing circumference, surrounded by a moat extending to the outer walls of Halemaumau. The moat was gradually filled by new lava flows that spilled over the levees around the active lake. By the end of the second phase, the active lava lake covered 40 percent of the floor formed by the first phase. The height of the active lake above the moat averaged about 9 meters. The activity of the second phase very closely resembled the continuous activity of the early 1900's in the central location of boiling fountains and the existence of an active pond of confined lava which never crusted over (*4*).

The second phase ended abruptly at 1945 on 19 November as fountaining stopped, and harmonic tremor became imperceptible at about 1955. Drainback began immediately, and by the morning of 20 November drainage had

Table 2. Rates of extrusion.

Phases	Average rate of filling of drained central lake at beginning of phases (10^6 m^3/day)	Rate of filling of Halemaumau, including periods of activity and inactivity (10^6 m^3/day)
	1967 Halemaumau eruption	
1		36.7 (first 7 hours)
1		4.7 (last 15.5 hours)
1		19.9 (total)
2–7	52.3	0.27
8–23	52.3	.43
24–28*		.16
28*–30		.28
	Other eruptions	
1952		.06–4.8
1961		.01–1.64
1823–1953†		.002–0.16

* Before 2 February. † See (*6*).

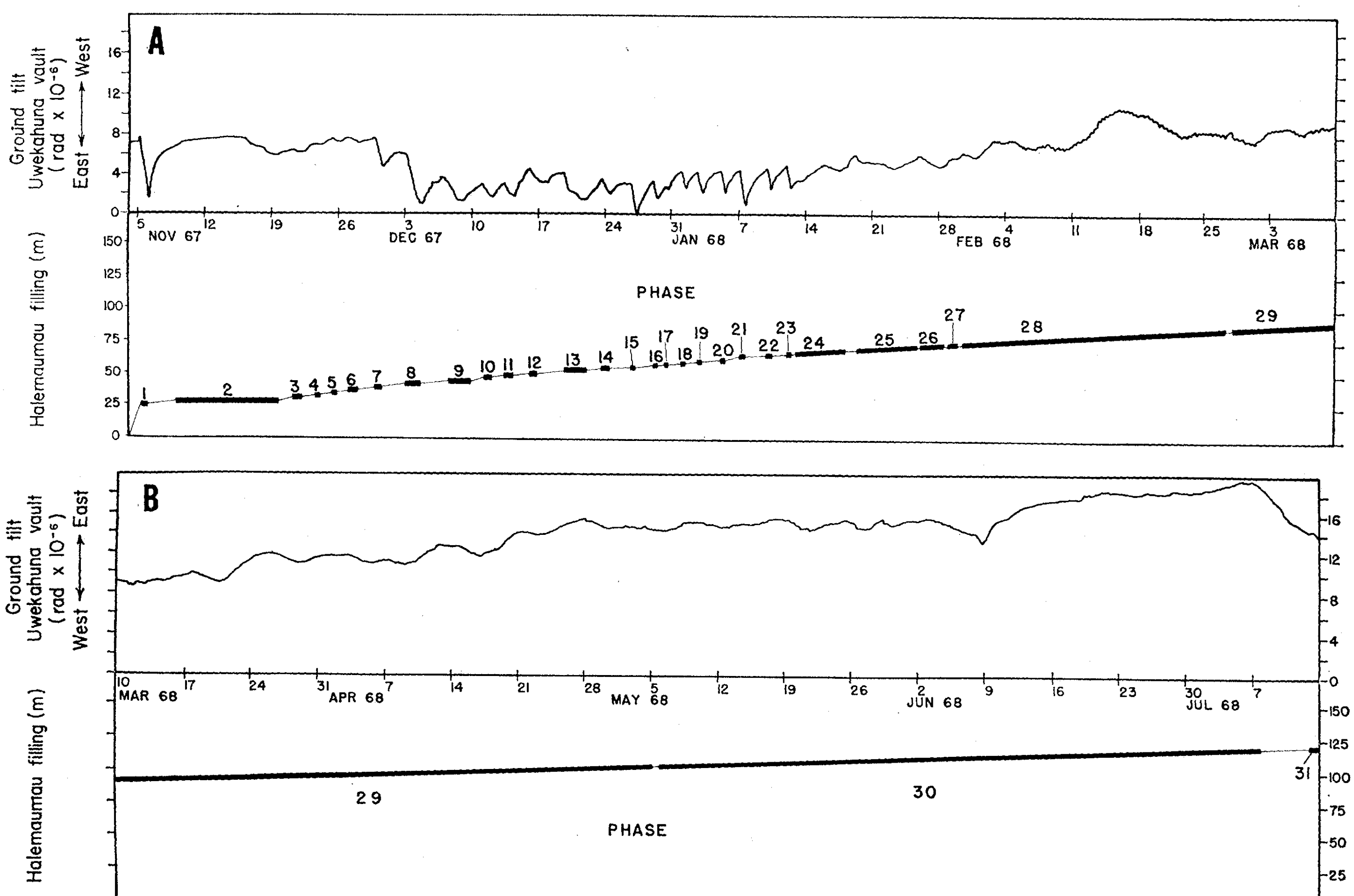


Fig. 2. (A and B) Hourly plot of tilt in east-west direction as registered on a continuous recording tiltmeter at Uwekahuna. The heavy line at bottom in A and B shows the average depth of lava in Halemaumau during the phase, as calculated from vertical angles obtained by survey from the crater rim.

caused the central part of the lake to drop by about 6 meters, leaving a surface of variable relief averaging about 28 meters above the 1961 floor.

The third phase of the eruption began at 0340 on 21 November 1967; continuous harmonic tremor was again recorded on the seismograph net around Kilauea summit, and fountaining was renewed in the central area of Halemaumau. Within 1½ hours, harmonic tremor built up to the level reached during the steady fountaining of the second phase. Phases 4 to 7 followed the pattern of phase 3.

Periods of quiescence between eruptive phases 2 to 7 were marked by drainback of the central lake, which lowered the lake level by 10 or more meters, and by explosive degassing at the site of the main fountain. The larger reports (which sounded like rifle or cannon shots) accompanied ground movement recorded by seismometers located near the edge of Halemaumau. Glowing, or even liquid, spatter was often thrown out during the degassing, and it was evident that the eruption could not be considered to have ceased.

The main characteristics of phases 2 to 7 were low tilt response and high tremor amplitude during extrusion. The tilt record showed low-amplitude oscillations of about 0.5×10^{-6} radian between eruptive and quiet periods. Except for the beginning of the second phase, the buildup of tremor amplitude was rapid; this was followed by a slow decay as the phase progressed.

Phases 8 to 23

Beginning with phase 8, on 29 November 1967, the pattern of eruption became more regular, and this regularity continued through phase 23. These phases were characterized on the tilt record (Fig. 4, B and C) by eastward-down (deflation) tilt of 2 to 5×10^{-6} radian during eruption. Each of the eruptive phases 8 to 23 took place in the following manner.

1) The beginning of harmonic tremor was followed within ½ to 1½ hours by sharp deflation of the Kilauea summit (see Fig. 4, B and C).

2) Tremor built up to a maximum within 1 to 1½ hours, during which time the central lake filled up and began to overflow its levees.

3) Several hours of overflow, which often reached to the walls of Halemaumau, were followed by decrease of tremor, partial drainback, and confinement of the active lake again within its levee.

4) The tremor amplitude showed a sharp decrease, and, simultaneously, the tilt showed the beginning of summit reinflation. Within 2 hours following the onset of inflation, the tremor ceased.

The periods of quiescence between eruptive phases were marked by explosive degassing at the site of the main fountain.

The construction of levees bounding the inner lake was spectacularly displayed during phases 8 to 23 (see cover). During periods of overflow the levee simply accreted material where overflow occurred. In the latter part of each phase, constant wave action against the inner side of the levee threw spatter onto the top of the levee. Remarkably, the area occupied by the active lake hardly diminished during this time, and the levees were built as nearly vertical edifices.

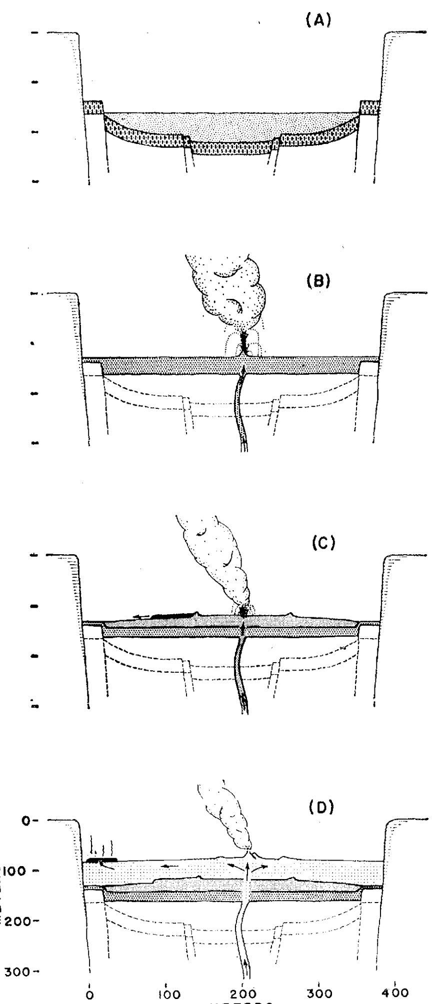


Fig. 3. The filling of Halemaumau crater, 1967–68 eruption. (A) Halemaumau as it appeared before the eruption. Light stipple, 1961 lava; faults in the central part of the crater mark the site of collapse in 1960. (B) Stage 1 of the eruption. Heavy stipple, lava of first phase before drainback. (C) Stages 2 and 3 of the eruption. Shown are the active central lava lake, the bounding levees, and the overflows that built up the lava fill between the active lake and the walls of Halemaumau. (D) Stage 4 of the eruption. The central lake is smaller, cinder cones are being built, and filling is by underflow and occasional ooze-outs near the walls of Halemaumau.

Another phenomenon displayed by phases 8 to 23 was the rising and sinking of "islands" of crust contained within the central active lake. Before an eruptive phase began, the island masses stood as much as 20 meters above the drained level of the lake. As soon as the islands were surrounded by the rising lava of a new eruptive phase, they began to sink, and, after a decrease in elevation of 5 or more meters, they were covered or nearly covered as the active lake began to overflow. During drainback the process ran in reverse: as the lake level subsided, the island masses rose. The exact cause of this phenomenon is not known. However, the observations show that these island masses were "floating" in the pond of active lava and, though not rooted to the floor of Halemaumau, did not move laterally.

Phases 24 to 28 (before 2 February)

The eruption changed pattern again on 13 January 1968, when, for the first time since phase 2, an eruptive phase began and was accompanied by *rising* tilt (Fig. 2). During phases 24 to 27 the level of the inner lake never exceeded the height of the confining levee, and gradually a new levee was built inside the one built during phases 2 to 23. The main island mass gradually became part of the new levee and eventually became rooted to the lake crust. There was little or no fountaining.

Transit readings, which had been made at intervals from the start of the eruption to measure the rate of filling, were halted, on the assumption that the lake had stopped filling. They were resumed, however, in the latter part of January, when a part of the active lava lake and confining levee unexpectedly became visible from the platform outside the Volcano Observatory on the bluff at Uwekahuna. Transit readings at that time indicated that the floor of Halemaumau was 1 to 9 meters higher than it had been 3 weeks earlier, and showed the central lake and its surrounding levee system were still rising at a rate of more than 0.3 meter a day. During this period, very few overflows were noted, but ooze-outs and small rootless flows were seen at many places between the levee and the crater walls of Halemaumau. Thus, by injection from below and by minor overflow from the active lake, the floor of Halemaumau continued to rise. This type of filling was similar to the "piston uplift" (Table 1) observed in the late 19th century.

During these phases the tilt pattern did not reflect the eruptive activity at the crater. The tilt pattern showed a cyclic alternation that had a period of

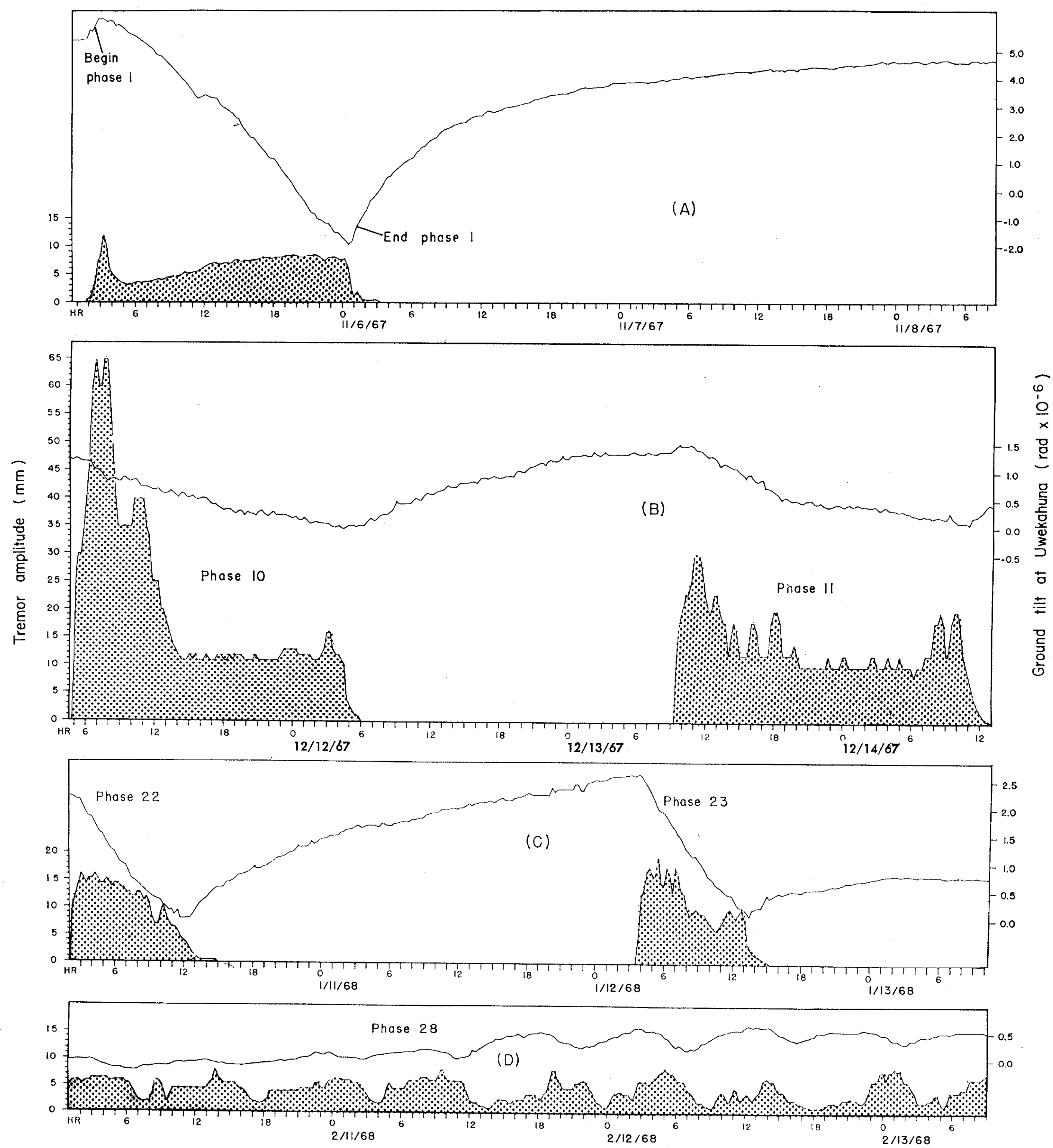


Fig. 4. Quarter-hourly plots of east-west tilt and of tremor amplitude for four periods: (A) 0100 hours Hawaiian Standard Time, 5 November 1967 to 1200 hours, 6 November. (B) 0430 hours, 11 December to 1300 hours, 14 December. (C) 0200 hours, 10 December to 1600 hours, 12 December. (D) 0900 hours, 11 February to 0900 hours, 13 February. Tremor amplitude is measured in A from the record obtained from the Mauna Loa seismometer (*ML* in Fig. 1) and measured in B, C, and D from the record obtained from the North Pit seismometer (*NP* in Fig. 1). The tremor amplitude was so great during most of the early part of the eruption that the North Pit record could not be read.

4 to 6 days and an amplitude of about 1×10^{-6} radian. Tremor accompanied the phases, but the amplitude of tremor was about 1/10 that recorded during phases 2 to 23. The relationship between tilting and eruptive activity that prevailed during every phase up to phase 23—that is, westward tilting (up) between phases and eastward tilting (down) during phases—was not consistently maintained during phases 24 to 28.

Phase 28 (after 2 February)

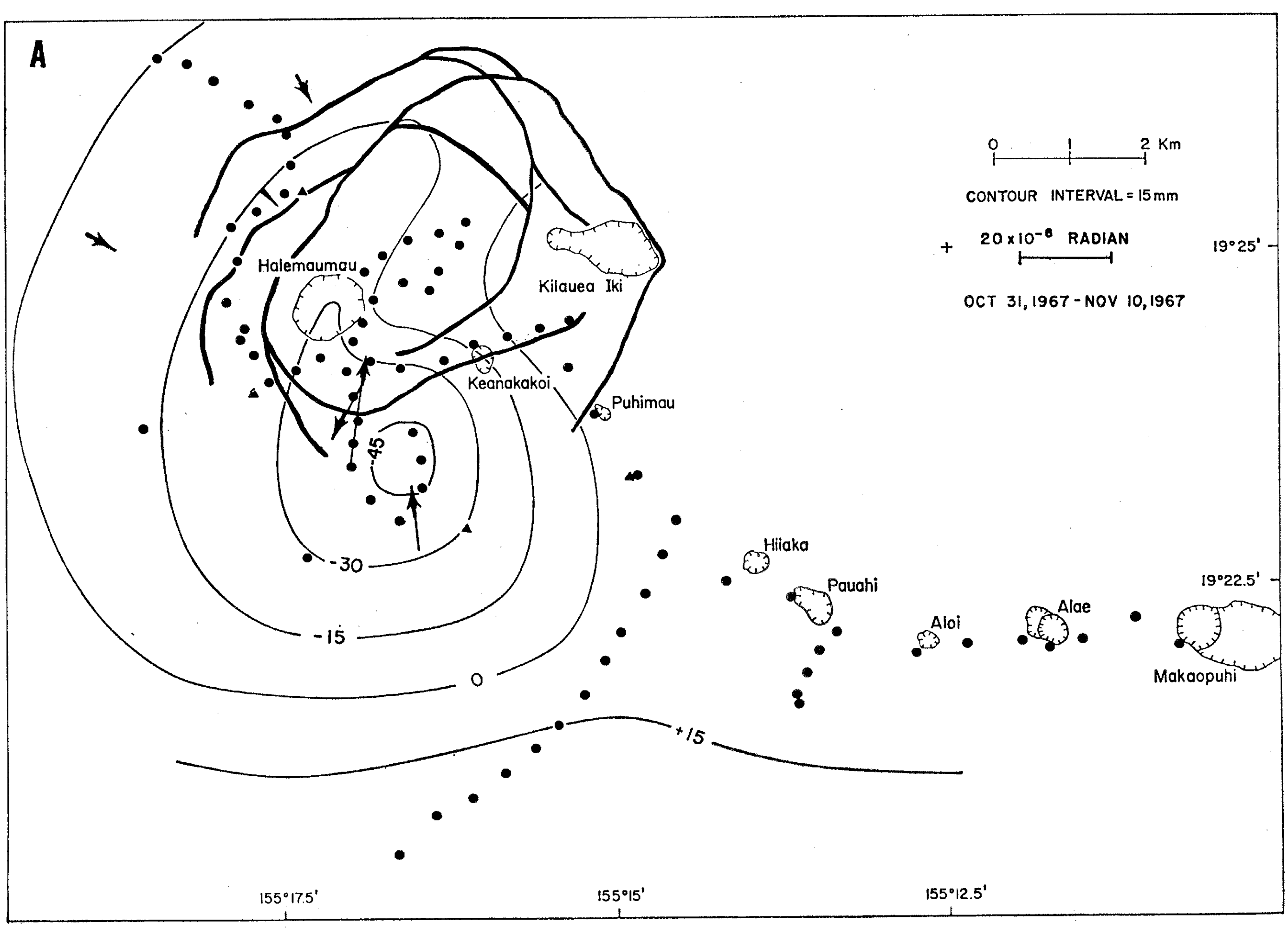
On 2 February 1968, the 4th day of phase 28, the type of eruptive activity changed to one of waxing and waning on an 8- to 12-hour cycle. Two new vents broke through to the surface at points outside the active lake (but within the original circle of fountains) and built steep-sided cones 6 to 15 meters high. These cones put on spectacular displays when they were active —"roman candle" blasts more than 30 meters high were noted on one occasion, and lava cascades pouring down the sides of the cones and free-falling 8 meters into the active lake were commonly observed. With the building of the cones, the landscape in Halemaumau began to resemble more and more that of the 19th century and early 20th century.

The tremor and tilt pattern for phase 28 after 2 February probably is the most fruitful for speculation about the relationship of eruptive activity, tilt, and tremor. Another cycle pattern of tilt, with a period of 8 to 12 hours and amplitude of about 0.5×10^{-6} radian, was superimposed on the cyclic pattern that continued from phase 24 (Fig. 4D). The period for the larger, preexisting pattern changed to a longer, 5- to 8-day cycle. A quarter-hourly plot of tremor amplitudes also showed an 8- to 12-hour cycle that seemingly matched lava output; high extrusion rates were observed during times of high tremor amplitude, and low extrusion rates during times of low tremor amplitude. The high points and low points of the tremor amplitude, however, always occurred about 2 hours later than the highs and lows of the tilt plot with the same 8- to 12-hour period. No attempts other than visual inspection have been made to correlate these patterns with other regular patterns, such as earth tides, but a comprehensive study may show some interesting results for this period of the eruption.

Phases 29 to 31

Following a 15-hour interval of quiescence on 27 February, the tilt pattern changed again, and over the next 10 days it gradually lost all short-period regularity. From 9 March to 5 May, when another brief interval of quiescence marked the end of phase 29, the east-west tilt rose and fell by several microradians on a 7- to 11-day cycle. After 5 May no regular long-period cyclic pattern was evident, and the short-period variations recorded are probably response to noise. Phase 30 ended on 7 July. Phase 31 represented renewed activity for 19 hours on 13 July, after which the eruption in Halemaumau ceased.

Following phase 28 the visible activity decreased in intensity. Fountaining was low, and the level of the lake remained within the confines of its levee.



From time to time flows issued from the many spatter cones, but the main rise of the spatter cones was, like the rest of the lake, from underflow rather than from actual addition of material to their tops.

The rate of filling in the later stages of the eruption was as follows: phase 28, 0.33 meter per day; phase 29, 0.37 meter per day; phase 30, 0.26 meter per day. The final depths of filling, measured from the 1961 floor were as follows: high lava marks, 110.5 to 114.4 meters; inner levee, 128 ± 3 meters; highest cone, 143 meters. Following the end of the eruption, lava drained out of the inner lake, leaving about a 15-meter depression in the center.

Summit Deformation and Ground Cracking during the Eruption

Deformation measurements defining the cycle of inflation preceding the eruption are described in an earlier article (*3*). Deformation data were gathered during the eruption, by means of the instruments and techniques described in that article.

The first data gathered after the eruption began indicate that the summit had subsided sharply (Fig. 5A). The area of subsidence appeared to be the same as the area of maximum uplift in the period just preceding the eruption (*3*). The measured amounts of subsidence are minimum values because they include inflation of the volcano between 30–31 October and the beginning of eruption, and because they were obtained relative to a bench mark which was arbitrarily assumed to be stationary but which actually probably subsided too.

The area of subsidence is marked by a trough of relatively large negative values which extends from this area northward across Halemaumau. As observed in the period directly preceding the eruption (*3*), the area near Halemaumau and the area 2 kilometers to the south show anomalously high values of linear strain (Fig. 5B). The highest values for contraction strain occur along the shorter lines that cross the minimum shown in Fig 5B. However, one line that crosses the trough mapped in the leveling shows extensile strains, whereas all the lines around it show contraction. The strain data are consistent with observations of ground cracking in the area of the trough and the north-south alignment of the earliest fissures across the floor of Halemaumau; apparently the trough is the surface expression of a narrow tensional zone through which magma could travel to the eruptive site. These anomalous strain values occur in an area of concentrated earthquake activity near the beginning of the eruption (Fig. 5B). Although several tens of shallow-focus earthquakes (focus depth, less than 5 kilometers) occur daily in the caldera, they seldom reach Richter magnitudes of 2½ to 3½, as the four shown in Fig. 5B did.

The summit region of Kilauea continued to show overall subsidence for the first 5 months after the first phase.

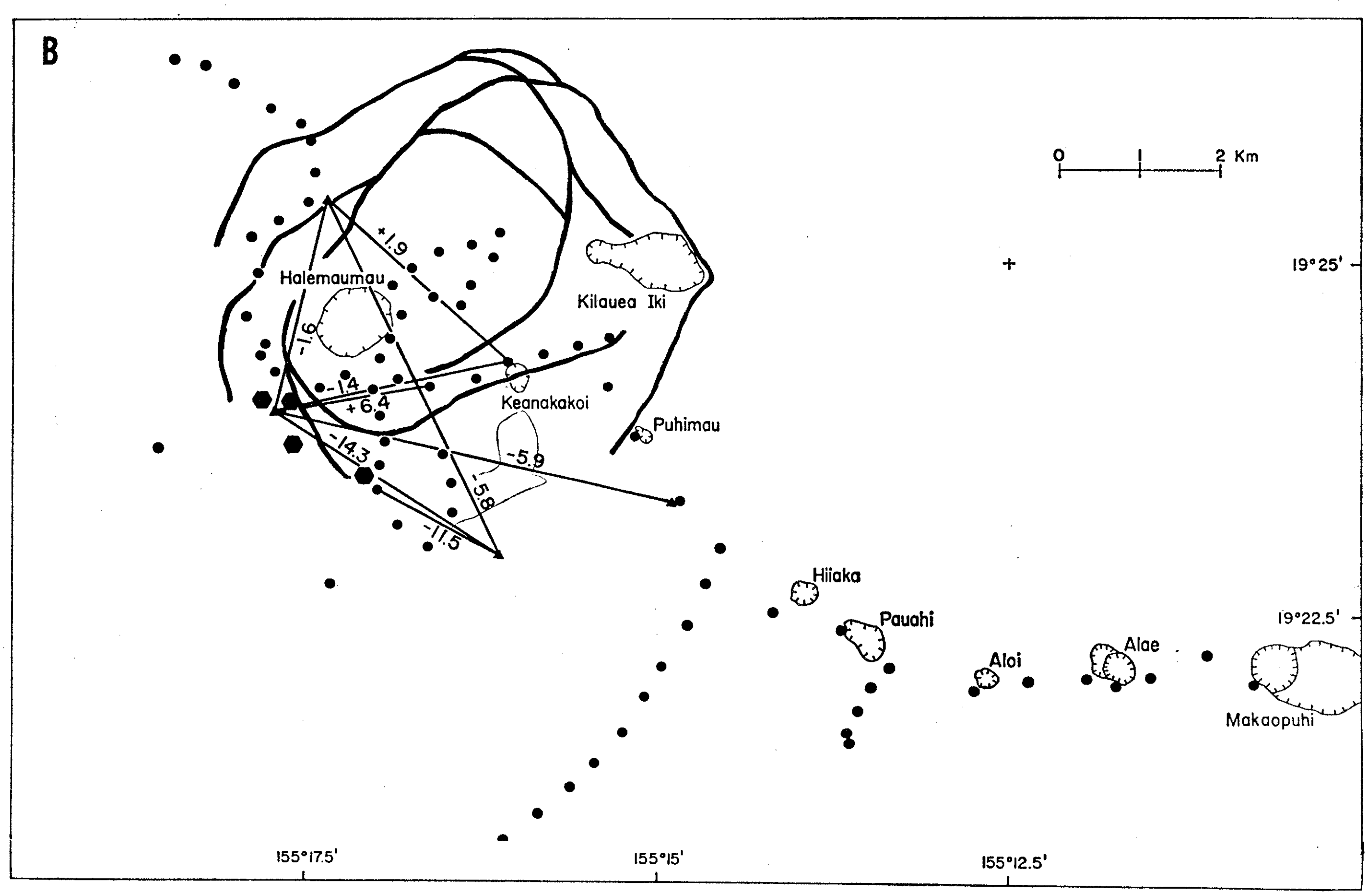
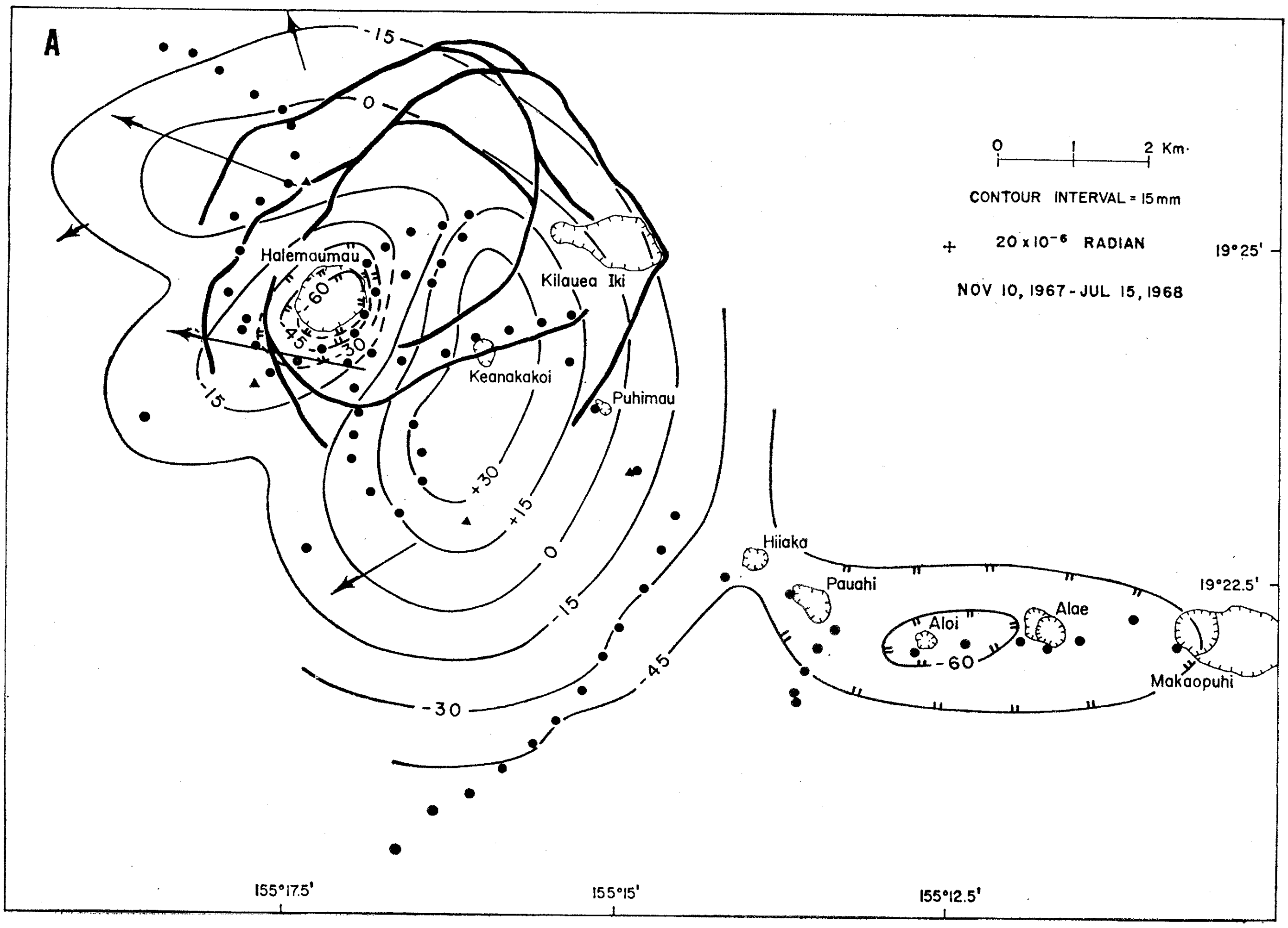


Fig. 5. (A) Contour map showing lines of equal subsidence (down-drop) that occurred during the period 31 October 1967 to 7–10 November 1967. The dots show locations of bench marks along the level-lines, Kilauea caldera. (B) The numbers along the straight lines show strain along those lines, in parts per million, during the period 16 October to 7 November 1967. Negative values indicate contractile strain; positive values indicate extensile strain. These strain values cover essentially the same time period that the contours do. The solid hexagons are epicenters for earthquakes of Richter magnitude greater than 2.0 that occurred between 16 October and 7 December 1967.


A
-15
0
0 1 2 Km
CONTOUR INTERVAL = 15 mm
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NOV 10, 1967 - JUL 15, 1968
Halemaumau
-60
-45
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-15
Kilauea Iki
Keanakakoi
Puhimau
+30
+15
0
-15
-30
-45
Hiiaka
Pauahi
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Makaopuhi
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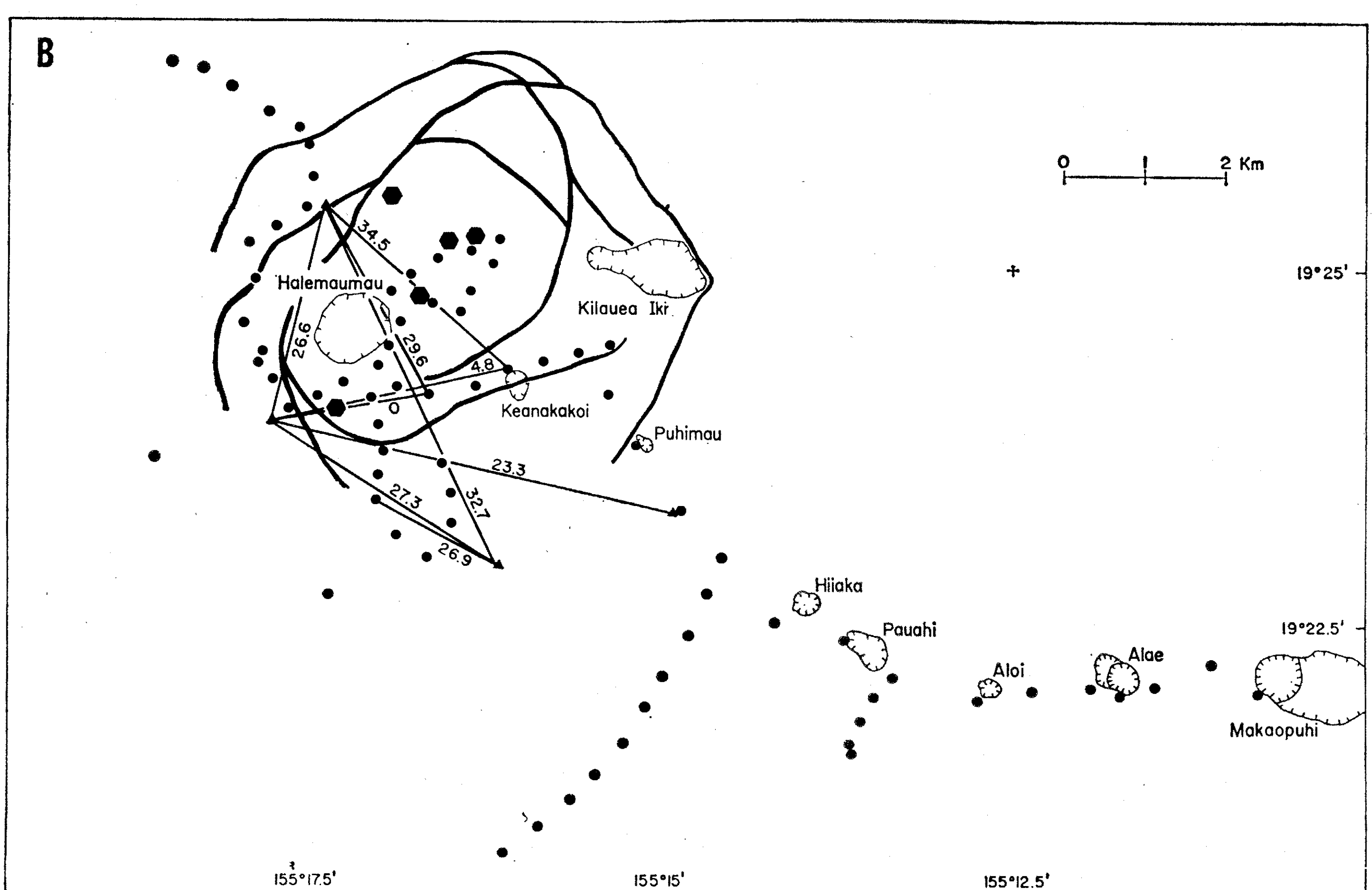
155°12.5'


B
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19°25'
Hiiaka
Pauahi
Aloi
Alae
19°22.5'
Makaopuhi
155°17.5'
155°15'
155°12.5'

The amount and rate of subsidence were small; in fact, one small area east of Halemaumau showed either no movement or slight uplift during those first 5 months. Beginning in April, the 6th month after phase 1, the deformation pattern shown in Fig. 6, A and B, began and continued to the end of the eruption. The maps of Fig. 6 show the cumulative ground deformation that took place between the end of the first phase and the end of the eruption.

The vertical changes represented by the contours of the level-change map and the arrows showing direction and amount of downtilt in Fig. 6A are in apparent disagreement; the tilt at stations at the outer edges of the map show uplift of the summit region, but the level-change map shows a small gain in altitude for only a portion of the summit. This disagreement probably results from two conditions. (i) The tilting was begun and completed in the 48-hour period 7 to 8 November, during which time the summit was undergoing rapid reinflation following the deflation that followed phase 1. The leveling, on the other hand, was not completed until 15 November, by which time the recording tiltmeter (Fig. 2) showed that the shallow magma chamber beneath the summit had apparently reinflated to the preeruption level. (ii) The reference bench mark for measuring the changes in level may have itself changed altitude. Leveling between it and a bench mark about 11 kilometers east of Halemaumau showed that our reference bench mark had subsided by about 1.8 centimeters between November 1967 and June 1968. In any event, the pattern and relative amplitudes of the "ups" and "downs" would be unchanged. The only probable discrepancy is that the values recorded for change in altitude are lower than the actual values by perhaps as much as 2 centimeters.

Fig. 6 (A) Contour map showing lines of equal subsidence (down-drop) that occurred during the period 7–10 November 1967 to 15 July 1968. The dots show locations of bench marks along the level-lines, and the heavy lines mark, roughly, the location of the main faults along Kilauea caldera. (B) The numbers along the straight lines show strain along these lines, in parts per million. All the lines show extensile strain. These strain values cover essentially the same time period that the contours do. The solid hexagons are epicenters for earthquakes of Richter magnitude greater than 2.0 that occurred between 8 November 1967 and 15 July 1968.

Table 3. Chemical composition of pumice, phase 1 of the 1967 Halemaumau eruption.*

Oxide	Percentage
SiO_2	50.24
Al_2O_3	13.56
Fe_2O_3	1.36
FeO	9.95
MgO	7.59
CaO	11.06
Na_2O	2.31
K_2O	0.54
H_2O^+	.04
H_2O^-	.01
TiO_2	2.65
MnO	0.26
P_2O_5	.17
CO_2	.01
Cl	.01
F	.03
Subtotal	99.79
Less O†	0.01
Total	99.78

* Analysis performed in the Rapid Rock Analysis Laboratory of the U.S. Geological Survey under the direction of L. C. Peck; analyst, G. O. Riddle. † Summation correction due to reporting of Cl and F.

If, as seems likely, about 15 millimeters should be added to all the values for change in level, most of the summit region would show uplift. Only an area in the upper east rift near Aloi crater and Halemaumau, the site of eruption, show subsidence. Since the subsidence along the upper east rift is inferred from a single line of bench marks, its actual form and areal extent are unknown. It may have been caused by withdrawal of magma from a shallow subchamber beneath the area of Aloi crater, or possibly by subsidence in the Koae fault system. The subsidence at Halemaumau can be explained entirely as being the effect of the loading at the surface caused by the extrusion of magma into Halemaumau. Assuming a reasonable density ($D = 2.5$ grams per cubic centimeter) for the 84×10^6 cubic meters of newly erupted lava and reasonable elastic parameters for the near-surface rocks, we find the calculated and observed subsidence at Halemaumau to be in very good agreement.

Average horizontal strains, in parts per million, along lines at the summit of Kilauea are shown in Fig. 6B. All but two of the lines show extensile strains of 2 to 3×10^5. Two east-west lines just south of Halemaumau show low strains; these are the two lines that crossed the area of most ground cracking in November 1967 and that showed anomalous strain at that time. It is interesting to note that the largest strains, though larger by only slight amounts, again occurred in the area of highest earthquake activity (Fig. 6).

Rate of Extrusion

Eruption in a pit crater permits simple calculation of the rate of extrusion. Table 2 gives average rates of extrusion for the various stages. Two kinds of rates are calculated: one is the rate of supply of magma to the small active lava lake; the other, the rate of filling of Halemaumau pit crater. Refilling of the partly drained active lake after an eruptive phase was very rapid, lasting about 1 hour. The rate of filling of Halemaumau averaged over periods of activity and inactivity is, of course, less than the rate of supply of magma to the pit during any one eruptive phase. Beginning with phase 24, however, the rate of filling of Halemaumau essentially represents the rate of supply to Halemaumau, and is surprisingly uniform. These rates are generally high as compared with those of earlier periods of activity of Halemaumau (Table 2). Because the net deformation of the summit area during the eruption was very small, the average rate for phases 24 to 30 may approximate the rate of supply of new magma from a source within the mantle to the shallow reservoir complex beneath Kilauea summit.

Temperature and Composition of the Lava

Maximum fountain temperatures, as measured by optical pyrometer during the first phase of the eruption and later, were 1110° to 1125°C. These are probably lower than the true eruption temperatures by 35° to 75°C. (*6*).

A chemical analysis of pumice collected during the first phase of the eruption is given in Table 3. The pumice contains rare skeletal olivine crystals and trace amounts of clinopyroxene and plagioclase. Chemically and petrographically the pumice resembles that collected during the Halemaumau eruptions of 1952, 1954, and 1961.

Possible Forecasting of the Eruption

Could this eruption have been predicted? The answer depends in part on the time interval considered significant for prediction. If we are speaking of hours, we note that this eruption and virtually every other eruption of Kilauea has been preceded, by an hour or more, by one or more felt earthquakes and by harmonic tremor. If we are speaking of years, we can say that presumably every cycle of inflation will end in an eruption of some kind. To predict exactly when and where the next eruption will occur while the volcano is still inflating, however, is impossible on the basis of our present knowledge. As shown by Fiske and Kinoshita (*3*), the volcano goes through a number of cycles of accelerated inflation during general inflation, many of which are not followed by eruption. In particular, the tilt and level data continue to show "normal" changes in the days, weeks, or months preceding an eruption. The horizontal strain may, in time, permit longer-range prediction. It has been pointed out elsewhere (*3*) that, during the inflation associated with the last center of uplift, the horizontal deformation was far greater than would be expected from any model proposed to fit the level and tilt data.

Although more data on horizontal strain during eruptive cycles are needed, monitoring of these strains in the summit area appears to give the most favorable criteria for prediction of a few weeks. About 1 month before the eruption of 5 November 1967, high strains were noted in the area south of Halemaumau. This area, as shown by the level and tilt data, was the last area to inflate before the eruption and the first to subside at the beginning of the eruption. If we calculate cumulative strains from July 1966, the month in which a complete series of geodimeter measurements of the summit was begun, we find that the strains recorded along the lines south of Halemaumau exceeded average linear strains of 1.3×10^{-4} in the month before the eruption. The next highest cumulative strains at that time were about 0.9 to 1.1×10^{-4} along the lines east of Halemaumau. Many data obtained over longer time intervals are needed to determine the significance of the cumulative strain values. A program for monitoring horizontal strain at intervals of 1 week has been initiated at Kilauea summit in the hope that eventually it will be possible to predict volcano eruptions.

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Prognosis for the Development of New Chemical Birth-Control Agents

Parochial attitudes in technologically advanced nations make prospects increasingly dismal.

Carl Djerassi

The very rapid rate of increase in the world's population, notably in the developing countries, has become a matter of worldwide concern. Fifteen years ago this was virtually a taboo subject, whereas the term *population explosion* has now become a household phrase. Symptomatic of the international concern with this problem and its enormous economic, political, and human implications is the fact that the very first report by the Committee on Science and Public Policy of the National Academy of Sciences dealt with the population problem (*1*). A veritable flood of articles and books has appeared on this subject in recent years, and the general consensus is that effective family planning must play a key role in the solution of this world problem.

At first glance, the prognosis for improved family-planning methods appears promising. During the past 10 years a major breakthrough in birth-control techniques has been achieved: the development of orally administered contraceptive agents (*2*, *3*) of virtually 100 percent effectiveness, and greatly increased use of improved intrauterine devices (IUD) (*4*). Both approaches lend themselves much more readily than conventional earlier methods (for example, the diaphragm, the condom, and so on) to broad-scale family planning in developing countries, and it is not surprising, therefore, that the well-publicized large-scale programs in such diverse countries as Chile, Egypt, South Korea, and Taiwan are based virtually exclusively on steroid oral contraceptive agents (*5*) and IUD's. Abortion is another effective means of population control, as demonstrated during the past 20 years on a country wide basis in Japan and eastern Europe, but the general tendency in research has been to concentrate on improved chemical agents for birth control, the dramatic effectiveness of the steroid oral contraceptive agents having provided the main impetus. Thus, considerable effort is being expended on overcoming one of the major drawbacks of these chemical agents—the necessity of taking a pill daily or with short interruptions—by developing "once-a-month" pills, or sustained-action formulations (Silastic implants, pellets, and so on) effective for many months or conceivably even years. Philanthropic organizations such as the Ford Foundation and the Population Council have been dedicating increasing amounts of money to the support of such research, and, during the past year, the National Institute of Child Health and Human Development of the U.S. Public Health Service has organized a Center for Population Research whose annual multimillion-dol-

The author is professor of chemistry at Stanford University, Stanford, California, and president of Syntex Research, Palo Alto, California.

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