CYCLING OF MAGMA BETWEEN THE SUMMIT RESERVOIR AND KILAUEA IKI LAVA LAKE DURING THE 1959 ERUPTION OF KILAUEA VOLCANO

By Jerry P. Eaton, Donald H. Richter, *and* Harold L. Krivoy

ABSTRACT

The fortunate combination of observations of deformation of the summit of Kilauea Volcano during the 1959 Kilauea Iki eruption and an accurate log of the eruption of lava into Kilauea Iki lava lake and its subsequent partial withdrawal provides a record of movement of magma into and through the summit reservoir during that eruption. The initial eruption of 30×10^6 m^3 of lava into Kilauea Iki, with an accompanying 50 μrad of eastward tilt at Uwekahuna, established a scaling factor relating the change in volume of the summit reservoir to tilting at Uwekahuna. A record of the initial deflation and subsequent reinflation of the summit reservoir was obtained by the liquid-level tiltmeter at Uwekahuna. A good record of episodic eastward tilting during the eruptive stage and westward tilting during the backflow stage of the later phases of the eruption was obtained by analysis of the zero-line deflections of the east-west-component Press-Ewing seismograph. Converted to volumes of deflation and inflation, the tilting associated with eruption of lava into and withdrawal of lava from the lava lake offers a means of determining the net gain or loss of lava in the lake-reservoir system during each phase. Analysis of the interplay between volcanic tremor and the details of the reinflation tilt records permits estimation of the volume of lava that escaped from the summit reservoir during individual backflow episodes.

The 30×10^6 m^3 of lava originally withdrawn from the reservoir was eventually more than replaced by about 60×10^6 m^3 of lava rising from depth. Of this 60×10^6 m^3, 40×10^6 m^3 finally was retained in the reservoir, 8×10^6 m^3 was added to the lava lake, and about 12×10^6 m^3 was driven out of the summit reservoir during the late-phase backflow episodes. Lava that erupted into Kilauea Iki from phase 2 onward was material from the reservoir, which was being refilled with new lava from below; this lava was repeatedly erupted from the reservoir and then withdrawn back into it. Overfilling of the reservoir, combined with sharp reinflation pulses during later backflow episodes, drove an estimated 12×10^6 m^3 of lava out of the reservoir, possibly into the upper end of the east rift zone.

The recycling process was made possible by a lava conduit, which remained open after phase 1, that connected a supply of lava in the lake with one in the reservoir. Large-scale vesiculation of lava in the conduit effectively pumped lava from the reservoir up into the lake. Flooding of the vent by devesiculated lake lava quenched the fountain and permitted lake lava to flow back into the reservoir. The process was rekindled repeatedly, after backflow stopped, by the introduction of fresh gas-charged reservoir lava into the conduit, which permitted the vesiculation pump to operate again.

INTRODUCTION

The 1959 eruption in Kilauea Iki Crater at the summit of Kilauea Volcano consisted of 16 separate principal phases that poured lava into the bowl-shaped crater from a main vent on the south wall about 90 m above its original floor (Richter and others, 1970). The first phase died out abruptly after the lake surface rose above the level of the vent, leaving a lake 102 m deep and containing 30×10^6 m^3 of lava ponded in Kilauea Iki. Except for basaltic pumice blown downwind (southwest) from the vent, much of which accumulated on the crater rim above the vent to form a cinder cone, all of the lava erupted was caught in the crater, where its volume could be determined from a simple measurement of the height of the lava lake surface. After each phase, a substantial volume of lava escaped back underground into the main vent or into another somewhat lower vent hidden by the lake nearby. Backflow of lava after cessation of fountaining is not uncommon at Kilauea (for example, the 1954 eruption in Halemaumau; see Macdonald and Eaton, 1957), but the 1959 eruption is the only one for which we have such complete measurements of ground deformation and volumes of eruption and backflow. Except for their smaller volumes of erupted lava and shorter durations, the 15 subsequent principal phases were much like the first. Lava that erupted from the vent collected in the lake, increasing its depth until ponded lava rose above the vent and caused the fountain to die out abruptly. As the lake flooded the base of the fountain, the height of the fountain often oscillated wildly before it was quenched. At the ends of several phases, notably phases 4 and 16, lowering of the lake surface and strong backflow toward the base of the still-active fountain showed that withdrawal of lava from the lake need not await cessation of fountaining. The drainback point appeared to be at or just below the base of the fountain.

Total volumes of lava erupted into and withdrawn from Kilauea Iki during its 16 principal eruptive phases between November 14 and December 19 were 102×10^6 m^3 and 63×10^6 m^3, respectively, leaving 38×10^6 m^3 of lava in the lake at the end of the eruption. Of the 71×10^6 m^3 of lava poured into the lake after the end of phase 1 fountaining, only 8×10^6 m^3 remained at the end of the eruption.

What was the fate of the 63×10^6 m^3 of lava that drained back underground from the lava lake? If it returned to its immediate source to be erupted again in later phases, then only about 8×10^6 m^3 of drainback lava must be accounted for (maximum lake volume at end of phase 8 minus final lake volume at end of eruption). The other 56×10^6 m^3 represents the same lava that was erupted many times in small batches and then withdrawn. An important question for this apparently closed lake-reservoir system is: What provided the driving force to erupt the same limited volume of lava over and over again? If the drainback lava escaped from an open lake-reservoir system into another storage zone beneath the summit or into the fluid core of the east rift zone (in preparation for the impending 1960 east-rift eruption), however, then the entire 63×10^6 m^3 must be found.

In addition to the unusual features of the eruption itself, some of which have been outlined above, the 1959 Kilauea Iki eruption was unusual in the range and abundance of geologic and geophysical observations on its progress and effects. There were reasons for this fortunate situation: a new geochemical laboratory had recently been added to the Hawaiian Volcano Observatory (HVO), with an appropriate augmentation of the observatory staff, and the networks of seismometers and tiltmeters around the summit of Kilauea were in the process of being upgraded and expanded in response to lessons learned during the 1954–55 summit and flank eruptions.

Specific measurements that were important for tracking magma as it rose into the volcano from depth, as it was stored temporarily in a shallow summit reservoir, and as it was subsequently erupted into Kilauea Iki Crater and then partially withdrawn include the following:

(1) Seismic network records for (a) locating individual earthquakes and earthquake swarms associated with the eruption and with the expansion of the reservoir before, and its deflation after, the eruption, and (b) the detection and approximate location of the source of volcanic tremor associated with underground movement and eruption of lava;

(2) Measurements of tilting of the Earth's surface around the summit of the volcano as magma moved into or out of the summit reservoir, including: (a) periodic releveling of a network of tilt bases around the summit of the volcano to map the slowly changing pattern of deformation of the entire summit, (b) daily measurement of level changes (tilting) at the Uwekahuna vault (west of Kilauea caldera) and at the Whitney vault (northeast of the caldera), and (c) minute-by-minute monitoring of the rate of tilting and short-term accumulation of tilting at the Uwekahuna vault by analysis of the zero-line drift of the horizontal-component long-period Press-Ewing seismograph;

(3) Systematic observation of the progress of the eruption and periodic measurement of parameters related to the eruption of lava into, and its withdrawal from, the lava lake, including: (a) accurate timing of the beginning and end of eruptive phases, frequent measurement of fountain height, and physical description of the fountain and any unusual phenomena associated with it, (b) periodic measurement of the height of the lava-lake surface, particularly at the end of fountaining and after cessation of drainback, (c) frequent sampling of basaltic pumice thrown out by the fountain and sampling of recently erupted lava from the lake, and (d) measurements of lava fountain temperatures (by optical pyrometer) when conditions at the fountain permitted.

Part of the data covered by item 3 above is from Richter and others (1970), where methods as well as results are described. Data on the volumetric progress of the Kilauea Iki eruption, which form the basis for Richter and others' (1970) figure 2, are presented in table 48.1. The seismic and tilt networks and results have not been treated comprehensively elsewhere, so we shall treat them in detail.

The main purpose of this paper is to present the record of ground-surface deformation at and around the summit of Kilauea that traces the movement of lava within the summit region of the volcano before, during, and after the 1959 eruption and to correlate that record with other measurements and observations carried out during the eruption to answer the question posed above: What was the fate of the 63×10^6 m^3 of lava that drained back underground from the lava lake? A second objective is to analyze the data on tremor amplitude, rate of eruption, fountain height, and recharge of the summit reservoir to discover what they might reveal about the process that caused the repeated eruptions in Kilauea Iki.

We shall begin with explanations of the methods used to measure long-, intermediate-, and short-term tilting at Kilauea and with a brief summary of the seismic network and some of the results obtained from it. Next, we shall trace the course of the eruption to examine the pattern of deformation associated with individual phases and with longer episodes of activity during the eruption. We shall then make a kinematic reconstruction that traces lava into the summit reservoir and through the phases of the Kilauea Iki eruption and that conforms with the observations presented. Finally, we shall examine the relationships among tremor, eruption rate, fountain height, and reservoir recharge quantitatively to develop a better understanding of the mechanics of the eruption.

ACKNOWLEDGMENTS

The manuscript was reviewed by David P. Hill and Fred Klein, whose many helpful suggestions help to clarify and augment the paper.

TILT MEASUREMENTS

TILT BASES

At the time of the 1959 eruption the primary system for measuring deformation of the summit region of Kilauea was a network of 9 permanent tilt bases encircling Kilauea caldera (fig. 48.1) and extending about 10 km south of the caldera. A typical tilt base consists of three concrete piers planted firmly in the ground (on rock if possible) at the vertices of an equilateral triangle about 50 m on a side. Each pier is capped by a brass hub that provides a reference surface and a clamp-down for a precise liquid-level system for measuring height differences between adjacent pairs of piers (Eaton, 1959). The tilt bases are releveled at intervals of 3–6 mo, and changes in the relative heights of the piers reveal any tilting of the base during the interval between measurements. Tilting as small as a few tenths of a microradian (<0.3 μrad) can be detected. The

TABLE 48.1.—*Volumetric progress of the 1959 Kilauea Iki eruption*

[H.s.t., Hawaii standard time; duration is time since last measurement or onset of new eruptive phases; bottom of crater before November 14 at elevation 954 m (3,130 ft) defines zero depth of lava lake; ΔV, change in lake volume since last depth measurement; V, volume of lava lake; rate, average rate of lava outpouring since last depth measurement or onset of new eruptive phase]

			Lava lake		Volume of lava		
Date	Time (H.s.t.)	Duration (h)	Depth (m)	Area (acres)	ΔV (10^6 m^3)	V (10^6 m^3)	Rate (10^3 m^3/h)
			Phase 1				
Nov. 14	2008	0	0 (elev. 954.0)	37.0	0	0	0
Nov. 15	0300	7.0	1.5	37.0	.2	.2	33
	1800	15.0	4.6	39.0	.7	.5	31
Nov. 16	1215	18.25	7.6	41.0	.5	1.1	25
	1400	1.75	8.2	41.5	.1	1.2	44
Nov. 17	1045	20.75	16.8	47	1.4	2.7	70
	1400	3.25	18.3	48.5	.3	3.0	94
	2030	6.5	22.0	51	.7	3.7	106
Nov. 18	1200	15.5	34.1	59	2.5	6.2	163
	2315	11.25	45.7	68	2.8	9.0	252
Nov. 19	1150	12.5	57.9	79	3.5	12.5	281
	2115	9.5	68.6	88	3.6	16.1	378
Nov. 20	1210	15.	82.3	106	5.4	21.5	357
Nov. 21	0930	21.25	97.5	120	7.0	28.4	327
	1925	10.0	102.1	125	2.2	30.7	222
Nov. 23	1000	[1]38.5	100.0	123	−1.1	29.6	−28
			Phase 2				
Nov. 26	0100	0					
	1000	9.0	102.4	125	1.1	30.7	128
	1635	6.6	107.0	130	2.4	33.2	371
	1940	3.0	103.9	127	−1.5	31.7	−510
Nov. 27	1230	16.75	[2]97.8	121	−3.0	28.7	−178
			Phase 3				
Nov. 28	1645	0					
Nov. 29	1500	22.25	100.9	124	1.5	30.2	69
	2147	6.75	103.9	126	1.5	31.7	226
Dec. 1	1500	41.25	[3]100.3	123	−1.8	29.9	−44
			Phase 4				
Dec. 4	[4]0100	0					
	2325	[4]22.5	114.3	138	7.4	37.3	368
Dec. 5	0330	4.0	117.3	142	1.7	39.0	420
	0630	3.0	120.4	145	1.8	40.7	586
	0730	1.0	[5]118.0	142	−1.5	39.3	−1453
	0927	2.0	120.1	145	1.2	40.5	612
	1155	2.5	115.5	140	[6]−2.5	38.0	−1009
	1230	0.5	114.0	137	−.8	37.2	−1682
Dec. 6	1448	26.25	110.0	134	−2.1	35.1	−79
			Phase 5				
Dec. 6	1448	0					
	2300	8.25	121.9	147	6.6	41.7	797
Dec. 7	0023	1.4	122.8	148	.5	42.2	382
	1530	15.1	114.3	138	−4.7	37.5	−314
			Phase 6				
Dec. 7	1530	0					
Dec. 8	0245	11.25	125.9	152	6.6	44.0	584
	0300	0.25	125.3	151	−.4	43.7	−1529
	1200	9.0	118.6	143	−3.7	39.9	−416
			Phase 7				
Dec. 8	[7]1300	0					[7](881)
	2012	7.25	125.3	151	3.7	43.7	518
Dec. 9	1045	14.5	118.9	143	−3.6	40.1	−248
Dec. 10	1515	28.5	115.2	139	−2.0	38.1	−70
			Phase 8				
Dec. 10	[8]1515	0					[8](746)
Dec. 11	1048	[8]19.5	126.2	153	6.2	44.3	317
	1130	0.75	124.7	150	−.9	43.3	−1223
	1200	0.5	124.1	150	−.4	43.0	−765
Dec. 12	1000	22.0	116.4	141	−4.2	38.8	−191
Dec. 13	0720	21.3	115.5	140	−.5	38.3	−21
			Phase 9				
Dec. 13	[9]0508	0					[9](765)
	1340	8.5	125.9	152	5.7	44.0	674
	1545	2.1	120.4	145	−3.1	40.9	−1492
Dec. 14	1000	18.25	112.5	136	−3.8	37.1	−209
			Phase 10				
Dec. 14	[10]0705	0.					[10](1269)
	1536	8.5	124.7	150	6.3	43.4	746
	1605	0.5	123.8	149	[11].5	43.0	917
Dec. 15	0800	15.9	115.5	140	−4.4	38.5	−279
			Phase 11				
Dec. 15	0611	0.					
	0800	1.8	118.3	143	1.3	39.8	722
	1025	2.4	123.4	149	2.7	42.5	1115
	1115	0.8	121.9	147	−.8	41.7	−1051
	2030	9.25	116.4	141	−2.6	39.4	−281
			Phase 12				
Dec. 15	1930	0					
	2030	1.0	118.0	142	.8	39.8	765
	2130	1.0	120.7	146	1.4	41.3	1453
Dec. 16	1015	12.75	114.6	138	−3.1	38.1	−246
			Phase 13				
Dec. 16	1335	0					
	1625	2.8	119.5	144	2.5	40.7	901
	1650	0.4	120.1	143	.4	41.1	956
	1719	0.5	120.7	146	.3	41.4	612
Dec. 17	0245	9.4	116.1	140	−2.4	38.9	−260
			Phase 14				
Dec. 17	0215	0					
	0402	1.75	[12]119.8	144	1.8	40.7	1048
	1100	7.0	118.0	142	−1.0	39.8	−142
			Phase 15				
Dec. 17	[13]1110	0					[13](989)
	1532	4.4	121.3	146	1.7	41.4	382
	1800	2.5	120.4	145	−.5	41.0	−183
Dec. 18	1500	21.0	115.2	139	−2.8	38.2	−131
			Phase 16				
Dec. 19	[14]0240	0					[14](1271)
	0616	3.6	122.8	148	4.1	42.4	1147
	1115	5.0	119.5	144	−1.7	40.7	−336
Dec. 20	1300	25.75	114.3	138	−2.7	38.0	−104
			Phase 17				
Dec. 19	2045 to						
Dec. 20	0800	11.25: Slight fountaining activity; no significant output of lava					

[1]This subsidence probably occurred during the first few hours of the period.
[2]These figures are approximate. Subsidence of the east pond was 25–30 ft; the smaller west pond subsided 35–45 ft.
[3]These figures are approximate. Subsidence of the east pond was about 7 ft; the smaller west pond subsided irregularly between 15–30 ft.
[4]Strong lava extrusion only during last half of this period. Continuous fountain and tremor after 0320 H.s.t.
[5]Visual estimate of subsidence in pond during eruption.
[6]Volume figures from end of phase 4 through phase 16 take into consideration the volume of the "black ledge."
[7]No appreciable lava output until 1515 on Dec. 8, 1959.
[8]No appreciable lava output until 0230 on Dec. 11, 1959.
[9]No appreciable lava output until 0615 on Dec. 13, 1959.
[10]No appreciable lava output until 1040 on Dec. 14, 1959.
[11]From phase 10 to phase 16 no appreciable volume of lava flowed into the small west pond.
[12]Estimated. Lava level never rose above the "black ledge."
[13]No appreciable lava output until 1350 on Dec. 17, 1959.
[14]No appreciable lava output until 1301 on Dec. 19, 1959.

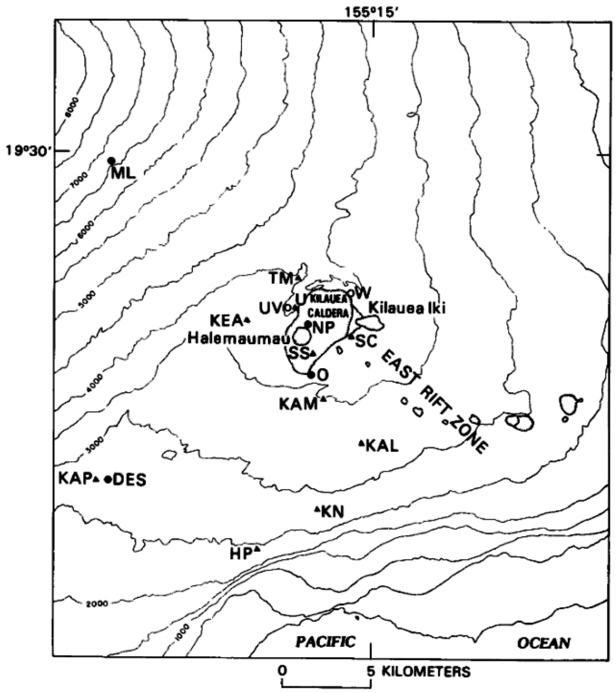

FIGURE 48.1.—Summit of Kilauea Volcano, showing tilt bases as triangles (TM, SC, SS, KEA, KAP, KAM, KAL, KN, HP), tiltmeter vaults as circles (UV and W), telemetered seismographs as dots (ML, DES, NP, O), and geographic localities mentioned in the text. Pit craters are indicated by hachures. Elevation contours in feet.

results are displayed as a map of vectors scaled according to the magnitude of tilt and pointing in the direction of maximum relative subsidence of the ground. Tilt maps for 12 intervals spanning the period February 1959 to November 1960 are shown in figures 48.2 and 48.3.

WHITNEY VAULT: BOSCH OMORI SEISMOGRAPH

The longest record of tilt measurements on Kilauea Volcano is from the Bosch-Omori horizontal pendulum seismograph at the Whitney vault on the northeast rim of Kilauea caldera. This mechanical seismograph responds to a tilt perpendicular to the seismometer boom by a deflection of the recording point. Systematic tracking of the position of the recording point relative to some standard reference provides a record of ground tilting. Such a measurement was made once a day from 1912 through 1961 (Jaggar and Finch, 1929). This measurement is a relative one and the reference must be reset whenever the instrument is adjusted. Moreover, the Whitney vault has proved to have a very large annual tilt cycle that must be removed before tilting caused by the volcano can be detected (Powers, 1946, 1947). For very large tilts like those associated with the 1959–1960 eruption, however, the signals from this instrument (north-south and east-west components) are much larger than the uncertainties due to the foregoing problems.

UWEKAHUNA VAULT: LIQUID-LEVEL TILTMETER

The Uwekahuna vault on the west rim of the caldera has proved to be much more stable than the Whitney vault. A liquid-level tiltmeter mounted on the walls of this vault has provided daily readings of tilt since 1956. The daily readings scatter through a range of several microradians, so the measurements are normally reported as weekly averages (Eaton and Fraser, 1958). During periods of strong tilting, such as during the 1959–1960 eruption, the daily scatter in readings is modest compared to the real tilt changes. The daily tilt readings at Uwekahuna and Whitney provide a somewhat noisy time history of tilting at Kilauea caldera that fills in details of tilting between the infrequent resurveys of the tilt bases. Tilt records for these two stations for the interval October 15, 1959, to April 1, 1960, are shown in figure 48.4.

UWEKAHUNA VAULT: PRESS-EWING SEISMOGRAPH

The most unusual record of tilting at the summit of Kilauea during the 1959 eruption was obtained from the long-period Press-Ewing seismograph in Uwekahuna vault. Part of the tilt response of the instrument is expected and can be calibrated in terms of the operating parameters of the seismograph. Another part of the response was unexpected: it resulted from faulty attachment of the suspension fibers in the galvanometers, which permitted them to detect tilting in the same way as a horizontal pendulum seismograph. This part of the Press-Ewing response is accidental, but it can be calibrated by reference to the liquid-level tiltmeter that was operating in the same vault.

The layout of the Press-Ewing seismometer pendulums and their recording galvanometers, as well as the two components of the Uwekahuna liquid-level tiltmeter, is shown in figure 48.5. The velocity transducer of the Press-Ewing horizontal component seismograph (a coil attached to the mass and moving in the field of a magnet fixed to the frame) produces a signal (output voltage) proportional to the rate at which the coil is moving relative to the fixed magnet. Thus, one obtains a constant output for a constant tilt rate. For tilt rates that change slowly (compared to the 90-s period of the Press-Ewing galvanometer), the displacement of the galvanometer is directly proportional to the output voltage from the seismometer and, hence, to the rate of tilting.

The response of the Press-Ewing seismograph to slow tilting of the ground is thus a displacement of the zero-line trace about which normal shorter period ground movements are recorded. A given seismograph responds to the same component of tilting as it does to displacement. A sharp northward or eastward displacement of the ground produces an upward displacement of the trace on the seismogram (as the HVO instruments are connected), but tilting downward toward the north or east produces a downward displacement of the seismogram trace. From the manufacturer's specifications for the seismometers and galvanometers and for the manner in which

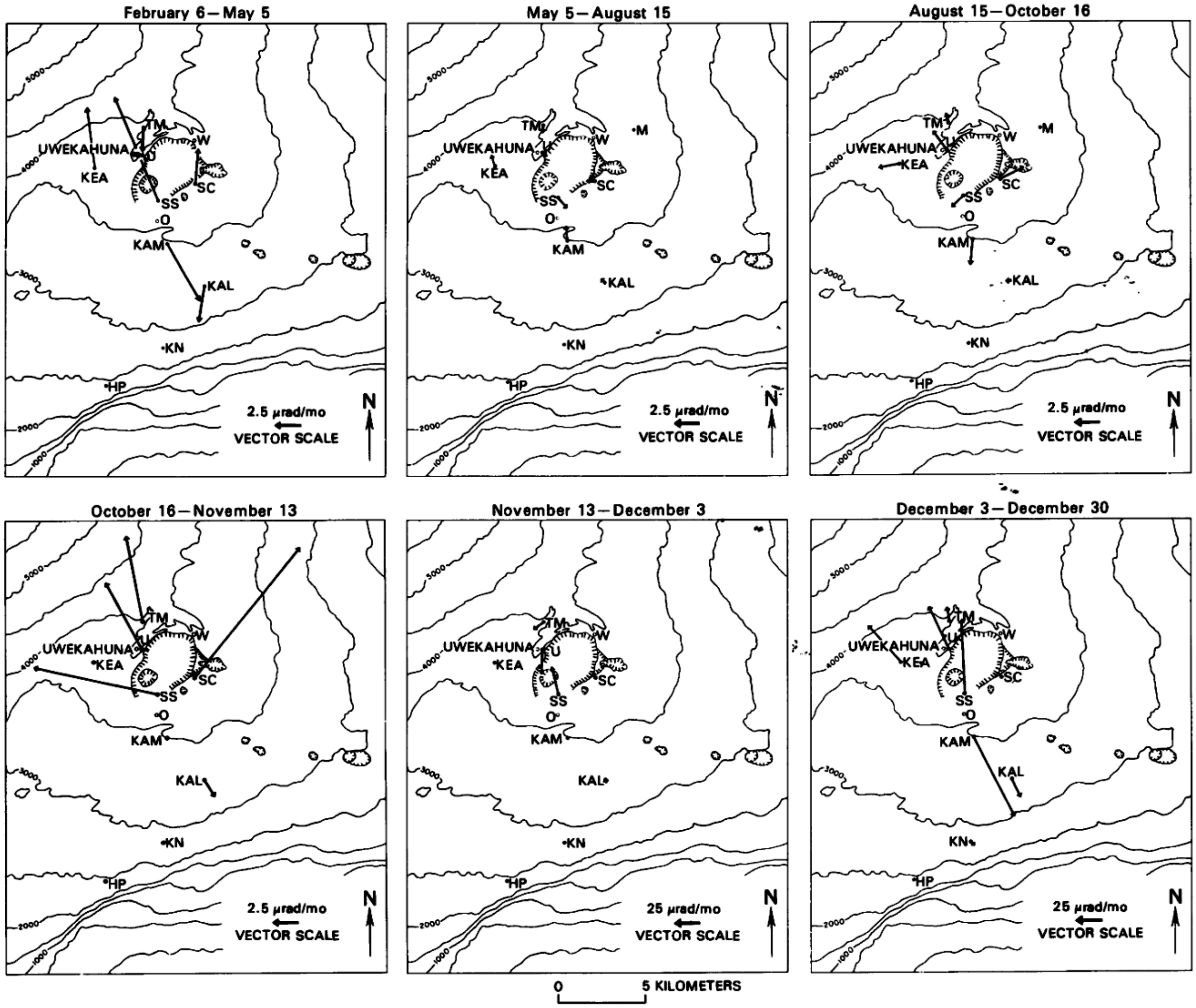

FIGURE 48.2.—Tilt diagrams for summit region for six intervals from February 6, 1959, to December 30, 1959. Tilt vectors point in direction of maximum subsidence of the ground. Note different vector scales used, depending on rate of tilt. For identity of data stations and geographic features, see figure 48.1.

they are set up at Uwekahuna, the theoretical rate-of-tilt sensitivity of both the north-south and east-west Press-Ewing seismographs (neglecting the direct tilt response of the galvanometers) is approximately 0.374 μrad/h per millimeter deflection of the trace.

The principal challenge in using the Press-Ewing seismograms to measure rate of tilt is in establishing an acceptable normal position of the trace from which deflections are to be measured. Surprisingly, however, measuring the position of the ambient zero line to within a fraction of a millimeter even in the presence of 5-mm microseisms is not too difficult. In the plotted results, features that repeat at intervals of 1 h or 1 d (corresponding to one rotation of the drum and to the daily record change, respectively) probably result from errors in the reference base. The east-west Press-Ewing seismogram for December 16–17, 1959, is shown in figure 48.6. Each line across the record is 1 h long. Zero-line excursions associated with the beginning and end of phases 13 and 14 are labeled.

An analysis of the Press-Ewing zero-line deflections from November 8 to December 1 (rapid collapse and recovery associated with the first phase of the eruption) revealed the imperfection in the galvanometers noted above: their coils are suspended in such a manner that the galvanometers, by themselves, act like simple tiltmeters for tilt at right angles to the normals to the galvanometer

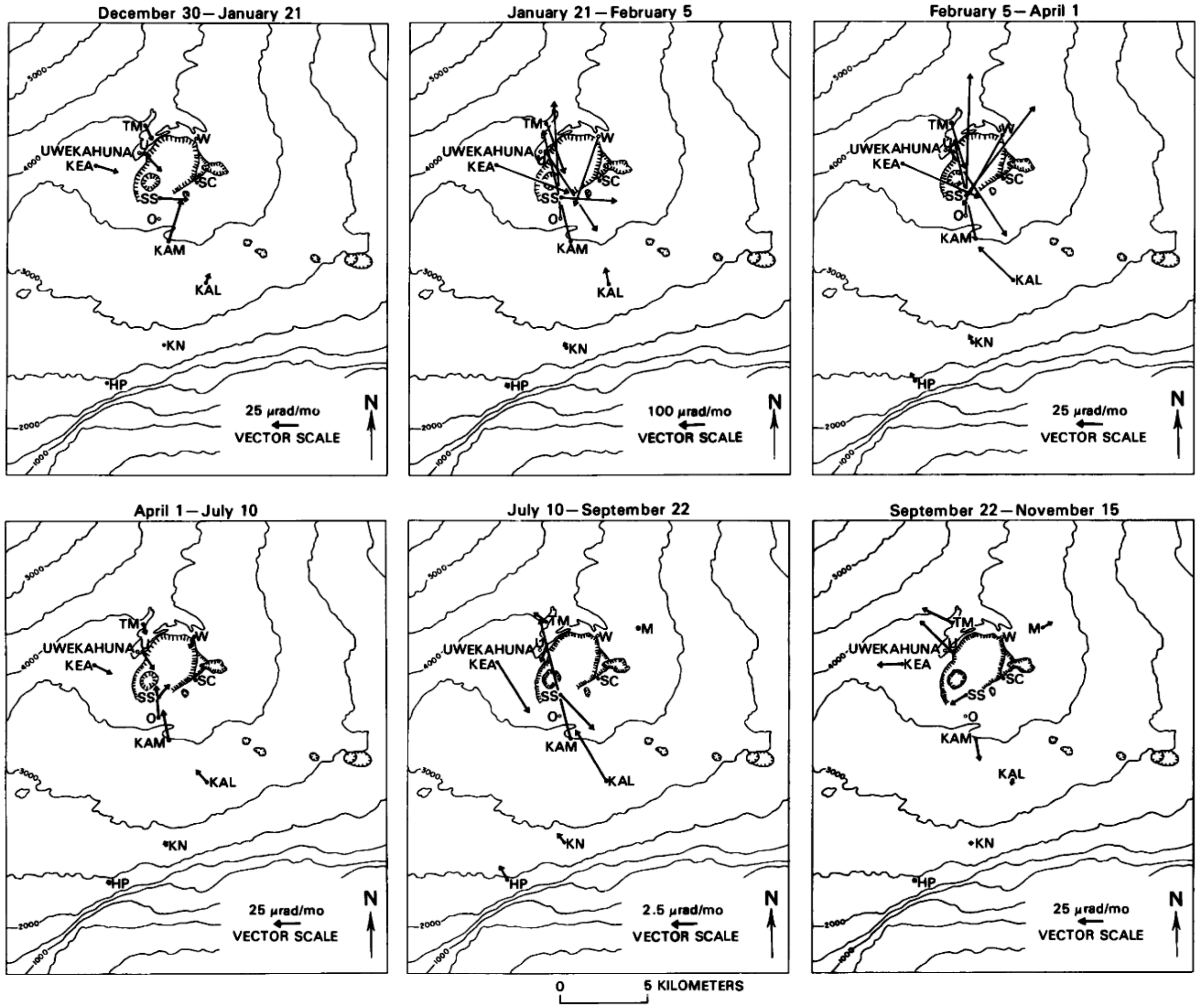

FIGURE 48.3.—Tilt diagrams for summit region for six intervals from December 30, 1959, to November 15, 1960. Tilt vectors point in direction of maximum subsidence of the ground. Note different vector scales used, depending on rate of tilt. For identity of data stations and geographic features see figure 48.1.

mirrors, in our case for tilt in an east-west direction. This effect is small for the east-west galvanometer, so the total seismometer-galvanometer response is dominated by the rate-of-tilt signal from the seismometer. The north-south galvanometer, on the other hand, is quite sensitive to the east-west state of tilt. As seen from Uwekahuna (on the liquid-level tiltmeter, for example) the center of swelling and collapse associated with Kilauea Iki eruptive phases lies almost due east. Thus, the north-south-component seismometer-galvanometer system response is dominated by the galvanometer (which records the east-west state of tilt with moderate sensitivity), the north-south component of tilt and its rate of change being small because of the azimuth to the active region. Large north-south rate-of-tilt deflections detected by the north-south Press-Ewing seismometer were recorded during the preoutbreak swarm on November 14 and during a large tilt transient between phases 4 and 5; moderate ones were recorded as transients when most of the phases stopped abruptly. In these cases the active center appears to have been south of that associated with the eruptions in Kilauea Iki.

In summary, during episodes of tilting associated with the Kilauea Iki eruption, the east-west Press-Ewing instrument measured east-west rate of tilt, and the north-south Press-Ewing instrument measured principally the east-west cumulative tilt at Uwekahuna. This point may be confusing, so it should be noted carefully.

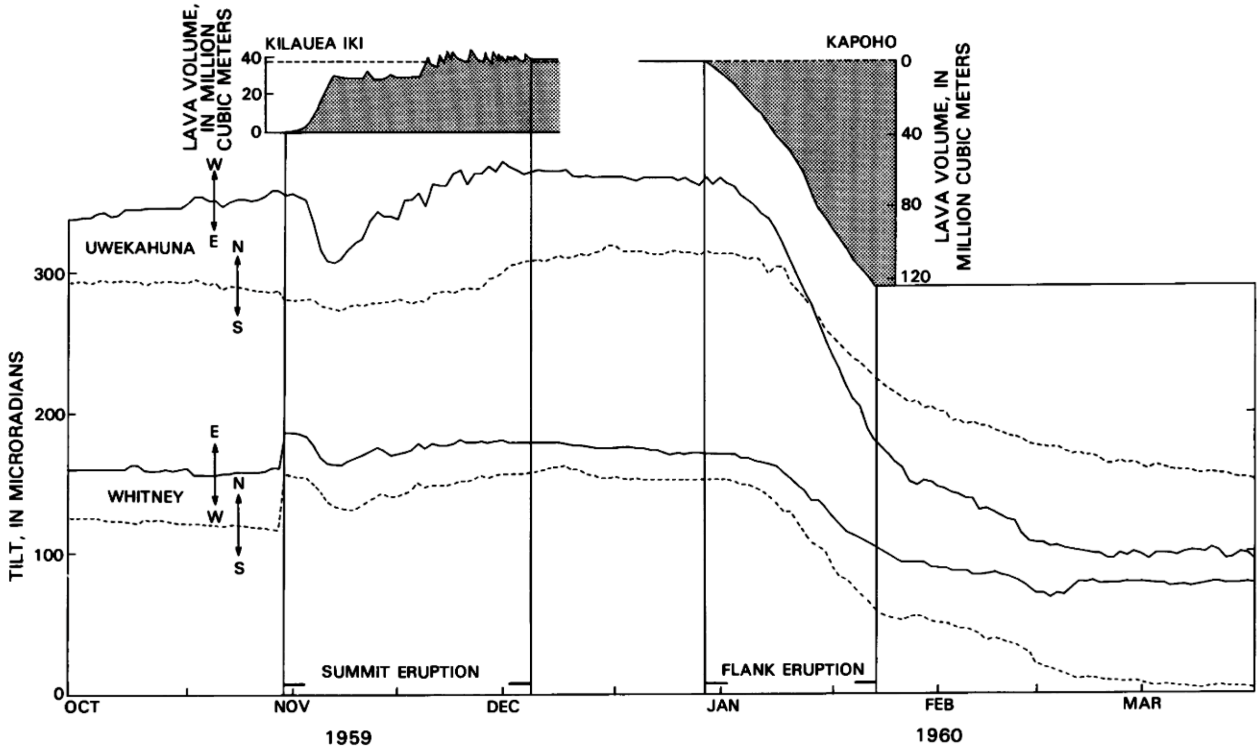

FIGURE 48.4.—Tilt at Uwekahuna and Whitney on Kilauea summit (UV and W of figure 48.1) from October 15, 1959, to April 1, 1960, and volumes of lava in Kilauea Iki Crater erupted during the 1960 eruption from the east rift zone near Kapoho.

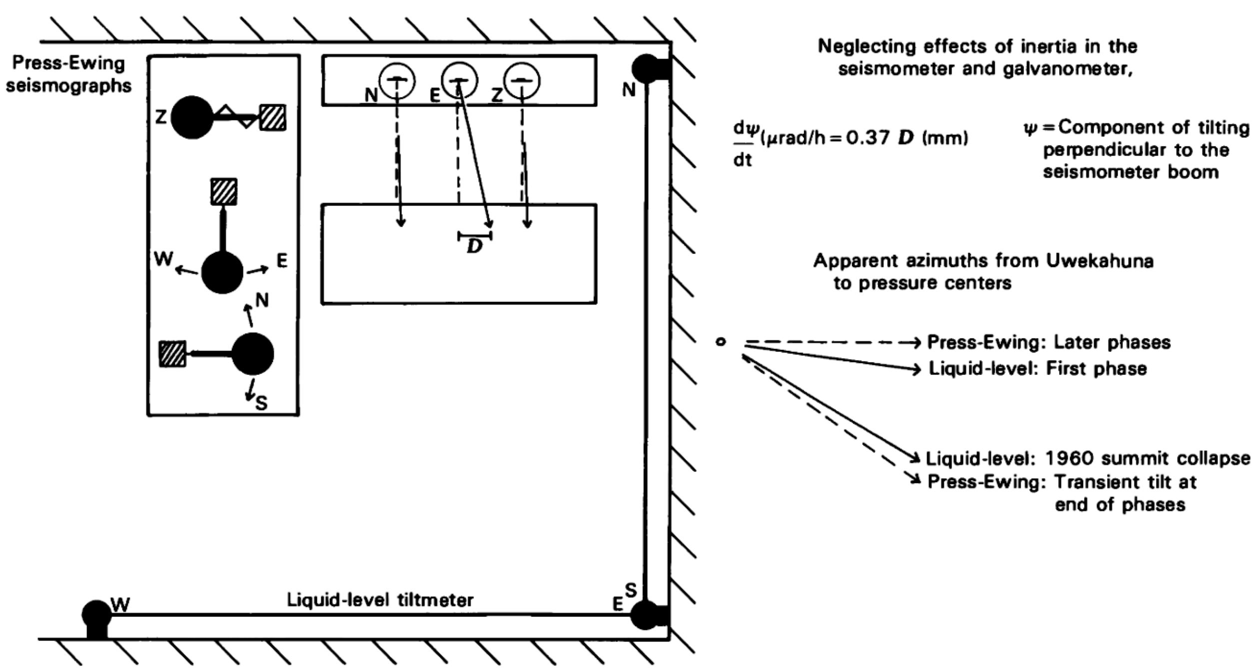

FIGURE 48.5.—Layout of liquid-level tiltmeter and long period Press-Ewing seismographs in Uwekahuna vault. Press-Ewing seismometers are shown at left, and their galvanometers are shown at top of figure. Letters Z, N, and E denote parts of instruments and the components of tilting they record: Z, vertical; N, north-south (N, S); E, east-west (E, W). D, deflection of seismogram trace from normal; dψ/dt, rate of tilting.

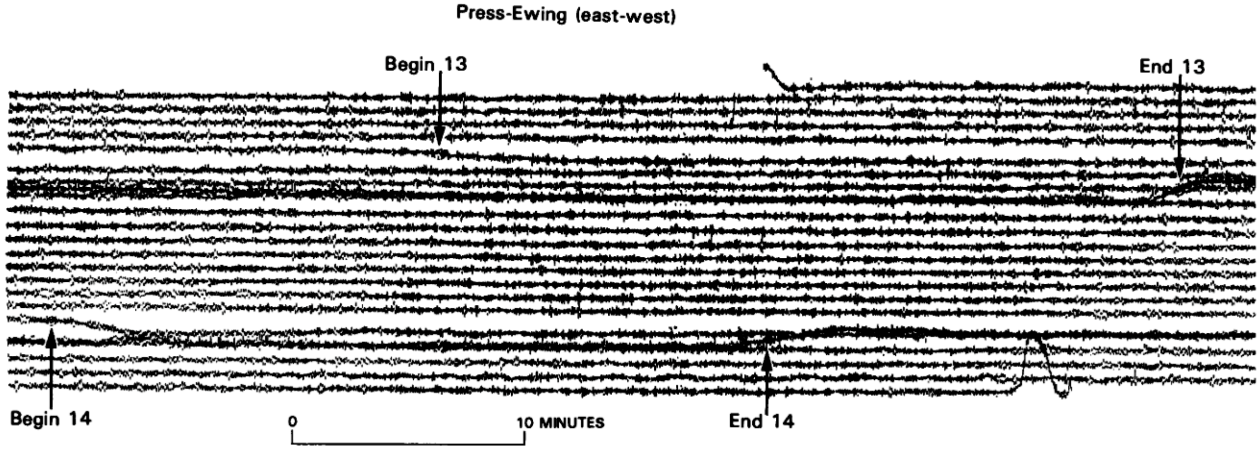

FIGURE 48.6.—Seismogram from east-west Press-Ewing seismograph for December 15–16, 1959, showing shifts in zero line associated with phases 13 and 14 (arrows).

SEISMIC NETWORK

Before the 1959 eruption a network of sensitive, telemetered, short-period seismographs had been installed around the summit of Kilauea and on the adjacent flank of Mauna Loa to facilitate study of the many earthquakes occurring regularly in that region. The telemetered network was augmented by optically recording seismographs with similar response characteristics that were deployed in a ring around the Island of Hawaii. The combined network provided the means for detecting and locating a variety of seismic manifestations associated with the volcano, including the following:

(1) Individual earthquakes throughout the volcano;

(2) Occasional swarms of small earthquakes marking the opening of dikes around the summit reservoir and in the rift zones;

(3) Volcanic tremor generated by rapid movement of magma within the volcano, particularly during eruptions; and

(4) Swarms of tiny deep earthquakes and associated irregular tremor thought to mark the region from which magma is collected to feed the volcano.

Activity of the last 3 types figure prominently in our analysis of the 1959 eruption.

OVERVIEW OF THE REGIONAL DEFORMATION OF THE KILAUEA SUMMIT AND DEEP EARTHQUAKE SWARMS ASSOCIATED WITH THE 1959 ERUPTION

DEFORMATION

The patterns of regional deformation of the Kilauea summit area during the 6 intervals from February 6, 1959, to December 30, 1959, that are shown in figure 48.2 indicate the location and intensity of inflation and deflation in this area before and during the 1959 eruption. The next 6 intervals (fig. 48.3), from December 30, 1959, to November 15, 1960, show the patterns of regional deformation of the summit area during the 1960 Kapoho eruption, the rapid deflation of the summit reservoir accompanying and following the Kapoho eruption, and the onset of rapid reinflation of the summit reservoir in the fall of 1960. The vectors depicting rate of tilting point outward away from centers of inflation and inward toward centers of deflation (fig. 48.3). The lengths of the vectors are scaled according to the rate of tilting. Note the large variation in scale factor from one interval to the next. These plots are shown together for easy comparison, but we shall return to consider them one at a time as the need arises.

A more continuous, but spatially limited, picture of inflation and deflation of the Kilauea summit region is shown in figure 48.4, where the north-south and east-west components of daily tilt measurements at Uwekahuna vault and Whitney vault are compared with the volume of lava ponded in Kilauea Iki and the volume of lava later erupted on the east rift zone near Kapoho in the 1960 eruption. Tilting in response to eruption of lava into Kilauea Iki during phase 1, and its removal from the summit reservoir, is most marked on the Uwekahuna east-west record, where the curve of eastward tilting very closely matches the lava-volume curve. After an initial sharp northeast offset in tilt at Whitney, the curves of both westward and southward tilting also closely match the lava-volume curve. Vectors representing tilting at these two stations during the phase 1 eruption both point into Kilauea caldera; they cross near the center of the caldera, indicating that the lava erupted into Kilauea Iki was removed from beneath Kilauea caldera. Rapid refilling of the depleted reservoir appears to have begun by the time phase 1 ended. Both the east-west and north-south curves at Uwekahuna had recovered approximately to their levels at the start of the phase 1 eruption by the time phase 4 began. As the east-west tilt curve rose still further during the next two weeks, the volume of lava retained in the lake after subsequent eruptive phases (and the height of the lake surface) also increased beyond the 30×10^6 m^3 left by phase 1 in about the same proportion that the east-west curve rose above its pre-phase 1 level. The movement of the east-west Uwekahuna curve during the later eruptive phases, such as phase 4, suggests eastward tilting while the eruptions were in progress followed by rapid westward tilting when they stopped. However, the once-per-day interval for tilt samples is too large to track individual phases, some of which lasted only a few hours.

A still simpler picture of the swelling and collapse of the Kilauea summit region is shown by a plot of the radial component of tilting at Uwekahuna tilt base relative to the center of collapse near the south rim of Kilauea caldera during and after the 1960 east-rift eruption near Kapoho. Figure 48.7 (adapted from Eaton, 1962) shows this curve for the period 1957–62. The approximate scale for ΔV, volume of the collapse, is based on fitting the tilt changes between January 21–April 1, 1960 (intervals January 21–February 5, 1960, and February 5–April 1, 1960, in fig. 3), to a curve based on Mogi's (1958) theoretical results for change in elevation versus distance for a small spherical source embedded in an elastic half-space (Eaton, 1962, fig. 12).

DEEP EARTHQUAKE SWARMS

From the early 1950's until the fall of 1960 occasional swarms of small earthquakes, accompanied by a continuous background agitation resembling tremor that waxed and waned during the swarms, were recorded from a source 45–65 km deep beneath the summit of Kilauea and the adjacent flank of Mauna Loa to the north. Until the introduction of the sensitive telemetered seismic net around the summit of Kilauea in 1958, these earthquakes were recorded most clearly on a mechanical horizontal-component seismograph, about 10 km northwest of Kilauea caldera (station ML, figure 48.1, with magnification of about 200). Typically, several hundred events were counted during a swarm, and the location of the swarm, including its depth, was poorly determined. From 1958 onward the detection threshold was lower and the locations were much improved, though still poor by modern standards. The sharpest recordings were obtained at stations 10 km northwest (station ML) or 10 km southwest (station DES) of the caldera (fig. 48.1), which were equipped with high-gain short-period vertical seismographs whose signals were telemetered to Uwekahuna for recording; but the earliest P-wave onsets clearly were at Uwekahuna. Swarms recorded by the improved network contained from less than 100 to several thousand individual events, plus many hours of background tremor during the larger swarms. The times of occurrence of nine of these swarms are indicated by arrows along the time axis in figure 48.7, and samples of two swarms are shown in figures 48.8 and 48.9. Between September 1953 and June 1956 (not shown on fig. 48.7) there were 10 additional swarms, but there were none between June 1956 and April 1958.

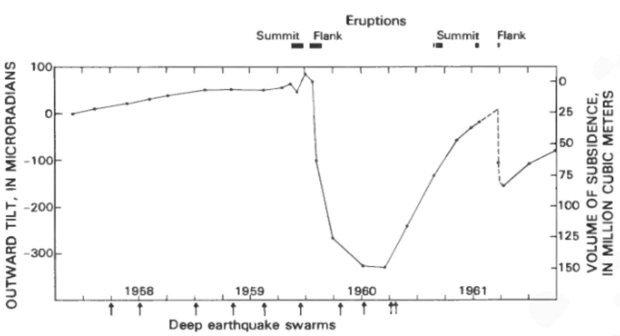

FIGURE 48.7.—Radial component of tilting at Uwekahuna tilt base for 1957–62, relative to 1960 center of subsidence at south edge of Kilauea caldera, showing swelling and subsequent collapse of Kilauea summit. Occurrence times of deep swarms of earthquakes beneath summit of Kilauea and of summit and flank eruptions also indicated.

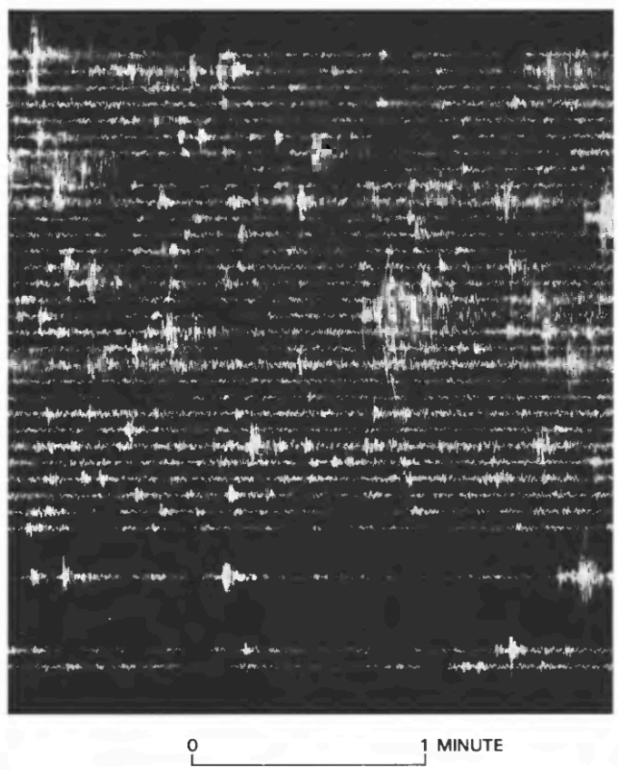

FIGURE 48.8.—Sample of Desert seismogram from August 16, 1959, illustrating swarm of deep earthquakes beneath the summit of Kilauea. Several thousand small earthquakes were accompanied by intervals of continuous tremor.

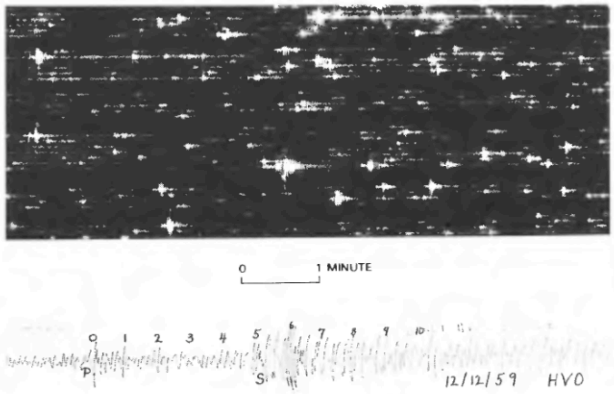

FIGURE 48.9.—Sample of Mauna Loa seismogram of swarm of deep earthquakes on December 11–12, 1959, beneath summit of Kilauea. Large-scale record of a member of this swarm recorded at Uwekahuna is shown at bottom (*P* and *S* arrivals and time in seconds after *P* are indicated).

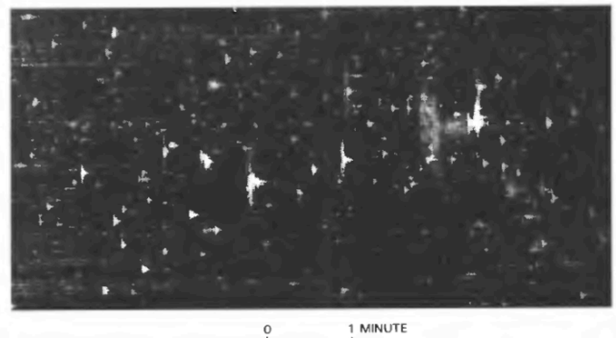

FIGURE 48.10.—North Pit seismogram from November 9–10, 1959, illustrating intense swarm of very small earthquakes that emanated from Kilauea caldera for several months before the 1959 eruption.

CHRONOLOGY OF TILTING AND EARTHQUAKE SWARMS LEADING UP TO THE 1959 ERUPTION

From November 1957 to May 5, 1959, the summit of Kilauea swelled slowly but steadily (fig. 48.2, 48.7). Deep swarms occurred on April 1, 1958 (weak), July 3–6, 1958 (strong), January 5–6, 1959 (moderate), and May 5, 1959 (very weak). From May 5 to August 15, 1959, the summit subsided very slowly. During August 14–20, 1959, there was a very strong swarm of earthquakes a few kilometers north of Kilauea caldera at a depth of 50–55 km (fig. 48.8). From August 15 to October 16, 1959, swelling of the summit resumed at about the same rate as during 1958.

In mid-September a swarm of tiny very shallow earthquakes began recording on the north Pit seismograph (NP, fig. 48.1) from a source in Kilauea caldera very near the northeast rim of Halemaumau. Initially about 50 per day, the frequency of quakes increased to about 100 per day by the end of September and to about 500 per day during the first week of October. By the first of November earthquakes of this swarm exceeded 1,000 per day, but they were so feeble that they were barely recorded on other seismographs less than 2 km away (fig. 48.10).

Remeasurement of tilting at bases around the caldera in the second week of November revealed that dramatic changes were in progress. The summit was swelling at least three times faster than in previous months (fig. 48.2, interval October 16–November 13, 1959). In midafternoon on November 14, earthquakes emanating from the caldera increased sharply in number and intensity. At frequent intervals during the next 5 h the entire summit region shuddered as earthquakes marked the rending of the crust by the eruptive fissure splitting toward the surface (fig. 48.11). At 2008 (this and all times given in this paper are Hawaii standard time) the lava broke through to the surface in a 900-m-long series of fissures

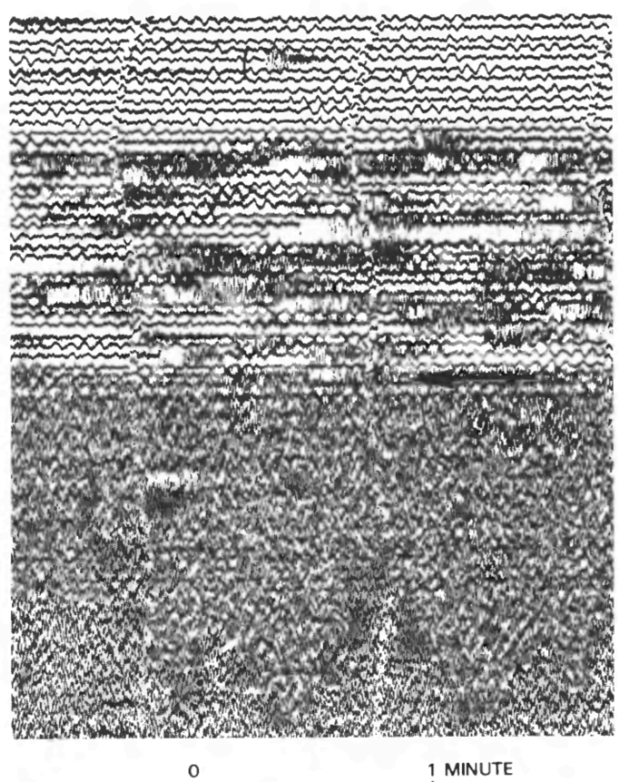

FIGURE 48.11.—Uwekahuna (short-period) seismogram from November 14, 1959, illustrating (upper part) 5-hour-long swarm of earthquakes that preceded the 1959 outbreak. The swarm gave way to strong harmonic tremor when fountaining began (arrow).

about halfway up the 180-m-high south wall of Kilauea Iki Crater, just east of Kilauea caldera. Abruptly the earthquakes stopped, and seismographs around the caldera began to record the strong harmonic tremor characteristic of lava outpouring from Hawaiian volcanoes (fig. 48.11).

Both horizontal components of the Press-Ewing seismograph recorded large excursions of the zero line during the five-hour-long swarm of caldera earthquakes preceding the outbreak of the eruption. Closer examination of the records revealed that the zero lines appeared to be erratic also for the preceding five days. This erratic signal was much stronger, and could be seen earlier, on the east-west than on the north-south component. The deflections of the zero lines from their expected positions were measured from the seismograms for the period 0600 November 6 through 0600 November 15 and the results are plotted in figure 48.12. The activity on the east-west graph before November 9 shows the level of noise (including error of measurement) before the erratic movement of the trace began. On November 9, long-period zero-line shifts began to appear on the east-west component. The disturbance was a distorted sinusoidal oscillation with a period just short of 1 h and a slightly asymmetric appearance: upward peaks (west tilt) were slightly broader than downward peaks (east tilt), and it appeared that the broad upward peaks constituted the zero line away from which the trace moved in brief downward excursions. The amplitude of the disturbance increased and its period decreased (to about 35 min) for several days. From November 12 onward this disturbance, which may be called a tilt storm, was also visible on the north-south component, though its amplitude there was only about one-fourth that of the east-west component. The amplitude of the tilt storm diminished gradually for about one day before the eruption began.

When the caldera swarm suddenly intensified at about 1420 on November 14, both of the Press-Ewing traces deflected abruptly from zero. The southward component of tilting rose rapidly to about 4 μrad/h. It then declined steadily, first to about 0.8 μrad/h by 1700 and then to about 0.2 μrad/h by 2000. The eastward component of tilting was more complex. A strong initial tilting toward the east was replaced after only a few minutes by an equally strong tilting toward the west, which declined rapidly to about 0.5 μrad/h. At 1630 the direction of tilting reversed again, and easterly tilting attained a rate of about 0.9 μrad/h at 1730; after that it decreased steadily to about 0.2 μrad/h by 2000. The complex transient tilting during the outbreak swarm of earthquakes was probably compounded from several effects, including fracturing and propping open of the eruptive fissure and subsidence of the summit owing to escape of lava from the reservoir into the fissure. The tilt storm preceding the outbreak earthquake swarm may have resulted from intermittent escape of lava from the reservoir as it continued to expand before the outbreak.

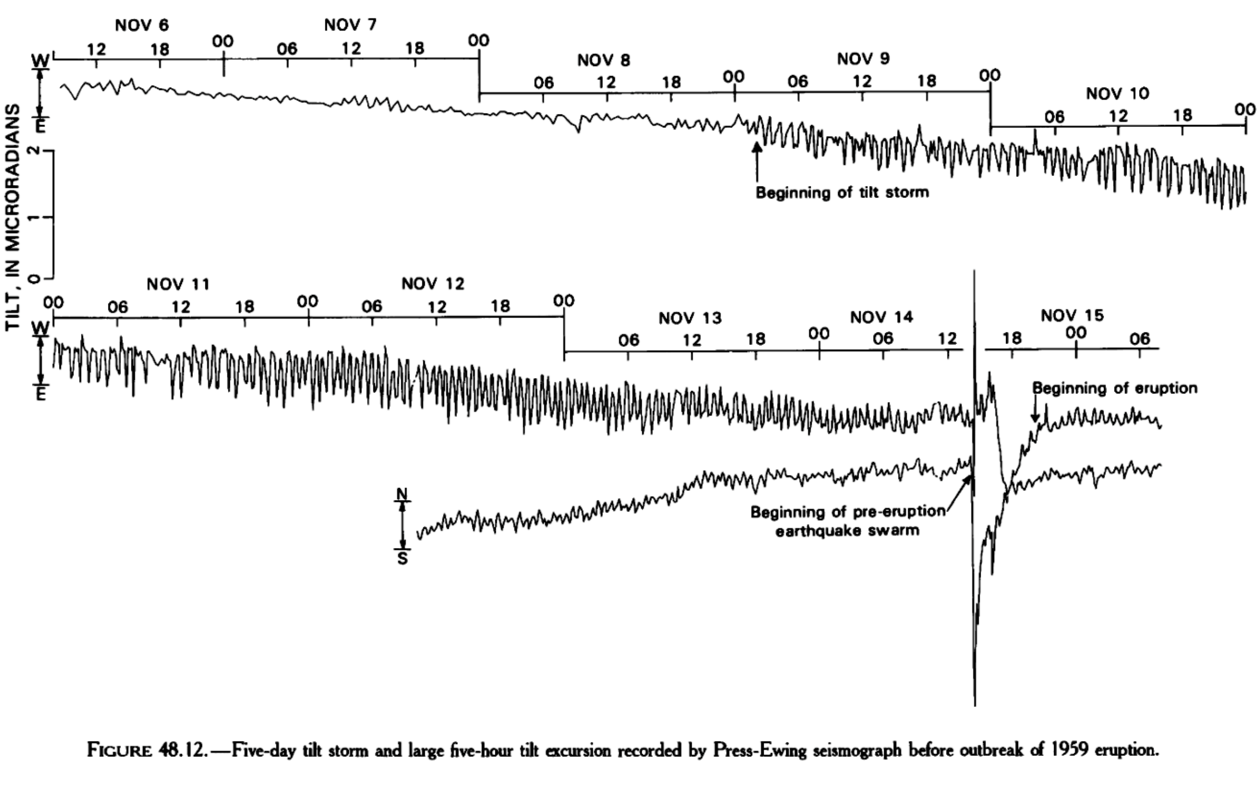

FIGURE 48.12.—Five-day tilt storm and large five-hour tilt excursion recorded by Press-Ewing seismograph before outbreak of 1959 eruption.

SUMMARY OF SELECTED FEATURES OF THE 1959 ERUPTION

The course of the 1959–60 eruption has been described in detail by Richter and others (1970), and we shall borrow several pictures from that report to illustrate features of the eruption that are related closely to the pattern of summit deformation and the amplitude of tremor that accompanied the eruption. The locations of Kilauea Iki Crater and the 1959 eruption vents relative to Kilauea caldera and other features at the summit of Kilauea are shown in figure 48.13 (Richter and others, 1970, fig. 3). The initial outbreak was in a short line of fountains, about half-way up the south wall of Kilauea Iki, which extended rapidly toward the east and slowly toward the west to form a 900-m-long "curtain of fire" during the first 80 min of the eruption (fig. 48.13, vents A through K). The line of fountains is seen in figure 48.14 at its maximum development from Byron Ledge overlook at 2130 on November 14. Fountaining at the ends of the fissure died out slowly, and fountaining near vent A (fig. 48.14, second group from the right) gradually increased in the following hours. By nightfall on November 15 activity was confined to a single fountain 30–45 m high near the site (vent A) that became the main vent for the rest of the 1959 eruption. The fountain grew slowly in height and lava output until it approached its maximum level late on November 18, when the fountain first exceeded 300 m and the depth of the lake reached 45 m. The fountain and lake are shown in figure 48.15 from Byron Ledge overlook when the fountain was 200 m high and the lake was 52 m deep. Spectacular fountaining and rapid filling of the lake continued unabated until the morning of November 20, when the lake, by then 98 m deep, rose above the level of the vent and began to interfere with the fountain. At 1925 on November 21 the fountain ceased abruptly, leaving a 102-m-deep lake containing 30×10^6 m^3 of lava.

Subsequent phases were similar to the last part of the first phase: large fountains with voluminous outpouring of lava filled the lake until it rose above the vent, and then the fountain died abruptly. The large fountains were accompanied by strong volcanic tremor throughout the summit region (fig. 48.16). When the lake rose above the vent, there was strong interaction between the fountain and the lake (fig. 48.17). Large waves generated at the fountain rolled out over the surface of the fluid lake and played against the north shore, alternately revealing and obscuring an incandescent band at the foot of the wall. Unlike the inconspicuous drainback from the first phase, which was not apparent for many hours after the fountain died, drainback from the later phases began almost immediately and was spectacular (fig. 48.18). The rate of withdrawal of lava during the early part of the drainback stage commonly exceeded the rate of eruption of lava during the previous eruptive stage. The very rapid backflow after cessation of fountaining was generally not accompanied by volcanic tremor, although there was a resurgence of tremor after an initial interval of quiet in many cases, particularly in the latest phases (fig. 48.19). At the end of the summit eruption the lake was 111 m deep and contained about 38×10^6 m^3 of lava (fig. 48.20). The level central part of the lake was surrounded by a black ledge about 15 m high and 15–60 m wide that marked the highest level of the lake at the end of phase 8.

The longest and most productive eruptive period, except for phase 1, was phase 4. It was characterized by unusually quiet outpouring of very hot lava and only moderate fountaining. The mouth of the vent had jumped about 12 m upslope between phases 3 and 4, and the level to which drainback could lower the lake appears to have moved upward a somewhat smaller amount.

During December 12–14, a strong swarm of small earthquakes was recorded from a source 15 km north-northeast of Uwekahuna and 40–45 km deep (fig. 48.9).

ANALYSIS OF LAVA MOVEMENT DURING INDIVIDUAL PHASES OF THE 1959 ERUPTION

The parameters of tilting, tremor, fountain height, and lava-lake volume measured during the eruption are closely interrelated. Properly understood, these relations should help clarify three important processes underlying the major facets of the eruption: (1) the accumulation of lava in the summit reservoir, (2) the eruption of lava into Kilauea Iki crater and its subsequent partial withdrawal, and (3) the escape of lava from the summit reservoir into a region other than Kilauea Iki.

The character of the phases changed during the eruption. The first phase differed most from the others, and the subsequent phases evolved generally toward more rapid outpouring and withdrawal of lava and toward more complex relationships among backflow into the vent, postfountaining (resurgent) tremor, and reinflation of the summit reservoir. The first phase offers the best opportunity to study the relations between lava-lake volume and cumulative tilting at Uwekahuna (and Whitney). The later phases are more suited to studies of the relation between the rate of east-west tilting, cumulative amount of east-west tilting, eruption rate, fountain height, and tremor amplitude.

The volume of lava in Kilauea Iki, the east-west component of liquid-level tilting at Uwekahuna, the north-south Press-Ewing zero-line drift (east-west cumulative tilting), the east-west Press-Ewing zero-line drift (east-west rate of tilting), fountain height, and tremor amplitude at Outlet (fig. 48.1) have been plotted against time for the first three phases, November 13–30 (fig. 48.21). The shapes of the first three curves (lava-lake volume, daily readings of east-west tilt from the liquid-level tilt meter, and a continuous record of east-west tilt determined from the north-south Press-Ewing zero-line drift) are so similar from start to finish of the first phase (November 14–21) that suitable scaling brings them into very close correspondence. The continuous east-west tilt curve recorded by the north-south Press-Ewing instrument corresponds almost exactly to the daily liquid-level tilt readings, but it gives far more detail of tilt excursions lasting less than one day. The east-west liquid-level tilt curve also corresponds closely to the lava-lake volume curve from the onset of phase 1 until its end. Eruption of 30×10^6 m^3 of lava into the crater was accompanied by about 50 µrad of eastward tilting.

After an episode of strong tremor with only small fountains during the first day of phase 1, the tremor amplitude diminished markedly. Thereafter, the curves of tremor amplitude and of fountain height are very similar. The rate of lava extrusion built up slowly during phase 1, and any offset of the east-west Press-Ewing zero

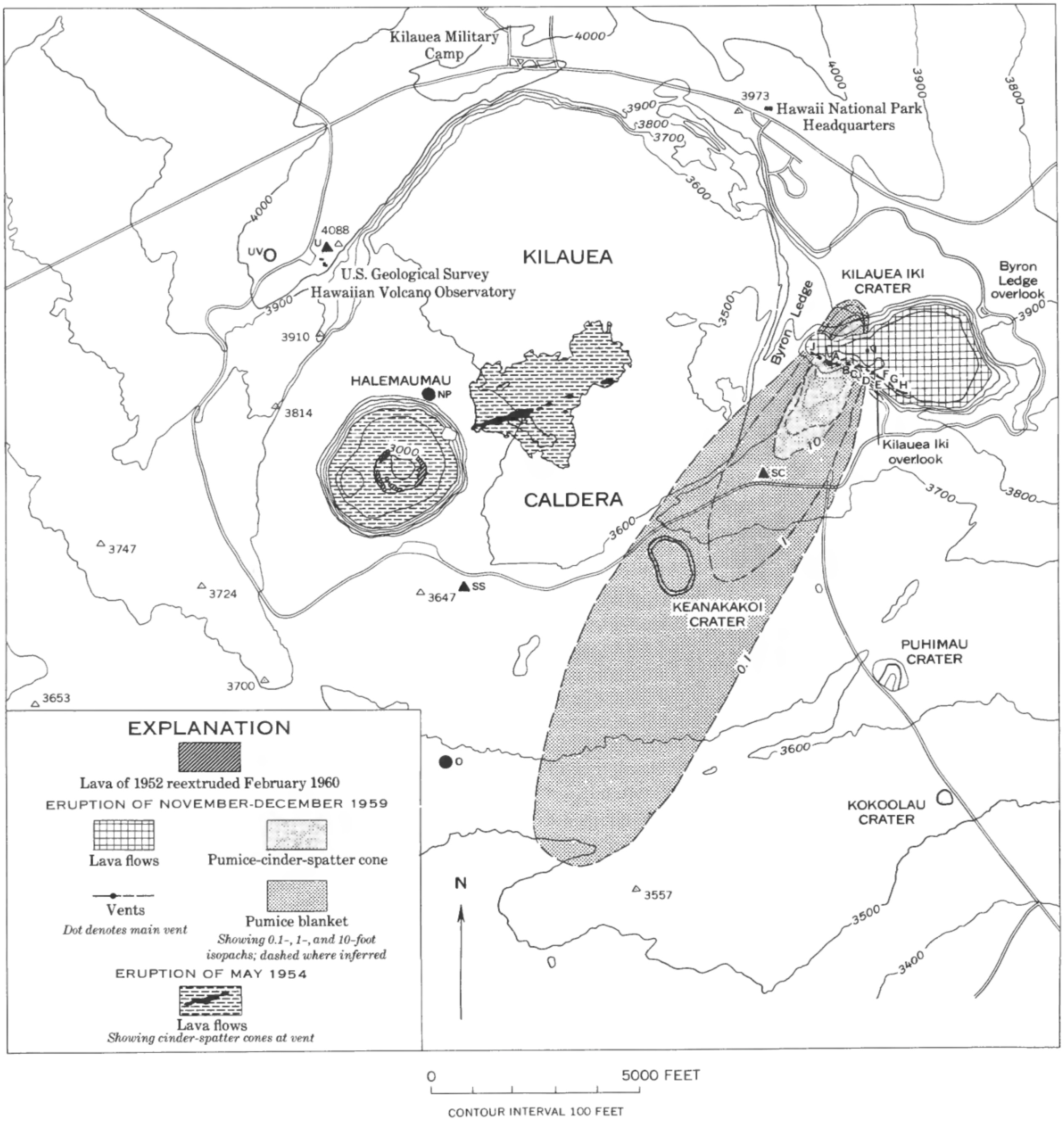

FIGURE 48.13.—Kilauea caldera region, showing relation of 1959 eruption in Kilauea Iki to Kilauea caldera, Halemaumau, east rift zone, and other localities mentioned in text. Modified from Richter and others (1970).

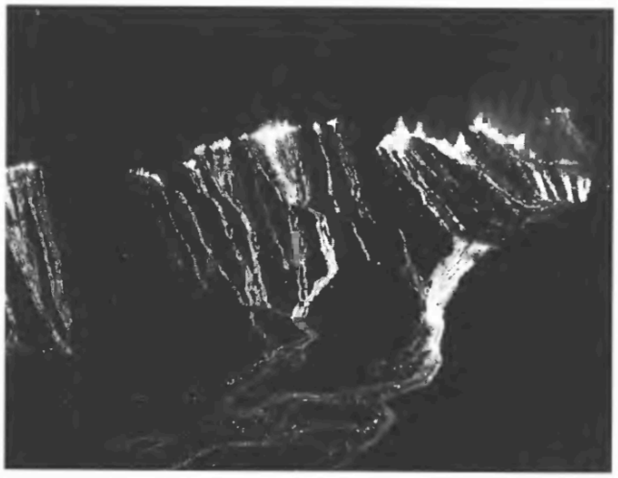

FIGURE 48.14.—Curtain of fire in Kilauea Iki at 2130 on November 14, 1959, 80 min after eruption began, showing maximum development of line of fountains 100 m above floor of crater. View from Byron Ledge overlook.

FIGURE 48.15.—Lava fountain 240 m high at main vent in Kilauea Iki at 0500 on November 19, 1959. Incandescent lava river from fountain is pouring into 50-m-deep lava lake. View from Byron Ledge overlook.

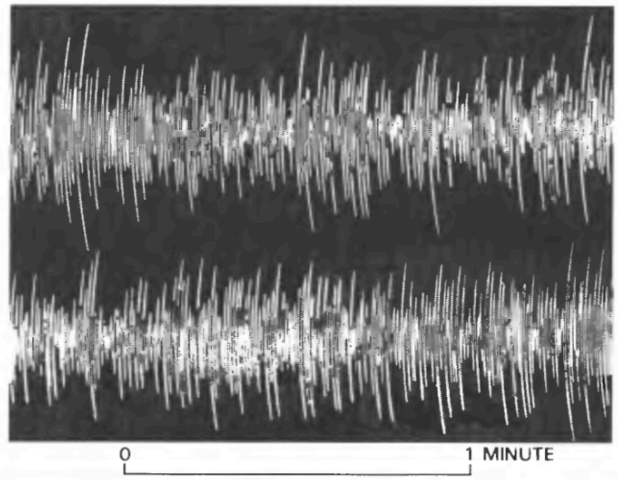

FIGURE 48.16.—Strong harmonic tremor recorded on Outlet seismograph during third phase of the 1959 eruption on November 29.

FIGURE 48.17.—Large fountain of phase 10 spurting through edge of lava lake, which has risen above the vent, at 1500 on December 14. Note waves on surface of lake. View from west end of Kilauea Iki overlook.

line resulting from the onset of the eruption would have been masked by the large tilt excursions that immediately preceded the outbreak. Cessation of fountaining was abrupt, however, and a zero-line offset marked the abrupt end of eastward tilting. Withdrawal of lava from the lake was first noticed about 20 h after the fountain died, and the volume of lava that drained back was small. No sharp rebound from eastward to westward tilting was noted at the end of the first phase.

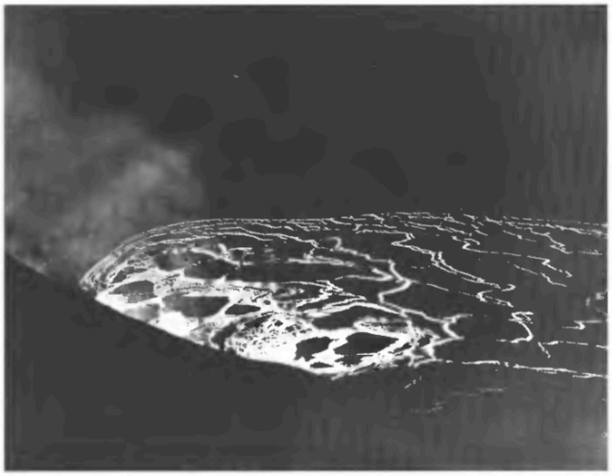

FIGURE 48.18.—Wide stream of lava pouring back into vent at 2200 on December 15, one-half hour after end of phase 12. Huge rafts of solid lake crust, disrupted as backflow stream converges near event, are mixed and swallowed by returning lava. View from top of cone almost directly above vent.

FIGURE 48.20.—Kilauea Iki lava lake on December 20, 1959, after all activity had ceased. The black ledge, 15–60 m wide and about 15 m high, surrounds entire lake surface. View from Byron Ledge overlook. Photograph by R.T. Haugen, National Park Service.

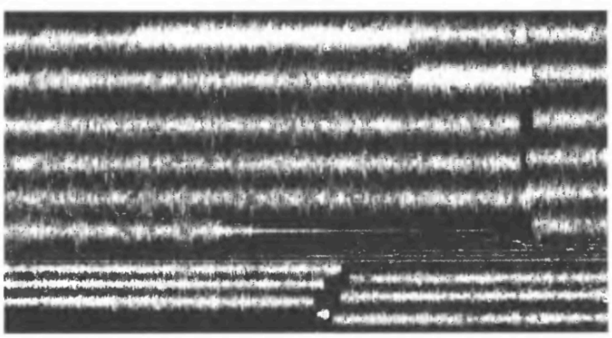

FIGURE 48.19.—Section of Outlet seismogram of December 8, 1959, showing harmonic tremor accompanying phase 7, abrupt dying out of tremor when fountain stopped, and resurgence of tremor during backflow after 50 min of quiet.

For phases 2 and 3, also shown in figure 48.21, the lava-volume changes are small and the east-west tilt changes (both liquid-level and north-south Press-Ewing) are difficult to pick out of the noise. The curves for tremor, fountain height, and rate of east-west tilting (east-west Press-Ewing zero-line offset) are clearly related. At the sharp onset of fountaining, the amplitude of tremor increased suddenly; its amplitude generally followed fountain height throughout each phase. With the onset of fountaining, also, clear eastward tilting began on the east-west rate-of-tilting curve. The shape of the rate-of-tilting curve is similar to those for fountain height and tremor. When the fountain stopped abruptly, tremor amplitude dropped to zero, and the tilt curve reversed rapidly from moderate eastward tilting to strong westward tilting. The reversal in direction of tilting corresponds closely in time to cessation of fountaining and the immediate onset of strong backflow into the vent. The rate of westward tilting was initially several times greater than the rate of eastward tilting just before the fountain died, but it diminished rapidly during the first few minutes of backflow and then more gradually for several hours until it fell below noise level.

With some variations, the remaining phases were similar to phases 2 and 3. Plots of east-west tilt (north-south Press-Ewing) and east-west rate of tilting (east-west Press-Ewing) for phases 4–16 are shown in fig. 48.22. This figure gives a useful overview of tilting for the rest of the 1959 eruption, but the phases were so short that the relationships discussed for the first three phases are not easily seen. From phase 4 onward, east-west rate of tilting and east-west cumulative tilt at Uwekahuna, fountain height, and tremor amplitude at Outlet are plotted against an expanded time scale in figure 48.23 (phase 4), 48.24, (phases 5–7), 48.25 (phases 8 and 9), 48.26 (phases 10–14), and 48.27 (phases 15 and 16). Isolated episodes of tilting and tremor that were unaccompanied by an eruptive phase occurred between phases 4 and 5 (fig. 48.23) and between phases 15 and 16 (fig. 48.27).

To follow the movement of lava from the summit reservoir to the lake and back again to the reservoir, we need good estimates of the total eastward tilting at Uwekahuna during the eruptive stage and of the total westward tilting during the backflow stage. These tilt totals can then be converted to volumes of lava removed or returned to the reservoir by comparison with the ratio of lava-lake volume to eastward tilting at Uwekahuna recorded during the first phase. Such a conversion assumes that all of the phase 1 lava was mined from the

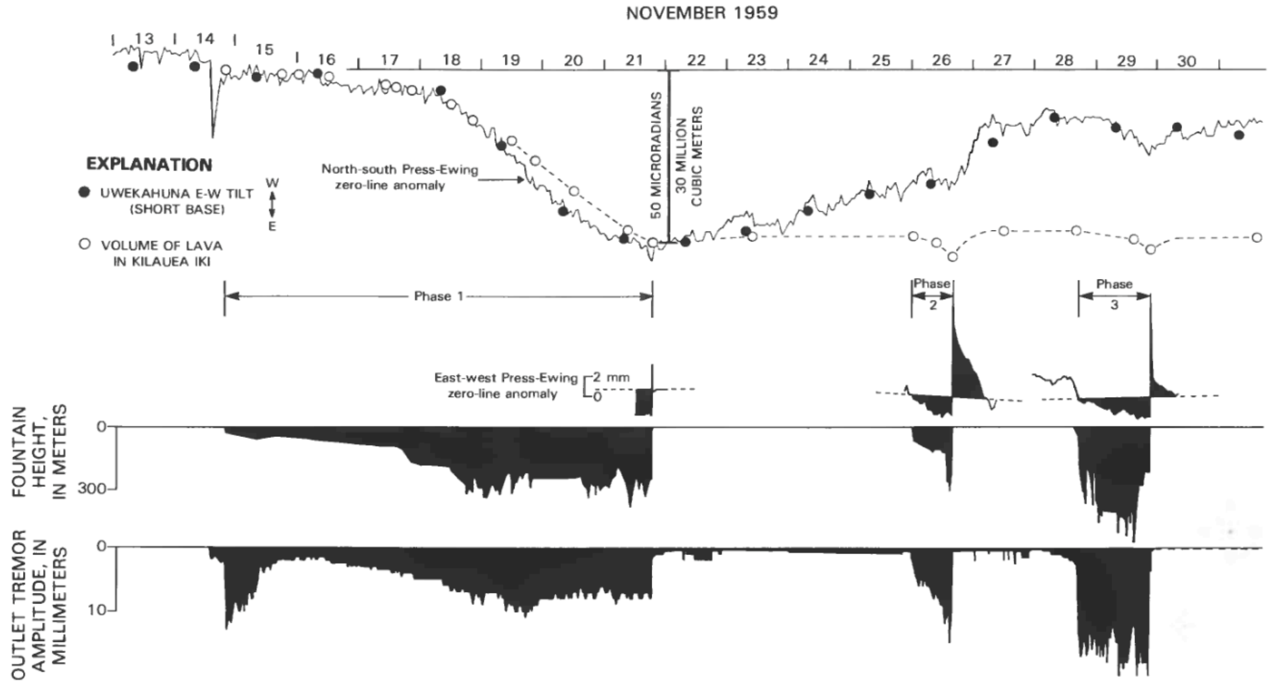

FIGURE 48.21.—Eruption and deformation parameters during first three eruptive phases of 1959 eruption. Volume of lava in Kilauea Iki, east-west component of Uwekahuna liquid-level tiltmeter, and north-south Press-Ewing zero-line anomaly are superposed in upper half of figure; fountain height and tremor amplitude at Outlet station are plotted in lower half. Duration of individual phases indicated.

summit reservoir and that replenishment of the reservoir from the deep source of magma during phase 1 was small compared to the volume of lava erupted. Replenishment during the eruption would lead to the calculated ratio (lava/tilt) being too large. Replenishment would be a less significant factor during very short but voluminous phases, but the estimation of the volume of lava poured into the lake during the later (smaller) phases is relatively less accurate than for the first (larger) phase. The ratio of lava volume to cumulative tilt for phase 1 so calculated is 0.6×10^6 m^3 per microradian of eastward tilting at Uwekahuna.

An independent estimate of the ratio of the volume of lava removed from the summit reservoir to the change in tilt on the east-west liquid-level tiltmeter at Uwekahuna can be obtained from the summit collapse that accompanied the 1960 flank eruption at Kapoho (fig. 48.4). During the actual outpouring of the estimated 0.12×10^9 m^3 of lava near Kapoho between January 13 and February 6, the east-west liquid level tiltmeter measured an eastward tilt of 188 μrad, yielding a ratio of 0.65×10^6 m^3/μrad. The eastward tilting at Uwekahuna did not stop abruptly when the eruption ended but continued until March 10, when the total eastward tilt since January 13 reached 268 μrad, yielding a ratio of 0.45×10^6 m^3/μrad. Considering the possibility of adding lava to, or withdrawing lava from, storage in the east rift zone itself, the range of values 0.45×10^6–0.65×10^6 m^3/μrad for the 1960 eruption is in good agreement with the value 0.6×10^6 m^3/μrad determined from phase 1 of the Kilauea Iki eruption.

To determine the cumulative tilt at Uwekahuna for the eruption and backflow stages of the short later phases, we must depend on the Press-Ewing records. The background noise levels on the north-south and east-west traces are comparable, but the east-west rate-of-tilt signal on the east-west component is much larger than the signal for cumulative east-west tilt on the north-south component; and it appears that the best estimates of cumulative tilting can be obtained by integration of the rate-of-tilt curves. These curves were initially plotted on millimeter cross-section paper, so the integration was performed simply by determining the areas (counting squares) under the rate-of-tilt curves. In some cases uncertainty in the choice of a zero line for the rate-of-tilt curves was a problem. Coupled with the zero-line problem is the fact that rates of backflow less than 0.1×10^6 m^3/h would probably not be above noise level on the rate of tilt curve.

The two principal means of measuring east-west tilt changes at Uwekahuna, the liquid-level tiltmeter and the integrated east-west Press-Ewing zero-line anomaly, are complementary. With only one measurement per day the liquid-level tiltmeter cannot follow the details of short tilting episodes, but it maintains an absolute record of daily changes. The east-west Press-Ewing zero-line anomaly is measured as a deviation from a zero-line reference that is keyed to

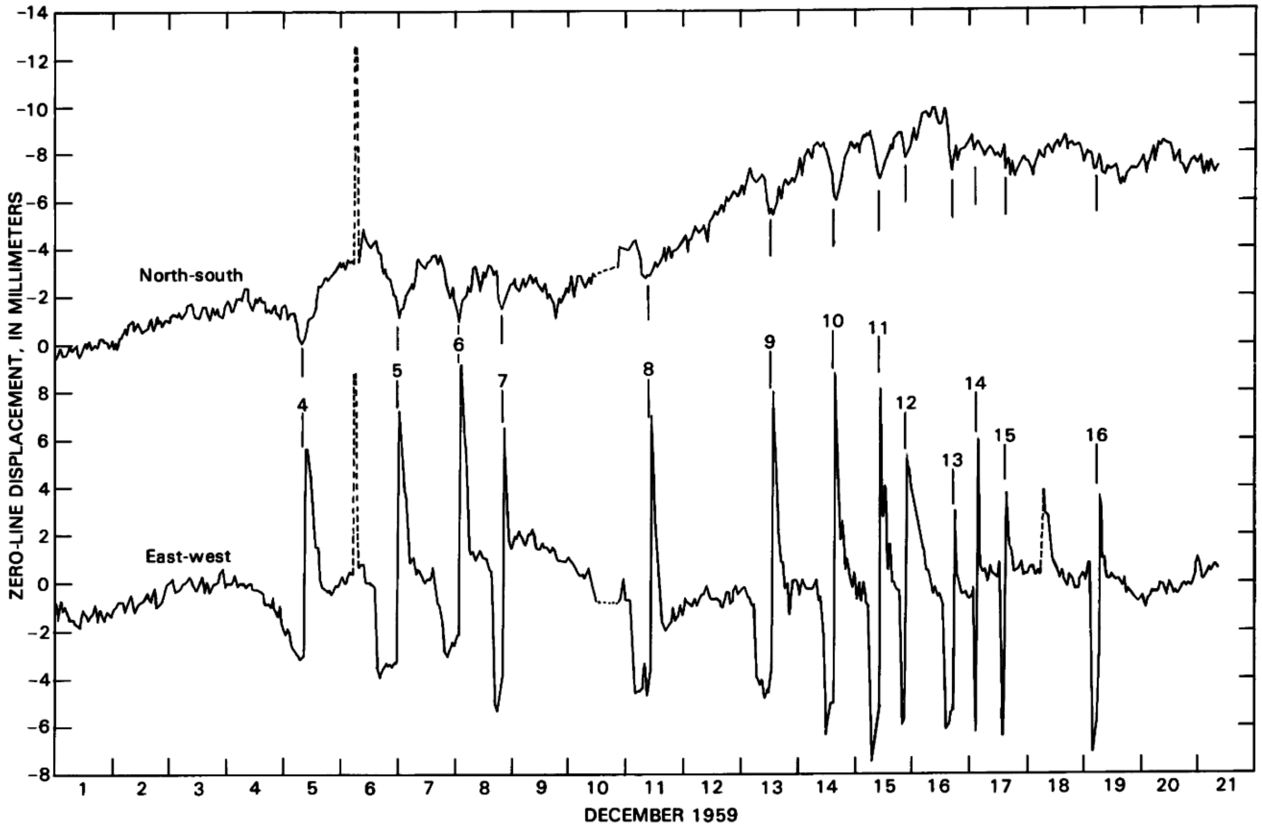

FIGURE 48.22.—Zero-line anomalies from north-south and east-west Press-Ewing seismographs accompanying phases 4–16. Numbers identify ends of individual eruptive phases as shown by abrupt reversals in the east-west zero-line anomaly curve.

what is considered the normal record before and after relatively short anomalous episodes. Thus, it maintains a sensitive record of changes during short episodes of tilting but is blind to slower, underlying, persistent changes like those that can be detected by the liquid-level tiltmeter.

The estimated volumes of lava removed from the summit reservoir during eruptive stages and returned during ensuing back-flow stages are compared (table 48.2) with, respectively, the volumes of lava poured into Kilauea Iki and then withdrawn during the principal phases of the eruption. The volume estimates for the summit reservoir were obtained by multiplying the integrated east-west rate of tilt by 0.6×10^6 m^3/μrad.

Use of this ratio of 0.6×10^6 m^3/μrad (volume of lava erupted during phase 1 divided by tilt change measured on the east-west liquid-level tiltmeter) to convert tilt changes determined from the east-west Press-Ewing zero-line anomaly to equivalent volumes of reservoir lava requires some justification. This justification proceeds in two steps. First, the east-west tilt changes detected by the north-south component Press-Ewing were scaled directly to the east-west tilt changes recorded by the liquid-level tiltmeter during phase 1. Second, the sum of eastward tilt during the fountaining stages of phases 4–16 measured by the north-south Press-Ewing (94.6 μrad) is almost exactly the same as that determined by integration of the east-west Press-Ewing zero-line anomaly (95.1 μrad). The comparison was made on the summed response to phases 4–16 because the Press-Ewing tilt measurements are much more certain for these phases than for phases 1–3.

The curves for fountain height, tremor amplitude at Outlet, and rate of eastward tilting at Uwekahuna were similar in shape during actual outpouring of lava (figs. 48.23–48.27). When fountaining ceased, tremor amplitude abruptly diminished nearly to zero, and eastward tilting abruptly reversed to westward tilting. Cumulative eastward tilt increased steadily during outpouring of lava. When fountaining ceased, brief sharp transients were recorded on both the north-south and east-west Press-Ewings instruments. On the east-west component this transient was a westward pulse of tilting superposed on the crest of the newly reversed tilt curve. On the north-south component it was a sharp northward pulse of tilt (detected by the seismometer, not the galvanometer). After the fountain died in phases 4, 5, and 9, tremor amplitude remained very

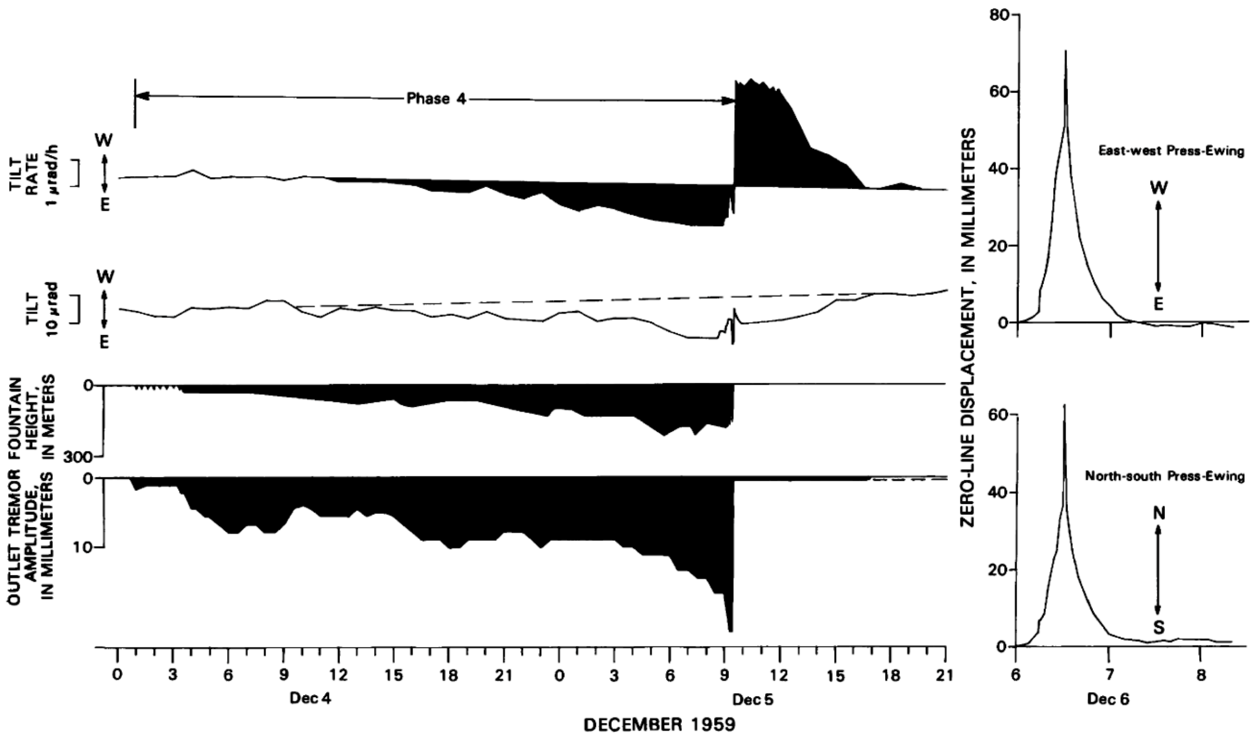

FIGURE 48.23.—East-west rate of tilting, east-west cumulative tilt, fountain height, and Outlet tremor amplitude for phase 4 and for the short but strong tilt excursion between phases 4 and 5.

low for many hours, and the westward tilting accompanying backflow declined steadily from its maximum to the noise level without large offsets or oscillations. Lava backflow rates were large, particularly at the beginning of the backflow stages, when they commonly exceeded the maximum rate of extrusion of lava during the eruptive stage they followed. Yet this rapid backflow was not accompanied by significant tremor. For phases 6–16 (omitting 9) the relationship between westward tilting and tremor was more complex, and it changed with time. After the fountain died and the amplitude of tremor at Outlet decreased abruptly, the tremor revived again after an interval of time that varied from phase to phase: phase 6, 2.5 h; phase 7, 50 min; phase 8, 35 min; phase 10, 1.5 h; phase 11, 50 min; phase 13, 20 min; phases 12, 14, 15, and 16, almost immediately. The renewed onset of tremor (resurgent tremor) was accompanied by a sharp drop in the rate of westward tilting and, presumably, the rate of reinflation of the summit reservoir.

The tremor and east-west rate-of-tilt curves for phases 10 and 11 were unusually complex. After the first resurgence of tremor, the tremor again died out and returned several times, accompanied by matching oscillations in the east-west rate-of-tilt curve. For phase 10, the first three episodes of tremor following cessation of fountaining were accompanied by sharp decreases in the reinflation of the reservoir (westward tilting), but later ones correlated with small increases in the rate of westward tilting. For phase 11 only the first interval of resurgent tremor was accompanied by a sharp drop in reinflation of the summit. Two prominent later episodes of tremor accompanied sharp increases in the rate of westward tilting.

The episode of tremor and tilting unaccompanied by an eruption (phase 15+, table 42.2) between phases 15 and 16 reveals another aspect of the relationship between tremor and tilting. Moderate fluctuating tremor that began abruptly at about 0600 on December 18 was accompanied by matching changes in the east-west rate-of-tilt curve (peaks in the tremor curve correlating with peaks of westward tilting). This behavior lasted for about 3 h. A large increase in tremor amplitude at about 0900 was accompanied by a large increase in rate of westward tilting. Tremor amplitude and westward tilting returned slowly to normal during the next 9 hours. The relationship between tremor and tilting during this episode is the same as that during the later parts of the phases 10 and 11 drainback, but it is opposite to that for the first interval of resurgent tremor for the 10 phases with significant resurgent tremor.

Another episode of very rapid tilting unaccompanied by an eruption took place on December 6 after phase 4. A rapid northwestward excursion began at about 0600. It peaked at 0631 with maximum rates of 26 μrad/h west and 24 μrad/h north, and it had died out by 0715. The net tilting toward the north and west was

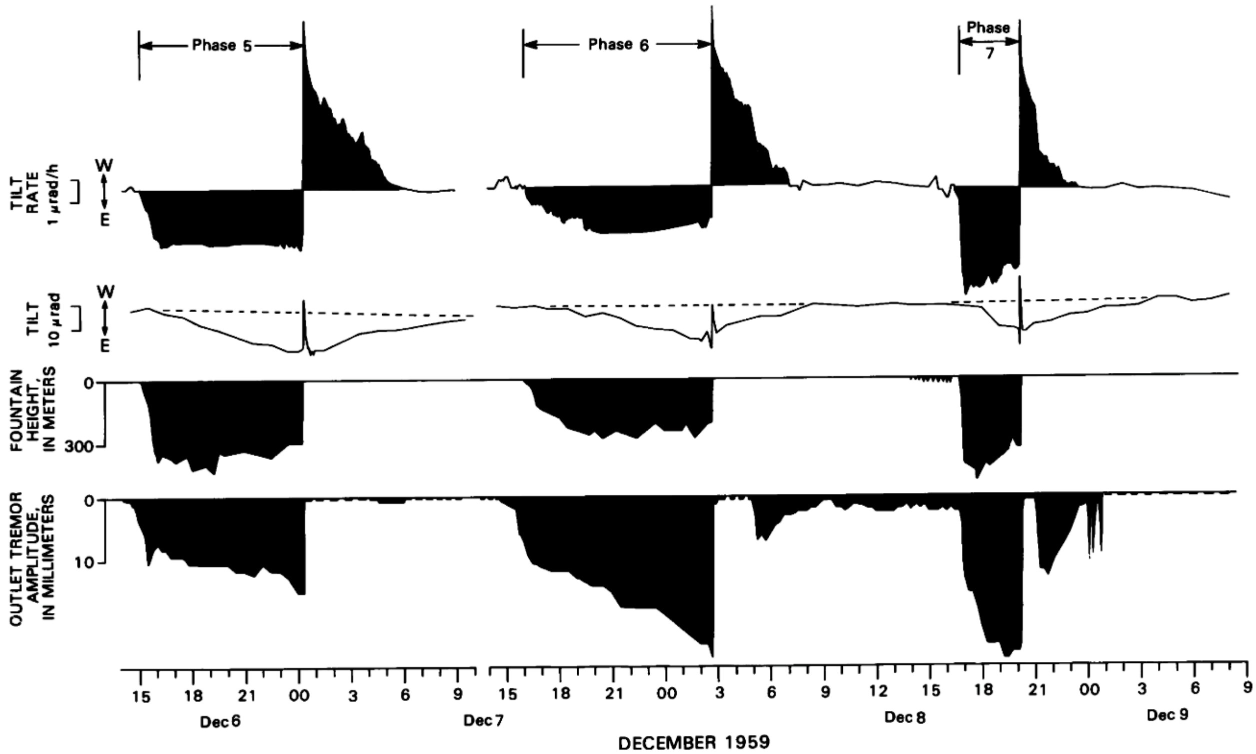

FIGURE 48.24.—East-west rate of tilting, east-west cumulative tilt, fountain height, and Outlet tremor amplitude for phases 5–7.

about 6.6 µrad and 4.8 µrad, respectively. The direction to the center of inflation from Uwekahuna was about az 126°. This azimuth is the same as that for the transient pulses that followed cessation of fountaining in the later phases. Tremor at Outlet remained low during this tilting episode, which was accompanied by a sequence of small earthquakes. At North Pit, inside Kilauea caldera, tremor was strong, and the earthquakes were more numerous and much larger (5–10 times larger amplitude) than at Outlet.

To provide a quantitative basis for discussing the movement of lava at the summit of Kilauea during the 1959 eruption, we have reduced the observations on tilting at Uwekahuna and the corresponding eruption and backflow of lava at Kilauea to tabular form (table 48.2). The state of tilt at the beginning of each eruptive phase (from the Uwekahuna east-west liquid-level tiltmeter) and changes in the east-west component of tilt measured from the Press-Ewing zero-line drift during the deflation and inflation of the summit reservoir that accompanied the eruptive and backflow stages of each phase are shown in columns 2–5. These tilt data are converted to reservoir volume changes and listed in columns 6–8 for comparison with the volumes of lava erupted into Kilauea Iki lava lake (column 9) and then withdrawn from it (column 10).

The best overall summary of the lava budget in the summit reservoir is shown in column 6 of table 48.2, where the volume of lava in the reservoir at the beginning of each phase is compared with that at the end of phase 1 fountaining. At the outbreak of phase 1 the reservoir contained the 30×10^6 m^3 that was poured into the lake during phase 1. Refilling of the reservoir began promptly at the end of phase 1, and it had regained 10.4×10^6 m^3 and 22×10^6 m^3 by the beginning of phases 2 and 3, respectively. At the beginning of phase 4, the entire 30×10^6 m^3 withdrawn during phase 1 had been replenished, presumably by new lava entering the system from below. The reservoir continued to fill steadily, but at a slower rate, until the beginning of phase 8, when at 40.4×10^6 m^3 it had exceeded the phase 1 outbreak level by 9.8×10^6 m^3. The volume of lava in the reservoir at the beginning of subsequent phases fluctuated from a low of 38.5×10^6 m^3 (phases 9 and 15) to a high of 42.8×10^6 m^3 (phases 12 and 14), and at the end of the summit eruption it stood at 40×10^6 m^3.

Net changes in the reservoir volume during deflation (table 48.2, column 7) and inflation (column 8) can be compared with the corresponding volumes of lava erupted into the lake (column 9) and withdrawn from it (column 10). Net changes in the volume of lava in

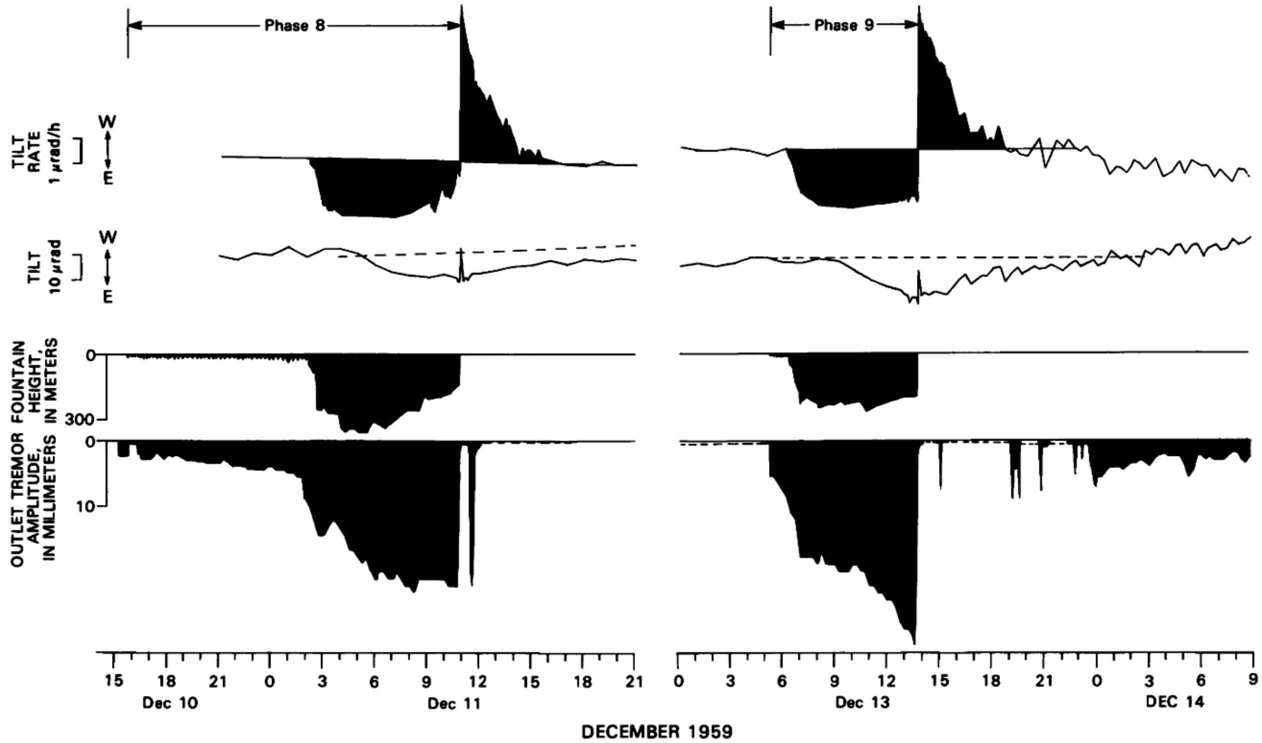

FIGURE 48.25.—East-west rate of tilting, east-west cumulative tilt, fountain height, and Outlet tremor for phases 8 and 9.

the lake-reservoir system during the eruptive stage, during the backflow stage, and during the entirety of each phase can be compared in columns 11, 12, and 13 of table 48.2, respectively. The changes measured during phases 2 and 3 are only poorly determined because of difficulties in establishing appropriate zero-line references for the east-west Press-Ewing instrument. There was a substantial increase in system volume during the first stage of phase 4 and significant increases also during phases 6, 10, and 12. There were substantial losses from the system during phases 7, 8, 9, and 15, principally during the backflow stage. There was a significant loss from the system during phase 13. During phases 5, 11, 14, and 16 the volume of the system showed little change. Phases with large system losses correlate with an overfilled summit reservoir (from phase 7 on), as do the most marked occurrences of resurgent tremor and associated irregularities in the curves of reservoir reinflation during backflow.

PROPOSED MODEL FOR THE 1959 ERUPTION

On the basis of the data on deformation at the summit of Kilauea and on lava eruption and withdrawal at Kilauea Iki during the 1959 eruption, we have constructed a model to explain the principal mechanical features of the eruption. The model is similar to one proposed by Helz (chapter 25) to explain the characteristics of olivine observed in samples collected at various stages of the eruption and in the lava lake. It is broadly based on the model of the Kilauea plumbing system deduced by Eaton and Murata (1960) and Eaton (1962) from the deformation of the Kilauea summit before, during, and after the 1959–60 eruption of Kilauea.

Following the summit collapse associated with the 1955 east-rift eruption, the Kilauea summit reservoir was slowly refilled by magma moving upward from the source zone 40–60 km deep beneath Kilauea. By early November 1959 the reservoir was sufficiently overpressured that a dike from the reservoir split upward through the enclosing rock and reached the surface inside Kilauea Iki Crater. All of the lava (except cinder and pumice blown away by the wind) accumulated inside the crater.

The initial overpressure required to open the dike to the surface sustained the early part of the first phase of the eruption, when lava flowed upward through the dikelike vent propped open by pressure of the lava. Rapid flow of lava through a section of the dike that was locally wider than average enlarged that section of the dike, forming the stable conduit leading to the main fountain and permitting the rest of the dike to close, either by freezing or because of a drop in the pressure of the lava in the dike. Less constricted passage of lava through the enlarging main-vent conduit relieved the confining pres-

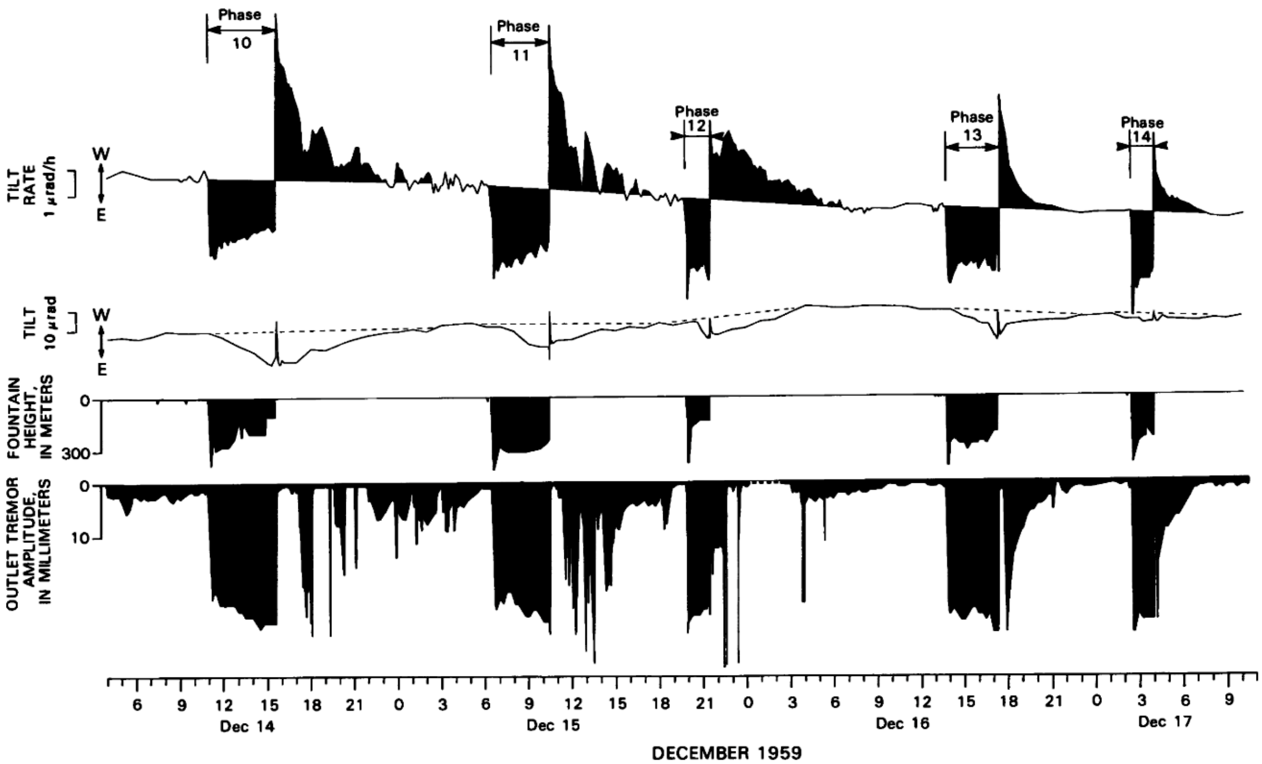

FIGURE 48.26.—East-west rate of tilting, east-west cumulative tilt, fountain height, and Outlet tremor amplitude for phases 10–14.

sure on the rising lava to increasingly greater depths in the conduit, permitting vesiculation and the consequent reduction in the density and viscosity of the lava-gas mixture in the conduit to penetrate to greater depths. This process reduced the average density of the column of lava in the conduit between the reservoir and the vent sufficiently that lava continued to be pumped from the reservoir to the lake even after the reservoir pressure had dropped below the level required to sustain outflow in an unvesiculated conduit. By this process a large volume of lava stored in the reservoir was pumped rapidly to the surface, where it accumulated in Kilauea Iki Crater. When the lava in Kilauea Iki rose significantly above the vent, heavy, degassed lake lava found entry to the conduit, possibly through another opening beside or below the fountaining vent. This inert, heavier lava sufficiently moderated the pumping action of vesiculation in the conduit to cut off the flow of ascending lava entirely, and fountaining stopped abruptly.

During most of phase 1, the rate of inflow of magma to the reservoir remained low. The large drop in reservoir pressure resulting from the rapid transfer of lava from the reservoir to the lake during the last few days of phase 1 led to a substantial increase in the hydraulic potential between the deep supply system and the reservoir, and the rate of inflow from depth therefore increased sharply late in phase 1.

The reservoir began to refill rapidly, and soon the reservoir pressure was again sufficient to raise the lava column, now partially degassed, to the vent in Kilauea Iki. This time overpressure such as required to drive a new dike to the surface was not needed. The flood of new hot magma entering the reservoir from below not only reinflated it but also introduced a supply of gas-rich lava that could help to sustain the vesiculation pump for lifting lava to the lake. The cycle of overfilling the lake, leading to a reversal of the density pump in the conduit, was repeated during phase 2. At the end of phase 2, either because the lake was sufficiently above the vent or because access of lake lava to the conduit was sufficiently less restricted (or both), a substantial volume of degassed lake lava flowed back down the conduit to further reinflate the reservoir. The same pattern was repeated during the subsequent phases of the eruption.

Refilling of the reservoir continued at a rate that was proportional to the hydraulic potential difference between the source at depth and the summit reservoir. As the reservoir was reinflated this potential difference decreased, and so did the rate of lava rising into the reservoir. When the reservoir was refilled to and beyond its state at the outbreak of phase 1, the enclosing rocks were again stressed to near their limits. During the rapid backflow following the later phases, the sudden sharp increase in reservoir pressure induced by the returning lava appears to have opened a temporary passageway,

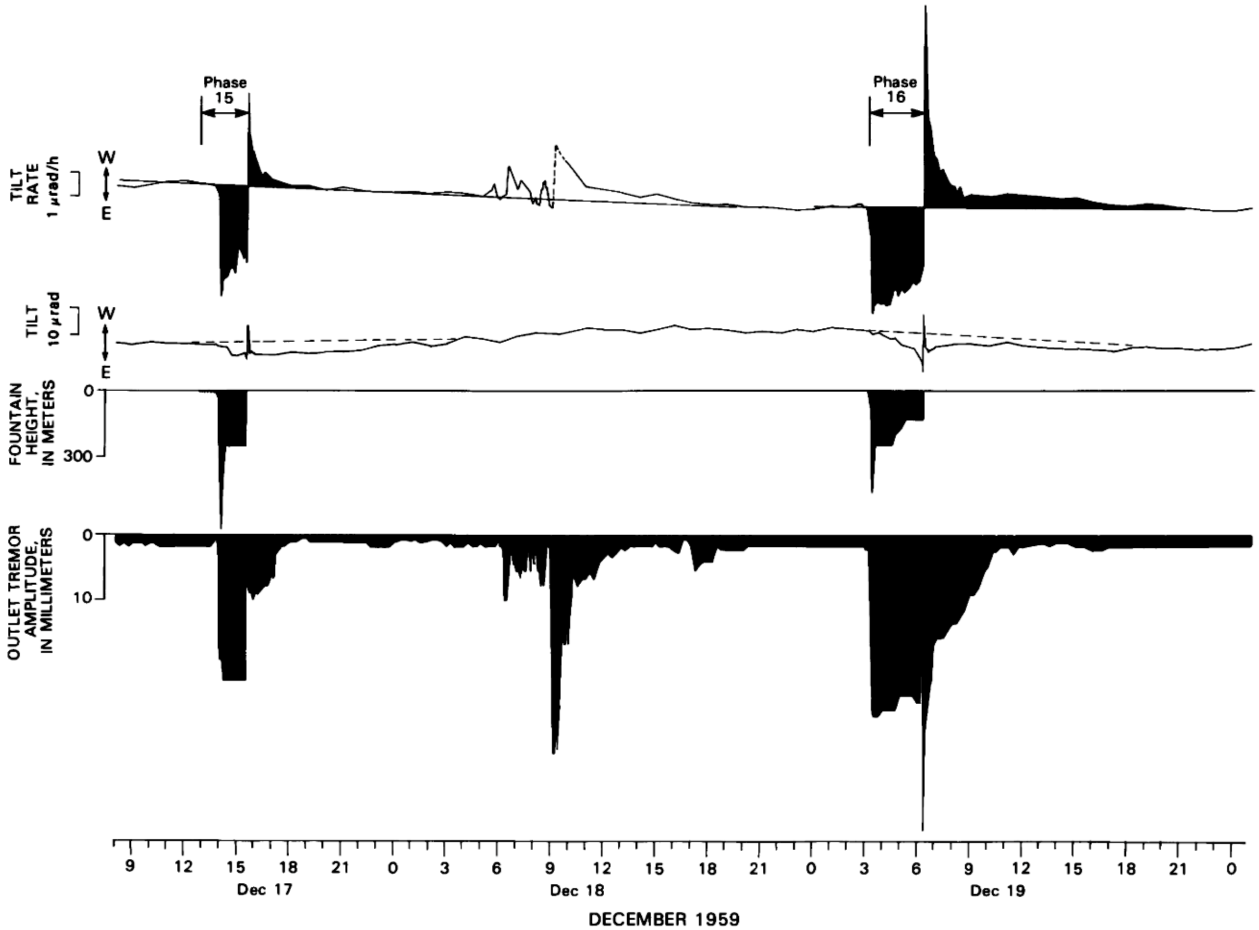

FIGURE 48.27.—East-west rate of tilting, east-west cumulative tilt, fountain height, and Outlet tremor amplitudes for phases 15 and 16 and for episode of tilting and tremor between them.

probably a dikelike zone propped open by excess reservoir pressure, and to have driven some reservoir lava into a nearby zone with lower hydraulic potential, possibly the fluid core of the upper end of the east rift zone.

A summary of the movement of lava into the summit reservoir from depth and out of the summit reservoir into Kilauea Iki lava lake and the east rift zone(?) is given in figure 48.28. The primary withdrawal of lava from the summit reservoir was the 30×10^6 m^3 erupted during the first phase. The outbreak of the eruption depended on the reservoir being overpressured by new lava entering from below. This new, more primitive material may have been included in the initial outbreak, only to be swamped later in phase 1 by larger volumes of lava withdrawn from reservoir storage, as suggested by Helz (chapter 25). The principal system response to the initial deflation of the reservoir was a (somewhat delayed) massive influx of new lava from depth to refill the reservoir, where it presumably was available to mix with lava still retained by the reservoir. Ongoing recharge of the reservoir repeatedly brought the summit reservoir-lava lake system back to a condition that essentially led to a restaging of the last part of the phase 1 eruption: the original conduit and the same vesiculation-pump mechanism that operated during the later part of the phase 1 eruption were utilized over and over again.

Lava draining back from the lake during the early phases was recaptured entirely by the reservoir. During the later phases, however, the reservoir was so full that it could not retain both the new lava that had entered it from below since the last phase and the batch of lava suddenly returned from the lake. Some fraction of the

TABLE 48.2.—*Record of ground tilt at Uwekahuna and volumes of lava erupted into and withdrawn from Kilauea Iki lava lake during the 16 principal phases of the 1959 eruption*

[Data in column 2 from liquid-level tiltmeter; data in column 3 from north-south Press-Ewing instrument; data in columns 4–5 and 7–8 from integrated east-west Press-Ewing instrument; data in column 6 derived from east-west liquid-level tilmeter data; data in columns 2 and 6 are relative to end of phase 1 fountaining]

	Tilt (μrad)				Lava volume (10^6 m^3)					Volume gain or loss (10^6 m^3)		
Phase	E-W at start of phase	Deflation episode (eastward)		Inflation episode (westward)	Reservoir storage relative end phase 1	Deflation episode	Inflation episode	Erupted into lake	Drainback from lake	First stage of phases (9–7)	Second stage of phases (8–10)	Entire phase
1	2	3	4	5	6	7	8	9	10	11	12	13
1	50	50	--	--	30.6	--	--	30.6	1.1	--	--	(−1.1)
2	17	5.5	4.5	21.5	10.4	2.8	13.1	3.6	4.5	+0.8	+8.6	+9.5
3	36	8.1	14.0	4.7	22.0	8.6	2.8	3.2	2.0	−5.4	+.8	−4.5
4	50	9.6	10.2	10.2	30.6	6.3	6.3	11.5	6.3	+5.2	.0	+5.2
5	55	10.0	9.7	7.6	33.6	6.0	4.7	6.5	4.7	+.5	.0	+.5
6	55	8.5	9.4	7.5	33.6	5.7	4.6	6.6	3.8	+.8	+.8	+1.6
7	59	6.7	7.3	3.4	36.1	4.4	2.1	3.7	5.6	−.7	−3.5	−4.2
8	66	7.0	10.2	6.0	40.4	6.2	3.7	6.7	6.0	.0	−2.3	−2.3
9	63	10.4	9.3	6.5	38.5	5.7	4.0	5.7	6.9	.0	−2.9	−2.9
10	67	9.6	8.2	9.9	41.0	5.0	6.0	6.3	4.9	+1.3	+1.1	+2.4
11	65	7.0	8.5	6.8	39.8	5.2	4.1	4.7	4.1	−.5	.0	−.5
12	70	4.8	3.4	7.8	42.8	2.1	4.7	2.2	3.1	+.1	+1.6	+1.8
13	70	8.1	6.4	3.0	42.8	3.9	1.8	3.2	2.4	−.7	−.6	−1.3
14	68	2.2	3.0	1.6	41.6	1.8	1.0	1.8	1.0	.0	.0	.0
15	63	3.3	3.1	1.1	38.5	1.9	.7	1.7	3.2	−.2	−2.5	−2.8
16	64	7.4	6.4	5.6	39.1	3.9	3.4	4.1	4.1	+.2	−.7	−.5
End	65											
[1]15+	63	--	--	3.9	38.5	--	2.4	--	--	--	2.4	+2.4

[1]Episode of reservoir inflation without eruption between phases 15 and 16.

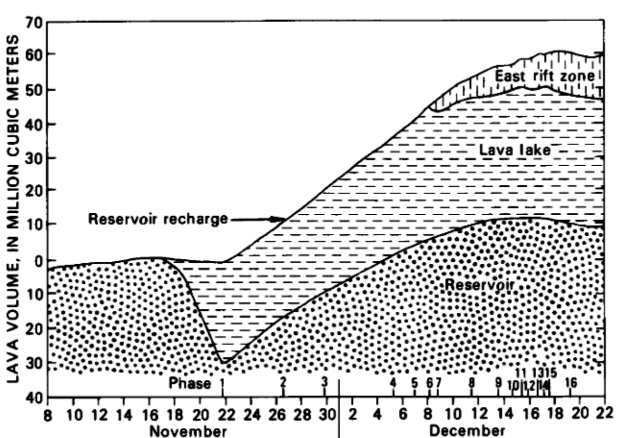

FIGURE 48.28.—Partitioning of lava that was in summit reservoir on November 14 and lava that subsequently recharged it from below between summit reservoir, lava lake, and loss from the reservoir-lake system (to east rift zone?).

returning lava, or a corresponding volume of lava already in the reservoir, was then expelled into the east rift zone (during an episode of resurgent tremor) from the reservoir.

The total volume of lava added to and retained within the summit reservoir after the end of phase 1 fountaining was 40×10^6 m^3. From the gain-loss figures for the individual phases in table 48.1 it appears that some 12×10^6 m^3 of additional lava was added to the reservoir from depth but was then expelled from it during late-phase backflow episodes. An additional 8×10^6 m^3 from the reservoir was added to the lake after phase 1. In summary, it appears that the volume of new lava entering the reservoir after the end of phase 1 was about 60×10^6 m^3, of which 40×10^6 m^3 remained in the reservoir, 8×10^6 m^3 had been transferred to the lava lake, and 12×10^6 m^3 had been driven out of the reservoir, possibly into the east rift zone, by the end of the eruption. Repeated cycling of lava between the reservoir and the lake, with the accompanying turbulence in the upper part of the lava conduit and the fountain, should have been a very effective means of homogenizing the contents of the reservoir. Such cycling of lava also explains the fate of the 63×10^6 m^3 total volume of lava that drained out of the lava lake during the entire eruption.

RATE OF ERUPTION, FOUNTAIN HEIGHT, AND TREMOR AMPLITUDE

Observations of harmonic tremor generated during various stages of lava outbreak, fountaining, and backflow from the lava lake provide a basis for an analysis of tremor amplitude as a possible function of fountain height, rate of eruption, state of recharge of the summit reservoir, and temperature of the erupting lava (the latter determined by Helz, chapter 25, from glass composition near olivine phenocrysts in air-quenched pumice samples collected during the eruption). The relations among the foregoing parameters are not simple, and they appear to have evolved during the eruption as a whole as well as during the first phase itself. Outlet tremor amplitude, rate of eruption, fountain height, and lava temperature are plotted in figure 48.29*A* versus time for phase 1. In figure 48.29*B*, summit reservoir recharge, Outlet tremor amplitude, rate of eruption, fountain height, and lava temperature are plotted versus eruption phase number. The intensity of eruption changed with time

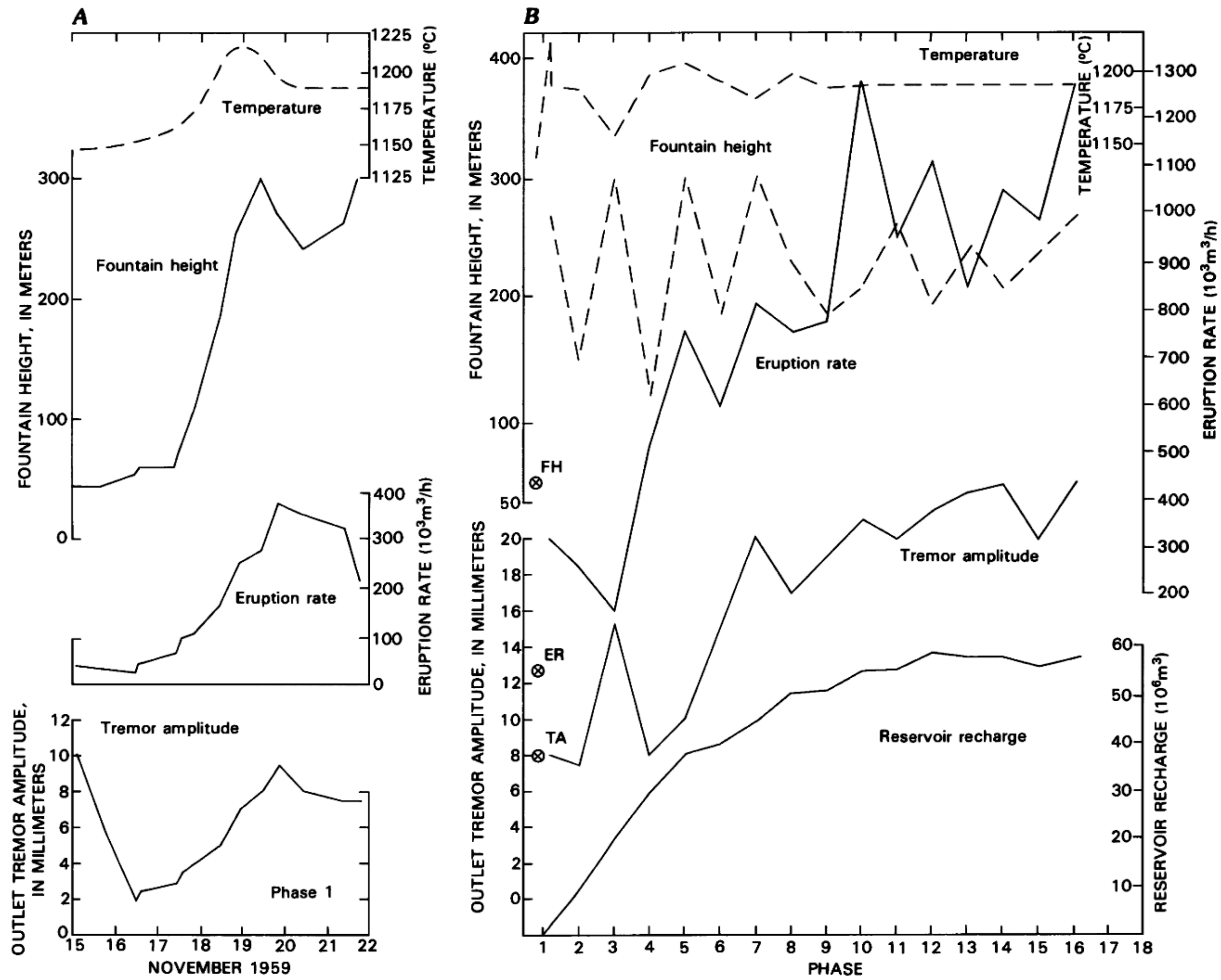

FIGURE 48.29.—Variation of eruption parameters during course of the 1959 Kilauea eruption. ***A***, Tremor amplitude, eruption rate, fountain height, and lava temperature plotted against time for phase 1. ***B***, Reservoir recharge, tremor amplitude, rate of eruption, fountain height, and lava temperature plotted against phase number for phases 1–16. Points for fountain height, eruption rate, and tremor amplitude for the first day of phase 1 are labeled FH, ER, and TA, respectively.

during several phases in addition to phase 1. In order to prepare the simplified plot of parameters versus phase number, values were selected from the parts of phases that seemed best to characterize the phase as a whole. The data plotted in figures 48.29 and 48.30 are also shown in tables 48.3 and 48.4, respectively.

The first few days of phase 1 were very different from the rest of that phase, so two sets of values are plotted. The first set represents the first day; the second set represents the last three days of the fully developed phase 1 eruption. Although tremor amplitude was similar (6–10 mm in the first, 8.5 mm in the second), the contrast between the two sets in other parameters is extreme: 34×10^3 m^3/h eruption rate, 45-m-high fountain, and 1,145 °C lava temperature for the first versus 340×10^3 m^3/h eruption rate, 300-m-high fountain, and 1,185–1,215 °C lava temperature for the second. The tremor amplitude remained virtually unchanged despite 7-fold and 10-fold increases in fountain height and rate of eruption, respectively.

During the first few hours of the eruption, lava streamed to the surface through the long thin dike, probably held open by the pressure of the lava, that was opened in response to overfilling the reservoir. Pressure variations in the moving lava interacted with the elastic walls and with lava velocity in the dike and rhythmically distended and contracted the dike as lava moved unsteadily through it. Such a structure is very efficient for generating tremor because of

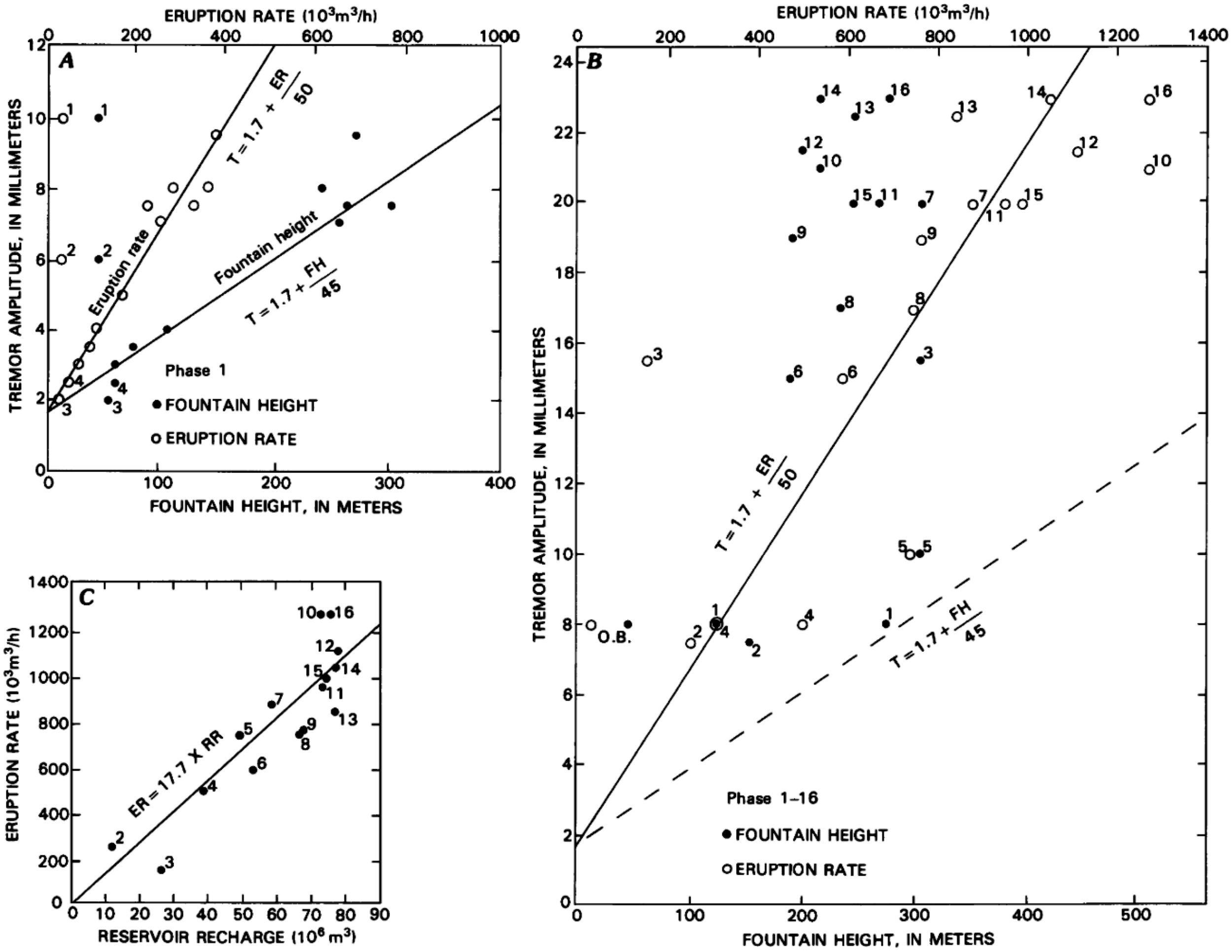

FIGURE 48.30.—Cross plots of eruption parameters for the 1959 Kilauea eruption. Numbers on plot *A* indicate sequence of readings during phase 1 on November 15–16. Numbers on plots *B* and *C* indicate phases. On plot *B*, the earliest data for phase 1 are plotted separately and labeled O.B. ***A***, Tremor amplitude plotted against eruption rate and fountain height for phase 1. ***B***, Tremor amplitude plotted against eruption rate and fountain height for phases 1–16. ***C***, Eruption rate plotted against reservoir recharge for phases 2–16.

its shape: the large surface-area-to-volume ratio of the dike permits good translation of pressure variations in the lava to movement of the walls of the dike.

In the course of the first day, fountaining died out along all of the original fissure except for one small section, where the main fountain gradually grew in height and volume as it took over the function of the dying fountains. The rate of eruption declined only slightly, but the Outlet tremor amplitude dropped from 10 mm to 2 mm (fig. 48.29*A*). After about 36 h, rate of eruption and tremor amplitude both began to rise steadily; and after about 60 h the height of the fountain began a rapid increase, accompanied by further increases in the growth of eruption rate and of tremor amplitude. Plots of tremor amplitude versus fountain height and tremor amplitude versus eruption rate for the first phase of the eruption are shown in figure 48.30*A*. Excluding the first day (points labeled 1 and 2), tremor amplitude is simply related to both eruption rate and fountain height: $T=1.7+ER/50$ and $T=1.7+FH/45$, where T is amplitude of Outlet tremor in millimeters, ER is eruption rate in thousand cubic meters per hour, and FH is fountain height in meters. Points 1 and 2, for the initial stage of phase 1, clearly do not fit with the rest of the data. During the first 36 hours of the eruption it appears that the tremor-generating system evolved from an initial stage dominated by the dike conduit, which produced strong tremor, to a later stage dominated by an open central conduit which was

TABLE 48.3.—*Detailed eruption parameters for phase 1 of the 1959 Kilauea Iki eruption*

[Dates and times are lava-lake depth measurements, from table 48.1; volume rate is average rate of eruption since last measurement of lake depth or onset of new eruptive phase; tremor measured at Outlet; temperatures are quench temperatures of pumice samples collected during the time intervals, from Helz (chapter 25)]

Date	Time (H.s.t.)	Volume rate (10^3 m^3/h)	Fountain height (m)	Tremor amplitude (mm)	Temperature (°C)
Nov. 14	2008	--	--	--	--
Nov. 15	0300	33	46	10.0	1,144
	1800	31	46	6.0	--
Nov. 16	1215	25	55	2.0	--
	1400	44	61	2.5	--
Nov. 17	1045	70	61	3.0	--
	1400	94	76	3.5	--
	2030	106	107	4.0	--
Nov. 18	1200	163	185	5.0	--
	2315	252	259	7.0	1,216
Nov. 19	1150	281	305	8.0	--
	2115	378	274	9.5	--
Nov. 20	1210	357	244	8.0	1,187
Nov. 21	0930	327	267	7.5	--
	1925	222	305	7.5	1,188

TABLE 48.4.—*Eruptive parameters characterizing the 16 principal eruptive phases of the 1959 Kilauea Iki eruption*

[Figures for volume rate of eruption, fountain height, and tremor amplitude (measured at Outlet) are averages for the particular phase; temperature is quench temperature of pumice sample collected during phase, from Helz (chapter 25); recharge is volume of lava that entered summit reservoir from depth from end of phase 1 fountaining to onset of current phase]

Phase	Volume rate (10^3 m^3/h)	Fountain height (m)	Tremor amplitude (mm)	Temperature (°C)	Recharge (10^6 m^3)
1a	32	46	8.0	1,142–1,144	--
1b	306	274	8.0	1,187–1,216	--
2	248	152	7.5	1,185	9.4
3	153	305	15.5	1,154	20.1
4	497	122	8.0	1,196	29.9
5	742	305	10.0	1,205	38.1
6	585	189	15.0	--	40.5
7	879	305	20.0	1,181	45.4
8	745	232	17.0	1,197	51.4
9	765	189	19.0	1,188	52.1
10	1,269	213	21.0	1,189	56.2
11	948	265	20.0	--	56.4
12	1,109	198	21.5	--	60.0
13	841	244	22.5	--	59.1
14	1,047	213	23.0	--	59.2
15	986	244	20.0	1,191	57.0
16	1,269	274	23.0	1,190	58.6
End	--	--	--	--	59.7

much less efficient in producing tremor. Thereafter, the eruption increased in intensity, and tremor, rate of eruption, and fountain height all increased proportionally.

The role of lava temperature appears to be important, because the large increases in tremor, rate of eruption, and fountain height appear to coincide with an increase in lava temperature from about 1,145 °C to 1,185–1,215 °C between November 15 and November 18. The exact role of temperature is not clear, however. Higher temperatures certainly are associated with greater fluidity of the lava, but they also mark the lava as being more primitive and less depleted of dissolved gases than cooler lava. The latter attribute may be more important than the former in its effect on the style of eruption.

The evolution of the eruption from phase to phase took a different course from the evolution of phase 1. As the reservoir was recharged with fresh lava after phase 1, tremor amplitude and rate of eruption generally increased from phase to phase, but fountain height was very erratic (fig. 48.29*B*). In an almost regular alternation from one phase to the next, it oscillated between 120–180 m and 270–300 m during the first seven phases. The alternation was slower (2 eruptive phases per half-cycle) and between narrower limits (180–270 m) thereafter. Tremor amplitude is plotted versus eruption rate and fountain height for all 16 phases, in figure 48.30*B*, as it was for phase 1 only in figure 48.30*A*. The lines relating tremor amplitude to rate of eruption and fountain height in the phase 1 plot are repeated in figure 48.30*B*. Although the scatter is somewhat greater here, the data for tremor amplitude versus eruption rate for the 16 phases fit the phase 1 curve very well. The data for tremor amplitude versus fountain height, however, depart widely and systematically from the phase 1 curve. After phase 4, fountain height is restricted to the range 180–300 m, and it appears not to be related to tremor amplitude. The extremely low value for rate of eruption in phase 3 (fig. 48.30*B*) may be explained, at least in part, by the large loss of material blown downwind and away from the lake from the high, very gassy fountain that characterized this phase.

Eruption rate appears to be simply related to reservoir recharge (fig. 48.30*C*) by the relationship $ER = 17.7 \times RR$, where ER is eruption rate in thousand cubic meters per hour and RR is reservoir recharge in million cubic meters. The error in the eruption rate predicted by this relationship for phases 4–16 is less than 25 percent of the measured value in all 13 cases and less than 10 percent in 7 cases. The predicted eruption rates for phases 2 and 3 are 34 percent too small and 133 percent too large, respectively. The discrepancy for phase 3 would be reduced if the volume of lava represented by the pumice blown away from the very gassy fountain (and the lake) during this phase were included.

A change in fountain behavior between the later phases and the earlier phases that is apparent in figure 48.21 and figures 48.23–48.27 deserves special mention. During the early phases the fountain grew steadily in height until it reached a high level that was maintained until the end of the phase. Exceptions to this rule were phase 2, in which the fountain height increased considerably just before it died, and phase 9, in which the fountain declined steadily from a maximum attained early in the phase. Before phase 10, no phase began with a sharp, high pulse of fountaining that declined rapidly to a lower level that then characterized the rest of the phase. From phase 10 through phase 16, however, all phases began with such an initial outburst. This phenomenon was most pronounced in phase 15, in which the outbreak fountain rose briefly to a height of 580 m, about twice the height of fountaining during the rest of the phase.

This change in behavior may reflect a change in composition or amount of gas in the lava of the summit reservoir. Gerlach and Graeber (1985) calculate very different compositions for the gas in the parental magma at depth and in lava stored in the summit reservoir equilibrated at 2-km depth. They find the concentrations, in weight percent, of the three principal gas components as follows:

	H_2O	CO_2	SO_2
Parental magma	0.30	0.65	0.13
Stored reservoir lava	0.27	0.034	0.070

At reservoir depths CO_2 would have already exsolved from the lava and collected as a separate phase in fluid inclusions, while H_2O would still be dissolved in the lava. At depths of 2–4 km, such low-density CO_2 inclusions would constitute 5–10 percent, by volume, of the lava and would reduce its density in approximately the same proportion. In the interval between eruptive phases, gravitative separation of lighter lava rich in CO_2 inclusions may have positioned such material near the top of the reservoir for early eruption during the next phase. The CO_2 may also be more effective than H_2O in producing rapid vesiculation because it is already exsolved from the lava, whereas H_2O must first diffuse out of the lava into bubbles before those bubbles can expand in response to a drop in confining pressure. After an episode of abnormally vigorous initial fountaining, the eruption would return to normal when the gas-enriched cap of lava in the reservoir was depleted.

The large phase-to-phase variation in fountain height, particularly during the early phases, that is shown in figure 48.30*B* may also result from variations in the composition and abundance of gas from place to place in the mixture in the reservoir of old stored lava and new lava from depth.

FURTHER DEVELOPMENT OF THE PROPOSED MODEL OF THE 1959 ERUPTION

During the first phase the conduit evolved from a long, thin dike held open by pressure in the lava to a much more stable conduit with a more equidimensional cross section. It remained sufficiently open at the end of phase 1 to admit 1.0×10^6 m^3 backflow from the lake. Descriptions of the onset of all subsequent phases, except the very short phase 14, whose onset is not described (Richter and others 1970), show that the conduit had remained open after the end of the last phase and that a fluid lava column, with large bubbles of gas rising through it and throwing up spatter when they burst, rose slowly to the mouth of the conduit. At the end of these phases lava flowed copiously back into the vent and disappeared underground. These observations strongly suggest that the conduit was an open pipe from the reservoir to the lake, and that the pressure of lava in the reservoir at the base of the conduit was in approximate balance with the weight of lava in the conduit. A slight change in this balance could cause lava to flow out of the reservoir through the pipe to the surface or the reverse.

Following phase 1, which poured about 30×10^6 m^3 of lava into the lake, where it was trapped, new lava from depth streamed up into the reservoir and mixed with the current contents of the reservoir. During subsequent phases some mixture of the older and newer reservoir lava was spewed out into the lake, undergoing intense local mixing in the conduit. Some fraction of the contents of the lake then drained back to the reservoir, with further mixing. As the eruption progressed and more and more lava moved up from depth to recharge the reservoir, its contents gradually took on more of the characteristics of the new lava, including its temperature and charge of dissolved (and exsolved) gases. Reinflation of the reservoir, at least through phase 8 or phase 10, raised the piezometric surface of lava in the reservoir, making onset of the next eruption easier and increasing the pressure drive that would help to sustain it.

As backflow from the last phase ceased, the heavy lake lava occupying the conduit would tend to flow back into the reservoir and be replaced by hotter, lighter lava from the reservoir (if the conduit were not too narrow). This process would be aided by any exsolved CO_2 that had come into the chamber with the recharge from depth. When the combination of lighter lava in the conduit and increased reservoir pressure (from further recharge) raised the top of the column sufficiently that it overflowed into the lake, the conditions for starting the next eruption had been met.

Next, consider the factors that might control rate of eruption and fountain height during an eruptive phase once it has started. In the system we have described the rate of eruption should be determined by the balance between the pressure difference driving the eruption and the pressure drop in the conduit resulting from the flow of lava through it. The pressure difference that drives the eruption is primarily a result of vesiculation of lava in the upper part of the conduit, which reduces its density substantially as it flows to the surface. The resulting decrease in weight of lava in the upper part of the conduit is available as a pressure difference to drive lava upward through the conduit. The efficiency of this vesiculation pump will depend on the gas content of the lava, the speed with which it can accumulate in bubbles, and the rate at which the bubbles can escape from the lava. These factors are related to lava temperature to the degree that temperature controls viscosity and is a measure of the proportion of new material from depth in the erupting lava.

The pressure drop owing to movement of lava through the conduit depends primarily on velocity and viscosity (and hence temperature) of the lava and the geometry of the conduit. In the course of the eruption, constrictions in the conduit would have been eroded (melted) away, progressively decreasing the resistance to flow; as the erupting lava was increasingly enriched in new hotter material from depth, its viscosity would have decreased, further reducing resistance to flow.

During an eruption of fairly viscous lava, we should expect a low rate of flow from the reservoir. For a fairly slow ascent of lava in the conduit, the exsolution and separation of gas should be nearly complete and should yield an abundance of gas deep in the conduit to drive the gas-lava mixture above it out of the conduit rapidly, producing a high fountain. During an eruption of less viscous lava, we should expect a high rate of flow from the reservoir. For a rapid ascent of lava in the conduit we may speculate that the short time that lava would spend in the upper, low-pressure part of the conduit would limit the amount of exsolution and, particularly, separation of gas from the lava and would result in a low, voluminous fountain in which the bubbles of gas would still be retained in the lava as it was thrown out of the vent. In the scheme outlined above, low eruption rates and high fountains would correlate with lower than average lava temperatures, and high eruption rates and low fountains would correlate with higher than average lava temperatures. This tendency would be superposed on one of increasingly larger eruption rates from phase to phase as the conduit was enlarged by continued use and the summit reservoir was refilled by hot, gas-rich lava from depth.

The first part of this pattern appears to have been observed during phase 3 (with its low lava temperature of about 1,155 °C, high fountain, and very low eruption rate) and the ensuing phase 4 (with its high lava temperature of about 1,200 °C, low fountain, and high eruption rate). The second part of the pattern is demonstrated by the relationship between eruption rate and reservoir recharge shown in figure 48.30*C*.

The apparent linear relation between tremor amplitude and eruption rate in figures 48.29*A* and 48.29*B* supports the view that tremor is generated primarily in the eruption conduit and that its amplitude is proportional to the rate of flow of lava through the conduit. However, tremor accompanying the initial rapid backflow of lava through the conduit when the fountain died was insignificant compared to tremor during fountaining. Thus, the existence of lava fountaining is strongly correlated with strong tremor, but fountain height (the most obvious measure of intensity of fountaining) does not correlate with tremor amplitude during the later phases of the eruption, which produced the strongest tremor. These observations, taken together, suggest that the source of the tremor accompanying the large fountains of the Kilauea Iki eruption was the vesiculation pump mechanism that operated in the upper part of the eruption conduit to lift lava out of the reservoir. Moreover, the amplitude of the tremor is proportional to the volume rate of lava moving through the conduit or, equivalently, to the power consumed in the pumping mechanism to lift the lava.

This tremor-generating mechanism, which operates in a stable open conduit but with rather low efficiency, does not explain the tremor generated during the initial stages of phase 1 nor during episodes of resurgent tremor accompanying backflow from the lake. In both of these cases, it appears that the movement of lava through a dikelike conduit that is being held open by pressure in the moving lava is a more likely mechanism. An important requirement of such a mechanism is that it produce strong tremor as a consequence of the movement of a fairly small volume of lava.

SUMMARY AND CONCLUSIONS

1. The 30×10^6 m^3 of lava erupted into Kilauea Iki Crater during the first phase of the 1959 eruption was drawn primarily from storage in the summit reservoir. After the outbreak and initial episode of eruption, which were driven by reservoir overpressure, vesiculation in the upper part of the conduit effectively pumped lava from the reservoir up into the lake. During this process the reservoir pressure dropped below that required to hold an unvesiculated column of lava in the conduit up to the level of the vent.

2. When the surface of the lake rose above the level of the vent, heavy degassed lake lava flooded the base of the fountain and poured back into the vent, where it sufficiently inhibited vesiculation in the lava emerging from below that it disabled the vesiculation pump and shut off the eruption. With degassed lake lava in the conduit, the pressure at the base of the conduit exceeded the pressure in the reservoir, and lake lava flowed back into the reservoir. When the lake surface fell below the vent, backflow ceased.

3. The sharp drawdown in reservoir pressure during the final stages of phase 1 led to a sharp increase in the flux of lava into the reservoir from the deep source beneath the volcano. The reservoir inflation rate increased from about 0.3×10^6 m^3/d for the month before the eruption, to about 3×10^6 m^3/d immediately after phase 1. Between the end of phase 1 and the end of the 1959 eruption, about 60×10^6 m^3 of fresh lava entered the reservoir from below.

4. The conduit remained open from the end of phase 1 until the end of the eruption. Increase of pressure in the reinflating reservoir and, possibly, replacement of heavy drainback lava in the conduit by lighter, gas-charged lava from the reservoir raised the lava in the conduit until it rose above the lip of the vent. Vesiculation of the fresh reservoir lava rising in the conduit further reduced the density of lava in the conduit and revitalized the vesiculation pump, turning on the next eruptive phase. When the erupting lava again raised the lake surface sufficiently above the level of the vent, degassed lava from the lake again poured back into the conduit and disabled the vesiculation pump. Cessation of fountaining was again followed by draining of the lake back down to the level of the vent.

5. The process described above was repeated 15 times after phase 1, until the supply to the summit reservoir of fresh lava from below abated. An additional 8×10^6 m^3 of lava was added to the lake, primarily during phase 4, when the mouth of the conduit broke out higher on the south wall of Kilauea Iki about 12 m above the original vent. An estimated 12×10^6 m^3 lava was driven out of the reservoir, probably into the core of the east rift zone, during backflow from the later phases of the eruption. At the end of the eruption the summit reservoir had been refilled with about 40×10^6 m^3 lava to replace the 30×10^6 m^3 that was withdrawn during phase 1. The lava budget of the entire eruption is shown in figure 48.28.

6. Tremor appears to have been generated under two different regimes with very different efficiency. Eruption of lava at even low rates through a long narrow fissure propped open by pressure in the lava produced strong tremor early in phase 1 and, perhaps, during episodes of resurgent tremor accompanying backflow. In the stable conduit that remained open between phases (and was, therefore, not propped open by excess reservoir pressure), tremor was generated with much lower efficiency. In this case, the amplitude of tremor was a linear function of eruption rate during fountaining, but it was much smaller during comparable rates of backflow. Tremor amplitude appears to be independent of fountain height, except during phase 1 when the conduit was being shaped by the flow of lava through it. These observations suggest that tremor in the open conduit was associated with the action of the vesiculation pump that lifted lava from the reservoir to the lake.

7. After the first 3 phases, rate of eruption was proportional to the volume of lava from below that had recharged the summit reservoir. This relation may be a result of the decrease in the work required of the vesiculation pump to move lava from the reservoir to the lake as reservoir pressure increased. It may also be caused by a

progressive change in the ratio in the reservoir of stored reservoir lava to fresh lava from depth.

8. From phase 10 onward, the eruptive phases began with an episode of high fountaining. Fountaining then diminished rapidly to a lower level that was sustained through the rest of the phase. Such behavior might be explained by the accumulation of a light, particularly gas rich batch of lava at the top of the reservoir between phases, which was expelled first during the next phase but was soon depleted. Because H_2O should be completely dissolved in the lava at reservoir depths, it is unlikely that it is the agent for such a process. A far better candidate is CO_2. If present in the amount deduced by Gerlach and Graeber (1985), light fluid inclusions of CO_2 would constitute 5–10 percent by volume of the parental magma when raised to reservoir depths. The large variation in fountain height, which appears to depend on lava temperature to some extent, might also be explained by a mixture of CO_2-depleted stored lava and CO_2-rich fresh lava in the reservoir. In the course of the eruption, as the proportion of fresh lava and the mixing of the reservoir contents increased, the range of variation in fountain height and temperature of erupted lava decreased.

REFERENCES CITED

Eaton, J.P., 1959, A portable water-tube tiltmeter: Bulletin of the Seismological Society of America, v. 39, p. 301–316.

———1962, Crustal structure and volcanism in Hawaii, *in* Macdonald, G.A., and Kuno, Hisashi, eds., The crust of the Pacific Basin: American Geophysical Union Monograph 6, p. 13–29.

Eaton, J.P., and Fraser, G.D., 1958, Hawaiian Volcano Observatory Summary 9, January-March, 1958: U.S. Geological Survey, 8 p.

Eaton, J.P., and Murata, K.J., 1960, How volcanoes grow: Science, v. 132, p. 925–938.

Gerlach, T.M., and Graeber, E.S. 1985, The volatile budget of Kilauea volcano: Nature, v. 313, p. 273–277.

Jaggar, T.A., and Finch, R.H., 1929, Tilt records for thirteen years at the Hawaiian Volcano Observatory: Bulletin of the Seismological Society of America, v. 19, p. 38–50.

Macdonald, G.A., and Eaton, J.P., 1957, Hawaiian Volcanoes during 1954: U.S. Geological Survey Bulletin 1061-B, p. 1–72.

Mogi, K., 1958, Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them: Bulletin of the Earthquake Research Institute, Tokyo University, v. 36, p. 99–134.

Powers, H.A., 1946, Reanalyzing tilt records at the Hawaiian Volcano Observatory: Volcano Letter 492, p. 1–3.

———1947, Annual tilt pattern at the Hawaiian Volcano Observatory: Volcano Letter 495, p. 1–5.

Richter, D.H., Eaton, J.P., Murata, K.J., Ault, W.U., and Krivoy, H.L., 1970, Chronological narrative of the 1959–60 eruption of Kilauea Volcano, Hawaii: U.S. Geological Survey Professional Paper 537-E, p. E1–E73.