THE PUU OO ERUPTION OF KILAUEA VOLCANO, EPISODES 1–20, JANUARY 3, 1983, TO JUNE 8, 1984

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ABSTRACT

The Puu Oo eruption began at Napau Crater in the east rift zone of Kilauea Volcano on January 3, 1983. After an initial series of intermittent fissure eruptions, the style changed to one of episodic central-vent eruptions. By early June 1984, 20 eruptive episodes had occurred, including the initial fissure-eruption episode, and approximately 240×10^6 m^3 of new basalt covered an area of more than 30 km^2. Fountains ranging up to nearly 400 m high built large cones at the central vents.

The eruption occurred in a part of the rift zone that had a long history as a locus for intrusions. Tilt changes and flurries of shallow earthquakes recorded accumulation of magma from 1978 through 1980 and again in late 1982. We interpret geodetic and seismic evidence to indicate a shallow magma reservoir in the area before emplacement of the feeder dike in early January 1983. Lava erupted during the first several months was differentiated beyond olivine control and was apparently derived from magma that had undergone prolonged storage and crystal fractionation in the rift zone.

The central-vent eruptive episodes, which began in February 1983 with episode 2, lasted from 9 hours to 12 days. They were characterized by high-volume discharge of lava, vigorous fountaining, rapid summit subsidence, and strong harmonic tremor in the vent area. The repose periods lasted from 8 to 65 days and were characterized by gradual reinflation of Kilauea's summit and persistence of weak harmonic tremor in the vent area. Alternating inflation and deflation in the summit and vent areas occurred sympathetically, suggesting that reservoirs in the rift zone and summit area were hydraulically linked.

After the initial episode, lava was erupted at an average rate of 13.4×10^6 m^3/mo. Long-term tilt change in the summit region was minimal, and, following the approach of Swanson (1972), we have calculated an average magma-supply rate of approximately 10×10^6 m^3/mo after correction for 25 percent porosity. This rate is higher than some estimates for long-term supply to the volcano, but evidence from SO_2-emission rates in the summit region also indicates that the Puu Oo eruption may have coincided with a period of increased magma supply.

After Puu Oo became established as the sole vent, olivine-controlled lava was erupted. Beneath Puu Oo, a column of magma, which may have been nearly vertical and several kilometers long, underwent short-term compositional changes during repose periods that apparently reflected fractionation of olivine. This process repeatedly produced a finite volume of MgO-depleted magma, which would be exhausted whenever the volume of the next eruptive episode exceeded that of MgO-depleted melt. A long-term compositional change manifested by gradually increasing CaO and MgO may have been a consequence either of gradually decreasing contamination of fresh summit melt by differentiated magma present in the rift zone or of gradually changing composition of the melt generated in the mantle.

INTRODUCTION

The Puu Oo eruption began at Napau Crater in the east rift zone of Kilauea Volcano (fig. 17.1) on January 3, 1983. An initial series of intermittent fissure eruptions was followed by a long and continuing series of central-vent eruptions. In the 17-month period reviewed in this paper, twenty major eruptive episodes occurred. Because it is difficult to maintain terminology that is both concise and consistent, for eruptive activity, we apply the term eruption both collectively to the entire series of related eruptive events in the east rift zone during 1983–84 and singly to individual periods of significant lava discharge within that series. Following the usage of Swanson and others (1979), we use the term episode to identify occurrences of fountaining and lava-flow production separated by relatively long quiescent periods during which Kilauea's summit reservoir inflated. Many of the eruptive episodes consisted of single fountaining and flow-production events. Others, however, such as episodes 1, 13, and 19, consisted of two or more such events separated by relatively brief quiescent periods. Thus, some of the episodes were, themselves, series of episodic events.

During those 17 months of activity, nearly 240×10^6 m^3 of basalt was erupted, covering more than 30 km^2 of largely forested country in the middle part of the rift zone and the adjacent part of the south flank of the volcano. Several flows entered sparsely populated areas and destroyed a total of 18 dwellings. Spatter falling from fountains that ranged up to nearly 400 m in height built large cones at the central vents. A 60-m-high cone, Puu Halulu, was formed within the first three months of the eruption; by the end of the twentieth episode, Puu Oo, the cone at the principal vent, stood about 130 m above the preeruption ground surface. At the time of writing (June 1985), the Puu Oo eruption continues unabated and has become the most voluminous historical eruption of Kilauea.

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Observational, instrumental, and laboratory results from the first one and one-half years of the Puu Oo eruption are presented in detail in separate papers covering geologic observations (Wolfe and others, in press), data on temperature and composition of sampled lavas (Neal and others, in press), gas studies (Greenland, in press; Greenland and others, in press), seismology (Koyanagi and others, in press), deformation studies (Okamura and others, in press), geoelectric studies (Jackson, in press), and petrology (Garcia and Wolfe, in press). Those papers provide a detailed foundation for this synthesis, and we refer the reader to them for details of topics treated here in summary fashion. Hereinafter, we draw on those papers extensively without further citation except as needed for clarity.

ACKNOWLEDGMENTS

In monitoring this long-lived eruption and organizing and analyzing the data, we received intensive and dedicated help from many associates. We especially thank geologic colleagues N.G. Banks, J. Buchanan-Banks, J.P. Lockwood, R.B. Moore, and G.E. Ulrich, who often joined or relieved us in observing eruptive activity and sampling the lavas. We also thank the staff of the Hawaiian Volcano Observatory for excellent and sustained support in all aspects of the work. John P. Hoffmann called our attention to the relation, illustrated in figure 17.27, between changes in effusion and changes in tilt rate during episode 19. Constructive reviews by T.L. Wright and D.A. Swanson are gratefully acknowledged.

GEOLOGIC SETTING FOR THE PUU OO ERUPTION

STRUCTURE AND MAGMATIC PLUMBING OF KILAUEA

A consistent generalized model of the geologic structure and magmatic plumbing of Kilauea Volcano has been developed from geologic and geophysical studies, particularly over the last three decades. This model has been recently reviewed and expanded by Ryan and others (1981, 1983), and additional recent reviews are given by Duffield and others (1982) and Dzurisin and others (1984). A brief summary of the model follows.

Basaltic magma generated at a probable depth of 60–90 km (Wright, 1984) rises through a system of fractures from deep in the mantle below Kilauea and accumulates within a relatively aseismic reservoir zone (Koyanagi and others, 1974) that lies approximately 2–6 km below the southern part of Kilauea caldera. Most likely the reservoir is a complex of interconnected sills and dikes. Continuing accumulation of magma causes inflation of the reservoir, which is manifested by uplift and distention of the crust that overlies it. Episodic relief from the magmatic stress that develops during filling of the reservoir is provided by summit eruptions and by intrusions that transfer magma from the summit to the rift zones of the volcano. During rift-zone intrusions and eruptions, subsidence and contraction occur in the crust overlying the reservoir; subsidence does not necessarily accompany summit eruptions. Inflations and deflations of the summit reservoir cause measurable tilts on the flanks of the zone of uplift or subsidence. The east-west component of such ground tilt, measured with a sensitivity better than 1 microradian by a continuously recording Hg-capacitance tiltmeter at the Uwekahuna vault (fig. 17.1), approximately 3 km northwest of the center of uplift and subsidence, is used to track the episodes of inflation and deflation. The frequency of shallow earthquakes in the vicinity of the summit reservoir also provides a continuous record of strain manifested as adjustments in the brittle country rock during eposides of inflation and deflation.

Intrusions into a rift zone are commonly accompanied by harmonic tremor and by swarms of shallow (depth <5 km) earthquakes that reflect fracturing of brittle rocks in response to dike emplacement or to volume changes in the magmatic conduit. Dike emplacement is commonly accompanied by ground cracking, extension perpendicular to the rift-zone axis, and vertically directed displacement above and flanking the dike (Pollard and others, 1983). Propagation of a dike to the surface results in an eruption. The close association of subsidence at the summit with intrusion in the rift zone implies a hydraulic link between the summit and the rift zone.

In some cases, either an aseismic zone separates the area of rift intrusion from the summit-reservoir region, or an intrusion occurs without generating an earthquake swarm in the rift zone. In the latter case, the intrusion is manifested by subsidence and related shallow earthquakes at the summit, geodetic and possibly electrical potential-field disturbances in the rift zone, and harmonic tremor. Aseismic transfers of magma, which are common, imply the presence of a preexisting magmatic conduit (Swanson and others, 1976b).

Kilauea abuts the seaward-sloping southeast flank of Mauna Loa, a much larger shield volcano that forms a massive buttress on Kilauea's northwest flank. Kilauea's summit is approximately 5 km above the adjacent sea floor, and its unbuttressed southeast flank is gravitationally unstable. Fiske and Jackson (1972) showed that this geometric arrangement results in orientation of the axis of least compressive stress perpendicular to the boundary between Mauna Loa and Kilauea. Consequently, extension and dike emplacement occur along two steeply dipping zones (the east and southwest rift zones) that approximately parallel the Kilauea-Mauna Loa boundary.

Repeated intrusion, extension, surface cracking, and extrusion have created, in each of the rift zones, a broad, gentle topographic ridge with numerous open cracks, normal faults of small throw, and linear vents, all aligned perpendicular to the direction of least compressive stress. The upper few kilometers of a rift zone must be laced by a complex of dikes that strike parallel to the rift-zone axis. The currently active part of the rift zone, as indicated by the distribution of historical (the last 200 yr) eruptive vents (Holcomb, 1980) is as much as about 2 km wide.

Geophysical evidence, including recognition of local inflation centers (see, for example, Jackson and others, 1975) and the occurrence of aseismic intrusions, indicates that magma persists along at least parts of the rift-zone interior for extended periods of time. This inference is supported by petrologic evidence, which

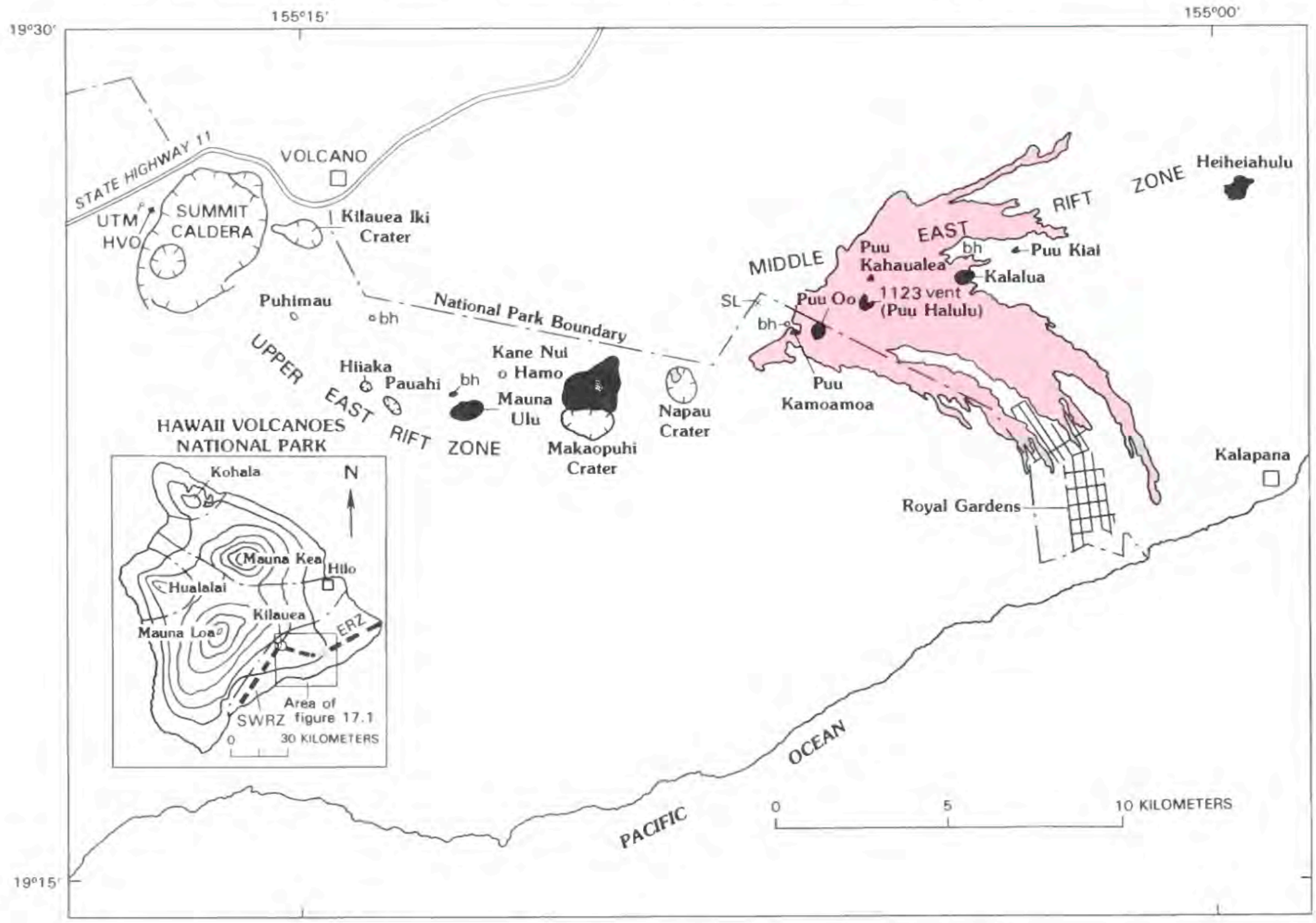


FIGURE 17.1.—Kilauea summit, upper and middle parts of east rift zone, and features discussed in text. HVO, Hawaiian Volcano Observatory; UTM, Uwekahuna tiltmeter; bh, borehole tiltmeter; SL, spirit-level tilt station. Red, flows of episodes 1–20, Puu Oo eruption. Black, shields and large cinder and spatter cones; all except Puu Oo and Puu Halulu predate the Puu Oo eruption. Inset shows location of area and outlines of volcanoes on Island of Hawaii. ERZ, east rift zone of Kilauea; SWRZ, southwest rift zone of Kilauea.

shows that melt of differentiated composition has been a significant component of rift-zone eruptions. Wright and Fiske (1971) have interpreted the differentiated melt as the product of cooling and partial crystallization of magma intruded into the rift zones from the summit region. Furthermore, geologic mapping in the lower east rift zone (Moore, 1983) has revealed areas where repeated eruption of differentiated melt has occurred, implying that local zones favorable to storage of intruded magma have persisted for hundreds of years.

Kilauea's seaward flank, generally called the south flank, is detached from the rest of the volcano along the rift zones, and it undergoes compression and seaward dislocation in response to intrusive activity in the rift zones (Swanson and others, 1976a). The approximate base of the mobile block is recorded by a zone of earthquake hypocenters, 8–9 km deep, that forms a belt parallel to the rift-zone axis but displaced southeastward from it (see fig. 17.8). Focal mechanisms indicate that fault movements occur parallel to a plane dipping 2–3° northwestward (Crosson and Endo, 1982); this subhorizontal zone of decoupling may correspond to a sediment-bearing layer at the interface between the young volcanic rocks that comprise the Island of Hawaii and the isostatically downbowed older sea floor beneath the island (Swanson and others, 1976a; Crosson and Endo, 1982).

The magma supplied to Kilauea from the mantle, then, is accommodated in summit storage, summit and rift-zone eruptions, and rift-zone intrusions. Growth of the volcano results primarily from addition of erupted basalt to its surface and from intrusion accompanied by seaward dislocation of the south flank. Dzurisin and others (1984) concluded that between 1956 and 1983 more than $2 \times 10^9\,m^3$ of magma had entered Kilauea, at an average rate of about $7 \times 10^6\,m^3/mo$. Approximately 35 percent of this magma was extruded during that period; the rest was stored in the rift zones, 55 percent in the east rift zone and 10 percent in the southwest rift zone. Apparently the summit reservoir has functioned in recent years, at least, mainly as a temporary holding tank.

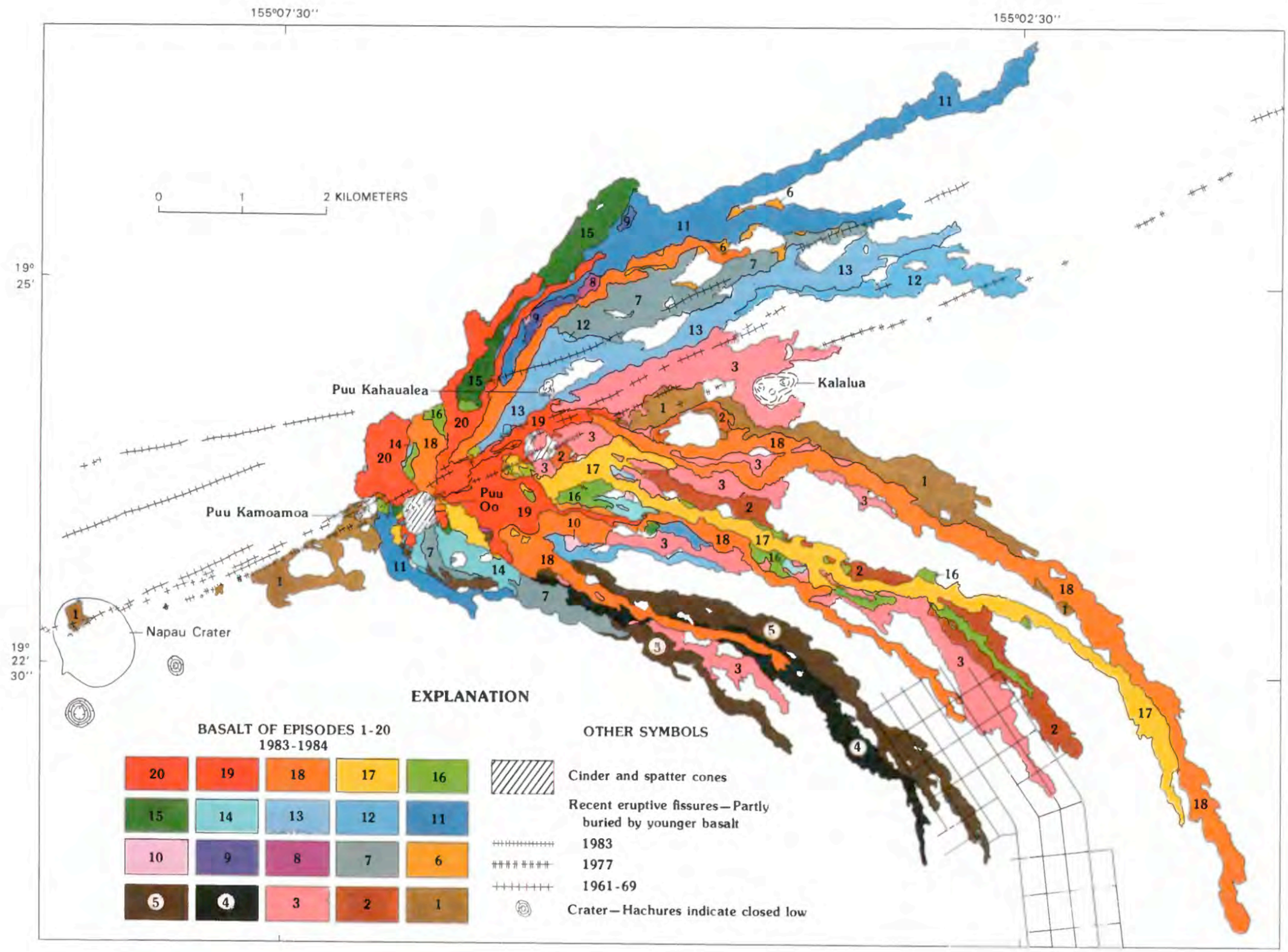


FIGURE 17.2.—Simplified geologic map of vents and flows for episodes 1–20 of the Puu Oo eruption. Also shows traces of recent pre-1983 fissure vents, which include 1977 vents (Moore and others, 1980; R.B. Moore, written commun., 1985) and 1961-69 vents (Moore and Koyanagi, 1969; Swanson and others, 1976b; Swanson and others, 1979). Flows were mapped and field checked using aerial photographs taken, when possible, after each eruptive episode.

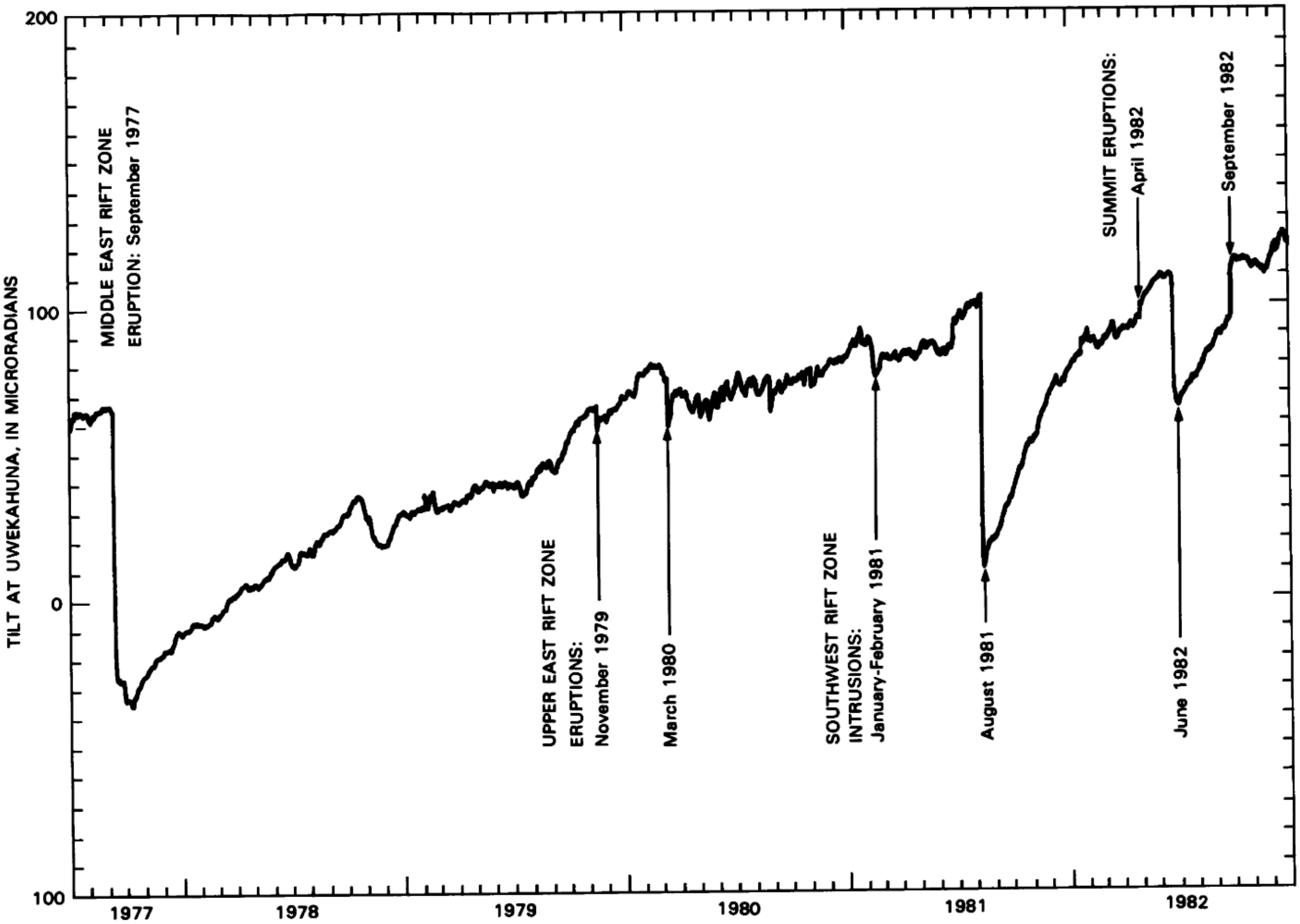


FIGURE 17.3.—East-west summit tilt at Uwekahuna, late 1977 to end of 1982. Increasing values indicate westward-directed (inflationary) tilt change; decreasing values indicate eastward-directed (deflationary) tilt change.

RECENT ACTIVITY IN THE EAST RIFT ZONE, 1955–1982

Eruptions occurred along the lower east rift zone of Kilauea in 1955 and 1960, following a virtual hiatus of 115 years (Macdonald and others, 1983). Thereafter, eruptive activity was confined to the upper and middle parts of the east rift zone. Since 1960, the frequency of earthquake occurrence has been low in the lower east rift and in the adjacent part of the volcano's south flank. Much higher seismicity, in both the rift zone and the south flank, west of the longitude of Heiheiahulu (fig. 17.1) indicates that post-1960 intrusive activity in the east rift zone has been confined to the upper and middle parts.

Fissure eruptions occurred repeatedly in the middle east rift zone from 1961 through 1969 (fig. 17.2). From 1969 through 1974, the two upper-east-rift eruptions at Mauna Ulu (Tilling and others, chapter 16; Swanson and others, 1979) dominated activity at Kilauea. Seaward displacement of Kilauea's south flank and consequent dilation of the rift zone during and after the large ($M = 7.2$) Kalapana earthquake on November 29, 1975, apparently changed the conduit system so that thereafter intrusions dominated rather than eruptions (Dzurisin and others, 1980). Dzurisin and others (1984) identified nine small but distinct intrusions that occurred in the east rift zone from 1976 through 1980. During that period, two minor eruptions (fig. 17.3) occurred in the upper part of the east rift zone, and a relatively voluminous ($35 \times 10^6 m^3$) eruption (Moore and others, 1980) occurred in the middle part (figs. 17.2 and 17.3) in September 1977.

The intrusions in the middle east rift zone were documented in part by tilt measurements. Except where covered by new flows, the middle east rift zone is heavily forested, access is difficult, and deformation data are limited. During the years between the later (1972–74) Mauna Ulu eruption and the 1977 eruption, spirit-level tilt stations in the east rift zone were largely limited to the upper part of the zone and to the part from Heiheiahulu eastward. In that eastern area, tilt measurements in early and mid-1977 showed a middle-east-rift inflation center near Heiheiahulu (Dzurisin and others, 1980). We do not know how far uprift the inflation extended. Following the 1977 eruption and through 1980, an expanded

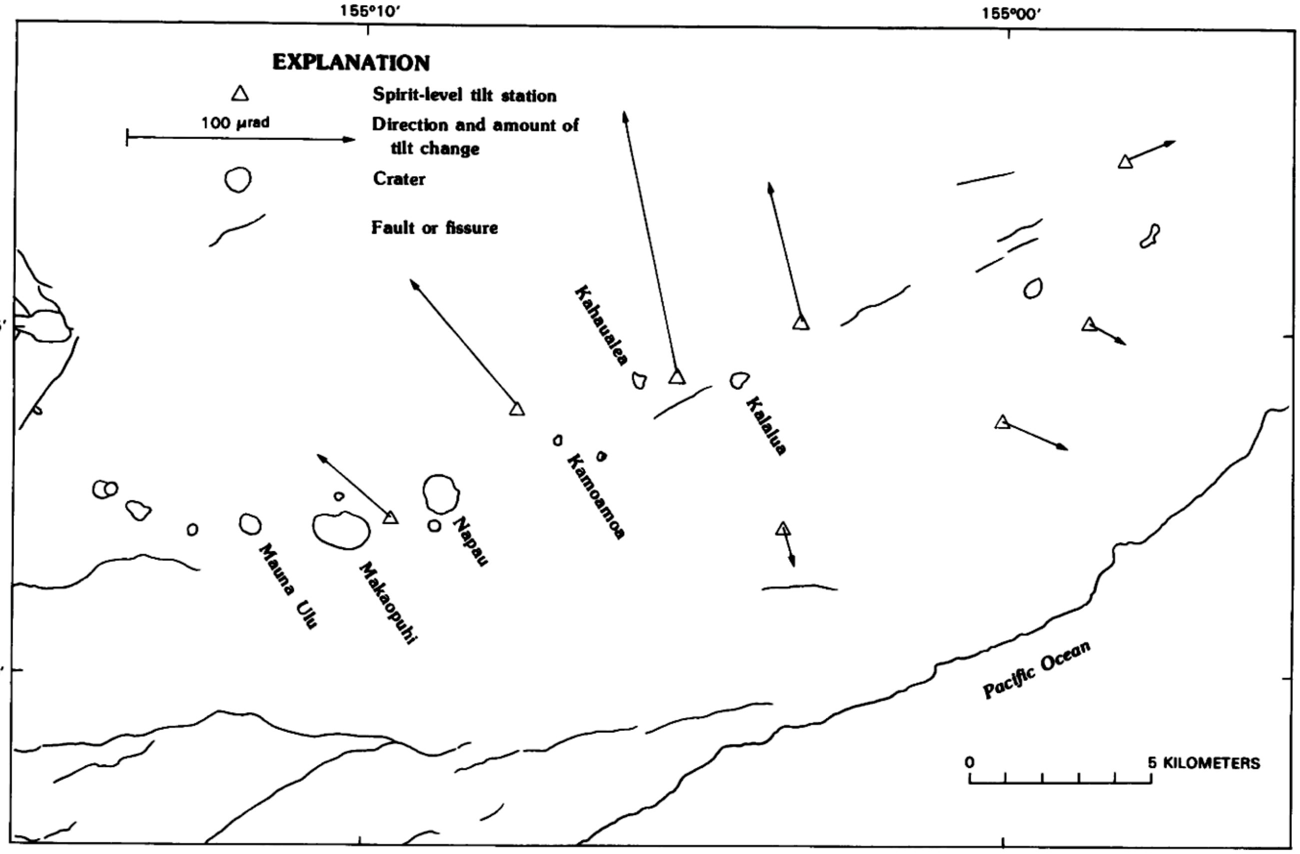


FIGURE 17.4.—Spirit-level tilt results, middle east rift zone, Kilauea Volcano, January 1978 through March 1981.

network of spirit-level tilt stations showed a broad inflationary zone approximately centered on the Puu Kamoamoa-Kalalua area (fig. 17.4).

Intermittent flurries of shallow earthquakes were recorded in the Puu Kamoamoa-Puu Kahaualea region between late 1978 and late 1980 (figs. 17.5*A*, 17.6). The flurries often occurred during or near the ends of episodes of gradual summit deflation. They may identify intrusive pulses that added magma to storage in the middle east rift zone as reflected by the increasing tumescence (fig. 17.4).

Intrusions into the east rift zone virtually ceased early in 1981 at the beginning of a series of southwest-rift-zone intrusions that continued intermittently through June 1982 (figs. 17.3, 17.5*B*). In addition to the seismic quiescence in the east rift zone during that time, there was an almost total absence of deformation, as shown by the borehole tiltmeter near Puu Kamoamoa (fig. 17.1), between early 1981 and late 1982.

Between 1956 and 1983, therefore, at least $1 \times 10^9 m^3$ of magma was added to east-rift-zone storage, according to the calculations of Dzurisin and others (1984). Earthquake distribution patterns indicate that magma accumulated only in the upper and middle parts of the rift zone after the eruption of 1960. Tilt measurements begun in the middle east rift zone after the 1975 Kalapana earthquake show that it was inflating through 1980 and was thus a major locus of magma storage. Magma reservoirs apparently became engorged, and the middle east rift zone became primed for the eruptive activity that began in 1983. The distribution of earthquake epicenters between late 1978 and late 1980 (fig. 17.5*A*) further indicates that intermittent intrusions were adding magma to a reservoir near the future main vents for the Puu Oo eruption.

IMMEDIATE PRECURSORS TO THE PUU OO ERUPTION

After a major intrusion in the southwest rift zone in August 1981, fairly sustained inflation of Kilauea's summit prevailed until late September 1982. A small summit eruption on April 30–May 1, 1982, and a second large southwest-rift intrusion in June 1982 punctuated the inflationary episode. An abrupt intrusion in the already inflated summit region on September 25 caused pronounced uplift (fig. 17.3) and led to a minor eruption in the southernmost part of Kilauea caldera. During the eruption and immediately following it, a swarm of shallow earthquakes migrated into the uppermost part of the east rift zone in the vicinity of Puhimau Crater (fig. 17.5C), and concomitant geoelectrical disturbances were measured in that area and also 4 km farther southeast near Pauahi Crater. However, no measurable surface deformation was detected at that time in the upper east rift, which suggests that no shallow dike was emplaced. Therefore, we infer that a surge of supply within the upper east-rift-zone conduit system led to fracturing of the shallow crustal rocks and development of an electrical anomaly.

Shallow earthquakes continued in the area between Puhimau and Pauahi Craters through early November, but with diminishing frequency after mid-October. A slow tilt change recorded by automatic tiltmeters along the upper east rift zone began on October 6, together with changes in self-potential near Pauahi. These events, which continued until about the end of the month, indicated that a gradual intrusion was under way in the upper east rift zone. Beginning about October 8, additional shallow earthquakes migrated from the upper east rift zone downrift as far as the Napau Crater area, where intermittent shallow earthquakes occurred in late October and early November (fig. 17.7). A gradual tilt change at the automatic tiltmeter near Puu Kamoamoa, beyond the downrift end of the flurry of earthquakes, began on November 8 and continued until about the middle of the month, indicating renewed accumulation of magma in the middle east rift zone.

A second intense earthquake swarm occurred in the upper east rift zone on December 9 and 10, 1982. Geoelectric response to this event was indistinct. However, a 70-mm subsidence northwest of Puhimau Crater, detected by leveling, may have been a response to emplacement of a dike within 2 km of the surface sometime between October 29 and December 9. As in the previous earthquake swarm, the shallow hypocenters once again migrated downrift to the vicinity of Napau Crater (fig. 17.7), where seismic activity continued through the end of the month. No tiltmeter disturbances occurred during early December in the upper east rift zone or near Puu Kamoamoa, but gradual tilt changes in the upper east rift and at Puu Kamoamoa began in both areas on December 20 and continued to the end of the year. The inferred intrusions during the last quarter of 1982 apparently reactivated the upper- and middle-east-rift-zone conduit system and set the stage for the Puu Oo eruption.

EMPLACEMENT OF THE FEEDER DIKE AND FISSURE ERUPTIONS OF THE FIRST EPISODE

The premonitory seismic swarm, accompanied by weak harmonic tremor, began about 1 km west of Makaopuhi Crater (fig. 17.8) at approximately 0030 (H.s.t.) January 2, 1983. When compared to the late-December seismicity, the swarm appears as an intensification of the already established earthquake pattern (fig. 17.9). However, tiltmeters located 2–4 km uprift near Mauna Ulu and Puhimau showed tilt changes virtually coincident with the onset of the swarm. Neither shallow earthquakes nor electrical changes occurred uprift in conjunction with the tiltmeter disturbances. Thus, the swarm was apparently initiated in response to a new surge of magma through melt-filled passages in which a pressure change could be transmitted rapidly and easily. An hour after the beginning of the swarm, the Uwekahuna tiltmeter began to register subsidence of the summit of Kilauea (fig. 17.10).

The located earthquakes of the swarm, mostly 2–4 km deep, formed a narrow band, 1–2 km wide, that apparently recorded magma intrusion in the form of a dike. The swarm elongated northeastward as its tip migrated downrift at a rate of approximately 0.7 km/h (fig. 17.11). The northeast end of the swarm had extended downrift nearly to Napau Crater by about 0400 January 2. Characterized by a sharply defined leading edge, the swarm continued downrift toward Puu Kamoamoa until about 0600. From then until the onset of eruptive activity early the next morning, the swarm lost its distinct leading edge (fig. 17.11) and was largely localized between Napau Crater and Puu Kamoamoa.

Surface deformation caused by the northeastward-migrating dike was detected by tiltmeters in the rift zone near both Puu Kamomoa and Kalalua while the earthquake swarm was still between Napau and Puu Kamoamoa. At 0430 January 2, the Puu Kamoamoa instrument, located north of the rift axis, started to detect a southeastward tilt of the ground, and two hours later, at 0630, the instrument north of Kalalua responded to a southward tilt. At 1030 at Puu Kamoamoa, the east-west tilt component, which was nearly parallel to the strike of the dike and thus more sensitive to passage of the dike tip (Maruyama, 1964), reversed direction from east down to west down; this reversal probably indicated the passing of the dike tip. In 10 hours, the dike tip had migrated slightly more than 7 km from the assumed starting point near Makaopuhi Crater. The migration rate based on the tilt reversal at the Puu Kamoamoa station, 0.7 km/h, agrees with the rate of downrift migration of the earthquake swarm.

The vertical surface-displacement field caused by the dike tip is expected to migrate downrift ahead of the tip, but the two should travel at the same rate (Maruyama, 1964), 0.7 km/h in this case. The initial tiltmeter disturbance at Kalalua, however, occurred at 0630, only 2 hours after that at Puu Kamoamoa, 5.4 km uprift, and nearly 6 hours earlier than predicted by downrift migration at 0.7 km/h.

This anomalous early arrival could have resulted from passage of a hydraulically induced surge of magma when the dike tip encountered another magma body. If that was the case, the migration of the pressure-induced surge from the dike tip to Kalalua may have been nearly instantaneous. At 0630, when the Kalalua tiltmeter first recorded movement, the dike tip should have been 4.2 km (0.7 km/h times 6 h) from the point of origin of the earthquake swarm. Thus it would have been between Napau Crater and Puu Kamoamoa, in the area where the leading edge of the swarm lost its definition (fig. 17.11).

About 20 hours after passage of the leading edge of the earthquake swarm, lava fountaining began at Napau Crater at 0031 January 3. The initial outbreak continued for 9.5 hours; it produced a 6-km-long, discontinuous line of erupting fissures that extended progressively downrift from Napau Crater and reached its temporary eastern limit, south of Puu Kahaualea, at 0740 (fig. 17.12). The overall migration of the vent system was downrift (fig. 17.13), but the sequence of vent opening was complicated in detail; at times, new vents opened uprift of already active ones. The sequence of

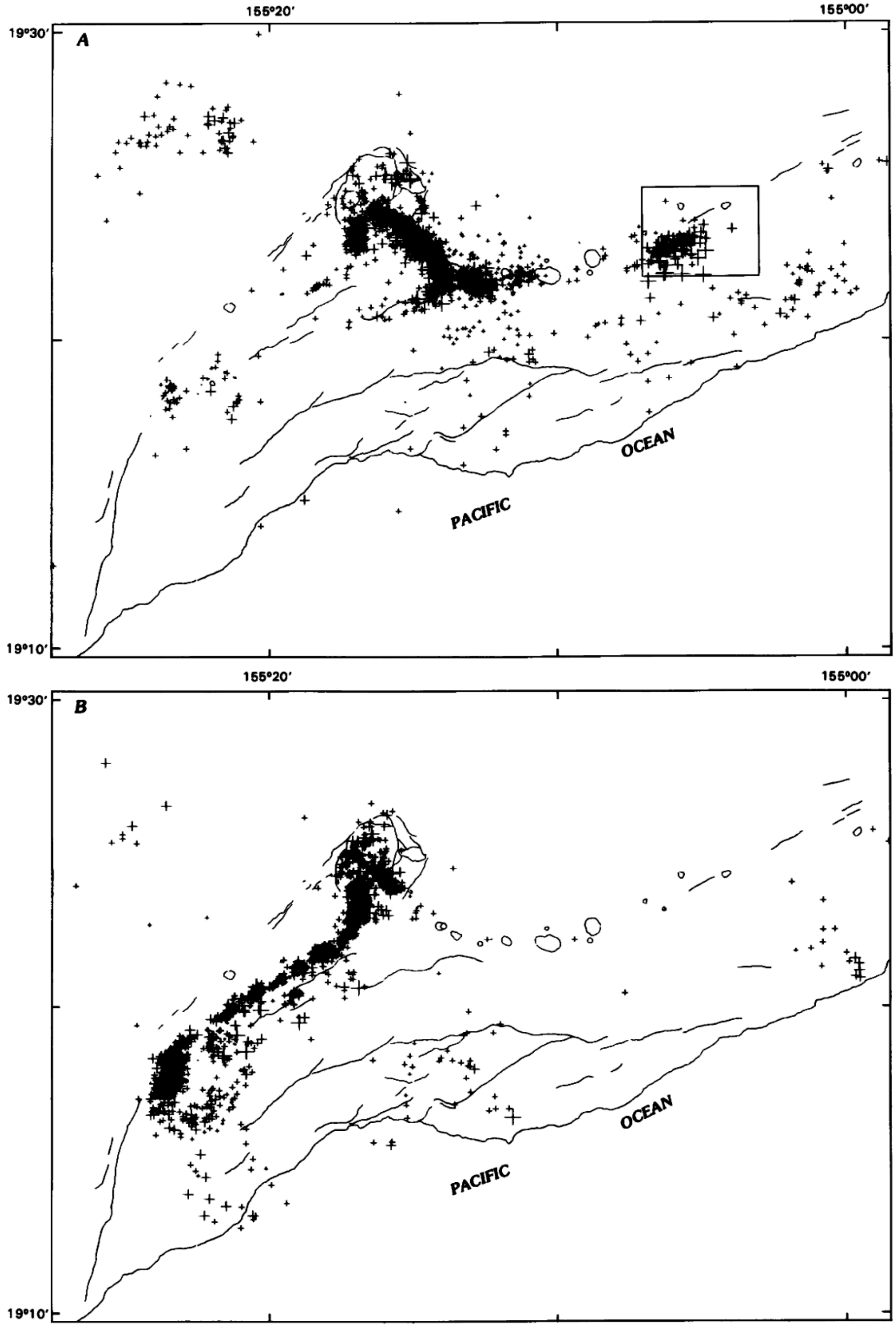


FIGURE 17.5.—Located shallow (<5-km depth) earthquakes at Kilauea from November 1978 through December 1982. ***A***, November 1978 through December 1980. Box shows location of earthquakes plotted in figure 17.6. ***B***, January 1981 through September 24, 1982. ***C***, September 25, 1982, through December 1982.

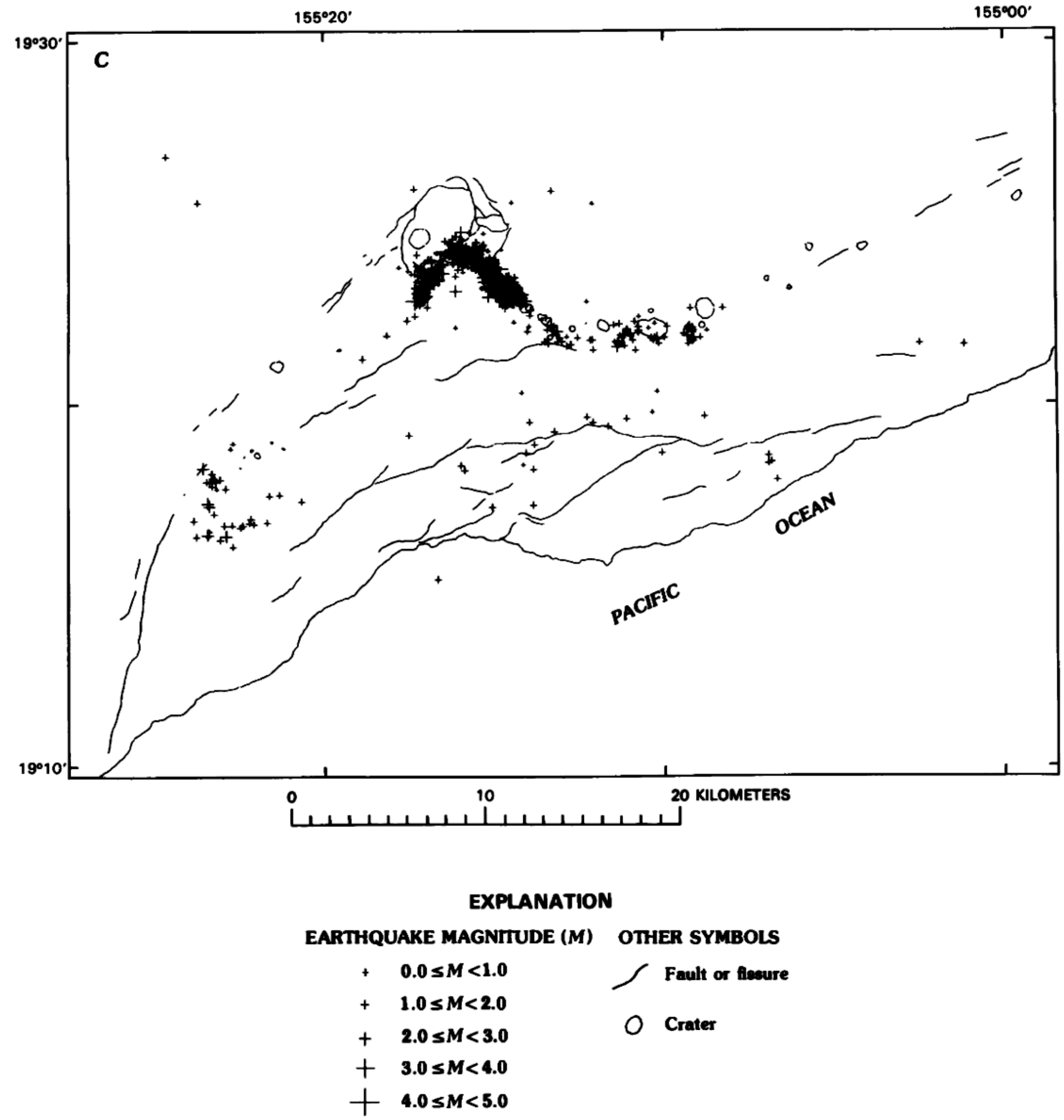


FIGURE 17.5.—Continued.

termination of eruption was also complex. The last vents to shut down, at 1000 that morning, were those at the middle of the fissure system, near Puu Kamoamoa.

Except for brief fountaining later that afternoon of the easternmost vent, which had opened at 0740, the initial outbreak was over; no further eruption occurred for approximately 2 days. Rapid subsidence of the summit stopped abruptly when extrusion stopped at 1000 January 3, and the summit reinflated until late on January 4, at which time subsidence resumed (fig. 17.10). During the respite in eruption from January 3 to January 5, shallow seismicity was distributed in a zone that extended nearly from Napau Crater to Kalalua (fig. 17.11).

Fountaining resumed at 1123 January 5, and nearly continuous fissure eruptions occurred alternately or sometimes simultaneously through January 5 and 6 at this 1123 vent, the previously active 0740 vent, and a third nearby vent that opened at 1708 January 5. Intermittent minor fissure eruptions also occurred during this period in the vicinity of Puu Kamoamoa.

Extension manifested by ground-cracking occurred on January 5 and 6 along zones that flanked the 0740-1123-1708 vent alignment (fig. 17.12). An estimated $0.5 \times 10^6\,m^3$ of lava poured into an open crack south of the 0740 vent. On strike with the open crack, widening of 2–3 m occurred on cracks cutting a flow that was emplaced sometime on January 5–6; flows erupted on January 8–9

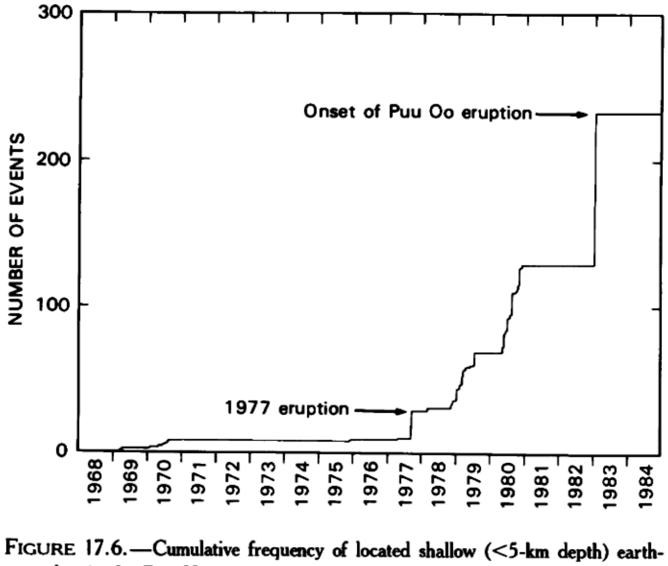


FIGURE 17.6.—Cumulative frequency of located shallow (<5-km depth) earthquakes in the Puu Kamoamoa-Puu Kahaualea area, 1978 through 1982. See figure 17.5*A* for location.

buried the cracks and showed no subsequent displacement.

Shallow earthquakes, sufficiently large to be well located, persisted in the eruption area between January 2 and 7. Early on January 7, seismicity increased markedly to form a renewed earthquake swarm near Kalalua, farther downrift than it had previously extended (fig. 17.11). Accelerated surface deformation in the same general area began during the evening of January 6 and, by midnight, had caused a large disturbance of the borehole tiltmeter about 300 m north of Kalalua. This event also perturbed the self potential in the same area. Daylight on January 7 showed the tiltmeter to be within a northeast-trending zone of new cracks that bounded a shallow graben. Immediate remeasurement of a horizontal distance across the zone of cracks north of Kalalua indicated that about 1.8 m of extension normal to the trend of the rift zone had occurred since the previous measurement on January 5 (Dvorak and others, in press; an additional 0.4 m of extension of the line was measured on January 11, after which there were no further changes). These events apparently recorded emplacement of the easternmost segment of the new dike system that had been delivering magma to the surface since January 3. Fountaining and flow production began on this segment of the dike at 1030 January 7 and continued for about 18 hours (fig. 17.13).

Forcible emplacement of a shallow dike apparently occurred near Kalalua on late January 6 and early January 7, but the effects of magmatic activity were evident earlier. An aseismic dislocation of the tiltmeter, discussed above, occurred at 0630 January 2, approximately 6 hours after the onset of the seismic swarm. Reoccupation, on the afternoon of January 3, of a self-potential measurement line crossing the rift zone near the tiltmeter showed a voltage increase, which contrasted with a previous long-term trend of generally decreasing self-potential. At the same time, production of profuse, hot, SO_2-rich fume was observed along newly lengthening cracks about 1 km east of the 0740 vent, where new vents would erupt four days later on January 7.

The earthquake swarm ended late on January 7. Thereafter, through at least the 20 eruptive episodes summarized here, no further concentrations of locatable shallow earthquakes occurred in the eruptive zone. The major subsidence of Kilauea's summit ended at about 0700 January 8. Thereafter, intermittent fissure eruptions, accompanied by sporadic minor tilt changes at the summit, occurred through January 15 at the 1123 and 1708 vents. An additional small eruption occurred near Puu Kamoamoa on January 23.

Fissure vents were dominant during the first episode of the Puu Oo eruption. They produced linear fountains as long as several hundred meters. Spatter from the fountains built low ramparts adjacent to the fissures, and thin fluid flows of pahoehoe, which changed locally to aa, normally spread near the erupting vents. A major exception occurred on January 7, when particularly intense effusion generated a fluid lava flow that rapidly moved 5.5 km down Kilauea's south flank at a rate that reached about 2 km/h. At the peak of that event, the discharge rate was greater than $1\times10^6\,m^3/h$. Normal discharge in episode 1 was much lower, usually by an order of magnitude. In approximately 99 hours of actual eruption, episode 1 produced about $14\times10^6\,m^3$ of new flows and vent deposits.

Subsidence related to the dike emplacement and the January eruptions occurred in Kilauea's summit area (fig. 17.14). The maximum vertical displacement, at least 55 cm, was in the southern part of the caldera, southeast of Halemaumau. The topographic volume loss, calculated from levelling data, was approximately $60\times10^6\,m^3$ (Dvorak and others, in press). A concentration of shallow earthquakes in the southern caldera region (fig. 17.8) recorded brittle-fracture events coincident with the subsidence.

The earthquake swarm was approximately 16 km long (fig. 17.8), and its base was about 3–4 km deep. The feeder dike intersected the ground surface along an 8-km-long part of the earthquake zone. Using an 8-km length, 2.2-m width (from the measured extension near Kalalua), and average 3.5-km distance from top to bottom, we calculate an approximate volume of $60\times10^6\,m^3$ for the dike, a value that is almost certainly an underestimate. Using the full 16-km length gives $120\times10^6\,m^3$, twice as much as the topographic volume change in the summit area and probably an overestimate because the dike did not reach the surface over the full length of the earthquake swarm.

Horizontal distance measurements over the period from January–May 1982 to September–October 1983 indicated a seaward displacement of Kalalua, with respect to reference points on Mauna Loa, of more than 3 m (Hawaiian Volcano Observatory data). During the same period, stations in the upper east rift zone and downrift at Heiheiahulu showed no movement. Stations on the south flank, near the coast, were displaced seaward approximately 0.5–1 m; maximum movement was in the same sector as the earthquake swarm and diminished to the northeast and southwest. The large disparity between the apparent displacements of Kalalua and the stations closer to the coast indicates that substantial compression of the south flank resulted from intrusion of the dike. Modeling a theoretical dike that would best account for the measured horizontal displacements, Dvorak and others (in press) found that the best fit

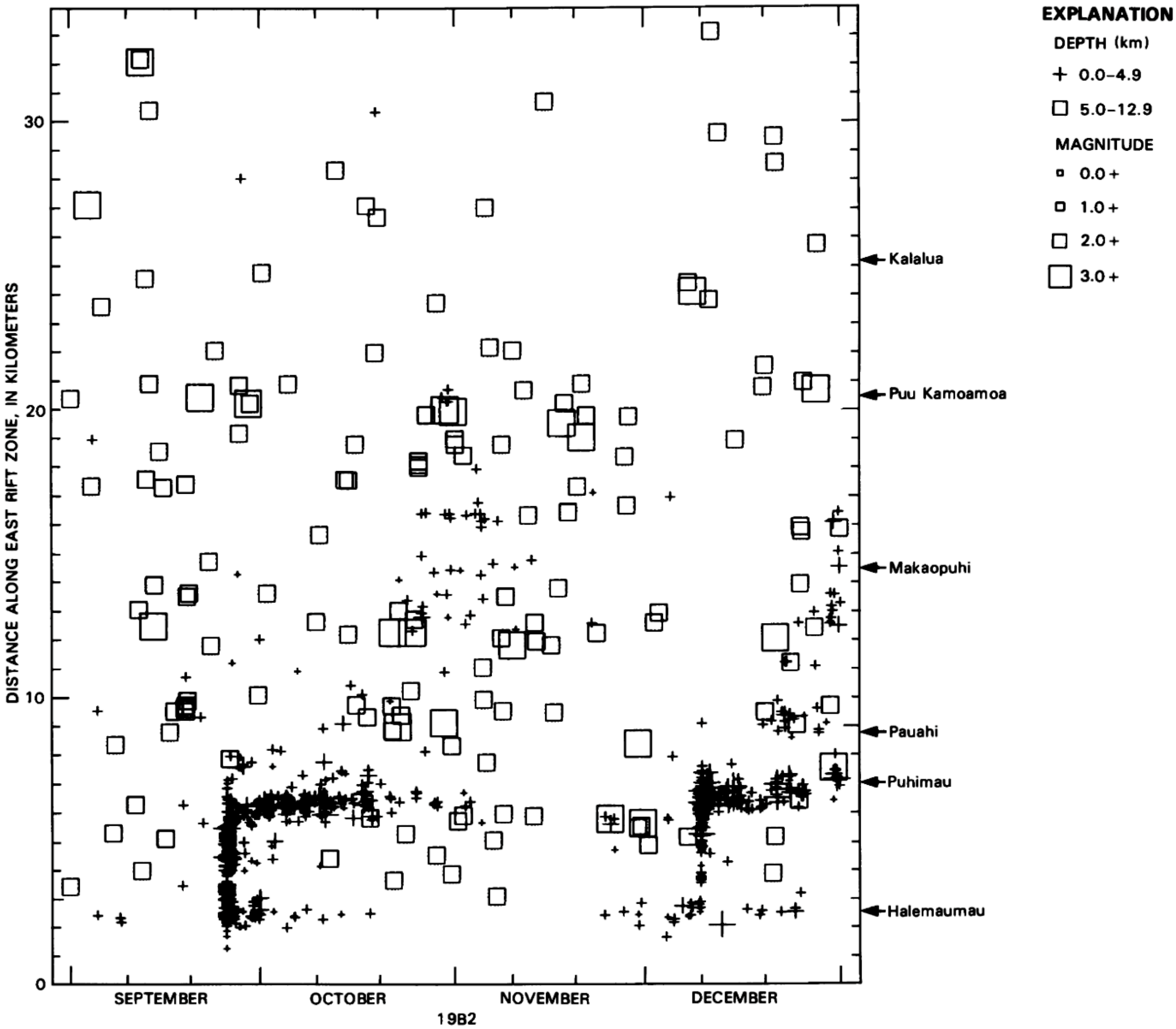


FIGURE 17.7.—Space-time diagram of earthquake epicenters in the summit, upper and middle east rift zone, and adjacent part of the south flank, Kilauea Volcano, from September through December 1982. Epicenters projected onto an east-west line.

was for a dike 11.4 km long, 2.4 km from top to bottom, and 3.6 m wide. These dimensions yield a volume of about $100 \times 10^6 m^3$, which is probably a reasonable approximation.

During the earthquake swarm, the area from Puu Kamoamoa to between Puu Kahaualea and Kalalua (fig. 17.8) showed a lower concentration of seismic activity. This area contains the major vents of the Puu Oo eruption: the 0740-1123-1708-vent complex south of Puu Kahaualea and the Puu Oo vent northeast of Puu Kamoamoa. It also coincides closely with the zone of shallow earthquake flurries that recurred repeatedly from late 1978 to late 1980 (figs. 17.5*A*, 17.6). Furthermore, the initial displacement field migrating downrift ahead of the dike tip passed through this area at a higher speed than in its passage farther uprift and produced the anomalous early tilt near Kalalua. Taken together, these data suggest that the major vents overlie a local magma reservoir established before the eruption started. The lower seismicity may record upward propagation of the dike through crust that, because of the magma reservoir, was more distended, fractured, and hotter than normal when dike emplacement occurred.

A zone of low seismicity was also found farther south in the same sector of the south flank (fig. 17.8), where it had been a persistent feature since at least the early 1960's (Hawaiian Volcano Observatory data). The quiet zone in the south flank may be related to the one in the 1983 earthquake swarm. If so, the persistence of

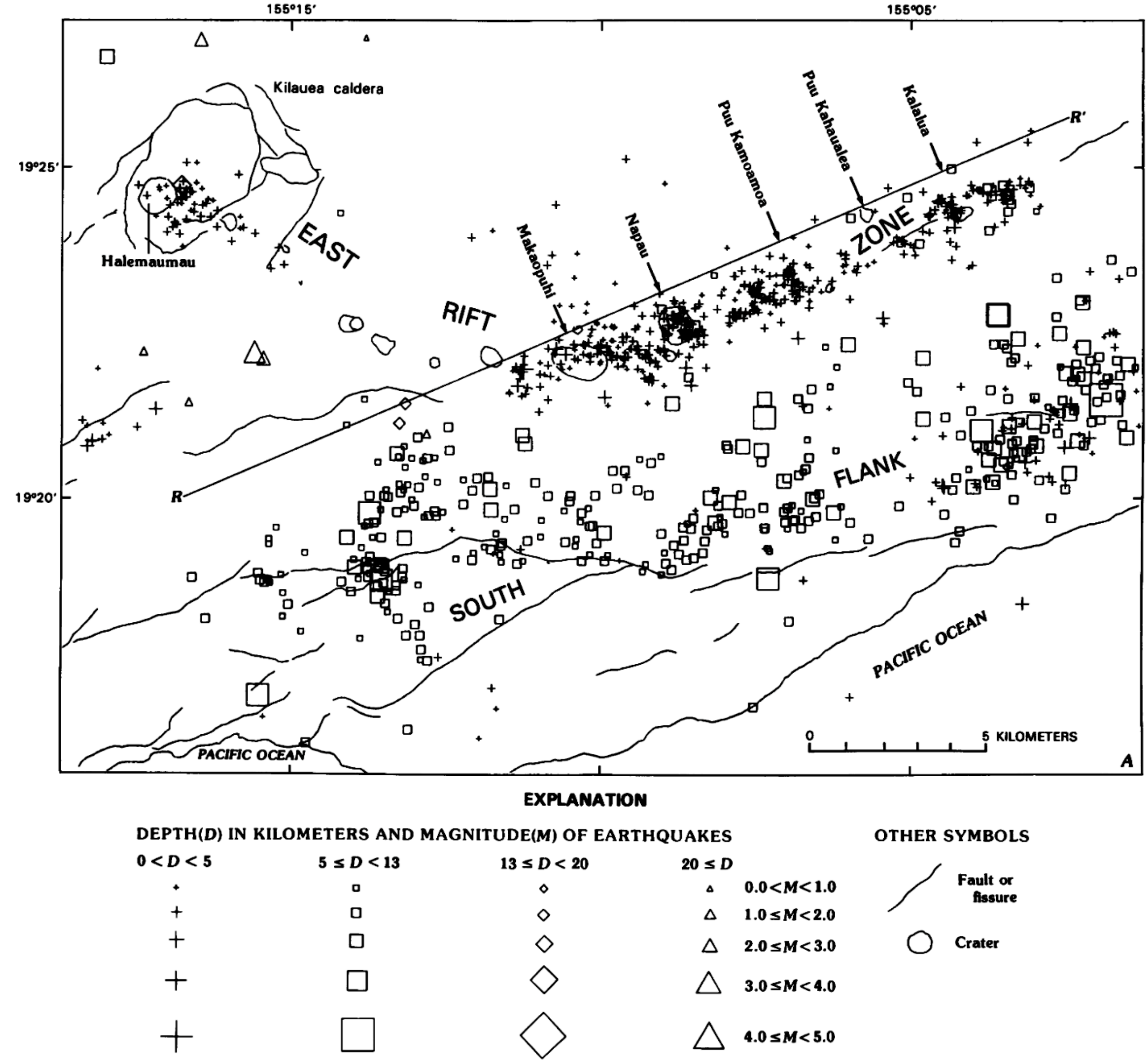


FIGURE 17.8.—Located earthquakes, January 1983, Kilauea caldera, east rift zone, and south flank. *A*, Distribution of epicenters. Cross section *R-R'* shown in figure 17.8*B*. *B*, Depth-distance distribution of hypocenters, projected onto line *R-R'*.

the south-flank feature may indicate that the Puu Kamoamoa-Puu Kahaualea area has had a magma reservoir for two decades or more. Two alternative explanations are that the south-flank seismic gap represents either a zone of aseismic slip or a locked zone that could yield abruptly to cause a large earthquake. Neither of these alternatives has a genetic or predictive relationship to the region of postulated magma storage in the rift zone.

EPISODIC CENTRAL-VENT ERUPTIONS: EPISODES 2–20

LOCATION, EPISODICITY, AND LAVA-DISCHARGE RATE

During episodes 2 and 3, the 1123 vent was the main eruptive vent, producing major flows that extended northeast within the rift

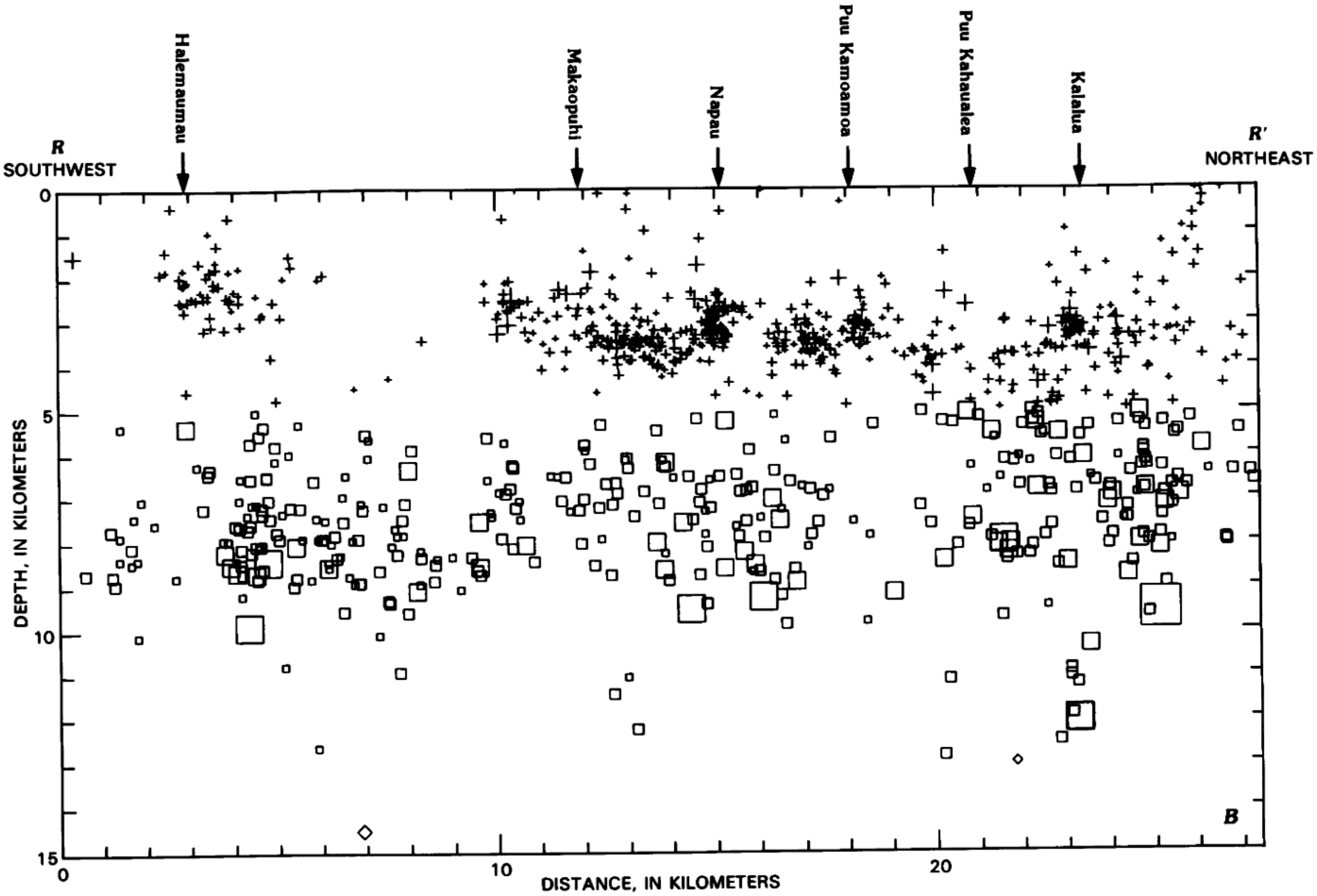


FIGURE 17.8.—Continued.

zone and southeast to the Royal Gardens subdivision (fig. 17.2). Less voluminous eruption also occurred in the area where Puu Oo would subsequently grow. Beginning with episode 4, the Puu Oo vent, supplemented on a few occasions by nearby local fissure vents, was the sole eruptive locus. During episodes 4 and 5, the major flows emerged from the south flank of Puu Oo and traveled southeast toward Royal Gardens. Thereafter, the major flows emerged from the northeast flank of Puu Oo. Many extended into dense forest north of Puu Kahaualea; others turned southeastward and advanced down the south flank toward the ocean.

An episodic pattern quickly developed (table 17.1, fig. 17.15). Eruptive episodes, which ranged in length from 9 hours to 12 days, were characterized by high-volume discharge of lava flows, vigorous fountaining, rapid summit subsidence, and strong harmonic tremor in the vent area. Repose periods, which ranged in length from 8 to 65 days, were characterized by reinflation of Kilauea's summit and weak harmonic tremor in the vent area; at times the upper surface of a magma column was evident in the conduit beneath the vent. The pattern was strikingly similar to that of the first 7 months (May–December 1969) of the 1969–71 Mauna Ulu eruption (Swanson and others, 1979). However, after 12 episodes with rapid discharge and high or sustained fountaining, the style of eruption at Mauna Ulu changed to one dominated by steady slow discharge that built the Mauna Ulu shield and transported large volumes of pahoehoe great distances from the vent through lava tubes (Tilling and others, chapter 16; Peterson and Swanson, 1974; Peterson, 1976; Swanson and others, 1979). In contrast, the episodic Puu Oo eruption has continued through episode 20 and beyond (33 episodes as of June 1985), producing one of the largest vent structures at Kilauea Volcano and creating an extraordinary complex of interleaved aa flows (fig. 17.2).

Both the duration of repose between eruptive episodes and the volume discharged during eruptive episodes varied significantly. Nevertheless, a striking regularity developed (fig. 17.16) that was particularly pronounced during episodes 4–12 and 13–17. During those two intervals, the time from the end of one eruptive episode to the end of the next varied from 9 to 31 days (from data of table 17.1) and averaged 19 ± 7 (1 standard deviation) days; erupted volumes of lava ranged from 6 to $14 \times 10^6\,m^3$ and averaged $10 \pm 3 \times 10^6$ (1 standard deviation) m^3. These intervals were times of slightly higher than normal supply of lava, averaging about $15.7 \times 10^6\,m^3/mo$. This difference is due largely to abnormally

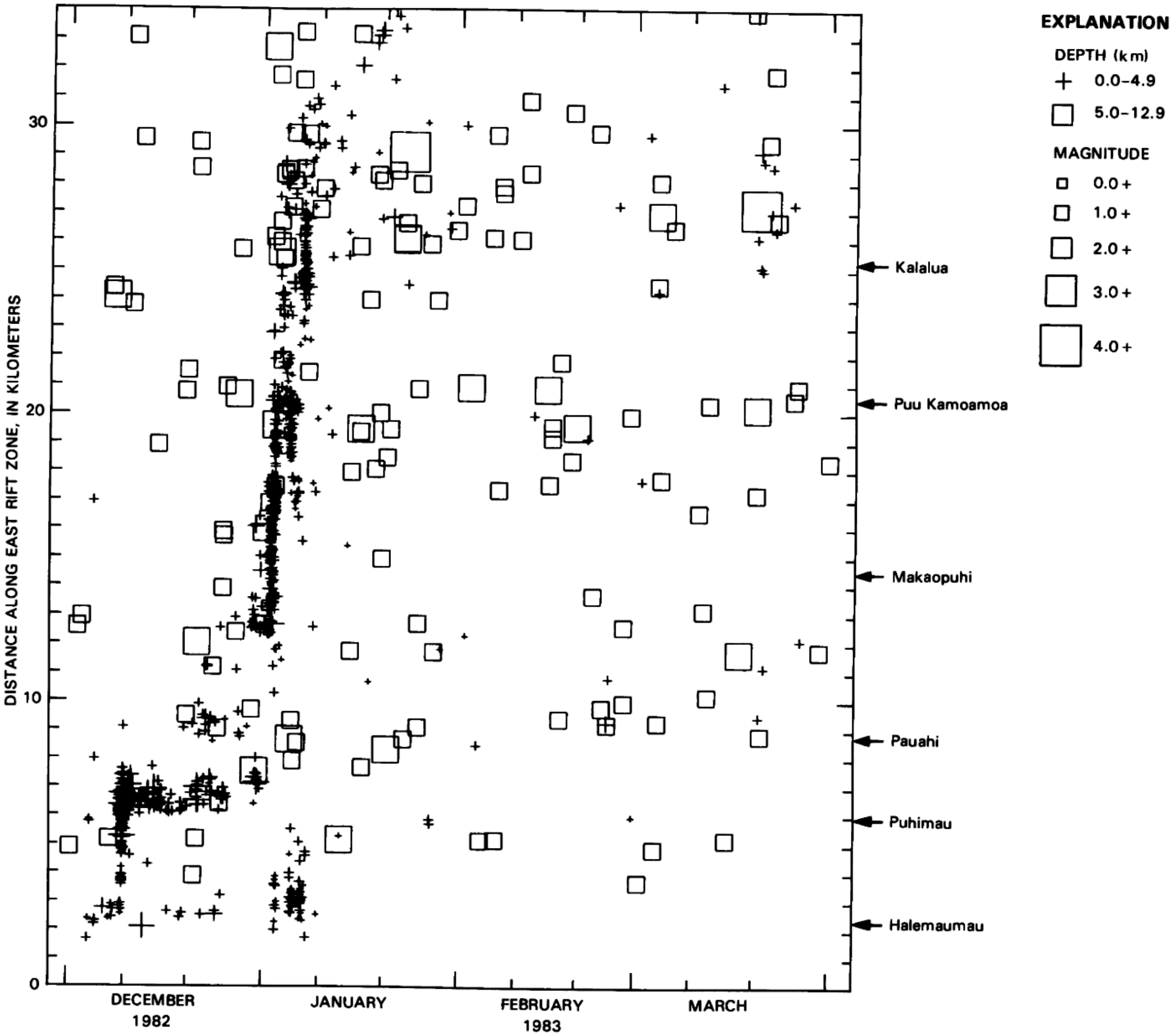


FIGURE 17.9.—Space-time diagram of earthquake epicenters in the summit, upper and middle east rift zone, and adjacent part of the south flank, Kilauea Volcano, for December 1982 through March 1983. Epicenters projected onto an east-west line.

prolonged repose before episodes 4 and 13. For comparison, during the 12 episodes of sustained fountaining that occurred in the early months of the 1969–71 Mauna Ulu eruption, lava was delivered to the surface at an approximate rate of $10 \times 10^6 \, m^3/mo$. During that period, average erupted volumes and average recurrence intervals at Mauna Ulu were also smaller than for the Puu Oo eruption (fig. 17.16).

As the Puu Oo eruption went on, the durations of individual episodes tended to decrease and the discharge rates to increase (table 17.1, fig. 17.17); thus comparable volumes of lava were delivered more rapidly in successive episodes. Presumably this reflected progressive enlargement and streamlining of the conduit system between the summit reservoir and the vent area.

MAGMA SUPPLY TO THE VOLCANO

Swanson (1972) examined the rate of lava production during three long eruptions of Kilauea—the 1952 Halemaumau eruption, the 1967–68 Halemaumau eruption, and the 1969–71 Mauna Ulu eruption—that were characterized by minimal net change in the degree of summit inflation as indicated by the summit tilt record. Assuming that minimal net tilt change at the summit implied minimal

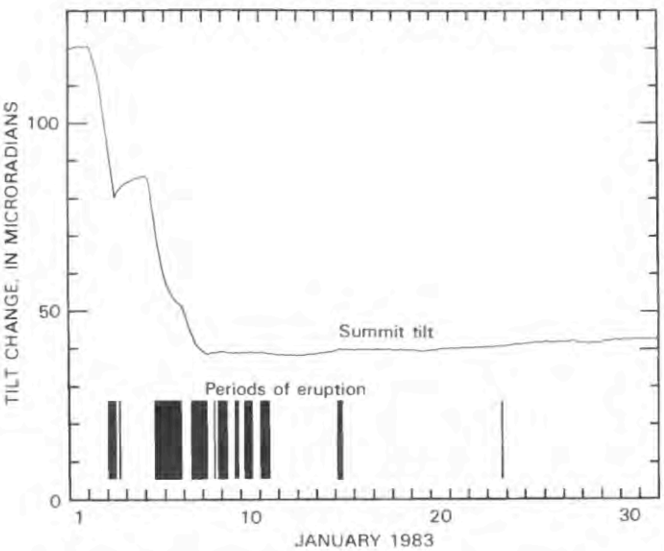


FIGURE 17.10.—East-west summit tilt record (Hg-capacitance tiltmeter at Uwekahuna) and episode 1 eruptive periods, Puu Oo eruption, January 1983. Increasing values indicate westward-directed (inflationary) tilt change; decreasing values indicate eastward-directed (deflationary) tilt change. Full magnitude of tilt change from January 5 through January 7 is greater than shown because of nonlinear response of tiltmeter to tilt change during that period.

change in the stored volume, he concluded that the erupted volumes approximated the supply of magma from the mantle. Correcting for an estimated 15 percent vesicularity, he calculated a magma-supply rate of approximately $9\times10^6\,m^3$/mo for the three sustained eruptions. Before applying Swanson's technique to infer magma supply from the rate of lava delivery during the Puu Oo eruption, we evaluate several factors, including the large subsidence related to dike emplacement in episode 1, a long-term decrease in average tilt value, and the correction for vesicularity.

A large subsidence of Kilauea's summit occurred at the beginning of the Puu Oo eruption, and we infer that a large volume of magma, on the order of $100\times10^6\,m^3$, remained in the intruded dike and this was not accounted for in the measured volume of episode 1 lava. After episode 1, the much smaller, alternately inflationary and deflationary tilt changes were roughly similar in magnitude and nearly cancelled each other. However, they were superimposed on a gradual, long-term decrease in average tilt that amounted to about 30 microradians by the end of episode 20 (fig. 17.15) after correction for the offset caused by the November 1983 Mauna Loa earthquake. This tilt change is equivalent to an apparent volume decrease of about $10\times10^6\,m^3$ of magma over 17 months (see discussion in subsequent section titled "Relation of Summit Tilt Changes to Rift-Zone Activity"), which is within the uncertainty of our volume measurements. Furthermore, in an analysis of deformation and gravity data for the caldera region, Johnson (chapter 47) found that cross-caldera distances measured perpendicular to the coast have been steadily increasing at a rate of about 2 microstrain (parts per million) per month. Thus the subsidence indicated by gradually decreasing average tilt values may not reflect

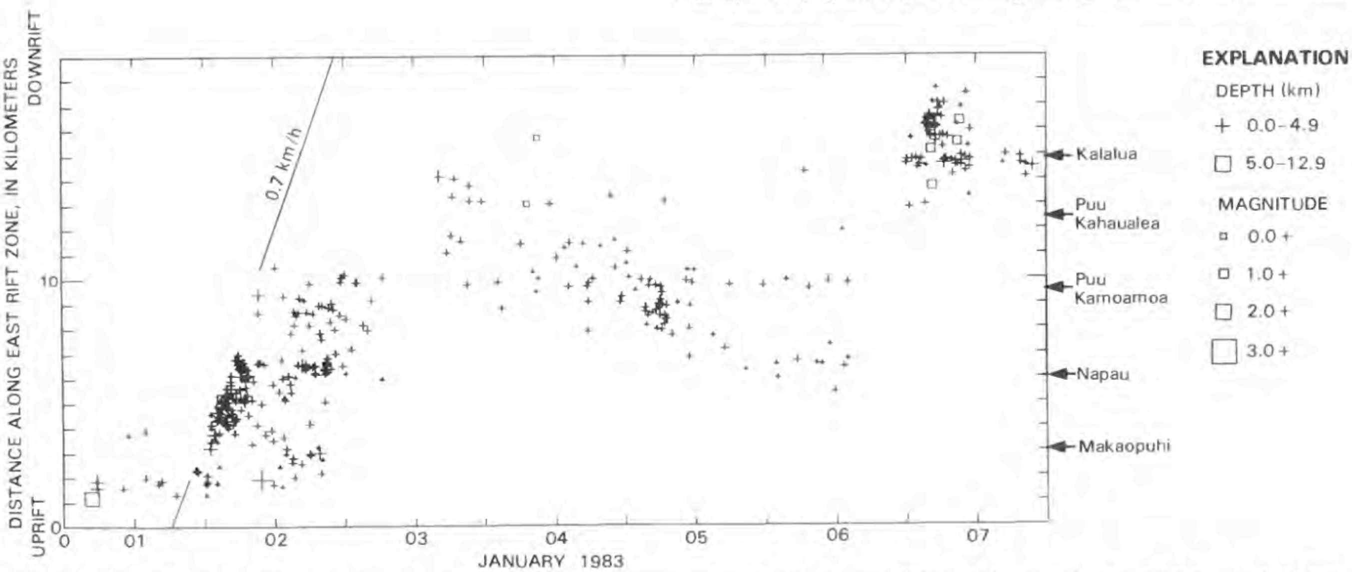


FIGURE 17.11.—Expanded space-time diagram of earthquake epicenters in upper and middle east rift zone, Kilauea Volcano, during the period January 1–7, 1983. Epicenters projected onto a line parallel to the axis of the middle east rift zone. A downrift migration rate of 0.7 km/h is inferred for the leading edge of the concentrated zone of shallow earthquakes during the morning of January 2. Location accuracy, based on horizontal and vertical standard error (Klein, 1978) for these earthquakes, is ±1 km.

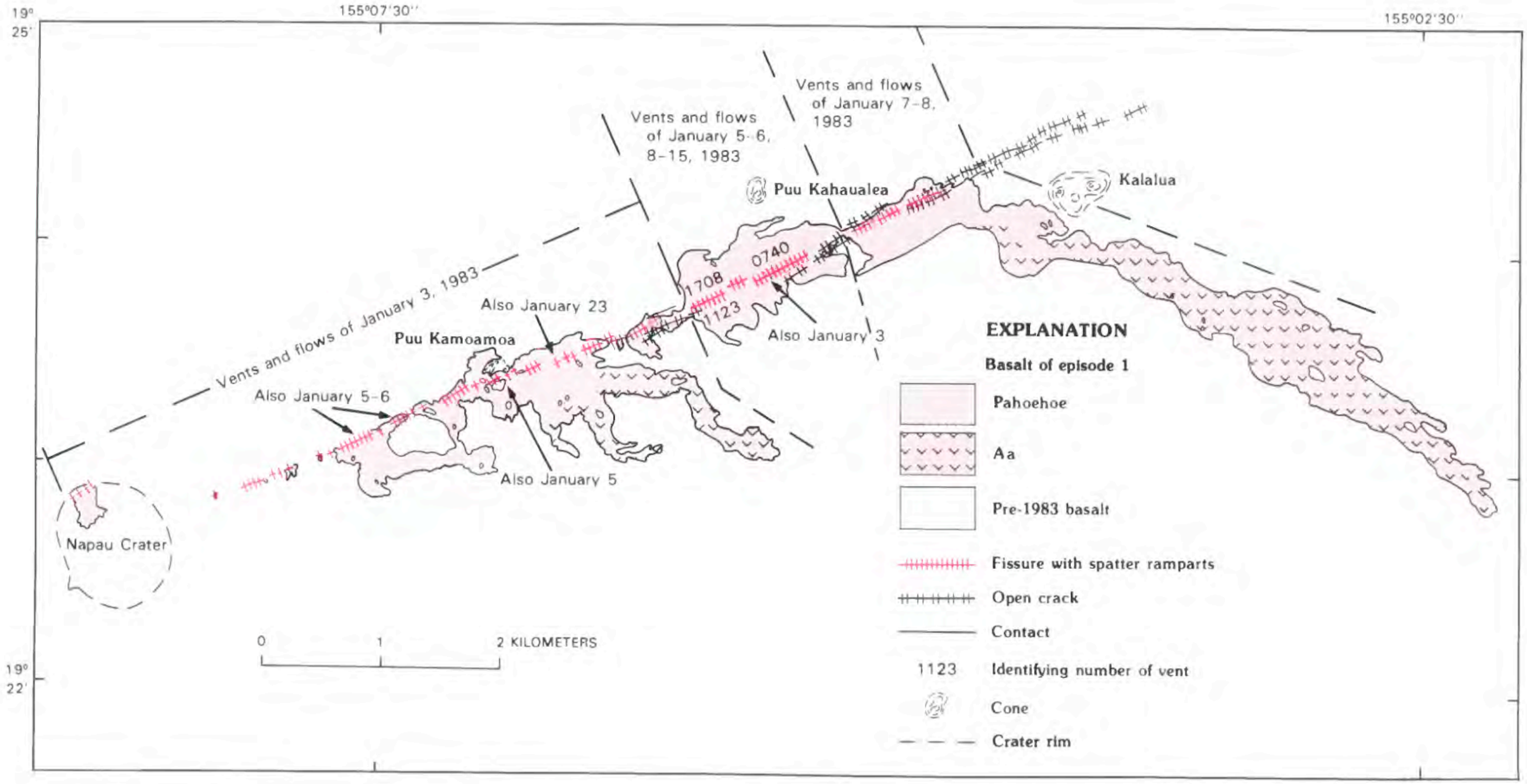


FIGURE 17.12.—Vents and flows of episode 1, Puu Oo eruption, Kilauea Volcano, January 1983.

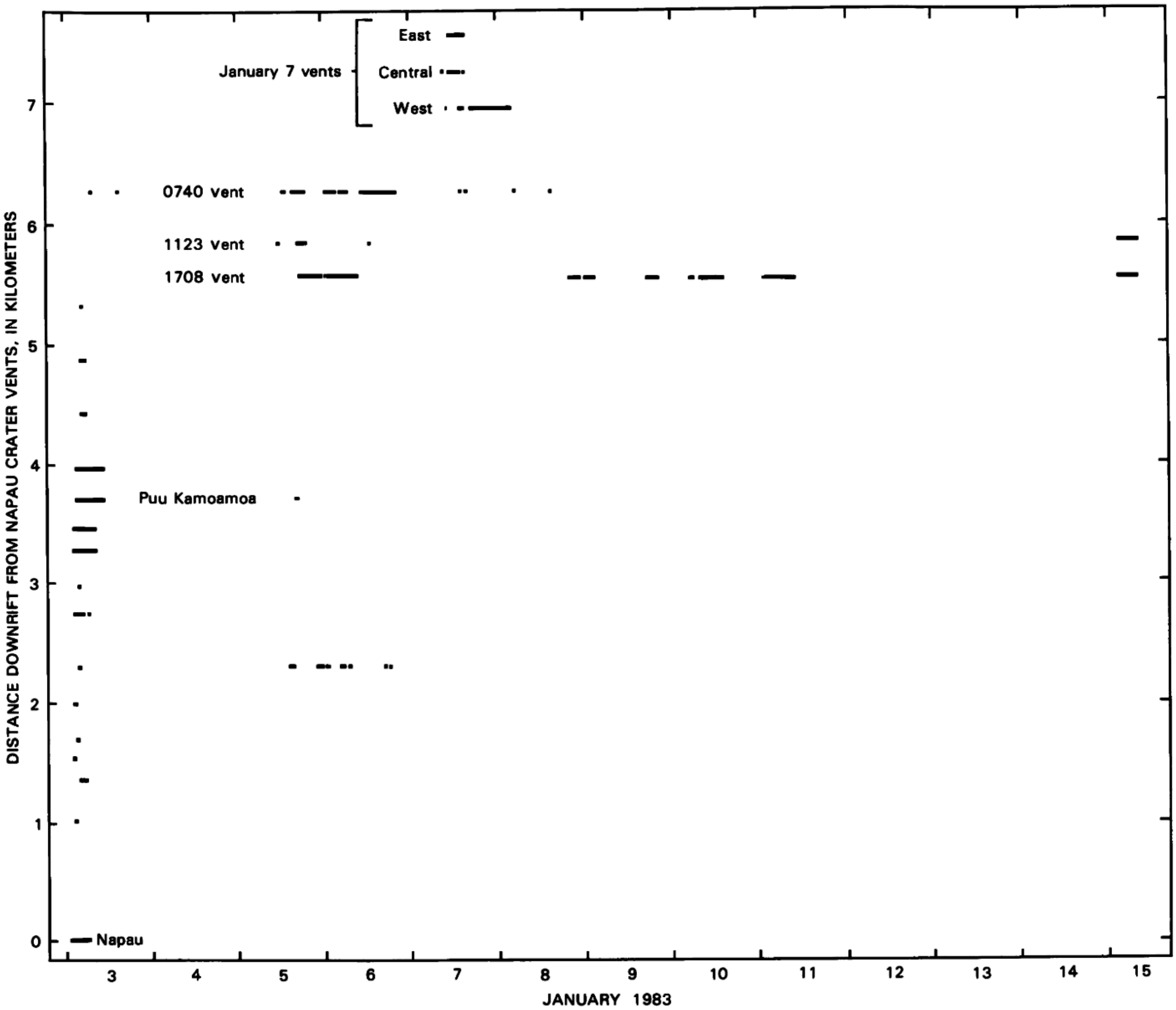


FIGURE 17.13.—Space-time diagram showing vent activity for January 3–15, episode 1 of the Puu Oo eruption. Approximate locations of centers of individual eruptive-fissure segments shown by distance downrift from the Napau Crater vents.

a reduction in reservoir magma volume but rather a gradual change in shape resulting from southeastward extension of the summit region. In addition, repeated gravity surveys from the beginning of 1984 through the time of writing (May 1985) have shown no long-term change in mass in the summit region, indicating that the average reservoir magma volume remained constant. We ignore both this gradual long-term subsidence and episode 1 with its dike emplacement in applying Swanson's technique for determining magma supply to the Puu Oo eruption.

The Puu Oo flows are dominantly vesicular rubbly aa. Average bulk densities of 1.94 and 2.17 g/cm^3 were determined from the results of two gravimeter and spirit-level profiles across the surface of an episode 3 aa flow where it overlies paved streets in a subdivision (D.J. Johnson, written commun., December 1984). These values suggest that the porosity is approximately 25 percent. Multiplying the average monthly lava supply of 13.4×10^6 m^3 by 0.75 to correct it to its dense-rock equivalent gives a rate of 10×10^6 m^3/mo of void-free lava. Thus, we infer an average magma-supply rate for episodes

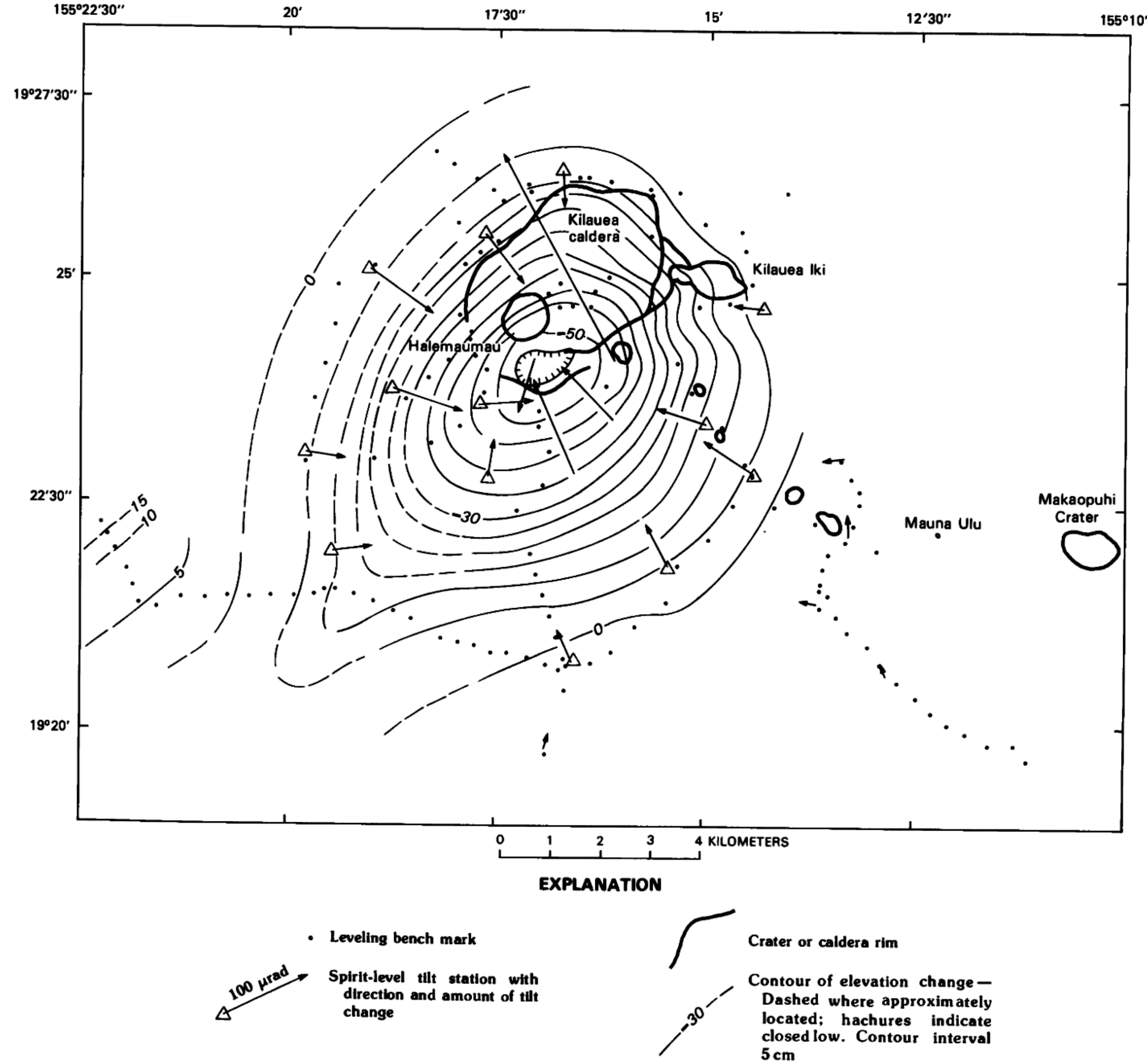


FIGURE 17.14.—Subsidence and tilt in the Kilauea summit region during the period from September 27–October 5, 1982, to February 7–11, 1983. Contours show relative elevation change.

2–20 of approximately $10\times10^6 m^3$/mo. Because volume-measurement errors may amount to 10 percent, this supply rate for the Puu Oo eruption is compatible with the rate determined by Swanson (1972) for other periods of sustained eruption. A slightly higher rate, approximately $11.8\times10^6 m^3$/mo, may be represented by the intervals encompassing episodes 4–12 and 13–17. The limited variation in recurrence interval and erupted volume (fig. 17.16) during those intervals indicates that an approximately steady-state condition had developed in the magma supply and transport system.

The question remains whether the Puu Oo magma-supply rate of at least $10\times10^6 m^3$/mo represents a period of elevated supply. Dzurisin and others (1984) reviewed magma-supply estimates more recent than Swanson's (Dzurisin and others, 1980; Duffield and others, 1982; Dvorak and others, 1983). They found a range of from 6×10^6 to $9\times10^6 m^3$/mo and concluded, from their analysis of the summit tilt record, that $7.2\times10^6 m^3$/mo is a reasonable minimum value for the average supply of magma from 1956 through 1983. Uncertainty arises from the possible addition of undetected

TABLE 17.1.—*Eruption data for episodes 1–20, Puu Oo eruption, Kilauea*

[All times are in Hawaii standard time (H.s.t.). ---, did not occur or was not observed]

Episode	First report of low-level eruption[1] Day	First report of low-level eruption[1] Hour	Beginning of vigorous eruption[2] Day	Beginning of vigorous eruption[2] Hour	End of vigorous eruption[3] Day	End of vigorous eruption[3] Hour	Duration of vigorous eruption (hours)	Area covered (10^6 m^2)	Erupted volume (10^6 m^3)	Discharge rate[4] (10^3 m^3/h)
					1983					
1	---		Jan 3	0031	([5])		([5])	4.8	14	([5])
[6]2	Feb 10	1030	Feb 25	0900	Mar 4	1451	174	2.7	14	80
3	Mar 21	0600	Mar 28	0100	Apr 9	0257	290	7.9	38	130
4	---		Jun 13	1025	Jun 17	1413	100	2.2	11	110
5	Jun 29	1000	Jun 29	1251	Jul 3	0715	90	3.4	13	140
6	Jul 21	0600	Jul 22	1530	Jul 25	1630	73	2.0	9	120
7	Aug 8	0610	Aug 15	0741	Aug 17	1600	56	3.7	14	250
8	Sep 2	0900	Sep 6	0511	Sep 7	0526	24	[7]2.0	[7]8	[7]330
9	Sep 14	0009	Sep 15	1541	Sep 17	1920	52	[7]2.1	[7]8	[7]150
10	Oct 2	0800	Oct 5	0106	Oct 7	1650	64	2.7	14	220
11	---		Nov 5	2350	Nov 7	1845	43	4.3	12	280
12	Nov 29	1600	Nov 30	0447	Dec 1	1545	35	3.0	8	230
					1984					
[8]13	Jan 20	1100	Jan 20	1724	Jan 22	1123	42	[7]2.6	[7]10	[7]230
[7]14	Jan 22	1123	Jan 30	1745	Jan 31	1318	19	[7]2.1	[7]6	[7]320
15	Feb 3	1000	Feb 14	1940	Feb 15	1501	19	2.2	8	420
16	Feb 27	1900	Mar 3	1450	Mar 4	2231	32	3.2	12	380
17	Mar 20	0910	Mar 30	0448	Mar 31	0324	23	3.0	10	430
18	Apr 5	1340	Apr 18	1800	Apr 21	0533	60	6.6	24	410
[9]19	Apr 23	0830	May 16	0500	May 18	0050	44	1.4	2	50
20	May 18	0800	Jun 7	2104	Jun 8	0625	9	1.6	4	480

[1]For episode 2, low-level eruption refers to a period of prolonged slow extrusion (averaging approximately 1,400 m^3/h) from February 10 to 25, 1983. For episodes 3–20, it refers to a period, preceding major eruption, during which any or all of the following phenomena were observed at the active vent: intermittent gas-piston activity, intermittent spattering, occasional extrusion of small pahoehoe flows, occurrence of a visible lava surface (sometimes partly crusted) in the conduit extending downward from the crater floor. Normally, low-level eruptive activity was confined to the interior of the crater, but on rare occasions short-lived pahoehoe flows spilled from Puu Oo.

[2]Normally, the onset of vigorous eruption was recognized in the following ways (order indicates priority): (1) direct observation of continuous emission of lava from the crater; (2) time-lapse camera record of beginning of continnous emission of lava from crater; (3) where spillway activity was not recorded, time-lapse camera record of first appearance of fountaining above the crater rim; (4) beginning of rapid increase in harmonic-tremor amplitude.

[3]The end of vigorous eruption was recognized in the following ways (order indicates priority): (1) direct observation of the cessation of lava discharge; (2) time-lapse camera record of cessation of fountaining; (3) rapid decay of harmonic-tremor amplitude.

[4]Discharge rate is calculated only for period of vigorous eruption. Except for episode 2, the volume of lava erupted during periods of low-level activity was negligible.

[5]Episode 1 was characterized by intermittent eruptive activity for nearly three weeks. Periods of active eruption totalled approximately 99 hours. The last sizeable event occurred on January 15; a minor one occnrred on January 23.

[6]During episode 2, approximately 0.5×10^6 m^3 of basalt was discharged during low-level eruption from February 10 to 25. The remaining 13.6×10^6 m^3 was discharged during the period of vigorous eruption at a rate of approximately 70,000 m^3/h.

[7]Flow was partly buried by younger basalt before it could be mapped. Thus uncertainty is increased in estimates of area, volume, and discharge rate.

[8]Fountaining and flow production during episode 13 occurred in two main periods. The first, approximately 31 hours long, was separated by about 5 hours from the 6-hour-long second period.

[9]Episode 19 was characterized by low fountain activity and intermittent low-volume overflows from the lava pond within the crater of Puu Oo. This activity was interrupted by four periods 1–3 h long, totalling about 7 hours altogether, of higher fountaining and increased lava discharge estimated as about $100–200\times10^3$ m^3/hr.

magma to rift-zone storage. Furthermore, Tilling and others (chapter 16) recognized two distinct episodes during the latter part of the Mauna Ulu eruption, February 1972 through April 1973 and December 1973 through July 1974, in which sustained lava extrusion coincided with negligible summit-tilt change. During the earlier episode, the lava-extrusion rate was about 8×10^6 m^3/mo; during the later one, it was 4×10^6 m^3/mo. Neither value is corrected for vesicularity. R.I. Tilling (oral commun., May 1985) regards the values as minimum estimates of magma-supply rate because of the unevaluated possibility that magma was being stored in the upper east rift zone during the 1972–74 Mauna Ulu eruption.

The data summarized above are only permissive evidence that the Puu Oo eruption coincided with a period of greater than normal magma supply. More substantial support may come from measurement of SO_2 flux to the atmosphere in the Kilauea summit area. The average flux increased abruptly after the beginning of the eruption in January 1983 from 130 t/d to 250 t/d; the elevated flux was maintained through at least episode 20 (fig. 17.18; Greenland and others, 1985). The near coincidence of the SO_2-flux change with the beginning of the Puu Oo eruption strongly suggests that the two events were related. The increased SO_2 flux may have been a direct and rapid response to an increased rate of supply of new magma to the summit reservoir; if so, the Puu Oo eruption coincided with a period of increased magma supply.

CHARACTER OF THE CENTRAL-VENT ERUPTIONS

Central-vent eruptions occurred during episodes 2 through 20. A nearly vertical pipe-like conduit delivered a spray of gas and fragmented vesiculating magma through a vent in the floor of a broad crater within a growing pyroclastic cone. Directed upward as a jet, the spray formed the fountain that was invariably present in the central-vent eruptions. Initial fallout from the fountain built a spatter ring, which, in repeated eruptive episodes, grew upward and outward by the addition of spatter, rootless flows, and unconsolidated lapilli and bombs.

The crater of Puu Oo evolved to a broad bowl mostly enclosed by steep walls. The diameter of its gently sloping floor gradually increased from about 20 m to 100 m. A deep breach that developed in the crater wall provided a passage through which lava left the

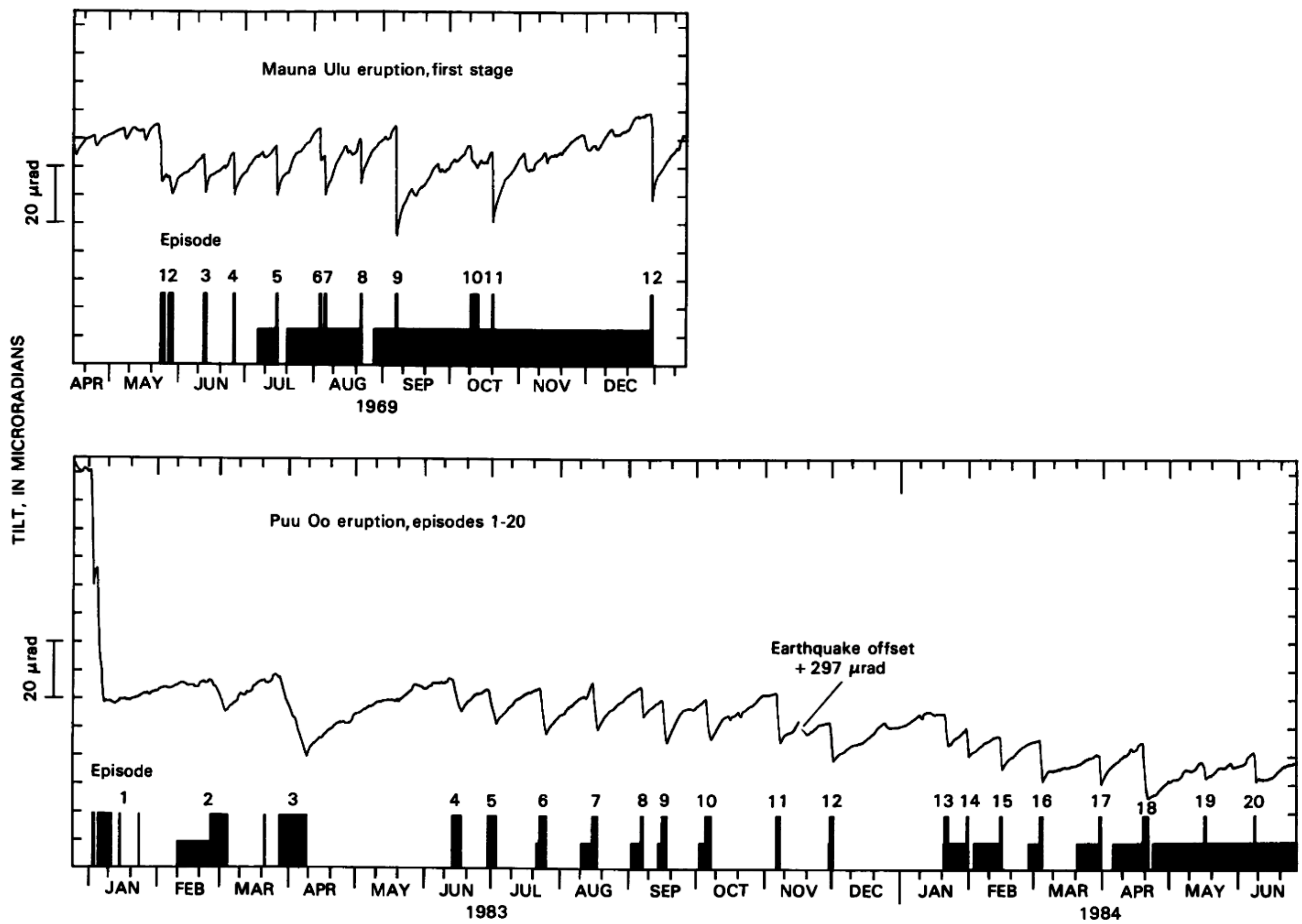


FIGURE 17.15.—East-west tilt at Kilauea summit (measured by the Uwekahuna Hg-capacitance tiltmeter), eruptive episodes (full- height bars), and observed repose-period eruptive activity (half- height bars) during episodes 1–20 of the Puu Oo eruption and the first stage of the 1969–71 Mauna Ulu eruption (Swanson and others, 1979).

crater. The floor of the breach was generally 5–15 m higher than the crater floor.

Before episode 13, rubble on the crater floor concealed the feeder conduit during most periods of repose. From episode 13 on, a persisting vertical and nearly cylindrical conduit about 20 m in diameter was revealed. Its walls exposed crudely layered platy to rubbly basalt; at its top, the pipe flared upward to meet the crater floor and was commonly draped with pahoehoe.

During eruptive episodes, the crater contained a lava pond and one or more fountains. The pond overflowed at the breach in the crater rim. Normally the spillway at the breach was fairly constricted, so that the surface of the hydraulically-dammed pond was several meters higher than the floor of the spillway. We estimate that the pond was normally at least 10–20 m deep. When high, broad fountains seemed to fill the crater, we could not see the pond, but continuing flow of lava over the spillway indicated its presence. However, flows produced during such periods were sometimes more sluggish than when a well-developed pond was seen to be present.

Though the pond shared the crater with a vigorous fountain, it maintained a fairly smooth surface that was commonly marked by a thin, flexible skin of slightly cooled lava undisrupted by effervescence. We infer that the pond consisted of mostly degassed lava that had coalesced from fragmented melt in the crater and the upper part of the conduit.

Fountains at the central vents during episodes 2–20 ranged in height from a few meters during periods of slow discharge to a maximum of nearly 400 m. In some of the eruptive episodes at Puu Oo, as, for example, episode 16, the fountain was highest in the early hours (fig. 17.19); this suggests that volatiles may have become more highly concentrated in the upper part of the conduit beneath the vent during periods of repose.

Fountain height was related at least in part to the rate of discharge. During both episodes 2 and 3, fountain height at the 1123 vent approximately doubled in concert with 2- to 3-fold increases in lava output. From episode 4 on, at Puu Oo, we normally saw no abrupt changes in discharge during an eruptive

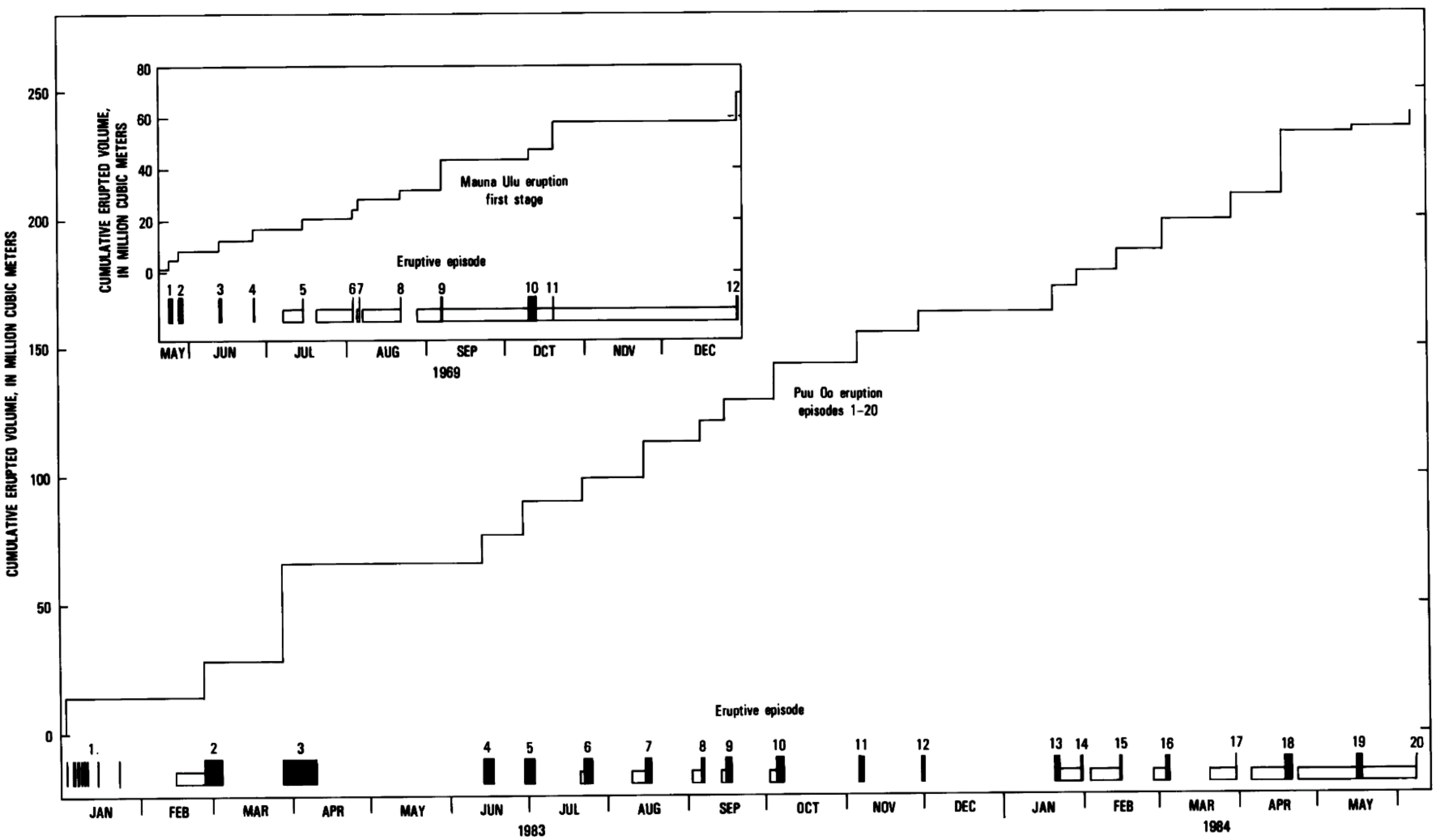


FIGURE 17.16.—Cumulative erupted volumes during episodes 1–20 of the Puu Oo eruption and the first stage of the Mauna Ulu eruption (Swanson and others, 1979). Solid full-height bar, eruptive episodes; open half-height bar, observed repose-period activity. Basalt volumes for Puu Oo eruption were determined by mapping flows and vent deposits of the individual episodes, measuring thicknesses by hand level at the flow edges, and measuring mapped area on a computerized digitizing tablet.

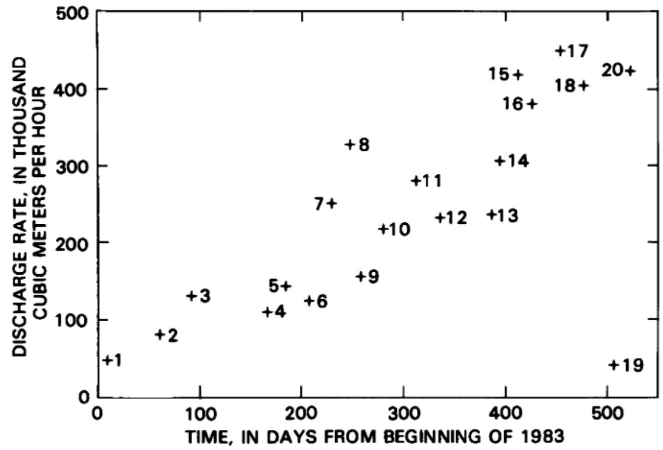


FIGURE 17.17.—Average lava-discharge rate for each of episodes 1-20, Puu Oo eruption, plotted against time.

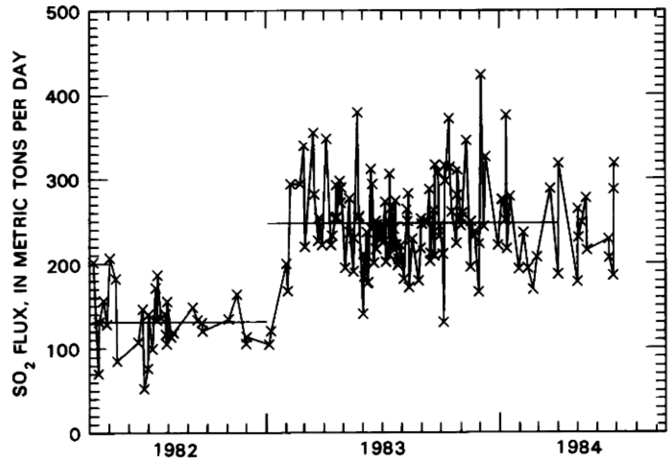


FIGURE 17.18.—Total sulfur dioxide (SO_2) flux from summit fumaroles of Kilauea Volcano, April 1982 through June 1984, based on ground measurements. Horizontal lines show change in average flux after the beginning of the Puu Oo eruption in January 1983. Modified from Greenland and others (1985); data extended through June 1984 by L.P. Greenland.

episode, but the rate was greater in successive episodes (fig. 17.17). Average fountain height at Puu Oo correlated roughly with average discharge (fig. 17.20), but appreciable scatter resulted from effects that may have included changing conduit conditions, enrichment of gas during repose periods, and damping of fountains by coalesced melt within the crater and upper part of the conduit.

Normally, each central-vent fountain episode produced one or more major elongate aa flows supplied by a river of fluid pahoehoe that originated from the steady overflow of the pond. Subordinate flows originated mainly from persistent near-vent overflows of the river and from mobilization of molten spatter that accumulated either rapidly or persistently on the flanks of the cone.

The river-fed flows evolved downstream through a similar progression of zones as that recognized in the aa lobes of the 1984 Mauna Loa eruption (Lipman and Banks, chapter 57). As at Mauna Loa, fluid channelized lava near the vent was inflated by gas but rapidly deflated downstream. The sustained cascade of spatter and the turbulence where the fountain burst from the pond apparently churned vent gases, including air, into the lava supplying the pond. Thus the pond was a continuing source of gas-rich fluid melt and was apparently fundamental in developing the long river-fed aa flows at Kilauea. Minimal development of the pond, such as during periods of high fountaining, was associated at times with production of less fluid flows. Furthermore, supply from a fountain with no basin or pond often produced thick, slow-moving aa directly.

Generally, the major flows were 4–8 km long and from 100–500 m wide. A few flows were significantly longer; the longest, produced during episode 18, extended more than 13 km from the vent (fig. 17.2). The average thickness of most of the river-fed aa flows was between approximately 3 and 5 m. However, the range of measured thicknesses was greater; locally, the distal parts of some flows were as thick as 10 m. The major river-fed flows advanced at average rates of 50–500 m/h. Surges of fluid lava at the flow fronts (Neal and Decker, 1983) resulted in more rapid advances that were sustained for tens of minutes at rates of as much as 2 km/h. Significant flow movement stopped when the lava supply was cut, generally at the vent but sometimes by diversion to a new flow. After the supply was terminated, however, slow creeping of the front sometimes continued for hours.

Low-level eruptive activity was evident during many repose periods. At Puu Oo, it was dominated by two phenomena: the gradual ascent of the magma column toward the surface and gas-piston activity much like that seen at Mauna Ulu (Swanson and others, 1979). After the open conduit descending from the crater floor became a permanent feature following episode 13, we could see that the magma-column surface rose gradually and sometimes spasmodically toward the crater floor during each repose period. If visibility was good, we would first see the top of the column when it was about 50 m down the conduit; the first sighting usually occurred at least 5 days and sometimes more than 3 weeks before the next major episode (fig. 17.15).

We were able to watch the beginnings of several of the fountaining episodes at Puu Oo. First the crater filled with lava, which steadily overflowed the spillway. Gas-piston activity, if it had been occurring, gave way to an open, roiled pond with a low dome fountain. Over a period ranging from tens of minutes to about two hours, the rate of overflow progressively increased from $1\text{–}10\times10^3\,m^3/h$ to normal discharge rates of $100\times10^3\,m^3/h$ or more. At the same time, the height of the fountain increased from less than 10 m to tens or hundreds of meters.

Central-vent activity at the 1123 vent during episodes 2 and 3 died gradually, as indicated by progressive decrease of fountain vigor during the last day of each episode. In contrast, eruptive episodes at the Puu Oo vent ended more abruptly. Sometimes the eruption suddenly stopped with no warning. More often, the fountain diminished and became less steady in the last 3–10 minutes of the episode; during that brief period, we sometimes saw pauses of a few seconds or tens of seconds in fountain and flow production. Normally the output of lava from Puu Oo was steady until the terminating moments of fountain activity, after which no further discharge occurred.

SEISMIC EFFECTS IN THE ERUPTION ZONE

Intense harmonic tremor occurred in the vent area coincident with vigorous eruption. However, the amplitude of the harmonic tremor did not vary systematically with major changes in fountain height during individual eruptive episodes (fig. 17.19). Throughout the central-vent activity, the amplitude showed a positive correlation with discharge (fig. 17.21) but not with the average fountain height (fig. 17.22). Thus, the recorded tremor reflected primarily processes at levels deeper than those from which fountaining originated. The symmetry, with respect to Puu Oo, of tremor-attenuation patterns implies that the tremor source and the vent were vertically aligned, but the depth of the tremor source is uncertain.

Harmonic tremor continued at low amplitude throughout repose periods and increased rapidly at the beginning of each episode of fountaining. Relatively deep south-flank earthquakes continued throughout the period of central-vent activity, but there was no shallow seismic swarm like that during emplacement of the dike in episode 1. We infer from the absence of seismic swarms after episode 1 and also from the continuous harmonic tremor and visible evidence of magmatic activity during repose periods that a continuous magma-filled conduit between the summit reservoir and the vents persisted after episode 1.

GEODETIC EFFECTS IN THE ERUPTION ZONE

Geodetic measurements in the eruption zone were limited by the difficulty and expense of obtaining access and by burial of measurement stations by new lava flows. However, two major inferences for the period of central-vent activity can be made from the available data: (1) over the long term, slight net deflation occurred; (2) over the short term, gradual inflation accompanied repose periods, and abrupt deflation accompanied eruptive episodes.

Measurements at a spirit-level tilt station about 1.5 km northwest of Puu Kamoamoa showed that the ground tilted northwestward, away from the rift-zone axis, during the early part of the eruption (table 17.2). The major change between December 15, 1982, and January 18, 1983, undoubtedly reflects deformation resulting from emplacement of the dike in early January. A smaller change between January 18 and March 8, 1983, may record inflation of the rift zone; a measured distance across the eruptive fissure farther downrift near Puu Kahaualea gradually lengthened during the same period. During episode 3, however, the ground tilted 12 μrad southeastward toward the rift axis, consistent with subsidence there. Measurements made after episode 3 and again 16 months later after episode 24 show an additional 19 μrad of tilt toward the rift-zone axis.

The automatic borehole tiltmeter 250 m northwest of Puu Kamoamoa operated during episodes 1–10 and from shortly after episode 15 through episode 20. No recognizable tilt change was associated with episode 2. However, beginning with southeast-directed tilt during episode 3, the ground normally tilted gradually northwest during repose periods and rapidly southeast during periods of fountaining (fig. 17.23). These opposed tilt changes were commonly of similar magnitude, in the range of 3–9 μrad, and were directed approximately normal to the rift-zone axis. They presumably recorded alternating inflation and deflation in the rift zone near Puu Kamoamoa. The largest deflations occurred during episodes 3 and 18, which were the most voluminous eruptions (table 17.1). No detectable tilt change occurred during episode 19.

SUMMIT BEHAVIOR

Repeated uplift and subsidence of Kilauea's summit region, recorded by the rising and falling trace of the Uwekahuna tiltmeter (fig. 17.15), dominated summit response to the episodic eruptions. Summit inflation occurred during repose periods and was accompanied by increasing numbers of shallow, short-period earthquakes beneath Kilauea caldera (fig. 17.24). Daily frequency of earthquakes generally increased to a maximum of 100–200 in the latter part of each repose period, then decreased sharply during and following the deflation. The earthquakes apparently recorded fracturing of country rock as it adjusted to distention of the summit reservoir.

Shallow long-period earthquakes, intergradational with related harmonic tremor, were abundant beneath the caldera during the later parts of summit subsidence and the early parts of the repose periods. Before episode 8, the daily number of long-period earthquakes seldom exceeded 100, but thereafter peak counts of many hundreds of events per day were normal (fig. 17.24). Greater intensity of long-period-earthquake activity was associated with higher rates of sustained deflation. Thus the long-period events and associated tremor in the caldera area were apparently responses to rapid evacuation of magma from the summit reservoir.

RELATION OF SUMMIT TILT CHANGES TO RIFT-ZONE ACTIVITY

COMPARISON OF SUBSIDENCE AND LAVA-DISCHARGE RATES

The average rate of summit subsidence as reflected in tilt changes at Uwekahuna (fig. 17.25) increased steadily from episode 2 through episode 8. Unlike the lava-discharge rate, which continued to increase thereafter (fig. 17.17), the subsidence rate later was variable and appeared to peak at an upper limit of about 0.5 μrad/h. In the following section we discuss some possible reasons for such a variable relationship between summit tilt change and erupted volume. Dvorak and Okamura (in press) attribute the early increase in deflation rate to progressive decrease of flow resistance in the conduit system. We agree and interpret the continued increase in effusion rate to indicate that the efficiency of magma delivery to the

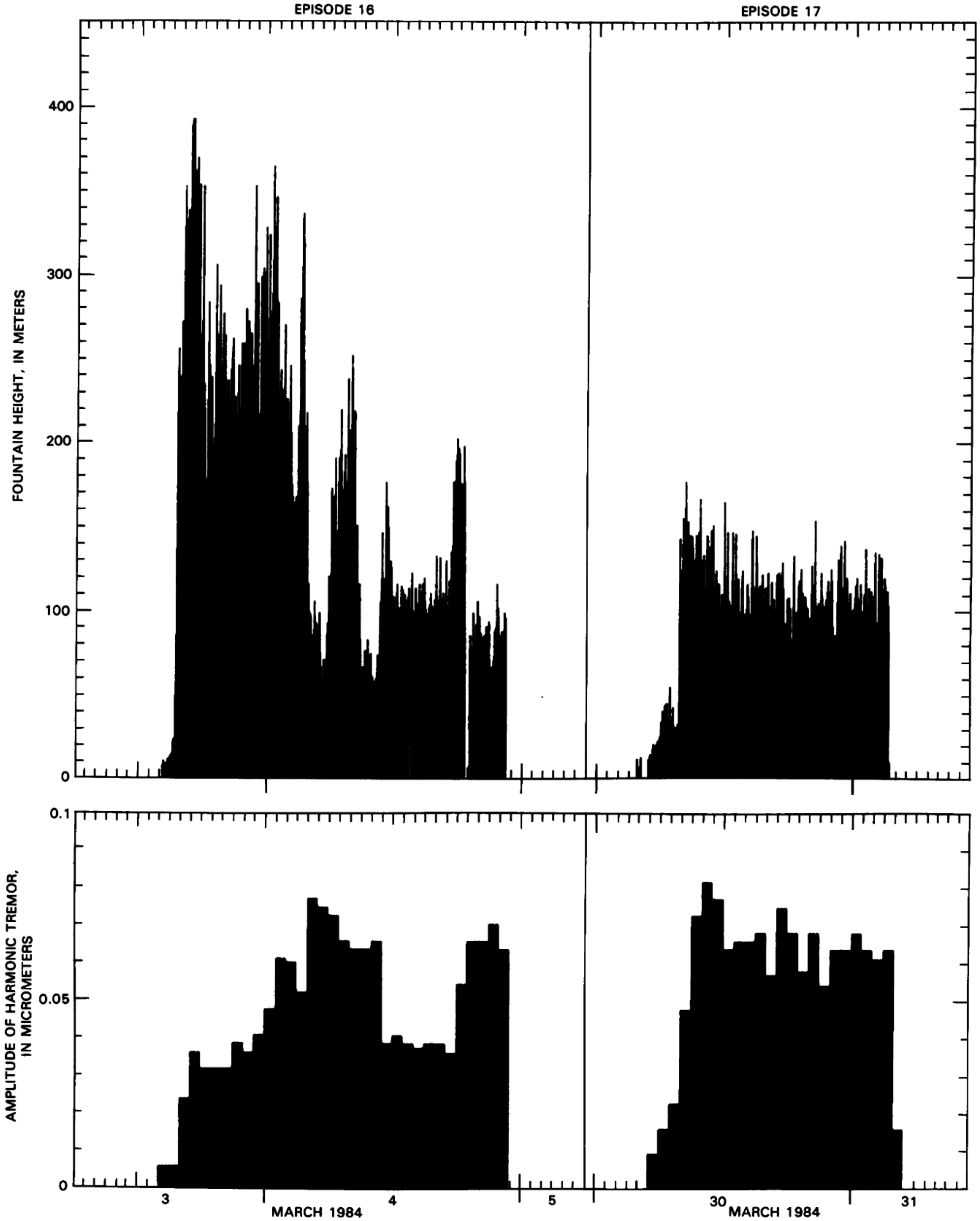


FIGURE 17.19.—Fountain height and amplitude of vent-area harmonic tremor recorded by seismometer at Makaopuhi Crater, episodes 16 and 17, Puu Oo eruption. Fountain height was measured from time-lapse film records. Gaps in fountain-height data record periods of poor visibility or inoperative camera.

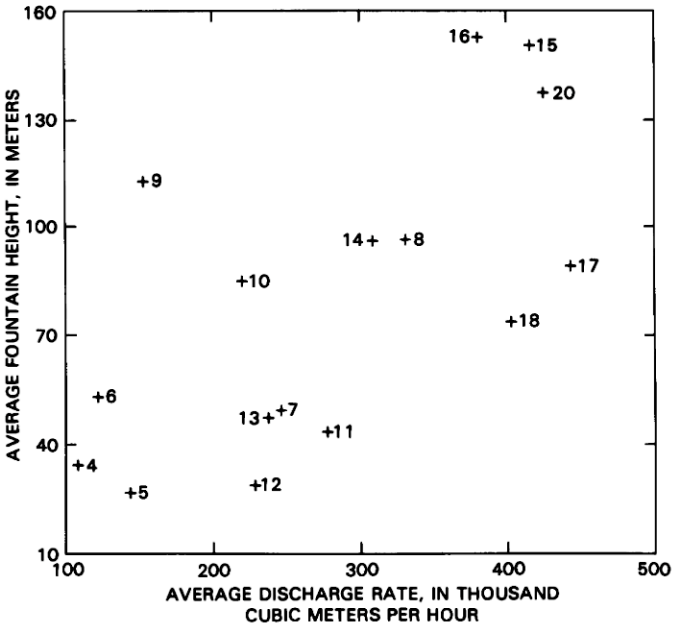


FIGURE 17.20.—Average fountain height versus average discharge rate at Puu Oo, episodes 4–18 and 20, Puu Oo eruption. Episode 19 is excluded because its intermittent fountaining yields a meaningless average.

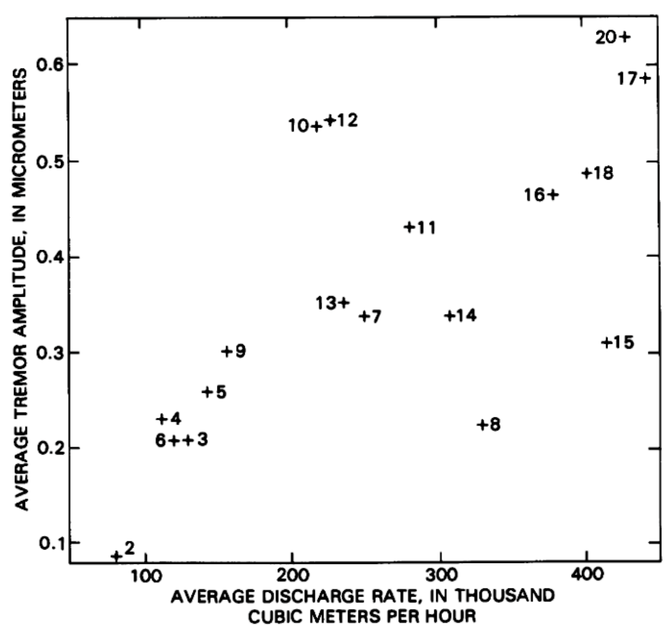


FIGURE 17.21.—Average harmonic-tremor amplitude, measured as ground displacement at the Makaopuhi Crater seismometer, versus average discharge rate at Puu Oo, episodes 2–18 and 20, Puu Oo eruption.

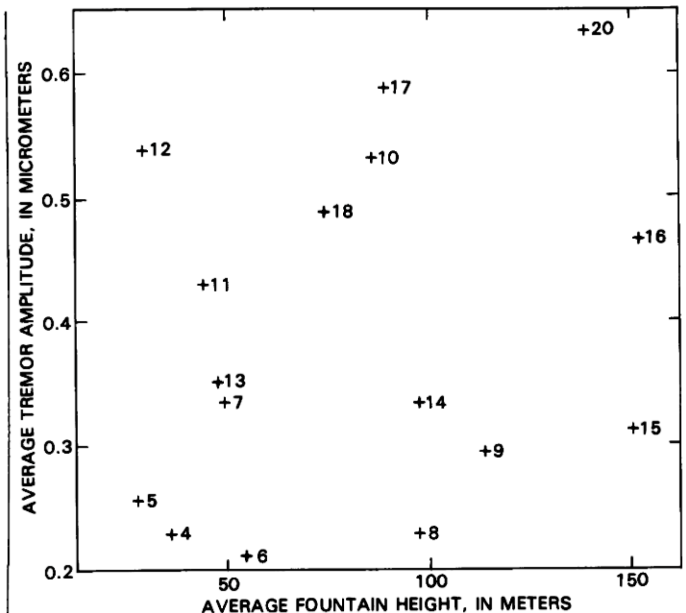


FIGURE 17.22.—Average harmonic-tremor amplitude, measured as ground displacement at the Makaopuhi Crater seismometer, versus average fountain height at Puu Oo, episodes 4–18 and 20, Puu Oo eruption. Fountain height value is a time-averaged arithmetic mean of fountain heights measured from time-lapse film records.

vent continued to increase after episode 8, even though the rate of tilt change at Uwekahuna did not.

VOLUMETRIC CONSIDERATIONS

The volume of lava erupted in each episode, adjusted for 25 percent porosity, ranged from approximately 0.3 to $1.0 \times 10^6 \text{m}^3$ per microradian of summit subsidence (table 17.3) measured on the east-west component of Uwekahuna tilt during episodes 2–20. The average value is 0.63 ± 0.21 (1 standard deviation) $\times 10^6 \text{m}^3/\mu\text{rad}$. The large variation may reflect several factors, including variable inequality between duration of eruption (table 17.1) and duration of subsidence (table 17.3), nonuniform summit response to reservoir-volume changes, variable rate of magma transfer from the summit reservoir to the rift zone during repose periods, and shifting position of the center of inflation and deflation with respect to the tiltmeter. The center of deflation did in fact shift within the region from east to

TABLE 17.2.—*Spirit-level tilt measurements at station 1.5 km northwest of Puu Kamoamoa*

[Vector azimuth gives direction of downward tilt]

Survey period	Vector magnitude (μrad)	Vector azimuth (degrees)
12/15/82–1/18/83	48	292
1/18/83–3/8/83	14	310
3/8/83–4/21/83	12	148
4/21/83–8/23/84	19	155

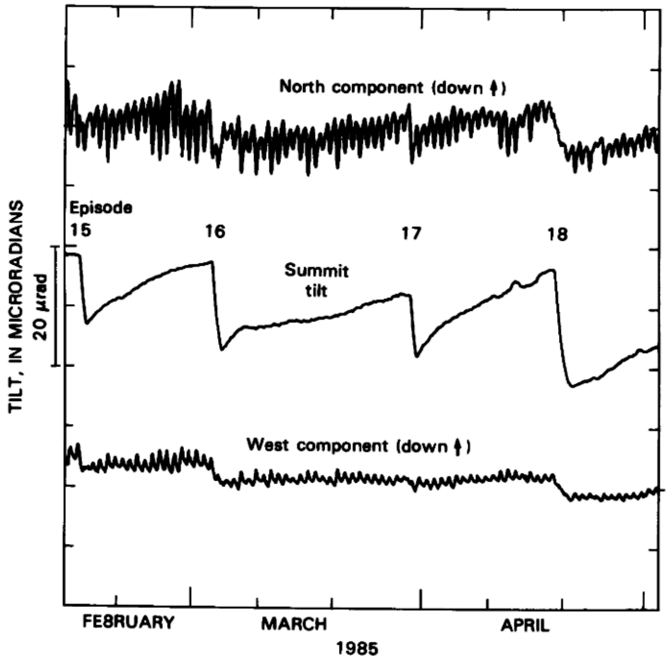


FIGURE 17.23.—East-west summit tilt and Kamoamoa borehole tilt (north and west components), episodes 15–18, Puu Oo eruption.

south of Halemaumau, as shown by levelling and spirit-level tilt surveys for the periods from February 7 to December 28, 1983, and December 28, 1983, to July 23, 1984 (fig. 17.26).

The first 12 fountaining episodes of the 1969–71 Mauna Ulu eruption produced lava at the rate of $0.34 \pm 0.09 \times 10^6 m^3/\mu rad$ of tilt change for a N. 60° W. vector calculated from Uwekahuna water-tube tilt data (Dzurisin and others, 1984). The first episode had a much lower than normal ratio of erupted volume to tilt change and was accompanied by an east-rift earthquake swarm (Swanson and others, 1979, plate 2). Thus, some of the volume of magma involved in the initial episode apparently formed a dike and is not represented at the surface. Eliminating the first episode from consideration, correcting for porosity (15 percent; Swanson, 1972), and adjusting the vector from N. 60° W. to east-west, we calculate a ratio for episodes 2–12 of the 1969–71 Mauna Ulu eruption of $0.35 \pm 0.08 \times 10^6 m^3$ of magma per microradian of east-west tilt change. This is slightly more than 50 percent of the value for episodes 2–20 of the Puu Oo eruption.

The ratio of volume change to tilt change has also been estimated by considering surficial volume change at the summit, determined from leveling surveys, as a measure of reservoir-volume change. Recent calculations of the ratio of surficial volume change to east-west Uwekahuna tilt change are $0.38 \pm 0.07 \times 10^6 m^3/\mu rad$ by Dzurisin and others (1984; value adjusted from N. 60° W. vector) and $0.45 \pm 0.13 \times 10^6 m^3/\mu rad$ by Dvorak and others (in press).

Johnson (chapter 47) attempts to relate elevation changes, Uwekahuna tilt changes, and summit-reservoir volume changes estimated from gravity measurements made from episodes 13–32 of the Puu Oo eruption, and he concludes that changes in reservoir volume may have been appreciably larger (perhaps 2.5 times) than measured surface-volume changes. If this is true, it could account for the high ratio of erupted-magma volume to tilt change for the Puu Oo eruption (0.63) compared to the lower ratio for the early Mauna Ulu episodes (0.35) and to the lower ratio calculated for surface--volume changes (0.38–0.45). We note that the ratio of erupted volume to tilt change for Mauna Ulu is slightly lower than the ratio of surface volume to tilt change; this relation implies that average reservoir-volume changes did not exceed surface-volume changes during the early Mauna Ulu episodes.

As an alternative, we suggest that the higher ratio for the Puu Oo eruption may have resulted from alternating additions to and subtractions from rift-zone storage. The rift zone, at least in the Puu Kamoamoa region, apparently inflated and deflated in tandem with Kilauea's summit (fig. 17.23). Thus we infer that successively accumulated and extruded volumes were accommodated in hydraulically connected summit and rift-zone reservoirs. If this is true, the volume of magma supplied to Kilauea during repose periods was accommodated by volume increases in both the summit and rift-zone reservoirs, and the volume of magma erupted during fountaining episodes was accommodated by volume decreases in both the summit and rift-zone reservoirs. Because part of the volume accommodation occurred in the rift-zone reservoir during Puu Oo eruptive episodes, surficial volume changes at the summit and related Uwekahuna tilt changes are insufficient measures of erupted volume.

The generally similar average ratios of volume to tilt change determined for the early Mauna Ulu episodes (0.35) and for surficial volume changes (0.38–0.45) represent about 55–70 percent of the average ratio of erupted volume to tilt change (0.63) for episodes 2–20 of the Puu Oo eruption. If the Mauna Ulu and surficial volume ratios are applied to Puu Oo episodes as a measure of summit-reservoir volume change, 55–70 percent, on the average, of the erupted volume (considered vesicle-free) was accommodated by summit-reservoir volume changes. The remaining 30–45 percent could have been accommodated by changes in the volume of rift-zone storage.

We emphasize that, because of large scatter in the ratios of erupted volume to tilt change for specific episodes (table 17.3), estimates of reservoir-volume change are at best generalized approximations. Furthermore, variations in summit-inflation rate (compare summit tilt-change patterns preceding episodes 16 and 17, fig. 17.24), including occasional deflationary episodes during repose periods, suggest that transfer of magma from the summit to the rift zone may have occurred during repose periods in an irregular and unpredictable pattern. Thus, we cannot predict the volume of rift-zone accommodation or the erupted volume for a single episode with reasonable precision from the Uwekahuna tilt record.

TIMING OF TILT CHANGES AND ERUPTIVE ACTIVITY

During eruptive episodes, changes in tilt rate or direction at the summit were often closely related to changes in eruptive activity.

Once the vent became established at Puu Oo, the tilt changes tended to lag behind the changes at the vent (table 17.3).

Typically, such changes occurred only at the beginnings and endings of eruptive episodes. However, discharge stopped and then resumed once during episode 13 and three times during episode 19. The rate of tilt change at the summit responded to each of these changes at the vent (fig. 17.27), emphasizing the effectiveness of the connection between vent and summit areas. In each case, however, the rate of summit tilt change reached a minimum several hours after the end of the related fountaining event. Similarly, the rate of tilt change reached a maximum in each case several hours after fountaining resumed.

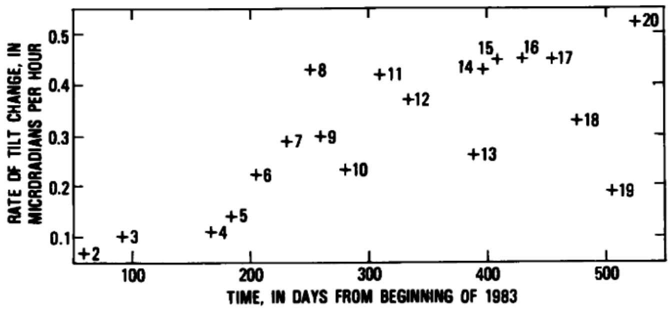


FIGURE 17.25.—Average rate of deflationary, east-west tilt change at Uwekahuna tiltmeter, episodes 2–20, Puu Oo eruption.

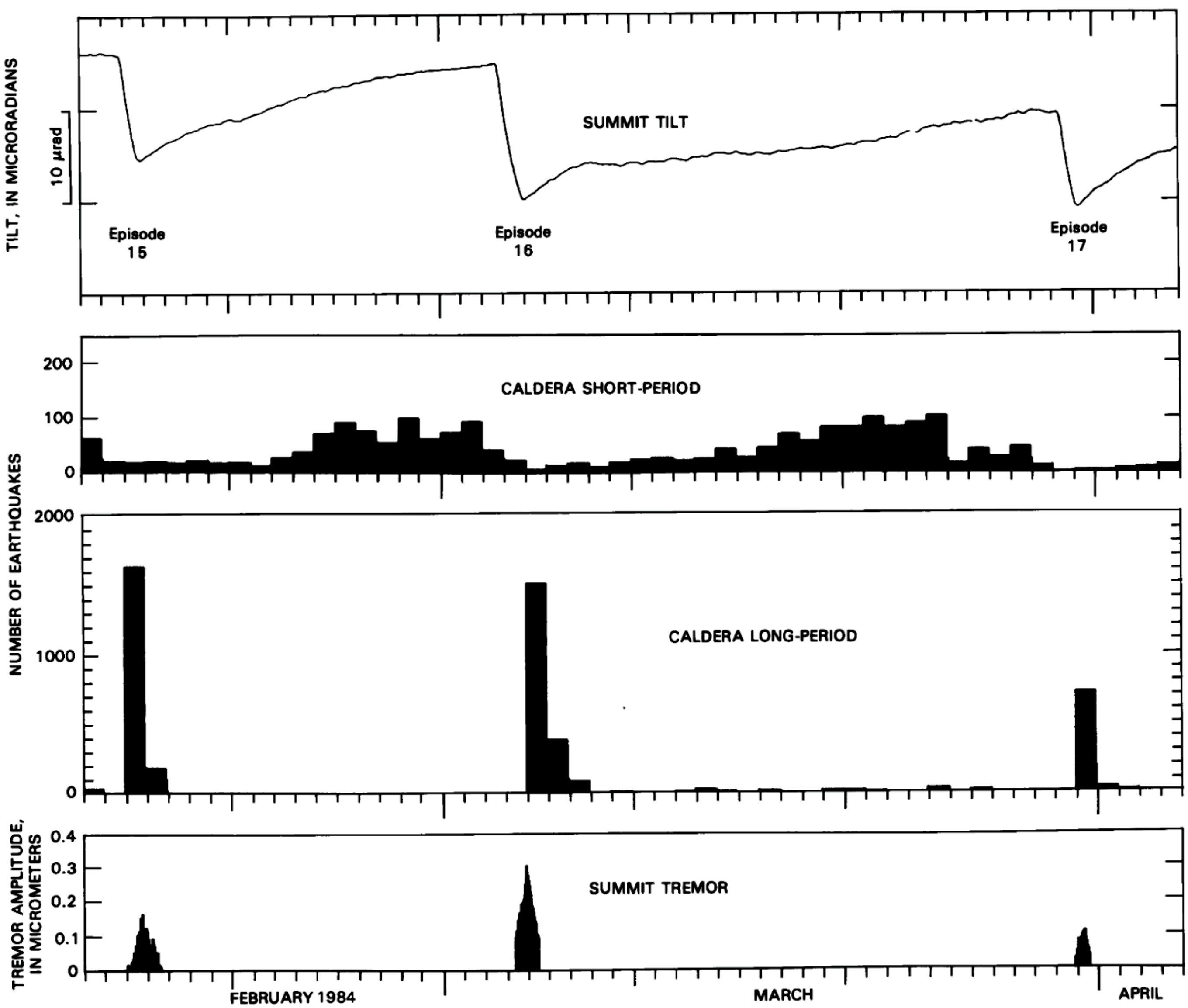


FIGURE 17.24.—East-west summit tilt, daily frequency of short-period and long-period caldera earthquakes, and amplitude of shallow harmonic tremor beneath Kilauea caldera, episodes 15–17, Puu Oo eruption.

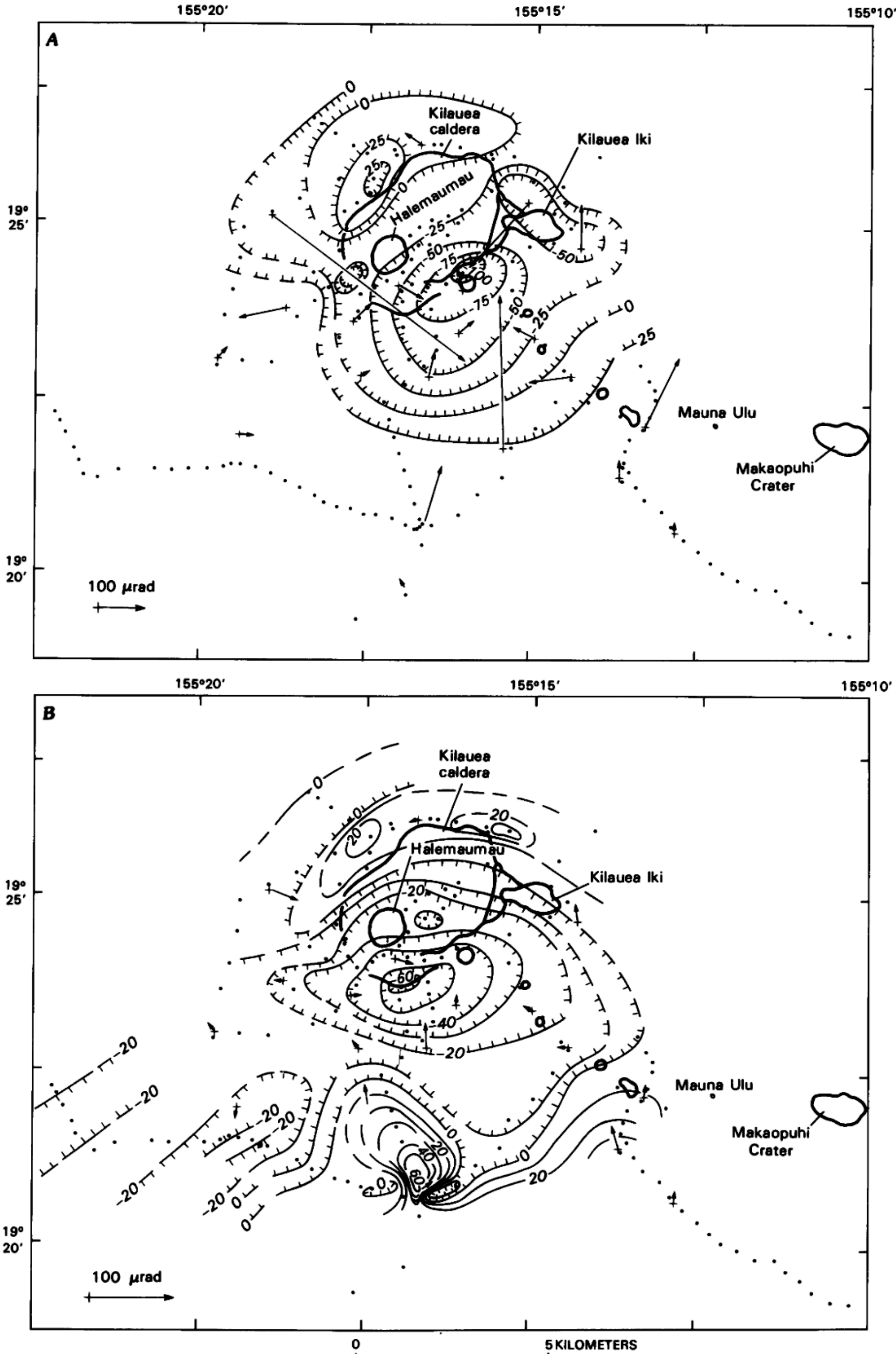


FIGURE 17.26.—Kilauea summit level change and tilt change during two periods of the Puu Oo eruption. ***A***, February 7 to December 28, 1983. ***B***, December 28, 1983, to July 23, 1984.

TABLE 17.3.—*Subsidence and relation to erupted volume, episodes 2–20, Puu Oo eruption, Kilauea*

[Tilt change is eastward on the east-west component of Uwekahuna tilt. Beginning lag is the time from start of eruption to start of accelerated, sustained deflation. For some episodes, uncertainty arises from the gradual nature of the onset of eruption or deflationary tilt change and from the absence of direct observation of the onset of eruption. Ending lag is the time from end of eruption to end of deflationary tilt change. Erupted volume corrected to remove 25 percent porosity.]

Episode	Tilt change (μrad)	Subsidence			Erupted volume/ tilt change ($10^6 m^3/\mu rad$)
		Duration (h)	Beginning lag (h)	Ending lag (h)	
2	10.9	151	−2.0	−24.8	.964
3	28.1	292	−1.0	1.0	1.014
4	11.2	98	4.6	3.3	.735
5	11.9	86	6.7	2.2	.819
6	16.2	72	3.5	2.5	.416
7	16.7	57	2.3	3.0	.630
8	10.0	23	5.8	4.5	.601
9	14.9	50	3.3	1.7	.402
10	14.1	60	3.9	.2	.745
11	17.4	41	2.2	.2	.517
12	13.8	37	.2	2.3	.434
13	11.1	43	3.6	4.6	.676
14	9.8	23	2.3	5.7	.458
15	11.3	25	.3	6.0	.531
16	14.8	33	1.2	2.5	.609
17	10.2	23	3.2	3.6	.732
18	19.4	58	2.0	.5	.928
19	4.1	21	6.0	[1]−16.8	.366
20	9.4	18	.9	9.6	.318

[1]Episode 19 included lava-pond activity and low-volume overflows that continued for a day after the end of intermittent fountaining and high-volume flow production. Ending lag = 6.6 h when considered with respect to end of high fountains and high-volume flow production.

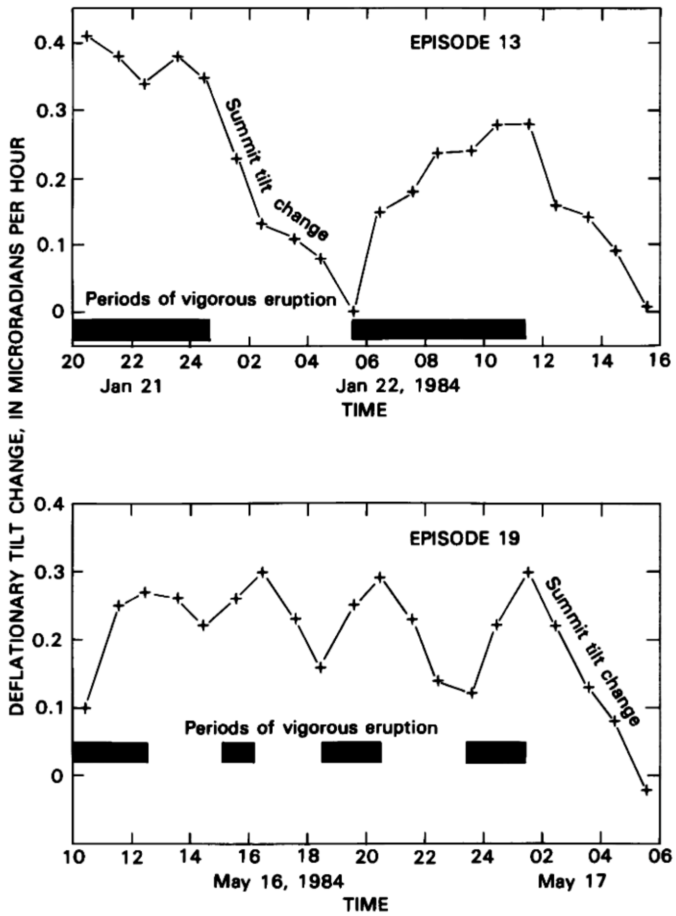


FIGURE 17.27.—Periods of vigorous discharge and variations in rate of summit tilt change for parts of episodes 13 and 19, Puu Oo eruption.

From episode 3 on, summit deflation continued for as long as several hours beyond the end of lava production (table 17.3). From episode 4 on, the beginning of sustained rapid deflation lagged behind the beginning of steady lava production. In contrast, we note that, during episode 2, lava production continued for a full day after summit deflation had stopped. The starts of episodes 2 and 3 were gradual and the time relations therefore somewhat subjective (table 17.3), but our interpretation is that vigorous discharge lagged slightly behind the onset of rapid deflation.

The approximate balance between Uwekahuna tilt changes during repose periods and during fountaining periods for episodes 2–20 (fig. 17.15) implies that eruptive episodes began and ended in response to increased and decreased pressure in the reservoir system. However, the abrupt terminations of fountaining from episode 4 on and the delayed response of summit tilt to eruptive changes suggest that a valve nearer to the vent than to the summit reservoir was the immediate control over the timing of fountaining.

EXPLANATION

- Leveling bench mark
- Contour of level change—Dashed where approximately located; hachures indicate direction of subsidence. Contour interval: *A*, 25 mm; *B*, 10 mm
- Spirit-level tilt station with direction and amount of tilt change
- Crater or caldera rim

FIGURE 17.26.— Continued.

PETROLOGY

EPISODES 1–3

Samples of lava erupted during episodes 1–3 contain less than 6.8 percent MgO (figs. 17.28, 17.29) and thus represent differentiated basalt in the terminology of Wright and Fiske (1971) and Wright (1971). They are also depleted in CaO and enriched in FeO_t ($FeO_t = FeO + 0.9Fe_2O_3$) and in the incompatible elements. Following Wright and Fiske (1971), we interpret this lava as having resulted from fractionation of clinopyroxene and plagioclase as well as olivine from magma that had partly cooled and crystallized during prolonged storage within the rift zone.

The lava of episodes 1–3 is compositionally heterogeneous, even among samples collected during a limited time from a small geographic area. For example, nearly the full compositional range of lava sampled during episodes 1–3 was produced during episode 1 within the relatively restricted area of the 0740 and 1123 vents. Thus the lava apparently originated from several magma bodies that had differentiated to varying degrees within the rift zone. Partly resorbed xenocrysts and reversely zoned phenocrysts are present in

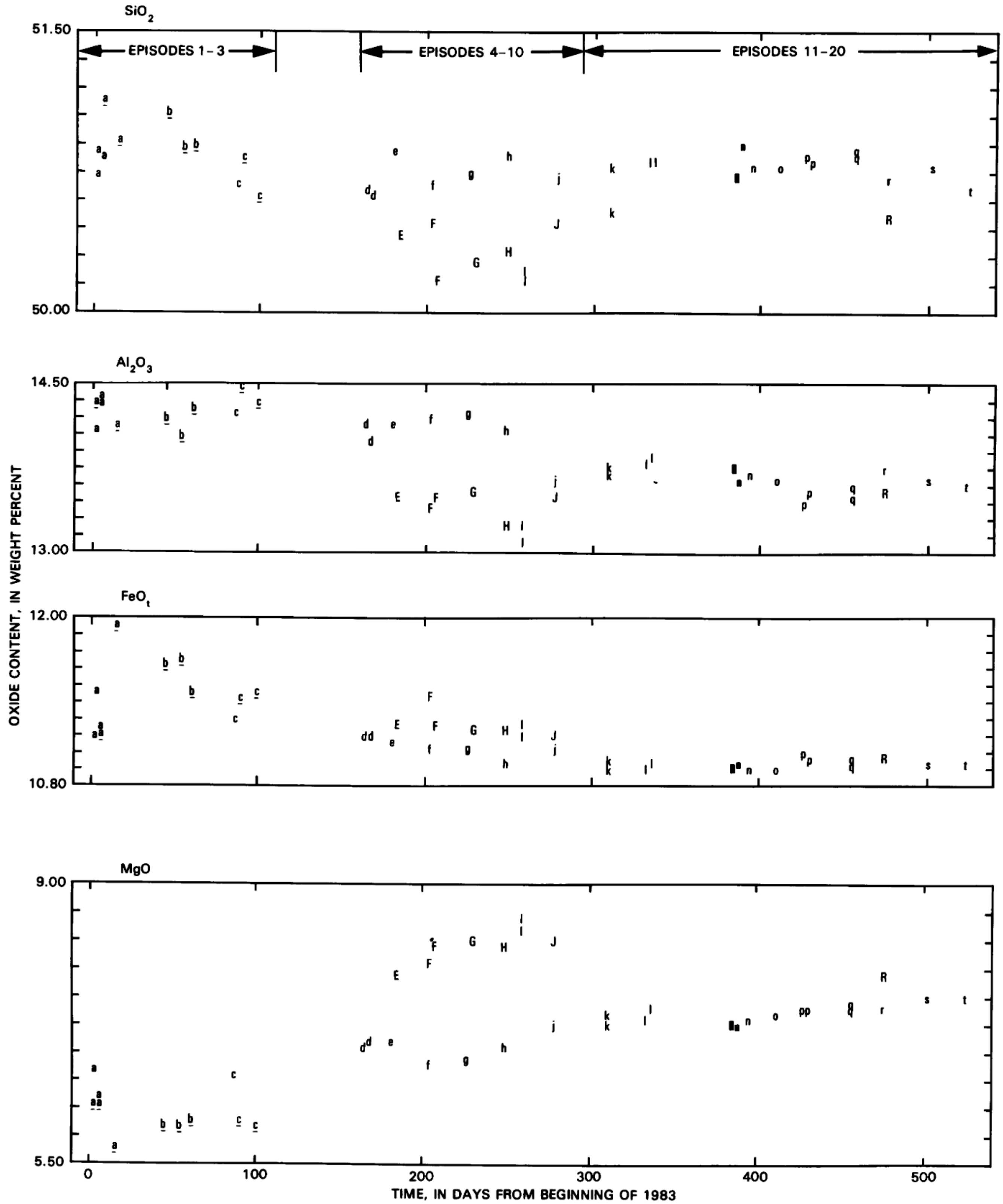
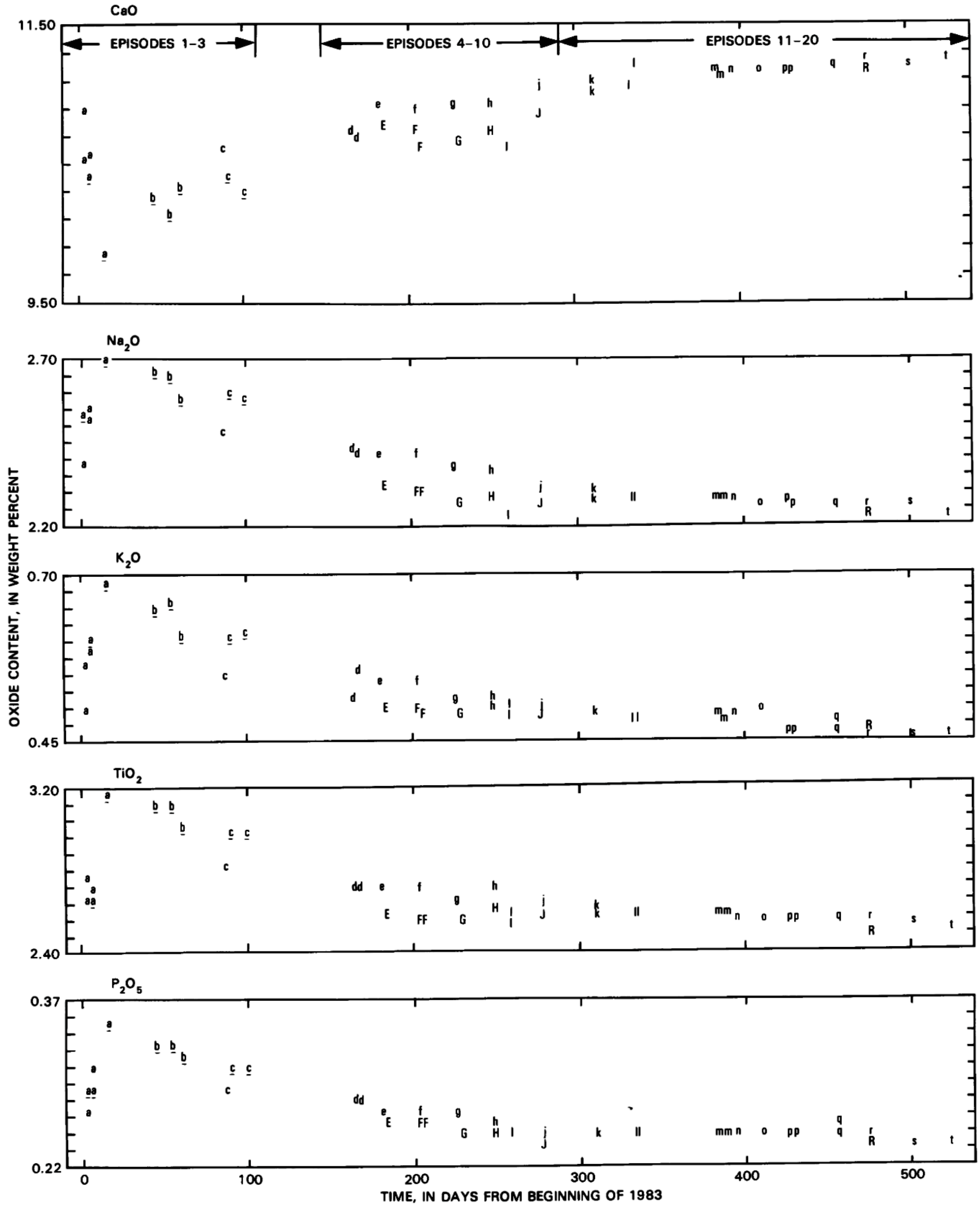


FIGURE 17.28.—Major-oxide concentrations in samples from Puu Oo eruption versus time of eruption. Letters identify episodes: a, episode 1; b, 2; c, 3; d, 4; e, 5; f, 6; g, 7; h, 8; i, 9; j, 10; k, 11; l, 12; m, 13; n, 14; o, 15; p, 16; q, 17; r, 18; s, 19; t, 20.



Capital letters designate MgO-rich lava erupted late in episodes 5–10 and 18. Underlined letters indicate samples from 0740 and 1123 vents (see fig. 17.12 for location). Compositions are from classical wet chemical analyses (see Neal and others, in press).

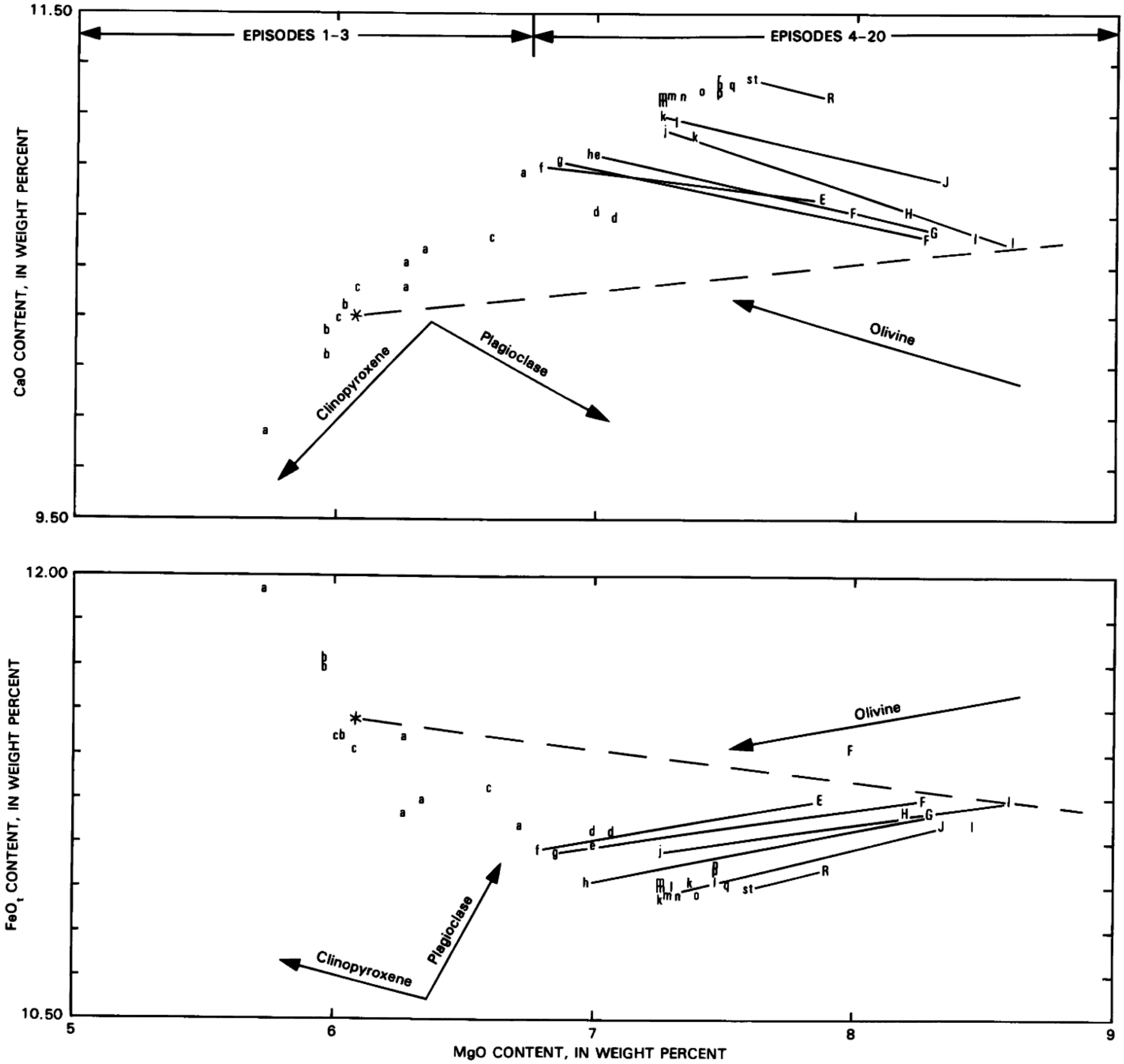


FIGURE 17.29.—CaO versus MgO and total iron (FeO_t) as FeO versus MgO for samples from Puu Oo eruption. Arrows show mineral-control lines calculated for samples with the same MgO content as the origins for the control lines (control lines have been shifted vertically to separate them from the other plotted data). Solid lines connect composition of MgO-rich lava erupted late in an episode with composition of MgO-poor lava erupted early in the succeeding episode. Long-dashed line connects average composition (*) for episode 1–3 lava (excluding the two most MgO-rich samples) and the most MgO-rich Puu Oo lava composition and is an approximate mixing line. Letters indicate episodes and capital letters MgO-rich lavas as in figure 17.28.

some of the samples, evidence that magma mixing had occurred to produce hybrid magmas.

EPISODES 4–20

Lava from episodes 4–20, all of which erupted from Puu Oo, contains 6.8 percent or more MgO. The most conspicuous compositional variation, which occurred within individual episodes 5 through 10 and to a lesser degree during episode 18, can be largely explained as a consequence of olivine fractionation; thus the lava is olivine-controlled in the terminology of Wright and Fiske (1971) and Wright (1971). An additional subtle long-term compositional change is not related to olivine control.

TABLE 17.4.—*Comparison of early episode 10 basalt and composition calculated by subtracting 3.74 percent late episode 9 olivine from late episode 9 basalt*

[Values given are in weight percent]

Oxide	(a) Early episode 10 basalt	(b) Calculated composition	Residual (a minus b)
SiO_2	50.91	50.88	0.03
Al_2O_3	13.71	13.70	.01
FeO_t	11.11	11.10	.01
MgO	7.30	7.30	.00
CaO	11.09	11.07	.02
Na_2O	2.32	2.33	−.01
K_2O	.50	.51	−.01
TiO_2	2.64	2.68	−.04
P_2O_5	.25	.26	−.01
MnO	.17	.18	−.01

During episodes 5–10 and 18, a transition to more MgO-rich lava occurred as the eruptive episode progressed, and all of the other oxides decreased in abundance as MgO increased (figs. 17.28, 17.29). Thus, eruption from a zoned body produced relatively MgO-poor lava early in an episode, and MgO-rich lava was erupted late. Samples for classical analyses represented in figures 17.28 and 17.29 were usually taken in the early and late parts of each eruptive episode. Additional analyses by electron microprobe, from episode 7 (not shown in figures 17.28, 17.29), indicate that the compositional change during the fountaining episode was gradational. Lava sampled during the period of small intracrater pahoehoe flows and pond activity that commonly preceded the major eruptive episodes was similar in composition to the early, MgO-poor lava of the following fountaining episode. Apparently magma in the column beneath the Puu Oo crater floor underwent a compositional change from MgO-rich to MgO-poor during some of the repose periods. Extension of the trends for the MgO-poor lava of episodes 5–10 indicates that only the MgO-poor variety was erupted during episodes 11–17 and 19–20.

Even though the repose periods were brief, crystal fractionation within the magma column seems the most plausible explanation for the compositional change that occurred between eruptive episodes. The most compelling example is the change from MgO-rich lava at the end of episode 9 to MgO-poor lava early in episode 10; it can be precisely accounted for by removal of 3.74 percent of late episode 9 olivine from late episode 9 basalt (table 17.4). Other repose-period compositional changes are fit less precisely by olivine fractionation alone. Nevertheless, the joins connecting the compositions of MgO-rich lava from late in one episode and MgO-poor lava from early in the next (fig. 17.29) are nearly parallel to the olivine-control line (calculated for late episode 9 basalt and its contained olivine). This near coincidence suggests that subtraction of olivine was the dominant cause of the compositional variation during single eruptive episodes. Petrographic data show that the higher MgO content of lava erupted late in a fountain episode does not reflect increased abundance of olivine crystals.

Episode 4 lava did not show the compositional change typical of episodes 5–10. Perhaps the specific magma-column geometry that led to fractionation of a limited melt volume during repose periods originated during episode 4. Thus, the fractionation occurred only during later repose periods.

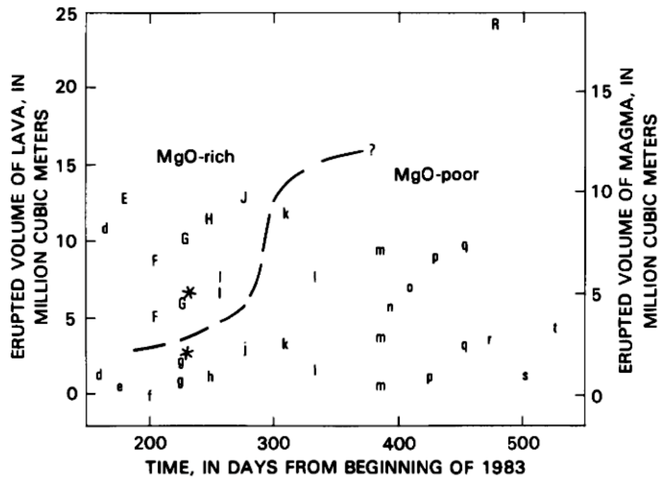


FIGURE 17.30.—Volume of lava (left axis) or magma (right axis) erupted in each episode (4–20) of the Puu Oo eruption at the time of collection of each analyzed sample. Letters indicate episodes and capital letters MgO-rich lavas as in figure 17.28. *, composition from microprobe analysis. Volume erupted by time of collection was estimated by multiplying the subsequently determined discharge rate by the time elapsed from the beginning of the eruptive episode.

The MgO-depleted magma in the zoned body was completely erupted in each of episodes 5 through 10. Thereafter, the MgO-depleted volume was too large to be exhausted in an eruptive episode, except for episode 18, which produced an appreciably greater volume than its predecessors at Puu Oo (table 17.1).

We have estimated the volume of lava that had been erupted in each episode at the time that each analyzed sample was collected (fig. 17.30). The first occurrence of both MgO-poor and MgO-rich lava in a single episode was during episode 5, but the volume of early MgO-poor lava is not well constrained. During episodes 6 through 9, MgO-poor lava gave way to MgO-rich lava after about 2.3×10^6 to $5.2 \times 10^6 m^3$ of lava had been produced. The volume of MgO-poor lava in episode 10 is poorly constrained but it was less than $12.7 \times 10^6 m^3$. Episode 11 produced $12 \times 10^6 m^3$ of lava that was all MgO-poor, as was the lava of subsequent episodes except for 18. Lava collected at the end of episode 18, after eruption of $24 \times 10^6 m^3$, was richer in MgO than early episode 18 lava but less so than most of the other MgO-rich lavas.

The volumes of MgO-poor lava, considered void-free so as to approximate magma volumes, indicate that about $3 \times 10^6 m^3$ of MgO-poor magma was available in the reservoir during the early parts of episodes 5 through 9. Between episodes 9 and 11, this increased to more than $9 \times 10^6 m^3$, but episode 18 indicates it did not exceed $18 \times 10^6 m^3$.

Subsidence of the Puu Oo crater floor and collapse of the crater walls occurred late in episode 10. In the next two episodes, fountain heights were dramatically lower, and lava issued from several vents

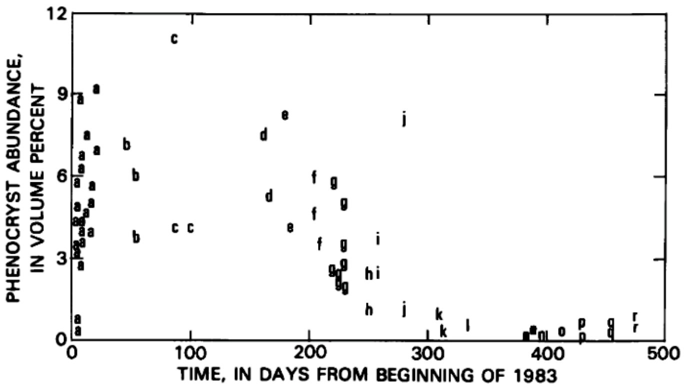


FIGURE 17.31.—Total percentage of olivine, augite, and plagioclase phenocrysts versus time of collection of lava samples from Puu Oo eruption. Letters indicate episodes as in figure 17.28.

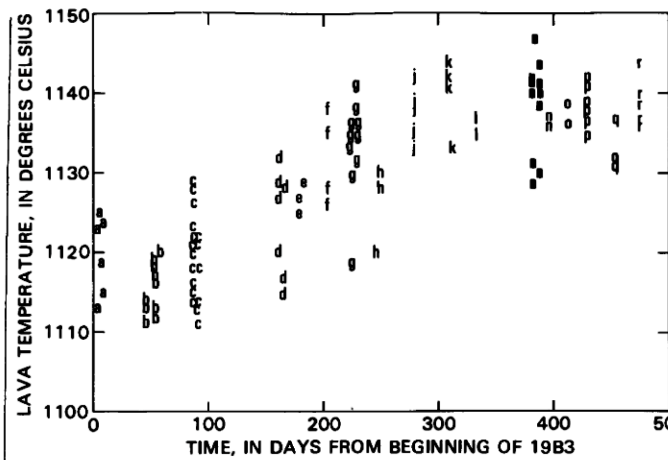


FIGURE 17.32.—Lava temperatures measured by chromel-alumel thermocouple, episodes 1–20 of Puu Oo eruption. Letters indicate episodes as in figure 17.28.

both within and outside the crater. These observations suggest that collapse in the conduit had partly blocked access to the normal vent. The marked increase in the erupted volume of MgO-depleted magma between episodes 9 and 11 may have recorded enlargement of the subcrater reservoir by the same event that caused crater collapse and disrupted the fountains.

If our hypothesis that MgO-depleted magma originated by crystal fractionation of MgO-rich magma in the magma-filled conduit beneath Puu Oo is correct, then the volume of MgO-depleted magma represents a minimum value for the volume of the magma column. We have no direct measure of the column length. However, we inferred previously from the distribution of earthquakes in the shallow swarm associated with episode 1 that the feeder dike was intruded upward to the surface from an aseismic zone at a depth of 3–4 km. If the aseismic zone persisted through the subsequent fountaining episodes as the subhorizontal zone of magma supply from the summit reservoir to the vent region, we can surmise that the magma column beneath Puu Oo was 3–4 km long. Using a 3.5-km length and the volume estimate of $3\times10^6\,m^3$ for episodes 5–9, we calculate a minimum average diameter for the magma column of about 30 m. For the volume estimates for the later episodes (9×10^6 to $18\times10^6\,m^3$), the calculated minimum average diameter is 60–80 m. These values are in close agreement with estimates of average conduit diameters of 40–70 m inferred from volumes of gas-enriched melt that caused high fountains early in some episodes (Wolfe and others, in press) and 50 ± 30 m inferred from interpretation of gas-flux and geodetic measurements (Greenland and others, in press).

The lava of episodes 4–20 shows a long-term compositional change marked by gradual increase in CaO and MgO and decrease in FeO_t and incompatible elements (figs. 17.28, 17.29). The changes are small, and the progression is imperfect. Nevertheless, figure 17.29 shows unmistakably that, in both the MgO-poor and MgO-rich lavas, CaO and MgO gradually increased together through time and FeO_t concomitantly decreased through time. Imposition of this progressive compositional change on both lava types supports our interpretation that each volume of MgO-depleted magma was derived from an associated volume of MgO-rich magma. In a sense, the two share a common fingerprint imposed by the gradual long-term compositional change.

Two possible reasons for the long-term compositional trend involve rift-zone mixing (see, for example, Wright and Fiske, 1971; Wright and others, 1975) and gradual compositional change of the melt produced in the mantle (see, for example, Hofmann and others, 1984). If mixing is the reason, fresh magma from the summit would become contaminated to progressively decreasing degrees from contact during its passage through the rift zone with older CaO- and MgO-depleted magma still in storage. We do not know the possible end-member compositions, but for illustration we have drawn an approximate mixing line (fig. 17.29) connecting the most MgO-rich sample (late episode 9) and an average composition that includes all analyzed lava from episodes 1–3 except for two samples that have significantly higher MgO contents (6.59 and 6.72 wt percent) and may reflect more recent involvement of summit magma than do other lavas of episodes 1–3.

If changing parent composition is the reason, then the progressive increase in CaO and depletion of incompatible elements, emphasized when the compositions from episodes 5–20 are normalized to a common MgO value by adjusting for olivine control, may have resulted from increasing melting of clinopyroxene in the mantle.

Reversely zoned phenocrysts in some samples from episodes 4–10 suggest magma mixing. Lava of episodes 11–20 was nearly aphyric (fig. 17.31), and no phenocrysts suggestive of disequilibrium were found. Lava-temperature measurements show much scatter (fig. 17.32) but suggest that the temperature increased through the early episodes, perhaps through episode 11, and then leveled off. This increase could have been a consequence of decreasing contamination of hotter summit melt by cooler rift-zone melt. We note that the change in phenocryst content and the change in measured temperatures through time roughly mimic the compositional changes

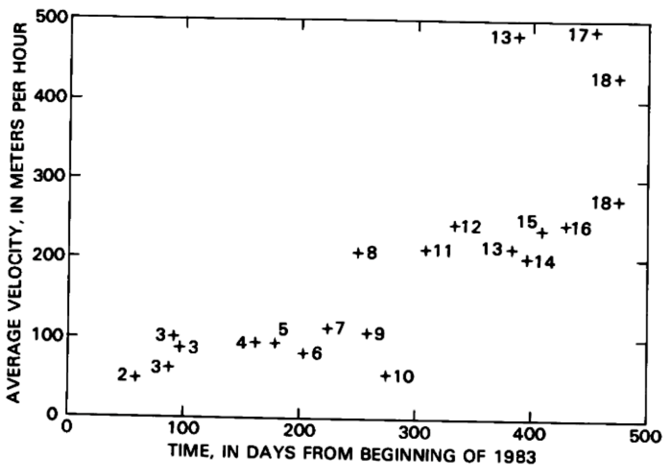


FIGURE 17.33.—Average flow-advance rate versus time of eruption for the major river-fed flow(s) of eruptive episodes 2–18, Puu Oo eruption. Flow-advance velocity was determined by periodic mapping of flow-front position.

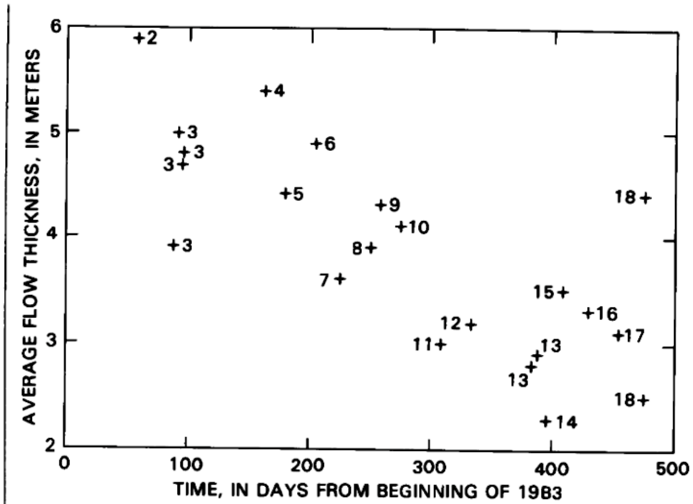


FIGURE 17.34.—Average flow thickness versus time of eruption, episodes 2–18 of Puu Oo eruption. Thickness was measured at numerous localities along flow margin. Average thickness was obtained from calculated volume/measured area.

recorded from episode 4 through 20. Average velocity and average thickness of the major river-fed lava flows (figs. 17.33 and 17.34) also roughly mimic these patterns. Velocity was greater and thickness less during episodes 11–20, suggesting that lava viscosity decreased, in accord with changing lava composition, petrography, and temperature.

NEGLIGIBLE EFFECTS OF MAUNA LOA EARTHQUAKE AND ERUPTION

A large ($M = 6.7$) earthquake (Buchanan-Banks, chapter 44; Koyanagi and others, 1984) occurred beneath Mauna Loa's southeast flank on November 16, 1983, between episodes 11 and 12 of the Puu Oo eruption. The earthquake caused an abrupt tilt change of nearly 300 μrad at the Uwekahuna tiltmeter (fig. 17.15), but it produced no recognizable change in the continuing events at Puu Oo.

A Mauna Loa eruption occurred from March 25 to April 15, 1984 (Lockwood and others, 1985); for the first time since 1919, Kilauea and Mauna Loa were in eruption simultaneously. Episode 17 of the Puu Oo eruption occurred on March 30–31, during the Mauna Loa eruption, and episode 18 on April 18–21 following the Mauna Loa eruption. The volume of episode 18 was larger than usual (table 17.1), but otherwise Puu Oo activity during and immediately after the Mauna Loa eruption was normal.

INTERPRETIVE SUMMARY

The east rift zone of Kilauea has been a major locus of magma storage as well as eruption; Dzurisin and others (1984) estimated that at least $1 \times 10^9 m^3$ of magma was added to east-rift-zone storage between 1956 and 1983. From late 1978 through 1980, the Puu Kamoamoa-Puu Kahaualea area, where the major vents of the Puu Oo eruption are located, was the site of repeated intrusions that caused flurries of shallow earthquakes and increasing tumescence of that part of the rift zone.

After a period of quiescence during 1981 and part of 1982, small intrusions into the Puu Kamoamoa area resumed following a summit intrusion and eruption on September 25–26, 1982. In early January 1983 a voluminous east-rift intrusion resulted in large subsidence of the previously distended summit reservoir, emplacement of a new feeder dike, and onset of the Puu Oo eruption.

The intrusion was initiated by an aseismic magmatic surge through magma-filled passages in the uppermost part of the east rift zone and by the onset of dike emplacement near Makaopuhi Crater. The distribution of shallow earthquakes indicates that the dike propagated upward from an aseismic region at a depth of 3–4 km within the rift zone, and its tip migrated downrift as intrusion continued. The upper edge of the dike eventually intersected the ground surface from Napau Crater to Kalalua, initiating nearly two weeks of intermittent fissure eruptions.

Over most of its length, the fissure system soon stopped erupting. Intermittent fissure eruptions during episode 1 of the series, in January 1983, became localized primarily south of Puu Kahaualea. During episodes 2 and 3, a central vent south of Puu Kahaualea, the 1123 vent, was the dominant eruptive locus, and a lesser one was located 1.5 km uprift in the area where Puu Oo was to develop. From episode 4 on, the Puu Oo vent was the main locus, and, except for fissures in the immediate vicinity of Puu Oo that were briefly active a few times, eruption has never recurred elsewhere along the fissure system (as of June 1985).

After episode 1, low harmonic tremor continued during repose periods, and subsequent fountaining episodes began without shallow earthquake swarms. Both these observations indicate that an active magma conduit was maintained between the summit and vent areas.

As the eruptive series progressed, the rift-zone conduit became more efficient in transporting magma, as indicated by the general increase in average lava-discharge rate. Factors that may have contributed to more rapid magma transport include enlargement and streamlining of passageways and reduction of melt viscosity as a consequence of increased temperature or decreased crystallinity. We have no direct means of evaluating the character of the magma-filled passageways, but enlargement or streamlining seem likely consequences of repeated passage of melt through them. We note that the lava generally became hotter and less porphyritic as the Puu Oo eruption progressed.

Several different phenomena, considered together, suggest that the main vents, located in the general Puu Kamoamoa-Puu Kahaualea area, overlay a zone of magma storage that antedated the beginning of the eruption. Effects specifically related to such a zone include: (1) anomalously rapid downrift passage of surface deformation preceding the tip of the dike; (2) dissipation of the tightly clustered concentration of shallow earthquakes that farther uprift recorded a systematic, steady downrift advance of the dike tip; (3) decreased concentration of shallow earthquakes associated with dike emplacement and establishment of the new vents; and (4) localization of repeated small intrusions from late 1978 through 1980.

The petrologic evidence suggests that a magma-storage zone had existed for a long time beneath the Puu Kamoamoa-Puu Kahaualea area. Lava erupted from the inferred storage zone during episodes 1–3 was differentiated beyond olivine control and was significantly cooler than olivine-controlled lava erupted later from Puu Oo. Following Wright and Fiske (1971), we infer that the lava of episodes 1–3 evolved as a consequence of crystal fractionation resulting from cooling and partial crystallization during prolonged storage in the rift zone. Additional compositional modification apparently resulted from magma mixing, as indicated by partly resorbed xenocrysts and reversely zoned phenocrysts. Approximately $50 \times 10^6 m^3$ of such differentiated and hybrid magma was erupted in episodes 1–3, and perhaps an additional $100 \times 10^6 m^3$ of this magma remained in the new dike.

Once the Puu Oo vent became established, the composition of lava was within the range of olivine control. Magma in the conduit beneath Puu Oo underwent a compositional change during repose periods that can be largely or entirely explained by fractionation of a few percent olivine. This produced MgO-depleted magma that was exhausted whenever the volume of the next eruptive episode exceeded the volume of MgO-depleted magma. During episodes 5–9, such MgO-poor magma gave way to MgO-rich magma after about $3 \times 10^6 m^3$ of magma had been erupted; in episodes 11–20, the volume of MgO-depleted magma available in each eruptive episode was between $9 \times 10^6 m^3$ and $18 \times 10^6 m^3$. The reservoir in which fractionation occurred during repose periods apparently was significantly enlarged between episodes 9 and 11.

Gradual enrichment of both CaO and MgO in the olivine-controlled magma erupted during episodes 4–20 may imply either decreasing levels of contamination of olivine-controlled summit magma by differentiated magma stored in the rift zone or gradually changing composition of magma generated in the mantle. The occurrence of reversely zoned phenocrysts in some of the lava of episodes 4–10 and the progressive increase in lava temperature through those episodes support the hypothesis that the lava composition was affected by magma mixing at least through episode 10.

Intrusion of summit magma into the rift zone apparently displaced differentiated magma already in storage, causing it to erupt during episodes 1–3. If olivine-controlled magma from the summit was contaminated thereafter by differentiated magma from the rift zone, the rift-zone conduit must have intersected one or more bodies of differentiated magma. Such magma bodies were possibly stored below the zone of brittle fracture indicated by shallow earthquakes generated during upward propagation of the dike. Thus, the bodies of stored magma and the rift-zone conduit were most likely at a depth of at least 3–4 km, within the normally aseismic deeper part of the rift zone.

Symmetry of patterns of attenuation of harmonic tremor with respect to Puu Oo indicates that, although the depth is uncertain, the tremor source and the vent were in vertical alignment. Furthermore, rift-zone dikes are generally near vertical (Pollard and others, 1983), and local, approximately cylindrical conduits that transport magma upward at higher flow rates and with lower heat loss than do dikes, can evolve from dikes by local erosion of wallrock as adjacent dike segments solidify and become inactive (Delaney and Pollard, 1981, 1982). These considerations suggest that a nearly vertical conduit descended from the Puu Oo vent in the plane of the initial dike. We suppose that the junction between the approximately vertical feeder conduit and the subhorizontal rift-zone conduit was located near the base of the episode 1 dike at a depth of 3–4 km. The mouth of the conduit, about 20 m in diameter, was nearly continuously visible in the crater floor after episode 13. The diameter may have increased downward. Erupted volumes of MgO-depleted melt were too large to have been accommodated in a conduit only 20 m in diameter and 3–4 km long; average diameters of 30 m for episodes 5–9 and 60–80 m for episodes 11–20 are implied if all of the inferred fractionation took place within this vertical magma column.

As eruptive activity became localized at Puu Oo, the presence of a nearby magma reservoir became evident from rift-zone tilt changes. Beginning with a subsidence during episode 3, rift-zone tumescence developed gradually during repose periods and rift-zone subsidence occurred rapidly during eruptive episodes, as indicated by a borehole tiltmeter northwest of Puu Kamoamoa. This deformation was congruent with tilt changes at the summit. Thus an approximate hydraulic equilibrium with the summit reservoir was continually maintained along the rift-zone conduit.

The limited range and approximate equivalence of opposed inflationary and deflationary tilt changes at the summit and also in the rift zone indicate that eruptive episodes began and ended in response to magmatic pressure in the reservoir system. The secondary reservoir in the rift zone apparently acted as a valve, controlling eruptive activity from the rift zone rather than from the summit. Thus, from the end of episode 3, starts and stops of vigorous eruption normally preceded, respectively, the onset of rapid summit deflation or the resumption of summit inflation as recorded by the

Uwekahuna tiltmeter. Summit response also lagged behind pauses and resumptions of lava discharge during individual eruptive episodes.

Eruptive episodes started gradually, possibly reflecting non-Newtonian behavior of the magma in the conduit system (Hardee, chapter 54). Reservoir pressure had to build sufficiently to overcome the yield strength of the melt, after which flow of magma accelerated.

The central-vent episodes at the 1123 vent died gradually, fountain height decreasing apparently in response to gradually diminishing magmatic pressure. However, lava discharge at Puu Oo normally stopped abruptly, without the gradual decay that characterized the earlier episodes. Perhaps this change was related to development of the rift-zone reservoir. Progressive depletion of the rift-zone reservoir, reflected by subsidence in the rift zone during eruptive episodes at Puu Oo, apparently led to abrupt termination of the eruption when pressure in the near-vent part of the reservoir system fell below a critical level sufficient to maintain the supply of fresh, nonvesiculated magma to the column below the vent. Summit deflation continued briefly as pressure was equalized in the linked summit and rift-zone reservoir systems.

We calculate an overall magma-supply rate of $10 \times 10^6 m^3/mo$ for episodes 2–20. Allowing for errors in volume measurement, this value is not different from the rate of $9 \times 10^6 m^3/mo$ determined by Swanson (1972) for earlier periods of prolonged eruption for which the relationships between volume change in the summit reservoir and the volume erupted could be evaluated. Higher rates, nearly $12 \times 10^6 m^3/mo$, prevailed at Puu Oo during episodes 4–12 and 13–17. In these two sequences, recurrence intervals and erupted volumes had a miniminal range, indicating that an approximately steady relationship was maintained between magma supply to the reservoir system and frequency and volume of eruption. Each of these periods of elevated supply of magma to the vent was preceded by an unusually long repose period. Thus, the long-term supply rate was less.

Inferred magma-supply rates during the Puu Oo eruption equal or exceed estimates of long-term supply given by Dzurisin and others (1984), causing us to speculate that the Puu Oo eruption may coincide with a period of increased magma supply to Kilauea. A marked increase in SO_2 flux to the atmosphere in the Kilauea caldera region occurred about one month after the beginning of the eruption and may reflect increased rate of supply of magma to the summit reservoir. We are unable to evaluate the rate of percolation of exsolved gas from the reservior region to the surface, and we have no other independent, short-term measure of supply to the reservoir. Thus, like Dzurisin and others (1984), we cannot distinguish whether the Puu Oo eruption was a response to possible increase in magma supply rate or whether it may have triggered increased supply. Nevertheless, a substantial rate of supply was apparently maintained through and beyond episode 20. It led to establishment of a comparatively unimpeded transport system from the summit reservoir to the vent at Puu Oo that is likely to remain open until disrupted by a tectonic event or until diminution of supply to the rift-zone conduit allows cooling, crystallization, and eventual termination of magma transport to the vent.

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