Correlation Between Lava-Pond Drainback, Seismicity, and Ground Deformation at Puʻu ʻŌʻō

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Abstract

The crater of Puʻu ʻŌʻō, a vent along Kīlauea Volcano's east rift zone on the island of Hawaiʻi, is occupied periodically by a lava pond. During the 50 days from September 30 to November 19, 1999, pond activity comprised periods of slow filling and rapid drainback. Pond filling typically occurred without measurable changes in seismicity or ground deformation. In contrast, the beginning of each drainback event was closely matched by heightened seismic tremor, as measured by a seismometer 2 km west-southwest of the lava pond. Intensified tremor typically continued after the end of visible drainback, lasting another 45–90 minutes before tremor returned to background level. Ground deformation, monitored by a borehole tiltmeter 1.8 km northwest of the lava pond, also correlated with pond drainback. The onset and cessation of local inflationary tilt more or less coincided with the beginning and completion of pond drainback.

Lava-pond filling is thought to be due to vesiculation within the magma column beneath the vent. The magma column expands, but pressurization within the system is minimized, owing to the free surface at the top of the column. Pond drainback is initiated by an abrupt release of gas at the vent orifice as vesiculation proceeds sufficiently to shred through the magma column. Within seconds, the downpipe flow of ponded lava occludes the conduit and inhibits gas escape. Pressurization increases until the vent clears, a cycle recorded by the tiltmeter as short-lived inflation, lasting only as long as is needed to drain the pond. The common absence of a lava pond for much of the time since 1997 suggests that systemic permeability in the Puʻu ʻŌʻō edifice has increased, likely by stoping of the cone. Cycles of pond filling and drainback may occur when the system is resealed by infiltrating magma.

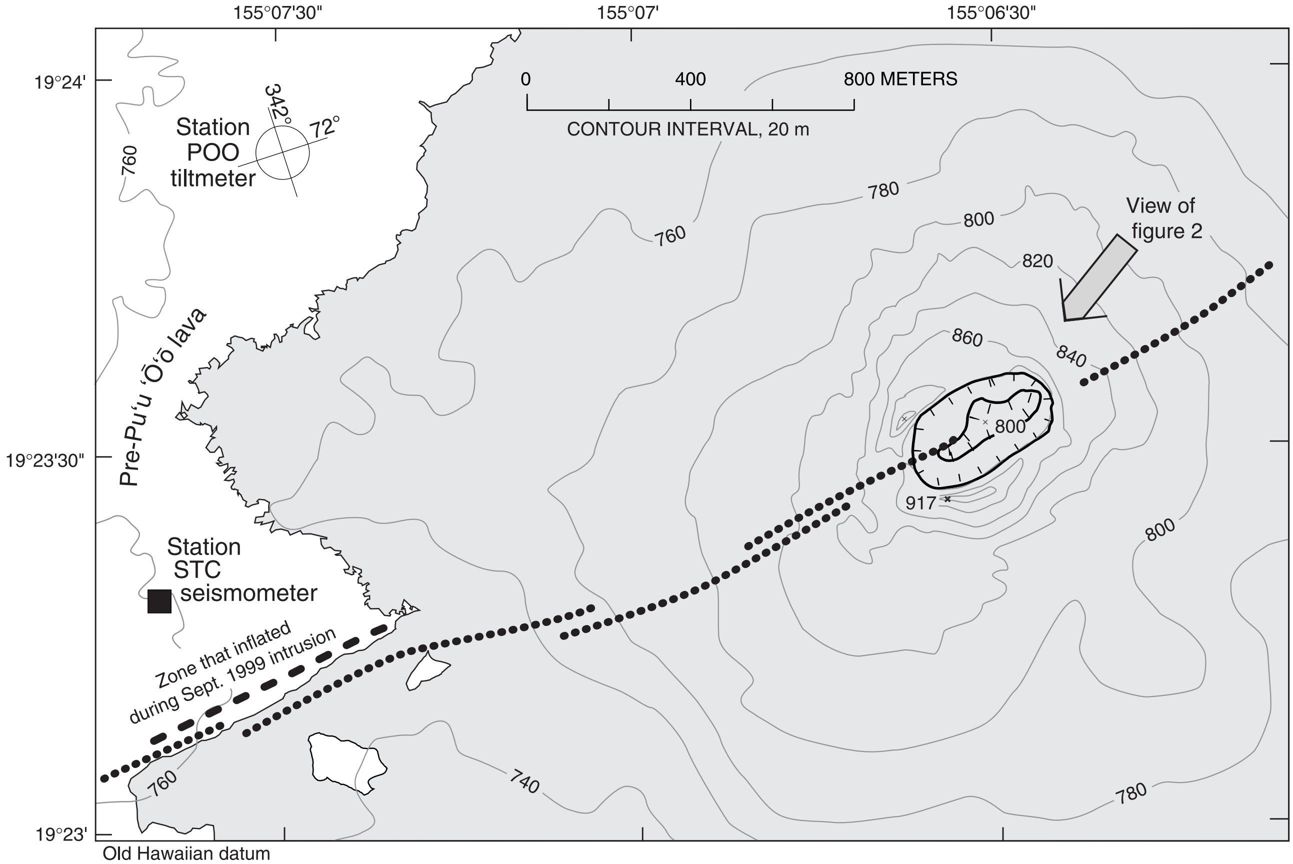
Setting

Kīlauea, one of the world's most active volcanoes, has been in a state of near-constant eruption since 1983 (for example, Wolfe and others, 1988; Mangan and others, 1995; Garcia and others, 1996; Heliker and others, 1998). Tholeiitic basaltic melt generated by hotspot processes is supplied to a magma chamber 1 to 4 km beneath the volcano's summit (Klein and others, 1987; Dawson and others, 1999). From there it travels 20 km through a shallow dike system along the east rift zone to the currently active vent, Puʻu ʻŌʻō (fig. 1). From this vent, lava is more or less at the land's surface, flowing downslope through lava tubes to the ocean or periodically spilling from the tubes to form pāhoehoe and ʻaʻā flows.

In this chapter we describe events that occurred between September 30 and November 19, 1999, a period when a lava pond intermittently filled and drained within the crater of Puʻu ʻŌʻō. During this time, a remote-surveillance camera monitored lava-pond activity, and nearby geophysical instruments monitored ground deformation and seismicity; the instruments provided records that correlate closely with lava-pond activity.

Puʻu ʻŌʻō's crater is elliptical, about 240 by 400 m in diameter (figs. 1, 2); its long axis parallels the east rift zone. From late September 1999 until January 2002, the crater's main floor remained about 35 m below the lowest crater-rim points. Inset into the floor during much of that time was an irregular elongate trough 285 m long and about 15 to 20 m deeper than the main crater floor. Through early 2000, this trough filled periodically to form a lava pond. Depth from the crater rim to the main crater floor shallowed only slightly as a few thin lava flows partly mantled the crater floor during overflow from the trough. The lava level from the main crater floor to the floor of the central trough subsided gradually after the trough was emptied.

During periods of pond activity, vesicular lava issued from vents at the east end of the trough and spread uprift to the west, flooding the trough to form a pond with a volume of as much as 4.2×10^5 m^3. Typically lava in the pond drained into the vent orifice after partly or completely filling the trough; more rarely it overflowed the trough to add a new coating to the main crater floor. The influx of lava and filling of the pond was commonly a steady, lengthy process, but drainback generally occurred abruptly and rapidly, in events typically lasting 20–50 minutes. During heightened activity, the complete filling-and-draining cycle varied from tens of minutes to several hours; at other times, the lava pond remained empty and essentially inactive for periods of 24 hours or more.



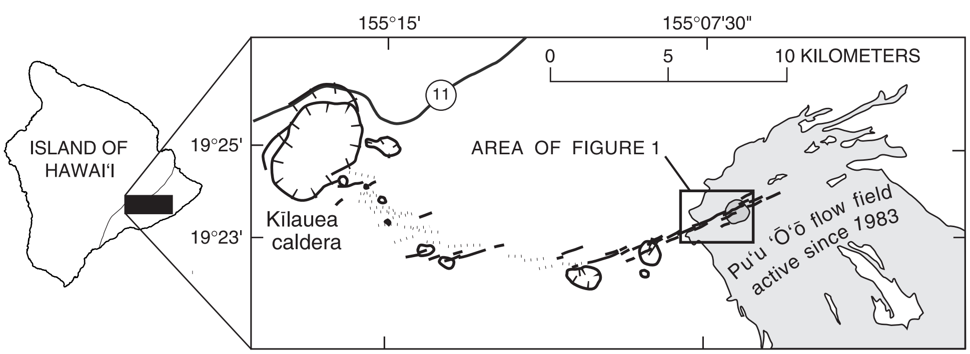


Figure 1. Eruption site, showing location of Pu‘u ‘Ō‘ō crater and adjacent tiltmeter and seismometer. Dotted lines, inferred rift-zone dike. Orientation of principal axes for station POO tiltmeter shown by crossed circle. Inset (left) shows path of echelon dike system from Kīlauea’s summit magma reservoir beneath Kīlauea caldera to Pu‘u ‘Ō‘ō, on basis of schematically depicted surface cracks (solid lines) and inferred dike orientations (dotted lines).

Monitoring Equipment and Results for 1-Day Sampling Periods

Remote-Surveillance Camera

Lava-pond activity in Pu‘u ‘Ō‘ō’s crater was monitored visually by a remote-surveillance camera that transmitted digital images to the Hawaiian Volcano Observatory (HVO; Thornber, 1997). This camera system is the latest stage in a lengthy history of monitoring that has included time-lapse 8-mm movie cameras and, more recently, video camcorders placed on the vent’s rim (fig. 2). In its 1999 configuration, the remote-surveillance camera received images about once every 5–10 s. An image-storing cycle occurred every 5 minutes, when 2 to 20 images were collected during a 1–minute interval. Thus, the approximate error when ascribing times to filling and drainback events that began between image-storing cycles was about 2.5–3.0 minutes.

Although fume, fog, or rain obscured the view of the lava pond in some images, these conditions were surprisingly sparse during the period of interest. Apparently enough heat was generated by active lava that steam was unable to condense or was driven off as updrafts ventilated the crater. Thus, if the pond was active, incandescent lava could commonly be seen in the images. Electronic failure at the camera site or in the image-processing software prevented the logging of images from October 7 to14 (UTC Julian days 280.5–287.9), 7 days of the 50-day period discussed here.

The near-constant depth of the drained central trough during October and November 1999 allows us to describe the depth of the lava pond by reference to its height below the main crater floor (from –1 m when full to –20 m when empty). For ease of representation, overflows onto the main floor were assigned heights between +3 and +5 m, depending on their thickness on the crater floor. The sequence and magnitude of 1 day's pond-filling events are listed in table 1, and the results for three representative days are plotted in figure 3.

Near-Vent Seismometer

Since August 7, 1985, a high-gain, short-period seismometer has operated at a site known as Steam Cracks (sta. STC, fig. 1), 2 km west-southwest of Puʻu ʻŌʻō. The station STC seismic record has been dominated by shallow-source tremor.

For the period September 30–November 19, 1999, an analysis of tremor variations was performed manually on analog printouts from the station STC seismometer by identifying times when distinctly higher amplitude tremor was superimposed upon a varying level of background tremor, forming banded tremor (fig. 4). The well-defined periods of increased tremor, which commonly lasted 0.5–2 hours, correlated closely with pond-drainback events (figs. 3*A*, 3*B*). (Pond filling lacked noticeable tremor.) Typically, high-amplitude tremor began at the onset of pond drainback, persisted throughout the drainback event, and continued for as much as 30–45 minutes after the end of visible drainback. Tremor for different events could begin a few minutes before, coincident with, or a few minutes after the start of drainback (table 1).

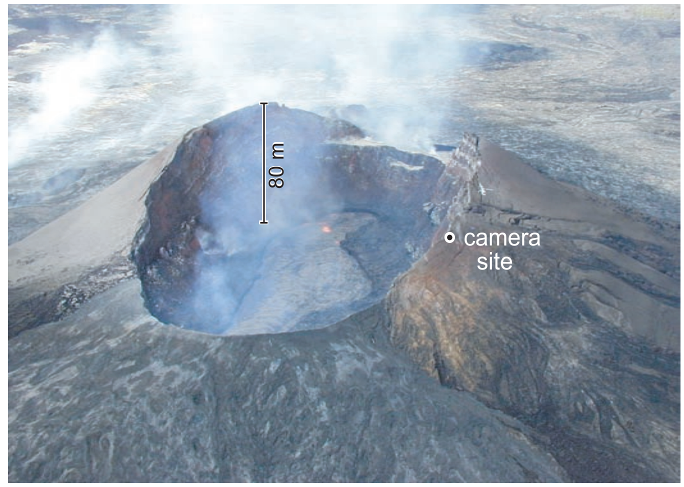


Figure 2. Puʻu ʻŌʻō crater and central trough holding active lava pond on crater floor. View orientation is indicated in figure 1. Crater, 400 m long by 240 m wide, has floor 35 m below low point on west rim and about 80 m below rim's highest point on south (left) side. View southwestward; photograph taken October 12, 1999.

This variability may stem from the relatively large imprecision associated with camera observations, probably the greatest weakness in the data set.

The banded tremor that we used for correlation with the video-camera data required low background tremor for its recognition. When other sources of high-amplitude tremor dominated the seismic record, the high-amplitude signal of banded

Table 1. Start and finish times for pond filling and drainback, high-amplitude seismic tremor, and abrupt inflationary tilt during a 24-hour period in 1999.

[Day is UTC Julian day 294, shown here as local time 1400 H.s.t. October 20 to 1400 H.s.t. October 21. Dashes denote events for which no banded tremor was present or, for tilt, no inflationary event occurred (see fig. 3*A*)]

Event	Drainback event			Banded tremor			Abrupt inflation		
	Start	Finish	Duration	Start	Finish	Duration	Start	Finish	Duration
October 20									
1	1436	1501	0:25	1445	1530	0:45	1430	1500	0:30
2	1551	1616	0:25	--	--	--	1550	1630	0:40
3	1736	1827	0:51	1730	1830	1:00	1730	1830	1:00
4	1951	2031	0:40	2000	2100	1:00	2000	2030	0:30
5	2141	2206	0:25	--	--	--	--	--	--
6	2231	2247	0:16	2230	2330	1:00	2230	2300	0:30
7	2331	2351	0:20	--	--	--	2330	2350	0:20
October 21									
8	0336	0401	0:25	0330	0415	0:45	0330	0400	0:30
9	0436	0456	0:20	0445	0530	0:45	0440	0500	0:20
10	0641	0711	0:30	0645	0745	1:00	0640	0710	0:30
11	1011	1100	0:49	1015	1145	1:30	1010	1100	0:50
12	--	--	--	1300	1400	1:00	1300	1340	0:40

tremor was obscured. For example, at 0930 H.s.t. on November 8, tremor amplitude increased substantially and remained high for 42 hours (fig. 3*C*). This period of high background tremor overwhelmed most or all of the component of tremor originating from drainback events. During this and similar periods, pond drainback and tilt correlated well, but tremor correlation was difficult to determine, owing to the high background signal.

Shallow Borehole Tiltmeter

In February 1999 an Applied Geomechanics 722 tiltmeter was installed 1.8 km northwest of Pu‘u ‘Ō‘ō (sta. POO, fig. 1). The borehole tiltmeter was positioned at 4.2-m depth (14 ft). Its dynamic range, precision, and accuracy were about 250, 0.002, and 0.02 µrad, respectively. Data were gathered every minute and relayed back to HVO at 10-minute intervals. The tiltmeter performed flawlessly, providing a complete record for the period September 30–December 1, 1999.

The horizontal axes of the tiltmeter were oriented north-northwest and east-northeast, the *y*-axis toward azimuth 342° and the *x*-axis toward azimuth 072° (fig. 1). The largest events recorded at station POO since its installation have been dike intrusions on September 11, 1999, and February 23, 2000. During these events, the axis of greatest response recorded inflation south-southwest at azimuth 192°, toward a source along the east rift zone about 2.3 km uprift of Pu‘u ‘Ō‘ō crater (fig. 1). After about 30 minutes during the September 11 event, this axis rotated counterclockwise 30°, pointing south-southeast at azimuth 167°, 1.5 km uprift of the crater. These results probably define a part of the rift-zone dike that supplies magma to Pu‘u ‘Ō‘ō. The dike commonly responds to large changes in pressurization and, possibly, even to the small changes that resulted from the drainback events of October and November 1999.

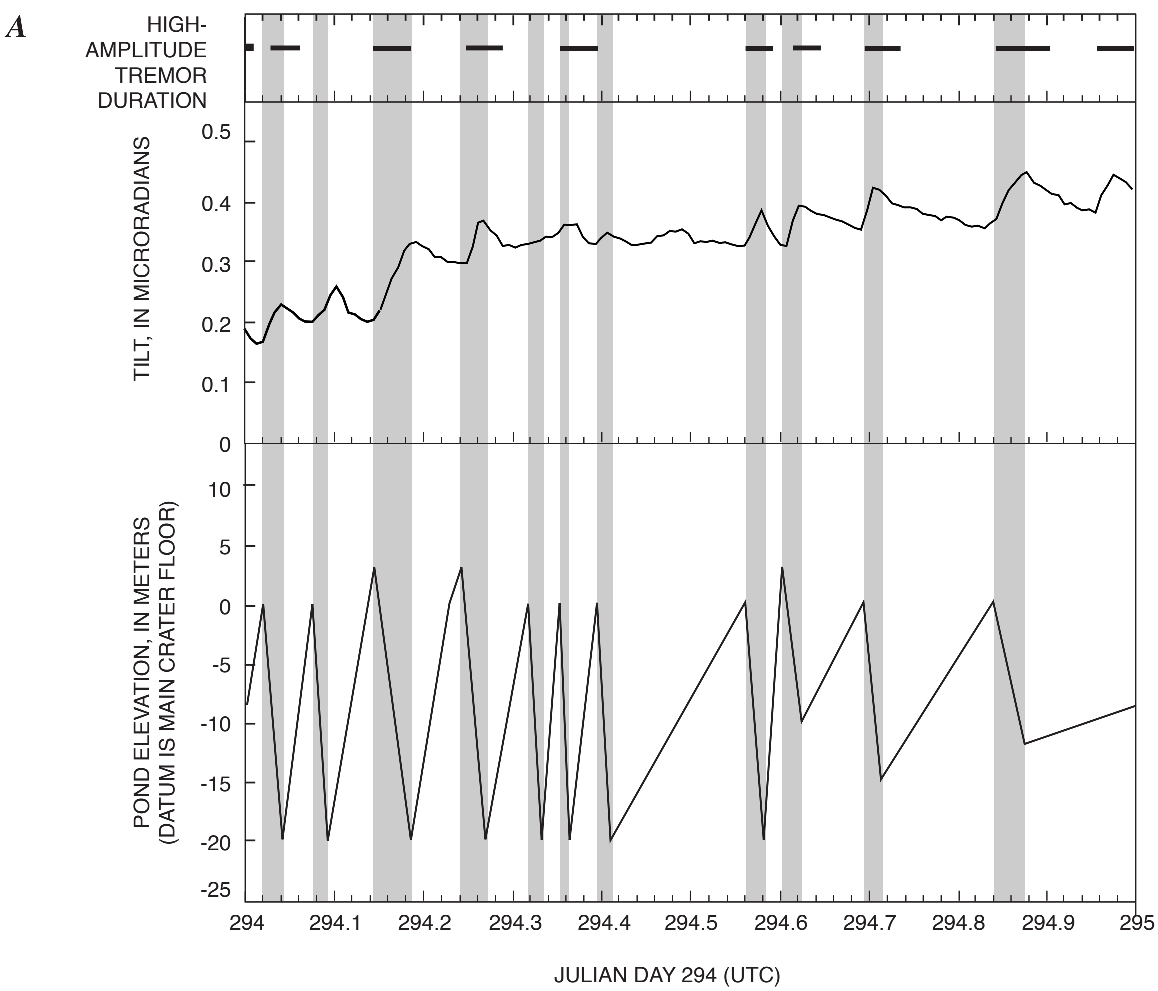
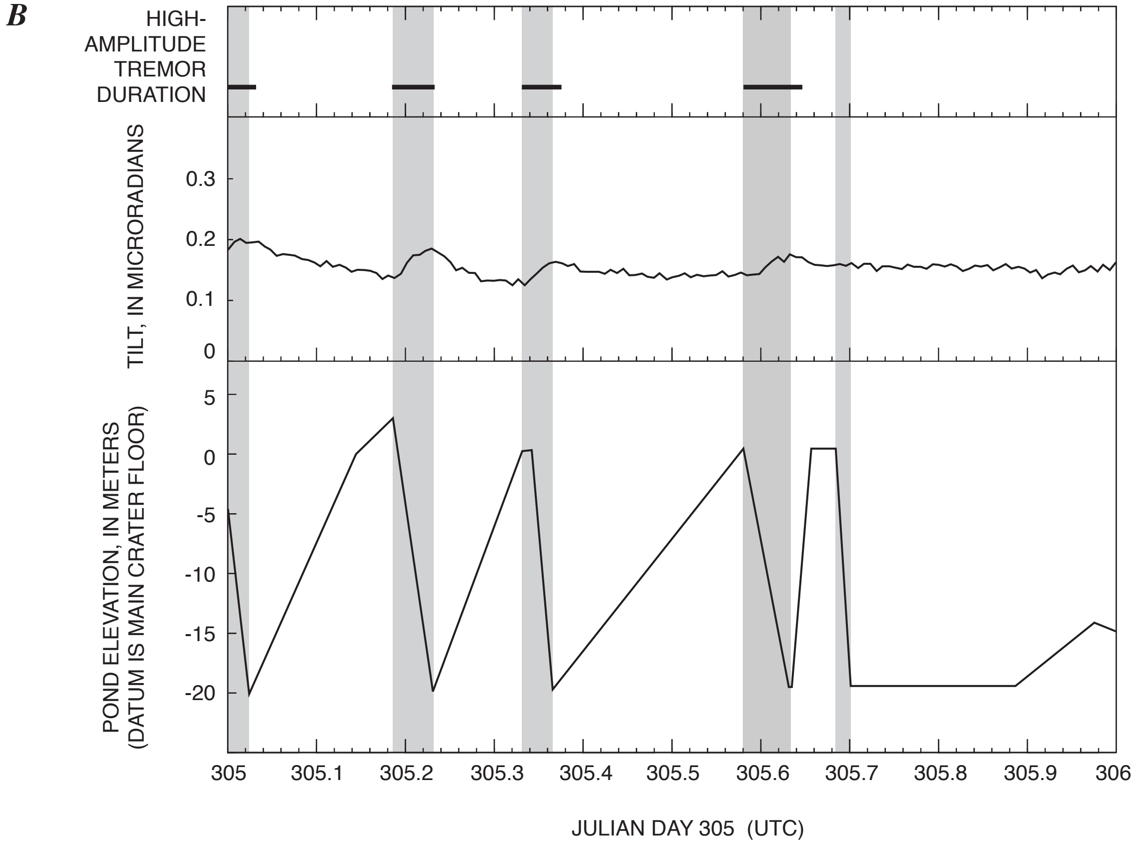


Figure 3. Correlation of pond drainback, tilt, and tremor. Shaded boxes indicate drainback events observed by remote video camera. *A*, Julian day 294, 1999 (1400 H.s.t. Oct. 20 to 1400 H.s.t. Oct. 21, 1999). *B*, Julian day 305, 1999 (1400 H.s.t. Oct. 31 to 1400 H.s.t. Nov. 1, 1999). *C*, Julian day 314, 1999 (1400 H.s.t. Nov. 9 to 1400 H.s.t. Nov. 10, 1999). The seismic trace was characterized by continuous high-amplitude tremor during this 24-hour period, and so correlation is limited to pond drainback and inflationary tilt.



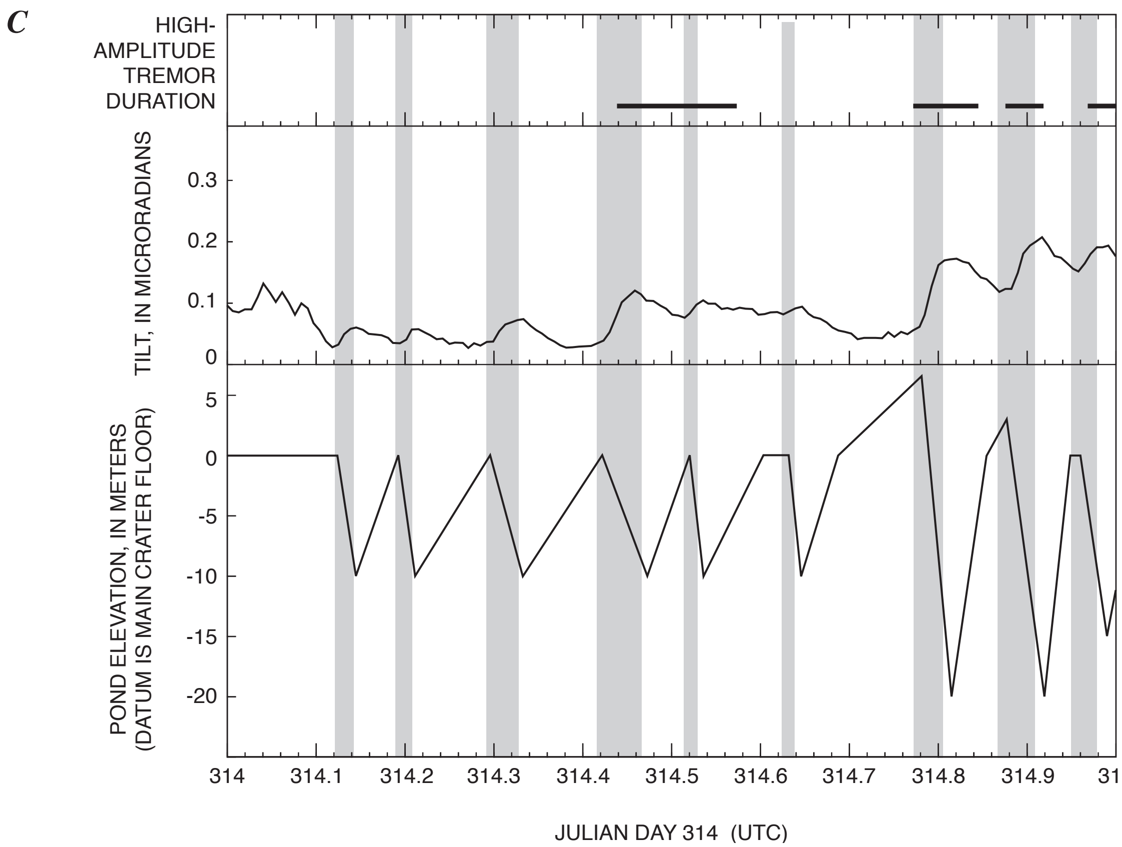


Figure 3. Continued.

During this period, the station POO tiltmeter data for a representative 24-hour period showed abrupt episodes of inflationary tilt (positive slope) that coincided closely with drainback events (table 1). The inflationary event began at the same time as drainback (within the error of timing for the video images) and ended when the lava pond had fully drained or within 10 minutes thereafter. As with the increased tremor, the tilt onset could precede, coincide with, or follow drainback as timed by the camera, probably owing to the imprecision associated with obtaining and analyzing the camera imagery. Deformation at the cone itself likely was similar in style, but no tiltmeter was there to measure it because the on-cone POC tiltmeter was not installed until early in 2000 (see Cervelli and Miklius, this volume).

The high-frequency tilt fluctuation, local to the Pu‘u ‘Ō‘ō area and seen only on the station POO tiltmeter, was superimposed upon a longer-period variation in tilt that resulted from systemwide pressurization and depressurization of Kīlauea's summit and east rift zone. Such systemwide events were recorded simultaneously at several tiltmeters on the volcano. The high-frequency variation commonly displays a sawtooth pattern reflecting the rapid and localized expression of drainback events. Pond filling resulted in no discernible record in the tiltmeter data.

We interpret the locus of inflation for the drainbacks to be oriented south-southeast (at az approx. 162°) from the station POO tiltmeter, along the tiltmeter's *y*-axis. Thus the locus of inflation is about 1.6 km uprift of the crater. The events were so small that a precise direction was difficult to determine, but we can say with certainty that most changes were broadly in the direction of the tiltmeter's *y*-axis.

Correlations between tilt amplitude and drainback characteristics are obscure. We note a crude positive correlation between tilt amplitude and the duration of each drainback event (fig. 5). Complete draining of the lava pond took from 10 to 80 minutes in most events, and tilt ranged in amplitude from 0.0 to 0.12 µrad. The larger tilt events tended to occur during the longer drainback episodes. Similarly, the data suggest that the larger-amplitude tilt events tended to occur when the largest pond volumes were involved (fig. 5).

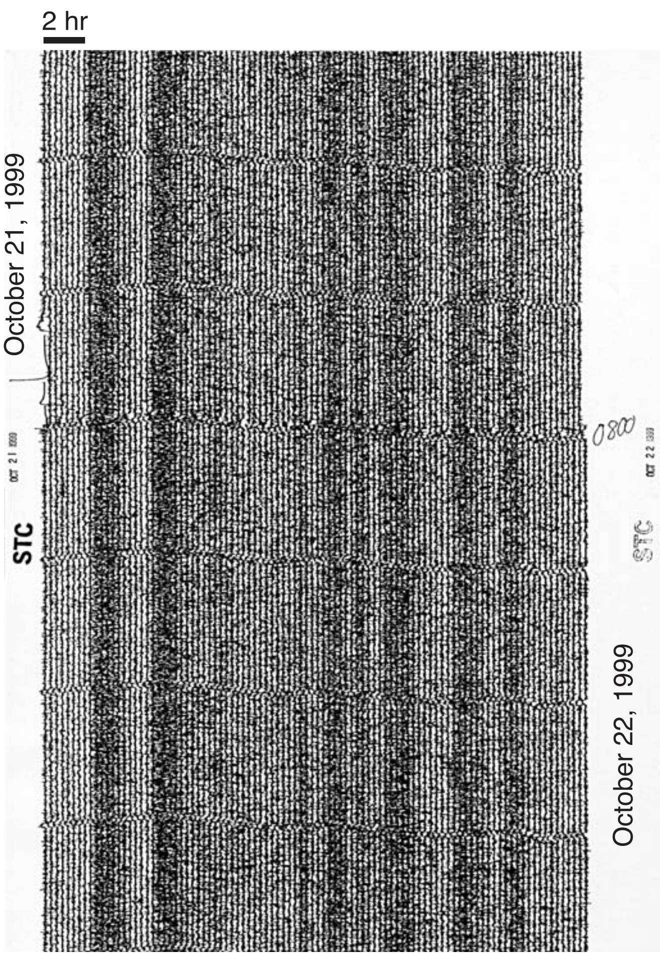


Figure 4. Seismic record at Steam Cracks (sta. STC, fig. 1) from a helicorder, showing part of the 24-hour period from 0800 H.s.t. on October 21 (left) to 0800 H.s.t. on October 22 (right), 1999. Banding is created by interspersed high- and low-amplitude tremor episodes. Abrupt regular steps on each line are 1-minute tickmarks, and each line is a 15-minute cycle of drum.

50 Days of Record

The temporal correlations that we have described between drainback, tremor, and tilt are characteristic of most days between September 30 and November 15, 1999. About 80 percent of pond-drainback events have correlative episodes of high-amplitude tremor.

When compiled, the daily correlations describe a longer-term (50-day) sequence of pond activity and inactivity (fig. 6). When active, the lava pond filled and drained as frequently as 11 times per day; when inactive, it remained empty for as long as 3 days. When the lava pond was active, as many as nine episodes of banded tremor occurred on any day; when it was inactive, banded tremor was sparse or absent.

Plotting the tilt data for a 50-day period obscures the detailed high-frequency (sawtooth) pattern that correlates with pond-drainback events. Instead, the record is dominated by (1) the long-term, low-frequency inflation and deflation that resulted from systemwide magmatic pressurization and (2) intermediate-frequency events that resulted from diurnal effects, such as earth tides and heating or cooling of the ground—the temperature effects discernible because the borehole was shallow. The presence or absence of high-frequency tilt fluctuations may be shown, however, by indexing the 24-hour average variation from the tilt record. This tilt index (fig. 6) was compiled by measuring the absolute value of the slope for each 10-minute segment of the tilt curve and calculating the mean value for each 24-hour period. A high tilt index generally corresponds to days when the tilt displayed the high-frequency pattern characteristic of pond filling and drainback.

In figure 6, vertical shaded bands are drawn to match the peaks of the tilt index after choosing an arbitrary index value to define the breadth of the peaks. These bands encompass most periods of frequent pond filling and drainback and

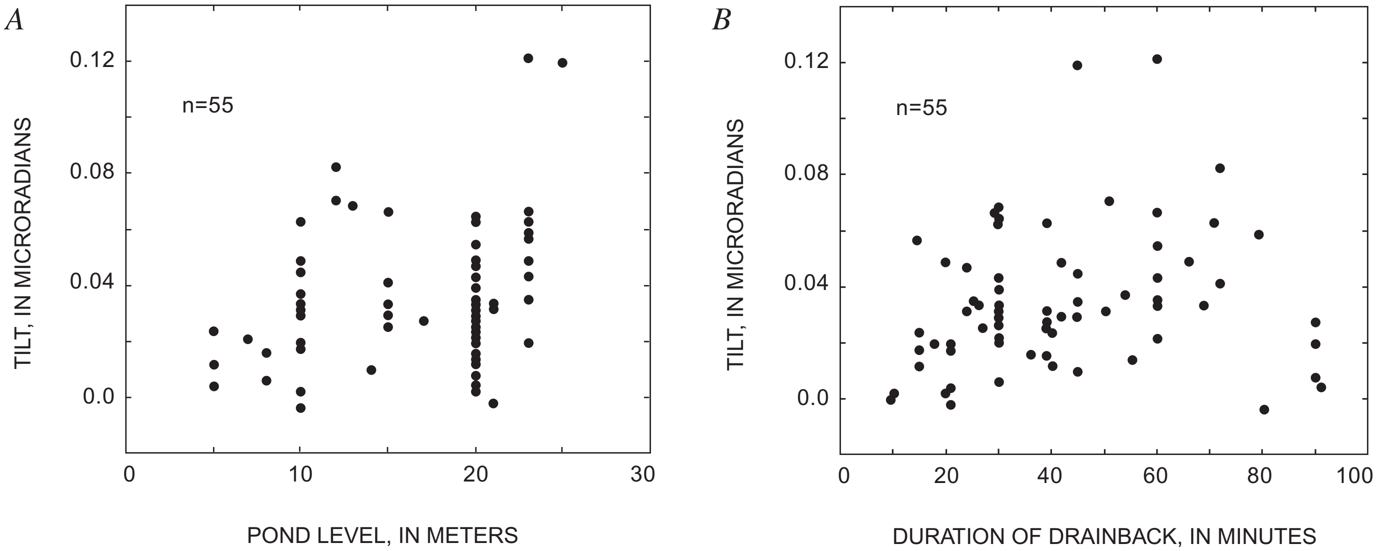


Figure 5. Comparison of tilt magnitude with pond level (*A*) and duration of drainback (*B*).

match fairly closely with days when banded tremor characterized the seismic record.

Another feature of figure 6 suggests a systemwide relation between lava-pond activity and magmatic pressurization during this 50-day period. Beginning on Julian day 279, the low-frequency tilt signal recorded at station POO showed broad inflation or relatively flat tilt during episodes of increased pond activity and banded tremor. In contrast, broad deflation occurred during periods of pond inactivity. Apparently the magmatic system needed suitable pressurization for pond activity to occur.

End of the Pond-Filling and Drainback Episodes

The lava-pond activity at Pu‘u ‘Ō‘ō diminished beginning about November 13, 1999. A final trough-filling event occurred on November 15. Subsequently, new lava flows were barely able to cover the trough's floor during rare extrusive events on November 17 and 18. After November 18, no within-crater extrusion was observed.

Banded tremor persisted in the seismic record until the afternoon of November 11, 1999. At 1530 H.s.t. on that day, a pause in the supply of lava to the flow field interrupted the eruption; however, lava was still present in the pond. The pause ended at 1030 H.s.t. on November 14, 67 hours later, accompanied by onset of high-amplitude tremor at station STC. Tremor amplitude decayed slowly thereafter, but banded tremor was absent from the seismic record.

After November 11, tilt returned to its more customary pattern in which lengthy periods of nearly no inflation or deflation were interspersed with the systemwide, sharp, steep inflations and deflations corresponding to magmatic pauses and restarts. Broad inflationary sequences were once again absent.

Discussion

Vent activity, seismic tremor, and ground deformation have been shown to correlate differently, depending on the location and magmatic scale of events at Kīlauea Volcano. At the volcano's summit, fountain heights during the 1959 Kīlauea Iki eruption correlated closely with tremor amplitude: the higher the fountaining, the higher the tremor (Eaton and others, 1987). The fountaining episodes were matched by broad deflation of the summit area as the magma reservoir discharged lava to the surface. Also well chronicled was the occurrence of deflationary tilt at Kīlauea's summit during eruptions along the east rift zone, such as during the August and October 1968 eruptions (Jackson and others, 1975) or the early years of the current Pu‘u ‘Ō‘ō eruption (Wolfe and others, 1988).

In contrast to those large-scale events are small-scale cycles of pond-filling and -drainback. Previous observers have described short-lived cyclic episodes known as gas-piston events. In the classic Mauna Ulu example described by Swanson and others (1979, p. 6), the magma column rose a few meters to several tens of meters in 15–20 minutes, without spattering. Their description continues:

> The next part of the cycle was violent. Suddenly, vigorous bubbling within the column generated intense spattering, the crust was torn to shreds, and the column withdrew turbulently to its starting level. The time from the onset of bubbling to the completion of withdrawal was generally a minute or two. This type of activity is ascribed to uplift of the column by expanding gases trapped beneath a relatively impermeable crust; eventually gas pressure overcame the strength of the crust, degassing of the column quickly resulted, and the lava withdrew to fill the void evacuated by the lost gas.

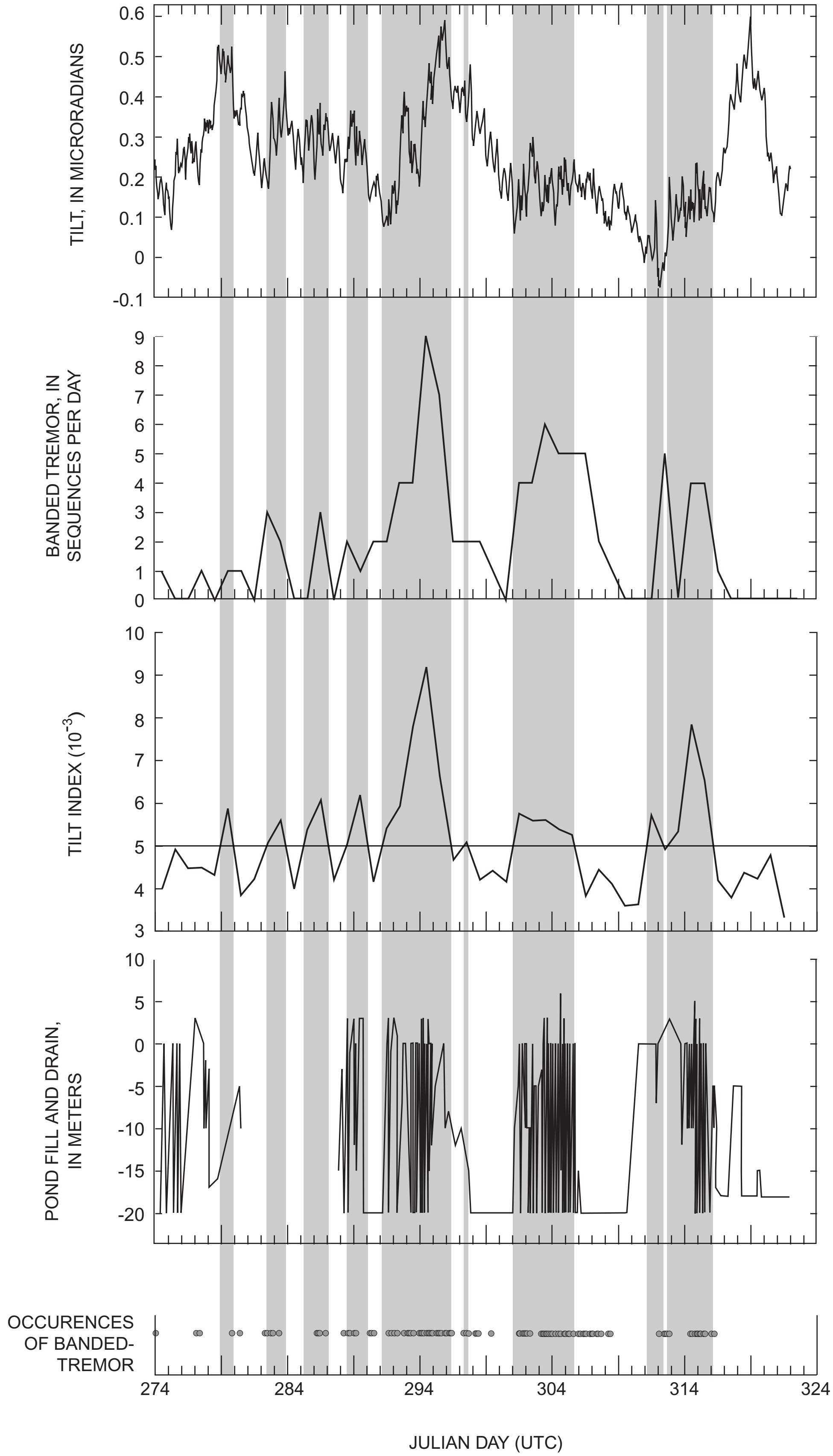


Figure 6. 50-day time series showing tilt, pond-filling and drainback events, banded-tremor occurrences, and indices for banded tremor and tilt (see text). Shaded bands correspond to peaks in tilt index.

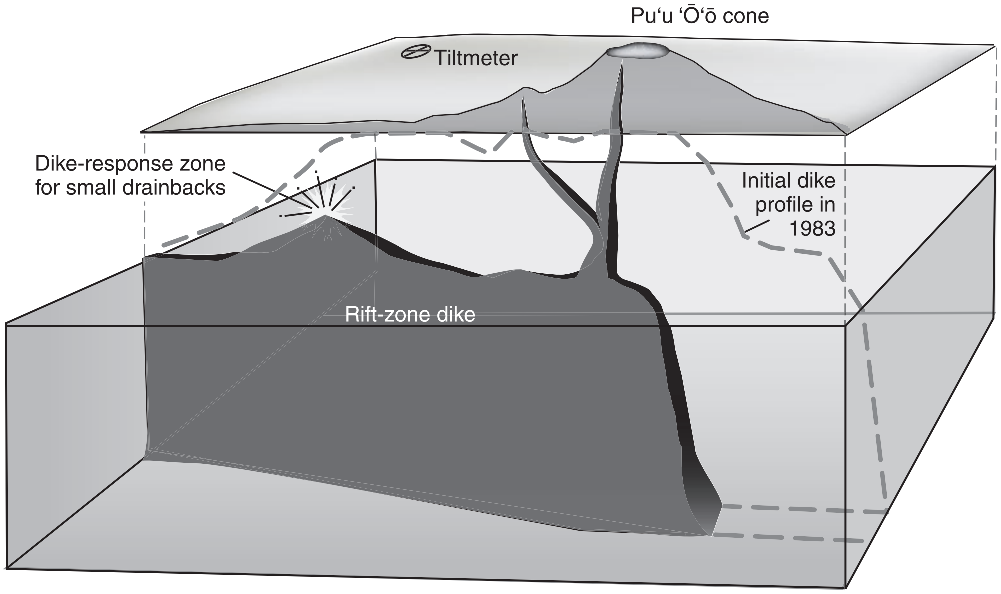


Figure 7. Cross section showing rift-zone dike, conduit into Pu‘u ‘Ō‘ō crater, and site where dike is believed to respond to drainback events from September 30 to November 15, 1999.

Gas-piston events occur sporadically at Pu‘u ‘Ō‘ō. For example, during February 1988, gas pistoning occurred repeatedly at intervals of 10–20 minutes over a period of several hours and produced a characteristic seismic record—a cigar-shaped amplitude envelope with a duration of about 80 s (Ferrazzini and others, 1991). During the February 1988 events, increasing amplitude of the seismic signal corresponded with accelerating rate of degassing as bubble bursts increased in size and number, such that the peak seismic amplitude corresponded to the violent phase of the degassing (Ferrazzini and others, 1991). The tremor sources were thought to lie beneath or close to the crater, within 1 km of the surface (Goldstein and Chouet, 1994).

The pond drainbacks we observed at Pu‘u ‘Ō‘ō in autumn 1999 were a more sustained and less intense version of lava-column rise and drainback than the isolated bursts etched on the seismic record by gas-piston events. Individual drainbacks during these autumn 1999 events ranged mostly from 10 to 80 minutes in duration. Ground deformation, expressed as inflation at or near the vent, was of similar duration. High-amplitude tremor persisted for 45–90 minutes before decaying fairly abruptly to background levels. Cigar-shaped amplitude envelopes were absent in the tremor record.

Interpretation and Conclusions

The most enigmatic part of the Pu‘u ‘Ō‘ō system is the subterranean conduit that feeds lava to the surface. Its connection to the dike system of the east rift zone is poorly understood but believed to lie in the depth range 0.4–2.0 km beneath the cone (fig. 7; Greenland and others, 1988; Wolfe and others, 1988; Hoffman and others, 1990; see Heliker and others, this volume, for more complete explanation). Also speculative are the depth and orientation of conduits that supply lava or gas into Pu‘u ‘Ō‘ō’s crater or that feed lava to the tube system of the adjacent flow field.

At the surface, pond filling and drainback were the events easiest to recognize and correlate among the tremor, tilt, and digital-camera records from September 30 to November 15, 1999. Pond filling was probably driven by vesiculation and expansion of the magma column, in a manner analogous to the vesiculation pump described from the 1959 Kīlauea Iki eruptions (Eaton and others, 1987). Whenever the system was suitably pressurized, the rising lava reached the surface and spilled onto the crater floor. As the pond filled, the top of the column became a slightly denser cap, owing to degassing and cooling. Meanwhile, bubbles presumably coalesced within the maturing magma column and began a more rapid ascent, hollowing out the shallow core of the column. Upon intercepting the pond, this gas-rich core first enhanced surface bubbling and spatter and then, once the gas escaped, initiated drainback. The gas-rich core is an interpretation to explain the mechanism of observed bubbling, spatter, and ensuing rapid drainback.

Lava-pond drainback disrupted the equilibrium of the vesiculating magma column, which became choked with degassed lava flushing down from the pond. Discharge of gas was probably stalled. As a result, the rift-zone dike momentarily swelled, possibly favoring sites where the dike was wider or where existing cracks yielded more readily (fig. 7). Magma entering the system through the dike continued its exit from the conduit that fed the tube system. Flow-field flux may have varied, but our tube-monitoring data were gathered too infrequently to determine the magnitude of changes that resulted from the filling-and-drainback process.

Tremor was heightened during and after drainback. Local inflation and drainback ceased nearly simultaneously, but the tremor began a lengthy response as some cracks drained, some filled, and vesiculation began anew in the upwelling magma column.

Once commonplace at Puʻu ʻŌʻō, a crater-filling lava pond has been largely absent since large-scale disruption of the cone in January 1997. We explain its late September 1999 reappearance by reference to an event on September 12, 1999, when a dike intrusion into the east rift zone led to collapse of the crater floor at Puʻu ʻŌʻō. This event probably created enough instability to close or diminish cracks and minor vents whose conduits might normally have discharged gas or been occupied by small magma columns. Thus lava in the central conduit was able to rise as high as the crater floor. This delicate balance of pressurization ended in November, when the supply of magma from the summit was interrupted. When resupply of magma began, stoping during repressurization probably reopened enough cracks and vents to lower the overall pressurization below some critical level. Thereafter, a vesiculating magma column could swell and shrink only within the subterranean realm, never burdened by the degassed cap of a lava pond.

Acknowledgments

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