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## Petrology of lavas from the Puu Oo eruption of Kilauea Volcano: III. The Kupaianaha episode (1986–1992)

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**Abstract** The Puu Oo eruption has been remarkable in the historical record of Kilauea Volcano for its duration (over 13 years), volume ( $>1 \text{ km}^3$ ) and compositional variation (5.7–10 wt.% MgO). During the summer of 1986, the main vent for lava production moved 3 km down the east rift zone and the eruption style changed from episodic geyser-like fountaining at Puu Oo to virtually continuous, relatively quiescent effusion at the Kupaianaha vent. This paper examines this next chapter in the Puu Oo eruption, episodes 48 and 49, and presents new ICP-MS trace element and Pb-, Sr-, and Nd-isotope data for the entire eruption (1983–1994). Nearly aphyric to weakly olivine-phyric lavas were erupted during episodes 48 and 49. The variation in MgO content of Kupaianaha lavas erupted before 1990 correlates with changes in tilt at the summit of Kilauea, both of which probably were controlled by variations in Kilauea's magma supply rate. These lavas contain euhedral olivines which generally are in equilibrium with whole-rock compositions, although some of the more mafic lavas which erupted during 1990, a period of frequent pauses in the eruption, accumulated 2–4 vol.% olivine. The highest forsterite content of olivines (~85%) in Kupaianaha lavas indicates that the parental magmas for these lavas had MgO contents of ~10 wt.%, which equals the highest observed value for lavas during this eruption. The composition of the Puu

Oo lavas has progressively changed during the eruption. Since early 1985 (episode 30), when mixing between an evolved rift zone magma and a more mafic summit reservoir-derived magma ended, the normalized (to 10 wt.% MgO) abundances of highly incompatible elements and CaO have systematically decreased with time, whereas ratios of these trace elements and Pb, Sr, and Nd isotopes, and the abundances of Y and Yb, have remained relatively unchanged. These results indicate that the Hawaiian plume source for Puu Oo magmas must be relatively homogeneous on a scale of 10–20  $\text{km}^3$  (assuming 5–10% partial melting), and that localized melting within the plume has apparently progressively depleted its incompatible elements and clinopyroxene component as the eruption continued. The rate of variation of highly incompatible elements in Puu Oo lavas is much greater than that observed for Kilauea historical summit lavas (e.g., Ba/Y  $0.09 \text{ a}^{-1}$  vs  $\sim 0.03 \text{ a}^{-1}$ ). This rapid change indicates that Puu Oo magmas did not mix thoroughly with magma in the summit reservoir. Thus, except for variable amounts of olivine fractionation, the geochemical variation in these lavas is predominantly controlled by mantle processes.

**Key words** Hawaii · Kilauea Volcano · magma · Volcano plumbing · lava geochemistry · mantle melting

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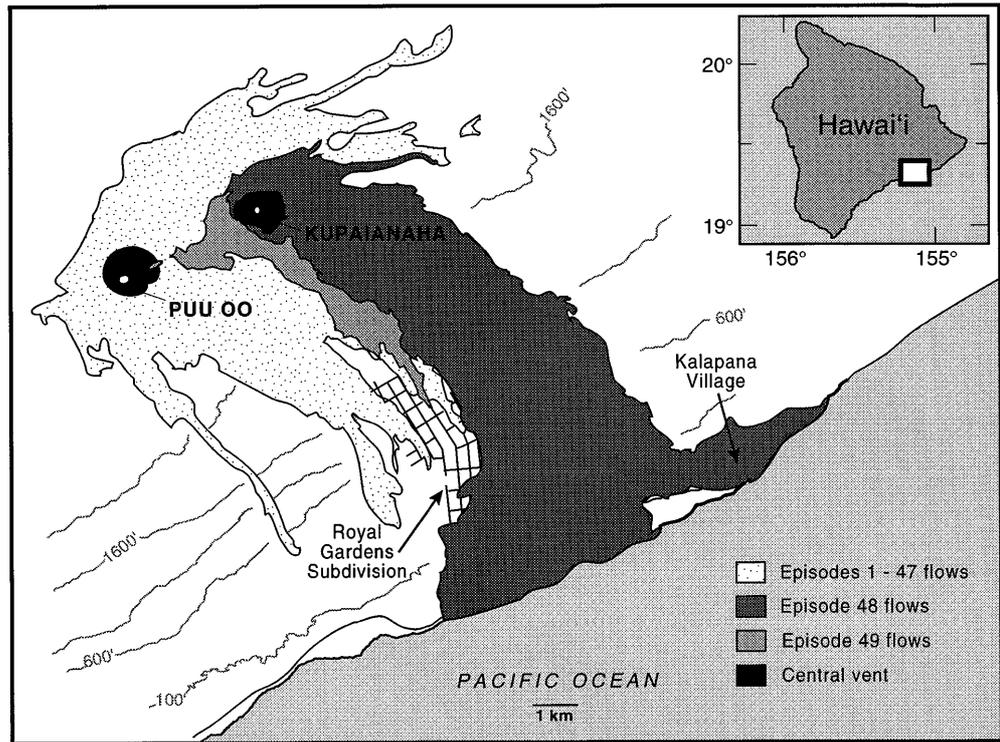
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### Introduction

The Puu Oo eruption is the longest-lived and most voluminous historical rift zone eruption of Kilauea. The eruption started in January 1983 and, at the time of this writing, was continuing vigorously. Between 1983 and 1995, the eruption produced over  $1 \text{ km}^3$  of lava, which destroyed 181 homes and a National Park visitor center on the south flank of the volcano (Fig. 1). Like the shorter and less voluminous Mauna Ulu eruption of Kilauea (1969–1974; Swanson et al. 1979; Tilling et al. 1987), the style of the Puu Oo eruption has changed

**Fig. 1** Map of the 1983 to 5 February 1992 Puu Oo eruption flow field on the east rift zone of Kilauea Volcano, Hawaii (after Mangan et al. 1995a). Lava has erupted primarily from two central vents during this period: Puu Oo (episodes 2–47) and Kupaianaha (episode 48). A fissure system formed between these vents during episode 49. Lavas from the Kupaianaha vent have extended the southern coastline of the island of Hawaii and destroyed numerous homes near the coast. The contour interval is 500 feet after the 100-foot contour (1 foot = 0.3048 m). The inset shows the location of the eruption site on the island



dramatically during its history. The initial episode of the eruption formed a “curtain of fire” along a 7-km discontinuous fissure system which intermittently produced lava for 20 days (Wolfe et al. 1987). During the next two eruptive episodes, eruptive activity became localized along two segments of the fissure system to form two central vents: Puu Halulu and Puu O (later named Puu Oo by Hawaiians). After episode 3, only the Puu Oo vent was active, and it was the main locus of lava flow production until just after the start of episode 48 (July 1986). Each of episodes 4 to 47 was preceded by a repose period of 8–50 days during which magma accumulated in a shallow reservoir under Puu Oo (Hoffmann et al. 1990). The eruptive episodes varied from 9 to 100 h in duration and had moderate to spectacular lava fountains (10’s to 400 m high; Wolfe et al. 1988). A 255-m-high spatter and cinder cone (Puu Oo) was constructed from these fountains.

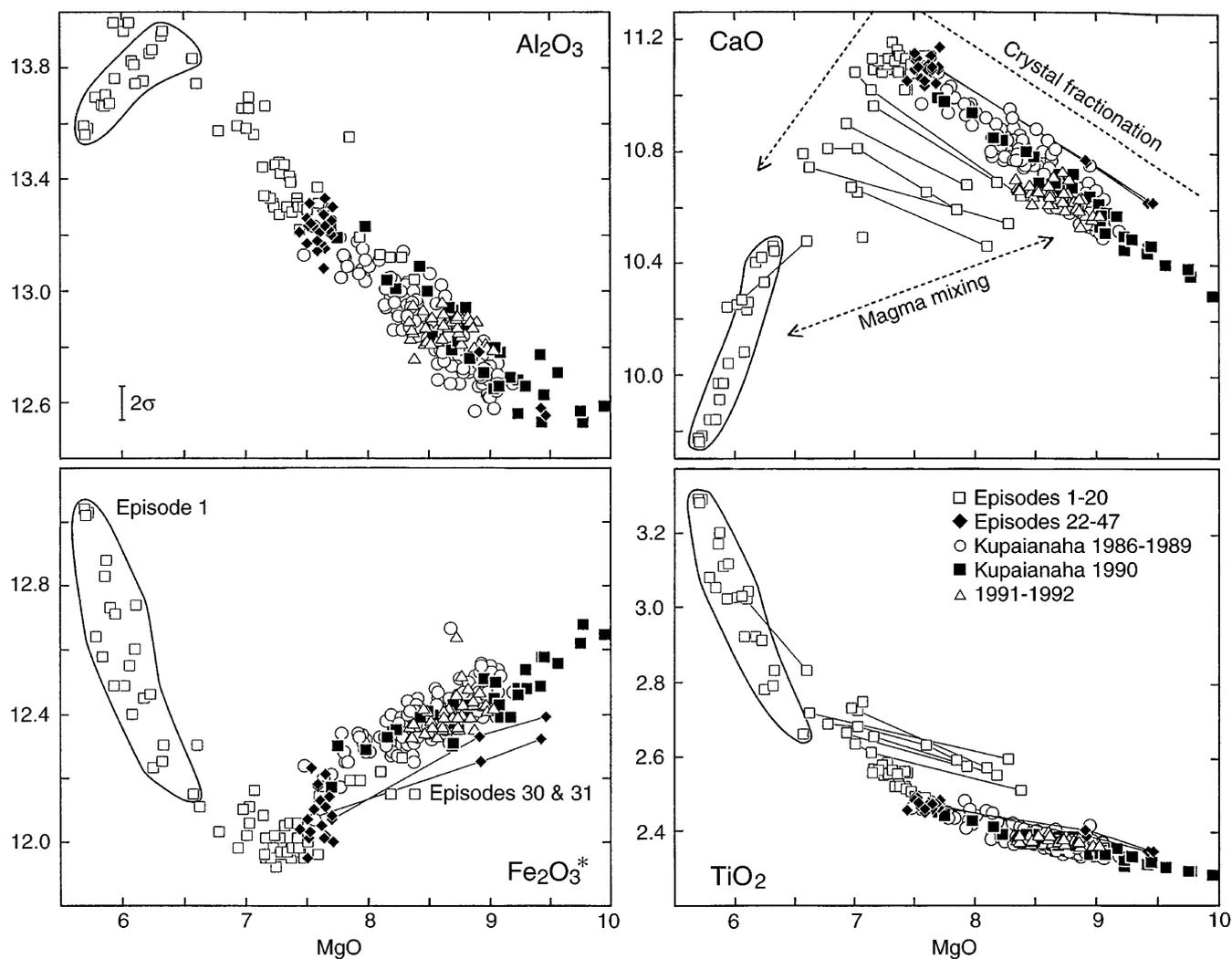
Episode 48 started in July 1986 on the flanks of Puu Oo from fissures which propagated both uprift (0.8 km) and downrift (3 km). At the distal end of the down rift fissure a new vent, Kupaianaha (which means mysterious or extraordinary in Hawaiian), formed. For the next 5.5 years (until February 1992), lava production was nearly continuous from the Kupaianaha vent, creating a large shield 56 m high with a central lava pond (Fig. 2) drained by lava tubes.

The Puu Oo eruption is the best-monitored, long-lived (>1 month) eruption of Kilauea (see Wolfe et al. 1988). In our previous papers we have documented the petrologic history of the Puu Oo lavas from episodes 1–47. These lavas show substantial geochemical variation (Fig. 3), reflecting the combined effects of crystal frac-



**Fig. 2** Oblique aerial photo looking uprift (west) of the Kupaianaha vent with its lava pond (egg-shaped light-gray area with a channel extending to the left) as it appeared in late 1986. Puu Oo, with a fume cloud, is the cone in the background. At this time Puu Oo was ~255 m high. (Photo by J. Griggs)

tionation and magma mixing within the east rift zone of Kilauea (Garcia et al. 1992). The lavas from the first three episodes of the eruption are evolved (MgO contents of 5.7–6.6 wt.%; Garcia and Wolfe 1988; Garcia et al. 1989). Later lavas are more mafic (6.6–10 wt.% MgO) with substantial short-term variations (e.g., 2 wt.% MgO in 24 h during episodes 30 and 31; Garcia et al. 1992). The lavas from the first 20 episodes of the Puu Oo eruption display both petrographic and geochemical evidence of magma mixing involving three distinct magmas (Garcia et al. 1992). Two of these mag-



**Fig. 3** MgO variation diagrams for lavas from episodes 1–49 of the Puu Oo eruption. The overall curved ( $\text{TiO}_2$ ) and kinked ( $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ , and  $\text{Fe}_2\text{O}_3$ ) trends indicate that crystal fractionation was a dominant process controlling compositional variation for the eruption, although mixing was important during the early portion of the Puu Oo eruption (squares for lavas from episodes 3–10 on the  $\text{CaO}$  diagram below *kink*). The scatter on these plots is greater than analytical error ( $2\sigma$ , which is approximately the size of the symbols except for  $\text{Al}_2\text{O}_3$ ), which indicates that the parental magma composition has changed during the eruption. All values are in weight%. The *fields* enclose episode-1 lavas; *tie lines* connect lavas from other episodes (3, 5–10, 30, 31) which have substantial compositional variations. The 1991–1992 lavas include samples from the Kupaianaha, Puu Oo, and episode-49 vents

mas were stored in the rift zone prior to the start of the eruption. A third, more mafic magma intruded from the upper part of the east rift zone just prior to the start of the eruption, and it apparently forced the two evolved magmas to mix and erupt as a hybrid magma. Approximately 10 days after the start of the eruption, the mafic magma began to mix with the evolved hybrid magma. The percentage of mafic magma in the erupted lava progressively increased for approximately 2 years (ca. episode 30) until it reached 100%. These interpre-

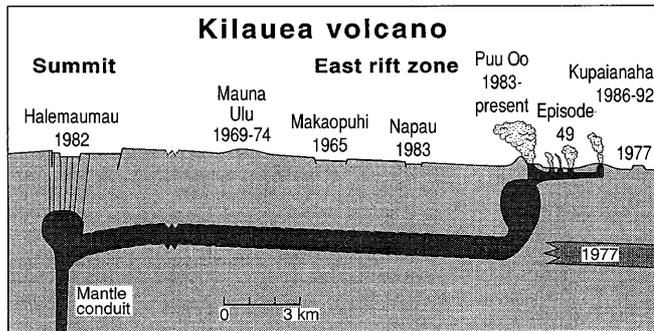
tations utilized petrography as well as mineral and whole-rock compositions combined with field observations and geophysical data (Garcia et al. 1992).

The purposes of this fourth paper in a series on the petrology of lavas from the Puu Oo eruption are to (a) document the petrology of the lavas from the next major segment in the Puu Oo eruption, episodes 48 and 49, the ~5.5-year period of nearly continuous lava extrusion from the Kupaianaha vent from July 1986 to February 1992, and (b) present ICP-MS trace element, and Pb, Sr, and Nd isotopic data for select samples from throughout the entire eruption (1983–1994). Our results show a remarkable temporal geochemical variation for the overall Puu Oo eruption. There has been a progressive decrease in the normalized abundances of incompatible elements with essentially no variation in ratios of these elements and Pb, Sr, and Nd isotopes (after the initial period of magma mixing). Similar geochemical features were observed for lavas from the previous long-lived Kilauea east rift zone eruption and were explained by an increase in partial melting (Hofmann et al. 1984). There is no evidence of an increase in partial melting for the Puu Oo eruption. Therefore,

we propose an alternative mechanism to explain the compositional variation of these more mafic Puu Oo lavas ( $>7.5$  wt.% MgO): progressive melting of a localized region of an essentially homogeneous mantle, which preferentially removes the highly incompatible elements and clinopyroxene component of the source. If Kilauea magmas are produced by 5–10% partial melting (e.g., Watson 1993) of the Hawaiian plume, then the plume must be homogeneous on a scale of at least 10–20 km<sup>3</sup>.

### Puu Oo magmatic plumbing system

Seismic (Koyanagi et al. 1988), petrologic (Garcia et al. 1992; this study), and deformation studies (Okamura et al. 1988; Hoffmann et al. 1990) of the Puu Oo eruption have allowed us to develop a model for the Puu Oo magmatic reservoir system (Fig. 4). This magmatic system extends from the mantle, where melting occurs at depths of at least 80 km to the shallow reservoir under the Puu Oo cone (Tilling and Dvorak 1993; Hoffmann et al. 1990). Mantle melts are focused into Kilauea's primary conduit, which delivers magma to its two rift zones and a reservoir 2–6 km beneath the volcano's summit (Klein et al. 1987). Two distinct models have been proposed for the structure of the summit reservoir: (a) a plexus of interconnected magma pockets (dikes and sills; e.g., Fiske and Kinoshita 1969); and (b) a single small magma body (e.g., Yang et al. 1992; Pietruszka and Garcia 1994). The magma supply rate to this summit reservoir is monitored by tiltmeters, which document the slow inflation of this reservoir as magma flows into it from the mantle, and its rapid deflation at the beginning of eruptions and during intrusions into



**Fig. 4** Hypothetical cross section of Kilauea's summit and sub-aerial portion of its east rift zone showing the inferred magma reservoir system for the Puu Oo eruption based on seismic and petrologic data. The summit reservoir is probably a spherical body (Yang et al. 1992); the east rift zone conduit and the shallow Puu Oo reservoir are dike-like bodies (Tilling and Dvorak 1993; Hoffmann et al. 1990). The rapid compositional variation in Puu Oo lavas during episode 48 is circumstantial evidence that magma from the vertical mantle conduit avoids mixing with magma in the summit reservoir. Dates and locations of recent Kilauea eruptions are given for reference. Note the break in section in the upper part of the rift zone and the uncertain uplift margin of the evolved magma which fed the 1977 eruption

the volcano's southwest and east rift zones. Based on lava volume measurements (corrected for vesicularity) and summit tilt measurements, Kilauea's average minimum magma supply rate from 1956–1983 (which includes the 1969–1974 Mauna Ulu eruption) was  $\sim 0.086$  km<sup>3</sup>/year (Dzurisin et al. 1984). The magma supply rate during the Puu Oo eruption is estimated to have been somewhat higher (0.120 km<sup>3</sup>/year; Wolfe et al. 1987).

The east rift zone has been the primary locus of magmatic activity on Kilauea for the past  $\sim 40$  years following a 115-year hiatus in eruptive activity. The active portion of the rift is 2–3 km wide at the surface. Its magmatic core may extend from 3 to 9 km deep (Delaney et al. 1990), although most of the seismic activity related to magma intrusions is above 5 km (Tilling and Dvorak 1993). The earthquake swarm which accompanied the dike intrusion which triggered the Puu Oo eruption was most intense between depths of 3–4 km, which may outline the upper surface of the conduit which has fed the Puu Oo eruption (Koyanagi et al. 1988). Prior to the Puu Oo activity, historical east rift zone eruptions occurred in 1790, 1840, 1923, 1955, 1960, 1961, 1962, 1963, 1965 (twice), 1967, 1968 (twice), 1969–1974 (Mauna Ulu and elsewhere along the upper part of the rift), 1977, and 1979 (Macdonald et al. 1983). Since 1955 (when tiltmeters were installed at Kilauea), east rift zone intrusions (without accompanying eruptions) were detected in 1963, 1965, and each year between 1969 and 1982, with the exception of 1972, 1975, and 1978 (Dzurisin et al. 1984). These frequent intrusions left bodies of magma within the rift zone; one such large body is thought to have been located at the site where the Puu Oo eruption started (Klein 1987; Okamura et al. 1988). Thus, the east rift zone was primed and ready for a major eruption in 1983 (Dzurisin et al. 1984).

The trigger for the Puu Oo eruption was the intrusion of a dike from the upper east rift zone on 2 January 1983 (Wolfe et al. 1987). Deformation and seismic data indicate that this dike intersected a pocket of rift-stored magma (Okamura et al. 1988). Petrologic studies of episode 1 lavas indicate that two petrographically and chemically distinct magmas (and their hybrid mixtures) were erupted during the initial phase of this eruption (Garcia et al. 1989). The dike and rift zone magmas commingled, forming a conduit system which extended from the summit to the eruption site (Fig. 4). This conduit system is thought to have had a delicate hydraulic balance (Dvorak and Okamura 1985). As the summit of Kilauea swelled with the influx of new magma from the mantle, the level of the lava lake in the throat of Puu Oo rose. This pattern became so repetitious that eruptive episodes could be anticipated from the level of summit tilt (in addition to the increases in seismicity and other eruption indicators; see Wolfe et al. 1987). During the Kupaianaha episode of this eruption, the magma plumbing system between the summit and the eruption site remained intact.

The geometry of the magma reservoir under the Puu Oo cone has been modeled from ground deformation measurements made between episodes 20 and 42. These models indicate that the reservoir during this period (mid-1984 to early 1986) was shallow (top at a depth of 0.4 km), approximately 2.5 km deep, approximately 1.6 km long (oriented parallel to the axis of the rift zone), and dike-like in shape (~3 m wide; Hoffmann et al. 1990). The volume of this reservoir is thought to have grown during the eruption from  $3$  to  $12 \times 10^6 \text{ m}^3$  (Hoffmann et al. 1990). The crown of this reservoir was open to the atmosphere, which together with the high surface-area-to-volume aspect of the reservoir, promoted rapid crystallization during the brief repose periods (4–6% during 20–30 days; Garcia et al. 1992).

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### Kupaianaha vent eruption history

In July 1986 the Puu Oo cone fractured and lava-producing fissures formed just uprift and downrift marking the beginning of the 48th and longest episode of the Puu Oo eruption (Heliker and Wright 1991). Two days later, this fissure system propagated 3 km downrift to where the Kupaianaha vent developed (Fig. 1), becoming the main center for lava production for the next 5.5 years. This change in vent location was accompanied by a change in eruption style from episodic high fountaining to virtually continuous, relatively quiescent effusion ( $\sim 3 \times 10^5 \text{ m}^3/\text{day}$  corrected for vesicles; Mattox et al. 1993). This change in eruption style was probably related to a change in vent geometry (Greenland et al. 1988). The Puu Oo vent remained active, with a vigorously fuming lava lake in its crater, but it produced no lava flows during episode 48.

Lava effusion from the Kupaianaha vent initially was from low fountains (<10 m), and a lava pond soon formed around the vent. Overflows from this pond and outbreaks on its flanks created a lava shield, which eventually grew to a height of 56 m. Lava erupted quietly in the pond, indicating that it was largely degassed. Degassing of Kupaianaha lava probably occurred in the Puu Oo reservoir prior to its transport through a shallow dike (<300 m to allow degassing) to the Kupaianaha vent (P. Greenland, pers. commun.; Fig. 4). The lava channels which drained the pond crusted over, and by November 1986 a 12-km-long lava tube system developed on the south flank of the rift zone from the vent to the ocean.

The first pause in the eruption at Kupaianaha occurred in April 1988 and lasted for 1 week. During this period the lava pond drained to a depth of 40 m but quickly refilled at the close of this eruptive hiatus (Heliker and Wright 1991). The largest deformational event on Kilauea since the 1975 M7.5 earthquake occurred in June 1989, an M6.1 earthquake on the south flank of Kilauea near Puu Oo (Delaney et al. 1993). It had, however, little apparent effect on eruptive activity

at the Kupaianaha vent (the pond level dropped ~2 m according to helicopter pilot David Okita). In 1990 there were 12 pauses in eruptive activity, each lasting 1–4 days. Despite these breaks in magma flow to the surface, the eruption did not switch back to episodic eruptions as predicted by Parfitt and Wilson (1994). After this interval of pauses, there were three intrusions from the summit reservoir into the upper east rift zone during the next 10 months (Heliker and Wright 1991) while the Kupaianaha vent was active. During this period of fluctuating magma supply in 1990–1991, the depth of the lava pond from the rim to its surface increased dramatically (1–20 m), making sampling very difficult. The lava pond crusted over in June 1990, but lava continued to drain from the vent through lava tubes.

In November 1991, a 2-km-long, discontinuous eruptive fissure system formed between Puu Oo and Kupaianaha vents (episode 49; see Fig. 1). This caused the Puu Oo lava lake level to drop further and the crater walls to collapse. This new fissure system was fed from the shallow reservoir under Puu Oo and it produced lava for 18 days, most of it during the first 10 days (see Mangan et al. 1995a for details on this episode). Lava continued flowing through Kupaianaha lava tubes during episode 49 but at a lower rate. In February 1992 fissures opened on the flanks of Puu Oo, marking the death of the Kupaianaha vent and the start of episode 50.

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### Sampling and petrography

We maintained a vigorous program of lava sampling during the Kupaianaha episode of the Puu Oo eruption. Initially, we collected samples frequently, sometimes several each day. In 1987 we switched to sampling once a week when we discovered that whole-rock compositions were changing slowly. Near the end of episode 48, we were collecting lavas only once or twice a month. Whenever possible, samples were collected in a molten state and water quenched to minimize post-eruptive crystallization. These samples were collected from the lava pond in the Kupaianaha vent, from breakouts on the flanks of the pond, and from lava tubes within a few kilometers of the pond. We also collected a few samples from the coastal plain approximately 12 km from the vent, where the tubes discharged their molten lava. Three of our samples were collected from the lava lake inside Puu Oo crater in 1991 prior to episode 49. Additional sampling, and petrography of some Kupaianaha and episode-49 lavas, are reported by Mangan et al. (1995a, b).

All of the Kupaianaha lavas are fresh, strongly vesicular, friable, and nearly aphyric. Honey-brown glass or black cryptocrystalline material generally composes 90% or more of the water-quenched samples. Olivine is the only phenocryst present in these weakly phyric lavas (Table 1). It is small (usually <1 mm), euhedral, and

**Table 1** Representative modes for lavas erupted from the Kupaianaha vent during the Puu Oo eruption based on 1000 point counts (except for samples with \*, which are based on 500 point counts). Phenocrysts (Phen) are >0.5 mm wide; micropheno-

crysts (Mph) are 0.1 to 0.5 mm wide. MgO content is for the whole rock. All values are in volume % and are vesicle-free (vesicles were not counted). Cpx (clinopyroxene); Plag (plagioclase)

Sample date	Olivine		Cpx (Mph)	Plag (Mph)	Matrix	MgO (wt. %)
	Phen	Mph				
31 July 86	<0.1	1.8	0	0	98.2	7.56
30 Aug 86	0.2	2.2	0.4	<0.1	97.6	7.48
11 Jan 87	0.4	4.2	0	<0.1	95.4	8.63
18 Feb 87	0.7	4.9	0	0	94.6	8.66
4 July 87	0.6	4.8	0	0	94.6	7.78
30 Jan 88	0.4	2.2	0	0	97.4	8.25
3 May 88	2.4	6.7	0	0	90.9	8.88
25 Sep 88	1.1	3.5	0	0	95.4	8.90
18 Apr 89	1.5	2.5	0	0	96.0	9.05
8 Apr 90*	0.6	2.6	<0.1	0.2	96.6	8.74
20 Apr 90	0.9	2.6	0.9	0.5	95.0	7.70
28 Apr 90*	0.8	4.0	<0.1	<0.1	95.2	9.23
14 May 90*	<0.1	3.2	<0.1	0.2	96.6	8.23
27 May 90	2.6	5.9	0.3	0.3	90.9	9.95
10 June 90	1.9	3.6	0.1	0.1	94.3	8.81
14 June 90	2.6	5.6	<0.1	0.1	91.7	9.77
25 June 90	1.7	5.3	<0.1	<0.1	93.0	9.02
12 Jan 91*	<0.1	2.4	0.2	0	97.4	8.57
22 Dec 91*	1.6	5.2	0.8	0.4	91.0	8.74

\* Based on 500 point counts

generally sparse (<2 vol.%), except in lavas with higher MgO contents (e.g., 2.6 vol.% in sample 5-27-90 (sample numbers are the date of collection), which has ~10% MgO, the highest recorded value for the Puu Oo eruption). Thus, the whole-rock compositions closely approach liquid compositions for all but a few of the samples. Olivine microphenocrysts (0.1–0.5 mm) are common (1.8–6.7 vol.%) in pond lavas. Chromium-rich spinel inclusions are found in olivines of all sizes. Mangan et al. (1995a) reported higher contents of olivine phenocryst in the 1991 Kupaianaha lavas (4.6 vol.% average), but did not report the presence of olivine microphenocrysts.

The abundance of olivine in the Kupaianaha lavas is generally correlated with the whole-rock MgO content, although the olivine abundance varies somewhat for a given MgO content (1–2 vol.%; Table 1). The correlation is better for total olivine content than for just olivine phenocryst content.

Plagioclase and clinopyroxene crystals are absent or small (<0.1 mm) in most Kupaianaha lavas, although rare microphenocrysts of both minerals are present in some slowly cooled lavas (Table 1). Both of these minerals are more common in lavas erupted during 1990, which was a period of frequent pauses in the eruption. The magma for these lavas may have cooled more during these pauses prior to eruption. Thus, among the observed minerals in the Kupaianaha lavas, only olivine crystallization (with minor Cr spinel) is likely to have had any significant effect on magma composition.

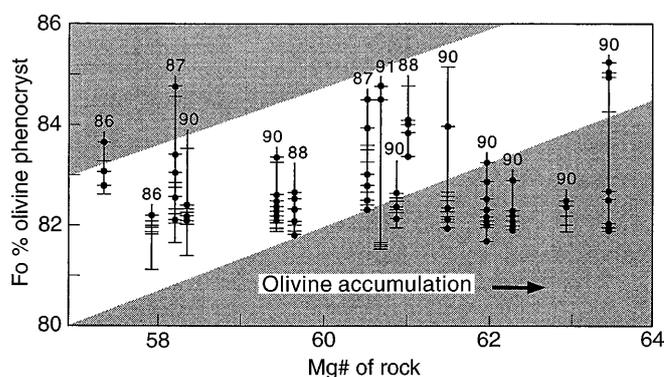
### Olivine chemistry

The composition of olivine phenocrysts and microphenocrysts in the Kupaianaha lavas was determined using the University of Hawaii, five-spectrometer, Cameca SX-50 electron microprobe. Operating conditions were a minimum spot size (~1 μm), and 20-nA beam current. The analyses reported in Table 2 are an average of at least three spots in the core of each crystal, although crystal rims also were analyzed to check for compositional zoning. Counting time on the peak for each element was 60 s. The lavas selected for olivine analysis span the entire observed range of whole-rock MgO contents (7.5–10.0 wt.%) for the Kupaianaha episode. They allow us to determine whether the olivines were in equilibrium with melts corresponding to the bulk-rock compositions.

The olivines in the Kupaianaha lavas are all normally zoned and show a relatively restricted range in composition (81–85% forsterite), with considerable overlap for phenocrysts and microphenocrysts (Fig. 5). This range is somewhat higher than the olivine composition assumed by Mangan et al. (1995a) in their modeling calculations (forsterite 80). The presence of ~85% forsterite olivines over a wide whole-rock compositional range (Fig. 5) probably indicates that olivine fractionation does not occur at the liquidus but over a significant crystallization interval [a feature Maaloe (1988) has called “delayed fractionation”], and that the parental magma for these lavas had an Mg# [(Mg/(Mg + Fe<sup>2+</sup>) × 100)] of ~63.5, assuming 90% of the total

**Table 2** Representative microprobe analyses of olivine cores in lava from the episode 48 of the Puu Oo eruption. All values are in wt.% except forsterite (Fo)

Date	30 Aug 86			4 July 87			30 Jan 88	
	0.8	1.0	0.4	0.4	0.8	0.2	0.6	0.3
Size (mm)								
SiO <sub>2</sub>	39.8	39.6	39.4	39.42	39.39	39.13	39.94	39.74
FeO	15.4	15.9	16.3	14.55	16.40	16.50	16.20	16.90
NiO	0.28	0.27	0.32	0.27	0.25	0.24	0.26	0.28
MgO	44.3	44.0	43.5	44.95	43.75	43.25	43.32	42.75
CaO	0.26	0.27	0.30	0.27	0.26	0.28	0.25	0.27
Total	100.24	100.25	100.07	99.49	100.05	99.40	99.97	99.91
Fo %	83.7	83.1	82.6	84.6	82.6	82.4	82.65	81.8
Date	28 Apr 90			27 May 90			12 Jan 91	
Size (mm)	1.2	1.2	0.4	0.7	0.6	0.8	0.6	0.5
SiO <sub>2</sub>	39.49	39.23	39.35	39.8	39.36	39.75	39.7	39.05
FeO	15.75	16.40	16.90	13.85	16.88	14.42	14.65	17.30
NiO	0.27	0.22	0.24	0.29	0.25	0.28	0.27	0.20
MgO	44.22	43.60	43.30	45.35	42.8	45.14	45.0	43.1
CaO	0.25	0.27	0.30	0.26	0.27	0.26	0.26	0.29
Total	99.98	99.72	100.09	99.55	99.56	99.85	99.88	99.94
Fo %	83.3	82.6	82.0	85.4	81.9	84.8	84.6	81.6



**Fig. 5** Whole-rock Mg#  $[(\text{Mg}/\text{Mg} + \text{Fe}^{2+}) 100]$  vs forsterite content (Fo%) of olivine crystal cores. The  $\text{Fe}^{2+}$ /total iron content is assumed to be 0.9 based on iron redox determinations on Hawaiian tholeiites (Moore and Ault 1965). The *solid circles* are phenocrysts (0.5–2 mm in diameter); the *horizontal lines* are for microphenocrysts (0.1–0.5 mm). The *numbers* above each vertical line give the year in which the lava was erupted. The *white field* is the shallow pressure equilibrium field for basaltic magma ( $K_d = 0.30 + 0.03$ ; Roeder and Emslie 1970; Ulmer 1989). Most of the olivines plot within the equilibrium field, except the mafic lavas from 1990. Six of the lavas, spanning a wide compositional range (Mg# 58–63), have olivines with forsterite contents of ~85%. These olivines probably grew in a liquid of approximately 10 wt% MgO, which is the most MgO-rich lava observed during the Puu Oo eruption. The *arrow* indicates the effect of olivine accumulation, which probably occurred in some of the mafic 1990 lavas

iron is ferrous (which is consistent with titration analyses for ferrous iron in Hawaiian lavas; e.g., Moore and Ault 1965; Byers et al. 1985). Using the observed iron and MgO variations in the Kupaianaha lavas, the parental magmas for these lavas would have had ~10 wt.% MgO.

Most of the olivines in Kupaianaha lavas could have been in equilibrium with their bulk-rock compositions, except the more mafic rocks from 1990 (Fig. 5). Although some of the phenocrysts in the 1990 mafic lavas are in equilibrium with the bulk-rock composition, many have forsterite contents too low to have been in equilibrium with the whole-rock Mg#. The composition of the lower forsterite olivine in these mafic lavas (~82%) is identical to that in the less mafic lavas which were erupted during this period. Accumulation of 2–4 vol.% olivine of the composition observed in the less mafic 1990 lavas is sufficient to duplicate the composition of the more mafic 1990 lavas, which is consistent with the modal differences of total olivine content between these rocks (Table 1). These results indicate that olivine accumulation probably occurred in some of the more mafic 1990 lavas, which were erupted during a period of frequent eruption pauses.

## Whole-rock geochemistry

### Methods

Representative samples from the Kupaianaha vent (episode 48) and the fissure eruption (episode 49), were analyzed by X-ray fluorescence (XRF) at the University of Massachusetts for major and trace (Nb, Rb, Zr, Sr, Y, V, Zn, Ni, Cr) elements. A total of 194 samples from the Kupaianaha vent, 3 from the Puu Oo lava lake and 5 from episode 49, were analyzed for this study. Table 3 includes approximately one lava sample/month except for periods when compositional variations are significant (e.g., 1990). The full data set can be obtained at an anonymous electronic mail FTP site [ele-

**Table 3** XRF major and trace element data for lavas from episodes 48, 49, 51, and 53 of the Puu Oo eruption. Samples are listed in chronological order for each episode. The sample name is the date of collection. Major element abundances are in wt.%; trace element concentrations are in ppm. Total iron as Fe<sub>2</sub>O<sub>3</sub>

Sample	Days	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Total	Y	Sr	Rb	Nb	Zr	Ni	Cr	V	
Episode 48 (Kuaupatanaha vent)																					
25-Jul-86	1300	50.45	2.477	13.30	12.20	0.17	7.64	11.14	2.23	0.468	0.25	100.32	25.4	340	7.6	14.6	158	113	342	295	
31-Jul-86	1306	49.98	2.459	13.23	12.07	0.18	7.56	10.97	2.31	0.469	0.24	99.47	24.5	340	8.0	16.9	155	113	350	299	
30-Aug-86	1336	50.04	2.462	13.13	12.24	0.17	7.48	11.08	2.17	0.464	0.24	99.48	24.8	341	7.8	16.9	156	111	349	300	
13-Sep-86	1350	50.24	2.441	13.13	12.28	0.17	7.80	11.03	2.33	0.458	0.24	100.12	24.4	339	7.5	15.1	158	125	365	300	
23-Oct-86	1390	50.08	2.422	13.05	12.29	0.17	7.97	10.97	2.27	0.453	0.24	99.92	24.3	339	7.7	14.9	159	133	382	300	
18-Nov-86	1416	50.23	2.450	13.19	12.17	0.18	7.77	11.02	2.32	0.466	0.24	100.04	24.7	343	7.9	15.3	159	113	339	294	
11-Jan-87	1470	50.07	2.389	12.96	12.36	0.18	8.57	10.80	2.22	0.453	0.26	100.24	24.3	336	8.1	15.1	156	156	431	292	
18-Feb-87	1508	50.12	2.405	12.93	12.38	0.18	8.67	10.81	2.21	0.446	0.23	100.38	24.0	334	7.3	14.7	155	156	437	296	
16-Mar-87	1534	49.98	2.387	12.89	12.36	0.18	8.62	10.74	2.31	0.447	0.23	100.14	24.2	332	7.6	14.9	156	160	450	292	
12-Apr-87	1561	49.97	2.396	12.98	12.27	0.18	8.19	10.85	2.21	0.451	0.24	99.74	24.7	337	7.5	15.1	153	145	421	291	
16-May-87	1595	49.82	2.389	12.94	12.30	0.17	8.15	10.78	2.24	0.464	0.23	99.48	24.5	334	7.4	15.3	152	143	426	297	
4-Jul-87	1644	49.94	2.434	13.05	12.34	0.17	7.78	10.94	2.33	0.448	0.24	99.67	24.7	336	7.7	15.4	155	130	397	299	
30-Jul-87	1670	50.25	2.440	13.09	12.28	0.17	8.01	10.94	2.20	0.450	0.24	100.07	24.6	333	7.8	14.0	155	128	391	294	
13-Aug-87	1684	50.25	2.458	13.15	12.31	0.17	7.96	10.94	2.26	0.447	0.24	100.19	24.2	331	7.7	15.4	154	135	399	294	
20-Sep-87	1722	50.22	2.417	13.11	12.28	0.17	7.98	10.94	2.19	0.450	0.24	100.00	25.3	337	7.3	14.5	155	135	411	300	
18-Oct-87	1750	49.94	2.377	12.95	12.33	0.17	8.14	10.80	2.21	0.440	0.23	99.59	24.6	334	7.7	14.8	154	145	422	294	
1-Nov-87	1764	50.03	2.381	12.96	12.35	0.17	8.22	10.82	2.19	0.441	0.23	99.79	24.1	333	7.8	14.8	156	142	428	294	
4-Dec-87	1797	49.95	2.367	12.90	12.38	0.17	8.31	10.77	2.29	0.444	0.24	99.82	24.4	328	7.2	13.7	153	149	440	291	
19-Jan-88	1843	50.01	2.369	12.89	12.41	0.17	8.39	10.77	2.22	0.443	0.24	99.91	24.3	330	7.3	14.2	153	151	458	294	
30-Jan-88	1854	49.95	2.371	12.91	12.37	0.17	8.25	10.78	2.17	0.443	0.23	99.65	25.1	334	7.6	14.9	161	139	438	301	
5-Mar-88	1889	49.85	2.364	12.79	12.48	0.17	8.55	10.69	2.12	0.438	0.23	99.68	24.9	330	7.0	14.7	158	153	462	290	
21-Apr-88	1936	49.91	2.368	12.73	12.49	0.17	8.89	10.67	2.08	0.430	0.23	99.97	23.9	320	7.4	14.7	151	169	514	296	
3-May-88	1948	49.61	2.330	12.57	12.52	0.17	8.88	10.58	2.07	0.427	0.23	99.34	23.7	317	6.5	14.2	153	157	489	289	
16-Jun-88	1994	49.77	2.347	12.70	12.49	0.17	8.98	10.59	2.02	0.426	0.24	99.78	24.2	321	7.5	14.1	154	170	528	296	
16-Jul-88	2022	49.86	2.359	12.78	12.49	0.18	8.96	10.65	2.11	0.428	0.23	100.05	24.1	323	7.5	14.7	154	168	510	292	
18-Aug-88	2055	49.93	2.361	12.73	12.55	0.17	9.00	10.66	2.15	0.430	0.23	100.21	23.8	319	7.5	15.9	154	176	526	301	
25-Sep-88	2093	49.70	2.342	12.74	12.48	0.17	8.90	10.58	2.33	0.426	0.23	99.90	23.7	317	7.2	15.0	150	169	519	290	
20-Oct-88	2118	49.60	2.355	12.66	12.41	0.17	8.91	10.60	2.28	0.442	0.23	99.66	24.1	319	7.0	14.3	153	163	508	292	
20-Nov-88	2149	49.78	2.364	12.77	12.39	0.18	8.94	10.60	2.14	0.427	0.23	99.82	24.2	321	6.8	14.1	152	161	498	286	
10-Dec-88	2169	49.63	2.356	12.72	12.44	0.18	8.84	10.59	2.19	0.437	0.23	99.61	23.9	320	6.9	13.9	151	161	495	286	
12-Jan-89	2202	49.56	2.364	12.66	12.47	0.18	8.91	10.57	2.28	0.432	0.23	99.66	23.6	322	7.7	14.1	151	168	511	283	
18-Feb-89	2239	49.82	2.369	12.74	12.41	0.18	8.91	10.60	2.29	0.428	0.23	99.98	24.2	319	6.7	14.2	151	169	510	285	
26-Mar-89	2275	49.59	2.349	12.62	12.43	0.18	9.00	10.52	2.12	0.427	0.23	99.46	23.2	319	7.3	14.3	154	174	526	287	
18-Apr-89	2298	49.76	2.370	12.64	12.45	0.17	9.05	10.56	2.15	0.423	0.23	99.80	23.9	317	6.6	14.4	155	169	527	291	
22-May-89	2332	49.71	2.343	12.69	12.55	0.17	8.93	10.55	2.22	0.421	0.23	99.82	24.0	321	7.5	14.1	153	171	515	288	
26-Jun-89	2367	49.90	2.347	12.72	12.44	0.17	8.95	10.58	2.21	0.425	0.23	99.97	24.5	322	7.6	14.1	155	167	509	292	
7-Jul-89	2378	49.68	2.342	12.70	12.43	0.17	8.92	10.54	2.17	0.419	0.23	99.60	24.2	322	7.2	14.0	153	163	504	290	
1-Aug-89	2403	49.96	2.363	12.79	12.46	0.17	8.74	10.64	2.29	0.433	0.24	100.09	24.5	324	7.3	14.2	152	159	486	284	
9-Sep-89	2442	49.71	2.354	12.75	12.40	0.17	8.63	10.60	2.21	0.421	0.23	99.48	25.0	324	6.9	14.3	151	157	481	292	

Table 3 Continued

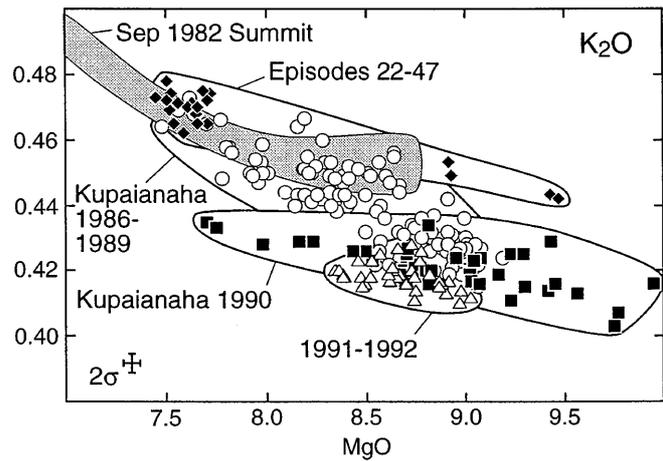
Sample	Days	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	Total	Y	Sr	Rb	Nb	Zr	Ni	Cr	V
14-Oct-89	2477	49.79	2.347	12.71	12.43	0.17	8.78	10.59	2.23	0.430	0.23	99.71	24.8	321	7.0	14.3	152	161	484	281
19-Nov-89	2513	49.84	2.344	12.72	12.43	0.17	8.78	10.58	2.10	0.421	0.23	99.61	24.3	320	7.2	14.5	154	163	491	294
16-Dec-89	2540	49.87	2.353	12.76	12.43	0.17	8.84	10.60	2.28	0.420	0.23	99.95	24.4	323	7.4	13.3	153	162	497	291
7-Jan-90	2562	49.95	2.369	12.84	12.40	0.17	8.53	10.69	2.21	0.423	0.23	99.81	24.3	322	7.1	13.8	153	156	465	289
6-Mar-90	2620	49.84	2.362	12.79	12.30	0.17	8.69	10.66	2.11	0.420	0.23	99.57	24.7	325	7.2	13.1	151	150	477	288
8-Apr-90	2653	50.08	2.373	12.82	12.36	0.17	8.74	10.69	2.16	0.422	0.23	100.05	24.7	323	7.5	14.7	154	150	483	291
20-Apr-90	2665	50.40	2.452	13.23	12.17	0.17	7.70	10.99	2.16	0.435	0.24	99.95	25.7	335	7.1	14.1	158	114	381	293
14-May-90	2689	50.34	2.392	13.01	12.35	0.17	8.23	10.84	2.21	0.429	0.24	100.21	24.7	325	7.1	14.1	156	135	431	293
27-May-90	2702	49.63	2.286	12.59	12.65	0.17	9.95	10.29	1.98	0.416	0.22	100.18	23.8	311	6.6	12.5	155	197	571	280
14-Jun-90	2720	49.82	2.297	12.53	12.68	0.17	9.77	10.36	2.03	0.407	0.23	100.29	23.5	312	7.4	14.2	151	192	564	286
25-Jun-90	2731	50.09	2.355	12.79	12.45	0.17	9.02	10.61	2.10	0.419	0.23	100.23	24.2	316	7.1	14.2	157	161	484	281
4-Aug-90	2771	50.21	2.390	13.00	12.41	0.17	8.49	10.78	2.13	0.426	0.23	100.24	24.2	319	6.7	14.4	149	142	451	287
16-Sep-90	2814	49.70	2.296	12.57	12.62	0.17	9.75	10.39	1.99	0.403	0.22	100.11	24.0	310	6.8	13.8	145	177	544	285
21-Oct-90	2849	49.95	2.372	12.94	12.39	0.17	8.67	10.69	2.01	0.419	0.23	99.84	24.3	317	7.3	13.4	151	152	493	296
9-Nov-90	2868	50.01	2.361	12.76	12.43	0.17	8.83	10.62	2.09	0.420	0.23	99.92	24.3	317	7.0	13.8	147	162	503	288
15-Dec-90	2904	50.39	2.413	13.04	12.33	0.17	8.16	10.85	2.02	0.429	0.23	100.03	24.3	323	6.6	14.5	151	131	433	292
12-Jan-91	2932	49.95	2.366	12.82	12.33	0.17	8.57	10.65	2.06	0.425	0.23	99.57	24.5	319	7.5	13.5	150	147	475	292
10-Feb-91	2961	50.31	2.383	12.91	12.46	0.17	8.73	10.73	2.28	0.428	0.23	100.64	24.7	318	7.0	14.4	153	157	499	297
1-Mar-91	2980	49.89	2.366	12.81	12.34	0.17	8.47	10.65	2.27	0.418	0.23	99.61	24.8	320	7.1	14.9	161	158	495	294
16-Apr-91	3026	49.93	2.370	12.82	12.41	0.17	8.49	10.64	2.27	0.416	0.23	99.75	24.2	319	7.3	13.8	153	151	477	289
12-May-91	3052	49.94	2.372	12.87	12.41	0.17	8.70	10.63	2.32	0.417	0.23	100.06	24.6	320	7.1	13.1	156	164	491	287
16-Jun-91	3087	49.91	2.372	12.87	12.42	0.17	8.67	10.64	2.32	0.419	0.23	100.02	25.1	320	7.5	13.8	158	155	495	291
16-Jul-91	3117	50.04	2.377	12.92	12.41	0.17	8.63	10.65	2.32	0.420	0.23	100.17	24.2	319	7.1	14.0	155	159	495	292
25-Aug-91	3157	49.94	2.377	12.87	12.39	0.17	8.74	10.62	2.41	0.411	0.23	100.16	23.9	317	6.9	14.5	150	168	544	288
20-Oct-91	3213	49.98	2.362	12.81	12.47	0.17	8.92	10.57	2.33	0.417	0.23	100.26	24.5	319	6.8	13.7	156	189	633	290
9-Nov-91	3233	49.87	2.387	12.95	12.93	0.17	8.38	10.66	2.37	0.418	0.23	100.36	24.6	318	6.9	14.5	151	164	552	285
11-Nov-91	3235	49.91	2.377	12.90	12.64	0.17	8.73	10.62	2.34	0.420	0.23	100.34	23.8	317	6.8	14.2	152	163	523	284
22-Dec-91	3276	50.12	2.378	12.91	12.36	0.17	8.74	10.65	2.25	0.418	0.23	100.23	24.8	321	7.2	13.8	157	165	513	290
11-Jan-92	3296	50.14	2.382	12.87	12.43	0.17	8.87	10.63	2.23	0.417	0.23	100.37	24.6	319	7.1	13.4	157	171	519	288
5-Feb-92	3321	49.96	2.387	12.91	12.36	0.17	8.53	10.66	2.15	0.423	0.23	99.77	24.7	320	6.9	12.8	151	155	499	282
Episode 48 (Puu Oo vent)																				
31-Jul-91	3132	49.96	2.378	12.83	12.35	0.17	8.62	10.61	2.21	0.417	0.23	99.78	-	-	-	14.3	152	174	537	300
2-Aug-91	3134	49.77	2.364	12.85	12.35	0.17	8.75	10.59	2.38	0.414	0.23	99.87	24.6	319	7.0	13.5	157	168	528	290
27-Oct-91	3220	49.75	2.357	12.80	12.35	0.17	8.88	10.53	2.35	0.416	0.23	99.83	24.2	317	6.3	14.6	151	172	544	285
Episode 49																				
8-Nov-91	3232	49.88	2.359	12.81	12.43	0.17	8.97	10.56	2.31	0.410	0.23	100.13	23.9	314	7.1	13.5	150	175	546	288
9-Nov-91	3233	49.97	2.361	12.80	12.41	0.17	8.98	10.57	2.30	0.414	0.23	100.21	25.3	317	6.7	13.6	155	180	537	292
17-Nov-91	3241	50.00	2.372	12.87	12.44	0.17	8.87	10.59	2.33	0.415	0.23	100.29	24.4	317	7.0	14.5	150	175	527	281
19-Nov-91	3243	49.99	2.361	12.79	12.42	0.17	9.03	10.57	2.23	0.412	0.23	100.20	24.2	315	7.3	13.3	155	179	544	288
Episodes 51 and 53																				
29-Dec-92	3649	49.57	2.355	12.69	12.42	0.18	8.80	10.52	2.22	0.419	0.23	99.40	24.0	318	6.8	13.5	149	170	498	280
25-Apr-94	4131	50.16	2.441	13.27	12.42	0.18	7.71	10.93	2.45	0.429	0.24	100.23	25.7	329	6.6	14.1	156	107	379	300

paio.soest.hawaii.edu] in the /pub/garcia directory. The XRF data are also provided for two additional lavas from episodes 51 and 53 because they were analyzed for isotopes and ICP-MS trace elements. All lavas analyzed by XRF were run in duplicate; the methods and the analytical precision for these analyses are given by Rhodes (1988). A subset of these lavas was analyzed for trace elements by ICP-MS at Washington State University using methods described by Garcia et al. (1993). The analytical precision ( $1\sigma$ ) for the ICP-MS analyses is estimated to be 1–3% based on repeated analyses of a Kilauea basalt standard (Kil1919; see Rhodes 1996) and a Columbia River basalt standard (BCR-P). The Pb, Sr, and Nd isotopes were determined at the University of Hawaii using a VG Sector mass spectrometer (for methods see Mahoney et al. 1991). Isotope fractionation corrections, standard values, total procedural blanks, and analytical uncertainties based on repeated measurements of standards are given with the isotope analyses.

### Major and trace elements

MgO is the most useful major element for evaluating compositional variation in Kupaianaha lavas because Mg-rich olivine (forsterite 81–85) is the dominant crystallizing phase. The lavas from the early part of episode 48 have the lowest MgO contents (7.5 wt.%); some of the 1990 lavas have the highest MgO contents (~10 wt.%). With decreasing MgO, the contents of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , CaO,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and  $\text{P}_2\text{O}_5$  increase and  $\text{Fe}_2\text{O}_3$  (as total iron) decreases in Kupaianaha lavas (Fig. 3). Within these broad trends, the episode 22–47 lavas (pre-Kupaianaha) generally have higher  $\text{TiO}_2$ , CaO,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , and  $\text{P}_2\text{O}_5$  contents and a lower  $\text{Fe}_2\text{O}_3$  content at a given MgO content than the episode-48 lavas. This temporal geochemical variation is particularly well illustrated on a  $\text{K}_2\text{O}$  vs MgO plot (Fig. 6). In this plot the Puu Oo lavas are subdivided into pre-Kupaianaha (episodes 22–47), early Kupaianaha (July 1986 to December 1989), the period of frequent eruption pauses (1990), and late Kupaianaha (January 1991 to February 1992).

Ni and Cr are the most compatible trace elements in Kupaianaha lavas. Plots of these elements vs incompatible elements (e.g., K) define steep negative trends for the pre-Kupaianaha lavas (episodes 22–47) and the 1990–1992 pond lavas (Fig. 7). Lavas within each of these two groups can be related to similar parental magmas by crystal fractionation. The episode-48 lavas erupted before 1990 form a compositional link connecting the more evolved lavas from episodes 22–47 with the more mafic 1990–1992 lavas (see Fig. 7). All of the other XRF-analyzed trace elements vary in their degree of incompatibility (variations of ~25% for Nb and Rb; ~7–10% for Sr, Zr, V, and Y, in decreasing order) and systematically decrease in abundance for lavas erupted between July 1984 and February 1992. Plots of these

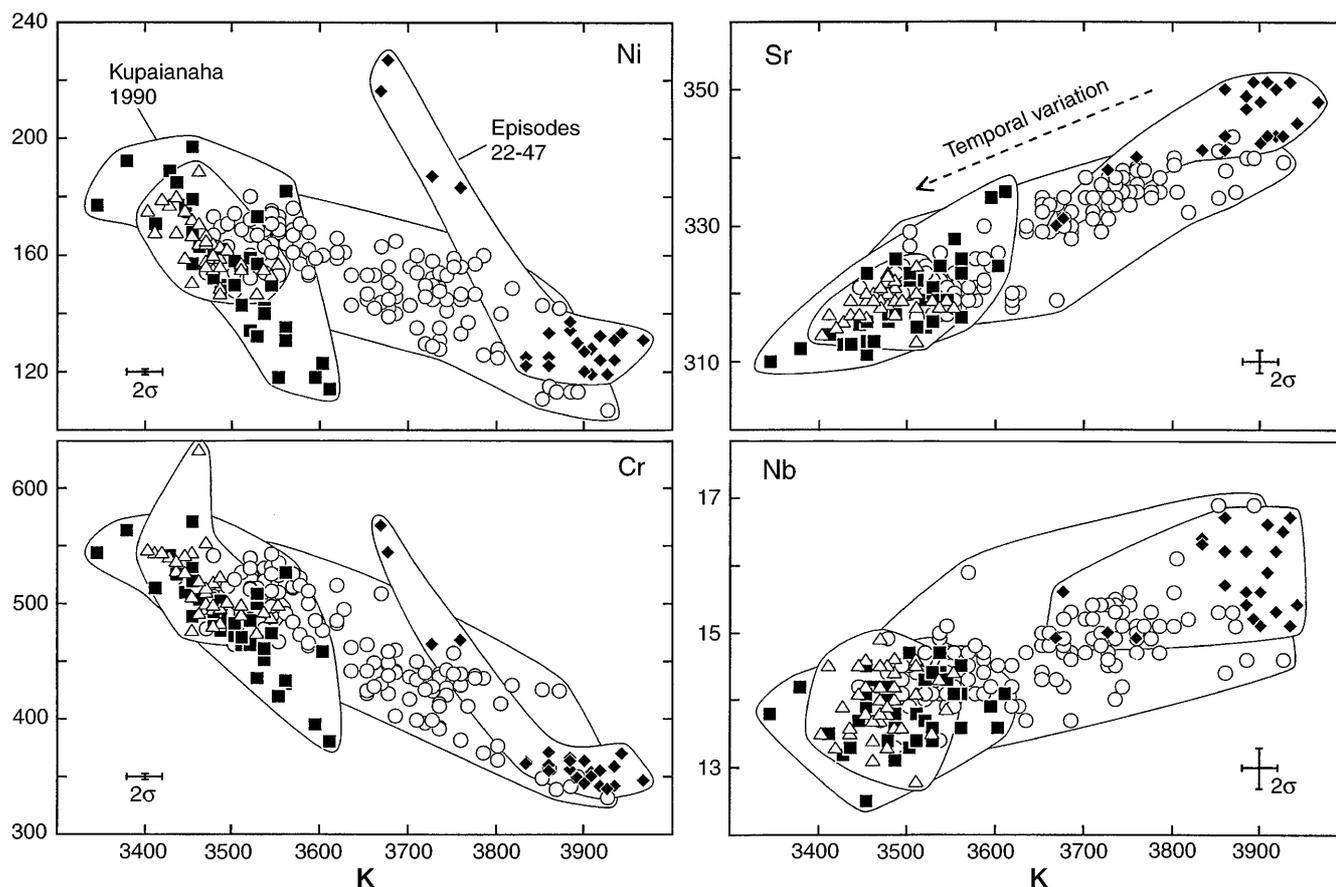


**Fig. 6** Whole-rock MgO vs  $\text{K}_2\text{O}$  content (both in wt.%) for Puu Oo lavas erupted between July 1984 (episode 22) and February 1992 (the end of episode 48). The lavas have been subdivided into four groups to highlight the temporal geochemical variation after episode 20, when magma mixing effectively ended (Garcia et al. 1992). The 1991–1992 lavas include samples from the Kupaianaha, Puu Oo, and episode-49 vents. The episode 22–47 lavas (pre-Kupaianaha) have the same relatively high  $\text{K}_2\text{O}$  contents at a given MgO content as the lavas from the September 1982 Kilauea summit eruption (stippled field). Note the subsequent progressive decrease in  $\text{K}_2\text{O}$  content at a given MgO content with time. Symbols are as in Fig. 3. The  $2\sigma$  error bars are given in the lower left corner

incompatible elements show linear trends with widths well beyond analytical error (Fig. 7).

Twenty lavas representing the overall compositional range for the Kupaianaha episode were selected for ICP-MS trace element analyses (Table 4). Twelve additional lavas from episodes 1–47 and one each from episodes 51 and 53 were also analyzed to evaluate overall Puu Oo geochemical variations. Plots of highly incompatible elements and of ratios of highly over moderately incompatible elements (e.g., La/Yb) show good linear trends when plotted against a highly incompatible element (Fig. 8). Ratio–ratio plots of highly incompatible elements form tight clusters which plot within or almost within analytical error (Fig. 8), which indicates a limited variation in the source composition for these lavas. Therefore, the variation in ratios of highly over moderately incompatible trace elements probably is related to either increasing degrees of partial melting or progressive depletion of the source during melting. A similar pattern was observed for the Mauna Ulu eruption and was explained by increased partial melting of the source (Hofmann et al. 1984).

Three elements were analyzed by both XRF and ICP-MS and the results are somewhat different. Although the ICP-MS data are more precise, we think the ICP-MS values for Rb are 0.5 ppm too high and the Nb values are approximately 1 ppm too low based on a comparison with a Kilauea basalt standard. The ICP-MS values for Y are 3–4 ppm low based on analyses of synthetic standards.



**Fig. 7** Whole-rock K-variation diagrams for trace elements (XRF data) from the Puu Oo eruptions (fields and symbols are as in Fig. 6). Ni and Cr behave as compatible elements in all of the Puu Oo lavas; Nb and Sr are incompatible. Note the shift towards lower incompatible element abundance with time and the large variation at a given K value relative to analytical error. All values are in parts per million. The  $2\sigma$  error bars are given in a lower corner of each plot

#### Pb, Sr, and Nd isotopes

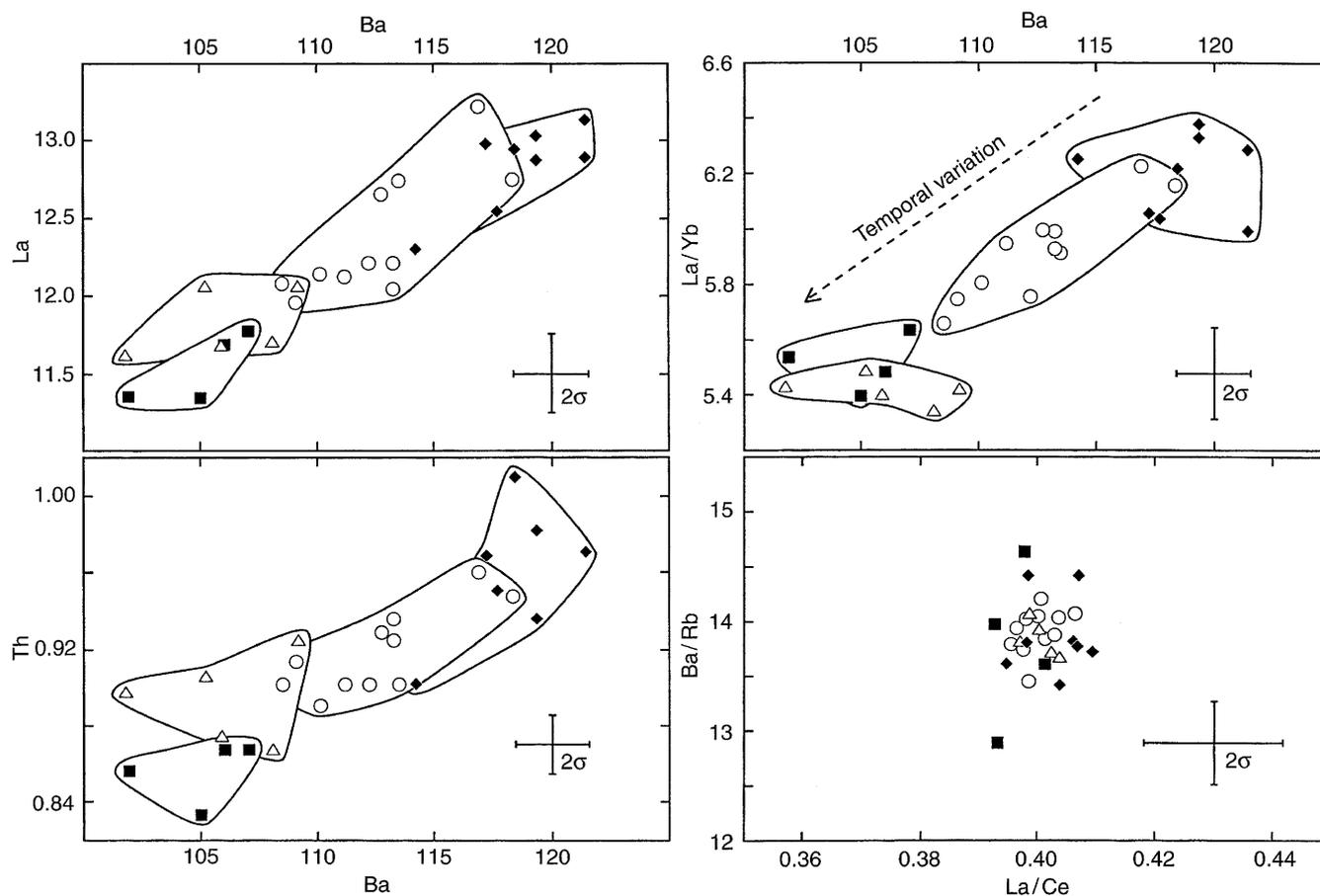
Eleven lavas from throughout the entire Puu Oo eruption (1983–1994) were selected for Pb-, Sr-, and Nd-isotope analyses (see Garcia et al. 1989, 1992 for XRF major and trace element data for the pre-Kupaianaha lavas). Isotopic data have previously been reported for three Puu Oo lavas. Newsom et al. (1986) gave Pb, Sr, and Nd data for one lava from episode 12 (late 1983). Sims et al. (1995) reported Th-, Sr-, and Nd-isotope data for two lavas; one was collected molten from the Puu Oo lava lake on 31 July 1991. The other lava was collected cold in 1992 on the extreme east flank of the coastal lava field and was probably erupted in November 1990 (K. W. W. Sims, pers. commun.). We have adjusted the isotopic data from these two labs to the same standard values that we use (see Table 5) and plotted the revised ratios in Fig. 9.

The Pb- and Sr-isotope data for Puu Oo lavas show small, but significant, variations during the early part of the eruption (Fig. 9). Pb isotopes show more variation relative to analytical error. The  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios decrease substantially over the first 800 days of the eruption [the 1983 lava from Newsom et al. (1986) sample plots within this trend; symbol with error bar]. The  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio of lavas erupted since early 1985 has remained relatively constant or may have increased slightly after 1990 (Fig. 9). The  $^{87}\text{Sr}/^{86}\text{Sr}$  variation is small (relative to analytical error), with the lowest ratios during the first part of the eruption (Fig. 9). Two of the three corrected Sr-isotope ratios from other labs (symbols with error bars) plot somewhat below these trends, but their values overlap with ours when the  $2\sigma$  errors are considered (Fig. 9). The  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios of Puu Oo lavas have been essentially constant during the eruption (Table 5), and the three Nd-isotope analyses from the two previous studies are within analytical error of our values (Fig. 9). There is a broad negative correlation of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  for Puu Oo lavas (Hawaiian tholeiites typically show a good negative correlation for these isotopes, e.g., West et al. 1987), but no correlation of Nd-isotope ratios with either Sr- or Pb-isotope ratios (Table 5).

**Table 4** ICP-MS trace element data for the matrix of Puu Oo lavas from episodes 1 to 53. All abundances are in ppm

Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ba	Th	Nb	Y	Hf	U	Rb	Cs
Episodes 1–46																						
1–49	14.2	35.0	5.11	23.2	6.20	2.08	6.4	0.96	5.64	1.07	2.82	0.39	2.22	0.33	130	1.12	14.3	30.0	4.25	0.37	9.4	0.09
1–54	17.9	43.7	6.30	28.1	6.92	2.36	7.3	1.05	6.15	1.13	2.93	0.41	2.42	0.34	163	1.40	20.2	34.0	5.09	0.48	12.3	0.12
5–139	14.8	36.7	5.25	24.0	6.22	2.13	6.7	0.97	5.70	1.06	2.77	0.39	2.29	0.32	135	1.16	16.1	30.2	4.49	0.39	9.6	0.09
12–197	13.5	33.7	4.94	22.5	5.81	2.02	6.2	0.91	5.46	1.02	2.63	0.37	2.20	0.31	127	1.07	15.2	29.6	4.17	0.37	9.3	0.09
22–283	12.9	32.5	4.66	20.8	5.64	1.89	5.9	0.88	5.21	0.99	2.62	0.36	2.08	0.29	118	1.01	14.0	28.5	3.92	0.33	8.6	0.08
30–359	13.1	32.1	4.63	21.3	5.50	1.89	5.9	0.88	5.19	0.97	2.58	0.36	2.09	0.29	121	0.97	14.2	28.4	3.69	0.34	8.8	0.08
30–362	12.3	30.3	4.36	19.8	5.17	1.80	5.5	0.85	4.94	0.90	2.42	0.33	1.97	0.28	114	0.90	13.2	27.0	3.52	0.32	8.3	0.07
31–363	12.9	31.7	4.65	21.0	5.49	1.94	5.9	0.91	5.25	0.98	2.58	0.36	2.15	0.30	121	0.97	13.7	27.6	3.83	0.35	8.4	0.08
31–367	12.5	31.5	4.61	21.0	5.42	1.90	5.8	0.87	5.16	0.98	2.51	0.36	2.08	0.29	118	0.95	13.7	27.8	3.84	0.32	8.2	0.08
35–419	12.9	31.9	4.59	21.0	5.60	1.96	5.8	0.89	5.22	0.97	2.53	0.36	2.02	0.29	119	0.98	13.8	28.6	3.77	0.34	8.9	0.08
40–484	13.0	32.9	4.78	21.9	5.80	2.00	6.1	0.92	5.37	1.03	2.67	0.37	2.14	0.30	117	0.97	13.8	28.6	3.95	0.33	8.6	0.09
46–549	13.0	32.0	4.66	21.0	5.58	1.95	5.8	0.91	5.29	0.97	2.58	0.37	2.06	0.29	119	0.94	13.8	28.8	3.75	0.34	8.7	0.08
Episode 48																						
25-Jul-86	13.2	33.2	4.80	21.9	5.88	1.95	6.3	0.93	5.59	1.06	2.78	0.37	2.12	0.31	117	0.96	13.6	28.6	4.17	0.32	8.7	0.09
13-Sep-86	12.7	31.8	4.58	21.0	5.51	1.89	5.9	0.91	5.31	0.99	2.59	0.35	2.07	0.30	118	0.95	13.7	28.1	3.82	0.34	8.5	0.08
16-Mar-87	12.0	30.2	4.39	20.4	5.30	1.86	5.6	0.87	5.04	0.95	2.49	0.34	2.01	0.29	113	0.94	12.7	27.5	3.65	0.32	8.1	0.08
30-Jul-87	12.7	31.9	4.71	21.3	5.66	1.89	6.0	0.90	5.26	1.02	2.69	0.38	2.11	0.30	113	0.93	13.3	28.1	3.89	0.32	8.1	0.08
18-Oct-87	12.7	31.6	4.62	21.3	5.58	1.92	6.0	0.88	5.33	1.00	2.65	0.38	2.15	0.30	113	0.90	13.5	28.0	3.85	0.30	8.2	0.09
19-Jan-88	12.2	30.5	4.47	20.4	5.47	1.85	5.6	0.90	5.28	0.99	2.53	0.35	2.06	0.30	113	0.92	13.7	28.0	3.79	0.32	8.1	0.07
18-Aug-88	12.1	30.3	4.46	20.3	5.43	1.85	5.8	0.88	5.23	0.99	2.58	0.35	2.04	0.30	111	0.90	12.7	27.6	3.89	0.31	7.8	0.07
20-Nov-88	12.2	30.0	4.51	20.7	5.44	1.91	5.8	0.90	5.24	1.00	2.56	0.36	2.12	0.31	112	0.90	12.8	28.2	3.79	0.31	8.0	0.09
26-Mar-89	12.1	30.1	4.47	20.5	5.53	1.91	5.8	0.89	5.28	1.00	2.65	0.36	2.09	0.30	110	0.89	12.8	28.3	3.87	0.31	7.8	0.07
26-Jun-89	12.0	30.1	4.41	20.6	5.43	1.90	5.8	0.90	5.26	0.98	2.56	0.35	2.08	0.30	109	0.91	12.8	28.3	3.78	0.32	7.9	0.07
7-Jul-89	12.1	30.5	4.49	20.9	5.65	1.94	6.1	0.90	5.36	1.02	2.66	0.37	2.14	0.31	109	0.90	12.9	28.7	3.96	0.31	7.9	0.07
7-Jan-90	11.8	29.3	4.36	20.2	5.41	1.90	5.7	0.90	5.30	1.00	2.59	0.36	2.09	0.30	107	0.87	12.4	28.3	3.89	0.30	7.9	0.08
27-May-90	11.3	28.9	4.24	19.9	5.37	1.87	5.6	0.90	5.26	0.98	2.59	0.35	2.10	0.30	105	0.85	12.1	27.8	3.81	0.28	7.5	0.07
25-Jun-90	11.3	28.9	4.27	19.7	5.30	1.85	5.7	0.88	5.24	0.98	2.57	0.35	2.05	0.30	102	0.86	11.9	27.4	3.85	0.30	7.9	0.07
21-Oct-90	11.7	29.4	4.31	20.3	5.48	1.91	5.8	0.91	5.43	1.03	2.68	0.37	2.13	0.31	106	0.87	12.2	28.5	4.05	0.30	7.2	0.07
10-Feb-91	11.7	29.4	4.45	20.5	5.52	1.91	5.7	0.92	5.41	1.03	2.68	0.37	2.19	0.32	108	0.87	12.3	27.8	4.01	0.30	7.7	0.07
12-May-91	11.6	28.9	4.38	20.3	5.49	1.86	5.8	0.90	5.30	0.99	2.63	0.37	2.14	0.31	102	0.90	12.3	28.6	3.85	0.30	7.4	0.08
25-Aug-91	11.7	29.2	4.38	20.1	5.32	1.87	5.8	0.88	5.15	0.98	2.53	0.36	2.16	0.30	106	0.87	12.5	27.9	3.82	0.30	7.6	0.07
11-Nov-91	12.1	29.9	4.48	20.6	5.62	1.89	6.0	0.90	5.39	1.03	2.71	0.37	2.20	0.31	105	0.91	12.6	28.7	3.96	0.31	7.7	0.08
5-Feb-92	12.1	30.4	4.57	21.0	5.61	2.00	6.1	0.93	5.55	1.03	2.72	0.37	2.22	0.30	109	0.92	13.0	30.0	4.12	0.32	7.9	0.08
Episode 51 and 53																						
29-Dec-92	11.7	29.0	4.35	20.0	5.34	1.88	6.0	0.88	5.19	0.98	2.58	0.37	2.11	0.29	103	0.87	12.8	28.4	3.84	0.29	7.2	0.07
25-Apr-94	12.0	30.5	4.63	21.5	5.65	1.95	6.2	0.91	5.47	1.03	2.78	0.37	2.20	0.30	105	0.89	13.0	29.2	4.04	0.31	8.0	0.07

Analytical uncertainties (1s) for each element are based on replicate analyses of an in-house basalt standard (BCR-P) run as an unknown during the sample runs (expressed as %): La (2.1), Ce (2.1), Pr (1.8), Nd (1.6), Sm (1.6), Eu (1.3), Gd (2.0), Tb (2.3), Dy (1.9), Ho (1.9), Er (3.1), Tm (2.4), Yb (1.8), Lu (1.8), Ba (1.4), Th (1.7), Nb (2.0), Y (2.5), Hf (3.1), U (2.0), Rb (2.4), Cs (2.4)



**Fig. 8** Trace element variation of Puu Oo lavas from episodes 22–48 based on ICP-MS data (Table 4). The plots of highly incompatible elements define linear trends with decreasing values with time (*arrow*). The scatter on these plots is almost within analytical error. The plot of highly incompatible element ratios demonstrates limited variation indicating that the ratios of these elements were not changing in the source during the eruption. The variation in La/Yb ratio could be caused by a systematic increase in partial melting or progressive depletion of highly incompatible elements in the source during the eruption. Fields and symbols as in Fig. 6

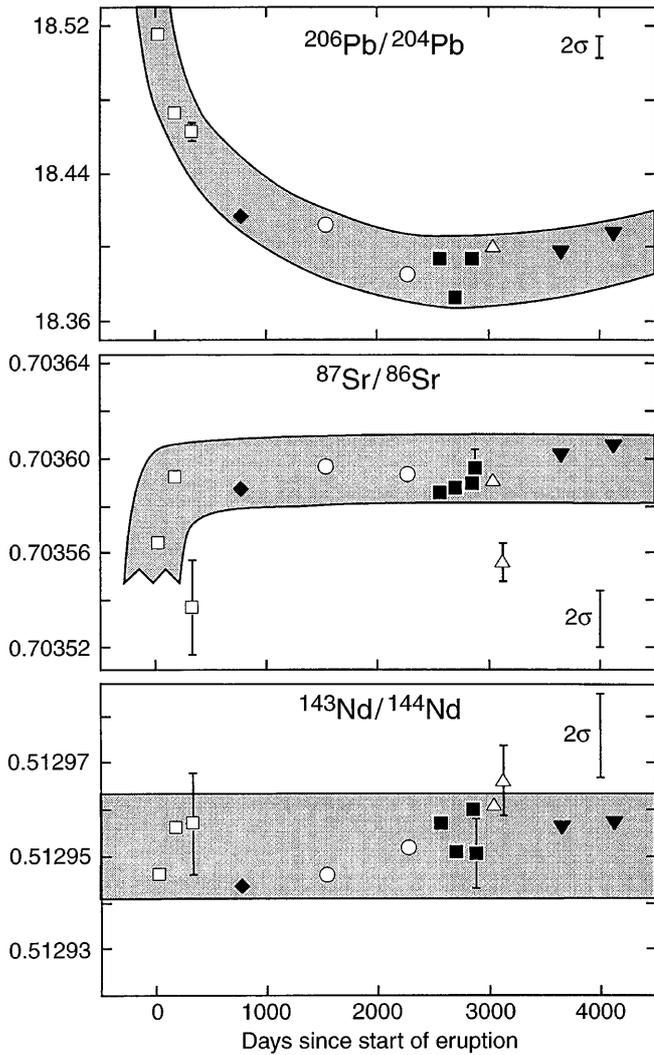
### Temporal geochemical variation

The Puu Oo eruption has shown substantial compositional variation during its history (Figs. 3, 6, and 7). This section presents the geochemical variation in a temporal context, summarizes our previous interpretations of the causes of geochemical variation for episodes 1–47 lavas, and presents a model for the MgO variations for some episode-48 lavas.

#### Episodes 1–47

The lavas from the first 3.5 years of the Puu Oo eruption display a wide compositional variation (Fig. 3). The early lavas (episodes 1–3) are strongly evolved

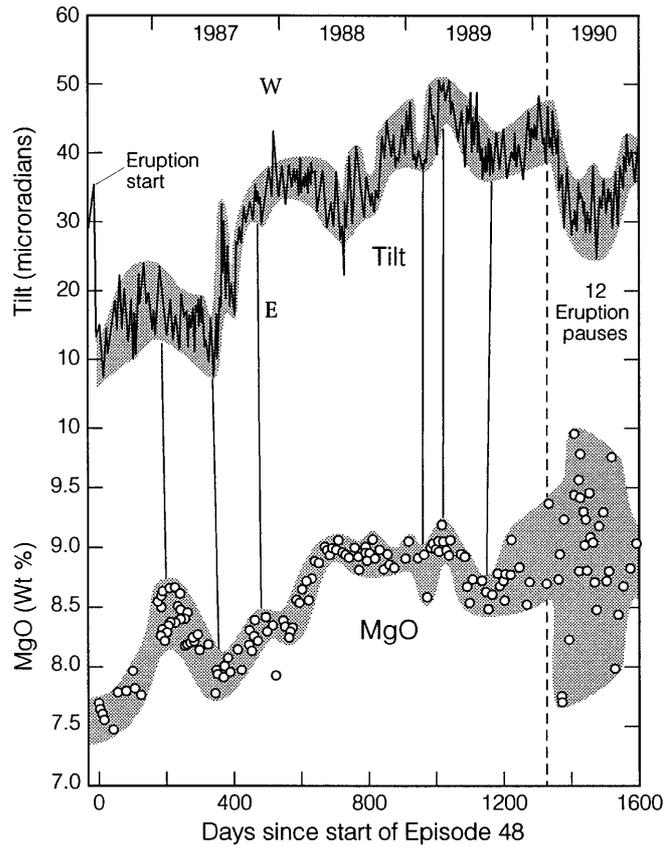
(5.7–6.6 wt.% MgO; Garcia et al. 1989) and the later lavas are more mafic (up to 9.5 wt.% MgO). During some high-volume episodes (5–10, 30 and 31), a systematic increase in MgO content of up to 2 wt.% was observed, indicating that the shallow reservoir under Puu Oo was compositionally zoned (Garcia and Wolfe 1988; Garcia et al. 1992). Superimposed on these short-term variations (20–30 days) was a long-term, progressive compositional change reflecting the increase in the percentage of mafic magma which was mixing with the evolved magma. This period of magma mixing was also the only portion of the Puu Oo eruption which showed significant variations in ratios of Pb and, to a lesser degree, Sr isotopes (Fig. 9). There is no petrographic or mineral chemical evidence for magma mixing after episode 20. Modeling of the geochemical variations in Puu Oo lavas, however, indicates that mixing probably continued to episode 30, after which only mafic magma from the feeder dike was erupted (Garcia et al. 1992). This interpretation is supported by the isotopic data, especially the Pb isotopes, which are essentially within analytical error during the rest of the eruption (Fig. 9). From episode 32 through 47, there was limited compositional variation in Puu Oo lavas. This probably indicates that only the more fractionated, upper portion of the shallow reservoir under Puu Oo was being erupted during this period. This situation changed markedly during episode 48.



**Fig. 9** Pb, Sr, and Nd isotopic variation during the Puu Oo eruption (averages of data from Table 5). Pb isotopes show the greatest variation as compared with analytical error, and most of the variation is within the first 2 years of the eruption (a period of magma mixing). The Sr isotope ratio data define a similar, but less well defined, trend because of the small variation in this ratio relative to analytical error during the eruption. The Nd isotope ratio data show essentially no variation beyond analytical error. Symbols with error bars are for data from other labs (*open square*: Newsom et al. 1986; *other two symbols*: Sims et al. 1995)

#### Episode 48

The switch from episodic to continuous eruption led to a  $\sim 1.3$ -wt.% increase in MgO for the lavas erupted during the first 200 days of this episode (Fig. 10). This was followed by  $\sim 1$  wt.% decrease in MgO over a 200-day period. The next 300 days was a period of increasing MgO ( $\sim 1.3$  wt.%) with an approximately 100-day interval of no compositional change in the middle. This period was followed by 400 days of nearly constant MgO content followed by a small decrease and then increase (0.7 wt.%). The subsequent time interval (1990)



**Fig. 10** MgO (wt.%) and summit tilt (E-W component in microradians) variations during the first 1600 days of episode 48, which began  $\sim 1300$  days after the start of the eruption in 1983. Changes in summit tilt are followed 20 days later by changes in MgO content. This pattern stopped in early 1990 (marked by *dashed line*), when a period of frequent eruption pauses started. These pauses caused large variations in MgO content due to olivine accumulation or depletion

was marked by 12 pauses in eruptive activity and large variations in MgO (Fig. 10). Although some of the MgO variations during 1990 can be explained by the observed variations in olivine content, most of the geochemical variations during the Kupaianaha episode cannot, i.e., more olivine accumulation is needed to explain the observed range in MgO content (7.5–10.0 wt.%) than is observed in the lavas. Furthermore, olivine alone cannot explain the observed temporal variations in  $K_2O$  content (and in other incompatible trace elements; Figs. 7 and 8) at a particular MgO content (Fig. 6).

What is the cause of the MgO variations? The MgO variations during the first 1200 days of episode 48 broadly correlate with variations in the E-W component of tilt at Kilauea's summit (Fig. 10). This correlation is remarkable because the geometry of the east rift zone conduit system probably changed during this 3.5-year period. This would cause variations in the amount of magma the rift zone could accommodate (without

**Table 5** Pb, Sr, and Nd isotope data for Puu Oo lavas from episodes 1–53

Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$
Episodes 1–30					
1–54	18.515	15.471	38.124	0.703564	0.512946
5–139	18.472	15.472	38.088	0.703589 0.703593 0.703595	0.512956
30–362	18.416	15.452	38.010	0.703587	0.512935 0.512952*
Episode 48					
16 March 87	18.412	15.478	38.073	0.703584 0.703596 0.703597 0.703609	0.512946
26 March 89	18.385	15.469	38.045	0.703576 0.703581 0.703588 0.703630*	0.512952
7 Jan 90	18.394	15.471	38.034	0.703586	0.512957
27 May 90	18.373	15.456	37.992	0.703584 0.703592	0.512951
21 Oct 90	18.393	15.475	38.049	0.703574 0.703578 0.703584 0.703603 0.703608	0.512960
12 May 91	18.400	15.470	38.035	0.703591	0.512956 0.512959 0.512968
Episodes 51, 53					
29 Dec 92	18.397	15.460	38.016	0.703601	0.512956
25 Apr 94	18.407	15.472	38.058	0.703605	0.512957

\* All isotopic measurements were made using the VG Sector solid source mass spectrometer at the University of Hawaii. Most replicate analyses were performed on aliquots of the same solution (separate sample dissolutions are in bold). Nd and Sr isotopic fractionation corrections are  $^{148}\text{Nd}/^{144}\text{Nd} = 0.242436$  ( $^{148}\text{Nd}/^{144}\text{Nd} = 0.241572$ ) and  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ . The data are reported relative to standard values for La Jolla Nd,  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511844$  and NBS 987 Sr,  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710258$ . Pb isotopic ratios are corrected for fractionation using the NBS 981 Pb standard values of Todt et al. (1984). The estimated uncertainties ( $1\sigma$ ) are based on repeated measurements of the standards:  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $\pm 0.006$ ;  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $\pm 0.006$ ;  $^{208}\text{Pb}/^{204}\text{Pb}$ ,  $\pm 0.017$ ;  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $\pm 0.000012$ ;  $^{143}\text{Nd}/^{144}\text{Nd}$ ,  $\pm 0.000009$ . Within-run uncertainties on individual sample measurements of Pb, Sr, and Nd isotopic ratios are less than or equal to the  $1\sigma$  mean external uncertainties of the La Jolla Nd, NBS 987, and NBS 981 standards in all cases. Total procedural blanks are negligible: 10–80 pg for Pb, <120 pg for Sr, and <20 pg for Nd

causing summit inflation or deflation) and thus destroy the apparent correlation between summit tilt and MgO content of the Puu Oo lavas. Changes in summit tilt are generally thought to represent variations in the magma supply rate from the mantle (Dzurisin et al. 1984), which may cause variations in the magma velocity and the extent of olivine fractionation within the volcano's magmatic plumbing system. Thus, we interpret the MgO variations in Kupaianaha lavas erupted before 1990 to be caused by minor changes in the magma supply rate to Kilauea.

There is a delay of approximately 20 days between summit changes and MgO variations in Kupaianaha lavas. The 20-day delay may represent the time required for magma to travel from the summit area to the Kupaianaha vent, a distance of  $\sim 19$  km. This would

suggest a magma velocity in the rift zone of  $\sim 1$  km/day (0.04 km/h), which is much slower than the initial dike intrusion that triggered the start of the Puu Oo eruption (0.6–0.7 km/h; Koyanagi et al. 1988; Okamura et al. 1988) and most other east rift zone dike intrusions (Klein et al. 1987).

During the previous long-lived Mauna Ulu eruption (1969–1974) on Kilauea's east rift zone, normalized abundances of incompatible elements progressively decreased with time, but abundances of Yb, ratios of highly incompatible elements, and Nd and Sr isotopes remained relatively constant (Hofmann et al. 1984). To compare geochemical results for lavas from the Puu Oo eruption with those from the Mauna Ulu eruption, we normalized our whole-rock data to 10 wt.% MgO because that is the composition of the most mafic Puu Oo

lava, and it is in equilibrium with the most forsteritic olivines from the eruption. The normalization was done in small increments (0.02 g of a mixture of 98.5% olivine and 1.5% Cr-spinel added to 100 g of liquid for each step) and, unlike the procedure used by Hofmann et al. (1984), the composition of the olivine that was added was calculated to be in equilibrium with the bulk-rock composition (assuming that 10% of the total iron is  $\text{Fe}^{3+}$ ) for each increment. The 1.5% spinel (using an average Kilauea Cr-spinel composition) was added to each step, because Wright (1971) found that Kilauea historical lavas contain approximately 1.5% Cr-spinel in olivines. Thus, we think we have achieved a normalization procedure that is representative of crystal fractionation in mafic Kilauea lavas. This procedure greatly reduces the scatter in the data related to variations in extent of crystal fractionation and allows us to identify coherent temporal variations. The normalization correction was applied only to the XRF data because the ICP-MS analyses were done on matrix material, which represents 91–98% of the rock. To evaluate the temporal variations of the ICP-MS data, we used ratios of elements which are unlikely to be modified by olivine fractionation.

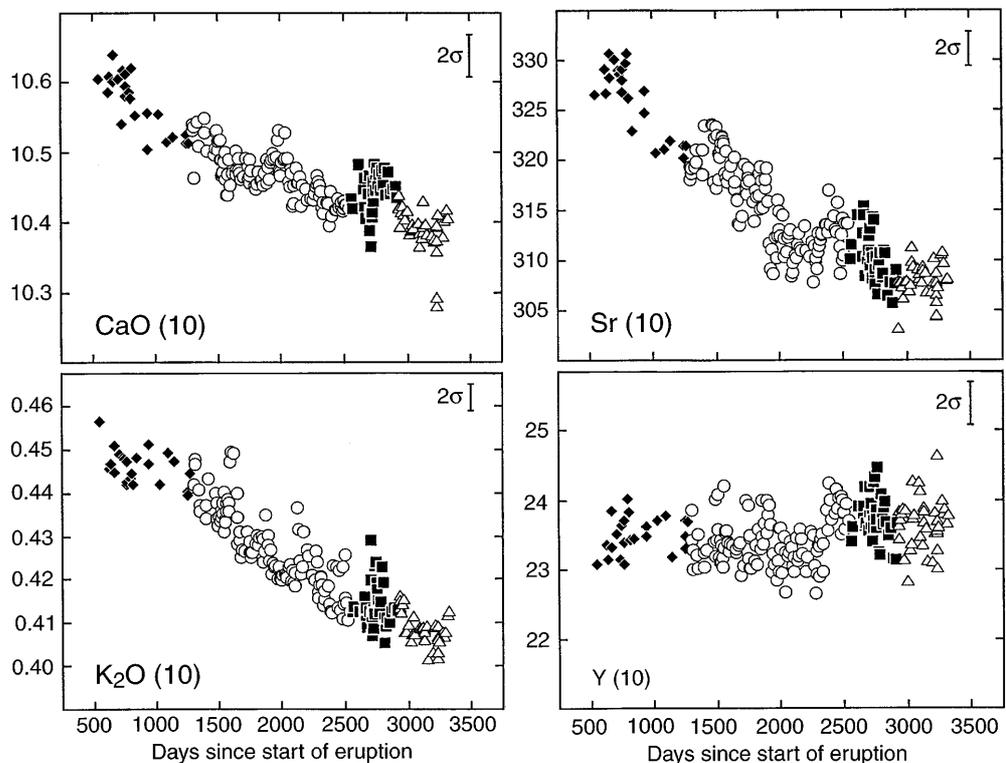
Puu Oo lavas erupted between mid-1984 (when mixing with the evolved rift zone hybrid magma effectively ended) and the end of episode 48 display a remarkably systematic decrease in the normalized abundance of incompatible elements and CaO (Fig. 11). In contrast, the normalized contents of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , FeO, and  $\text{Na}_2\text{O}$ , the abundance of Y, and ratios of highly incompatible elements have remained constant (Figs. 11 and 12).

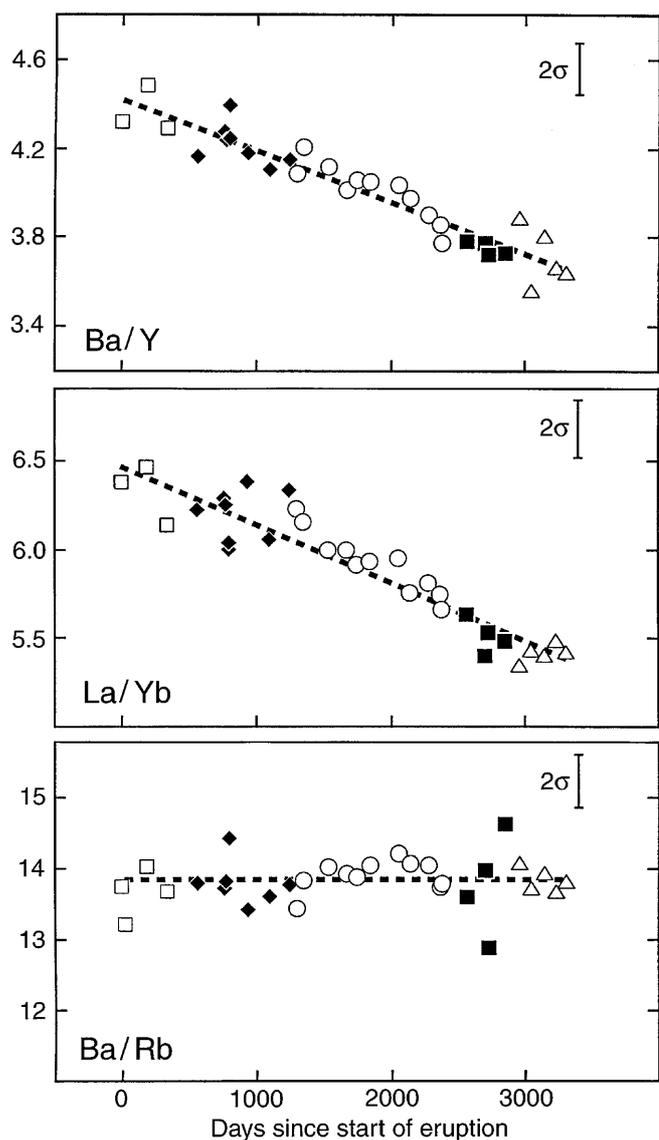
Pb and Sr isotopic ratios record small but systematic variations during the early portion of the Puu Oo eruption (when magma mixing was occurring; Garcia et al. 1992), but have remained nearly constant since (Fig. 9). Nd-isotope ratios have been essentially constant throughout the eruption (Table 5). Thus, the trace element and isotope results indicate that a relatively homogeneous portion of the Hawaiian plume was melted to provide the  $\sim 1 \text{ km}^3$  of mafic magma ( $>7 \text{ wt.}\%$  MgO) which has been erupted during the Puu Oo eruption. If we assume that Kilauea lavas are created by 5–10% partial melting (e.g., Watson 1993), then the Hawaiian plume must be homogeneous on a scale of at least  $10\text{--}20 \text{ km}^3$ .

### Cause of temporal geochemical variations during the Puu Oo eruption

The Puu Oo eruption offers an outstanding opportunity to investigate magmatic processes because many of the factors which complicate the study of other suites of volcanic rocks are missing. Puu Oo lavas are pristine, from a single well-documented eruption, and have had only relatively simple olivine fractionation (since mid-1984); thus, the effects of variable amounts of fractionation can be easily removed. These rocks show a remarkable temporal decrease in incompatible trace element abundances (after normalization to a constant MgO content) with little or no variation in ratios of isotopes or highly incompatible trace elements (Figs. 9, 11, and 12).

**Fig. 11** Temporal variation of CaO and  $\text{K}_2\text{O}$  contents, and Sr and Y abundances normalized to 10 wt.% MgO (the most MgO-rich composition erupted from Puu Oo; see text for description of normalization procedure) for lavas from episodes 22–48 (data from Table 3 and Garcia et al. 1992) of the Puu Oo eruption. Note the overall decrease in these contents and abundances during the course of the eruption. Symbols as in Fig. 6





**Fig. 12** Temporal variation in ratios of highly (Ba/Rb) or highly over moderately (La/Yb and Ba/Y) incompatible elements for Puu Oo lavas. The flat trend of the ratio of highly incompatible elements (and of Nd-, Sr-, and Pb-isotope ratios since episode 30) and the decrease in the other ratios during the course of the eruption indicate that the source of the Puu Oo lavas has been relatively homogeneous, but that either the degree of partial melting has progressively increased during the course of the eruption (which seems unlikely because the measured lava volumes have decreased during the eruption; Kauahikaua et al. 1996) or that the source is being systematically depleted of highly incompatible elements as the eruption proceeds. Symbols as in Fig. 6. The  $2\sigma$  error bar for each ratio is given in the upper right corner of each panel

The early Puu Oo elemental and isotopic compositional variation (episodes 3–20) was strongly influenced by mixing between an evolved rift zone hybrid and a summit reservoir-derived mafic magma (Figs. 3 and 9; Garcia et al. 1992). The presence of an evolved magma in the early Puu Oo lavas is indicated by their low CaO/TiO<sub>2</sub>, reverse compositional zoning in olivine, and the

occurrence of plagioclase and/or pyroxene phenocrysts. These features were not observed in Puu Oo lavas erupted after episode 20 (~550 days after the start of the eruption; Garcia et al. 1992). The composition of the lava erupted during the next 2 years (July 1984–June 1986) was essentially identical to that erupted during the September 1982 summit eruption of Kilauea (Fig. 6).

The composition of Puu Oo lavas progressively changed during the next 5.5 years (episodes 48 and 49; Figs. 6 and 7). Mixing between two compositionally and temporally distinct mafic magmas, with the percentages of the later magma progressively increasing with time, could explain many of the compositional variation features. However, the apparent compositionally distinct end members (1985 and 1990) which form steep linear trends for compatible elements (Ni and Cr; see Fig. 7) were formed during atypical periods of the Puu Oo eruption. Episodes 30 and 31, during 1985, were high-volume eruptions and 1990 was a period of frequent eruption pauses. If similar events had occurred between these years, we suspect that lavas with large compositional variations might have also been erupted. Another problem for the magma-mixing hypothesis is that there was no reservoir of old magma (1985) with which the new magma could mix. The old magma would have been flushed out of the Puu Oo reservoir long before 1990, given the relatively small size of the Puu Oo reservoir (~12,000,000 m<sup>3</sup>; Hoffmann et al. 1990) compared with the volume of lava erupted between 1985 and 1990 (~400,000,000 m<sup>3</sup>).

Hofmann et al. (1984) explained similar geochemical and isotopic results for the Mauna Ulu eruption by a 20% increase in partial melting over a 2-year period. They recognized that “this might be too short a period for such a large increase in the degree of partial melting.” Another problem for this model as an explanation for the Puu Oo eruption is that it predicts that the magma supply rate to Kilauea should increase during the eruption. The slow deflation of the summit reservoir during this eruption (Delaney et al. 1993), and the lower eruption rates during episode 48 (Mattox et al. 1993) as compared with episodes 1–20 (Wolfe et al. 1987), clearly indicate that the Puu Oo eruption did not experience an increased magma supply rate. Instead, the magma supply rate probably decreased somewhat, especially during episode 48, as witnessed by a linear decrease in lava production (Kauahikaua et al. 1996).

An alternative explanation for the Puu Oo geochemical variation which explains the apparent decrease in magma supply rate is progressive melting of an essentially homogeneous source. During continued melting the highly incompatible elements and CaO decreased as this clinopyroxene-rich component of the source was preferentially melted. Thus, a continuum of slightly more depleted parental magmas may have been supplied to the Puu Oo reservoir during this eruption. The consistency of Y and the slight increase in Yb during episode 48 require that a mineral with a high parti-

tion coefficient for these elements (garnet) was a residual phase during melting. The ratio of residual garnet to clinopyroxene in the source probably progressively increased during the eruption based on the decrease in CaO/Yb and CaO/Al<sub>2</sub>O<sub>3</sub> with time in Puu Oo lavas.

### Implications of Puu Oo geochemical variations for Kilauea's magmatic plumbing system

The temporal variation in the incompatible trace element ratios of historical lavas has been used to estimate the volumes of magma reservoirs and the residence times of magma in them for several active volcanoes including Mt. Etna, Vesuvius, and Piton de la Fournaise (e.g., Albarede 1993). The Ba/Y ratio in lavas from Kilauea's Puu Oo eruption systematically decreased from 4.27 during episode 30 (764 days) to 3.61 at the end of episode 48 (3321 days; Fig. 12). This corresponds to a secular decrease in the Ba/Y ratio equal to 0.094 a<sup>-1</sup> based on a linear regression of the data. This rate of change is high compared with lavas erupted over the past 200 years at the summit of Kilauea (~0.03 a<sup>-1</sup>; Pietruszka and Garcia 1994). As is demonstrated below, the rapid rate of compositional change for the Puu Oo eruption might be related to its magma avoiding mixing with magma in the summit reservoir.

A few assumptions are made for the analysis method of Albarede (1993) to calculate magma residence time and reservoir volume: (a) all of the erupted Puu Oo lava passes through the summit reservoir (which is consistent with seismic data; Koyanagi et al. 1988); (b) the summit reservoir is essentially at steady state (summit tiltmeter data indicate a long-term slow subsidence of only 10 cm a<sup>-1</sup>; Delaney et al. 1993); (c) the secular geochemical variation of the Puu Oo lavas results from the mixing of a resident magma in the summit reservoir with a Ba/Y of 4.3 with an input magma of a different but uniform Ba/Y (3.6); and (d) the Y concentrations in the input and resident magmas are equal (which is consistent with our results). Using these assumptions, Eq. (14) of Albarede (1993) is simplified to

$$\tau = \frac{(\text{Ba/Y})^{\text{input}} - (\text{Ba/Y})^{\text{output}}}{d(\text{Ba/Y})^{\text{output}}/dt}$$

The residence time of magma ( $\tau$ ) in the summit reservoir of Kilauea is found to be (3.61–4.27)/(-0.094 a<sup>-1</sup>) ≈ years. The Puu Oo lava effusion rate is 0.12 km<sup>3</sup> a<sup>-1</sup> (Wolfe et al. 1987), so the volume of the summit reservoir would be 0.84 km<sup>3</sup> (magma residence time × lava output rate; Albarede 1993). This calculation is sensitive to the assumed input magma Ba/Y ratio (which may be lower than 3.6). If we use the lowest Ba/Y value observed for Kilauea historical summit lavas (3.0; Pietruszka and Garcia 1994), the corresponding magma residence time would be ~14 years and the reservoir volume would be ~1.6 km<sup>3</sup>. These increases are only slightly compensated by the observed deflation of the

summit reservoir of ~9 cm a<sup>-1</sup> during the Puu Oo eruption, which is equivalent to a deflation of ~0.002 km<sup>3</sup> a<sup>-1</sup> (Delaney et al. 1993). These revised estimates are below other estimates of Kilauea magma residence time (e.g., ~120 years; Cohen and O'Nions 1993) and the summit reservoir size (e.g., ~40 km<sup>3</sup>, Klein et al. 1987; 2–13 km<sup>3</sup>, Johnson 1992). The difference between our estimates and those of others would be even larger if the Ba/Y of the parental magma was assumed to progressively decrease during the course of the eruption, as is observed during the Mauna Ulu (Hoffman et al. 1984) and Puu Oo eruptions. Thus, one of our assumptions is probably incorrect. Because we already considered the probable effects of two of our assumptions on our residence time and volume estimates (Kilauea's overall historical geochemical variation and the deflation of the summit reservoir), the most likely error in our analysis is assuming that Puu Oo magma mixes with summit reservoir magma before being injected into the east rift zone. The observed rapid change in Ba/Y (0.09 a<sup>-1</sup>) for Puu Oo lavas compared with historical lavas (past 200 years) erupted from the summit reservoir (average 0.03 a<sup>-1</sup>; Pietruszka and Garcia 1994) probably indicates that Puu Oo magmas did not mix thoroughly with the main mass of the summit reservoir. Thus, we propose that the Puu Oo magmas at least partially bypassed the summit reservoir on their transit from the mantle to the shallow magma reservoir under Puu Oo (see Fig. 4). Similar interpretations have been made for other Kilauea eruptions including the Kilauea Iki 1959 eruption (which has been estimated to have had a magma storage time of 10 years; Mangan 1990) and the Mauna Ulu eruption (based on seismic data; Ryan et al. 1981). Thus, some Kilauea lavas (e.g., from the Puu Oo and Mauna Ulu eruptions) apparently avoid mixing with magma in the summit reservoir and offer us an opportunity to "witness" mantle melting processes.

### Episode 49 and the nature of the shallow magmatic plumbing for the Puu Oo eruption

The fissure system which opened between Puu Oo and Kupaianaha vents during episode 49 (Fig. 1) produced lavas of nearly constant composition (e.g., 8.95 ± 0.10 wt.% MgO). The composition of these lavas is virtually identical to that of the lava collected from the Puu Oo crater lava lake 12 days before the start of episode 49 (8.88 wt.% MgO) and to those of the three lavas collected from skylights fed from the Kupaianaha vent during the month before episode 49 (8.90 ± 0.02 wt.% MgO. Mangan et al. (1995a) reported similar, but more variable, MgO contents for pre-episode-49 Kupaianaha lavas. During the first 2 days of episode 49, the MgO content of the Kupaianaha lavas dropped ~0.5 wt.%, then increased slightly by the fourth day and remained constant until the end of the Kupaianaha episode (with some minor fluctuation;

8.7 ± 0.2 wt.%). Mangan et al. (1995a) reported a smaller difference in MgO content between coeval episode 49 and Kupaianaha lavas (~0.2 wt.%), but did not discuss any temporal variation, although their data show approximately the same MgO variation as ours.

Earthquake data are commonly used to infer the location of a conduit system within Kilauea (e.g., Ryan et al. 1981; Koyanagi et al. 1988). The paucity of earthquake data under the Kupaianaha vent (P. Okubo, pers. commun.) requires that we use other indirect methods to infer the nature of the vent's conduit system. The geochemical data for these lavas can be used to help constrain the nature of the magma conduit system between the Puu Oo and Kupaianaha vents and the episode-49 fissures. One important constraint is the essentially identical composition of the lavas erupted from the three vents during the same period in late 1991 (Table 3). It is extremely unlikely that this could have occurred unless all three vents were being supplied from the same reservoir of well-mixed magma. Another important piece of evidence is that the Puu Oo vent released much larger quantities of volcanic fume than the other two vents. Similar features have been reported for some historical rift zone eruptions on Kilauea's neighbor, Mauna Loa. They were explained by degassing at the uprift vent and lateral flow of magma through a shallow conduit to vents at lower elevations (Lockwood et al. 1987). We propose a similar vent geometry for the Puu Oo–Kupaianaha conduit system (Fig. 4). Because the episode-49 eruption had little effect on the Kupaianaha vent (Mangan et al. 1995a), the episode-49 conduit probably tapped a shallower portion of the Puu Oo reservoir than the Kupaianaha conduit (e.g., tens vs hundreds of meters below the surface).

A much different conduit system for the Kupaianaha vent was proposed by Mangan et al. (1995a). They thought that the Kupaianaha vent was supplied by a near-vertical conduit from deeper within the east rift zone (~2.5 km). This model does not explain the degassed nature of the lava erupted at the Kupaianaha vent or the identical composition of lavas erupted from the three vents during 1991. It seems unlikely that Kupaianaha and Puu Oo would erupt lavas with identical compositions if they were being supplied independently from the core of the rift zone, because the Kupaianaha vent is probably underlain by a body of differentiated magma left over from the 1977 east rift zone eruption (Fig. 4). Vents for the 1977 eruption are located on either side of the Kupaianaha vent, and magma of a composition similar to that erupted in 1977 was mixed with more mafic magma and erupted in the area of the Kupaianaha vent during the initial episode of the Puu Oo eruption (Garcia et al. 1989). Thus, we think it is unlikely that the Kupaianaha vent was fed from a vertical conduit tapping the magmatic core of the east rift zone. Instead, we think the Kupaianaha vent was supplied by a shallow dike (a few hundred meters deep) which formed at the start of episode 48. The formation

of a second, shallower conduit (tens of meters deep) between Puu Oo and Kupaianaha vents during episode 49 (not shown in Fig. 4 because of scale limitations) resulted in lower eruption rates at the Kupaianaha vent and its eventual death ~40 days later.

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## Summary

The Puu Oo eruption of Kilauea is noteworthy in the historical record for Kilauea volcano for its long duration, large volume, and its substantial geochemical variation in lava composition. The long duration of this eruption has allowed us to better resolve magmatic processes within Kilauea volcano. The simple mineralogy and pristine nature of the Puu Oo lavas (especially since 1984 when mixing with an evolved magma ended) have played an important role in simplifying the adjustments which are needed to interpret the temporal variations in Puu Oo geochemical data. Variations in MgO content of Puu Oo lavas during the first half of episode 48 may have been controlled by variations in magma supply from the mantle (as witnessed by variations in summit tilt), indicating that there was a hydraulic balance between the summit of Kilauea and the Puu Oo vent system. This correlation was terminated as a result of the numerous eruptive pauses during 1990.

Ratios of Pb and Sr isotopes for Puu Oo lavas show moderate to small variations during the first ~2 years of the eruption due to magma mixing involving a hybrid, evolved magma and mafic magma which was intruded in the middle east rift zone of Kilauea just before the start of the eruption. Subsequent lavas are essentially homogeneous for isotopes of Pb, Sr, and Nd (which did not vary beyond analytical error during the entire eruption). Ratios of highly incompatible elements are also constant for these lavas, which together with the isotopic data indicate that the source for the 1 km<sup>3</sup>+ of Puu Oo lavas was essentially constant. If Kilauea magmas are produced by 5–10% partial melting (e.g., Watson 1993) of the Hawaiian plume, then the plume must be homogeneous on a scale of 10–20 km<sup>3</sup>.

The MgO content of the parental magmas for Kupaianaha lavas was at least 10 wt.%, based on the composition of olivine phenocrysts in these lavas. When the composition of the Puu Oo lavas is normalized to 10 wt.% MgO, the abundances of highly incompatible elements and CaO progressively decrease while Y and Yb abundances remain nearly constant. Our preferred model for the Puu Oo temporal geochemical and isotopic results is progressive melting of a relatively homogeneous portion of the Hawaiian plume, which locally caused a systematic depletion in the incompatible-bearing, clinopyroxene component, with garnet remaining a residual phase.

Systematic geochemical variations are not normally observed during Kilauea eruptions. A notable exception is another east rift eruption, Mauna Ulu (Hofmann et al. 1984). Two factors may be important in observing

such temporal geochemical variations. The eruption must continue beyond emptying the local reservoir, and the magmas which feed the eruption must avoid mixing with magmas in the summit reservoir and/or pods of evolving magma residing along the rift zone. Thus, the lavas from these two eruptions are valuable tools for understanding the dynamics of Kilauea's magmatic plumbing system.

The Puu Oo eruption has changed in style several times over the past 13 years but shows no signs of ending. Long-lived eruptions (many decades to over a century) have been common at Kilauea for the past 700–800 years (Delaney et al. 1993), so it is possible that the Puu Oo eruption may continue for several more decades.

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