

Geochemical Variations during Kīlauea's Pu'ū 'Ō'ō Eruption Reveal a Fine-scale Mixture of Mantle Heterogeneities within the Hawaiian Plume

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Long-term geochemical monitoring of lavas from the continuing 25-year-old Pu'ū 'Ō'ō eruption allows us to probe the crustal and mantle magmatic processes beneath Kīlauea volcano in unparalleled detail. Here we present new Pb, Sr, and Nd isotope ratios, major and trace element abundances, olivine compositions, and petrographic data for Pu'ū 'Ō'ō lavas erupted from 1998 to 2005. Olivine fractionation and accumulation are important crustal processes for the eruption, with minor clinopyroxene fractionation observed in the most recent lavas. Small, yet systematic variations in $^{87}\text{Sr}/^{86}\text{Sr}$ and incompatible trace element ratios, and MgO-normalized major element abundances document rapid changes in the parental magma composition delivered to Pu'ū 'Ō'ō. Recent (1998–2003) lavas display a systematic temporal evolution towards an intermediate area between the compositional fields of historical Kīlauea and Mauna Loa lavas. At least three distinct mantle source components are required to explain the overall isotopic and chemical variability of Pu'ū 'Ō'ō lavas. Two of these source components observed in pre-1998 Pu'ū 'Ō'ō lavas have similar Pb, Sr, and Nd isotope ratios, although one underwent a recent (<8 ka) small-degree melting event and became depleted in incompatible trace elements. This recently depleted component was an increasingly important source for lavas erupted between 1985 and 1998. The third component is a hybrid mixture of nearly equal portions of Kīlauea- and Mauna

Loa-like mantle source compositions. It was progressively tapped in greater amounts from 1998 to 2003 and then subsequently decreased. The increasing importance of the hybrid source can be explained if melt pathways migrated from an area within Kīlauea's typical melting region (important for the 1985–1998 lavas) towards Mauna Loa, where a similar proportion of Kīlauea- and Mauna Loa-like mantle components might exist. The Pu'ū 'Ō'ō data suggest that Kea and Loa mantle components are distributed on a fine-scale within the Hawaiian plume, and both are present beneath Kīlauea volcano. Based on the geochemical and isotopic variations during the Pu'ū 'Ō'ō eruption, the estimated volume for Kīlauea and Mauna Loa compositional heterogeneities is <10–35 km³.

KEY WORDS: Hawaii; Kīlauea; volcanoes; geochemistry; mantle heterogeneity

INTRODUCTION

Time-series studies of geochemical variations during long-lived eruptions or eruptive sequences provide valuable insight into the magmatic processes within active volcanoes (e.g. Arenal, Costa Rica, Bolge *et al.*, 2006;

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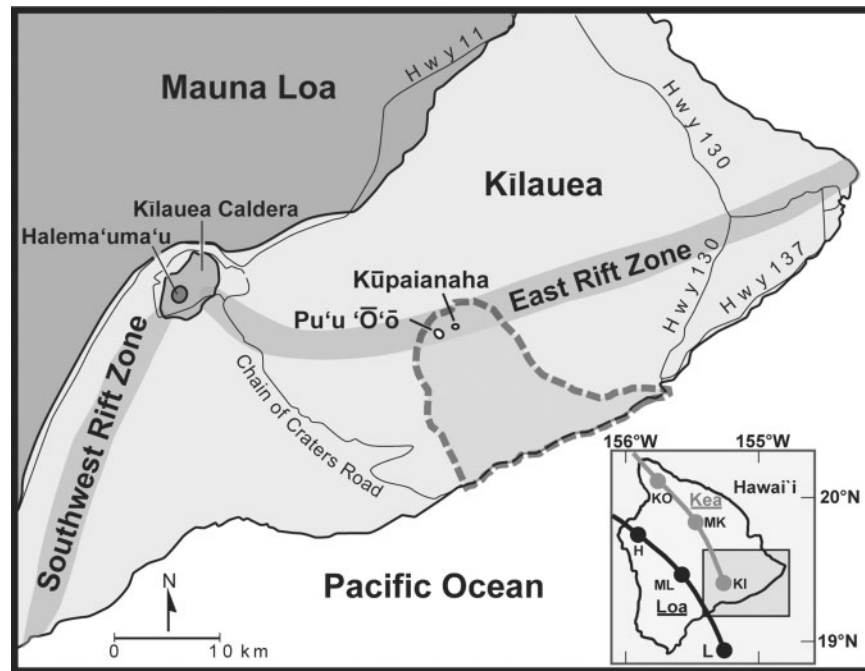


Fig. 1. Location map of the Pu'u 'Ō'ō eruption flow field (dashed outline) on the East Rift Zone of Kīlauea volcano, Hawai'i (after Mittelstaedt & Garcia, 2007). Lava erupted from two primary vents: the Pu'u 'Ō'ō cone between 1983 and 1986 and between 1992 and 2007 (episodes 4–47, 50–53, and 55), and at Kūpaianaha between 1986 and 1992 (episodes 48 and 49). The inset map shows the distribution of Loa (H, Hualālai; ML, Mauna Loa; L, Lō'ihi) and Kea (KO, Kohala; MK, Mauna Kea; KI, Kīlauea) volcanoes.

Etna, Italy, Rizzo *et al.*, 2006; Grímsvötn, Iceland, Sigmarrsson *et al.*, 1992; Parícutin, Mexico, Wilcox, 1954; McBirney *et al.*, 1987; Piton de la Fournaise, Réunion, Vlastelic *et al.*, 2005). These studies provide a detailed view of the crustal- and mantle-related magmatic processes occurring on short time scales (days to years). Kīlauea volcano, located on the island of Hawai'i (Fig. 1), has erupted ($\sim 4.3 \text{ km}^3$; Macdonald *et al.*, 1983; Sutton *et al.*, 2003) frequently during the past 200 years, making it an ideal location to investigate temporal variations in lava chemistry that are related to changes in mantle source compositions and melting conditions within the Hawaiian plume.

Previous seismic and petrological studies suggest that Kīlauea magmas originate from partial melting at mantle depths $>60\text{--}80 \text{ km}$ within the upper Hawaiian plume (e.g. Eaton & Murata, 1960; Watson & McKenzie, 1991; Tilling & Dvorak, 1993). Rapid melt extraction from the mantle source region into chemically isolated channels (e.g. McKenzie, 1985; Williams & Gill, 1989) is probably the dominant melt transport mechanism beneath Kīlauea because it provides a relatively large amount of melt for sustained, high-volume eruptions such as Pu'u 'Ō'ō (Pietruszka *et al.*, 2006). After accumulating, these melts are thought to ascend through a primary conduit delivering magma to Kīlauea's shallow (2–6 km deep) magma reservoir, and may subsequently erupt in the summit caldera or feed the volcano's two rift zones (e.g. Tilling & Dvorak, 1993; Wright & Klein, 2006).

The Pu'u 'Ō'ō eruption is the longest sustained (25+ years) and most voluminous ($\sim 3 \text{ km}^3$ erupted lava) historical eruption of Kīlauea volcano (Garcia *et al.*, 2000; Heliker & Mattox, 2003). Pu'u 'Ō'ō magmas are thought to partially bypass the summit reservoir (based on the rapid variations in incompatible trace element ratios for Pu'u 'Ō'ō lavas compared with Kīlauea summit lavas) before intruding Kīlauea's East Rift Zone to feed a shallow ($<3 \text{ km}$ depth) magma reservoir system beneath the Pu'u 'Ō'ō cone (Garcia *et al.*, 1996; Shamberger & Garcia, 2006). Since the start of the eruption in January 1983, there have been small but systematic variations in the Pb, Sr, and O isotope ratios and major and trace element abundances of Pu'u 'Ō'ō lavas. These fluctuations provide an unprecedented opportunity to document the crustal processes (e.g. crystal fractionation and accumulation, and crustal assimilation) and mantle source and melting variations (e.g. mantle source heterogeneity, and melt production, extraction, and transportation) within the Hawaiian plume on a time scale of months to years (e.g. Garcia *et al.*, 1989, 1992, 1996, 1998, 2000; Putirka, 1997; Thornber, 2001, 2003; Pietruszka *et al.*, 2006).

Two different length scales of mantle heterogeneity within the Hawaiian plume have been recognized based on the distinct isotopic variations of single volcanoes. Large-scale heterogeneity has been proposed based on the persistent intershield geochemical differences of Hawaiian volcanoes over tens to hundreds of thousands of years

(e.g. Frey & Rhodes, 1993; Chen *et al.*, 1996), and the long-term differences in Pb isotope ratios (Tatsumoto, 1978; Abouchami *et al.*, 2005) along two NW–SE-trending loci of volcanoes (Fig. 1): the northeastern ‘Kea’ trend (e.g. Kīlauea) and the southwestern ‘Loa’ trend (e.g. Mauna Loa). The Kea end member is defined by higher $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ and lower $^{87}\text{Sr}/^{86}\text{Sr}$ and is predominantly observed in lavas from Kīlauea, Mauna Kea, West Maui, and East Molokaʻi volcanoes (Stolper *et al.*, 1996; DePaolo *et al.*, 2001; Blichert-Toft *et al.*, 2003; Eisele *et al.*, 2003; Xu *et al.*, 2007). The Loa end member is defined by higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ and is mostly observed in lavas from Mauna Loa, Hualālai, Lanaʻi, Kahōolawe, West Molokaʻi and Kōōlau volcanoes (Hauri, 1996; Lassiter & Hauri, 1998; Abouchami *et al.*, 2005; Fekiacova *et al.*, 2007).

Single volcanoes (e.g. Kīlauea and Mauna Loa) also record isotopic variations over shorter time scales (years to centuries) that are attributed to partial melting of small-scale compositional heterogeneities within the plume (e.g. Frey & Rhodes, 1993; Kurz *et al.*, 1995; Rhodes & Hart, 1995; Pietruszka & Garcia, 1999a; Marske *et al.*, 2007). Estimates for the size and shape of small-scale heterogeneities range from vertical streaks that are several tens to hundreds of kilometers long (e.g. Farnetani *et al.*, 2002; Eisele *et al.*, 2003; Abouchami *et al.*, 2005) to heterogeneous blobs set in a compositionally distinct matrix (e.g. Frey & Rhodes, 1993; Rhodes & Hart, 1995; Blichert-Toft *et al.*, 2003). A range of vertical length scales for these compositional heterogeneities from 6.5–160 km (Blichert-Toft *et al.*, 2003) to 0.06–12 km (Kurz *et al.*, 2004) have been estimated based on isotopic fluctuations recorded in 550–180 ka Mauna Kea lavas. In contrast, the presence of a pancake-shaped heterogeneity (>18 km wide and <5–10 km thick) has been inferred based on systematic Pb, Sr, and Nd isotopic fluctuations in young prehistoric (<2.6 ka) Kīlauea and Mauna Loa lavas (Marske *et al.*, 2007). Unlike these previous studies, which document the size of mantle heterogeneities on a scale of hundreds to thousands of years, the Puʻu ‘Ōʻō eruption offers an opportunity to probe the finer-scale compositional variations related to distinctive mantle sources on very short time scales (months to years). Here we provide a comprehensive petrological evaluation of the most recent (1998–2005) Puʻu ‘Ōʻō lavas using petrography, olivine and whole-rock chemistry, and Pb, Sr, and Nd isotope ratios, and discuss the compositional evolution of these lavas and their implications for the nature and scale of mantle source heterogeneity within the Hawaiian plume.

OVERVIEW OF THE PUʻU ‘ŌʻŌ ERUPTION

The onset of the eruption (episode 1) in January 1983, began with intermittent fire fountaining along an

8-km-long fissure system in the middle of Kīlauea’s East Rift Zone (Wolfe *et al.*, 1987; Garcia *et al.*, 1989; Fig. 1). During episodes 2 and 3, activity was localized to a 1 km section of the fissure system. A central vent, Puʻu ‘Ōʻō, was the focus of effusion for episodes 4–47 (June 1983–June 1986). These episodes were generally short-lived (5–100 h) with variable (10–400 m) lava fountaining heights (Garcia *et al.*, 1992; Heliker & Mattox, 2003). In July 1986, the primary vent migrated 3 km downrift from the Puʻu ‘Ōʻō cone to the Kūpaianaha lava shield (Fig. 1). This shift coincided with a change in eruptive style from episodic, fire-fountaining events to nearly continuous and gentle effusion (Garcia *et al.*, 1996). Kūpaianaha was the site of nearly continuous lava effusion (episodes 48 and 49) until February 1992, when activity shifted back to Puʻu ‘Ōʻō. From February 1992 to January 1997 (episodes 50–53), a shield 60 m high and 1.3 km in diameter was built at Puʻu ‘Ōʻō (Heliker *et al.*, 1998). On January 29, 1997, the lava lake inside the Puʻu ‘Ōʻō shield suddenly drained, and a 22 h eruption (episode 54) occurred 2–4 km uprift (Harris *et al.*, 1997; Thornber *et al.*, 2003).

Following a 24 day hiatus, episode 55 began, marking the longest (1997–2007) and most voluminous ($\sim 1.6 \text{ km}^3$) effusive interval for this eruption. Episode 55 activity displayed nearly continuous eruption of lava (except for infrequent 1–4 day pauses) from vents on the south and west flanks of the Puʻu ‘Ōʻō cone (Garcia *et al.*, 2000; Heliker & Mattox, 2003). The most significant event during episode 55 occurred on September 12, 1999, when magma-induced earthquake swarms and surficial deflation of the Puʻu ‘Ōʻō cone were followed by intrusion of magma into the upper East Rift Zone of Kīlauea (Nakata *et al.*, 2000). An 11 day hiatus followed as magma supplying the Puʻu ‘Ōʻō cone was temporarily diverted to the upper rift zone. Episode 55 ended after a 1 day eruption (episode 56) that occurred ~ 6 km uprift of the Puʻu ‘Ōʻō cone in mid-June 2007 (Poland *et al.*, 2008). Following a 2 week pause, lava effusion resumed in early July 2007, and, as of May 2008, lava continues to erupt from a vent 2 km downrift of the Puʻu ‘Ōʻō cone.

PETROGRAPHY

A majority of samples studied here were collected in a molten state and most were quenched in water. The sample label (e.g. 17-Aug-01) is the date it was collected, and in nearly all cases is within a day of when it was erupted. The vast majority of the 1998–2005 Puʻu ‘Ōʻō lavas petrographically studied are glassy, strongly vesicular, friable and aphyric to moderately olivine-phyric (<3 vol. % phenocrysts; Table 1). Olivine is almost always the only phenocryst in these samples and is usually small (~ 0.5 –1 mm in diameter), euhedral and undeformed with spinel and glass inclusions. Olivine is somewhat less common (~ 1 vol. %) in the 1998–2005 lavas compared

Table 1: Modal mineralogy of representative 1998–2005 Pu‘u ‘Ō‘ō lavas

Sample	Whole-rock MgO (wt %)	Olivine		Clinopyroxene		Plagioclase mph	Matrix
		ph	mph	ph	mph		
21-Jan-98	7.96	0.6	3.6	0.0	0.0	0.0	95.8
13-Feb-99	7.41	0.6	3.4	0.0	1.4	0.2	94.4
19-Jun-99	8.17	0.9	2.5	0.0	0.1	0.0	96.5
11-Aug-99	6.85	0.0	2.0	0.0	0.4	0.6	97.0
27-Oct-99	7.98	0.6	3.8	0.0	0.2	0.4	95.0
4-Jan-00	9.54	3.0	3.2	0.0	1.2	0.8	91.8
21-Jun-00	7.23	2.5	0.6	0.0	1.7	0.6	94.6
4-Aug-00	8.29	2.8	2.6	0.0	1.4	1.0	92.2
8-Apr-01	7.93	1.9	3.7	<0.1	2.8	0.2	91.4
29-Sep-01	6.69	0.0	1.9	0.0	2.0	1.1	95.0
12-Apr-02	8.03	2.8	3.0	0.0	3.0	0.4	90.8
20-Aug-02	8.11	1.6	2.8	0.6	3.0	0.2	91.6
21-Nov-02	7.39	0.6	1.0	0.0	<0.1	0.0	98.4
12-Mar-03	7.53	2.4	2.8	0.0	1.0	0.2	93.6
29-Aug-03	6.87	0.6	1.6	<0.1	0.8	0.2	96.8
15-Jan-04	7.18	1.6	0.6	<0.1	3.0	0.6	94.2
23-Jul-04	6.97	0.6	0.6	0.0	3.0	1.4	94.4
31-Oct-04	6.90	1.8	3.0	0.0	1.4	0.8	93.0
6-Feb-05	7.03	0.8	2.0	0.0	0.8	0.8	95.6
23-Jun-05	6.85	1.0	1.6	0.0	0.4	0.2	96.8

All values are in vol. % and are based on 500 point counts/sample, without vesicles. Phenocrysts (ph) are >0.5 mm long; microphenocrysts (mph) are 0.1–0.5 mm long. Matrix contains glass and crystals <0.1 mm long.

with those from the preceding 6 years of eruptive activity but similar in abundance to lavas erupted from the Kūpaianaha vent (1986–1992; Garcia *et al.*, 1996). The total olivine abundance (phenocrysts and microphenocrysts) generally correlates with whole-rock MgO content, although it can vary ~4 vol. % for a given MgO (Table 1). Clinopyroxene phenocrysts are rare in the 1998–2005 Pu‘u ‘Ō‘ō lavas, yet microphenocrysts of clinopyroxene (up to 3 vol. %) are present in almost all of these lavas (Table 1). In contrast, clinopyroxene is absent or rare (<1 vol. %) in earlier Pu‘u ‘Ō‘ō lavas (except in the more evolved 1983 lavas; Garcia *et al.*, 1992, 1996). Clinopyroxene crystals are small (0.1–0.3 mm), occur commonly in clusters of 3–12 grains, and commonly display sector zoning. Plagioclase microphenocrysts occur in most of the 1998–2005 Pu‘u ‘Ō‘ō lavas, although they are usually rare (<1 vol. %; Table 1) and small (0.1–0.2 mm wide laths). Plagioclase is less common in earlier erupted Pu‘u ‘Ō‘ō lavas (except for the lavas from episodes 1–10 and 54, which were affected by magma mixing in Kīlauea’s East Rift Zone

(Garcia *et al.*, 1989, 1992, 2000; Thornber *et al.*, 2003). The groundmass of the 1998–2005 lavas generally consists of honey-brown glass or black cryptocrystalline material with microlites (<0.1 mm) of plagioclase, clinopyroxene, olivine, and spinel.

OLIVINE COMPOSITION

A five spectrometer Cameca SX-50 electron microprobe with SAMx automation was used for the olivine analyses at the University of Hawai‘i using techniques described by Garcia *et al.* (2000). Olivine compositions (Table 2) were determined for 175 olivine crystals from 19 lavas erupted between 1998 and 2005 that span a wide compositional range (whole-rock MgO contents of 6.7–9.5 wt %). All of the analyzed olivine crystals are unzoned or normally zoned with up to 3% forsterite (Fo) variation from core to rim. The forsterite content of the olivine cores range from 76.5 to 86.0% (Fig. 2) with phenocrysts and microphenocrysts overlapping in composition. The average Fo content is ~81.1%, which is similar to lavas from the previous 6 years and somewhat lower than olivines in the earlier lavas (1986–1992) erupted from the Kūpaianaha vent (~82.5% on average; Garcia *et al.*, 1996, 2000). The NiO and CaO contents in the olivines are moderate (Table 2) indicating crystallization at crustal depths from somewhat fractionated parental magmas (e.g. Garcia, 2002).

Olivines in the 1998–2005 lavas typically have Fo compositions that are in equilibrium with their whole-rock Mg-number, particularly for lavas with lower Mg-number (<58; Fig. 2). Most samples with Mg-number >58 have olivine compositions that plot below the equilibrium field, especially the sample with the highest Mg-number (4-Jan-00; Fig. 2). The higher Mg-number lavas probably accumulated olivine, which is consistent with their higher abundance of this mineral (e.g. 4-Jan-00 contains the highest olivine content; Table 1). The highest measured forsterite content of olivine within the 1998–2005 lavas (Fo₈₆) occurs in a sample with an intermediate Mg-number, 21-Jan-98 (Table 2). This olivine, like all of the other crystals, shows no signs of deformation. Thus, it is probably indicative of the parental magma composition for recent Pu‘u ‘Ō‘ō lavas (Mg-number ~59; Fig. 2), consistent with estimates for previous Pu‘u ‘Ō‘ō lavas (Garcia *et al.*, 2000).

WHOLE-ROCK ANALYTICAL METHODS

Eighty-two new Pu‘u ‘Ō‘ō lava samples erupted between 1998 and 2005 were analyzed for major and trace element (Rb, Sr, Y, Nb, Zr, Zn, Ni, Cr, V, Ba, and Ce) abundances over a 7 year period using X-ray fluorescence spectrometry (XRF) at the University of Massachusetts (Table 3). The Kīlauea basaltic standards collected from the same flow, K1919 ($n=13$) and BHVO-1 ($n=13$), were run as

Table 2: Representative microprobe analyses of olivine cores from 1998–2005 Pu‘u Ō‘ō lavas

Sample	SiO ₂	FeO	NiO	MgO	CaO	Total	Fo	Mg-no.
21-Jan-98	38.89	17.14	0.22	42.46	0.26	98.98	81.5	58.9
	39.16	16.73	0.21	43.01	0.25	99.37	82.1	
	39.74	13.28	0.35	45.64	0.20	99.22	86.0	
13-Feb-99	39.36	18.03	0.18	41.86	0.27	99.64	80.5	57.3
	39.11	16.76	0.22	43.26	0.24	99.59	82.1	
	39.64	15.94	0.26	43.88	0.25	99.96	83.1	
19-Jun-99	39.28	17.22	0.19	42.85	0.25	99.48	81.6	59.4
	39.53	16.96	0.22	42.97	0.26	99.95	81.9	
11-Aug-99	39.13	17.51	0.19	42.40	0.26	99.49	81.2	55.6
	39.27	17.13	0.22	42.79	0.26	99.67	81.7	
	39.31	16.19	0.21	43.45	0.22	99.38	82.7	
4-Jan-00	38.78	17.82	0.16	42.29	0.28	99.34	80.9	62.6
	38.86	17.50	0.21	42.57	0.28	99.42	81.3	
	39.04	17.29	0.19	42.92	0.27	99.72	81.6	
21-Jun-00	38.92	17.82	0.16	42.33	—	99.51	80.9	56.9
	38.95	17.59	0.17	42.55	—	99.51	81.2	
	39.29	17.24	0.18	43.08	—	100.04	81.7	
4-Aug-00	38.72	17.42	0.18	42.47	0.30	99.10	81.3	59.8
	38.69	17.37	0.16	42.59	0.27	99.07	81.4	
8-Apr-01	38.55	19.41	0.16	41.26	0.25	99.64	79.1	58.8
	38.68	18.34	0.16	42.08	0.26	99.53	80.4	
	38.76	17.12	0.20	43.24	0.25	99.57	81.8	
29-Sep-01	38.43	21.55	0.12	39.44	—	99.83	76.5	54.7
	38.88	18.68	0.14	41.62	—	99.61	79.9	
	39.05	17.81	0.18	42.55	—	99.87	81.0	
12-Apr-02	38.87	18.02	0.18	42.26	0.25	99.57	80.7	59.0
	39.10	17.28	0.18	42.75	0.23	99.54	81.5	
	39.45	15.57	0.23	44.04	0.22	99.51	83.4	
20-Aug-02	39.25	17.95	0.23	42.42	0.27	100.13	80.8	59.1
	39.11	17.68	0.20	42.68	0.26	99.94	81.1	
	39.42	16.35	0.20	43.57	0.25	99.79	82.6	
21-Nov-02	39.11	17.99	0.19	42.54	0.25	100.09	80.8	57.1
	39.05	17.43	0.20	42.67	0.27	99.62	81.4	
	39.14	16.86	0.21	43.32	0.25	99.78	82.1	
12-Mar-03	39.26	17.60	0.21	42.35	0.26	99.69	81.1	57.5
	39.08	17.38	0.17	42.27	0.26	99.15	81.3	
	39.02	17.14	0.21	42.46	0.26	99.09	81.5	
29-Aug-03	40.06	17.95	0.16	40.89	0.34	99.41	80.2	55.3
	39.77	17.46	0.19	41.62	0.27	99.30	80.9	
	39.92	17.33	0.14	41.83	0.25	99.46	81.1	

(continued)

Table 2: Continued

Sample	SiO ₂	FeO	NiO	MgO	CaO	Total	Fo	Mg-no.
15-Jan-04	39.38	18.25	0.19	41.99	0.27	100.08	80.4	56.5
	39.35	17.60	0.22	42.36	0.26	99.79	81.1	
23-Jul-04	39.70	18.44	0.18	41.44	0.26	100.02	80.0	55.9
	39.79	17.80	0.22	41.96	0.26	100.04	80.8	
	39.43	17.45	0.20	41.89	0.25	99.22	81.1	
31-Oct-04	38.35	18.83	0.19	41.52	0.29	99.17	79.7	55.6
	38.67	18.68	0.23	41.73	0.30	99.61	79.9	
	38.53	18.02	0.25	42.13	0.26	99.19	80.6	
6-Feb-05	38.18	19.26	0.19	41.51	0.33	99.48	79.3	56.1
	38.94	18.64	0.17	41.59	0.27	99.62	79.9	
	39.16	17.07	0.28	42.95	0.27	99.73	81.8	
23-Jun-05	38.50	19.03	0.23	41.12	0.30	99.19	79.4	55.4
	38.85	18.08	0.23	42.00	0.28	99.45	80.5	
	38.92	16.94	0.28	42.95	0.27	99.36	81.9	

Values are the average of three spot analyses per sample. All oxides concentrations are in wt %.

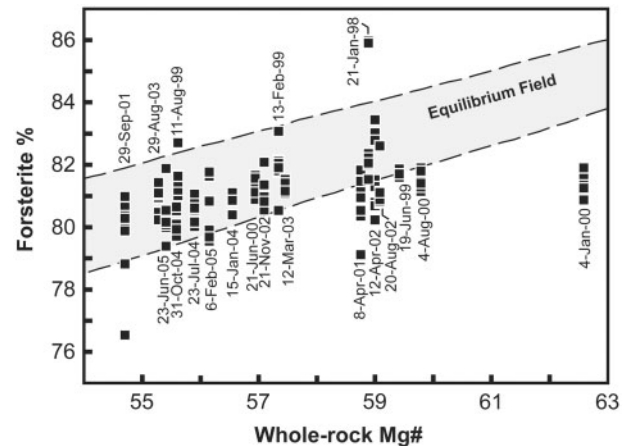


Fig. 2. Representative whole-rock Mg-number $[(\text{Mg}/\text{Mg} + \text{Fe}^{2+}) \times 100]$ plotted against olivine core forsterite content (Fo %) for 1998–2005 lavas. The Mg-number is calculated assuming 90% of the total iron is Fe^{2+} , which is consistent with measurements on Kīlauea lavas (e.g. Moore & Ault, 1965; Byers *et al.*, 1985; Rhodes & Vollinger, 2005). The date with each set of olivine data is the sample number. The diagonal field is the shallow pressure (1 atm) equilibrium field for basaltic magma ($\text{Fe}/\text{Mg } K_d = 0.30 \pm 0.03$; Roeder & Emslie, 1970; Ulmer, 1989). Lava samples that plot below the equilibrium field (e.g. 4-Jan-00) have probably experienced olivine accumulation.

internal controls for major and trace element abundances during this period, respectively (Table 3). All Pu‘u Ō‘ō samples presented here were analyzed in the same XRF laboratory using the same calibration procedures. Thus, any long-term analytical drift in the major and trace element abundances is expected to be relatively minor.

Details of methods used and estimates of analytical precision for the XRF analyses have been given by Rhodes (1996) and Rhodes & Vollinger (2004).

In addition, 27 samples were analyzed over a 1 week period for Sc, V, Cr, Co, Ni, Cu, Zn, Sr, Cs, Rb, Ba, Th, U, Nb, Zr, Hf, Y, and rare earth element (REE) abundances using inductively coupled plasma mass spectrometry (ICP-MS) at the Australian National University (Table 4). The Kīlauea rock standard BHVO-2 ($n=2$) was analyzed with these samples. Analytical methods and estimates of precision for the ICP-MS trace element analyses are given in Table 4 and by Norman *et al.* (1998). Prior to both XRF and ICP-MS analyses, the Pu'u Ō'ō lava samples were washed in an ultrasonic bath of deionized water for 10–20 min, hand picked (30–100 g) to remove any rare altered rock chips, and powdered in a tungsten carbide swing mill for the XRF analyses and an agate mill for the ICP-MS analyses.

Fourteen Pu'u Ō'ō lavas erupted between 1998 and 2005 were analyzed for Pb and Nd isotope ratios (Table 5) by multi-collector (MC)-ICP-MS using a Nu Plasma system at San Diego State University (SDSU). Strontium isotope ratios were measured using this instrument and/or by thermal ionization mass spectrometry (TIMS) using a VG Sector 54 instrument at SDSU to compare the results of the two instruments. Additionally, four lavas erupted from 1989 to 1998 (Garcia *et al.*, 1992, 1996, 2000) were reanalyzed for Sr isotope ratios from the original dissolutions using TIMS to improve the analytical precision for these samples (Appendix, Table A1). A detailed overview of the analytical methods used in this study has been given by Marske *et al.* (2007). Additional details pertinent to this study are presented in Table 5.

GEOCHEMISTRY OF 1998–2005 PU'U Ō'Ō LAVAS

The 1998–2005 Pu'u Ō'ō lavas are compositionally similar to earlier lavas from this eruption (Fig. 3). For example, their MgO contents (6.7–9.8 wt %) lie within the range of 1985–1998 lavas (6.7–10.1 wt %), excluding mixed and evolved lavas from episode 54). However, small, but significant short-term (years) variations in major element abundances (at a given MgO) are evident in these lavas (Fig. 3). Similar variations have been observed for historical Kīlauea summit lavas and were related to changes in parental magma composition (e.g. Wright, 1971; Garcia *et al.*, 2003). Overall, Pu'u Ō'ō lavas have become progressively lower in CaO/Al₂O₃ ratios and incompatible element (TiO₂ and K₂O) contents, and higher in SiO₂ abundances (at a given MgO content) during the eruption (even if more differentiated samples with <7.2 wt % MgO are excluded; Fig. 3). At a given MgO content, the total variation of Fe₂O₃* (i.e. total iron), Al₂O₃, and Na₂O abundances (not shown)

for the 1998–2005 lavas lie within the compositional field of previous lavas. The high SiO₂ and low CaO, TiO₂, and K₂O contents, and CaO/Al₂O₃ ratios of the recent lavas expand the known compositional range for historical Kīlauea lavas towards historical Mauna Loa lavas (Fig. 3).

The relatively low abundances and ratios of incompatible elements (e.g. Nb and La/Sm) in 1998–2005 lavas form trends that partially overlap with 1989–1997 Pu'u Ō'ō lavas, but also expand the compositional range to the lowest values observed during the eruption (Fig. 4). Recent Pu'u Ō'ō lavas continue the overall temporal decrease in highly to moderately incompatible trace element ratios (i.e. La/Yb) and abundances (i.e. Nb and Ba) since the early part of the eruption (Figs 4 and 5). These trace element abundances and ratios of the recent lavas, like the major element contents, extend the Pu'u Ō'ō compositional range toward the field of historical Mauna Loa lavas (Fig. 4).

The ⁸⁷Sr/⁸⁶Sr ratios of the 1998–2005 lavas (0.70360–0.70364) are higher than those of previous Pu'u Ō'ō lavas (0.70357–0.70360). In contrast, Pb (Figs 5 and 6) and Nd isotope ratios are within the range of previous lavas. However, the 1998–2005 lavas make a small, yet distinctive trend in ²⁰⁶Pb/²⁰⁴Pb vs ⁸⁷Sr/⁸⁶Sr that expands the isotopic range for this eruption (Fig. 6). Unlike the major and trace element chemistry, these Pb and Sr isotope variations trend towards an area between the compositional fields of Kīlauea and Mauna Loa (rather than directly towards the field of Mauna Loa lavas). Furthermore, this trend does not project towards a Hawaiian mantle end member (e.g. Kea or Loa) or towards the known isotopic composition of any other Hawaiian volcano.

CRUSTAL MAGMATIC PROCESSES DURING THE ERUPTION

Olivine fractionation plays a dominant role in controlling the compositional variations in Hawaiian lavas (e.g. Powers, 1955; Wright, 1971). The importance of olivine crystallization in Pu'u Ō'ō lavas is evident from their wide range of MgO contents (5.6–10.1 wt %), and the presence of normally zoned olivine phenocrysts (Garcia *et al.*, 1996, 2000). Shallow magma mixing between stored rift magmas and 'fresh' MgO-rich magma(s) was an important process that controlled the composition of lavas erupted before February 1985 (episodes 1–29; Garcia *et al.*, 1992), and during episode 54 in January 1997 (Garcia *et al.*, 2000; Thornber *et al.*, 2003). Most (~93%) Pu'u Ō'ō lavas (excluding evolved lavas from episodes 1–29 and 54) have >7.2 wt % MgO, suggesting that the variation in the major element abundances of these lavas is primarily related to olivine fractionation and/or accumulation (i.e. olivine control; Wright, 1971). However, the MgO and Ni abundances of the Pu'u Ō'ō lavas have systematically decreased (with much scatter) since the eruption location

Table 4: ICP-MS analyses of 1998–2005 Pu`u`ō`ō lavas

Sample	Day	Rb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu
17-Jan-98	5493	6.8	0.070	93.4	10.2	26.4	3.90	18.3	5.05	1.72	5.31	0.85	4.88	0.93	2.28	1.93	0.275
11-May-98	5607	7.0	0.072	95.8	10.3	26.8	3.96	18.5	5.10	1.71	5.36	0.85	4.90	0.93	2.31	1.95	0.273
7-Sep-98	5726	7.1	0.076	98.2	10.6	27.4	4.03	18.9	5.21	1.78	5.47	0.88	4.92	0.95	2.33	1.97	0.286
13-Feb-99	5885	7.3	0.073	99.4	10.7	27.7	4.09	19.1	5.26	1.80	5.62	0.89	5.07	0.97	2.38	2.02	0.288
19-Jun-99	6011	7.1	0.073	97.3	10.5	27.2	4.01	18.8	5.20	1.77	5.46	0.88	5.00	0.96	2.34	1.99	0.281
27-Oct-99	6141	6.9	0.070	96.8	10.5	27.1	3.99	18.8	5.11	1.77	5.52	0.88	4.95	0.96	2.34	2.00	0.278
19-Feb-00	6256	6.7	0.068	93.3	10.2	26.2	3.86	18.2	5.00	1.74	5.34	0.86	4.86	0.95	2.29	1.98	0.277
21-Jun-00	6379	6.7	0.065	93.9	10.2	26.2	3.83	18.3	4.97	1.73	5.43	0.87	4.90	0.95	2.31	2.00	0.278
12-Oct-00	6492	6.8	0.067	95.8	10.5	26.8	3.95	18.6	5.09	1.79	5.55	0.89	5.06	0.98	2.42	1.99	0.282
8-Jan-01	6580	6.9	0.070	95.9	10.5	26.7	3.97	18.7	5.10	1.78	5.53	0.88	5.03	0.98	2.38	2.03	0.283
8-Apr-01	6670	7.0	0.070	100	10.8	28.0	4.15	19.5	5.27	1.81	5.70	0.90	5.20	1.00	2.45	2.08	0.287
7-Jul-01	6760	6.9	0.069	98.4	10.6	27.6	4.07	19.1	5.20	1.79	5.65	0.89	5.07	0.99	2.43	2.03	0.284
13-Oct-01	6858	6.9	0.069	98.4	10.6	27.6	4.08	19.2	5.18	1.79	5.70	0.89	5.09	0.99	2.42	2.05	0.282
9-Feb-02	6977	6.6	0.067	93.1	10.1	26.1	3.86	18.1	4.95	1.71	5.39	0.85	4.86	0.95	2.29	1.94	0.273
5-Jun-02	7093	6.7	0.069	95.5	10.3	26.8	3.96	18.7	5.12	1.75	5.59	0.87	5.01	0.96	2.39	2.02	0.276
20-Aug-02	7169	6.7	0.070	95.9	10.3	26.8	3.96	18.7	5.15	1.79	5.48	0.89	5.08	0.98	2.41	2.02	0.286
21-Nov-02	7262	6.6	0.066	93.7	10.1	26.2	3.88	18.4	5.05	1.76	5.50	0.88	4.99	0.97	2.38	1.99	0.282
12-Apr-03	7404	6.9	0.071	98.0	10.6	27.4	4.04	19.1	5.28	1.83	5.68	0.90	5.21	1.01	2.46	2.07	0.290
19-Sep-03	7564	6.9	0.070	97.1	10.5	27.2	4.03	18.6	5.30	1.82	5.69	0.90	5.16	1.00	2.44	2.05	0.286
15-Jan-04	7682	7.1	0.073	99.3	10.7	27.8	4.10	19.4	5.31	1.86	5.69	0.92	5.22	1.02	2.51	2.10	0.293
23-Apr-04	7781	7.1	0.071	98.7	10.7	27.7	4.09	19.2	5.26	1.82	5.70	0.91	5.13	1.00	2.42	2.04	0.287
7-Jun-04	7826	7.4	0.078	103	11.2	29.0	4.28	20.0	5.47	1.89	6.00	0.94	5.37	1.04	2.52	2.14	0.300
15-Oct-04	7956	7.1	0.070	98.4	10.7	27.6	4.09	19.1	5.27	1.80	5.69	0.91	5.12	1.00	2.41	2.01	0.282
31-Jan-05	8064	7.5	0.076	104	11.2	29.0	4.30	20.1	5.55	1.89	5.92	0.95	5.31	1.05	2.50	2.13	0.294
22-Apr-05	8145	7.1	0.072	100	10.9	28.2	4.19	19.6	5.42	1.83	5.83	0.92	5.17	1.01	2.46	2.06	0.291
8-Aug-05	8253	7.2	0.073	102	11.0	28.4	4.18	19.8	5.46	1.85	5.87	0.93	5.30	1.01	2.49	2.09	0.295
14-Nov-05	8351	7.1	0.071	100	10.9	28.4	4.16	19.5	5.39	1.86	5.83	0.93	5.21	1.01	2.48	2.07	0.292
<i>Hawaiian rock standard (Kīlauea volcano)</i>																	
BHVO-2	—	9.2	0.106	129	14.8	36.7	5.27	23.9	6.02	2.02	6.11	0.94	5.18	0.98	2.35	1.92	0.275
±2σ	—	0.2	0.006	2.0	0.2	0.1	0.01	0.01	0.11	0.001	0.14	0.02	0.09	0.01	0.02	0.01	0.003
Sample	Day	Th	Y	Nb	Hf	U	Pb	Zr	Sr	Sc	V	Cr	Co	Ni	Cu	Zn	Ga
17-Jan-98	5493	0.81	23.8	12.0	3.42	0.260	1.01	139	313	30.8	264	432	52.6	171	120	105	18.9
11-May-98	5607	0.83	24.1	12.4	3.49	0.265	1.07	141	317	30.5	266	446	52.0	178	119	103	18.8
7-Sep-98	5726	0.84	24.3	12.6	3.55	0.278	1.04	143	322	30.8	268	449	49.3	149	120	103	18.9
13-Feb-99	5885	0.86	25.1	12.9	3.59	0.277	1.05	146	331	31.7	278	380	45.5	100	126	102	19.4
19-Jun-99	6011	0.84	24.9	12.7	3.59	0.271	1.04	145	327	31.4	277	440	50.5	137	122	104	19.2
27-Oct-99	6141	0.80	24.3	12.4	3.52	0.260	1.00	141	318	31.1	266	389	48.0	118	123	103	19.2
19-Feb-00	6256	0.80	23.8	12.1	3.44	0.259	1.07	138	309	30.7	261	418	50.3	133	121	106	18.8
21-Jun-00	6379	0.80	24.0	12.1	3.44	0.261	0.98	138	312	30.8	264	374	48.7	115	121	101	19.0
12-Oct-00	6492	0.81	24.7	12.3	3.52	0.261	1.04	142	318	31.9	268	364	47.8	103	123	109	19.5
8-Jan-01	6580	0.81	24.7	12.4	3.56	0.265	0.98	144	320	31.3	269	354	47.2	99	123	111	19.4
8-Apr-01	6670	0.85	25.1	12.6	3.65	0.282	1.00	144	325	31.4	270	302	45.4	89	124	104	19.9
7-Jul-01	6760	0.83	24.8	12.4	3.59	0.273	0.99	142	320	31.4	267	342	46.3	96	122	104	19.7
13-Oct-01	6858	0.83	24.7	12.4	3.58	0.264	0.97	142	320	31.3	266	347	47.2	105	121	105	19.6
9-Feb-02	6977	0.78	23.7	11.7	3.40	0.261	0.93	135	306	30.6	256	417	51.5	140	114	102	18.6

(continued)

Table 4: Continued

Sample	Day	Th	Y	Nb	Hf	U	Pb	Zr	Sr	Sc	V	Cr	Co	Ni	Cu	Zn	Ga
5-Jun-02	7093	0.80	24.4	12.1	3.50	0.266	0.96	139	315	30.6	262	347	47.5	108	117	101	19.1
20-Aug-02	7169	0.78	24.3	12.2	3.54	0.269	0.95	139	314	30.4	260	325	47.7	108	119	103	19.2
21-Nov-02	7262	0.78	24.1	11.9	3.48	0.257	0.93	137	309	31.0	260	409	48.2	114	116	104	18.9
12-Apr-03	7404	0.81	25.0	12.4	3.62	0.270	0.98	143	322	31.2	267	306	44.7	82	122	103	19.7
19-Sep-03	7564	0.81	25.1	12.4	3.56	0.271	0.97	143	322	31.5	268	341	47.9	98	124	107	19.9
15-Jan-04	7682	0.83	25.2	12.6	3.67	0.268	1.00	145	326	31.1	270	287	44.5	83	120	102	19.6
23-Apr-04	7781	0.83	25.2	12.7	3.61	0.267	1.00	146	327	31.6	271	297	45.8	91	122	105	19.9
7-Jun-04	7826	0.87	26.3	13.3	3.77	0.284	1.02	153	341	32.4	281	261	46.0	85	127	108	20.7
15-Oct-04	7956	0.83	25.1	12.7	3.61	0.275	1.01	145	327	31.7	272	304	45.0	90	120	104	19.9
31-Jan-05	8064	0.88	26.2	13.4	3.78	0.279	1.06	153	342	32.0	281	214	44.3	77	126	107	20.4
22-Apr-05	8145	0.86	25.2	12.9	3.68	0.278	1.02	147	329	31.8	273	267	46.0	93	123	107	20.1
8-Aug-05	8253	0.84	25.5	12.8	3.65	0.281	1.01	147	331	31.8	273	255	45.1	89	124	106	20.2
14-Nov-05	8351	0.85	25.2	12.7	3.64	0.273	0.89	146	331	31.8	271	—	45.4	94	122	105	20.1
<i>Hawaiian rock standard (Kilauea volcano)</i>																	
BHVO-2 av.	—	1.25	24.4	18.0	4.17	0.408	1.68	169	388	31.2	278	282	42.9	115	121	99	20.0
$\pm 2\sigma$	—	0.02	0.5	0.6	0.04	0.008	0.04	3	9	1.0	9	10	2.2	6	6	4	0.5

Day is the number of days since the start of the Pu'u Ō'ō eruption on January 3, 1983; values are in ppm. BHVO-2 ($n=2$) was analyzed as an internal standard for these analyses.

shifted in early 1992 from the Kūpaianaha vent to the Pu'u Ō'ō cone (Figs 3 and 5), suggesting that Pu'u Ō'ō magmas are becoming increasingly differentiated with time. Clinopyroxene fractionation has become an increasingly important process for 1998–2005 lavas. For example, there is a greater abundance of clinopyroxene microphenocrysts in the 1998–2005 lavas (up to 3 vol. %; Table 1) compared with earlier erupted Pu'u Ō'ō lavas (<1 vol. % or absent), and ~50% of the most recent lavas (2004–2005) have differentiated beyond olivine control (<7.2 wt % MgO; Fig. 5).

Olivine accumulation has also affected some Pu'u Ō'ō lava compositions based on the low Fo contents of some olivines compared with their whole-rock Mg-number (Fig. 2). For example, the maximum MgO difference for two olivine-controlled 1998–2005 lavas (23-Jul-04, 7.0 wt % MgO; 4-Jan-00, 9.5 wt % MgO) with similar olivine Fo contents (81–82%; Fig. 2) can be explained by the accumulation of ~6.1 vol. % olivine. This is consistent with the 5% greater modal abundance of olivine phenocrysts in sample 4-Jan-00 compared with 23-Jul-04, and the position of sample 4-Jan-00 to the right of the equilibrium field in Fig. 2. All of the 2003–2005 lavas analyzed have Fo contents in equilibrium with their bulk compositions (Fig. 2).

TEMPORAL COMPOSITIONAL VARIATIONS

Pu'u Ō'ō lavas display systematic temporal variations of MgO-normalized major element abundances, ratios of

highly to moderately incompatible trace elements (e.g. La/Yb), highly incompatible trace element ratios (e.g. Ba/Nb), and Pb and Sr isotope ratios (Fig. 5). At least three distinct end-member magma compositions may be delineated based on correlated temporal changes among some MgO-normalized major element abundances, and incompatible trace element and Sr isotope ratios: (1) 1985–1998 (days ~760–5500); (2) 1998–2003 (days ~5501–7400); (3) 2003–2005 (days ~7401–8400). Magma mixing affected the composition of lavas erupted before February 1985 (days 1–745; Garcia *et al.*, 1992) and during episode 54 in January 1997 (day 514; Garcia *et al.*, 2000; Thornber *et al.*, 2003), and these lavas were excluded from the plots.

The SiO₂ temporal trend for Pu'u Ō'ō lavas inversely correlates with the temporal variations of CaO and TiO₂ (Fig. 5). Between ~1985 and 1998, MgO-normalized major element abundances display relatively flat (SiO₂) and slightly decreasing (CaO and TiO₂) trends. However, lavas erupted between ~1998 and 2003 display changes in slope with significant increases and decreases in these abundances, respectively, until mid-2003 (Fig. 5). Following a compositional reversal in mid-2003, the MgO-normalized SiO₂ abundances have decreased whereas CaO and TiO₂ contents have increased. In contrast, Al₂O₃ and Fe₂O₃ contents (not shown) have remained nearly constant.

Pu'u Ō'ō lavas also display systematic fluctuations in incompatible trace element ratios that correlate with the major element changes (Fig. 5). Between ~1985 and 1998

Table 5: Pb, Sr and Nd isotope data for Pu'u 'Ō'ō lavas

Sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵ_{Nd}
7-Sep-98	18.4107	15.4727	38.0752	0.703601 ± 6	0.512956	+6.21
13-Feb-99	18.4124	15.4736	38.0764	0.703616 ± 6	0.512944	+5.97
27-Oct-99	18.4018	15.4726	38.0687	0.703622 ± 9	0.512948	+6.04
19-Feb-00	18.4072	15.4712	38.0720	0.703634 ± 7	0.512944	+5.97
21-Jun-00	18.4067	15.4704	38.0688	0.703644 ± 7	0.512947	+6.04
8-Jan-01	18.4116	15.4721	38.0737	0.703639 ± 12	0.512946	+6.01
7-Jul-01	18.4137	15.4719	38.0729	0.703626 ± 9	0.512943	+5.95
9-Feb-02	18.4139	15.4707	38.0691	0.703637 ± 8	0.512940	+5.89
20-Aug-02	18.4152	15.4722	38.0719	0.703639 ± 5	0.512945	+5.98
12-Apr-03	18.4161	15.4726	38.0715	0.703641 ± 5	0.512953	+6.14
15-Jan-04	18.4154	15.4719	38.0694	0.703632 ± 7	0.512946	+6.01
7-Jun-04	18.4146	15.4716	38.0680	0.703623 ± 7	0.512943	+5.95
31-Jan-05	18.4170	15.4735	38.0752	0.703624 ± 5	0.512955	+6.19
8-Aug-05	18.4119	15.4727	38.0699	0.703622 ± 10	0.512953	+6.14
<i>Hawaiian rock standard (Kīlauea volcano)</i>						
Kil1919	18.6562	15.4903	38.2092	0.703477	0.512973	+6.53

The Pb, Sr and Nd isotope ratios of the samples were measured over two periods of time. The 1998–2004 Pu'u 'Ō'ō lavas were analyzed at the same time as the Kīlauea samples presented by Marske *et al.* (2007), whereas the 2005 lavas, a new dissolution of Kil1919 (a Hawaiian rock standard collected from the same flow as K1919, BHVO-1, and BHVO-2) and the reanalyzed 1989–1995 lavas in Table A1 in the Appendix [previously studied by Garcia *et al.* (1996, 2000) and Pietruszka *et al.* (2006)] were analyzed subsequently by MC-ICP-MS (for Pb and Nd isotopes) and TIMS (for Sr isotopes). Analytical details relevant to the 1998–2004 samples have been presented by Marske *et al.* (2007). The following analytical details apply to the other samples, unless otherwise noted. Pb isotope ratios were corrected for instrumental mass fractionation using the measured isotope ratio of Tl (SRM997) added to the sample compared with an assumed $^{205}\text{Tl}/^{203}\text{Tl} = 2.3889$ for this standard from Thirlwall (2002). The average Tl-corrected value for NBS981 Pb ($n=5$) was $^{206}\text{Pb}/^{204}\text{Pb} = 16.9434 \pm 15$ (2σ), $^{207}\text{Pb}/^{204}\text{Pb} = 15.5019 \pm 16$ (2σ), and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7298 \pm 42$ (2σ). All of the Pb isotopic data are reported relative to the NBS981 Pb standard values of Galer & Abouchami (1998): $^{206}\text{Pb}/^{204}\text{Pb} = 16.9405$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4963$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7219$. Sr and Nd isotope ratios were corrected for instrumental mass fractionation relative to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The average measured values for Sr and Nd standards were $^{87}\text{Sr}/^{86}\text{Sr} = 0.710246 \pm 17$ (2σ ; $n=18$) for SRM987 (by TIMS) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512103 \pm 7$ (2σ ; $n=6$) for Ames Nd (by MC-ICP-MS). All Sr and Nd isotopic data are reported relative to constant standard values for SRM987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710250$) and Ames Nd ($^{143}\text{Nd}/^{144}\text{Nd} = 0.512130$). After correcting to this value for Ames Nd, a single analysis of the La Jolla Nd standard as an unknown gave $^{143}\text{Nd}/^{144}\text{Nd} = 0.511845$. The estimated reproducibility ($\pm 2\sigma$) for all of the data is based on multiple analyses of the La Jolla Nd standard and the Kil1919 rock standard by Marske *et al.* (2007). Uncertainties of the single Sr analyses are based on the $\pm 2\sigma_m$ ($n > 4$) of replicate analyses of each sample reported in Table A1 and by Garcia *et al.* (1996, 2000) and Pietruszka *et al.* (2006). Total procedural blanks were negligible compared with the amount of sample used (> 0.6 g) and the concentrations of Pb, Sr, and Nd in the samples.

there are small but significant decreases in some ratios of incompatible trace elements until day ~ 5500 . Between ~ 1998 and 2003 these incompatible trace element ratios display flattening (e.g. La/Yb) or nearly constant (e.g. Ba/Nb) temporal trends. Some ratios of highly over moderately incompatible trace elements (e.g. La/Yb) record a small compositional reversal in mid-2003, followed by a small increase similar to the reversal recorded by the normalized major element abundances (Fig. 5).

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of Pu'u 'Ō'ō lavas gradually increased between ~ 1985 and 1998, before a sharper increase occurred in 1998 (day ~ 5500). This shift coincided with the significant increases in MgO-normalized SiO_2 abundances and decreases in the CaO and TiO_2

abundances (Fig. 5). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increased to the highest observed values for this eruption in mid-2003, and reversed from 2003 to 2005. This is also analogous to the reversals of MgO-normalized major element abundances and incompatible trace element ratios (Fig. 5). In contrast, the Pb and Nd isotope ratios have remained relatively constant since 1985 (relative to analytical error), especially for the 1998–2005 lavas (Fig. 5; Table 5).

In summary, three distinct end-member compositions are important during the Pu'u 'Ō'ō eruption. First, an early end member (~ 1985) has relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and MgO-normalized SiO_2 abundances, and high CaO and TiO_2 abundances and incompatible trace element ratios (e.g. Ba/Nb or La/Yb). Second, a later end

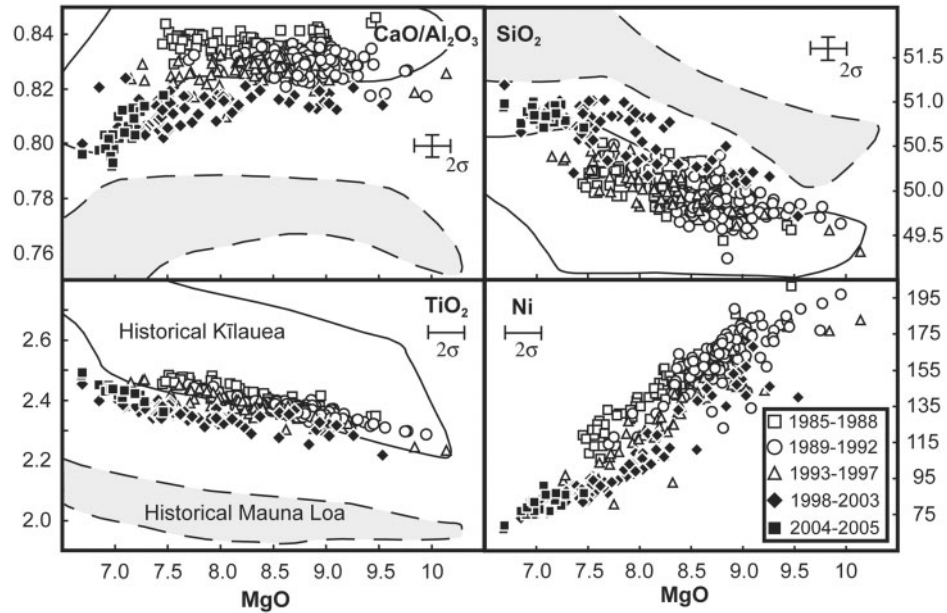


Fig. 3. Whole-rock MgO variation diagrams for Pu'u 'Ō'ō lavas, historical Kīlauea (Garcia *et al.*, 2003), and historical Mauna Loa (Rhodes & Hart, 1995) lavas. The Pu'u 'Ō'ō lavas are grouped according to eruption date (see inset for symbols). The new 1998–2005 Pu'u 'Ō'ō data (filled symbols) from Table 3 are plotted with previous data (open symbols) from Garcia *et al.* (1992, 1996, 2000). These groups were further subdivided to better resolve the systematic geochemical changes, and to emphasize the rapid temporal changes during the eruption. Mixed and/or evolved Pu'u 'Ō'ō lavas (episodes 1–29 and 54) are not shown in this and subsequent figures. All values are in wt % (except CaO/Al₂O₃). The 2σ error bars are shown in the corner of each plot unless they are smaller than the size of the symbols.

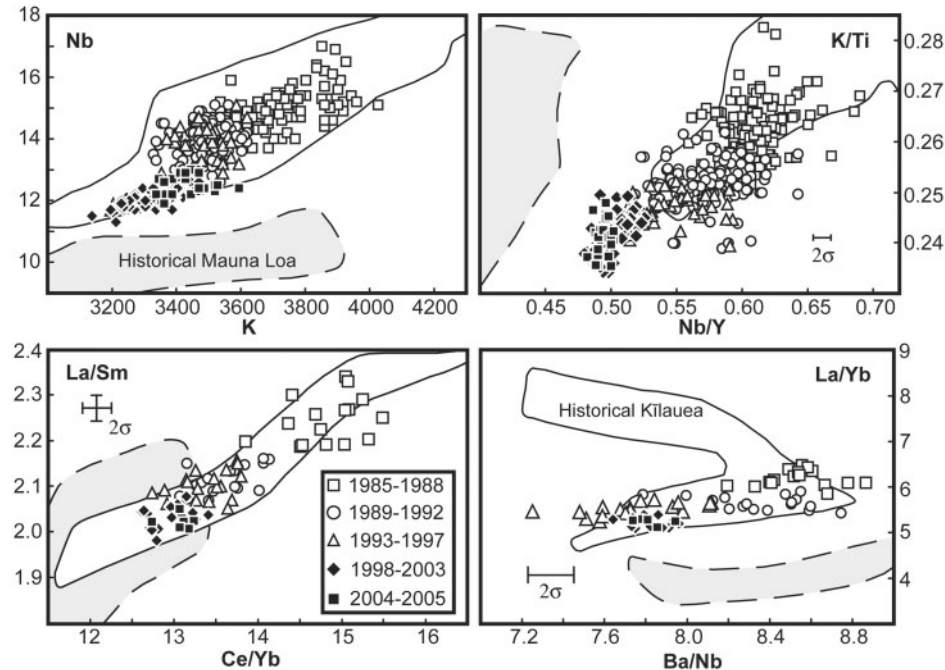


Fig. 4. Incompatible trace element abundance and ratio–ratio variation diagrams for Pu'u 'Ō'ō lavas. The compositional fields of historical Kīlauea (Pietruszka & Garcia, 1999a; Garcia *et al.*, 2003) and Mauna Loa (Rhodes & Hart, 1995; J. M. Rhodes, unpublished data, 2008) lavas are also plotted. The 2σ error bars are shown in the corner of each plot unless they are smaller than the size of the symbols. The values are in ppm except for the ratios. Estimates for the analytical precision of Pu'u 'Ō'ō lavas analyzed (by ICP-MS) prior to this study have been given by Garcia *et al.* (1996, 2000). The Kīlauea rock standards Kill1919 and BHVO-2 come from the same lava flow. Pu'u 'Ō'ō ICP-MS trace element data from previous studies were corrected by normalizing the average Kill1919 standard ($n = 11$) used for 1985–1998 Pu'u 'Ō'ō lavas to the BHVO-2 standard values for this study. Although the Kill1919 and BHVO-2 standards differ by 0.3 wt % MgO, if this was due to olivine control (as expected) the maximum difference in the incompatible trace element concentrations would be 0.7%, which is within analytical uncertainty of the ICP-MS data (Norman *et al.*, 1998).

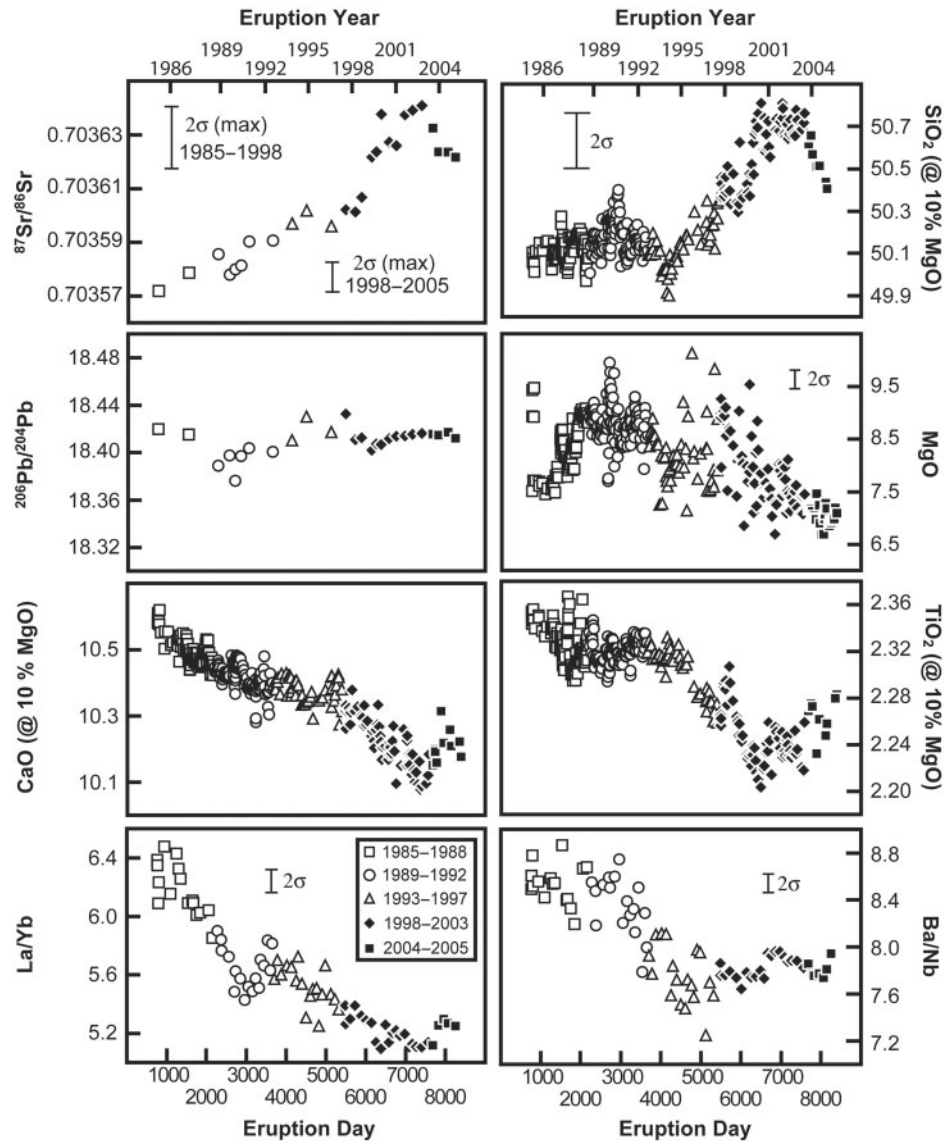


Fig. 5. Temporal geochemical variations during the Pu'u 'Ō'ō eruption. The 1985–1998 Pu'u 'Ō'ō lava data are from Garcia *et al.* (1992, 1996, 2000). SiO₂, CaO, and TiO₂ were normalized to 10 wt % MgO (the most primitive lava erupted from Pu'u 'Ō'ō; Garcia *et al.*, 2000) by the addition of equilibrium composition olivine (98.5%) and spinel (1.5%) in 0.5 mol % steps (Garcia *et al.*, 2003; Rhodes & Vollinger, 2005). Pu'u 'Ō'ō lavas with <7.2 wt % MgO may have crystallized minerals other than olivine (e.g. clinopyroxene and plagioclase) and were not included in the olivine normalization procedure. The decrease in scatter for the ²⁰⁶Pb/²⁰⁴Pb, Ba/Nb, and La/Yb ratios after 1998 is attributed to higher precision for the more recent trace element and Pb isotopic data. The 2σ error bars are shown in the corner of each plot unless they are smaller than the size of the symbols. The maximum 2σ error bars are presented in the Sr isotope panel for lavas erupted between 1985 and 1998 and between 1998 and 2005. The ⁸⁷Sr/⁸⁶Sr analytical uncertainties for each sample (presented in Table 5) are typically smaller than the maximum 2σ error bar.

member (~1998) from a recently depleted source (Pietruszka *et al.*, 2006) has slightly higher ⁸⁷Sr/⁸⁶Sr and MgO-normalized SiO₂ contents, yet lower incompatible trace element ratios and CaO and TiO₂ abundances. Third, the most recent end-member composition (~2003) displays the highest ⁸⁷Sr/⁸⁶Sr ratios and MgO-normalized SiO₂ abundances, and lowest abundances of CaO and TiO₂ and ratios of incompatible trace elements for the eruption.

PU'U 'Ō'Ō SOURCE CHARACTERISTICS

A lithospheric source component for Pu'u 'Ō'ō lavas?

Magmas originating from partial melting within the Hawaiian plume can be compositionally modified at shallower depths by the assimilation of hydrothermally altered oceanic crust (e.g. Eiler *et al.*, 1996) or lower gabbroic crust

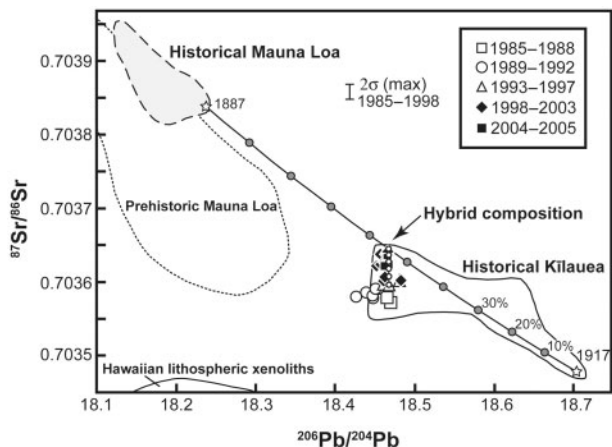


Fig. 6. $^{206}\text{Pb}/^{204}\text{Pb}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios for Pu'ū Ō'ō lavas compared with historical Kīlauea, and prehistoric and historical Mauna Loa lavas. Data sources: Garcia *et al.* (1992, 1996, 2000) for 1985–1998 Pu'ū Ō'ō lavas; Pietruszka & Garcia (1999a) and Abouchami *et al.* (2005) for historical Kīlauea lavas; Kurz & Kammer (1991), Kurz *et al.* (1995), Rhodes & Hart (1995), Wanless *et al.* (2006), and Marske *et al.* (2007) for historical and prehistoric Mauna Loa lavas. The compositional fields of Pacific mid-oceanic ridge basalts ($^{206}\text{Pb}/^{204}\text{Pb} = 18.24\text{--}19.48$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.70264\text{--}0.70367$; King *et al.*, 1993; Fekiacova *et al.*, 2007) and most Hawaiian lithospheric xenoliths ($^{206}\text{Pb}/^{204}\text{Pb} = 17.58\text{--}18.38$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.70271\text{--}0.70347$; Okano & Tatsumoto, 1996; Lassiter & Hauri, 1998) lie off the figure (below the isotopic fields of Kīlauea and Mauna Loa). Mixing lines between AD 1917 Kīlauea and AD 1887 Mauna Loa lavas (line with gray circles) and between a Pu'ū Ō'ō sample (10-Jan-1997) and a hybrid source (line with small open circles) containing a 55:45 proportion of the historical Kīlauea and Mauna Loa compositions are shown. The Pb abundances assumed for the mixing model are 1 ppm for Kill1917 ($^{206}\text{Pb}/^{204}\text{Pb} = 18.653$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.703478$) and 10-Jan-1997 ($^{206}\text{Pb}/^{204}\text{Pb} = 18.417$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.703596$) based on the average Pb concentrations in Table 4, and 0.9 ppm Pb for the 1887 Mauna Loa ($^{206}\text{Pb}/^{204}\text{Pb} = 18.187$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.703838$) lava. The Sr concentrations in the mixing end members are from Pietruszka & Garcia (1999a) for the 1917 Kīlauea lava (389 ppm Sr), Rhodes & Hart (1995) for 1887 Mauna Loa lava (275 ppm Sr), and Garcia *et al.* (2000) for the 10-Jan-1997 lava (307 ppm Sr). The maximum 2σ error bars are presented for 1985–1998 lavas. The 2σ error bars for 1998–2005 Pb and Sr isotope ratios are smaller than the size of the symbol.

(e.g. Gaffney *et al.*, 2004), or by partial melting of the upper ambient mantle (lithosphere or asthenosphere) beneath Hawai'i (e.g. Tatsumoto, 1978; Chen & Frey, 1985; Stille *et al.*, 1986; Lassiter *et al.*, 1996). However, it is unlikely that crustal assimilation or melting of the upper ambient mantle significantly modified the chemical signature of Pu'ū Ō'ō lavas. Pu'ū Ō'ō lavas erupted between 1983 and 1986 have relatively low $\delta^{18}\text{O}$ groundmass values (4.6–5.0‰) that are in disequilibrium with their olivine phenocrysts, suggesting that these early magmas interacted with shallow wall rock in the rift zone just prior to eruption (Garcia *et al.*, 1998). The switch in eruptive style from episodic lava fountaining to near-continuous effusion in 1986 led to a marked reduction or elimination of contamination, based on higher $\delta^{18}\text{O}$ groundmass values (5.0–5.3‰) in equilibrium with olivines in the 1986–1998

lavas (Garcia *et al.*, 1998). Furthermore, the 1998–2003 Pu'ū Ō'ō lavas record systematic temporal increases in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and relatively constant $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (Fig. 6) that trend away from the compositional fields of lithospheric mantle xenoliths from Salt Lake Crater, O'ahu (Okano & Tatsumoto, 1996) and Hualālai volcano, Hawai'i (Lassiter & Hauri, 1998), and Cretaceous Pacific mid-oceanic ridge basalts near Hawai'i (e.g. Ocean Drilling Program Site 843; King *et al.*, 1993; Fekiacova *et al.*, 2007).

Historical Kīlauea summit lavas have relatively low $\delta^{18}\text{O}$ isotope values that are attributed to <5–12% contamination of parental magmas with altered country rock from both Kīlauea and Mauna Loa (Garcia *et al.*, 2008). The overall increase of Sr isotopes in Pu'ū Ō'ō lavas could potentially be explained if a more typical Kīlauea parental magma (e.g. 1993–1997 Pu'ū Ō'ō lavas) progressively assimilated a roughly constant (55:45) mixture of older Kīlauea and Mauna Loa basement rocks (Fig. 6). However, this would require ~100% contamination because the Pu'ū Ō'ō lava with the highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio overlaps with the composition of the 55:45 Kīlauea–Mauna Loa assimilant. These combined observations suggest that melt interaction with the upper mantle, crust, or volcanic edifice beneath Kīlauea is minimal for recent Pu'ū Ō'ō lavas.

A third mantle source for the Pu'ū Ō'ō eruption

At least three distinct mantle source components are required to explain the compositional variability of Pu'ū Ō'ō lavas (Fig. 7). The 1985–1998 Pu'ū Ō'ō lavas originated from at least two distinct source components with similar Kīlauea-like Pb, Sr, and Nd isotopic compositions but different incompatible element abundances and ratios (Garcia *et al.*, 2000). One component with higher MgO-normalized CaO and TiO₂ abundances and incompatible trace element ratios (e.g. Ba/Ce or La/Yb) was important during the early part of the eruption (~1985; Figs 5 and 7), following the period of magma mixing during episodes 1–29. The temporal decreases among ^{230}Th – ^{238}U and ^{226}Ra – ^{230}Th disequilibria, incompatible trace element ratios (e.g. Th/U or Nd/Sm), and some normalized major element abundances in lavas from 1985 to 2001 (Fig. 5) suggest that a second mantle component was tapped (Pietruszka *et al.*, 2006). This 'recently depleted' component is thought to have formed at <8 ka (based on modeling of ^{226}Ra – ^{230}Th – ^{238}U disequilibria) by the removal of melt from Kīlauea's source region within the Hawaiian plume, causing it to become depleted in incompatible trace elements (Pietruszka *et al.*, 2006). A progressive increase in the proportion of the recently depleted component is indicated by the temporal trends between 1985 and 1998 (Figs 5 and 7; Garcia *et al.*, 2000; Pietruszka *et al.*, 2006).

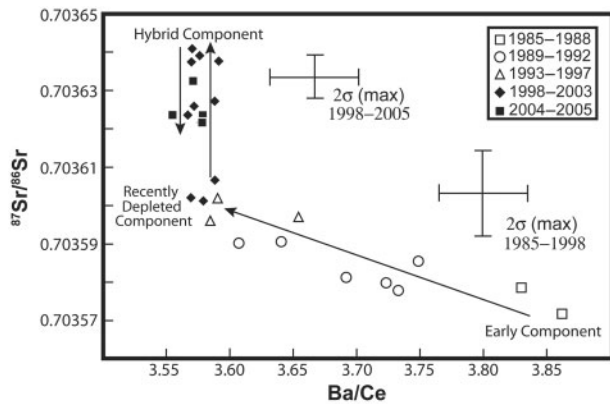


Fig. 7. Ba/Ce vs $^{87}\text{Sr}/^{86}\text{Sr}$ for Pu'u 'Ō'ō lavas. The 1985–1998 Pu'u 'Ō'ō lava data are from Garcia *et al.* (1992, 1996, 2000). At least three distinct mantle sources (termed the early, recently depleted and hybrid components) are required to explain the chemical variability during the Pu'u 'Ō'ō eruption. The maximum 2σ error bar is presented for 1985–1998 and 1998–2005 lavas (Sr isotopes only). Historical Mauna Loa lavas display a lower Ba/Ce range (2.6–3.5; J. M. Rhodes, unpublished data, 2008), with higher Sr isotope values (>0.70375 ; Rhodes & Hart, 1995).

The systematic geochemical variations from 1998 to 2003 (Figs 5–7) require a third component that was increasingly tapped during this time interval. Based on the temporal increases of some highly incompatible trace element ratios (e.g. Ba/Th) in lavas erupted from 1999 to 2001, Pietruszka *et al.* (2006) suggested that Pu'u 'Ō'ō lavas are derived in greater proportions of a source component similar to historical Mauna Loa lavas. However, simple mixing of melt from a Mauna Loa-like source (with relatively low $^{206}\text{Pb}/^{204}\text{Pb}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$) with an earlier Pu'u 'Ō'ō composition (i.e. the recently depleted component) cannot explain the increase in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at relatively constant $^{206}\text{Pb}/^{204}\text{Pb}$ ratios between 1998 and 2003 (Fig. 6).

Rhodes *et al.* (1989) proposed that magma from Mauna Loa may periodically invade Kīlauea's plumbing system. Pre-mixing of nearly equal proportions of historical Kīlauea- and Mauna Loa-like magmas prior to eruption could potentially explain the trends of recent Pu'u 'Ō'ō lavas (Figs 6 and 8). Although this pre-mixing could occur in Kīlauea's $\sim 2\text{--}3\text{ km}^3$ summit reservoir (Pietruszka & Garcia, 1999b), the rapid compositional

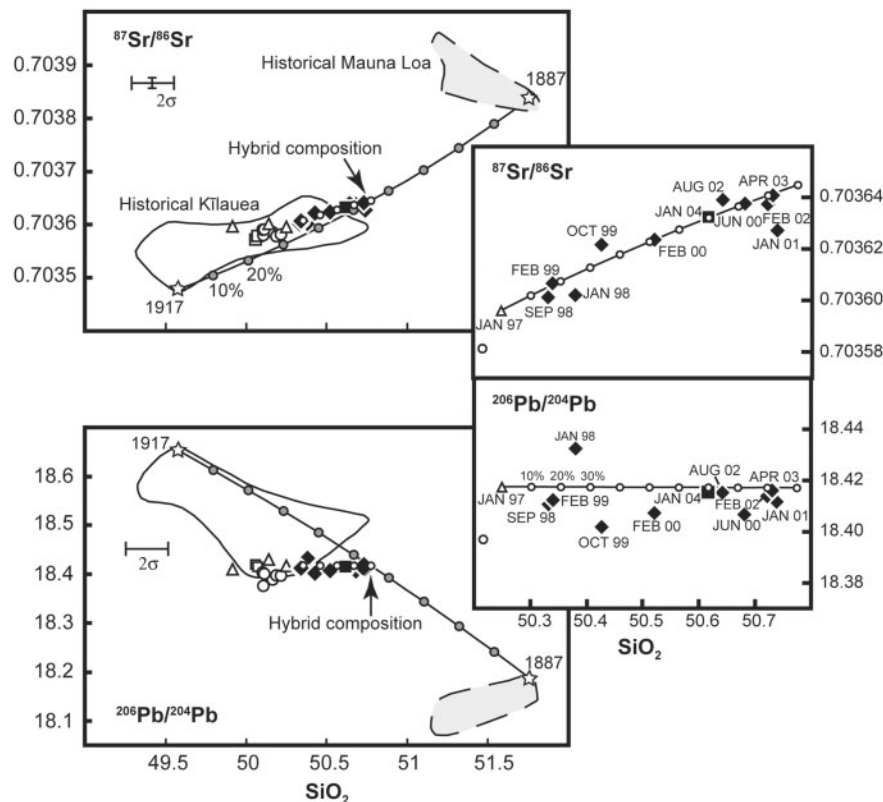


Fig. 8. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ vs MgO-normalized SiO_2 abundances for Pu'u 'Ō'ō and historical Kīlauea and Mauna Loa lavas. Data sources: Garcia *et al.* (1992, 1996, 2000) for 1985–1998 Pu'u 'Ō'ō lavas; Pietruszka & Garcia (1999a), Garcia *et al.* (2003), and Abouchami *et al.* (2005) for historical Kīlauea lavas; Rhodes & Hart (1995) for historical Mauna Loa lavas. Mixing lines between a Pu'u 'Ō'ō sample (10-Jan-1997) and a hybrid composition containing a 55:45 proportion of historical Kīlauea (i.e. AD 1917) and Mauna Loa (i.e. AD 1887) compositions are shown. Mixing model details are listed in the caption of Fig. 6. The 2σ error bar applies to 1985–1998 ($^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios) and 1985–2005 (SiO_2 contents) lavas. The 2σ error bars for 1998–2005 Pb and Sr isotope ratios on the main plots are smaller than the size of the symbols.

changes in Pu'u 'Ō'ō lavas are inconsistent with mixing in this reservoir (Garcia *et al.*, 1996). No other suitable crustal reservoir is known to accommodate this magma mixing. Thus, crustal magma mixing is an unlikely explanation for the 1998–2003 Pu'u 'Ō'ō compositional variations. Instead, these recent lavas can be explained if they were derived from a mixture of Mauna Loa- and Kīlauea-like mantle sources that subsequently melted. This hybrid source represents a new component for the eruption.

Historical lavas from Kīlauea and Mauna Loa volcano provide an important window to the present-day composition and distribution of mantle components in the Hawaiian plume (e.g. Rhodes & Hart, 1995; Pietruszka & Garcia, 1999a). Consequently, the origin of the recent Pu'u 'Ō'ō lavas is discussed below in terms of mixing between the mantle source components defined by historical lavas from these two volcanoes (rather than the more extreme end-member isotopic compositions observed in Kōōlau and Mauna Kea lavas). The proportions of Kīlauea and Mauna Loa components in the hybrid source can be estimated from compositional mixing trends (Figs 6 and 8). The 1917 Kīlauea lava was chosen as an end member because it has the highest $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ and lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among olivine-controlled historical Kīlauea lavas (Pietruszka & Garcia, 1999a). Although a range of historical Mauna Loa lavas would make reasonable isotopic end members for this calculation, the 1887 Mauna Loa lava (Rhodes & Hart, 1995) was selected because it creates a suitable mixing trend on the plots of MgO-normalized major elements vs $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 8). The 10-Jan-1997 Pu'u 'Ō'ō sample was chosen to represent the recently depleted Kīlauea source component because it has the lowest ratios of highly incompatible trace elements (e.g. Ba/Nb or Ba/Rb) for this eruption. Mixing trends between the 1917 Kīlauea (55%) and 1887 Mauna Loa (45%) lavas (Figs 6 and 8) pass within analytical error of the 2001–2003 Pu'u 'Ō'ō lavas (i.e. the samples with the highest $^{87}\text{Sr}/^{86}\text{Sr}$ and MgO-normalized SiO_2 values). Therefore, this 55:45 Kīlauea–Mauna Loa composition might be a good estimate of the hybrid source.

This mixing model suggests that the melt contribution from the recently depleted source component decreased starting in early 1998 as melt derived from the hybrid source was tapped in greater proportions until mid-2003 (Figs 7 and 8). Following the mid-2003 compositional reversal, the lavas display chemical and isotopic variations that overlap with the compositional fields of the 1998–2003 lavas (Figs 3–8), indicating a diminishing importance for the hybrid component since 2003.

A pyroxenite source for Pu'u 'Ō'ō lavas?

Partial melting of a heterogeneous plume source containing a mixture of peridotite and ancient recycled oceanic crust \pm sediment (pyroxenite or eclogite) has become

a common explanation for the chemical and isotopic variations in Hawaiian lavas (e.g. Hauri, 1996; Lassiter & Hauri, 1998; Blichert-Toft *et al.*, 1999; Takahashi & Nakajima, 2002; Gaffney *et al.*, 2005; Sobolev *et al.*, 2005, 2007; Herzberg, 2006). For example, Kōōlau lavas, with relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ (~ 0.7044) and SiO_2 (~ 53 – 55 wt %), are explained by melting ancient recycled oceanic crust within the Hawaiian plume (Hauri, 1996; Lassiter & Hauri, 1998; Blichert-Toft *et al.*, 1999; Huang & Frey, 2005; Fekiacova *et al.*, 2007). Further support for a pyroxenite source within the Hawaiian plume comes from modeling compositional variations of lavas during long-lived eruptions, including Pu'u 'Ō'ō (Reiners, 2002). This model predicts that the continuous SiO_2 increases and CaO decreases could be explained if Pu'u 'Ō'ō lavas originated from a mixed pyroxenite–peridotite source with different solidi.

The temporal increases in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and SiO_2 abundances (normalized to 10 wt % MgO) in the 1998–2003 lavas (Fig. 5) could be evidence for increased melting of an eclogite or pyroxenite lithology (i.e. recycled oceanic crust) in the Hawaiian plume. However, an increasing contribution of this source lithology during the eruption is unlikely for the following reasons. (1) The MgO-normalized SiO_2 trend is relatively flat prior to 1998, increased from 1998 to 2003, and has decreased since mid-2003. Moreover, the CaO trend has increased since mid-2003. Both trends are inconsistent with a simple mixed lithology source (e.g. Reiners, 2002). (2) The long-term decreases in CaO abundances (normalized to 10 wt % MgO; Fig. 5) from 1985 to 2003 suggest that there has been a decrease in the amount of clinopyroxene that is melted in the mantle source region, rather than the predicted increase of this mineral. (3) The Ni abundances of the lavas have progressively decreased (at a given MgO) from ~ 1992 to 2005 (Fig. 3). Because Ni is highly compatible in olivine relative to clinopyroxene (e.g. Sobolev *et al.*, 2005), the decreases in Ni content suggest that recent Pu'u 'Ō'ō lavas originated from a peridotite source that became more olivine-rich and/or clinopyroxene-poor with time. A peridotite source is also supported by the positive correlation between ^{226}Ra – ^{230}Th and ^{230}Th – ^{238}U disequilibria of 1985–2001 Pu'u 'Ō'ō lavas (Pietruszka *et al.*, 2006).

SMALL-SCALE MANTLE HETEROGENEITY

The timing of the temporal inflections of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the Pu'u 'Ō'ō lavas may be used to help constrain the scale of heterogeneity within Kīlauea's melting region. The steady increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 1998 (day ~ 5500) and 2003 (day ~ 7400) suggests that the proportion of the hybrid component progressively increased during this period. The lack of significant changes in the volume of magma stored in the shallow summit reservoir beneath Kīlauea during prolonged (months to years) historical

Kīlauea rift eruptions (i.e. Mauna Ulu and Puʻu ʻŌʻō) suggests that the magma supply rate is similar to lava effusion rate (Tilling *et al.*, 1987; Dvorak & Dzurisin, 1993; Denlinger, 1997). Assuming that the magma supply rate is approximately equal to the lava effusion rate ($\sim 0.13 \text{ km}^3/\text{year}$; Sutton *et al.*, 2003) for the Puʻu ʻŌʻō eruption, the total volume of melt extracted from Kīlauea's source region from 1998 to 2003 (~ 1900 days) was $\sim 0.7 \text{ km}^3$. This estimate probably represents the maximum volume of melt derived from the hybrid source during this period. If 100% of the recently depleted and hybrid components were being tapped at the temporal inflections in 1998 and 2003, respectively, melt from the hybrid source might represent $\sim 50\%$ of the total lava volume erupted from 1998 to 2003 ($\sim 0.35 \text{ km}^3$). Models for tholeiitic basalt production within the Hawaiian plume suggest that the melt-zone porosity within Kīlauea's source region is $\sim 2\text{--}3\%$ (Sims *et al.*, 1999; Pietruszka *et al.*, 2001). Thus, if melt tapped from 1998 to 2003 represents $\sim 2\text{--}3\%$ of the total volume from which it was extracted, then the volume of the source region that supplied melt during this period would be $\sim 10\text{--}35 \text{ km}^3$.

The 1998–2003 lavas plot within analytical error along the mixing line from the recently depleted source (10-Jan-1997) towards the hybrid component (Figs 6 and 8). If these recent lavas are derived from a hybrid mantle source containing a mixture of Kīlauea and Mauna Loa components, then the size of these components must be significantly smaller than the volume of the source region that was tapped from 1998 to 2003 ($<10\text{--}35 \text{ km}^3$). Thus, the Kīlauea and Mauna Loa mantle components that make up the hybrid component are thought to be mixed on a fine scale in the Hawaiian plume.

CHEMICAL STRUCTURE OF THE HAWAIIAN PLUME

The long-term geographical and compositional differences between Hawaiian shield volcanoes have been related to the distribution of large-scale heterogeneities in a radially (Lassiter *et al.*, 1996; Bryce *et al.*, 2005), asymmetric (Abouchami *et al.*, 2005) or irregularly zoned (Kurz *et al.*, 2004) Hawaiian plume. For example, Kīlauea and Mauna Loa volcanoes have erupted geochemically distinct lavas for most of their known eruptive history, suggesting that the source components of these volcanoes (i.e. Kea and Loa) have remained compositionally distinct [except for some young prehistoric (AD 900–1400) Kīlauea and Mauna Loa lavas; Marske *et al.*, 2007] over a time scale of thousands of years (e.g. large-scale heterogeneity; Frey & Rhodes, 1993; Abouchami *et al.*, 2005). However, the recent Puʻu ʻŌʻō compositional trends suggest that both Kīlauea- and Mauna Loa-like components are present within Kīlauea's source region with a spatial distribution capable of creating the rapid fluctuation towards the hybrid composition on a time scale of years.

To explain the recent trend of Puʻu ʻŌʻō lavas towards the hybrid composition we propose a model with large-scale compositional heterogeneity (e.g. Lassiter *et al.*, 1996; DePaolo *et al.*, 2001; Bryce *et al.*, 2005) that is gradational across the Hawaiian plume (black to white shading in Fig. 9a). On a finer scale, Kīlauea- and Mauna Loa-like heterogeneities ($<10\text{--}35 \text{ km}^3$) are assumed to be present (within the enlarged circles in Fig. 9a), but vary in relative abundance depending on location within the Hawaiian plume. For example, the darker zonation within Kīlauea's typical source region contains more Kīlauea heterogeneities, and vice versa for the whiter zone below Mauna Loa. Similarly, the intermediate gray zone located between these two volcanoes represents a source with approximately equal amounts of Kīlauea- and Mauna Loa-like compositions (Fig. 9a).

Resolving the spatial distribution of these small-scale compositional heterogeneities ($<10\text{--}35 \text{ km}^3$) is problematic given the wide range in estimates for the size of Kīlauea's melting region. These estimates vary from an $\sim 55 \text{ km}$ thick region near the central axis of the plume (Watson & McKenzie, 1991) to a thickness of $<5\text{--}10 \text{ km}$ (Marske *et al.*, 2007). The maximum radius of this melting region is probably $\sim 17 \text{ km}$ (i.e. half the distance between the summits of Kīlauea and Mauna Loa; Pietruszka *et al.*, 2001). Estimates for the rates of mantle melting in the Hawaiian plume range from >0.0005 to $>0.03 \text{ kg/m}^3$ per year (Cohen *et al.*, 1993; Hemond *et al.*, 1994; Sims *et al.*, 1999; Pietruszka *et al.*, 2001). Even the highest melting rates would require melting over a voluminous mantle source region ($\sim 8500 \text{ km}^3$; Pietruszka *et al.*, 2006) to account for the vigorous lava effusion rate during the Puʻu ʻŌʻō eruption ($\sim 0.13 \text{ km}^3/\text{year}$; Sutton *et al.*, 2003). Tapping such a large melting region would probably homogenize the melts derived from the three distinct sources for this eruption. Instead, the compositional variability of Puʻu ʻŌʻō lavas could be preserved if compositionally distinct melts are extracted into chemically isolated channels and efficiently transported to the surface (Pietruszka *et al.*, 2006).

The melting region beneath Hawaiian volcanoes is predicted to be zoned, with higher degrees of partial melting (and higher melt productivity) in a relatively thin zone near the top of the melting region (Watson & McKenzie, 1991). Thus, melt extraction would probably be more effective if it occurred laterally over a thinner (i.e. $\sim 5\text{--}10 \text{ km}$ thick; Marske *et al.*, 2007) region. As melt migrates into channels to supply the Puʻu ʻŌʻō eruption, it must be extracted from more distal areas to sustain the flow of melt to the surface, otherwise the melt supply would become exhausted (Pietruszka *et al.*, 2006). In this context, we propose that the systematic geochemical trends toward the hybrid composition from 1998 to 2003 could be explained if melt pathways migrated from an area within Kīlauea's typical melting region dominated

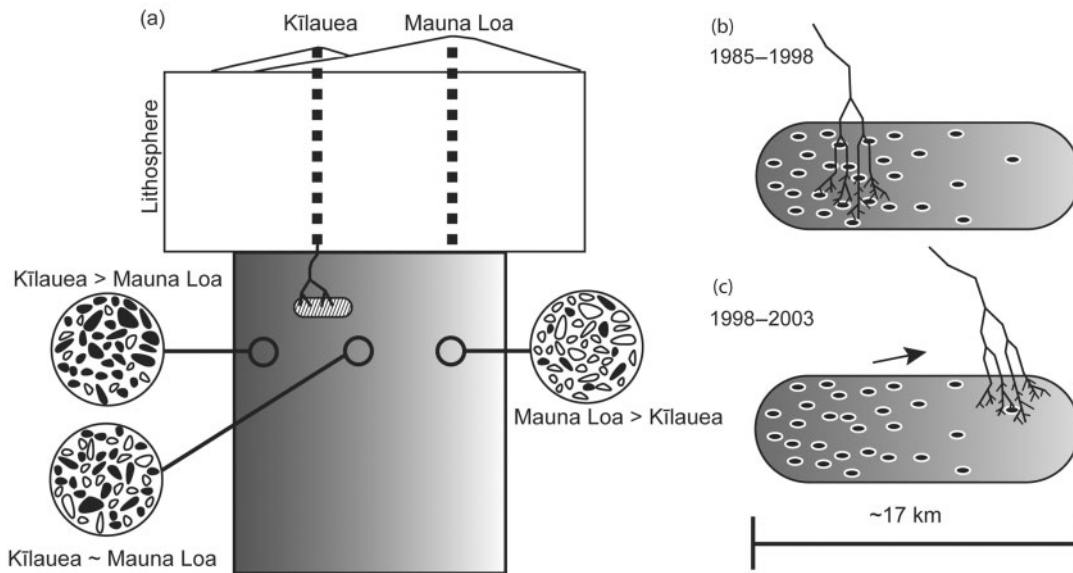


Fig. 9. Hypothetical cross-section of the lithosphere and the upper part of the Hawaiian plume beneath Kīlauea and Mauna Loa. (a) The long-term compositional differences between Hawaiian shield volcanoes are illustrated with black to white gradation representing large-scale compositional heterogeneity within the plume (e.g. Lassiter *et al.*, 1996; Kurz *et al.*, 2004; Abouchami *et al.*, 2005; Bryce *et al.*, 2005). Superimposed on this large-scale heterogeneity are small-scale heterogeneities ($<10\text{--}35\text{ km}^3$; blobs within the enlarged circles) that reflect a predominance of Kīlauea (black) and Mauna Loa (white) components beneath these volcanoes. An isotopically distinct plume matrix (white area between the blobs) is also thought to be present in the plume based on the Pb, Sr, and Nd isotopic evidence for at least three components within the Hawaiian plume (e.g. West & Leeman, 1987; Eiler *et al.*, 1996; Hauri, 1996). The matrix is a schematic representation and other geometries of the three mantle components are possible (e.g. three isotopically distinct blobs or streaks with no matrix). Melt extraction via chemically isolated channels (inverted tree structures) may be the primary mechanism to withdraw melt from Kīlauea's melting region [striped region in (a)] into the volcano's primary magma conduit (thick dashed black line; Pietruszka *et al.*, 2006). (b) and (c) are enlargements of Kīlauea's melting region. The small-scale heterogeneities from (a) are not shown in (b) and (c) for simplicity, yet are assumed to be present. Between 1985 and 1998 (b), the recently depleted source (black ovals) was an important component in Kīlauea's melting region. The importance of the Kīlauea–Mauna Loa hybrid component (gray zone) that was progressively tapped from 1998 to 2003 can be explained if the melt channels migrated towards Mauna Loa while possibly extracting melt at shallower depths (c).

by the early and recently depleted component (black ovals; Fig. 9b) towards Mauna Loa, where more Mauna Loa-like components would be expected (Fig. 9c). In contrast, the MgO-normalized SiO₂ abundances are thought to be controlled by the depth of partial melting (e.g. Hirose & Kushiro, 1993; Kushiro, 1996; Longhi, 2002). Thus, the temporal increase in normalized SiO₂ abundances in 1998–2003 lavas could also be explained if melt production and segregation occurred at progressively shallower depths (e.g. Stolper *et al.*, 2004) during this interval (Fig. 9b and c). This model for a fine-scale mixture of compositionally distinct mantle heterogeneities (i.e. Kīlauea and Mauna Loa components) within the Hawaiian plume is consistent with the presence of both Kea and Loa compositions in young prehistoric (AD 900–1400) Kīlauea and Mauna Loa lavas (Marske *et al.*, 2007), and in the melt inclusions of East Maui lavas (Ren *et al.*, 2006).

CONCLUSIONS

The Pu'ū Ō'ō eruption is exceptional among historical eruptions for its long duration (25+ years) and compositional variability. The systematic geochemical fluctuations in Pu'ū Ō'ō lavas document the short-term crustal

(e.g. crystal fractionation) and mantle (melting and source heterogeneity) processes in the Hawaiian plume. Pu'ū Ō'ō lavas erupted from 1985 to 1998 are thought to have originated from at least two distinct source components with similar isotopic compositions, although one was more depleted in incompatible trace elements by a recent ($<8\text{ ka}$) melting event in the Hawaiian plume. Post-1998 Pu'ū Ō'ō lavas record small but distinctive variations of MgO-normalized major element abundances, and Sr isotope and incompatible trace element ratios (compared with earlier erupted lavas) that require a third source component. Lavas erupted between 1998 and 2003 display a temporal geochemical evolution toward an intermediate area between the compositional fields of historical Kīlauea and Mauna Loa lavas. Based on mixing models, the 1998–2003 Pu'ū Ō'ō lavas trend towards a hybrid mantle source composition made of roughly equal proportions of Kīlauea- and Mauna Loa-like components. The contribution from a recently depleted Kīlauea component decreased starting in early 1998 as the volcano tapped greater proportions of a hybrid component until mid-2003. The systematic geochemical trends toward this hybrid composition can be explained if melt pathways migrated from an area within

Kīlauea's melting region (important for 1985–1998 lavas) towards Mauna Loa, where an equal mixture of Kīlauea- and Mauna Loa-like components may exist. The presence of Kīlauea (i.e. Kea) and Mauna Loa (i.e. Loa) components ($<10\text{--}35\text{ km}^3$) in Pu'u Ō'ō lavas suggests that both of these components are present as a fine-scale mixture in Kīlauea's source region.

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APPENDIX

Table A1: Sr isotope ratios for Pu'u 'Ō'ō lavas

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$ (TIMS)	$^{87}\text{Sr}/^{86}\text{Sr}$ (MC-ICP-MS)	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$ (TIMS)	$^{87}\text{Sr}/^{86}\text{Sr}$ (MC-ICP-MS)	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$ (TIMS)	$^{87}\text{Sr}/^{86}\text{Sr}$ (MC-ICP-MS)	Sample	$^{87}\text{Sr}/^{86}\text{Sr}$ (TIMS)	$^{87}\text{Sr}/^{86}\text{Sr}$ (MC-ICP-MS)
26-Mar-89	0.703586		27-Oct-99	0.703610	0.703627	15-Jan-04	0.703625	0.703642	Kil1919	0.703472	
	0.703582			0.703619			0.703634			0.703476	
	0.703581			0.703630			0.703638			0.703483	
							0.703623				
12-May-91	0.703586		19-Feb-00	0.703617	0.703634						
				0.703623							
				0.703621		7-Jun-04	0.703623	0.703635			
29-Dec-92 #1	0.703606						0.703627				
	0.703585						0.703621				
	0.703598		21-Jun-00		0.703644		0.703612				
			8-Jan-01		0.703639		0.703616				
29-Dec-92 #2	0.703609		7-Jul-01	0.703616	0.703635	31-Jan-05	0.703622				
	0.703591			0.703631			0.703627				
	0.703594			0.703621			0.703616				
27-Apr-95	0.703594		9-Feb-02	0.703636	0.703628		0.703622				
	0.703612			0.703646			0.703616				
	0.703598			0.703639			0.703634				
7-Sep-98	0.703607		20-Aug-02	0.703642	0.703633		0.703629				
	0.703592			0.703638							
	0.703607			0.703643		8-Aug-05	0.703620				
	0.703602						0.703631				
	0.703592		12-Apr-03	0.703634	0.703641		0.703611				
	0.703608			0.703643			0.703613				
				0.703644			0.703641				
13-Feb-99		0.703616					0.703613				

Multiple analyses for a given sample are from a single dissolution. The average $^{87}\text{Sr}/^{86}\text{Sr}$ value for each sample is presented in Table 5. Samples 26-Mar-89, 12-May-91, 29-Dec-92 (#1 and #2), and 27-Apr-95 were re-run to further improve the precision of these analyses compared with the data presented by Garcia *et al.* (1996, 2000) and Pietruszka *et al.* (2006). Samples 29-Dec-92 #1 and #2 represent separate dissolutions performed by Pietruszka *et al.* (2006). The $^{87}\text{Sr}/^{86}\text{Sr}$ values of the SRM987 standard by TIMS were 0.710255 ± 17 (2σ ; $n = 60$) for the 1999–2004 Pu'u 'Ō'ō lavas, and 0.710246 ± 17 (2σ ; $n = 18$) for Kil1919 and the 1989–1998 and 2005 Pu'u 'Ō'ō lavas. Multiple analyses of the SRM987 standard by MC-ICP-MS with the 1998–2004 lavas gave $^{87}\text{Sr}/^{86}\text{Sr} = 0.710220 \pm 13$ (2σ ; $n = 35$). The in-run errors are less than the external reproducibility of SRM987. All Sr isotope ratios are reported relative to $^{87}\text{Sr}/^{86}\text{Sr} = 0.710250$ for SRM987.