

# Magma-Reservoir Processes Revealed by Geochemistry of the Pu‘u ‘Ō‘ō-Kūpaianaha Eruption

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## Abstract

Geochemical data were examined for a suite of approximately 1,000 near-vent lava samples, collected from January 1983 to October 2001, from the Pu‘u ‘Ō‘ō-Kūpaianaha eruption of Kīlauea Volcano, Hawai‘i. Bulk lava and glass compositions reveal short- and long-term changes in preeruptive magma conditions that can be correlated with changes in edifice deformation, shallow magma transfer, and eruptive behavior. Nearly two decades of eruption on Kīlauea’s east rift zone have yielded about 2.3 km<sup>3</sup> of lava, 97 percent of which is sparsely olivine-phyric with an MgO range of 6.8 to 9.6 weight percent. During separate brief intervals of low-volume fissure eruption (episodes 1 to 3 and 54), isolated rift-zone magma pods with lower-MgO compositions and with phenocrysts of olivine, clinopyroxene, and plagioclase were mixed with more mafic magma immediately before eruption. During prolonged, near-continuous eruption (episodes 48 through 53 and most of 55), steady-state effusion was marked by cyclic variations in olivine-saturated magma composition. Bulk-lava MgO content and eruption temperatures vary in cycles of monthly to biennial frequency, while olivine-incompatible elements vary inversely to these cycles. MgO-normalized values and ratios of highly to moderately incompatible elements, which are not affected by olivine fractionation, however, reveal cycles in magma composition that occur before olivine crystallization over the magmatic temperature range tapped by this eruption (1,205–1,155°C). These short-term cycles are superimposed on a long-term decrease of incompatible element ratios, which has been proposed to reflect a progressive 20-year change in mantle-source conditions. Such variation in primitive recharge magma cannot be ruled out, but the short-term fluctuations of this signature may require unreasonably complex mantle variations. Alternatively, the correspondence of geochemical cycles with edifice deformation and eruptive behavior suggests that the long-term evolving magmatic condition is a result of a prolonged succession of short-term shallow magmatic events. The long-term trends can be explained by episodic mixing of chemically uniform recharge melt with diminishing proportions of pre-1983 summit magma (maintained at near-cotectic conditions). The occurrence of long-term summit deflation since the 1982 eruption suggests that progressive summit-reservoir depletion may be responsible for observed geochemical and isotopic trends in post-1982

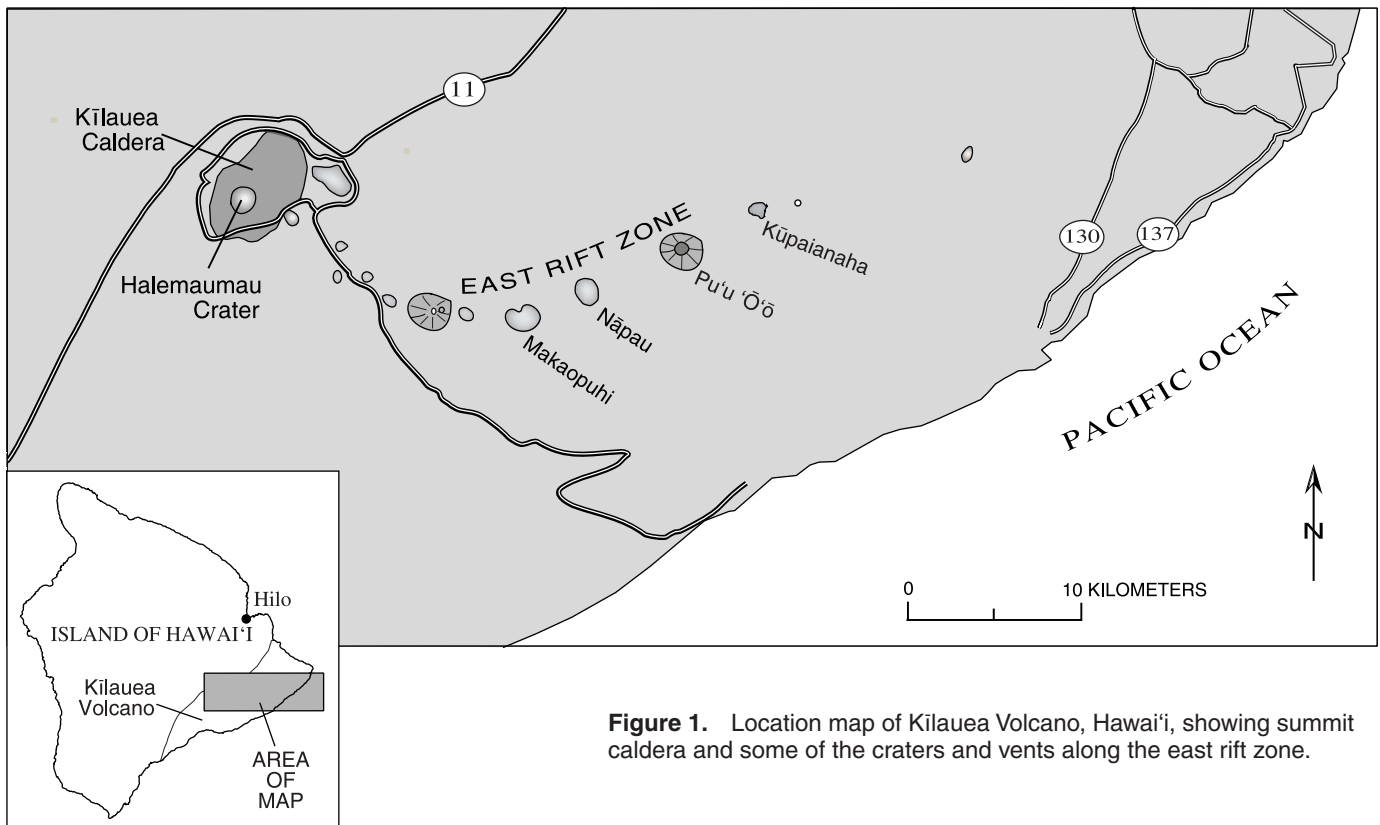
steady-state eruption products. New magma derived from a uniform mantle source has apparently flushed out older resident magma and may now completely occupy the shallow magmatic plumbing system.

## Introduction—Magmatic Setting

During the past two decades, geophysical and geochemical monitoring have helped define how and where magma is transported, stored, erupted, and recharged within the edifice of Kīlauea Volcano. Recent geophysical interpretations of the magmatic plumbing system are consistent with earlier models summarized and refined by Tilling and Dvorak (1993). Magma generated at depths greater than 60 km within the Hawaiian hotspot is transported to storage beneath Kīlauea’s summit. Subsequently, behind an unbuttressed and seaward-moving flank, the magma is transported via episodic dike injection to the two rift zones that radiate from the summit.

Interpretations of variations in seismic velocity beneath the summit caldera (Dawson and others, 1999; Ohminato and others, 1998) reveal that a body of magma is presently located 1 to 4 km below an area southeast of Halemaumau, and a magma conduit connects this summit reservoir to the uppermost east rift zone (see fig. 1). Carbon dioxide (CO<sub>2</sub>) concentrations in summit and rift-zone gas fumaroles, measured since 1983, suggest that magma recharge is restricted to the summit, beneath the vicinity of Halemaumau (Gerlach and others, 2002). Gerlach and others provide reasonable evidence that turbulent magma mixing occurs at the base of the summit reservoir as primitive (CO<sub>2</sub>-rich) melts are introduced. A shallow summit magma reservoir has probably been maintained by such open-system recharge for more than two centuries of episodic summit eruptions (Pietruszka and Garcia, 1999a).

Before the Pu‘u ‘Ō‘ō-Kūpaianaha eruption began, an estimated 55 percent of magma supplied to the shallow edifice from 1952 to 1983 intruded along the rift zones (Dzurisin and others, 1984). Despite the intrusion and eruption that occurred at the summit during the same time period, Dzurisin and others indicate that little or no net change occurred in the volume of magma stored in the summit reservoir. Since 1983, however, amidst near-continual rift eruption and influx



**Figure 1.** Location map of Kilauea Volcano, Hawai'i, showing summit caldera and some of the craters and vents along the east rift zone.

of new magma into the summit reservoir, the shallow reservoir has steadily deflated. This deflation indicates that the summit magma chamber has gradually lost stored magma.

In concert with this 20-year-long deflationary trend at the summit, progressive outward movement of the south flank has accommodated development of an increasingly efficient magma conduit through the shallow upper and middle east rift zone. Evidence that pockets of magma also exist along the east rift conduit is shown in geophysical and petrologic studies (Thornber and others, in press; Garcia and others, 1989, 1992; Hoffman and others, 1990; Okamura and others, 1988). Such pockets of rift-resident magma may be physically isolated from magma flowing continuously through the shallow rift zone or may persist as open-system reservoirs, maintained in connection with fresh magma supplied from the summit region.

Changes in vent location and eruptive vigor throughout the Pu'u 'Ō'ō-Kūpaianaha eruption (Heliker and Mattox, this volume) are a consequence of the ebb and flow of magma within this dynamically evolving system. Over the short term (year-to-year, month-to-month, and day-to-day), seemingly erratic cycles of summit inflation and deflation result from magma intrusion into, or withdrawal from, the summit reservoir, combined with magma transport into and along the east rift zone (Wolfe and others, 1987; Okamura and others, 1988; Denlinger, 1997; Garcia and others, 1996; Owen and others, 2000; Thornber, 2001; Cervelli and others, 2002; Thornber and others, in press; Cervelli and Miklius, this volume).

Surges and lulls in downrift vent activity, which correlate with these cycles, demonstrate that a fluid-pressure balance is maintained between the summit and the east rift zone.

## Geochemical Data

The geochemical data in this paper are culled from the Hawaiian Volcano Observatory (HVO) database of lava samples from the Pu'u 'Ō'ō-Kūpaianaha eruption. As an integral part of the ongoing eruption-monitoring effort, such data have been continuously obtained, using U.S. Geological Survey analytical laboratories. Sampling information and complete analyses for about 1,000 near-vent samples collected from episodes 1 through 55 (up to October 2001) are available from the author.

The selected suite of HVO's lava samples from the eruption is limited mostly to rapidly quenched eruptive products of spatter; tephra (reticulite and Pele's hairs and tears) collected near the vent; lava collected from skylights of lava tubes; and lava from pond or surface flows collected at the vent. Collection techniques used were similar to those described by Thornber (2001). Glass and whole-rock chemistry tends to change during emplacement of distal surface flows (Cashman and others, 1999; Sharma and others, 1999) and in sluggish lava-tube flows associated with eruptive pauses; such samples are not included in this database. Eruption temperatures were

determined, using the Kilauea MgO-glass thermometry of Helz and Thornber (1987), with an average distance correction factor of 0.9°C/km applied to lava-tube flow samples collected at variable distances from the vent (Thornber, 2001).

Geochemical data compiled for near-vent samples includes 793 bulk lava major-element analyses obtained by wavelength dispersive x-ray fluorescence (WDXRF) techniques; 652 major-element glass compositions, each an average of 10 electron microprobe analyses (EMPA) per sample; and 85 instrumental neutron activation analyses (INAA) of trace elements from representative bulk lava samples. Glasses in a subsuite of 37 samples of Pele's tears erupted from 1995 to 1996 were analyzed for trace elements, using laser-ablation inductive-coupled plasma mass spectrometry (LAICPMS). The database also includes Nd, Sr, and Pb isotopic data obtained for 10 of the samples analyzed by INAA that erupted between 1983 and 1994. For this report, two vent-spatter samples from the last summit eruptions in April and September 1982 were also collected and analyzed for major elements.

## Overview of Eruption Geochemistry, January 1983 to October 2001

Nearly continuous magma infusion beneath the summit for 19 years has yielded about 2 km<sup>3</sup> of lava on the rift zone (fig. 1). Approximately 97 percent of this lava is weakly olivine-phyric, with minor chromian spinel, and has MgO contents of 6.8 to 9.6 weight percent. Small volumes of cooler and relatively MgO-poor magma, erupted during episodes 1 through 3 (January to April 1983) and during episode 54 (January 30–31, 1997), are saturated in clinopyroxene and plagioclase. MgO variation diagrams for major and trace elements that are incompatible with crystallization of olivine and spinel define different geochemical trends of erupted lava (fig. 2). At or below about 7 weight percent MgO, moderately incompatible elements that are incorporated by plagioclase and clinopyroxene (such as Ca and Sc) are depleted, whereas highly incompatible elements (such as large-ion lithophile elements, rare earth elements and Ti, Zr, and Hf) are variably enriched, relative to olivine-controlled compositions. Above about 7 weight percent MgO, the incompatible element variation is consistent with olivine-only fractionation from a limited range of magmatic temperatures and delineates an olivine-control trend of slightly increasing incompatible elements with decreasing MgO. As indicated in figure 2, this olivine-saturated liquid line of descent (LLD) shifts progressively, from episode 48 to 55, toward lower concentrations of K<sub>2</sub>O and other incompatible elements.

Throughout most of the eruption, matrix glass compositions varied with bulk lava compositions. Increases and decreases of MgO content in bulk lava correlated positively with changes in eruption temperature, as determined by MgO content of the glass (fig. 3A, B). In addition to having relatively low MgO content and temperature, the bulk signature of lava

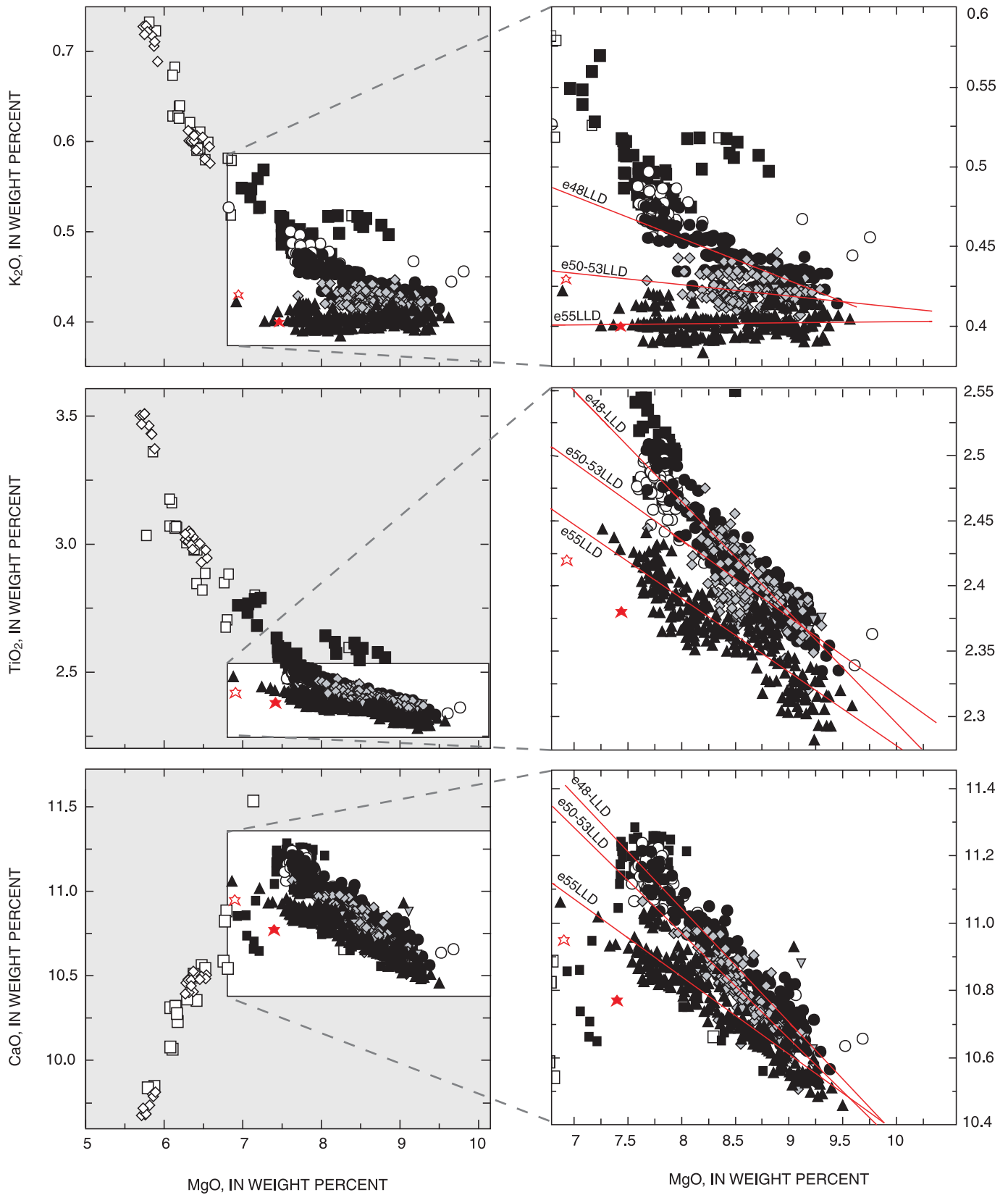
erupted during episodes 1–3 and 54 is clearly distinguished from the common olivine-controlled composition in temporal variation plots of olivine-incompatible elements, such as Ca and Ti (figs. 3C, D).

Concentrations of incompatible elements in olivine-phyric lava vary inversely with bulk lava MgO and eruption temperature over periods of 6 months to 2 years (fig. 3). On this time scale, cycles of variation in temperature and in MgO and incompatible-element concentrations are broadly consistent with repeated cycles of olivine fractionation from melts of about 10 to 7 weight percent MgO. When normalized to constant MgO (7 and 10 percent), variation owing to olivine fractionation is nullified, revealing short-term incompatible-element cycles between end members of 7 and 10 weight percent MgO, superimposed on a long-term decrease of concentrations, independent of olivine fractionation (fig. 3C, E).

The trend of long-term decrease, more pronounced for more highly incompatible elements, results in well-defined temporal decreases in ratios of incompatible elements, such as Ca/Al and K/Ti (fig. 4A, B). These ratios track a gradual and persistent change in the composition of olivine-saturated magma that feeds the eruption. Such progressive changes of an olivine-controlled LLD are apparent in a temporal decrease in ratios of highly to moderately incompatible trace elements (for example, La/Yb, fig. 4C) and in the change of averaged olivine-normalized trace element patterns for successive intervals of steady-state eruption (fig. 5). The long-term trends of elements incompatible with olivine in lava erupted during episodes of prolonged effusion extend back in time to the last magma erupted from the summit in September 1982, four months before the onset of the current eruption (figs. 3, 4, and 5). As discussed later, these post-1983 trends are coincident with that of long-term summit deflation (fig. 4D).

Within estimated analytical errors for matrix glasses (Thornber and others, 2002), incompatible elements show the same overall temporal trends observed for whole-rock data, but with more scatter. The greater variability of glass data is due to minor cooling and crystallization associated with drainback at the vents and transport of lava in tubes. Some of the variation can be attributed to microlite development in poorly quenched vent samples. The variability of glass data is minimized for ratios of olivine-incompatible elements, which reveal the same overall long-term trends as bulk-lava ratios (fig. 4A, B). Incompatible trace element concentrations for Pele's tears (glass) collected from mid-1995 to mid-1996 are consistent with the temporal variations observed for major and minor elements (fig. 5).

Isotopic determinations of Sr, Nd, and Pb for 10 representative olivine-phyric samples erupted from 1983 to 1993 complement similar determinations for 14 samples collected between 1983 and January 1998, reported by Garcia and others (1996, 2000), and for 1982 summit magma (Pietruszka and Garcia, 1999a). For all three datasets, <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>87</sup>Sr/<sup>86</sup>Sr remain fairly constant (within analytical error), but, in a fashion similar to olivine-incompatible element ratios, <sup>206</sup>Pb/<sup>204</sup>Pb decreases steadily from the values of 1982 summit lava until 1988, then increases slightly again (fig. 6).



**Figure 2.** MgO variation diagrams for selected incompatible elements. Symbols (facing page) pertain to groups of eruptive episodes, as indicated in figure. All values are for bulk lava analyses except the averaged compositions of glasses in Pele's tears collected during episodes 53 (open red star) and 55 (filled red star) (from Thornber, 2001). Scales are expanded in duplicate figures for  $K_2O$ ,  $TiO_2$ , and CaO to show progressive shift in an olivine-saturated liquid line of descent (LLD) toward lower concentrations of incompatible elements, shown by red lines fit to data for episodes 48 (e48LLD), 50–53 (e50–53LLD) and 55 (e55LLD).

## Chronological Evolution of Volcanic and Magmatic Conditions

The eruption began with lava of a historically preponderant Kīlauea composition extruded from a small fissure that is still exposed on the west side of Nāpau Crater (Wolfe and others, 1988). At 6.8 weight percent MgO, its composition is at the low end of an olivine-control trend. Garcia and others (1989) found no petrographic evidence for preruptive magma mixing in this initial 1983 lava, which is similar in character and composition to that which last erupted at the summit in September 1982. Those authors provide evidence that subsequent early fissure eruptions during episodes 1 to 3, extending 7.5 km from the west edge of Nāpau, were fed by mixing of this near-cotectic magma with cooler magma stored beneath the rift.

During the vigorous Pu‘u ‘Ō‘ō eruptive intervals (episodes 4 to 47) that followed the mixing events of episodes 1 to 3, cycles of low to high MgO are repeated within and between episodes (fig. 3B). Tephra deposited by waxing and waning fountains contains heterogeneous glass fragments that yield eruption temperatures from 1,161 to 1,173°C (fig. 3A). High-temperature glass data are correlated with high-MgO in bulk lava for some samples collected during episodes 5 to 10 and 30 to 31, but high-temperature glasses in low-MgO bulk lava are more common in these episodes and may reflect olivine loss after drainback and recirculation associated with eruptive pulses.

During episodes 4 to 29, erupted lava became gradually hotter, richer in MgO, and more depleted in incompatible elements (figs. 2–4). In the light of additional petrologic and geophysical evidence, Garcia and others (1988, 1992) interpreted this trend to be a result of progressive flushing of rift magma reservoirs intersected by the developing conduit between the summit and the Pu‘u ‘Ō‘ō vent. The final flushing of hybrid magma at Pu‘u ‘Ō‘ō had occurred by episodes 30 and 31, when the hottest and most MgO-rich magma was erupted (1,173°C matrix glass temperature and 9.6 weight percent bulk lava MgO).

From episodes 32 to 47 of the eruption, bulk lava and glass compositions portray cyclic fractionation over a limited range of olivine-saturated magma conditions (1,161–1,165°C). Through this interval, olivine phenocrysts formed at near-equilibrium conditions in host liquids, possibly within the conduit beneath Pu‘u ‘Ō‘ō during lengthy repose periods between these episodes (Garcia and others, 1992).

A failure of the conduit beneath Pu‘u ‘Ō‘ō resulted in downrift propagation of fissure vents and the establishment of long-term continuous eruption from the Kūpaianaha vent (episode 48). From July 1986 to February 1987, during the building of the Kūpaianaha shield, bulk-lava MgO steadily climbed (to about 8.6 weight percent from the lower values of about 7.6 weight percent for magma erupted during episodes 32 through 47) as hot, summit-derived magma moved through the newly developed extension of the shallow rift conduit. Determination of MgO glass temperatures remained erratic, owing to difficulties in obtaining well-quenched near-vent samples.

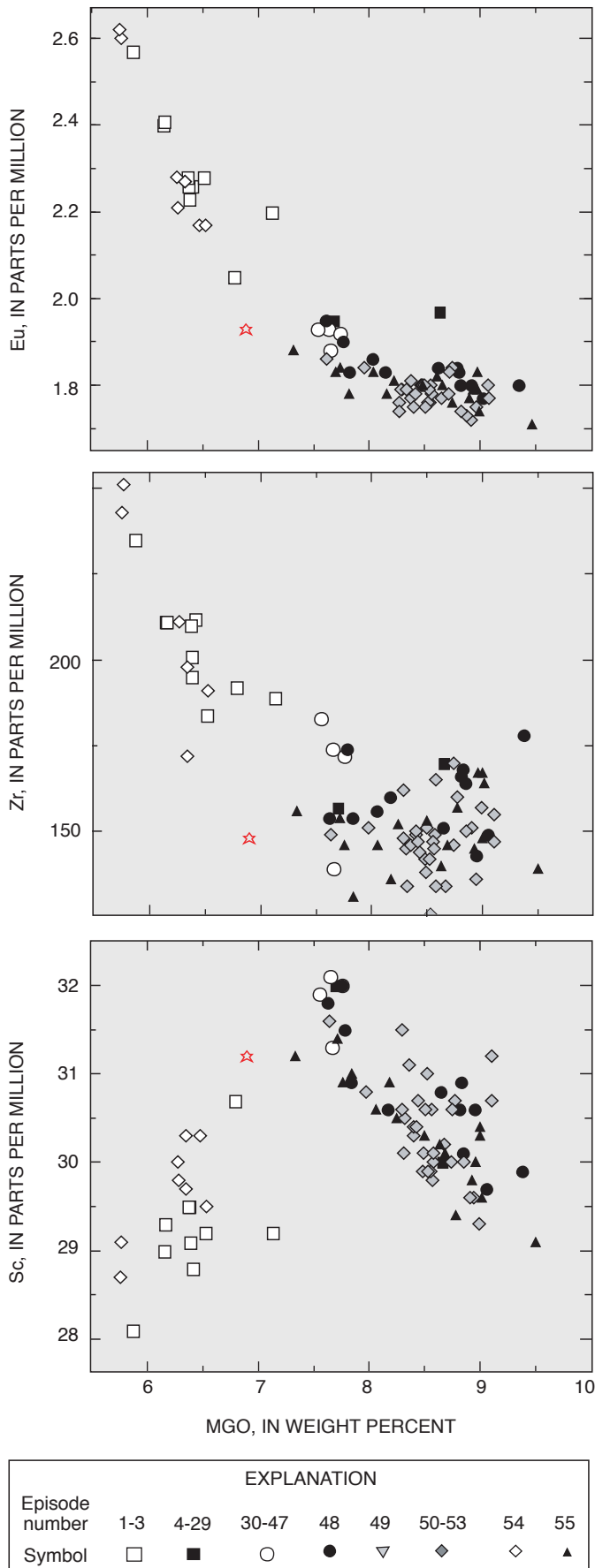
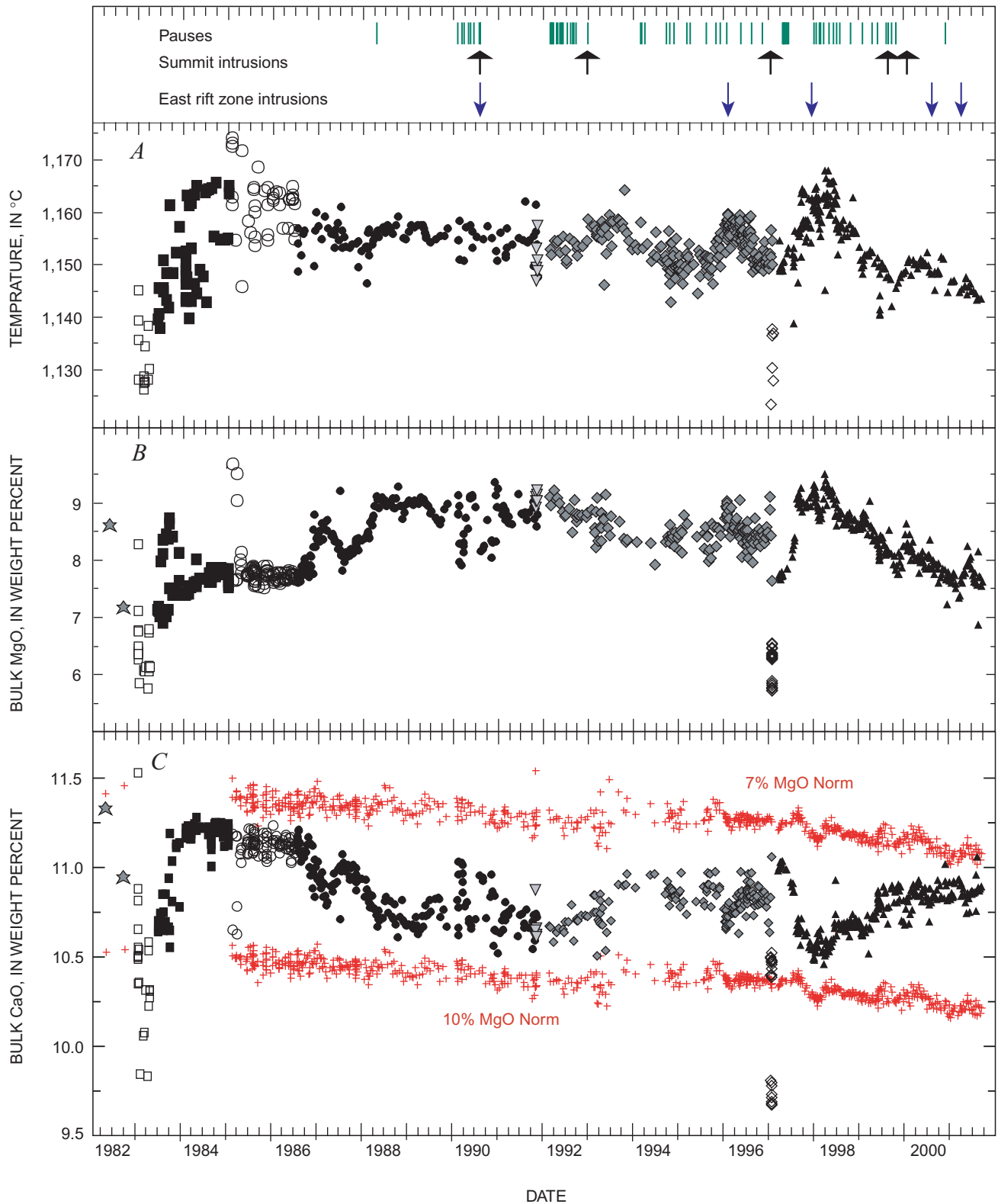


Figure 2. Continued.





**Figure 3.** Time-series plots of eruption temperature and lava composition from January 1983 to October 2001, plus 1982 summit compositions. Summit lava of 1982 is indicated with gray stars. The crosses plotted above and below data in *C* and *E* are CaO and TiO<sub>2</sub> values for olivine-phyric samples normalized to 7 weight percent and 10 weight percent MgO, by removal or addition of equilibrium olivine, respectively. Shown above *A* is a timeline of summit intrusions (upward arrows), rift zone intrusions (downward arrows), and eruptive pauses (hash marks). *A*, Eruption temperature, as determined by MgO glass thermometry and corrected for distance to vent for distal tube samples (see text). *B*, Bulk lava MgO variation. *C*, Bulk lava CaO variation. *D*, Bulk lava TiO<sub>2</sub> variation. *E*, Expanded scale for bulk lava TiO<sub>2</sub> variation in olivine-saturated lava, episodes 30–53 and 55.

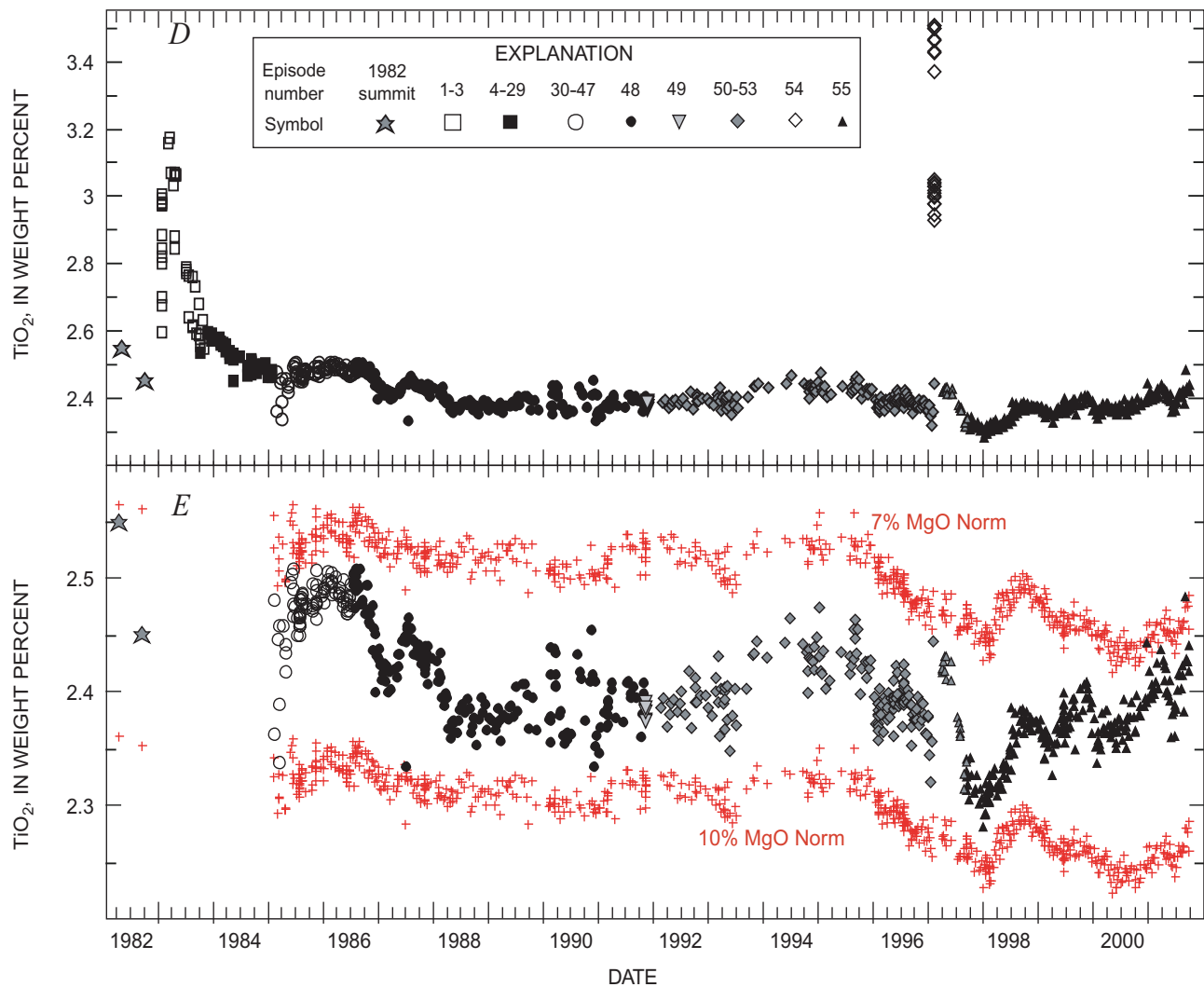
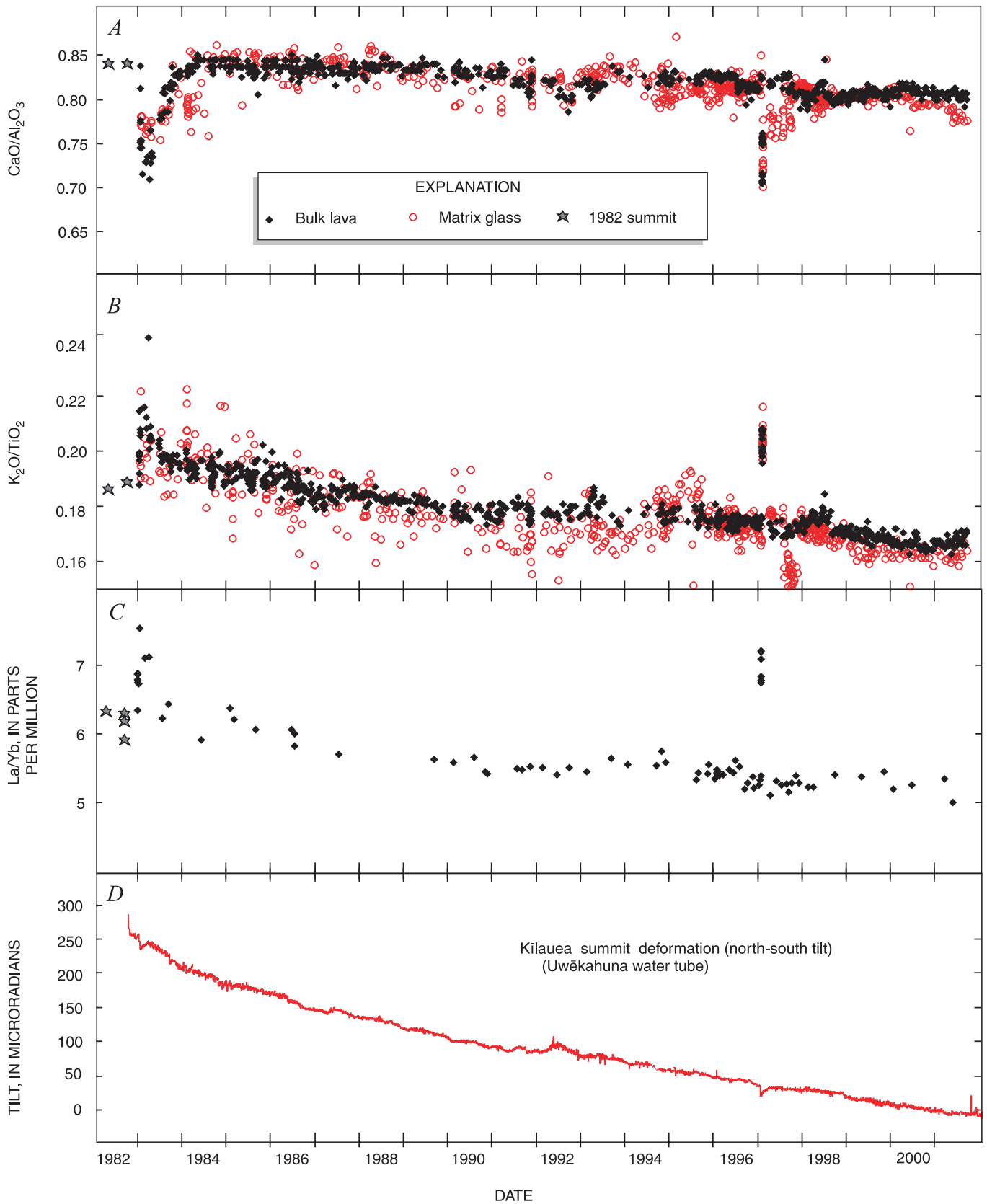


Figure 3. Continued.

After peaking in February 1987, bulk lava MgO and eruption temperature declined simultaneously until July 1987 in the first of numerous magmatic cycles that typify prolonged eruptive intervals. In this relatively steady-state situation, the conduit delivered hotter and cooler olivine-saturated magma as pulses and lulls in the eruption occurred in response to summit deformation and in accordance with a delicate pressure balance within the shallow magmatic plumbing system (Garcia and others, 1996; Thornber, 2001).

Cyclic variation of MgO and temperature persisted for 11½ years (episodes 48 through 53), undisrupted by the interlude of uprift vent migration back to Pu‘u ‘Ō‘ō from November 1991 to February 1992 (late episode 48, episodes 49 and 50; Mangan and others, 1995; Heliker and others, 1998). The uprift shift to Pu‘u ‘Ō‘ō coincided with three intrusions along the rift zone, after a period of 9 eruptive pauses during 1990 and 1991 (Heliker and Mattox, this volume) when the Kūpaianaha pond crusted over as magma flux waned (Kauahikaua and others, 1996) and bulk lava MgO and eruption temperature showed an overall decline amidst sporadic highs and lows (fig. 3).

In January 1997, the near-steady-state flow of olivine-saturated magma through a well-developed conduit from summit to rift zone was disrupted by shallow rift-zone extension and a brief eruption at Nāpau Crater (episode 54; Owen and others, 2000; Thornber and others, in press). Geophysical and petrologic evidence indicates preeruptive mixing of hotter, olivine-saturated melts with older and colder fractionated pockets of magma within the shallow rift during this event (Thornber and others, in press). Mixing resulted from passive intrusion associated with rift extension during episode 54, in contrast to the forceful dike intrusion of summit magma into rift magma during episodes 1 through 3. The first five months of episode 55 until July 1997 were characterized by a steady increase in temperature and bulk-lava MgO in samples erupted from several sporadically active Pu‘u ‘Ō‘ō flank vents. A gradual return to steady-state eruptive conditions occurred as the summit steadily reinflated, indicating that the shallow magmatic plumbing system was being repressurized. Major- and trace-element variation during early episode 55 is consistent with the gradual flushing of cooler, near-cotectic magma residing within the conduit (Thornber and others, in



**Figure 4.** Time-series plots of bulk lava composition (data in weight percent) from January 1983 to October 2001 showing selected incompatible-element ratios for major elements in bulk lava and matrix glasses, and Kilauea summit deflation during this period. Gray stars denote April and September 1982 summit lava; A,  $\text{CaO}/\text{Al}_2\text{O}_3$ ; B,  $\text{K}_2\text{O}/\text{TiO}_2$ ; C,  $\text{La}/\text{Yb}$  (data are from Pietruzka and Garcia, 1999a); D, Long-term Kilauea summit deflation, as represented by Uwēkahuna north-south water-tube tilt data.



press). Since mid-1997, episode 55 lava compositions have varied cyclically, like those of episodes 48 through 53, and are superimposed on an overall decline of bulk-lava MgO and eruption temperature (Thornber, 2001; fig. 3).

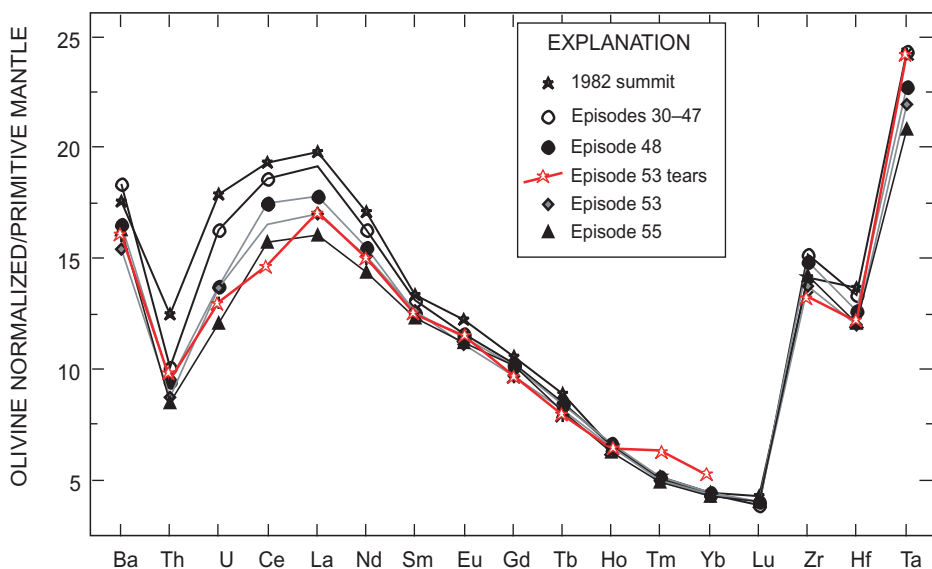
## Relation Between Geochemical Cycles and Open-System Shallow Magmatism

Throughout periods of nearly continuous eruption (episodes 48 to 53 and most of 55), olivine-liquid relations predicate near-equilibrium olivine crystallization from melts equivalent to the lava's bulk composition, without significant loss or accumulation of olivine during transit along the length of the rift conduit (Garcia and others 1996; Thornber, 2001). The cyclic variation of olivine-controlled compositions indicates repetition of a limited range of olivine-saturated magmatic conditions that may be typical of nearly continuous magma recharge.

As documented for the pre-Kūpaianaha/post-mixing stages of the eruption (episodes 30 to 47), the hottest and most MgO-rich magmas erupted during subsequent episodes of prolonged effusion are also correlated to temporary increases in eruption rate and vigor that occur in association with intrusion or displacement of summit magma. Such events include the dramatic surges in eruption flux on February 1, 1996 (episode 53), and on January 14, 1998 (episode 55) (see fig. 3). The highest eruption temperatures since episode 30, observed in April 1998, were associated with summit inflation and high eruptive flux. In this event, magma with about 9.5 weight percent MgO that was transported to the vent originated at about 1,205°C, in equilibrium with Fo<sub>84.5</sub> olivine. Cyclic variation accompanying overall decreasing trends in temperature and MgO content occurred during waning stages of episode 48, throughout the pause-riddled episodes 50 to 53 until late

1995, after the summit intrusion of February 1, 1996, and from April 1998 until October 2001. The low-temperature end of these olivine-controlled cycles occurred at the end of the latter sampling interval, when magma with about 7.5 weight percent MgO, saturated with Fo<sub>81.5</sub> olivine at about 1,165°C, was tapped by the eruption.

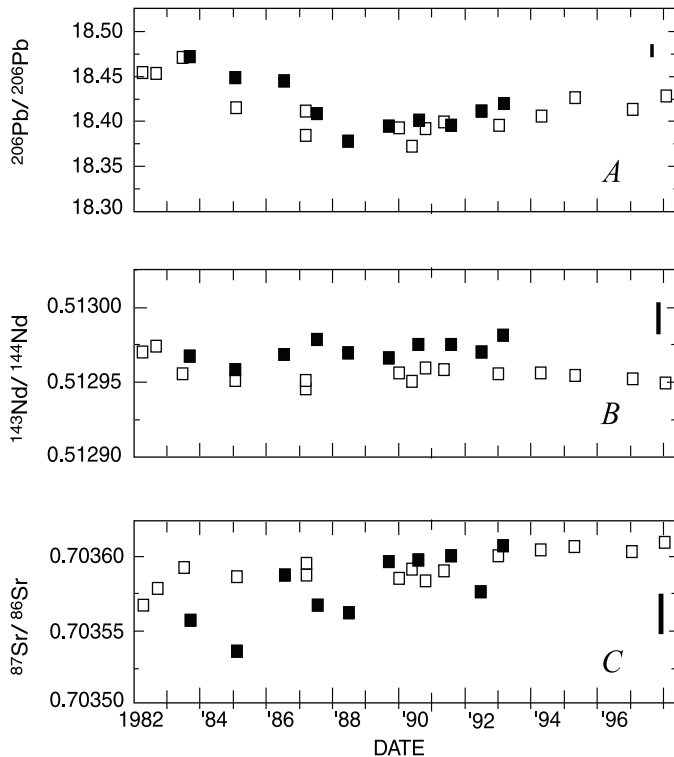
The MgO variability during prolonged steady-state eruption is within the range shown by olivine-controlled magma erupted before episode 48 (6.8 weight percent MgO at the onset of eruption and 9.8 weight percent MgO during episode 30). This overall range is consistent with the combined range of MgO in glass of summit tephra and of Kīlauea Iki lava (Mastin and others, 2001; Murata and Richter, 1966) and with bulk lava MgO for historic summit eruptions other than the 1959 Kīlauea Iki eruption (Wright, 1971). Such characteristic and recurring compositions suggest that these represent end-member magmatic conditions within the shallow magmatic plumbing system. The low end of MgO variation approaches a stable end-member condition maintained at the low-pressure multiphase cotectic for Kīlauea basalt (about 7 weight percent MgO at about 1,155°C; Thompson and Tilley, 1969; Helz and Thornber, 1987; Yang and others, 1996). As pointed out in numerous studies of olivine-basalt systematics (O'Hara, 1977; O'Hara and Matthews, 1981; Defant and Nielson, 1990; Rhodes and Hart, 1995), the lack of differentiation below the multiphase cotectic is attributed to "buffering" effects of open-system replenishment of a persistent magma reservoir. This dynamic magma-buffering process accounts for the preponderance of Kīlauea and Mauna Loa lava compositions at the low end of an olivine-controlled liquid line of descent (see Rhodes, 1995). The high-temperature end member of about 10 weight percent MgO is regulated by the amount of olivine that fractionates from the recharge magma when it is turbulently mixed with a portion of near-cotectic resident magma. The consistent limit of magmatic temperatures reflected by eruptive products richest in MgO is likely to be controlled by a constant composition of primitive melt entering the system, estimated at about 15 weight percent MgO (Clague



**Figure 5.** Trace-element spidergram comparing range of highly to moderately incompatible elements in bulk lava averaged for successive episode groups (symbols are same as in figures 1 and 2). Values (ppm) were all normalized to 7 weight percent MgO by olivine subtraction and plotted relative to primitive mantle values of Sun and McDonough (1989). Summit data for 1982 are from Pietruzka and Garcia (1999a; sample number 1982-s14). Red line portrays average trace-element composition of Pele's tears collected from mid-1995 to mid-1996 (analyzed by LAICPMS).

and others, 1995). Fractionation of more forsteritic olivine ( $\sim\text{Fo}_{85}$  to  $\sim\text{Fo}_{90}$ ), below the zone of replenishment and turbulent mixing tapped by the current Kīlauea eruption, feeds a layer of olivine cumulate within the edifice at depths greater than 4 to 5 km beneath the summit and south flank (Clague and Denlinger, 1994; Delaney and others, 1998; Denlinger and Okubo, 1995).

Concentrations of incompatible elements in steady-state eruption products inversely mimic the cyclical repetition of eruption temperature and bulk-lava MgO content between compositions normalized to 7 and 10 weight percent MgO end members (fig. 3C, E). These variations are consistent with olivine fractionation during cooling after intermittent recharge. However, the temporal variation of major and minor incompatible-element ratios (and olivine-normalized compositions) indicates that subtle but analytically significant short-term fluctuations in the relative concentrations of these components must occur before olivine crystallization over the magmatic temperature range of about 1,200 to about 1,160°C that is tapped by this eruption.



**Figure 6.** Time-series plots of Pb, Nd, and Sr isotope variation in Kīlauea lava samples erupted from 1982 to 1998. Filled squares are previously unpublished values determined by D. Unruh, U.S. Geological Survey (Denver) on samples submitted by the author (see Thornber and others, in press, for details on techniques and precision). Open squares are data compiled from Peitruszka and Garcia (1999a) and Garcia and others (1996, 2000). No interlaboratory corrections were made to the data. The error bars (thick vertical lines) shown at the right of each figure represent 2-sigma errors for U.S. Geological Survey data, as established by the analyst.

Cyclic variations of olivine-incompatible element ratios (such as Ti/Ca and K/Ti) have monthly and annual-to-biennial durations and generally increase and decrease in delayed response to cycles of increasing and decreasing magmatic temperatures (fig. 7), as reflected by bulk-lava MgO changes. Comparison with continuous GPS measurements of summit deformation (since mid-1996) shows trends of increasing and decreasing incompatible-element ratios associated with intervals of summit inflation and deflation (fig. 8).

Precise temporal correlations between this subtle petrogenetic signature and documented intrusive events and eruptive surges are clouded by the physical complexities of the dynamic open-system magmatic setting. The general tendency of these ratios to increase coincident with summit inflation, however, suggests that variably fractionated melts are incorporated during mixing between mantle-derived magma and pre-1983 near-cotectic magma residing within the edifice. The feasibility of this shallow mixing hypothesis is supported by linear trends in plots of incompatible-element ratios versus incompatible elements for successive sampling intervals from February 1996 to October 2001. These trends can be extended back to 1982 summit magma compositions and are consistent with periods of summit inflation and deflation (fig. 9).

The short-term cycles of increasing and decreasing olivine-incompatible element ratios are superimposed on the long-term decrease in olivine-saturated magma delivered to the vent. It is unlikely that such frequent and erratic changes can be attributed to the mantle source of Kīlauea basalt. An interpretation involving a prolonged succession of short-term shallow mixing events may account for the long-term evolving magmatic condition. This interpretation does not require a gradual change in mantle-melting conditions over the 20-year duration of this eruption.

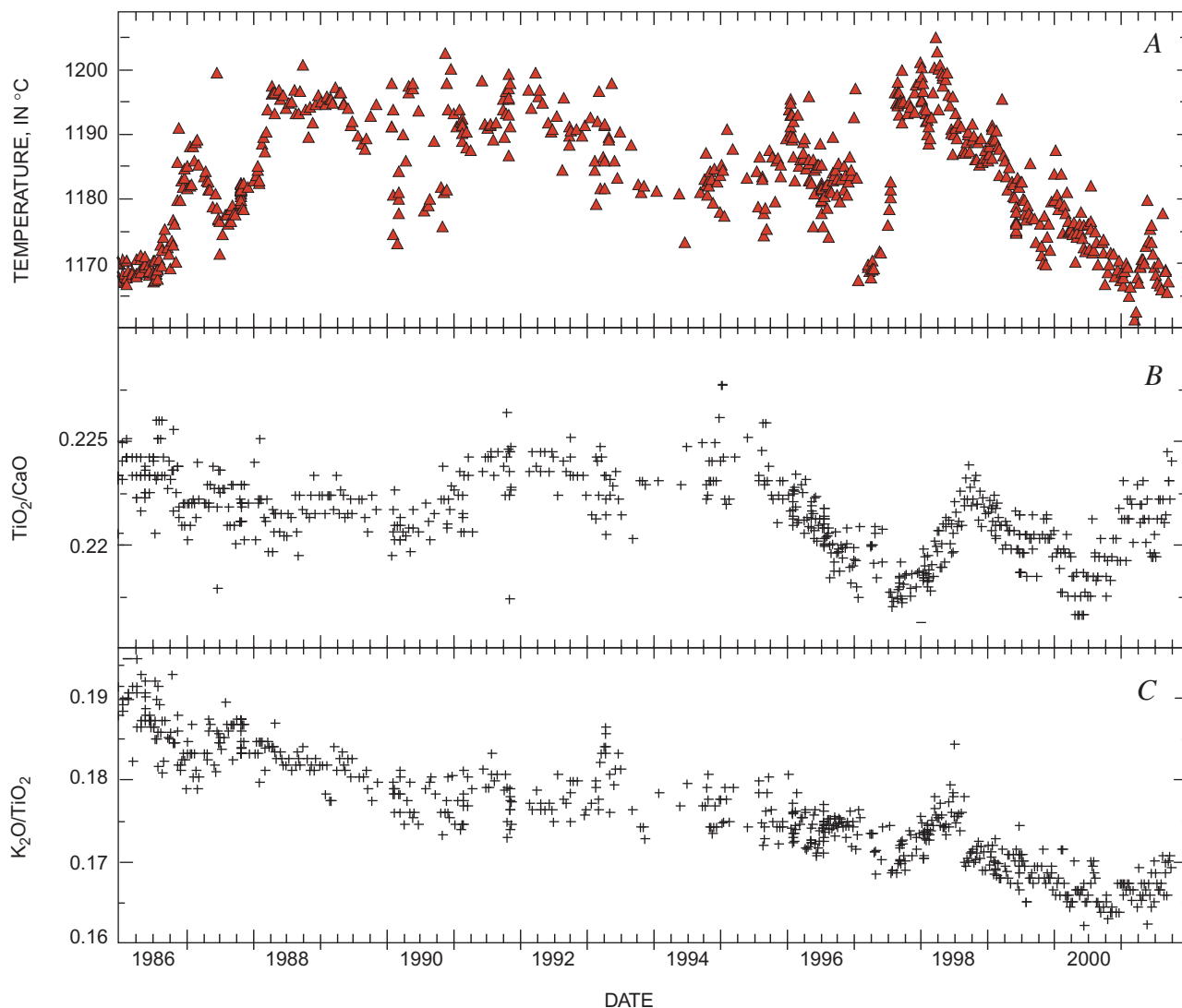
## Is Evolution of Eruption Geochemistry Effected from the Bottom Up or from the Top Down?

Trace-element geochemical trends in lava erupted over the past two decades have been interpreted to reflect a gradual change in source melting components or processes in the mantle (Garcia and others, 1992, 1996, and 2000). Garcia and others presented justified and feasible geochemical models for the source evolution of Pu‘u ‘Ō‘ō-Kūpaianaha basalt. The models range from progressive depletion amid greater degrees of adiabatic melting of a constant mantle source to mixing of primitive melts derived from multiple and heterogeneous sources within the zone of mantle melting. Such changes of source conditions cannot be ruled out as factors affecting the systematic long-term decrease in olivine-incompatible element ratios. This trend, however, is consistent with an equally plausible process involving the evolution of an almost continuously recharged shallow magmatic plumbing system.

Subtle geochemical differences in terms of dynamic processes that persist in continuously fed, shallow magma chambers must be understood before ascribing dynamic source characteristics to monogenetic basalt eruption (O'Hara, 1977). The correlations of inflation-deflation cycles with incompatible-element geochemistry lend credibility to the idea that such changes in geochemistry reflect an evolution of shallow magmatic conditions during prolonged rift-zone eruption. If the temporal decrease of incompatible-element ratios were to be effected from the top down rather than from the bottom up, then the geochemical signature of this eruption would approach that of steady-state flux from a consistent and uniform mantle source.

Pietruzska and Garcia (1999b) provide minimal estimates of a 30- to 40-year residence time for late 20th century summit magma. By their reasoning, the 1982 summit eruption is representative of magma that may still reside in a

summit reservoir, persisting at cotectic conditions (about 7 weight percent MgO). Geochemically, isotopically, and geophysically, the long-term trends of the Pu'u Ō'ō-Kūpaianaha eruption can be explained by efficient turbulent mixing of chemically uniform recharge melt with diminishing proportions of 1982 summit magma maintained at near-cotectic conditions. The 20-year decline in ratios of highly to moderately incompatible elements may signify either that a progressively greater proportion of recharge magma is being diverted directly to Pu'u Ō'ō, with minimal summit interaction, or that the mass ratio of those mixing end members has changed, owing to a shrinking summit chamber, or both. The coincidence of steady, long-term summit deflation since 1982 and the continuous trend of decreasing incompatible-element ratios and Pb isotopes in steady-state eruption products from those of 1982 summit magma (figs. 3, 4, 5 and 6)

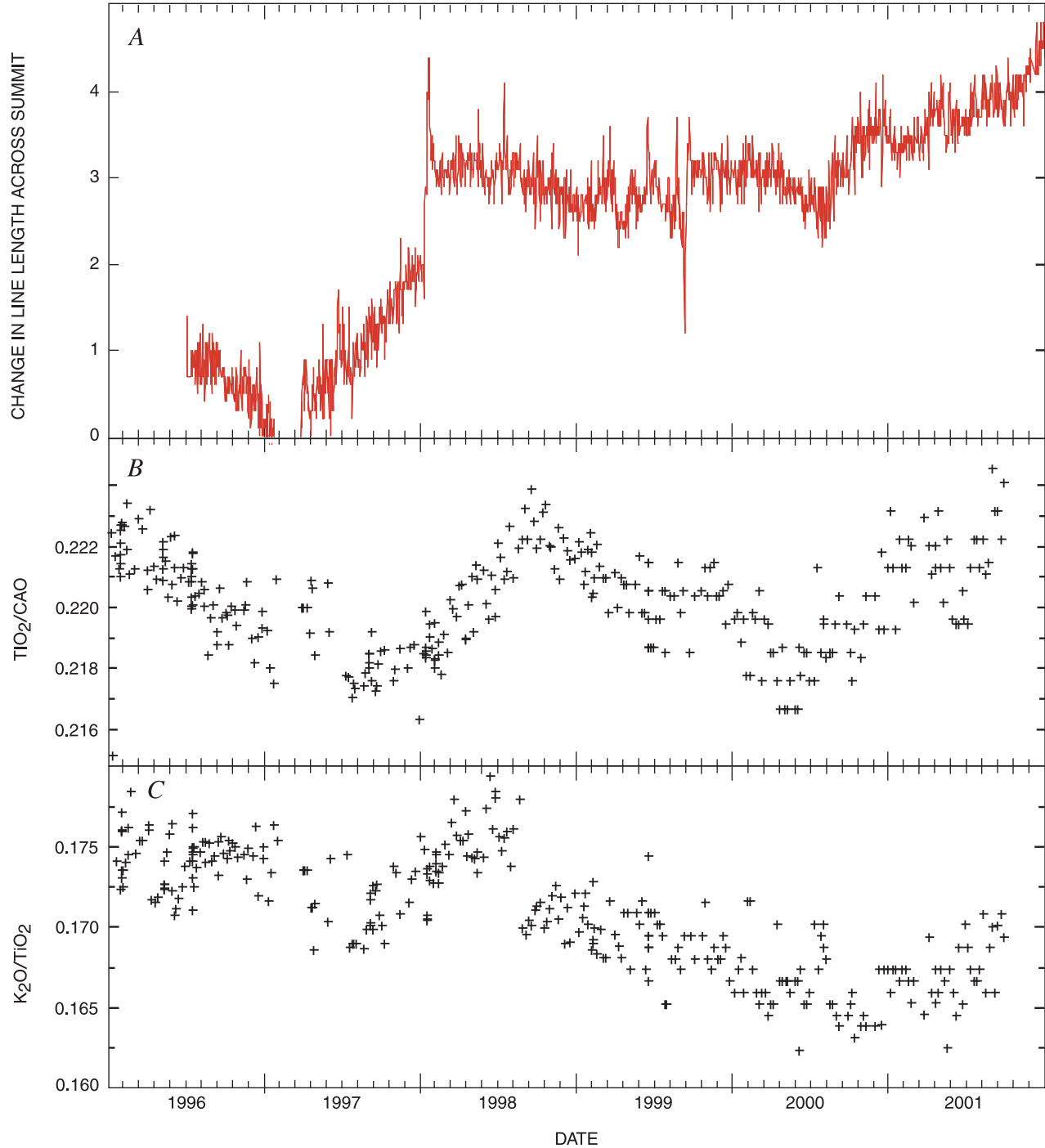


**Figure 7.** Time-series plots comparing inferred magmatic temperature and incompatible-element ratios of steady-state eruption products from January 1986 to October 2001. Original chemical data in weight percent. A, Magmatic temperature derived using bulk-lava MgO in MgO thermometry calculation of Helz and Thornber (1987), assuming melts have compositions equivalent to bulk lava (see Thornber, 2001). B,  $\text{TiO}_2/\text{CaO}$  (1-sigma error is 0.0004, based on reproducibility of this ratio in standard analyses over time). C,  $\text{K}_2\text{O}/\text{TiO}_2$  (1-sigma error of 0.001).

suggest the possibility of a long-term evolution of erupted magma composition inherently linked to summit reservoir shrinkage.

To test this relation, parameters for a single spherical chamber of about 2–3 km<sup>3</sup> volume extending to 4 km depth (Pietruska and Garcia, 1999b) were used for geodetic modeling of recent cross-summit continuous GPS data (UWEV-

AHUP line), combined with older leveling and electronic distance measurement (EDM) data across the summit, to yield a Mogi-modeled volume reduction of 2 percent per year since 1982 (M. Lisowski, written commun., June 2002). A similar volume reduction of about 2 percent per year is independently ascertained from the gradual change in La/Yb from September 1982 to October 2001. This result is achieved, using the



**Figure 8.** Time-series plots comparing summit deformation and incompatible-element ratios in lava produced during steady-state eruption from January 1996 to October 2001 (excluding episode 54). Original chemical data in weight percent. *A*, Continuous GPS measurement of line-length changes across summit. *B*,  $\text{TiO}_2/\text{CaO}$  (1-sigma error of 0.0004). *C*,  $\text{K}_2\text{O}/\text{TiO}_2$  (1-sigma error of 0.001).

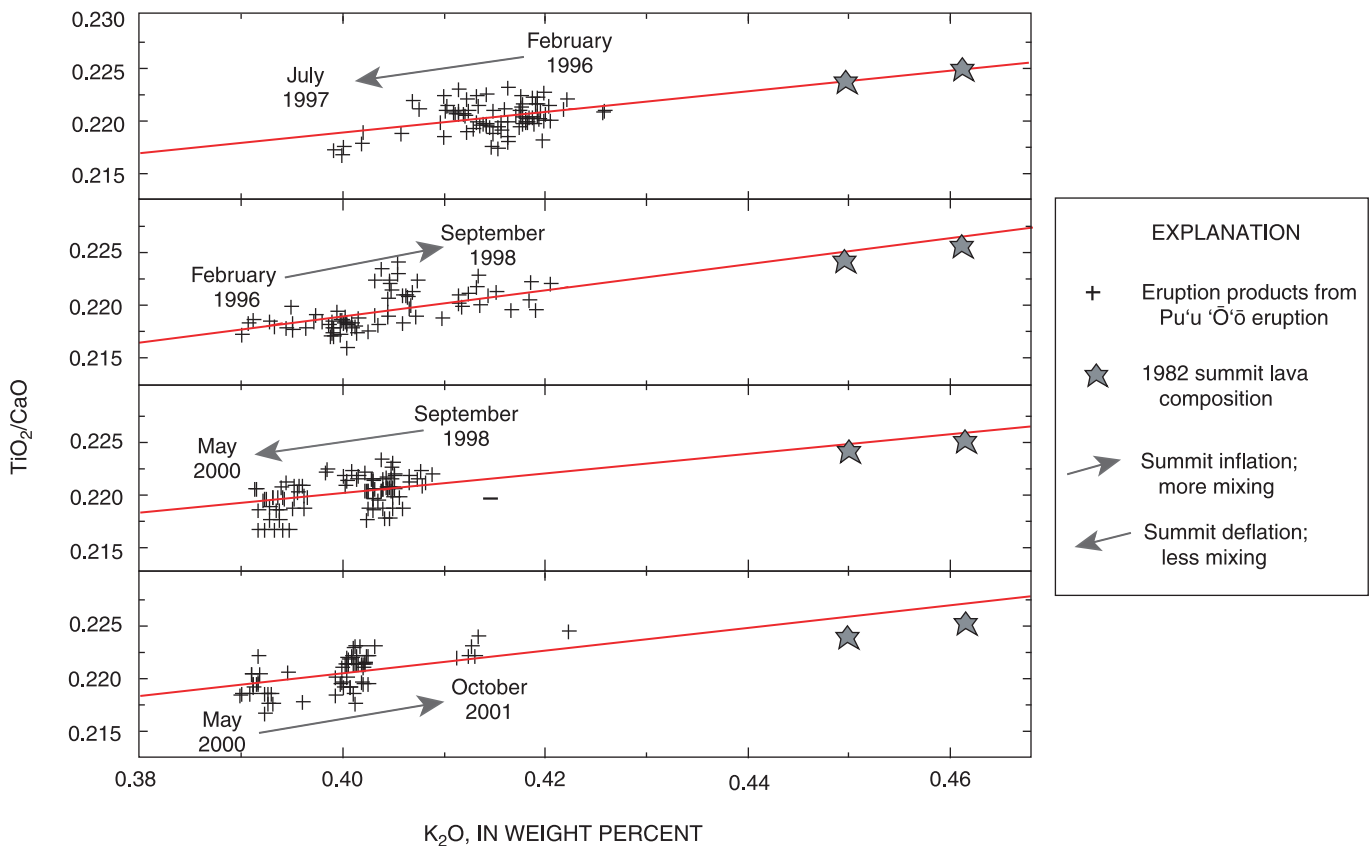
mixing equations presented in Pietruszka and Garcia (1999b), assuming that the 2001 end product is representative of chemically uniform and constant mantle flux of 0.1 km<sup>3</sup> per year. The mixing of 1982 and episode 55 end members is also reflected in the progressive change in incompatible trace-element patterns with time (fig. 5). Both deformation and petrologic models suggest that the eruption is an outlet for repeated flushing of magma that was resident within the edifice at the onset of near-continuous activity.

Further geochemical evidence for progressive batch mixing between 1982 summit magma and October 2001, episode 55 magma is suggested by linear relations between incompatible-element ratios and incompatible elements (fig. 10A). The array of K<sub>2</sub>O/TiO<sub>2</sub> versus K<sub>2</sub>O for steady-state eruptive products from late episode 48 through 53 and episode 55 straddles a mixing line between these end members, using binary mixing equations of Langmuir and others (1978). Likewise, a comparison of La/Yb versus Ce data from September 1982 summit magmas (Pietruszka and Garcia, 1999a) and the compositional range of steady-state eruption products defines a similar binary mixing relation between these temporally distinguished end members (fig. 10B). These relations verify the plausibility of a shallow mixing scenario, though they do not preclude a progressive change in source characteristics.

In this model of shallow, open-system magmatism, a zone of magmatic buffering between resident and recharge magma approaches a condition in which all of the resident magma is derived from a uniform long-term source. Intrusive recharge events enhance the efficiency of mixing and removal of a limited supply of pre-1983 cotectic magma, producing short-term cyclic increases of incompatible elements that are contrary to their overall long-term decrease. The net effect of prolonged magma supply and eruption is increasing efficiency of the plumbing system that transports mantle-derived melt into the shallow summit region and out through the east rift zone.

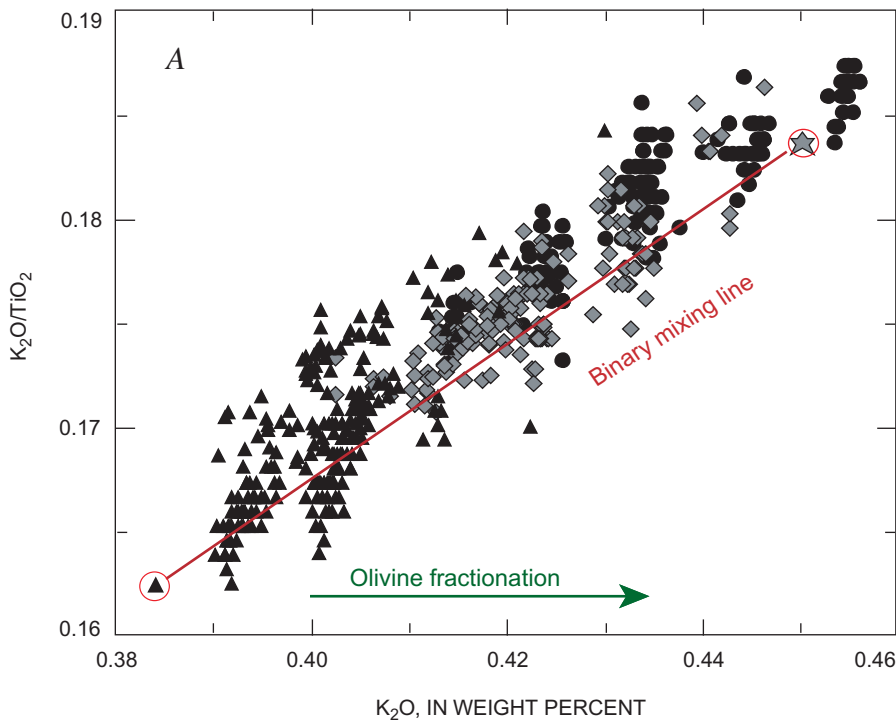
## Summary

Correlations of geochemical and geophysical data indicate that three magma sources have contributed to the Pu'u 'Ō'ō-Kūpaianaha eruption: (1) magma from a uniform mantle source, (2) pre-1983 summit magma, and (3) pre-1983 fractionated rift magma. Two processes are responsible for the array of non-olivine-controlled geochemical traits observed: turbulent mixing of old and new source magmas at the base of

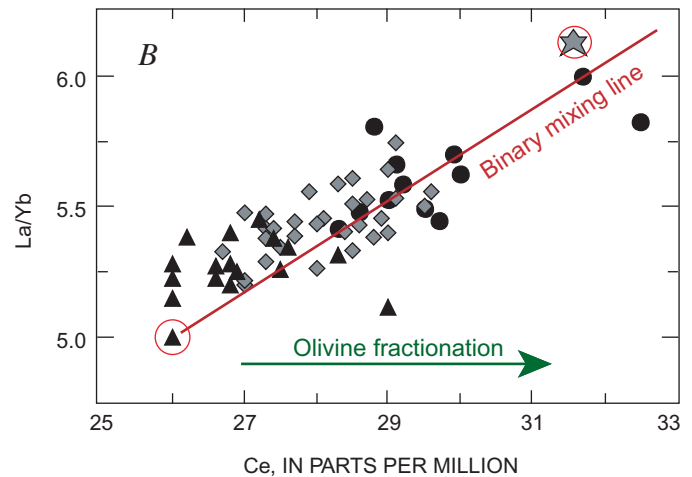


**Figure 9.** Plots comparing incompatible-element ratio (TiO<sub>2</sub>/CaO) and incompatible-element (K<sub>2</sub>O) content of steady-state eruption products from 1996 to 2001. Original chemical data in weight percent. Intervals shown correspond to cycles depicted in figure 8B. Red lines in each plot correspond to linear fit to eruption data, which project through or near 1982 summit composition and are consistent with binary mixing lines between averaged 1982 summit magma and episode 55 magma.





**Figure 10.** Variations of incompatible-element ratios, independent of olivine crystallization, in lava of episodes 48, 50–53, and 55 for (A)  $K_2O/TiO_2$  versus  $K_2O$  and (B)  $La/Yb$  versus  $Ce$ . Symbols are same as in figures 1 and 2 and indicate progressive incompatible element ratio depletion in successive steady-state eruptive intervals. Red lines in each figure are calculated binary mixing lines between averaged 1982 summit magma and October 2001, episode 55 magma (see text). Trace-element data for 1982 summit magma are the averaged values of three September 1982 ICPMS analyses from Pietruszka and Garcia (1999a).



the summit reservoir, and mixing of summit-derived olivine-controlled magma with rift-fractionated magma.

Primitive magma, entering through the base of the summit region, is mixed with a reservoir of near-cotectic magma at 1- to 4-km depth. Such mixtures produce an intermediate range of olivine-saturated magma compositions that reflect the buffering capacity of the mixture before it is routed through the east rift zone to the vent. Near-equilibrium crystallization from the newly mixed olivine-saturated melt ensues with cooling during transport down the rift. The hottest magma tends to initiate compositional cycles of irregular duration, as vigorous eruption pulses occur in response to intrusive events at the summit. Subsequent cyclic change toward lower, near-cotectic magmatic temperatures is associated with periods of overall summit deflation, relatively low-level effusion, and frequent eruptive pauses. These short- and intermediate-term geochemical and eruptive cycles record the ebb and flow within a complex, delicately balanced, shallow plumbing system that is open to nearly continuous magmatic recharge.

Significant proportions of rift-stored magma were incorporated by more mafic magma immediately prior to geochemically aberrant and volumetrically insignificant eruptive intervals (episodes 1 to 3 and 54). As long as isolated pods of cooling magma exist near the active rift conduit, they may be flushed from the edifice by a near-continuous flux of magma derived from the summit region.

Geochemical variations observed throughout periods of prolonged rift-zone effusion constrain dynamic processes of recharge, assimilation, displacement, and eruption associated with a complex and continuously evolving shallow magmatic plumbing system. The consistent limits to repeated compositional and temperature variation of steady-state rift-eruption products are within the slightly larger range of historical

summit lava. These limits of cyclic  $MgO$  variation define a persistent temperature range of olivine-saturated, end-member magmatic conditions regulated by recharge of the shallow magmatic plumbing system that feeds the prolonged eruption.

Cyclic variations in the concentrations of olivine-incompatible elements consistent with olivine-fractionation trends are superimposed upon cycles in which the relative concentrations of these elements increase and decrease, independent of subsequent crystallization of olivine. Variations in this compositional signature of erupted lava are interpreted to result from episodic assimilation of pre-1983 magma, maintained within the shallow edifice at near-cotectic conditions by long-term magmatic recharge. Repeated short-term assimilation cycles have resulted in the gradual flushing of a limited supply of older resident magma, as is reflected in the steady, long-term decrease in incompatible-element ratios and  $Pb$  isotopic ratios from values of magma last erupted at the summit in 1982.

This model of shallow magmatic processes accounts for the long-term evolution of erupted magma compositions and is consistent with 20-year trends in deformation of the shallow edifice. Amid nearly continuous magma influx, overall summit deflation requires a gradually diminishing volume of summit reservoir magma. Long-term summit deflation is accompanied by continual outward flank movement, which has accommodated an increasingly efficient magma conduit from the summit to the east rift zone. These overall trends in volcanic and magmatic behavior support an interpretation of prolonged effusive eruption approaching a steady-state tectonomagmatic condition in which magma derived from a uniform mantle source, having purged older resident magma, may now completely occupy the shallow magmatic plumbing system.

## Acknowledgments

This work owes much to the vision of Ken Hon, who, in 1992, originated the HVO eruption database as an ongoing depository of geochemical analyses. In addition to myself and Ken Hon, other HVO staff geologists who collected lava samples used in this study include Christina Heliker, Ed Wolfe, George Ulrich, Maggie Mangan, Jim Kauahikaua, Dave Sherrod, Tari Mattox, Frank Trusdell, and Rick Hoblitt. I also acknowledge the collaborative contribution and precise analytical work of James Budahn (INAA), Ian Ridley (LAICPMS), and Dan Unruh (isotopic data). Thomas Wright and Wendell Duffield provided insightful and helpful reviews. Editorial revisions by Christina Heliker, Jane Takahashi, Jenda Johnson, and Don Swanson are greatly appreciated.

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