Long-Term Trends in Microgravity at Kīlauea's Summit During the Puʻu ʻŌʻō-Kūpaianaha Eruption

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Abstract

Microgravity measurements at the summit of Kīlauea Volcano over the course of the Puʻu ʻŌʻō-Kūpaianaha eruption show distinctly different trends during different periods of the eruption. Rates of mass accumulation and withdrawal during these periods, computed from excess gravity changes after correction for measured elevation changes, reveal that the rates of mass change beneath the summit were only a few percent of the total volume of magma going through the volcano plumbing system and erupting at Puʻu ʻŌʻō. Furthermore, the rate of net mass change in the summit reservoir was not constant; indeed, the data suggest that magma was accumulating beneath the summit from 1983 to mid-1985 and from 1991 to mid-1993. The changes in excess gravity correspond to both changes in the stress regime at the summit and changes in eruptive style. Geodetic data show that the summit was extending during periods of magma accumulation and contracting during most of the period of magma withdrawal. The periods of net loss from the summit reservoir were characterized by efficient magma transport to the eruption site. The current precise gravity monitoring of a few benchmarks can provide information about subsurface accumulation or withdrawal of mass, but monitoring can be improved by either continuous measurement at a few benchmarks or frequent measurement over a network of benchmarks.

Introduction

Precise gravity monitoring of volcanoes has come of age in the last decade or so, judging by its inclusion in recent books on volcano monitoring (Murray and others, 2000). With a spatially dense network, gravity and elevation measurements can be used to determine the amount of subsurface mass that has been added or withdrawn beneath or within a volcano. Even with a sparse network, gravity and elevation data can provide information about the density of the material added or withdrawn, if the signal is large enough and if the elevation changes are associated only with the same source as the mass change. The density can indicate the state of compression of the source material (Johnson and others, 2000).

Two early applications of the method were on Kīlauea (Dzurisin and others, 1980; Jachens and Eaton, 1980), where three distinctly different gravity-elevation relationships were observed in 1975–77, during a time of a major earthquake, rift zone intrusions, and a rift zone eruption. When the current eruption started, gravity monitoring was an obvious technique to pursue. Johnson (1992) found that mass changes in the magma reservoir could be elucidated with gravity measurements during the several-days-long inflation-deflation events associated with fountaining episodes at the beginning of the Puʻu ʻŌʻō eruption. During these episodes, the large volumes of magma that were moving from the summit to the east rift in a short amount of time resulted in relatively large gravity and deformation signals. From 1984 through 1985, however, Johnson (1987) found that the ratio of gravity change to elevation change at the summit was near the free-air value; apparently no mass change was associated with the subsidence over that time. He suggested, rather, that the subsidence was due to long-term extension across the summit.

On the basis of geodetic data, Delaney and others (1998) modeled deformation rates during the current eruption using a combination of sources that fit the subsidence and extension across the summit. They found that approximately 60 percent of the subsidence from 1983 to 1991 could be attributed to deflation of a point source beneath the summit. Cervelli and Miklius (this volume) reached a similar conclusion for the 1996–2002 time period. These conclusions are based on average deformation rates over long time periods during the eruption. Changes in the deformation rates at Kīlauea's summit over the past 20 years—subtle in contrast to the large fluctuations in deformation rates in historical time (see, for example, Delaney and others, 1998)—can be correlated in time with changes in both the eruption and gravity rates. Before the advent of continuously recording geodetic networks, temporal resolution was insufficient to fully model small changes in the rate of magma withdrawal or accumulation in the summit reservoir. The gravity rate changes are subtle, as well, with average gravity-change/elevation-change ratios over the course of the eruption near the free-air gradient. The small signal-to-noise ratio, together with multiple sources of elevation change, complicate the interpretation of the gravity data.

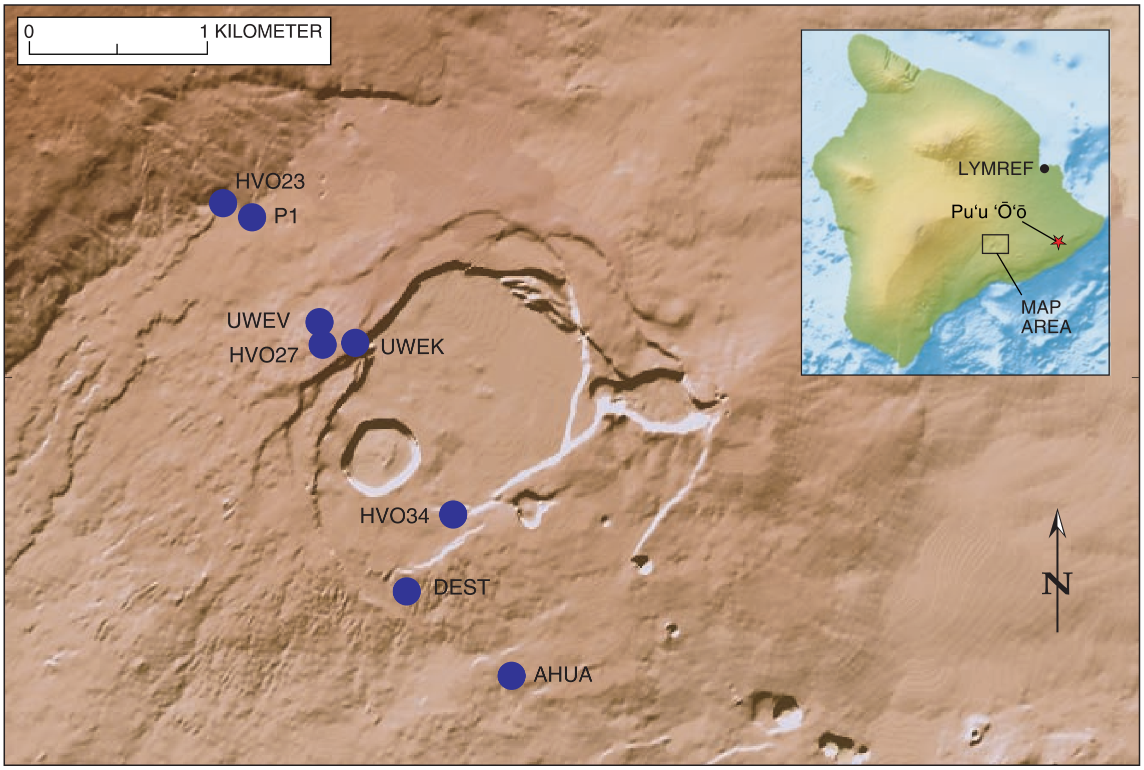


Figure 1. Shaded relief map of Kīlauea summit region showing location of gravity and elevation monitoring sites (blue dots). Inset shows location of station LYMREF and box indicating area of larger map. The Hawaiian Volcano Observatory (HVO) is located between UWEK and HVO27.

In this chapter, we use rates of gravity and elevation change, combined with the good resolution of the magma-source location provided by the long-term geodetic data, to elucidate the subtle differences in mass withdrawal and accumulation in the summit reservoir during the past 20 years of the current eruption.

Data Reduction Methods

Each precise gravity measurement consists of multiple readings with two LaCoste & Romberg gravity meters, G615 and G721, employed simultaneously. Measurements were usually continued until the standard errors were reduced below 10 µGals. The data were corrected for the effects of meter drift and tides.

Over the course of the current eruption, frequent microgravity measurements were made at two benchmarks in the summit area of Kīlauea (fig. 1). Those locations are benchmarks HVO27, on the caldera rim near the Hawaiian Volcano Observatory (HVO), and HVO34, less than 1 km from the persistent center of vertical deformation in the southern part of the Kīlauea caldera (Delaney and others, 1998; Cervelli and Miklius, this volume). The gravity measurements at these benchmarks were made relative to benchmarks LYMREF, 41 km distant in Hilo and, more frequently, P1, 2 km northwest of HVO27 (fig. 1).

Elevation changes were measured by precise leveling, usually yearly, although more frequent measurements were made early in the eruption. Expected random error of leveling surveys prior to 1988 propagates as 7 mm/km$^{1/2}$, and after 1988, as 2 mm/km$^{1/2}$ (Delaney and others, 1994). Vertical displacements in the Kīlauea summit network are measured relative to a local datum, HVO23 (fig. 1). The gravity reference site P1, only 200 m from HVO23, is also part of the leveling network, as are HVO27 and HVO34. Thus, the vertical motion of the summit gravity sites, relative to P1, is well constrained. However, only three leveling surveys originating in Hilo, far from active deformation, have been conducted since the start of the Pu‘u ‘Ō‘ō eruption; these were in 1986, 1988, and 1989.

Additional vertical information is available from GPS measurements, but reasonable resolution of the vertical signal has only been possible since about 1993. All GPS data were collected on dual-frequency receivers and processed with Gipsy/Oasis II software (Lichten and Border, 1987). The data are filtered to minimize the effects of reference frame errors (Cervelli and others, 2002).

Long-Term Data Trends

Precise gravity monitoring of a volcanically active region generally requires interpretation of gravity and elevation changes measured over the same time period at several sites.

Table 1. Computed rates of gravity and elevation change at benchmark HVO34 relative to P1.

[g is the observed gravity rate of change; Δh is the observed elevation rate of change; Δg* is the gravity rate of change corrected for the observed elevation rate of change; and s.e. is the standard error. Dashes indicate insufficient data for estimate.]

Period	Δg, mGals/yr	s.e.	Δh, m/yr	s.e.	Δg*, mGals/yr	s.e.
1983–1991	0.036	0.0004	-0.0976	0.00134	+0.0042	0.0039
1983–Apr 1985	.053	.00082	-.0976	.00134	+.021	.0040
Apr 1985–1991	.030	.00085	-.0976	.00134	-.0022	.0040
1991–1993	.0097	--	-.0142	--	+.0050	.0011
1993–2002	.019	.00067	-.060	.00054	-.0008	.0027

Table 2. Computed rates of gravity and elevation change at benchmark HVO27 relative to P1.

Period	Δg, mGals/yr	s.e.	Δh, m/yr	s.e.	Δg*, mGals/yr	s.e.
1983–1991	+0.00884	0.00075	-0.0187	0.00072	+0.0027	0.0034
1983–Apr 1985	+.0175	.00242	-.0187	.00072	+.0011	.0040
Apr 1985–1991	+.0159	.00314	-.0187	.00072	+.0097	.0045
1991–1993	.0	--	+.0163	--	+.0054	--
1993–2002	-.00383	.00186	-.0074	.00036	-.0063	.0032

Table 3. Computed rates of gravity and elevation change at benchmark HVO34 relative to LYMREF.

Period	Δg, mGals/yr	s.e.	Δh, m/yr	s.e.	Δg*, mGals/yr	s.e.
1988–1991	+0.0547	--	--		--	0.0034
1991–1993	-.00385	--	--		--	--
1993–2002	+.0229	--	[1]-0.0718		-0.00085	--

[1]Data from GPS station DEST.

Table 4. Computed rates of gravity and elevation change at benchmark HVO27 relative to LYMREF.

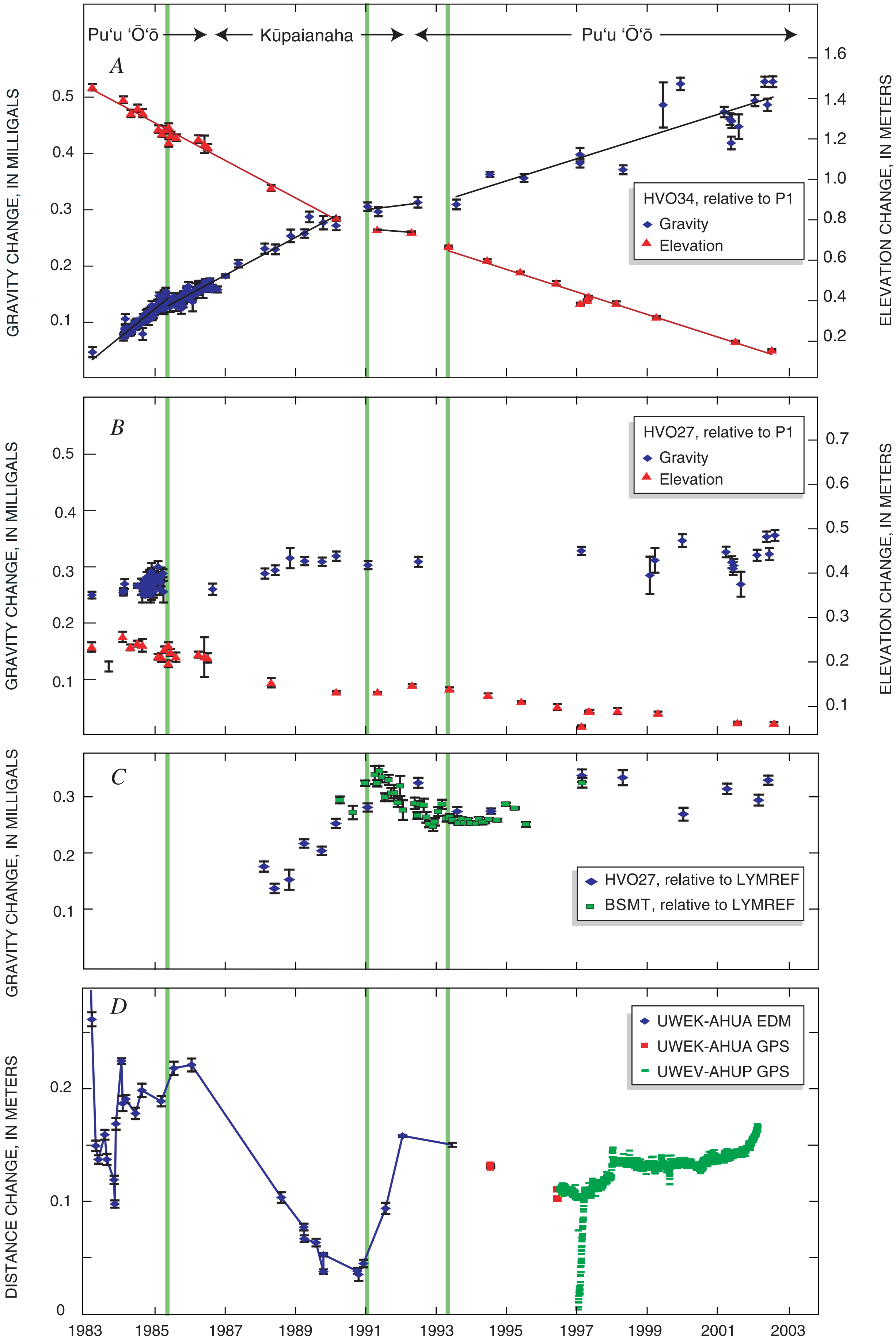
Period	Δg, mGals/yr	s.e.	Δh, m/yr	s.e.	Δg*, mGals/yr	s.e.
1988–1991	+0.0473	--	--	--	--	--
1991–1993	[1] -.0309	0.00184	--	--	--	--
1993–2002	+.00154	--	[2] -0.0144	--	-0.0032	--

[1] Data from BSMT instead of HVO27
[2] Data from continuous GPS station UWEV

The approach in this paper is a little different, using long-term trends in both the gravity and elevation data at two sites to determine simultaneous rates of gravity and elevation change for several different periods during the current eruption.

The rates of gravity and elevation change during specific periods were computed to minimize χ^2 in fitting the data to a line. The measured rate of elevation change was then multiplied by the measured free-air gradient and subtracted from the measured gravity change to get the residual gravity change. Formulating the rate as a χ^2 problem allowed the calculation of a standard error for each rate. These errors allowed the calculation of the standard error (s.e.) of the residual gravity rate by error propagation. The results are shown in tables 1–4.

The ratio of gravity to elevation change at the Earth's surface, called the free-air gradient, is –0.33025 ($\pm$0.0055) mGals/m at Kīlauea's summit. This value is the result of 5 measurements over the last 10 years on the 4 floors (total elevation range of 9.0 m) within the Hawaiian Volcano Observatory building on the rim of Kīlauea's caldera and agrees well with the value of –0.3273 that Johnson (1992) measured for elevation changes of about 1 m within the caldera. The free-air gradient measured at Kīlauea is nearly 10 percent more negative than the theoretical value of –0.3086 mGals/m.



Pu‘u ‘Ō‘ō
Kūpaianaha
Pu‘u ‘Ō‘ō
A
GRAVITY CHANGE, IN MILLIGALS
ELEVATION CHANGE, IN METERS
HVO34, relative to P1
Gravity
Elevation
B
HVO27, relative to P1
Gravity
Elevation
C
HVO27, relative to LYMREF
BSMT, relative to LYMREF
D
DISTANCE CHANGE, IN METERS
UWEK-AHUA EDM
UWEK-AHUA GPS
UWEV-AHUP GPS
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003

The general trends for the entire 20-year span examined here are characterized by elevation decreases and corresponding gravity increases (fig. 2). The average ratio of gravity change to elevation change is very close to the free-air gradient and indicates very small mass changes beneath the summit. Several changes in rate of gravity increase correspond with changes in rate of elevation decrease and with the rate of extension/contraction across Kīlauea's summit area. Furthermore, these changes can be correlated with distinct periods of the Pu'u 'Ō'ō eruption. The time series of gravity at HVO34 relative to P1 (fig. 2*A*) best illustrates most of these changes, as this pair of stations has the densest temporal sampling of both gravity and relative elevation measurements. In addition, HVO34 is the station closest to the magma reservoir and thus records the largest rates of change, increasing the signal-to-noise ratio.

The microgravity data can be separated into four periods for which there are distinct differences in linear trend: 1983–April 1985, April 1985–January 1991, January 1991–April 1993, and April 1993–September 2002 (time of this writing).

From 1983 to mid-1985, gravity at HVO34, relative to P1, was increasing 0.05 mGals/yr, and the elevation was decreasing about 10 cm/yr (fig. 2*A*). Following an initial contraction in response to the start of the eruption, the northwest-southeast summit-crossing baseline (UWEK-AHUA, fig.1) extended about 4 cm/yr (fig. 2*D*).

As the Pu'u 'Ō'ō fountaining episodes became more regular in mid-1985, progressing to continuous effusion in mid-1986 at Kūpaianaha, the HVO34-P1 gravity trend slowed to 0.03 mGals/yr, while the elevation of HVO34 relative to P1 continued to decrease about 10 cm/yr. The summit-crossing baseline changed from extension to contraction around this time, and it contracted at a rate of about 4.5 cm/yr until 1991.

In early 1991, the lava output from Kūpaianaha began to decline (Kauahikaua and others, 1996), and gravity and elevation measurements started to record a period of very little change relative to P1. An additional gravity time series for BSMT (HVO basement), relative to the distant station LYMREF, pinpoints the inflection very clearly (fig. 2*C*). This dense, but brief, gravity time series was obtained between 1990 and 1994 in support of a cryogenic gravimetry experiment. Gravity differences between BSMT and LYMREF were measured several times a year during this experiment and are shown in figure 2*C*, along with data from nearby HVO27. These data clearly show a gravity decrease that started in early 1991 and flattened out during 1993. The rate of elevation change at the summit relative to P1 was greatly reduced during this period, although few measurements exist (fig. 2*B*). No elevation data relative to Hilo are available for this period. Stress across the summit changed from contraction to extension in early 1991 (fig. 2*D*).

Gravity measurements were sparse from 1993 to 2002. On average, gravity increased 0.02 mGals/yr and the elevation of HVO34 relative to P1 decreased at a rate of 6.0 cm/yr.

Interpretation

Quantitative interpretation of microgravity data requires precise elevation measurements at the same locations because of the dominant effect that elevation change has on gravity. Without subsurface mass changes, gravity at the Earth's surface will vary with elevation changes brought about by earth movements in a predictable fashion, defined by the free-air gradient (*FAG*). Subsurface mass changes will be evident by non-zero residual gravity changes, Δg^*,

$$g\Delta^* = \Delta g - FAG \times \Delta h\,,$$

where Δg is the observed gravity change and Δh is the observed elevation change. If the subsurface mass change, ΔM_{magma}, can be approximated as a point source at horizontal distance X and depth Z from the measurement location, the resulting residual gravity can be computed

$$g\Delta^* = \Delta M_{magma}\, G \frac{Z}{(Z^2 + X^2)^{3/2}}$$

(Dzurisin and others, 1980), where G is the gravitational constant. One can solve for the mass change (or volume change assuming the density) responsible for the residual gravity response, knowing the source location. The source location cannot be determined uniquely from this sparse set of gravity data alone.

Magma accumulation and withdrawal rates for the summit chamber of Kīlauea have been estimated using these equations and the source location determined by Cervelli and Miklius (this volume). Using the average source-volume change during the eruption determined from geodetic modeling (about 0.002 km^3/yr; Delaney and others, 1993; Cervelli and Miklius, this volume) yields unrealistic magma densities. Therefore, rates of mass change were converted to rates of volume change of uncompressed magma, assuming a density of 2,600 kg/m^3 (Fujii and Kushiro, 1977) and tabulated in table 5. The horizontal parameters of this source location, determined by others (for example, Delaney and others, 1993; Owen and others, 2000), are almost identical to those used here, but depth estimates vary by about 0.5 km. An increase in source depth of 0.5 km corresponds to a 20 percent increase in estimated mass at HVO34, within the error of the estimates, and no significant increase at HVO27.

This simple model, applied to the P1-referenced data, suggests that magma accumulation occurred in the first and

Figure 2. Time series of gravity and deformation data. Green vertical lines denote time periods discussed in text. Error bars, 1 sigma. *A*, Gravity and elevation data for HVO34 relative to P1, *B,* Gravity and elevation data for HVO27 relative to P1, *C,* Gravity data for HVO27 and BSMT relative to LYMREF, and *D*, Line-length changes across summit between UWEK and AHUA. Blue symbols are EDM measurements; red, campaign GPS measurements; and green, continuous GPS measurements between UWEV and AHUP (immediately adjacent to AHUA). Rapid fluctuations in line length,1983–86 caused by episodic fountaining at Pu'u 'Ō'ō and by M6.6 Ka'ōiki earthquake, November 1983. Large contraction/extension in January 1997 corresponds to Nāpau intrusion.

Table 5. Estimated magma accumulation or withdrawal rates at Kīlauea summit, in km^3/yr as computed from data for four pairs of benchmarks (see tables 1–4).

[Assumed density is 2,600 kg/m^3 (Fujii and Kushiro, 1977). Mogi source is 1.11 km south of HVO34 and at 3.0 km depth (Cervelli and Miklius, this volume). Dashes indicate insufficient data for estimate.]

Period	HVO34 (P1)	HVO27 (P1)	HVO34 (LYMREF)	HVO27 (LYMREF)
1983–April 85	+0.020±.004	+0.038±.01	--	--
April 85–June 91	-.0021±.004	+.033±.01	--	--
June 91–1993	+.0047±.001	+.018	--	--
1993–2002	-.00075±.003	-.021±.01	-0.0010	-0.011

third periods and magma withdrawal during the current period. There is agreement in sign between estimates made using data from different benchmarks for the same period, although the values differ by a factor of as much as 2 or 3. The results from HVO34 and HVO27 appear to conflict for the second period; the estimate with the lowest error suggests no appreciable change in mass (HVO34), and the other available estimate suggests mass accumulation (HVO27). The results from HVO34 and HVO27 are somewhat equivocal for the current period; the estimate from HVO34 is not significantly different from zero, but the estimate from HVO27 indicates magma withdrawal. The estimated accumulation rates for the Hilo-based (LYMREF-referenced) data can be calculated only for the last period and are within two-sigma agreement with the P1-based data, indicating a small amount of magma withdrawal. In all cases, the absolute value of the estimated rates is much smaller than the estimated rate of eruption of material during the current eruption, typically around 0.13 km^3/yr (Sutton and others, this volume). In other words, the magma accumulating in, or draining from, the summit reservoir is only a small fraction of the amount of lava erupted from the east rift zone.

Insights Offered into Eruption Mechanism

The estimated amounts of mass accumulation or withdrawal are only a few percent of the total magma throughput of around 0.13 km^3/yr in the Kīlauea summit-Puʻu ʻŌʻō system. Even though the accumulation or withdrawal rates are very small, they reflect important behavioral changes in the ongoing eruption.

The gravity data from both HVO27 and HVO34 indicate that residual amounts of magma accumulated beneath the summit area in two periods. During the first period (1983–April 1985), Puʻu ʻŌʻō fountain heights were increasing, reaching their maximum by late 1984 through early 1985. The average discharge continued to increase until late 1985, when average discharge, repose-period lengths, and total summit deflation stabilized (George Ulrich, unpub. data, 1986). These trends suggest that the magma-transport system between the summit reservoir and Puʻu ʻŌʻō became more streamlined as the eruption progressed.

During the second period of magma accumulation (early 1991 to 1993), lava output from Kūpaianaha declined almost linearly to zero by early 1992, when lava returned to Puʻu ʻŌʻō (Kauahikaua and others, 1996). Estimated lava output rates did not return to average until early 1993. Magma-accumulation rates at the summit are estimated at 4 and 15 percent of the average rate at which lava was erupted during this period.

The final, post-1993, period is a time of sparse gravity measurements. Since lava returned to Puʻu ʻŌʻō in early 1992, it has continued to issue from flank vents on the cone as of November 2002. Many short-term events have occurred since 1992, but the gravity data are too sparse to provide more information. Within errors, the data in this period suggest long-term magma withdrawal from the summit amounting to a few percent of the eruptive flux, in agreement with Cervelli and Miklius (this volume). In other words, slightly more lava is being erupted than is supplied to the summit magma reservoir.

Sutton and others (this volume) and Heliker and Mattox (this volume) show that the average eruption rate during the first 19.5 years of this eruption has been about 0.13 km^3/yr. By comparison, our gravity and elevation results show that magma has been either accumulating or withdrawing from the summit magma chamber during that time at rates amounting to only a few percent of the erupted rate. The temporal correspondence between residual accumulation or withdrawal at the summit magma reservoir and the dynamics of the Puʻu ʻŌʻō-Kūpaianaha eruption supports the well-accepted idea that erupting lava is supplied through the summit magma chamber (Dvorak and others, 1992). The mass changes at Kīlauea's summit are much smaller than the erupted mass, and the erupted magma is clearly not supplied mainly from storage in the summit magma reservoir. Rather, the summit magma chamber is only a waypoint for magma en route to eruption.

Lessons for the Future of Precise Gravity Monitoring

In principle, the combination of precise gravity and elevation measurements can be useful in monitoring magma accumulation and withdrawal in the Kīlauea summit region. This paper demonstrates what can be done with limited microgravity data at two benchmarks during an eruption. Coincident elevation data allow calculation of residual gravity changes with time. However, gravity and elevation, infrequently measured at a few benchmarks, are not sufficient to determine source location or density when more than one deformation source exists. Interpretation of such data requires an estimate of source location derived from other geodetic data. The source volumes estimated by Delaney and others (1993) and Cervelli and Miklius (this volume) are broadly consistent with those calculated from gravity and elevation data in this paper. Therefore, the current sparse gravity-monitoring data can corroborate and, perhaps, refine some aspects of an eruption model determined with the modern geodetic network. The effectiveness of gravity-monitoring measurements can be increased by making continuous measurements at a few key sites in order to better constrain the rates (Zerbini and others, 2001) or by making frequent measurements at a network of sites. Inclusion of gravity data within the geodetic data sets remains the only way to measure the accumulation or withdrawal of subsurface mass and is, therefore, worthy of this increased effort.

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