January 30, 1997 eruptive event on Kilauea Volcano, Hawaii, as monitored by continuous GPS

Susan Owen[1,2], Paul Segall[1], Michael Lisowski[3], Asta Miklius[3], Mark Murray[1],

Michael Bevis[4] and James Foster[4]

Abstract. A continuous Global Positioning System (GPS) network on Kilauea Volcano captured the most recent fissure eruption in Kilauea's East Rift Zone (ERZ) in unprecedented spatial and temporal detail. The short eruption drained the lava pond at Pu'u O'o, leading to a two month long pause in its on-going eruption. Models of the GPS data indicate that the intrusion's bottom edge extended to only 2.4 km. Continuous GPS data reveal rift opening 8 hours prior to the eruption. Absence of precursory summit inflation rules out magma storage overpressurization as the eruption's cause. We infer that stresses in the shallow rift created by the continued deep rift dilation and slip on the south flank décollement caused the rift intrusion.

1. Introduction

Since 1983, Kilauea Volcano has been erupting almost continuously from the Pu'u O'o or Kupaianaha vents in the ERZ (Plate 1). During this time, there have been few intrusions into either the summit or the rift zones [*Delaney et al,* 1993] other than the magma flowing out to the Pu'u 'O'o vents. On January 30, 1997, new fissures erupted in Napau Crater, ~3 km up rift from Pu'u 'O'o [*Thornber et al,* 1997]. The lava pond at Pu'u O'o drained, causing a section of its cone to collapse and temporarily stopping eruptive activity there. The eruption at Napau Crater was atypical in that it occurred without any precursory inflation at the summit. Precursory inflation is generated by increasing magma pressure within Kilauea's summit reservoir. When the pressure reaches a critical value a dike is injected from the reservoir into the rift zone or summit area, sometimes leading to an eruption [*Tilling and Dvorak,* 1993]. In this case, continuous GPS sites spanning the summit recorded long-term slow contraction leading up to the January 30th fissure eruption (Figure 1), more consistent with deflation. The absence of summit inflation makes it difficult to explain the occurrence of this fissure eruption, especially during an on-going rift eruption. That seismic tremor and earthquake swarms initiated near Napau Crater [*Thornber et al.,* 1997], rather than at the summit, is also inconsistent with a rift intrusion originating beneath the summit.

The eruption was preceded by 8 hours of volcanic tremor, deflation at Kilauea's summit, and extension across the ERZ

(Figure 2). Tremor was first detected at 0445 UTC January 30 near Napau Crater, the eventual eruption site, and reached high intensity by 0514 UTC. Strong tremor began at the summit of Kilauea at 0515 UTC. Tiltmeters indicate that summit deflation began at approximately 0530 UTC [*Thornber et al.,* 1997]. The eruptive activity around Napau Crater ended by February 1. Pu'u O'o did not erupt again until March 28, 1997. While the volume of erupted lava was only 300,000 m^3 [*Thornber et al.,* 1997], the effect on the magmatic system was large, halting the Pu'u O'o eruption for longest period since 1986 [*Heliker et al.,* 1997], and causing significant surface displacements around the summit and ERZ.

Rift intrusions pose an eruptive hazard and could influence the fault system that has produced Kilauea's largest recent earthquakes (1975 M7.2, 1989 M6.1). It has been proposed that forceful intrusion of magma into the rift zones builds strain energy that is then released in large seismic events [*Ando,* 1979, *Swanson et al,* 1976, *Dvorak et al.,* 1986]. Others hypothesize that a deep cumulate core at the base of the rift system is extending under its own weight and driving décollement slip [*Clague and Denlinger,* 1994]. GPS surveys since 1990 have shown high displacement rates on the south flank and steep gradients in deformation [*Owen et al.,* 1995, *Owen et al.,* 2000]. These observations can be explained by deep dilation within the rift zone coupled with slip along the décollement [*Delaney et al.,* 1990, *Owen et al.,* 1995, *Owen et al.,* 2000]
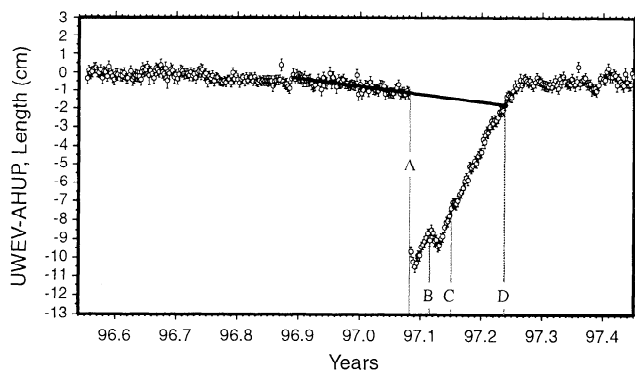

Figure 1. Time series of distance estimates between two continuous stations (UWEV, AHUP) that span the summit caldera. Points represent daily solutions minus a nominal value. Error bars are 2 standard deviations. Event A: Jan. 30, 1997 rift event. Event B: a 4 hour tilt episode in which the summit inflated for several hours and then rapidly deflated (2/11/97). Event C: the return of a lava pond to Pu'u O'o (2/24/97). Event D: the resumption of the eruption at Pu'u O'o (3/28/97). A line shows a velocity estimate between a significant pause in the Pu'u O'o eruption (11/18/96) and 1/29/97. The line is extrapolated to the time when the Pu'u O'o eruption resumed.

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1. Geophysics Dept., Stanford Univ., California
2. Now at Earth Sciences Dept., Univ. of S. Calif., Los Angeles
3. U.S. Geological Survey, Hawaiian Volcano Obs., Hawaii
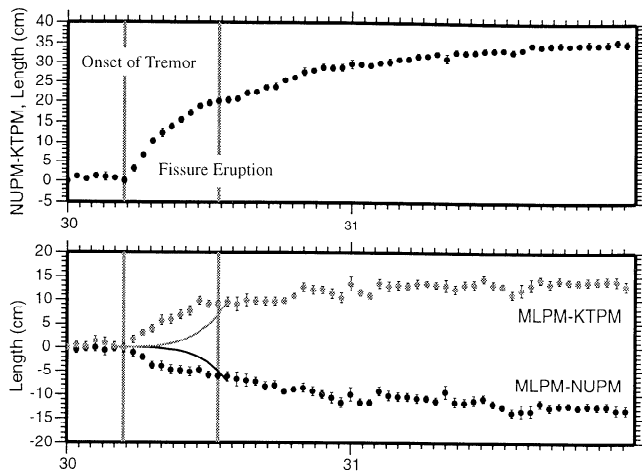4. Dept. of Geology and Geophysics, Univ. of Hawaii, Honolulu

Figure 2. Extension across the rift zone as a function of time. Distance between continuous stations NUPM-KTPM, MLPM-NUPM and MLPM-KTPM is plotted for the 48 hour period of eruptive activity at Napau Crater (UTC days 1/30 and 1/31/97). MLPM was not affected by the rift intrusion and is thus a stable reference station. The error bars are 2 standard deviations. Solid lines in the bottom plot show the predicted displacements from a dike of increasing length propagating upward at constant rate with opening proportional to the minimum crack dimension.

2. Data

The surface deformation caused by the January 30, 1997 rift intrusion was observed using continuous and campaign GPS data. The data were processed using GIPSY-OASIS software in point-positioning mode [Zumberge et al., 1997]. The local network positions were solved for in a single solution, allowing ambiguitiy resolution and improving the relative position precision [Blewitt, 1989]. The formal errors were scaled to reflect the consistency of repeated station position measurements.

Station positions were measured in separate campaigns both before and after the eruption. Permanent GPS station data collected on January 29 established their pre-eruption positions. Corrections were made at many campaign stations for the displacements that occurred between the prior campaign measurements and the eruption. Stations 69FL, DEST, LAVA, MANU, PALI, PULU, and SAND were surveyed in mid-January, 1997 and so were left uncorrected. Stations east of Napau Crater had been last surveyed in July 1996 and their corrections were calculated from the average 1992-96 GPS campaign velocities [Owen et al., 1996]. The station closest to Napau Crater, KANE, had only been surveyed once prior to the January 30, 1997 intrusion. A model-predicted rate, calculated from an elastic dislocation model for the 1992-96 velocities [Owen et al, 1996], was used to correct KANE. KANE's one sigma uncertainty was calculated from the model's residual velocity at NUIO, the nearest station to KANE. The majority of the post-event locations are based on a weighted average of the station positions between February 3 and February 8, inclusively. Several stations were not surveyed until a few weeks after the event and their errors were increased to account for post-intrusion deformation.

The displacement vectors (Plate 1) display a clear pattern of rift extension around Napau Crater. They are roughly symmetric about the rift zone but directed inward at the ends of the fissure, consistent with a dike-like source. The surface deformation decays rapidly with distance from the vent, in-

dicative of a shallow source depth. Horizontal contraction across the summit is consistent with deflation of the summit magma chamber, commonly observed during rift intrusions. Three stations had vertical displacements that were significant at the two sigma level: UWEV, -4.6 ± 1.8 cm, KTRA, 4.7 ± 2.1 cm, and KTPM, 4.9 ± 1.7 cm. The subsidence at the summit is consistent with deflation of the summit magma reservoir. The uplift of the stations on the south flank is also consistent with a rift intrusion beneath Napau Crater.

3. Model

In order to interpret the observed displacements, we estimated the surface deformation assuming simple dislocations [Okada, 1985] and point sources of volume change [Mogi, 1958] in a homogeneous elastic half-space. Nonlinear optimization, using a combination of the random cost method [Berg, 1993, Murray et al., 1996] and a constrained non-linear least squares algorithm [Grace, 1994], was used to find the best-fitting source geometry. The best-fitting model for the simplest case of a summit point source and a rift zone opening mode dislocation (model 1, Table 1) seriously misfit some of the observed displacements.

We then tested more complex models. The model that best fit the data includes a planar dike dipping 76° to the south, a point source of volume decrease within summit, and a second point source of volume decrease underneath Makaopuhi Crater (Plate 1; model 2, Table 1). Although the mean square error is 6 for this model, there is no pattern in the model misfit to indicate missing sources of deformation. The model uncertainties were calculated using methods based on an F statistic [Murray et al., 1996]. The F statistic assumes that the minimization function can be linearized near the global minimum and that data errors are normally distributed. Approximately 80,000 trial models were used to set the confidence regions listed in Table 1. Since the estimation problem doesn't satisfy the assumptions required by the F statistic, these confidence regions are approximate.

Table 1. Estimated Model Parameters and Uncertainties.

	Model 1	Model 2
Rift		
length (strike ‖, km)	$^{-1.86}5.56^{+0.59}$	$^{-0.77}5.15^{+0.69}$
width (km)	$^{-1.82}2.93^{+0.96}$	$^{-1.50}2.24^{+1.45}$
depth (bottom, km)	$^{-0.80}2.52^{+1.02}$	$^{-1.25}2.40^{+1.12}$
dip (degrees)	$^{-1.73}58.9^{+14.02}$	$^{-9.04}76.0^{+4.79}$
strike (degrees)	$^{-0.32}64.9^{+6.13}$	$^{-0.67}67.6^{+0.52}$
north (latitude)[a]	$^{-0.35}21.80^{+0.53}$	$^{-0.40}22.26^{+0.06}$
east (longitude)[b]	$^{-0.22}8.18^{+0.07}$	$^{-0.09}8.47^{+0.05}$
opening (m)	$^{-0.32}1.30^{+2.78}$	$^{-0.82}1.96^{+3.37}$
Summit		
north (latitude)[a]	$^{-0.01}24.71^{+0.03}$	$^{-0.03}24.72^{+0.08}$
east (longitude)[b]	$^{-0.49}16.19^{+0.63}$	$^{-0.004}16.268^{+0.444}$
depth (km)	$^{-1.16}1.87^{+1.82}$	$^{-1.11}1.28^{+1.57}$
Δ volume (10^6 m³)	$^{-0.4}-2.0^{+0.1}$	$^{-2.4}-1.5^{+0.6}$
Makaopuhi		
north (latitude)[a]		$^{-0.23}22.4^{+0.06}$
east (longitude)[b]		$^{-0.168}10.152^{+0.003}$
depth (km)		$^{-0.41}0.60^{+0.66}$
Δ volume (10^6 m³)		$^{-1.1}-1.2^{+0.7}$
Mean Square Error	17.2	6.0

a. Latitude of center is presented in units of minutes after 19° N.
b. Longitude of center is presented in units of minutes after 155° W.

The planar dike is quite shallow, extending from near the surface to 2.4 km depth. The top edge of the model dike matches well with the location of the surface fissures (Plate 1). The model dike extends farther along strike than the surface fissures, but this parameter is well constrained by the surface deformation. The estimated amount of opening across the rift plane is 2 m, which is consistent with the 1.8 m of opening measured across the fissures [*Thornber et al.*, 1997]. The rift is not vertical, but is dipping steeply to the south, similar to the model estimated for the 1983 rift intrusion by *Wallace and Delaney* [1993] and consistent with the predominant dip of the dikes in the exposed Koolau dike complex on Oahu [*Walker*, 1987].

4. Precursory Rift Extension

During the eruption, significant deformation occurred within the 24 hour time period used in routine data analysis. We therefore modified the data processing to determine displacements at 48-minute intervals over the 48 hours spanning the eruption (Figure 2). The solutions used 24 hours of GPS data to estimate station positions as piecewise constant stochastic parameters with random walk variance. In this way, the data strength from a 24-hour period is used to estimate the atmospheric delay parameters and to resolve integer phase biases. The station positions were considered constant over 48-minute time intervals. The random walk variance was set to a high value ($1 \text{ m/hr}^{1/2}$) to allow for large displacements between intervals.

The extension across the rift zone, as shown in the change in the distance between NUPM and KTPM (Figure 2), began ~8 hours prior to the eruption, at approximately the same time as the seismic tremor started. The extension rate was fastest at the onset (~4 cm/hr), and decreased with time, even before the eruption. After the fissure eruption began, the extension rate slowed, and by the end of January 31st the extension rate
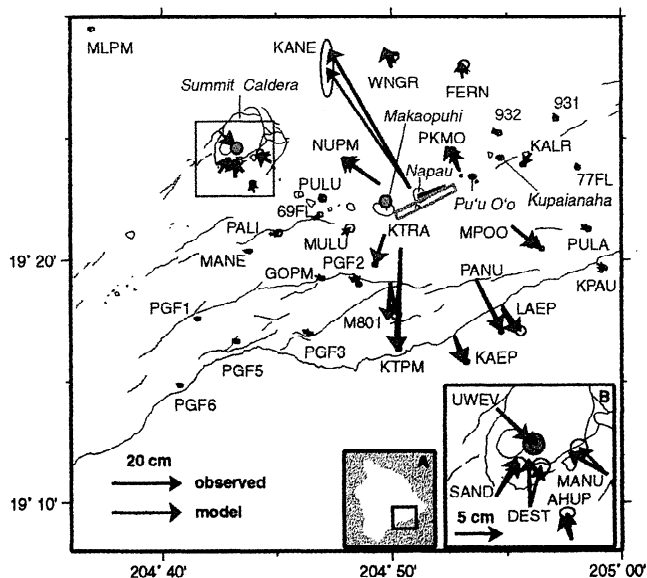

Plate 2. Schematic cross-sections showing (A) décollement slip and deep rift opening leading up to the January 30 eruption and (B) dike opening during the eruption and intrusion.

had dropped to 0.07 cm/hr. It is significant that the station north of the rift zone, NUPM, and the station south of the rift zone, KTPM, began to move away from the rift zone at the same time. This result implies that the first event in the January 30, 1997 eruption was a widening of the rift, not fault slip beneath the south flank. No significant precursory deformation was seen at any of the other continuous stations. The temporal evolution of the extension rate across the rift zone has important implications for the mechanics of dike growth. The continual decrease in the extension rate disagrees with the simplest models of dike growth. For instance, a dike opening under constant driving pressure, growing upward or laterally at constant velocity, would increase its volume proportional to t^3, where t is time. The magnitude of the surface displacements at NUPM and KTPM are primarily functions of the dike volume, and so should also increase as t^3. The observed extension, however, do not match this model. For comparison, the solid line in Figure 2 shows the predicted displacements from a dike of increasing in length along strike and propagating upward at constant rate with opening proportional to the minimum crack dimension. Clearly, the model does not fit the data and thus we can rule out magma pressure remaining even approximately constant with dike growth.

5. Discussion

The total volume decrease in the two model magma chambers is not consistent with the total amount of erupted and intruded magma. The volume of the rift intrusion alone (~23 x 10^6 m^3) is an order of magnitude greater than the total magma drawn from the Makaopuhi and summit magma chambers, suggesting that magma was supplied from sources that did not substantially deform the earth's surface. Some magma from deep within the rift zone may have filled the dike. The Napau lavas were more fractionated than recent Pu`u O`o lavas, suggesting that deep rift zone magma bodies supplied the eruption [*Thornber et al.*, 1997]. However, tests using the observed displacements and data covariance show that if the deep rift below the intrusion collapsed due to drainage of magma, we would have been able to identify this source.

Plate 1. Model-predicted and observed displacements with 95% confidence error ellipses. The gray line marks the location of the eruptive fissures. The orange rectangle is the surface projection of the model rift plane. The orange circles represent the model volume sources. Inset A: the island of Hawaii, with a rectangle indicating the enlarged area. Inset B: a close-up of the summit region.
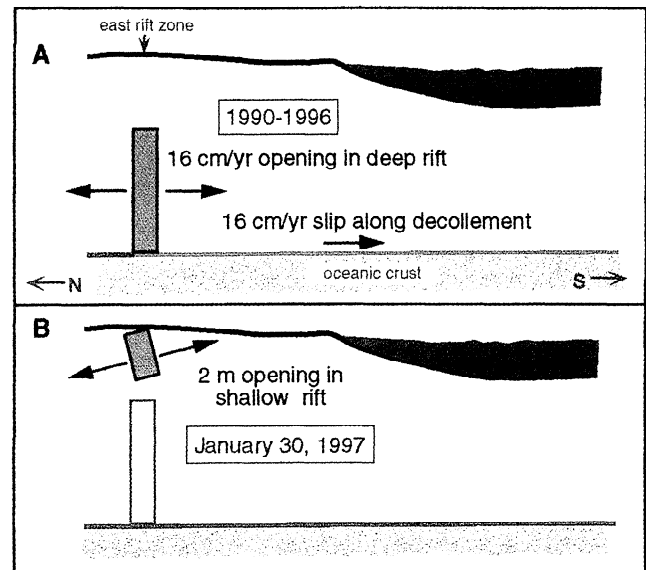
Draining of the lava pond at Pu'u O'o contributed 12.7×10^6 m^3 of magma [*Hawaii Volcano Observatory, unpublished data*]. The conduit between the summit chamber and Pu'u O'o may have drained without completely collapsing, thus generating negligible surface deformation. The conduit presumably refilled during the 25 days between January 30 and February 24, when lava was first sited in Pu'u O'o. Assuming an average flux of 4×10^5 m^3/day [*Thornber et al.*, 1997], and neglecting the small amount of summit inflation, we estimate the conduit volume to be $\sim 10 \times 10^6$ m^3. This volume, combined with the magma drained from Pu'u O'o, would account for the amount of magma intruded into the rift zone.

Deformation at the summit before and after the rift intrusion is shown in Figure 1. Prior to the event, the summit-crossing line between UWEV and AHUP had been slowly contracting, consistent with a deflating summit magma chamber. At the time of the intrusion, the distance across the caldera decreased by ~ 10 cm, consistent with magma withdrawal. Beginning a few weeks after the event (B), the distance increased at a rapid rate of 69 ± 1 cm/yr until the contraction caused by the January eruption had fully recovered (D). While the summit magma chamber was extending, lava was sighted at Pu'u O'o (C), indicating that the magma storage system from the summit to Pu'u O'o was refilling. The continued extension across the rift zone observed during this same time period is consistent with rift inflation and the rising level of the lava pond within Pu'u O'o. The eruption at Pu'u O'o resumed when the UWEV-AHUP baseline reached the length predicted by an extrapolation of the pre-eruptive trend. This baseline, then, appears to be quite sensitive to the pressurization of the summit magma chamber. Although tiltmeters are even more sensitive to changes in the magma chamber, they are not reliable over long time periods due to measurement drift [*Wyatt et al.*, 1984]. If there are future events that cause depressurization of the summit magma reservoir and a pause in an on-going eruption, it should be possible to predict the resumption of the eruption by monitoring the length between UWEV and AHUP.

The geodetic data collected prior to the eruption indicated that the summit region was contracting, consistent with summit magma chamber deflation. This raises the question, then, of what caused the fissure eruption on January 30, 1997. It cannot be attributed to overpressurization of a magma storage system in the rift given the on-going eruption at Pu'u O'o. One hypothesis is that deep dilation in the rift zones plus slip on the décollement decreased the minimum horizontal stress in the upper few kilometers of the rift, causing the shallow rift to fracture and initiate a fissure eruption (Plate 2). ~ 16 cm/yr [*Owen et al*, 2000], gives ~ 2.2 m of deep extension in the 14 years since the previous rift intrusion into the ERZ in 1983, comparable to the 2 m of shallow opening that occurred on January 30, 1997. Fracturing caused by extensional stress is also consistent with the fissure eruption occurring in the midst of the on-going Pu'u O'o eruption. The dike was not initially forced open by magma, but magma on its way to Pu'u O'o was diverted by the fracture once it started to grow.

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M. Bevis and J. Foster, Geology and Geophysics Department, University of Hawaii, Honolulu, HI, 96822.

M. Lisowski and A. Miklius, Hawaiian Volcano Observatory, Hawaii Volcanoes National Park, Hawaii, 96718.

M. Murray and P. Segall, Geophysics Department, Stanford University, Stanford, CA 94305.

S. Owen, Earth Sciences Department, University of Southern California, Los Angeles, CA 90089 (email: owen@terra.usc.edu).