Deep Magma Body Beneath the Summit and Rift Zones of Kilauea Volcano, Hawaii

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A magnitude 7.2 earthquake in 1975 caused the south flank of Kilauea Volcano, Hawaii, to move seaward in response to slippage along a deep fault. Since then, a large part of the volcano's edifice has been adjusting to this perturbation. The summit of Kilauea extended at a rate of 0.26 meter per year until 1983, the south flank uplifted more than 0.5 meter, and the axes of both the volcano's rift zones extended and subsided; the summit continues to subside. These ground-surface motions have been remarkably steady and much more widespread than those caused by either recurrent inflation and deflation of the summit magma chamber or the episodic propagation of dikes into the rift zones. Kilauea's magmatic system is, therefore, probably deeper and more extensive than previously thought; the summit and both rift zones may be underlain by a thick, near vertical dike-like magma system at a depth of 3 to 9 kilometers.

As one of the Earth's most active volcanoes, Kilauea has frequent and usually gentle eruptions that have made it the focus of a wide range of volcanological research. Systematic studies began in 1912 with the establishment of the Hawaiian Volcano Observatory and continue to the present day. These studies have revealed much about the physical and chemical processes that trigger and sustain volcanic eruptions and have served as models for investigations of other, often more violent, volcanoes in many parts of the world.

Kilauea receives a steady supply of basalt magma, estimated to be 0.1 km^3 $year^{-1}$ (*1*), from a hot-spot source in the upper mantle. The intermittent rise of lava to the surface, however, indicates that magma accumulates in an underground plumbing system during periods of surface quiescence. Since the mid-1950s, intensive efforts have been made to understand the configuration and functioning of this underground system in the belief that it plays a central role in both the eruptive behavior of the volcano and the structural events that lead to the frequent, damaging earthquakes in Hawaii. Most of these efforts have been focused on specific eruptions or earthquakes and, in general, have yielded information only on the shallow (<5 km) components of Kilauea's magmatic system. In this article, we analyze ground deformation data gathered over an extensive region before and since the magnitude (*M*) 7.2 earthquake of November 1975. These data span numerous eruptions, shallow intrusions, and thousands of small to moderate earthquakes. The widespread deformation associated with and following occasional large earthquakes and the subsequent multiyear response of nearby magmatic systems can provide information about deep structure and processes unavailable from the study of individual volcanic events.

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Kilauea's shallow magmatic system. The top of the magma reservoir at the summit of Kilauea is about 2 km below the surface. This reservoir typically inflates slowly as basalt magma rises from its mantle source (*2, 3*). When the reservoir inflates to the point of failure, magma sometimes escapes directly to the surface, producing an eruption in or near the volcano's summit caldera (Fig. 1A). More often, magma leaks laterally and intrudes either of two rift zones (Fig. 1A) to form thin, steeply dipping dikes (magma-filled cracks) that can feed eruptions tens of kilometers from the summit. Most of Kilauea's eruptions have been fed by such rift-zone dikes, which account for the long, ridge-like shape of its edifice. These dikes serve only as transient conduits, and magma in them solidifies soon after the end of an eruption. Kilauea's rift zones contain thousands of dikes, the cumulative result of many episodes of rift-zone intrusion.

Events surrounding the eruption of December 1965 provided the first clear indication that rift-zone dikes play an important role in the structural evolution of Kilauea (*4*). A brief eruption in the upper east rift zone was followed by an intense, 4-day swarm of earthquakes and extensive ground cracking. Analysis of this eruption and the associated structural adjustments suggested that the wedging action of the dike pushed the entire south side of the volcano toward the south. A review of data available by the early 1970s demonstrated that many other rift-zone dike injections had also caused similar displacements of the volcano's south flank (*5*). As much as 0.5 m of seaward south-flank displacement is thought to have occurred during the 1983 dike injection that initiated the current Pu'u 'O'o eruption in the middle east rift zone (*6*); available geodetic and seismic data suggest that this dike extended to a depth of only 2.5 km. Analysis of earthquakes accompanying other rift-zone intrusions indicates that dikes are typically not deeper than 4 to 5 km (*7*). Thus, Kilauea's south flank has been thought to deform mainly in response to intermittent wedging action of shallow dikes that propagate laterally from the summit reservoir and forcibly intrude the rift zones.

Seismicity and magmatism. Hawaii's largest instrumentally recorded earthquake, a *M* 7.2 event on 29 November 1975 (*8*), originated beneath the south flank of Kilauea about 25 km southeast of the summit (Fig. 1A). The earthquake triggered a brief summit eruption, and the summit subsided 1.0 to 1.5 m. Concurrently, the rift zones subsided 0.5 to 0.8 m and dilated up to 1 m along most of their length. Most of the south flank moved seaward 3 to 8 m and subsided 1 to 3.5 m; this movement caused a local tsunami that killed two people. Although ground breakage with up to 1.5 m of normal fault slip was distributed along 25 km of the Hilina fault system (Fig. 1A), the earthquake probably originated from thrust motion on the shallow-dipping contact between the volcanic pile and underlying oceanic sedimentary rocks at ~9 km depth (*9*). From the hypocenter, the slip surface is thought to have propagated ~30 km westward and ~20 km southward. The 9- to 10-km focal depth and widespread deformation of the 1975 event revealed that some of Kilauea's fundamental structures are deeper and more extensive than had been supposed on the basis of observed shallow magmatic events. Additionally, many thousands of earthquakes have occurred along a 60-km zone south of Kilauea's summit and rift zones at depths of 5 to 10 km (*7*). The largest Kilauea event since 1975, a *M* 6.1 earthquake on 25 June 1989, disrupted the otherwise steady rates of deformation in the east rift zone discussed below.

Measurements of ground tilt along a line radial to the most common center of inflation and deflation document the fitful motions of Kilauea's summit (Fig. 2). The measurements, begun in 1956, indicate that gradual inflations and rapid deflations of the volcanic system were superposed upon a net inflationary trend up to 1975 (*10*). From 1969 to 1974 this trend coincided with the near continuous eruption of Mauna Ulu in the upper part of the east rift zone (Fig. 1A). Although increased tilt does not necessarily reflect an increase in the absolute height of the summit, Kilauea's summit was probably higher, and therefore more inflated, just before the 1975 earthquake than at any time since the major summit collapse of 1924 (*11*). During the first 8 years after the earthquake, gradual inflations and rapid deflations continued with no apparent trend toward net inflation or deflation (Fig. 2). During the subsequent 7 years of the ongoing Pu'u 'O'o eruption, from 1983 to 1990, the summit has deflated almost continuously. Kilauea is now probably as low—and as deflated—as it has been at any time in the 20th century (*11*). Apparently the ability to sustain an eruption is not directly related to the magnitude of summit inflation.

Since 1970, there have been approximately 30 rift-zone dike injections, as recognized by their distinctive seismicity (*7*). Since 1975, however, only two dikes have propagated past the upper section of the east rift zone (September 1977 and January 1983), and only two have propagated a comparable distance along the southwest rift zone (August 1981 and June 1982). These four dike injections accounted for the major post-1975 drainages of magma from the summit reservoir and associated injections into the rift zones (rapid deflations in Fig. 2). As shown by the time-series data summarized below, however, these events are not the primary source of post-1975 summit, south flank, or east-rift-zone deformation.

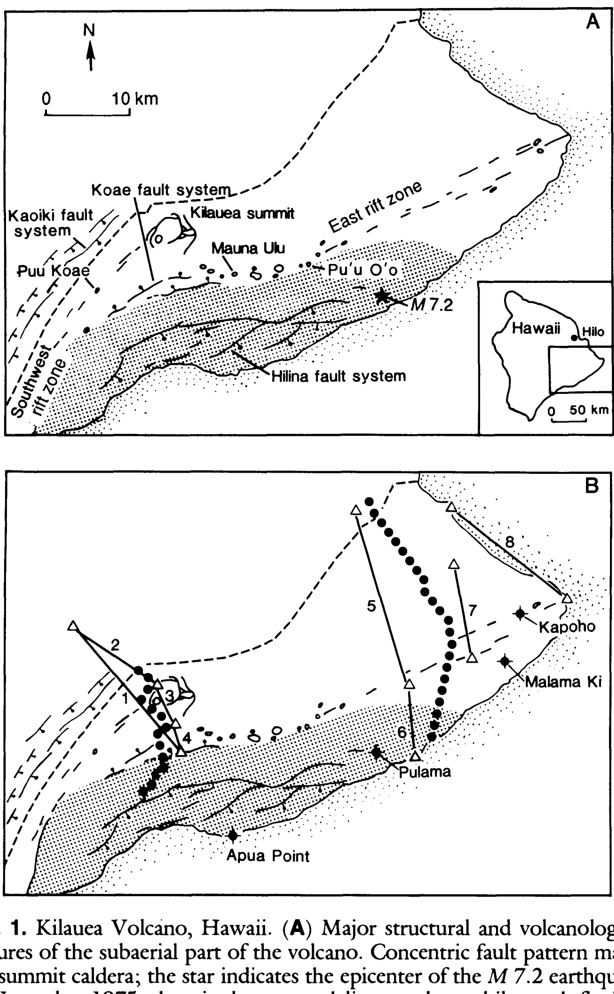

Fig. 1. Kilauea Volcano, Hawaii. (**A**) Major structural and volcanological features of the subaerial part of the volcano. Concentric fault pattern marks the summit caldera; the star indicates the epicenter of the *M* 7.2 earthquake of November 1975; the stipple pattern delineates the mobile south flank of the volcano; dashed line shows boundary of Kilauea with adjoining Mauna Loa Volcano. (**B**) Locations of geodetic stations. Open triangles define ends of lines measured by electrooptical distance meters (numbers identify lines referred to in text); dots indicate portions of precise leveling lines used to construct leveling transects; circles (with crosses) indicate tide gauge and water wells.

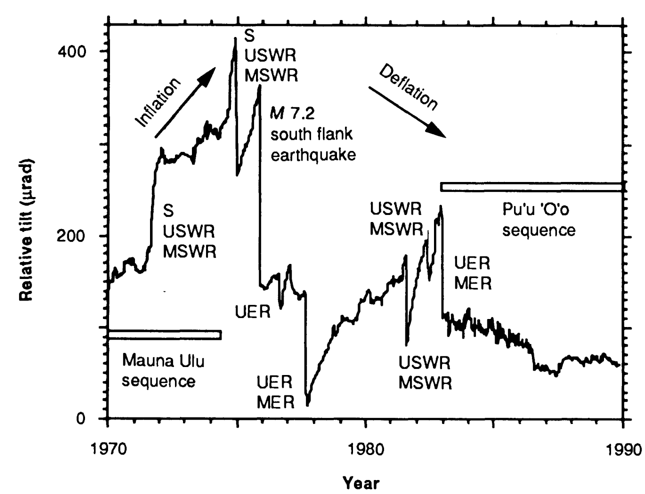

Fig. 2. Relative tilt magnitude near the summit of Kilauea, 1970 to present. Component of tilt is oriented N60°W, radial to the most common center of summit inflation and deflation; data are weekly averages of daily recordings. Mauna Ulu and Pu'u 'O'o eruptive sequences on the east rift zone are denoted by open boxes. Major deflations associated with eruptive activity are labeled so as to distinguish activity on the summit (S), upper and middle east rift zone (UER, MER) and upper and middle southwest rift zone (USWR, MSWR). General inflation occurred before the *M* 7.2 1975 earthquake, whereas general deflation has occurred since. The tilt site recorded a net inflation during the 1971 dike injection because it is situated on the deformation field of the dike, which originated in the summit and migrated southwestward. Another dike injection and eruption on the southwest rift zone occurred in late 1974. Substantial deflation was associated with the 1977 dike injection, which traveled ~30 km to the middle east rift zone, and with the 1981 injection of a 20-km-long dike in the southwest rift zone. Minor deflations were associated with the 1976 dike injection to the upper east rift zone and with the 1982 summit eruption. Tilt change of 219 µrad due to instrument disturbance during the 15 November 1983 *M* 6.6 Kaoiki earthquake, located ~10 km northwest of Kilauea summit, was removed from the record.

Summit extension and subsidence. Reference baselines spanning Kilauea's summit have been measured with electrooptical distance meters (*12*) since the late 1960s in order to monitor summit inflations and deflations and to identify deformations along structural elements near the summit. The longest of these (line 1 in Fig. 1B) has end stations on Mauna Loa Volcano to the north and on the northernmost edge of Kilauea's south flank to the south. This line crosses the structural boundary between Mauna Loa and Kilauea (the Kaoiki fault system, Fig. 1A), the locus of summit inflation (just south of the summit caldera), and a region of extensional ground cracks and normal faults just south of Kilauea's summit (the Koae fault system, Fig. 1A). Three shorter baselines extend from Mauna Loa toward Kilauea's summit, across the summit, and across the Koae fault system (lines 2, 3, and 4, respectively, in Fig. 1B); these allow changes in the length of line 1 to be spatially resolved.

Line 1 has extended 5.3 m since 1970 (Fig. 3A). Of the 39 measurements taken during this time, the line shortened by an amount exceeding 2 SD of the estimated procedural error (5 cm) on four occasions, but it extended by a similar amount 25 times (no significant change was measured on the other occasions). From 1970 to 1975, the extension rate was 20.7 ± 2.5 cm year^{-1} (all error limits are ± SE). During the 1975 earthquake, the line extended 180 to 190 cm. After the 1975 earthquake but before the January 1983 dike injection, line 1 extended at a rate of 26.6 ± 1.5 cm year^{-1}. Since 1984, extension has been 4.6 ± 0.5 cm year^{-1}. These simple approximations for the extensional behavior of the long baseline spanning Kilauea's summit probably reflect pervasive and consistent processes that span numerous episodes of inflation, eruption, and deflation as measured by the summit tilt [Fig. 2; see also (*13*)]. Although the continuous eruptive activity since 1983 may be responsible for the present low rate of summit deformation—the rate of summit extension appears to have decelerated greatly soon after the onset of the Pu'u 'O'o eruptive sequence—similar activity at Mauna Ulu from 1969 to 1974 was associated with a relatively high rate of extension. There does not appear to be, therefore, a simple relation between the rate of summit extension and the style of eruptive activity.

All major inflation-deflation cycles discerned in Kilauea's summit tilt record are also observed as changes in the length of the shorter cross-summit baseline, line 3 (Fig. 3A); the 1977 and 1983 dike injections are the most notable episodes since 1975. Inflationary episodes generally correspond to times of appreciable extension of line 3 but modest contractions of lines 2 and 4, which cross the flanks of the summit. Similiarly, when line 3 suddenly contracted, as in 1977, lines 2 and 4 extended. Nevertheless, even though the tilt record from late 1975 to 1983 shows little net inflation, line 3 extended at an average rate of 18.0 ± 1.6 cm year^{-1}. An appreciable amount of the total summit extension (line 1) also resulted from deformation along line 4; this 3.4-km line extended at 10.6 ± 0.9 cm year^{-1} from 1975 to 1983. Thus, during this time extension occurred pervasively across both the summit and the Koae fault system. The more recent extension of line 2, and thus also line 1 (Fig. 3), may be related to seismicity on Mauna Loa that began after its 1984 eruption. If so, the rate of extension of Kilauea has evidently slowed to less than 1 cm year^{-1} since 1983 or 1984.

Precise levelings from a vertical control datum in the city of Hilo (Fig. 1A) were completed in 1976, 1979, 1986, 1988, and 1989 (*14*). Benchmarks crossing the summit caldera and Koae fault system record the pattern and extent of subsidence (Figs. 1B and 4A). Between 1976 and 1988, there was modest subsidence north of the summit and a maximum subsidence of 165 ± 4 cm just south of the summit caldera, near the common center of inflation and deflation. Farther south, the subsidence diminished toward zero at the southern boundary of the Koae fault system. The southernmost normal fault of the Koae system has slipped ~40 cm since 1976 and marks the transition to south flank uplift. Unlike the summit extension, subsidence does not appear to be slowing. Height differences between the 1986 and 1988 levelings indicate that the maximum subsidence rate was 6 to 7 cm year^{-1}.

South flank uplift. South of the Koae fault system (Figs. 1B and 4A), upward displacements increase southward. From 1976 to 1988, uplift south of the southernmost fault scarp of the Koae system was 20 ± 4 cm; there has been 58 ± 4 cm of uplift at the southern extent of the network, which is at the northern edge of the Hilina fault system (Fig. 1). The maximum south flank uplift is south of the region of vertical geodetic control, far from any known summit or rift-zone magmatic activity. The summit subsidence appears to be part of the same deformation pattern as the uplift of

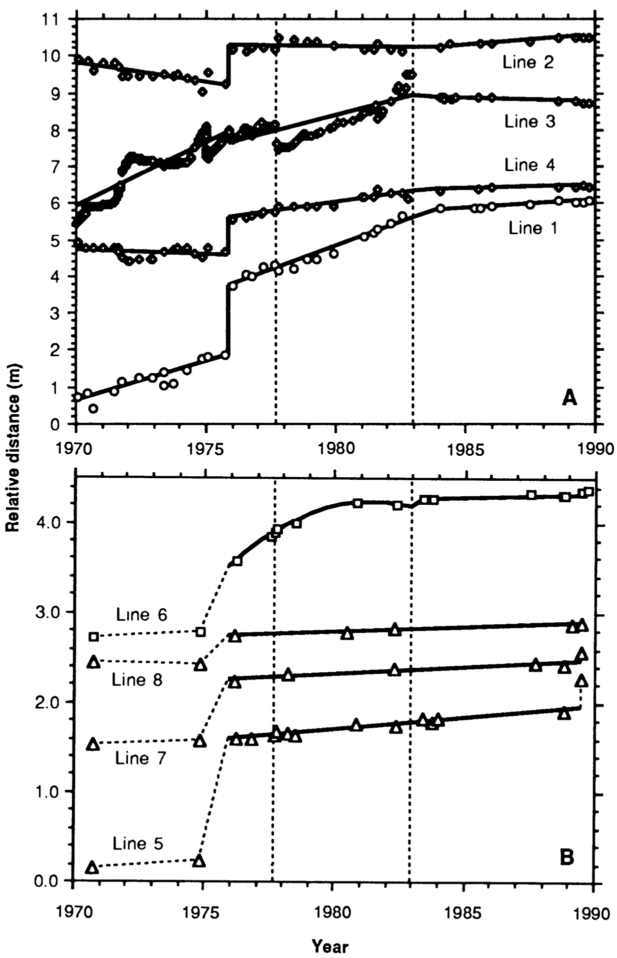

Fig. 3. Relative distances along baselines shown in Fig. 1B, 1970 through 1989. Vertical dotted lines mark the 1977 and 1983 dike injections on the east rift zone. Where data are too sparse to be fitted, a dashed line is used. Changes in length due to the November 1975 south-flank earthquake are apparent; the last datum for each line post-dates the June 1989 south-flank earthquake (*M* 6.1). (**A**) Lines across Kilauea's summit. Linear fits are applied to data for three periods: (i) from 1970 until the November 1975 south flank earthquake, (ii) from the earthquake until the onset of Pu'u 'O'o eruptive activity in January 1983, and (iii) until the 25 June 1989 earthquake. There were no significant changes in length due to this most recent south flank earthquake. (**B**) Lines in the lower east rift zone. For lines 5, 7, and 8, linear fits are applied to data for the post-1975 period until 25 June 1989. Line 6 is fit to a parabola for the post-earthquake period and a line for the time of the Pu'u 'O'o eruptive sequence. The *M* 6.1 earthquake on 25 June 1989 generated appreciable deformation. Post-seismic measurements revealed the following line-length changes relative to measurements completed in fall 1988 and winter 1989: lines 5, 7, and 8 extended 34.7 ± 2.2, 14.7 ± 1.3, and 0.8 ± 1.8 cm, respectively; and line 6, which crosses a zone of extensional ground rupture, extended 5.5 ± 1.0 cm.

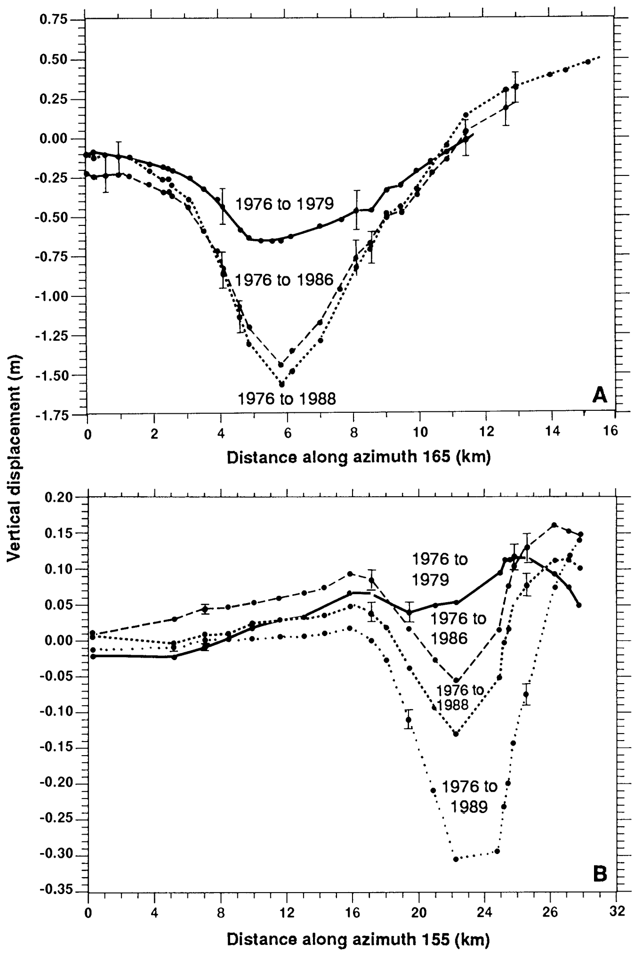

Fig. 4. Cumulative vertical displacements since 1976 as a function of distance. Those portions of leveling routes used in transects are shown in Fig. 1B. Representative error bars are 2 SE. Vertical datum is a benchmark in the city of Hilo (inset, Fig. 1A). (**A**) Summit and south flank, leveled in 1976, 1979, 1986, and 1988, projected onto a line trending 165°. (**B**) Lower east rift zone, leveled in 1976, 1979, 1986, 1988, and 1989, projected onto a line trending 155°.

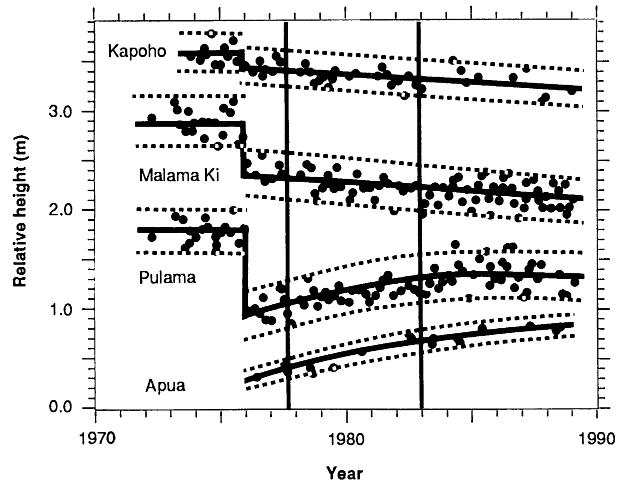

Fig. 5. Relative elevations above sea level, 1970 to present at tide gauge and water wells. Error envelopes are 2 SE. Vertical dotted lines mark the 1977 and 1983 dike injections on the east rift zone.

the south flank; the transition from subsidence to uplift occurs over a region where deformation diminishes to zero for a distance no greater than the spacing between a few benchmarks. Indeed, the extent of the deformation since 1975 exceeds the 16-km transect shown in Fig. 4A.

The areal extent of south flank uplift is not known. Westward and southward from the leveling transect, no accurate monitors of elevation are available. To the east, however, data from a tide gauge (*15*) and water well (*16*) document the history of uplift. There has been 50 to 55 cm of uplift at Apua Point (Figs. 1B and 5) since the 1975 earthquake; this uplift is of opposite sense to the 2 m of subsidence that occurred at this site during the earthquake (*8*). Initial uplift at 7.0 ± 0.9 cm year^{-1} has evidently decelerated at 0.3 ± 0.1 cm year^{-2}. Not knowing the variance of the monthly averaged tidal elevations, we are unable to reject the possibility that some of the Apua Point uplift occurred suddenly, as might be expected if the site responded to the 1977 or 1983 dike injections. However, most of the data can be accounted for by gradual uplift. The 1975 earthquake generated ~80 cm of subsidence at the Pulama water well (Figs. 1B and 5); this site has since been uplifted 40 to 45 cm. Initial uplift at 7.9 ± 1.4 cm year^{-1} has decelerated at 0.4 ± 0.1 cm year^{-2}. Although some sudden or short-term motions may have occurred, as at Apua Point, we are unable to identify confidently such jumps in the pattern of apparently continuous uplift. At both sites, the past 4 years of data alone do not indicate that the uplift is continuing.

Rift-zone subsidence and extension. Since 1975, Kilauea's rift zones have been subsiding. As determined by leveling, the axis of the upper southwest rift zone near Pu'u Koae (Fig. 1A) had subsided more than 85 cm by mid-1988, although about 40 cm of this subsidence occurred during a 1981 dike intrusion. Near Mauna Ulu (Fig. 1A), the axis of the upper east rift zone had subsided more than 60 cm and, unlike the southwest zone, the subsidence pattern was relatively unaffected by the 1977 and 1983 dike intrusions.

The magnitude of the subsidence decreases downrift. The pattern of post-1975 deformation is displayed in a leveling transect across the lower east rift zone ~40 km from the summit (Figs. 1B and 4B). By mid-1988, the maximum subsidence was greater than 15 cm; an additional 23 cm of subsidence occurred locally during the *M* 6.1 earthquake on 25 June 1989 beneath the south flank. The deformation pattern across the east rift zone reveals that before the 1989 earthquake, the axis of subsidence was flanked by uplifts ~6 km away. In 1988, the maximum uplifts north and south of the lower east rift zone were 5 and 12 cm, respectively.

To better ascertain the timing and extent of the rift-zone subsidence, we analyzed repeated measurements of water level (*16*) at Malama Ki and Kapoho wells (Figs. 1B and 5), which are 40 km and 50 km, respectively, from Kilauea's summit and 10 km and 20 km downrift from the nearest known post-1975 intrusive activity. The ground surfaces at Malama Ki and Kapoho subsided 38 cm and 18 cm, respectively, during the 1975 earthquake. Since then, there have been 25 to 30 cm of additional subsidence at Malama Ki and 20 and 25 cm at Kapoho, in good agreement with height changes at nearby benchmarks measured during the 1976 and 1988 levelings. Subsidence appears to have been essentially continuous at a rate of 2.0 ± 0.3 cm year^{-1} at Malama Ki and 1.7 ± 0.4 cm year^{-1} at Kapoho; the hypothesis of impulsive subsidence events, such as might accompany a dike injection, is not well supported. These rates are too rapid by an order of magnitude to be caused by isostatic deformation of the oceanic crust beneath Hawaii (*17*).

Intermittent measurements of distance (*14*) have been made from stations on cinder cones located along the axis of the east rift zone to stations located both to the north and south; we have analyzed data from four such baselines (Fig. 1B). The westernmost pair of baselines (lines 5 and 6) are only a few kilometers east, or downrift, from the distal extent of post-1975 dike intrusions. (The rift-axis station has been the site of fumarolic activity since the 1977 dike injection.) Line 6, directed southward from the rift-zone axis, crosses the easternmost extension of the Hilina fault system.

All baselines oriented northward from the lower east rift have been extending at rates that decrease in the downrift direction. Line 5 (Fig. 3B) lengthened by about 135 cm during the 1975 earthquake. Until the 25 June 1989 earthquake, this baseline had been lengthening steadily at 2.9 ± 0.2 cm year^{-1}; the data are well characterized by this linear fit. The 1977 and 1983 dike injections can account for no more than 30% of the 40 cm of post-1975 extension. Farther downrift, lines 7 and 8 lengthened about 65 cm and 35 cm, respectively, during the 1975 earthquake. Until the 25 June 1989 earthquake, these baselines had been lengthening steadily at 1.5 ± 0.3 cm year^{-1} and 1.1 ± 0.1 cm year^{-1}, respectively. Although these rates are relatively modest, they attest to the persistent unrest of Kilauea's east rift zone in a region that has not been the site of an eruption since 1960.

Line 6, which is directed southward from the rift zone, shows a more complicated pattern of extension. It lengthened approximately 80 cm during the 1975 earthquake (Figs. 1B and 3B). From the 1975 earthquake until the 1983 dike injection, the rate of extension decreased by 2.4 ± 0.2 cm year^{-2} from an initial rate of 26.3 ± 1.7 cm year^{-1}; between 1983 and 25 June 1989, it lengthened by 0.8 ± 0.4 cm year^{-1}. We assumed that the post-1983 deformation rate differs from that occurring between 1975 and 1983; nevertheless, the deformation recorded by line 6 is well characterized by gradual motions. Although extensions resulting from the 1983 dike injection were ~6 cm, most of the 77 cm of post-1975 extension appears to be unrelated to dike injections or other shallow east rift events. The pattern of deceleration from an initially high rate of deformation along line 6 resembles that recorded at the nearby Pulama well (Fig. 5).

Deep magma body. The inflation and deflation of Kilauea's summit area caused by changes in magmatic pressure in the shallow summit reservoir generally deform an area less than 100 km^2. The motions we have described are far more extensive, affecting more than 500 km^2 of Kilauea's subaerial surface and an unknown, but probably appreciable, part of its submarine surface.

Both the remarkably continuous motions at widespread sites distant from known magmatic reservoirs and the long wavelength (>10 km) of the leveling profiles spanning the summit and lower east rift zone (Fig. 4) suggest that the deformation is originating deep within Kilauea's edifice. Although gravitational subsidence can account for some of the deformation, the horizontal motions across the summit and rift zones and the extensive uplift of the volcano's south flank indicate that another mechanism is involved. We suggest that this extensive deformation is caused by inflation of a magma system situated along Kilauea's rift zones and the Koae fault system at depths extending downward from the known shallow system to the base of the volcanic pile at 9 to 10 km. The presence of this deep magma system is also suggested by the 1955 and 1960 lower east rift-zone eruptions, neither of which were heralded by shallow seismicity in the middle or upper rift zone, as would be expected if these eruptions had been fed by shallow dikes propagating downrift (*18*). Likewise, onset of summit subsidence was recorded ~10 days after the onset of these eruptions, in contrast to the rapid response typically observed during intrusion of shallow dikes.

If a deep magmatic body is deforming the volcano's surface in concert with slip along a deep, seismically active south flank thrust system, what is the configuration of this body? Axial subsidence with flanking uplifts are characteristic of elastic displacements associated with pressure changes in a dike (*19*). The deformation observed along the east-rift-zone transect (Fig. 4B) between 1976 and 1988 can be accounted for by the inflation of a dike that dips ~80° southward. However, such a simple model does not account for the persistent south flank seismicity. Although surface-deformation data cannot provide a unique interpretation of subsurface processes, elastic dislocation models (*20*) allow prediction of the vertical displacements resulting from inflation of a deep, dike-like magma body beneath the east rift zone, along with concomitant slip along a horizontal fault located near the base of the south flank (Fig. 6, A and B). One meter of dilation of an infinitely long vertical dislocation extending downward from 3 to 9 km, accompanied by the same amount of slip along a 7-km-wide horizontal dislocation, produces surface displacements that resemble those observed along the east-rift-zone leveling transect (compare Fig. 6C). The dilation of this body, as well as the amount of slip on the thrust fault system most likely increase westward to account for the greater amplitude of ground-surface motions near the summit (Fig. 4A).

Data collected on the earth's surface allows only relatively simple interpretations of structures and processes acting at depth. Most likely, the postulated dike-like magma body is complex in form and is comprised of numerous pockets of magma separated by partially molten and solidified material. Although we estimate that the dilation near the east rift leveling transect is 1 m (Figs. 1B and 4B), the thickness of the body is probably much greater. Ryan (*21*) argued that a deep, rift-zone magma body is likely to contain primarily dense, picritic magma. Dieterich's (*22*) recent analysis of Kilauea's south flank motions in terms of a critical Coulomb wedge is based on a continuous magma column from the surface to the base of the volcanic pile.

A model consisting of a point source of dilation in an elastic half-space (*23*) has commonly been used to interpret the inflations and deflations associated with the well-established shallow magma reservoir at Kilauea's summit. Such a model, however, can account for neither the pervasive extension (Fig. 3A) nor the long wavelength of

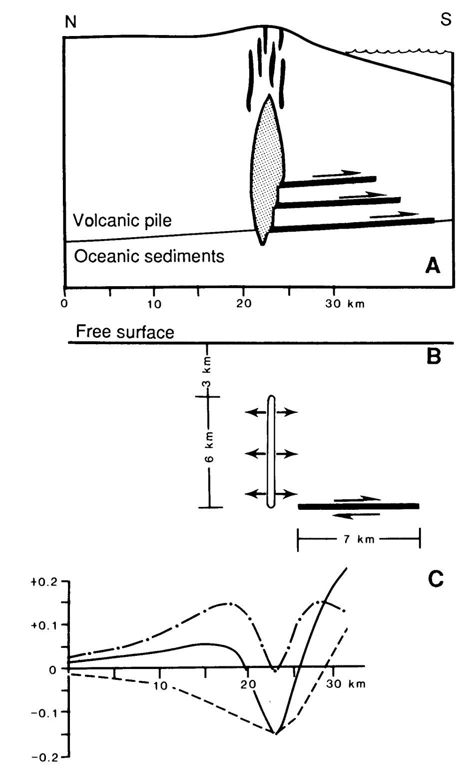

Fig. 6. Model of deformation processes of the Kilauea rift zone. (**A**) Schematic north-south section showing shallow dikes (vertical black lines) emplaced by lateral propagation from the summit reservoir, deep dike-like magma system (stippled), and south flank thrust-fault system located at and above the contact between the volcanic pile and underlying oceanic sediments. This contact dips toward the center of the island of Hawaii because of loading caused by the weight of the volcanic pile. Vertical exaggeration 3×. (**B**) Idealization of deep, dike-like magma system and seaward motion on a horizontal thrust fault. (**C**) Calculated vertical displacements (in meters) due to 1.0 m of dilation of a vertical dike (dash-dotted line), 1.0 m of slip along a horizontal thrust fault (dashed line), and combination of the two (solid line). The profile for combined dilation and slip resembles the pattern of vertical deformation in the level transect shown in Fig. 3B for the period from 1976 to 1988.

the vertical displacements (Fig. 4A). An apparent paradox thus emerges: the overall structure of Kilauea, while consisting of a clearly defined summit with radiating rift zones, can also be thought of as a single large rift system that is dilating the entire volcanic edifice. These two views can be reconciled by noting that the respective structures operate at different depths in the volcanic pile. Kilauea's primary near surface structures—the summit magma reservoir, two rift zones, and Hilina Pali and Koae fault systems—respond to processes operating deep in the volcanic pile. These processes—inflation of a long, dike-like magma body and seaward motion along the thrust system near the base of Kilauea's south flank—interact with those associated with the already well-identified shallow features.

The uplift of Kilauea's south flank is perhaps alarming, in view of the destructive 1975 earthquake and accompanying tsunami. Could continued uplift lead to another large earthquake? We cannot answer this question with any assurance because processes defining the mechanics of the earthquake cycle for such events remain uncertain. The seismicity beneath Kilauea's south flank and the associated ground deformation appear to be temporally pervasive. Many thousands of small, nondamaging earthquakes have taken place at depths of 5 to 10 km along the south flank since 1975, just as they did before that event. Although future destructive earthquakes are inevitable, the data do not necessarily support the view that such an event can be expected in the near future. What is clear, however, is that summit inflation and shallow rift-zone injection are not the only means for pushing the south flank seaward. Rather, the proposed deeper magma system is likely to hold the key to our understanding of the pervasive extension of Kilauea's summit and rift zones and the mobility of its south flank.

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6. The present eruption of Kilauea began with injection of a dike that fed an eruptive fissure along ~8 km of the middle east rift zone [J. J. Dvorak *et al.*, *Tectonophysics* **124**, 193 (1986); E. W. Wolfe, Ed., *U.S. Geol. Surv. Prof. Pap. 1463* (1988)]. Activity soon localized to a single vent, eventually christened Pu'u 'O'o. Over the next 3.5 years, month-long periods of quiescence separated more than 40 phases of activity, each comprised of gas-driven lava fountains that were active from a few hours to a few days; cinders and other ejecta built Pu'u 'O'o to a height of 255 m. During phase 48, in July 1986, activity migrated to a new vent ~4 km downrift. This phase of the eruption has been characterized by continuous activity. A lava shield has been built by successive overflows from an active pond that forms the present vent. The Kupaianaha pond has remained active and has supplied lava through a system of underground lava tubes to surface flows at the coast, 10 to 11 km to the south.
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11. From the first western visitations in the early 19th century until 1924, eruptive activity at Kilauea caldera was essentially continuous, predominantly in the form of a lava pond, and thus the magma column reached the surface. The elevation of a benchmark (BM3973) on the northeast rim of Kilauea caldera was 1211.00 m in 1912, 1211.92 m in 1921–1922, and 1210.83 m in 1926–1927 [R. M. Wilson, *Univ. Hawaii Res. Publ. 12* (1935), Table IX]. Continuous summit activity ended in 1924 with a phreatic eruption at the summit that was preceded by numerous earthquakes and ground-surface cracking near Kapoho (Fig. 1B), 60 km away, at the east end of the island. Apparently, a major drainage of magma from the summit magma chamber into the east rift zone preceded the eruption, caused more than 1 m of ground-surface subsidence at benchmark BM3973, and led to a long-term adjustment of the height of Kilauea's magma column. The elevation of BM3973 was 1210.86 m in 1958, 1211.01 m in 1971, 1211.13 m before the earthquake in 1975, 1210.72 m in 1976, 1210.54 m in 1979, 1210.39 m in 1986, and 1210.46 m in 1988, as determined by leveling carried out by the U.S. Geological Survey. The summit magma chamber is centered beneath the southern wall of Kilauea caldera, ~5 km southeast of BM3973. The vertical motions of the ground surface directly above the magma chamber are considerably greater than those at BM3973; benchmarks in this region continue to indicate summit subsidence.
12. Expected variance of baseline length was determined from $\sigma^2 = a^2 + b^2L^2$, where $a \simeq 1$ cm and $b \simeq 10^{-6}$. For the longest lines of 22 km, $\sigma \simeq 2.5$ cm; for the shortest lines of 3 km, $\sigma \simeq 1$ cm. Although these values have not been independently confirmed for the instruments we used, they are consistent with both the manufacturer's specifications and the nominal precision for methods in which end-station measurements of temperature and pressure are used [S. H. Laurila, *Electronic Surveying in Practice* (Wiley, New York, 1983), chap. 5].
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14. Random-walk error propagation, $\sigma = aD^{1/2}$, where D is distance, was used for weighted least-sum-of-squares network adjustment [P. Vaníček and E. J. Krakiwsky, *Geodesy, the Concepts* (North-Holland, New York, 1986), chap. 19]. The 1976 leveling survey spanned 6 months and included double runs of most sections near Kilauea's summit and south flank; use of only the first runs would increase the estimates of uplift at the south end of the section by ~10 cm and increase the summit subsidence by ~20 cm. For the summit region, error estimates are obtained from the loop misclosures for each survey; these can be substantial because of the appreciable motions of the summit in the months following the M 7.2 earthquake. For the lower east rift zone, where deformation rates were modest, error estimates are $a = 3.5$ mm km$^{-1/2}$ for the 1976, 1979 and 1986 levelings and $a = 2$ mm km$^{-1/2}$ for the 1988 and 1989 levelings. The former value is obtained from loop misclosures; the latter value is from the standards for second-order, class-II leveling [Federal Geodetic Control Committee, *Standards and Specifications for Geodetic Control Networks* (National Oceanic and Atmospheric Administration, Rockville, MD, 1984)]; all loop misclosures for the 1988 and 1989 levelings are less than predicted by this standard.
15. Benchmark elevations at tide gauges are computed from monthly averages, usually with six or more measurements per day, during yearly, 1- to 3-month recording periods in late spring or early summer.
16. Well-head elevations are based upon single measurements of depth to water table. Each of the wells are less than 3 km from the coast; they penetrate highly permeable and porous rocks (bulk specific gravity is ~2.3). Continuous monitoring of Pulama well revealed daily fluctuations of ~30 cm that correlate well with ocean tides. Although Kapoho well produces potable water, the others are brackish. Accordingly, the wells are good measures of sea level, and the data variance is ascribed primarily to ocean tides and short-term response to rainfall. The wells were monitored for a few years before the 1975 earthquake, during which time there was no evidence for vertical motion. We therefore accept the data variances for this period as the best estimates of water table fluctuations in the absence of vertical motion of the aquifer.
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18. When reports describing the 1955 and 1960 eruptions were written [(*2*); G. A. Macdonald and J. P. Eaton, *U.S. Geol. Surv. Bull. 1171* (1964); D. H. Richter, J. P. Eaton, K. J. Murata, W. U. Ault, H. L. Krivoy, *U.S. Geol. Surv. Prof. Pap. 537-E* (1970)], there had been no observations of intense, shallow seismic swarms that migrated downrift from the summit. Seismicity preceding and accompanying both eruptions was predominantly in the lower east rift, near the sites of the eruptive vents. The 1955 vents propagated ~12 km uprift, in contrast to the typical downrift propagation of shallow dikes coming from the summit region. Although there was a swarm of shallow earthquakes at one locale in the middle east rift during the 1955 eruption, there was no migration of seismicity along the upper or middle east rift zone during either eruption and the intensity of the activity was much less than has been typical of the numerous rift-zone dike injections that occurred between the late 1960s and early 1980s (J. P. Eaton, personal communication). Although the seismic network of 1955 was sparse and suffered from poor timing mechanisms, the Kilauea summit network was capable of recording earthquakes with magnitudes greater than 1.5 along the upper and middle east rift zone, had they occurred at the time of the 1960 eruption.
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