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Mechanism of explosive eruptions of Kilauea Volcano, Hawaii

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Abstract. A small explosive eruption of Kilauea Volcano, Hawaii, occurred in May 1924. The eruption was preceded by rapid draining of a lava lake and transfer of a large volume of magma from the summit reservoir to the east rift zone. This lowered the magma column, which reduced hydrostatic pressure beneath Halemaumau and allowed groundwater to flow rapidly into areas of hot rock, producing a phreatic eruption. A comparison with other events at Kilauea shows that the transfer of a large volume of magma out of the summit reservoir is not sufficient to produce a phreatic eruption. For example, the volume transferred at the beginning of explosive activity in May 1924 was less than the volumes transferred in March 1955 and January-February 1960, when no explosive activity occurred. Likewise, draining of a lava lake and deepening of the floor of Halemaumau, which occurred in May 1922 and August 1923, were not sufficient to produce explosive activity. A phreatic eruption of Kilauea requires both the transfer of a large volume of magma from the summit reservoir and the rapid removal of magma from near the surface, where the surrounding rocks have been heated to a sufficient temperature to produce steam explosions when suddenly contacted by groundwater.

Introduction

Eruptions of Kilauea Volcano, Hawaii, often produce high lava fountains, caused by rapid expansion of volatiles contained in lava. The mild explosive nature of these fountains poses little hazard and results in little, if any, destruction. Much of the summit region of Kilauea, however, is covered by deposits formed during explosive activity much more intense than occurs during lava fountaining. Some deposits were produced by large explosions that formed base surges and resulted in accumulation of several meters of pyroclastic material.

The rarity and potential destructiveness of explosive eruptions at a volcano where most eruptions are relatively mild prompted my investigation of the conditions that might produce these unusual eruptions. In this paper I examine the sequence of events associated with the May 1924 explosive eruption, as well as activity that, at other times, had characteristics similar to some aspect of the 1924 eruption, but did not result in explosive activity. In particular, by using tilt measurements, I compare the magnitude of activity that occurred during draining of a lava lake or a large subsidence of the summit in May 1922, August 1923, February to June 1924, March 1955, and January to June 1960.

Kilauea Volcano

The structure of Kilauea, a basaltic shield volcano that forms the east portion of the island of Hawaii, is dominated by a summit caldera and two rift zones radial to the caldera (Fig. 1). The summit caldera formed by repeated collapses when large volumes of magma were withdrawn from an underlying reservoir (Macdonald 1965). Subsequent summit eruptions partially refill the caldera and may overflow sections of the caldera walls before the next major collapse.

The eruptive cycle of Kilauea has been documented by many researchers (e.g. Eaton and Murata 1960; Fiske and Kinoshita 1969; Swanson et al. 1976). Magma rises from a source region in the upper mantle to a reservoir that lies within the volcano. Most of the net movement of magma in this reservoir occurs at depths of 2 to 4 km beneath the caldera floor (Dvorak et al. 1983). Magma accumulation in the summit reservoir has been recorded by a variety of geodetic techniques that measure the accompanying uplift, distension, or tilting of the ground. Eventually increased pressure in the reservoir caused by magma accumulation opens old conduits or forms new cracks, which act as pathways for magma to move from the reservoir either to the surface, producing a summit eruption, or into a conduit system that underlies both rift zones. Rift eruptions often precede the movement of

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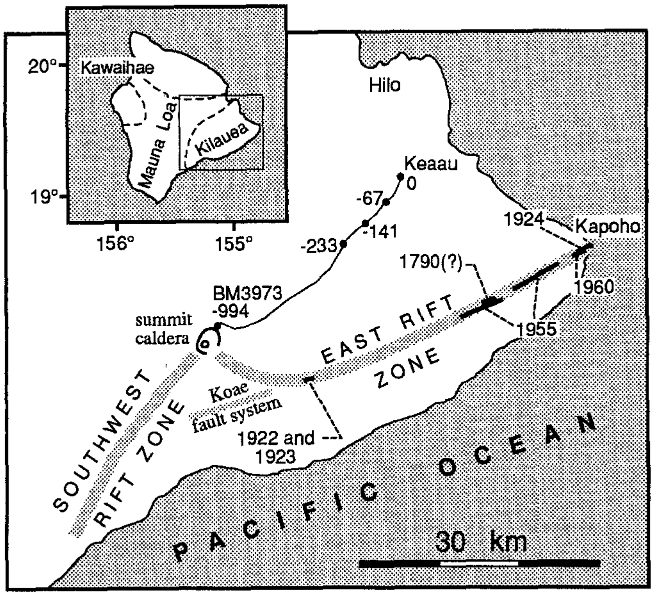

Fig. 1. Location map of Kilauea Volcano on the island of Hawaii. The structure of the volcano is dominated by a summit caldera, which formed by collapse, and two radial rift zones. The locations of eruptive fissures and ground cracks associated with the events described in the text are shown as *short line segments* along the east rift zone. The level route from Keaau to BM3973, on the northeast rim of the caldera, is shown by a *thin solid line.* The elevation changes at four benchmarks, measured between 1920–1922 and 1926–1927, taken from Wilson (1935), are relative to Keaau and expressed in millimeters. A negative value indicates subsidence

magma from the summit reservoir to the rift zone, which causes the summit region to subside. The progress of this subsidence is easily monitored by making frequent tilt measurements (Dvorak and Okamura 1987).

Explosive eruptions have occurred from vents in the summit region, probably as steam explosions when groundwater interacted with hot rock or magma (Decker and Christiansen 1984). These eruptions produced fallout and base-surge deposits, which comprise less than 1% of the volcanic products of Kilauea exposed above sea level (Macdonald 1972). Deposits of three episodes of explosive eruptions are exposed in the summit region. A few outcrops of the oldest, the Uwekahuna Ash Member, deposited 1500 to 2100 years ago, are still visible at the base of the caldera wall (Casadevall and Dzurisin 1987). The other two deposits are the Keanakakoi Ash Member, which covers most of the surface beyond the caldera rim, and debris from the 1924 explosions that originated in the main summit pit crater Halemaumau.

These explosive eruptions were probably produced by the expansion of steam during rapid interaction of groundwater and hot rock or magma (Decker and Christiansen 1984). The source of water for this steam is probably a water table at a depth of about 500 m, encountered in a deep research hole drilled in the south caldera region in July 1973 (Zablocki et al. 1974). Geoelectric soundings suggests this elevated water table lies beneath most of the summit region and is the result of impoundment of rainwater by lateral barriers within the volcano, possibly by high-angle dike complexes or faults (Jackson and Kauahikaua 1987).

Chronologies and characteristics of events

The next section summarizes activity in 1924, which culminated in a series of explosions in May of that year, and activity associated with four other events that had characteristics similar to some stage of the 1924 activity, but did not result in explosions. By examining these four non-explosive events, it is possible to constrain the conditions that led to explosive activity in 1924. The first two events were sudden drops in the level of active lava lakes in May 1922 and August 1923; the former also coincided with the partial collapse and enlargement of Halemaumau, which produced cauliflower-shaped clouds rising from the pit crater. The other two were large summit subsidences in 1955 and 1960; the later one caused a 150 m drop of the floor of Halemaumau.

The May 1924 explosive eruption

In December 1923, the lava lake stood within 50 m of the rim of Halemaumau (Fig. 2). The lake began to drop rapidly in mid February 1924 and had drained completely by 21 February, leaving the floor of Halemaumau 120 m below the rim. This was not a unique event. Several times since the founding of a volcano observatory in 1912 when continuous observations were begun of volcanic conditions at Kilauea, the lava lake had dropped suddenly, and even drained completely. Such activity often preceded the start of rift activity and the occurrence of summit-wide subsidence, indicated by tilt changes measured in Whitney vault, located on the caldera rim 4 km northeast of Halemaumau. Rift activity and summit-wide subsidence occurred also in 1924.

During the night of 22–23 April, many earthquakes were felt and ground cracking began along the lower east rift zone in the Kapoho area (Fig. 1), an indicator that magma was moving along this section of the rift zone. A week later the floor of Halemaumau began to drop again, though the major collapse and enlargement of the crater did not begin until 10 May, shortly before the start of explosions.

Explosions from Halemaumau, which began during the night of 10–11 May and occurred at irregular intervals lasting up to a few hours, were accompanied by a continuous roar, frequent lightning flashes and thunder, and ejection of blocks, lapilli and ash. Each explosion produced a cauliflower-shaped cloud reaching heights of as much as 4 km above the caldera floor. By the end of the explosions, the diameter of Halemaumau had increased to about 1 km and the floor was as much as 400 m below the rim, an engulfment corresponding to the removal of 200 million m^3 of material (Jaggar 1924a). The lack of noxious fumes, the absence of a major glassy component in fragments ejected by the explosions, and the appearance of white steam clouds at the end of activity led Jaggar (1924b) and others to suggest these explosions were entirely phreatic.

Summit-wide subsidence, as indicated by the Whitney tilt record (Jaggar and Finch 1929), may have begun as early as mid March and continued until mid June (Fig.

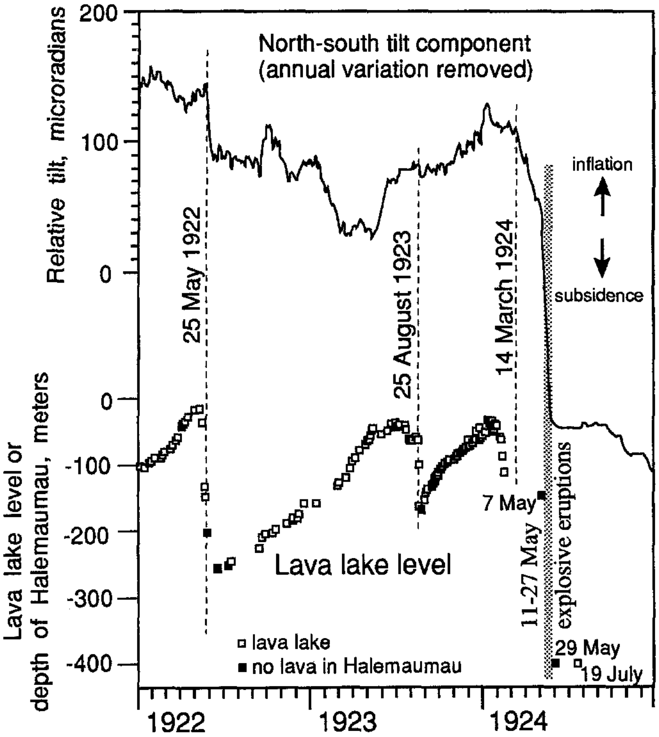

Fig. 2. North-south tilt component measured at Whitney vault from 1922 to 1924. The annual variation in tilt has been removed from these measurements (Powers 1947). *Open squares* show the depth of the lava lake below the rim of Halemaumau; *solid squares* show the depth of Halemaumau when no lava was present in this pit crater. Draining of the lava lake preceded the onset of tilt changes in May 1922 and March 1924. The lava lake drained three times during this period: 13–26 May 1922; 23–28 August 1923 and 15–21 February 1924. No tilt change was associated with the August 1923 draining. Eruptions occurred along the upper east rift zone on 28 May 1922 and 28 August 1923. Steam explosions occurred from Halemaumau from 11 to 27 May

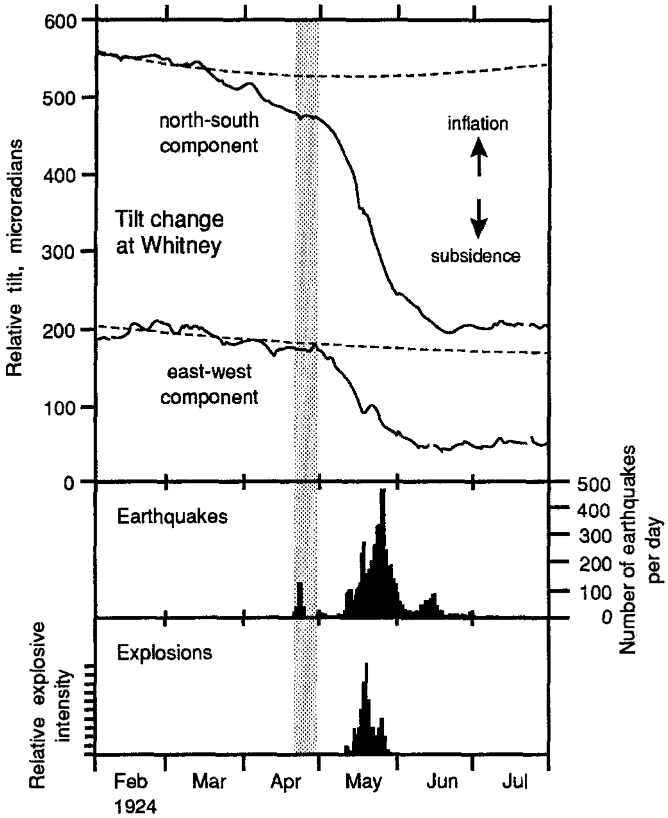

Fig. 3. Tilt changes and number of earthquakes recorded per day between February and July 1924 by a seismograph in Whitney vault. A decrease in tilt is a downward deflection of the ground to the south or west, both trends corresponding to summit subsidence. The *dashed lines* show the seasonal tilt pattern measured for each tilt component during periods of quiescence (Powers 1947). The relative explosive intensity, shown at the bottom, is an empirical estimate made by observers. The *shaded vertical bar* indicates when cracks were opening along the lower east rift zone near Kapoho

3). About one-third of the total tilt change between March and June 1924 occurred before the start of explosive activity.

While the tilt record shows the timing of the subsidence, the volume of subsidence is estimated from the results of level surveys conducted before and after 1924. Surveys were conducted from Keaau to the summit of Kilauea and along several short routes in the summit region between June 1920 and February 1922 and again between November 1926 and June 1927 (Wilson 1935). The elevation changes published by Wilson for the route from Keaau to BM3973, on the northeast rim of the caldera near the Whitney vault, showed progressively larger subsidence closer to the summit region (Fig. 1). Because this progressive change may indicate a problem in the rod corrections applied to the 1920–1922 survey (DA Swanson, unpublished data), I used only elevation changes in the summit region *relative* to BM3973 to compute a subsidence volume.

Of the 15 benchmarks in the summit region of Kilauea listed by Wilson, only 14 were used to compute a subsidence model to match the elevation changes measured between the 1920–1922 and 1926–1927 surveys. The measured elevation change of the benchmark called Beggar located on the east rim of Halemaumau (Fig. 4) was more than 1 m lower than nearby benchmarks, suggesting that some downward movement of Beggar was caused by local slumping of the rim of Halemaumau, perhaps during enlargement of the pit crater. For this reason, I excluded the elevation change at Beggar from my calculations.

The relative elevation changes for the other 14 benchmarks were used to compute a pressure center based on a point-source of dilation embedded in an isotropic, homogeneous, elastic half-space. For this model, the values for the parameters listed in Table 1 minimize in the least-squares sense the difference between measured and computed elevation changes. The vertical movement of the reference benchmark BM3973 was also a parameter. The least-squares model estimated a subsidence volume of 400 million m^3, about twice the volume of enlargement of Halemaumau in 1924 (Table 2). The tilt change at Whitney computed for this model is within 30 microradians of the changes measured between 14 March and 23 June 1924 (Table 3).

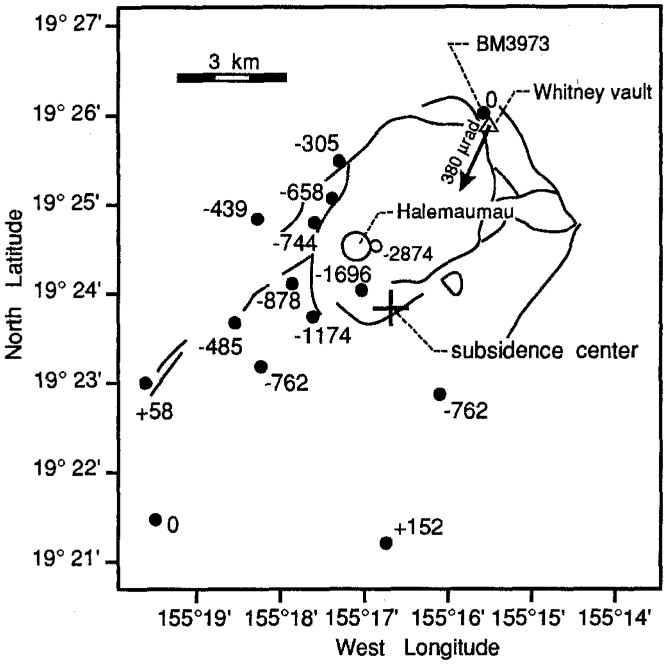

Fig. 4. Level benchmarks surveyed between June 1920 and February 1922 and again between November 1926 and June 1927. The elevation change for each benchmark is given in millimeters, relative to BM3973 on the northeast rim of the caldera. A negative value indicates subsidence. The horizontal seismograph used to record earthquakes and tilt is located in Whitney vault near BM3973. The vector shows the tilt direction measured at Whitney between 14 March and 23 June 1924. The subsidence center for the 1924 activity was determined from a least squares solution to the elevation changes

A comparison of measured and computed elevation changes is shown in Fig. 5. I estimate the reference benchmark BM3973 subsided 1130 mm (±200 mm), which, within the uncertainty, is consistent with Wilson's value of 994 mm for the measured amount of subsidence of BM3973 (Fig. 1). This restores confidence that the elevation changes between Keaau and BM3973 listed by Wilson indicate actual ground movement, perhaps the existence of a deep center of deflation, as suggested by Mogi (1958). While this is one possible interpretation, the limited coverage of this single, long level line makes it difficult to identify the cause of the far-field vertical movement; it cannot be explained by the shallow point-source model listed in Table 1.

Table 1. Location and volume of 1924 and 1960 subsidence centers
See Figs. 4 and 9 for map positions of subsidence centers

Level surveys: (July 1920–December 1921) to (November 1926–June 1927)		
Longitude	155° 16.7′	± 0.4 km
Latitude	19° 23.8′	± 0.3 km
Depth	4.5 km	± 0.7 km
Volume	400×10^6 m^3	± 70×10^6 m^3
Upward movement of BM3973	1130 mm	±200 mm
Tilt surveys: (28–31 December 1959) to (5–14 July 1960)		
Longitude	155° 17.0′	± 0.3 km
Latitude	19° 24.3′	± 0.2 km
Depth	3.5	± 0.7 km
Volume	180×10^6 m^3	± 60×10^6 m^3

May 1922 and August 1923

In 1922, the lava lake, which had risen to within 15 m of the rim, began to drop on 13 May and drained completely by 26 May, when the floor was 220 m below the rim (Fig. 2). Earthquake activity peaked on 25–26 May, and was followed by a two-day eruption along the east rift zone (Fig. 1). Summit-wide subsidence, indicated by the Whitney tilt record (Fig. 6), also began on 25 May.

Large rock avalanches from the walls of Halemaumau began on 26 May and continued for five days, producing cauliflower-shaped clouds of red dust, which rose hundreds of meters above the rim of Halemaumau. A thunderous roar associated with this avalanching was heard several kilometers away (Jaggar 1922). After the avalanching ended, the diameter of Halemaumau had increased slightly to 600 m, and the floor was 270 m below the rim.

Jaggar (1924b) suggested that minor steam explosions may have occurred in Halemaumau in May 1922, but went unnoticed, perhaps because the observers of this activity had never witnessed this type of activity. Con-

Table 2. Dates of activity and volume changes

Year	Tilt change at Whitney	Exploded debris	Lava lake	Engulfment of Halemaumau
1922	25–29 May 20×10^6 m^3	26–30 May negligible	13–26 May 4×10^6 m^3	26–30 May 4×10^6 m^3
1924	14 March–mid June 400×10^6 m^3	10–27 May 0.8×10^6 m^3	15–21 February 3×10^6 m^3	29 April–30 May 200×10^6 m^3
1955	5 March–9 April 120×10^6 m^3	none	no lake	none
1960	17 January–mid June 180×10^6 m^3	none	no lake	7 February–11 March 25×10^6 m^3

Table 3. Measured and calculated tilt changes at Whitney vault (given in microradians)
(A negative tilt change is a downward deflection of the ground to the south and west.)

	Measured		Calculated	
	N/S	E/W	N/S	E/W
25 to 29 May 1922	− 50	− 35		
14 March to 23 June 1924	−340	−160	−350	−140
8 March to 9 April 1955	−140	− 80		
18 January to 5 May 1960	−260	−120	−240	−160

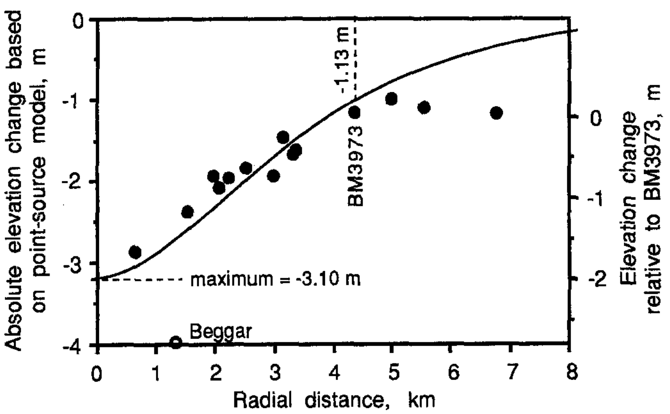

Fig. 5. Measured and computed elevation changes in the summit region of Kilauea related to the 1924 subsidence, plotted as a function of radial distance from the subsidence center. The *solid line* shows the elevation changes computed for the point-source model given in Table 1. According to the elastic model, the maximum subsidence was 3100 mm, located about 1 km southeast of Halemaumau. According to this model, the reference benchmark BM3973 subsided 1130 mm. Measured elevation changes are denoted by *circles*. The *unfilled circle* at a radial distance of 1.4 km is for the benchmark Beggar located on the east rim of Halemaumau. Because this benchmark subsided about 1 m more than nearby benchmarks, its movement was probably the result of local slumping of the rim of Halemaumau. Subsequently, the elevation change for Beggar was not used to compute the elastic point-source model

tinuous rock avalanches and the rise of cauliflower-shaped clouds in May 1922 may have been similar to the activity witnessed during the first days of explosive activity in May 1924.

After a 14 month rise, the lake level dropped again between 25 and 28 August 1923, leaving the floor 170 m below the rim by the end of August. No summit tilt change accompanied the drop, but a small eruption, first seen on 26 August, occurred near the 1922 outbreak (Fig. 1).

March 1955

The 1955 eruption occurred along the lower east rift zone, a few kilometers from the 1924 and 1960 rift events (Macdonald and Eaton 1964), possibly in the area of at least one of the 1790 eruptive vents (Fig. 1). The

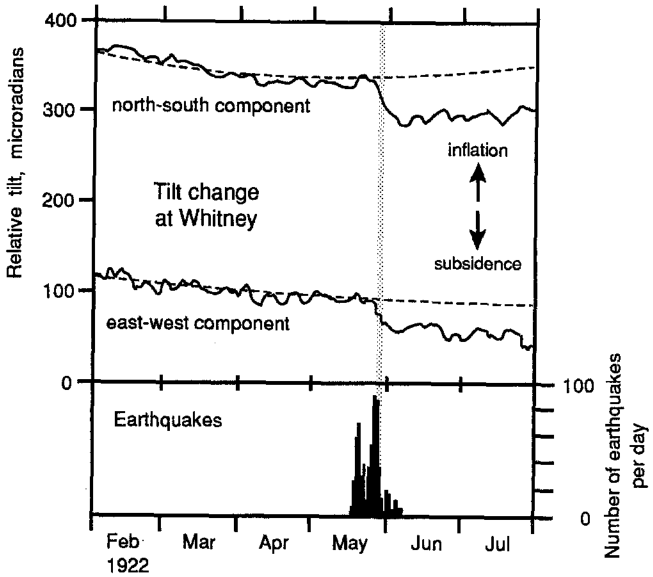

Fig. 6. Tilt changes and number of earthquakes recorded per day at Whitney vault between February and July 1922. Draining of the lava lake in Halemaumau preceded by a few days the summit subsidence recorded in the Whitney vault between 25 and 29 May and a small eruption along the upper east rift zone on 28 May. The *shaded vertical bar* indicates the timing of the rift eruption. See Fig. 3 for explanation of *dashed lines*

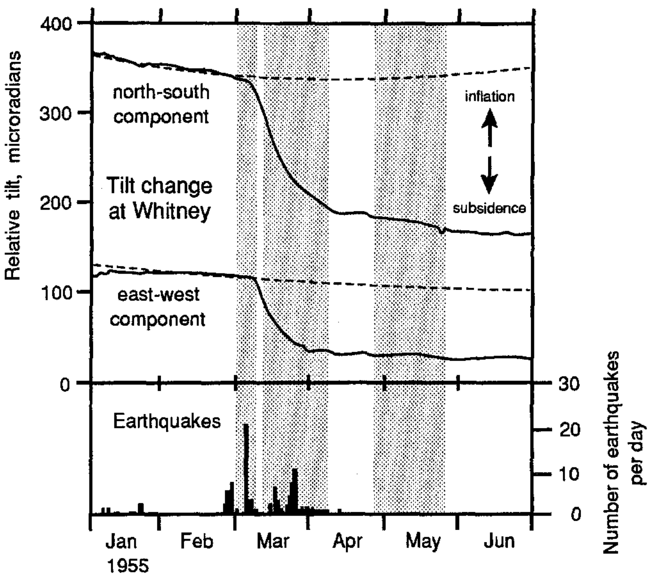

Fig. 7. Tilt changes and number of earthquakes recorded per day at Whitney between January and June 1955. See Fig. 3 for explanation of *dashed lines*. The *shaded vertical bars* indicate the occurrence of eruptive activity along the east rift zone

1955 eruption lasted nearly two months and produced 100 million m^3 of lava.

Summit subsidence began on 8 March and continued about four weeks (Fig. 7). The net tilt change was 160 microradians, slightly more than half the amount recorded a few years later in 1960 (Table 3). By scaling the tilt change recorded at the Whitney vault in 1955 to the tilt changes recorded in 1924 and 1960 (see next subsection), the volume of summit subsidence in March 1955 was about 140 million m^3.

January to February 1960

From 13 January to 14 February 1960, an eruption, which produced 120 million m^3 of lava, occurred on the lower east rift zone near Kapoho, near the location of the 1924 ground cracks (Fig. 1). During the few weeks after the eruption ended, the floor of Halemaumau dropped 150 m, corresponding to a collapse of 20 million m^3, one-tenth the volume of the 1924 collapse.

Summit-wide subsidence began on 17 January and continued until early May (Fig. 8). The total tilt change recorded at Whitney vault, using a water-tube instrument (Eaton 1959), was 290 microradians.

The volume of the 1960 summit subsidence was estimated from tilt measurements using portable water-tube instruments at seven sites in the summit region on 28–31 December 1959, and again on 5–14 July 1960. Intersection of the resultant tilt vectors located the subsidence center in the south caldera (Fig. 9), within several hundred meters of the May 1924 subsidence center (Fig. 4). The least-squares point-source model to these tilt vectors is listed in Table 1. The total volume of subsidence in 1960, which includes both the deepening of Halemaumau and the summit-wide subsidence determined by tilt measurements, was about 200 million m^3, about one-third the total volume of subsidence in 1924.

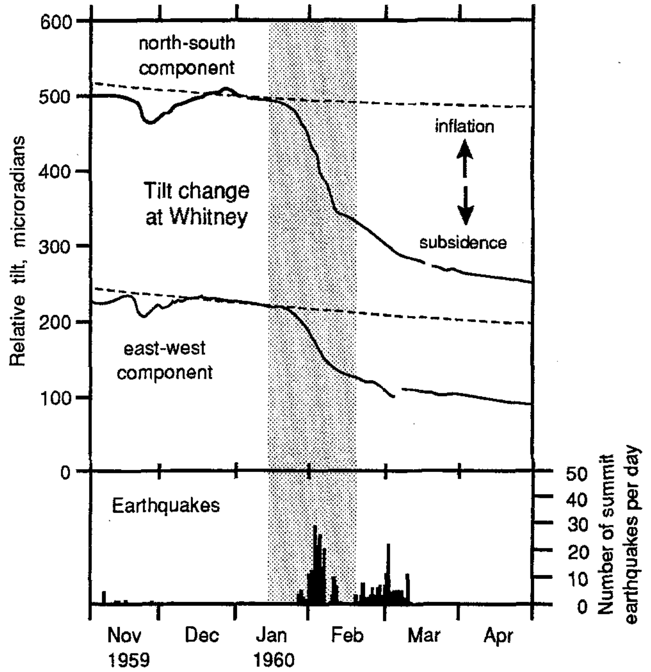

Fig. 8. Tilt changes and number of summit earthquakes recorded per day at Whitney vault between November 1959 and April 1960. The floor of Halemaumau deepened 150 m between 7 February and 11 March. See Fig. 3 for explanation of *dashed lines*. The *shaded vertical bar* indicates the occurrence of eruptive activity along the east rift zone

Mechanism of Hawaiian phreatic eruptions

Part of the activity that led to the May 1924 phreatic eruption was the rapid draining of the lava lake, followed by large rock falls from the walls of Halemaumau as the floor of this pit crater dropped. Immediately before the start of explosive activity, the floor of Halemaumau was 150 m below the rim. In May 1922 the floor was about 200 m below the rim when large rock falls began and cauliflower-shaped clouds first rose from the crater; however, this did not lead to vigorous explosions. In August 1923 the floor dropped to a level 170 m below the rim without causing large rock falls and the rise of cauliflower-shaped clouds, and without explosions. The lava lakes dropped at the same average rate in 1922, 1923 and 1924, about 20 m per day. What was the difference in volcanic conditions during these three events that produced a phreatic eruption only in 1924?

A major difference was the amount of summit-wide subsidence, as indicated by the Whitney tilt record. No measurable change was recorded in 1923, and only 60 microradians in 1922. Before the start of explosive activity in 1924, the tilt change at Whitney vault was 200 microradians, which, if scaled to the model given in Table 1, corresponded to the withdrawal of about 200 million m^3 of magma from the summit reservoir to the east rift zone. The withdrawal of this large volume of magma reduced the hydrostatic pressure in the magma column be-

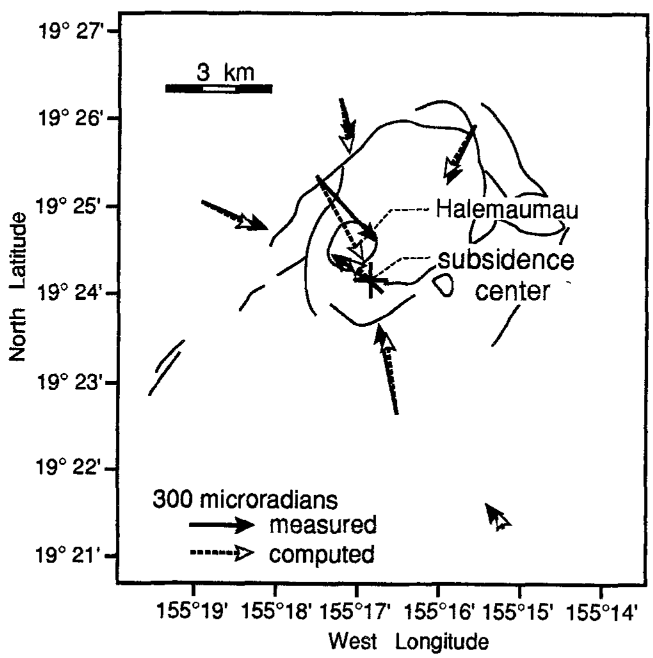

Fig. 9. Measured and computed tilt changes associated with the 1960 summit subsidence. Solid vectors are tilt changes measured using a portable water-tube between 28–31 December 1959 and 5–14 July 1960. The *dashed vectors* are computed changes for the point source solution listed in Table 1. According to the model, the subsidence center dropped 2300 mm

neath Halemaumau, allowing rapid lateral flow of groundwater into high-temperature areas that had been heated for several decades by the magma conduit supplying the lava lake.

A large summit subsidence, however, is not sufficient to cause explosive activity, as suggested by the lack of steam explosions in the summit region in 1960, when 200 million m^3 of magma was removed from the summit reservoir, equal to the volume of summit subsidence at the beginning of explosive activity in May 1924. Also, a high rate of magma withdrawal from the summit reservoir seems to be unimportant. The average subsidence rates measured at Whitney vault in 1924, 1955 and 1960 were three to five microradians per day; much slower than the tilt rates of tens to hundreds of microradians per day recorded when eruptions occur along the upper and middle sections of the east rift zone (Dvorak and Okamura 1987).

From these comparisons, I suggest that two essential elements are needed to produce a Hawaiian phreatic eruption: (1) a drop by a few hundred meters in the level of a long-lived lava lake, which means removal of magma from a shallow depth surrounded by groundwater, and (2) withdrawal of at least a few hundred million cubic meters of magma from the summit reservoir. The latter requirement probably occurs only when rift activity is located at low elevations or along an undersea portion of a rift zone (Epp et al. 1983). The prior existence of a long-lived lava lake is needed to heat the surrounding rocks to sufficiently high temperatures, at least several hundred degrees Celsius, in order to have the conditions for film boiling that can lead to steam explosions.

Discussion

My investigation into the volcanic conditions necessary to produce a phreatic eruption at Kilauea has led me to wonder about other, larger explosive eruptions in Hawaii. In particular, how does the study of the minor explosive eruption in 1924 relate to the devastating, and fatal, explosive eruption in 1790?

A series of explosive eruptions, much larger than the 1924 explosions, occurred from the summit region of Kilauea in 1790. An eruptive column produced by this activity was probably seen from Kawaihae on the northwest coast of Hawaii, about 100 km from the summit of Kilauea (Jaggar 1921), indicating the clouds produced by these explosion must have risen several kilometers. The later phases of this activity, which resulted in the deaths of some members of a Hawaiian army traveling across the summit region, are probably recorded in Hawaiian oral tradition (Ellis 1827). The explosions produced a series of ashfall and surge deposits (the Keanakakoi Ash Member) up to 11 m thick that cover most of the caldera rim and are still exposed as patches on the caldera floor. The upper third of the Keanakakoi was the result of phreatic activity (McPhie et al. 1990), possibly produced by conditions similar to those set up in 1924, that is, rapid draining of a lava lake and eruption of a large lava flow along the lower east rift zone (Holcomb 1987). The 1790 phreatic explosions were more intense than those in 1924 because of a larger lava lake, a more extensive shallow magma conduit in 1790, or a deeper caldera floor, so that the hot rock-water interaction occurred at a shallower level in 1790 than 1924. (As noted by McPhie, the earliest descriptions and maps of Kilauea, both dating from the 1820s, indicate the caldera floor was about 200 m deeper than it is today.)

The lower two-thirds of the Keanakakoi is composed of glassy and vesiculated particles, the result of phreatomagmatic activity. These particles indicate a major magmatic component was vigorously degassing as the lower two-thirds of the Keanakakoi was erupted. Decker and Christiansen (1984) and McPhie et al. (1990) suggest the transition from phreatomagmatic to phreatic activity in the Keanakakoi was the result of lowering of a magma column, so that less magma was involved during the later stages of the explosive activity. However, none of these researchers explained why vigorous magma degassing should occur during a drop of the magma conduit and, as suggested by Decker and Christiansen, collapse of the summit caldera. The observations made in 1924 would indicate otherwise: the lava lake had drained and hundreds of millions of cubic meters of magma had left the summit reservoir before explosive activity began.

Based on the observations recounted in this paper, I interpret the phreatomagmatic and phreatic sections of the Keanakakoi Ash Member as the result of two different volcanic conditions. The phreatomagmatic section may have been produced by the eruption of lava fountains through shallow groundwater, when the caldera was deeper, and not during a drop of the magma conduit. Later, draining of a lava lake and withdrawal of a large volume of magma from the summit reservoir, as in 1924, produced the 1790 phreatic deposits.

Summary

Groundwater, supplied by an elevated water table, was involved in the explosive eruptions that produced tephra deposits in the summit region of Kilauea. This elevated water table exists in the summit region because rainwater that percolates beneath the summit region is restricted from flowing to lower regions of the volcano, perhaps by barriers, such as dike complexes or gouges in fault systems that ring the summit caldera. The lack of tephra deposits exposed in the walls of Mokuaweoweo, the summit caldera of Mauna Loa, which lies at an elevation 3 km higher than Kilauea, leads me to suspect that a shallow water table does not underlie the summit region of this other volcano. The few patches of shattered boulders and rocky debris found in small areas on the east side of Mokuaweoweo near the summit cabin and around the true summit were probably produced when lava encountered a pocket of ice or snow, which are plentiful in many of the cracks and crevices that ring the caldera.

At Kilauea I suggest the phreatic and phreatomagmatic eruptions occur during different volcanic conditions. Phreatic eruptions, such as occurred in 1924 and during the latter stages of activity in 1790, which form the upper third of the Keanakakoi Ash Member, require the prior existence of a long-lived lava lake. A sudden drop in lake level to within a hundred meters of the elevated water table in the summit region *and* a decrease in hydrostatic pressure as the magma column beneath the lava lake drops are both needed to produce a phreatic eruption. The drop in the magma column occurs by withdrawal of a large volume of magma (at least a few hundred million cubic meters) from the summit reservoir. As a result, groundwater is able to flow rapidly into areas of very hot rock. The large temperature difference between groundwater and very hot rock, previously heated by magma, sets up conditions conducive to large steam explosions. This would seem to rule out the possibility of a phreatic eruption under the present conditions of Kilauea: the lack of a summit lava lake for several decades and the low temperatures measured in a drill hole (Zablocki et al. 1974) makes it unlikely that high enough temperatures exist to produce the condition of film boiling needed to produce steam explosions.

The key to understanding the conditions necessary for Hawaiian phreatomagmatic eruptions is the presence of glassy and vesiculated particles, which indicate vigorous magma degassing, in the lower two-thirds of the Keanakakoi Ash Member, possibly also erupted in 1790 before the phreatic deposits were erupted. Decker and Christiansen (1984) and McPhie et al. (1990) suggested this occurred by continual withdrawal of magma from the summit reservoir, and subsequently lowering of magma in a shallow conduit. I suggest the phreatomagmatic deposits were formed before collapse of the summit region, by eruption of lava fountains through very shallow groundwater when the caldera floor was a few hundred meters deeper than today and, possibly, nearer the water table.

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