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The 1919-1920 eruption of Mauna Iki, Kilauea: chronology, geologic mapping, and magma transport mechanisms

Scott K Rowland and Duncan C Munro

Planetary Geosciences, Dept. of Geology and Geophysics, School of Ocean and Earth Science and Technology, 2525 Correa Rd. Honolulu, Hawaii 96822

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Abstract. Utilizing historical accounts, field mapping, and photogeology, this paper presents a chronology of, and an analysis of magma transport during, the December 1919 to August 1920 satellitic shield eruption of Mauna Iki on the SW rift zone of Kilauea Volcano, Hawaii. The eruption can be divided into four stages based on the nature of the eruptive activity. Stage 1 consisted of the shallow injection of a dike from the summit region to the eventual eruption site ~10 km downrift. During stage 2, a low ridge of pahoehoe formed in the vent area; later a large a'a flow broke out of this ridge and flowed ~8.5 km SW at an average flow front velocity of 0.5 km/day. The eruption continued until mid-August producing almost exclusively pahoehoe, first as gas-rich overflows from a lava pond (stage 3), and later as denser tube-fed lava (stage 4) that reached almost 8 km from the vent at an average flow-front velocity of 0.1 km/day. Magma transport during the Mauna Iki eruption is examined using three criteria: (1) eruption characteristics and volumetric flow rates; (2) changes in the surface height of the Halemaumau lava lake; and (3) tilt measurements made at the summit of Kilauea. We find good correlation between Halemaumau lake activity and the eruptive stages. Additionally, the E-W component of summit tilt tended to mimic the lake activity. The N-S component, however, did not. Multiple storage zones in the shallow summit region probably accounted for the decoupling of E-W and N-S tilt components. Analysis of these criteria shows that at different times during the eruption, magma was either emplaced into the volcano without eruption, hydraulically drained from Halemaumau to Mauna Iki, or fed at steady-state conditions from summit storage to Mauna Iki. Volume calculations indicate that the supply rate to Kilauea during the eruption was around 3 m^3/s, similar to that calculated during the Mauna Ulu and Kupaianaha shield-building eruptions, and consistent with previously determined values of long-term supply to Kilauea.

Key words: Lava lakes - dikes - plumbing - tilt - eruptive characteristics - gas content - satellitic shield

Introduction

Satellitic shield eruptions on Kilauea contribute significantly to the growth of the volcano and they are closely associated with lava tube systems and long-duration eruptions; >65% of the present Kilauea surface is covered with tube-fed pahoehoe (Holcomb 1987). Of the 15 satellitic shields found on Kilauea (Holcomb 1987), three formed in post-contact times: (1) Mauna Iki in 1919-1920 (e.g. Jaggar 1919c, 1920a-f; Finch 1920a-c); (2) Mauna Ulu in 1969-1974 (e.g. Swanson et al. 1979; Tilling et al. 1987); and (3) Kupaianaha in 1986-1992 (e.g. Ulrich et al. 1987; Heliker and Wright 1991a, 1991b). In general, the three eruptions can be characterized by a brief a'a-producing stage at their outset followed by a longer-duration (months to years) tube-fed pahoehoe-producing stage. However, in detail each eruption differs with regard to the relative volumes of a'a and pahoehoe and the nature of their eruption, as well as the overall eruption duration.

Near-surface transport of magma at Hawaiian volcanoes has been the subject of intense study (e.g. review by Peterson and Moore 1987). At Kilauea, the frequent, readily observable activity and high degree of instrumentation have resulted in the determination of the location of major magma conduits and storage regions, and the ability of real-time tracking of magma movement. Geophysical modelling, theoretical considerations, and in particular seismic data (e.g. Ryan et al. 1981; Hill and Zucca 1987; Rubin and Pollard 1987; Klein et al. 1987; Wilson and Head 1988; Delaney et al. 1990) all provided contraints on the depths and locations of sub-surface magma storage and transport features.

These studies have shown that there are two main components of magma storage and transport at Kilauea. A central magma chamber extends from ~2 to ~9 km below the summit with a near-vertical conduit connecting it with the upper mantle (e.g. Fig. 6 of Ryan et al. 1981; Klein et al. 1987). The chamber is probably a series of smaller interconnected spaces rather than a single large void (Fiske and Kinoshita 1969). Two rift zones ex-

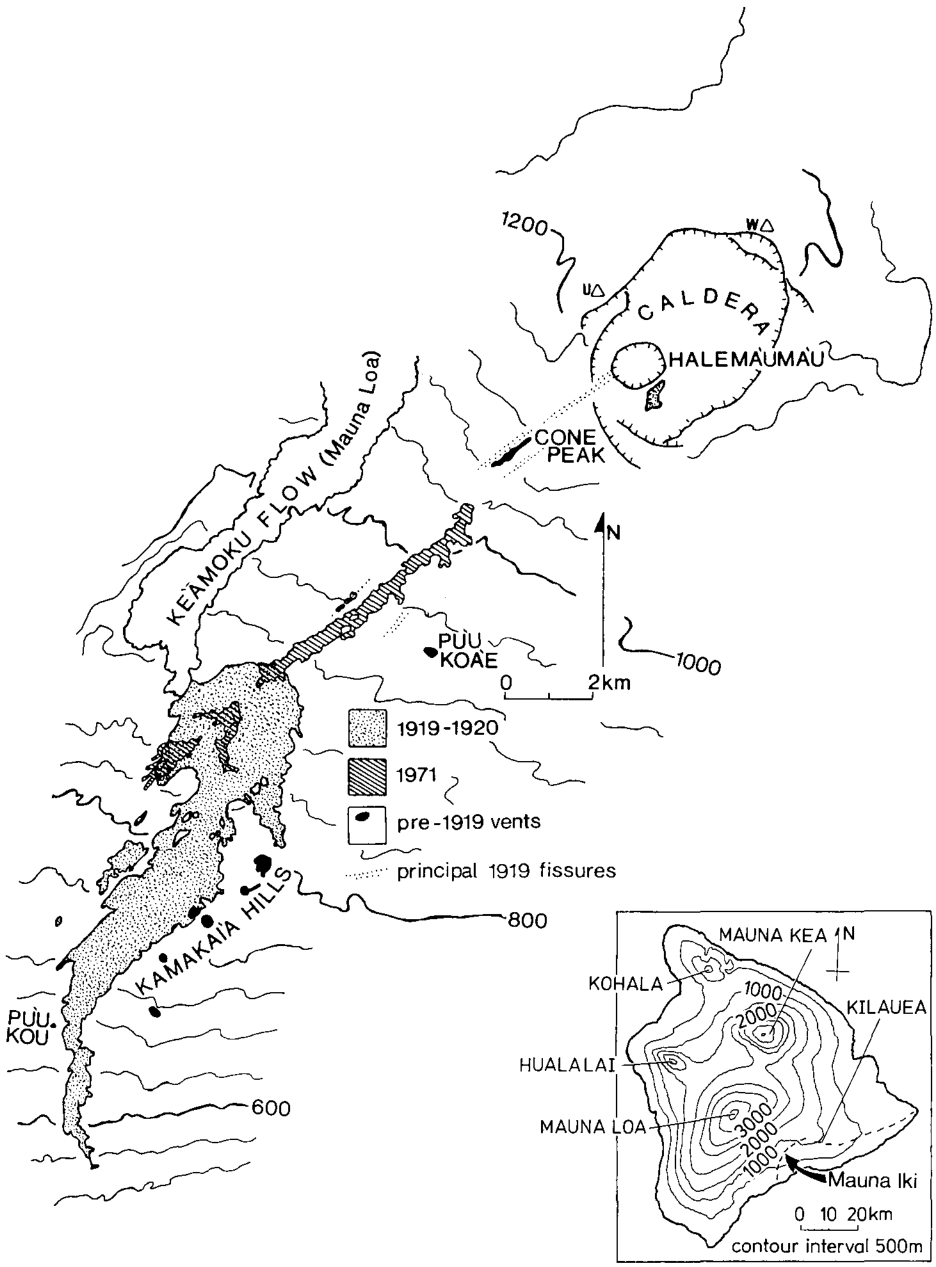


Fig. 1. Location map showing the products of the Mauna Iki eruption as well as geographical features mentioned in the chronology. Flow outlines are from Holcomb (1987) and C Neal, personal communication (1992). Contour interval 40 m U and W indicate locations of Uwekahuna and Whitney vaults (see text). *Inset* shows the location of Mauna Iki on Kilauea volcano (rift zones *dashed*; contour interval 500 m)

tend from the magma chamber to the E and SW. These are the preferred directions of sub-horizontal magma excursions (dike propagation) that result in intrusions and/or eruptions. Magma may also travel vertically from the magma chamber to erupt at the summit. The Mauna Iki eruption took place near the end of (at least) 96 years of sustained activity in the summit caldera (e.g. Jaggar 1947).

Halemaumau is a circular pit crater ~ 1 km across located in the SW part of Kilauea caldera (Fig. 1). A lava lake in Halemaumau was first observed by Westerners in 1823 (e.g. Peterson and Moore 1987). Until late 1919, the lake maintained a relatively stable level a few tens of meters below the rim of Halemaumau (Jaggar 1947). For long periods of time the lake would be perched a few meters above the surrounding caldera floor, contained by levees constructed of overflows. Very detailed observations of the Halemaumau lake were made by Thomas Jaggar once he had established the Hawaiian Volcano Observatory in 1912, including measurements of the fluctuations in lake level, the forming of subsidiary pools and the motions of the 'crags' that separated them, as well as observations of the amount and nature of fume being emitted. Observations of the relationship between activity at the summit of Kilauea and downrift at Mauna Iki provided much of the qualitative support for early ideas of hydraulic connections between the summit and rift zones of Kilauea (e.g. Jaggar 1920b). Jaggar also made many inferences about how the activity of the Halemaumau lake responded to eruptive activity at Mauna Loa. We will not discuss these here, except to note that any proposed shallow fluid connection between Mauna Loa and Kilauea is not consistent with chemical (Wright 1971) or seismic (Klein et al. 1987) data (but see Rhodes 1989 for evidence of a possible prehistoric, deep connection).

Eruptive products and features

The Mauna Iki eruption (Fig. 1) produced a small flow field of vesicular pahoehoe in the SW portion of the Kilauea caldera, a set of fissures extending discontinuously from the caldera 13 km down the SW rift, a small patch of lava 7 km down the rift, the main Mauna Iki shield (centered 9.5 km from the caldera rim) and associated flows, a smaller shield (here termed the downrift shield) 3 km farther to the SW, and three smaller patches of pahoehoe (C Neal, personal communication) between 11 and 15 km down the rift zone. Most of the intra-caldera lava was buried by eruptions in 1921 (Peterson 1967; Walker 1967; Holcomb 1987). The Mauna Iki shield (Figs. 2 and 3) is about 3 km long in a SW-NE (along-rift) direction, and 2 km wide. The NE end of the shield is the highest part at 36 m above the surrounding area. It has a relatively flat surface of vesicular pahoehoe, collapse pits, and lava tube skylights.

Small flows of a'a and toothpaste lava (e.g. Rowland and Walker 1987) are also found on the main shield. The largest of these flowed down the W flank, and is ~1 km long by 300 m wide. A second such flow came from an area of uplifted blocks near the summit of the

Fig. 2. Mosaic of air photographs showing the Mauna Iki shield and lava flows. (Agricultural Stabilization and Conservation Service photos EKL-500-39 to 44, taken 29 December 1964)

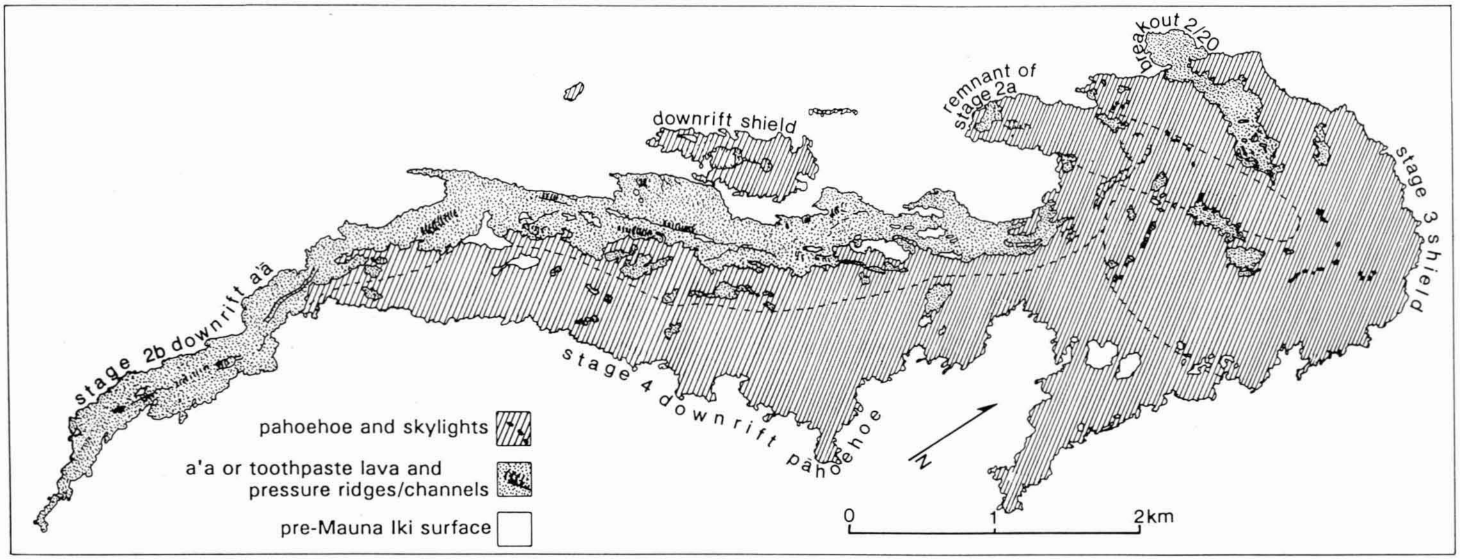


Fig. 3. Geologic map compiled from stereo air photographs taken in 1964. The contacts and structures around and within the Mauna Iki flow-field were field-checked in 1989 and 1991. *Dashed lines* show the approximate buried margins of stages 2a, 2b, and 3

shield, and flowed to the S. These were breakouts of lava that had been stored in pockets within the shield and had cooled and lost gas during this storage (Jaggar 1920a). A'a flows such as these were observed on both Mauna Ulu (Peterson and Tilling 1980) and Kupaianaha (Heliker and Wright 1991b).

Issuing from near the SW edge of the shield is the downrift a'a flow (Figs. 2 and 3). This flow began forming shortly after the onset of eruptive activity at the Mauna Iki site and was active for a period of ~ 18 days. The downrift pahoehoe flow was fed by lava tubes that developed during the final stage of the Mauna Iki eruption. Active tube skylights were observed only near the summit of the Mauna Iki shield, and these skylights are preserved today as elongate rubble-filled depressions 30–50 m long by ~ 20 m wide (Figs. 2 and 3). The pahoehoe flow parallels and overlaps the E margin of the downrift a'a flow for a distance of about 8 km.

Tilt data

Most of our inferences about sub-surface magma transport come from an analysis of summit tilt measurements presented in Jaggar and Finch (1929; see Appendix) and recently replotted by the Hawaiian Volcano Observatory (courtesy of John Dvorak). The seismometer location at the Whitney vault (Fig. 1) meant that Halemaumau was at an azimuth of 230°. NS changes in tilt were considered by Jaggar and Finch (1929) to be due to the rise and fall of lava in Halemaumau and EW tilt changes to activity of Mauna Loa, the summit of which is 35 km away at an azimuth of 285°. It is now known that the amount of inflation at Mauna Loa required to affect tilt at Kilauea is too large to be reasonable (J Dvorak and A Okamura, personal communication).

Fiske and Kinoshita (1969) attributed migrating centers of deformation to the sequential filling or emptying of interconnected voids that constitute the shallow storage system beneath the Kilauea summit. During the Mauna Iki eruption EW tilt usually mimicked activity at Halemaumau (inflation during rise in lake level and vice versa), whereas NS tilt usually did not. We propose that this decoupling of tilt responses occurred because there were (at least) two voids acting as centers of deformation during the Mauna Iki eruption. Because EW tilt and Halemaumau activity were often in concert, we suggest that one of these voids was located roughly due W from the Whitney vault, that it was directly connected to the lake, and that it was shallow(?). We further suggest that the NS tilt component was instead dominated by changes to a (deeper?) storage zone less-directly connected to Halemaumau, and S of the Whitney vault. The 'shallow' and 'deep' terms for these two storage zones are very poorly constrained; both are proposed to be parts of the summit magma chamber system 2–9 km below the caldera.

Volumes of lava flowing into or out of the summit magma chamber system have been estimated from the comparison of erupted lava volumes and summit tilt measurements. Conversion factors range from 0.33 to 0.45×10^6 m^3 of magma per microradian of tilt for data from the Uwekahuna vault (Dzurisin et al. 1984; Dvorak and Okamura 1987, respectively). Dvorak (1992) presents a conversion factor of 1×10^6 m^3 of magma/microradian for Whitney vault tilt data, and we have adopted this value for our volume calculations (see Appendix). We made these calculations only for the NS component of tilt which, as noted above, we suggest was responding to a deformation center less affected by surface activity. Without knowing exactly where it was, we have no basis for making any angular corrections hence the tilt-derived volumes are constraints only.

Tilt data have also been used to calculate long-term supply rates from the mantle (e.g. Dzurisin et al. 1980; Duffield et al. 1982; Dvorak and Okamura 1987). Rift zone eruptions at Kilauea have either been at high-discharge rates (30–400 m^3/s) associated with rapid tilt response indicating deflation of the summit magma chamber system, or at low and constant discharge rates (2–5 m^3/s) associated with no clear tilt response. In the latter case, input and output to and from the summit magma chamber system are essentially equal (e.g Swanson 1972; Swanson et al. 1979; Tilling et al. 1987) or possibly the summit magma chamber system is bypassed altogether (Ryan et al. 1981).

We have adopted the commonly accepted value of 25% vesicularity of erupted lava compared to sub-surface magma (e.g. Wolfe et al. 1987). Beyond this, the margin of error in the various volume calculations (see Appendix) is difficult to determine. We estimate that they are accurate to within $\pm 10\%$ for the lava flows and $\pm 20\%$ for those determined from tilt measurements.

Eruption chronology

We divided the eruption into stages based on the nature of the surface eruptive activity, and in the chronology that follows, we describe that activity along with Halemaumau lake depth changes and summit tilt measurements prior to, during, and after the Mauna Iki eruption to try and characterize both the surface and sub-surface activity. Two additional techniques routinely used to characterize an ongoing eruption are seismology and chemical analysis of the lavas. There was one seismometer operating during the Mauna Iki eruption (at the Whitney vault) and we have dealt with the data only qualitatively. A few chemical analyses of Mauna Iki lavas collected well after the eruption show essentially no chemical variation between samples (Wright 1971) even though they consist of products of different stages.

Accounts of the eruption and Halemaumau lake level data come from the monthly *Bulletins* of the Hawaiian Volcano Observatory for November 1919 through September 1920 (Jaggar 1919b, 1920a–f; Finch 1920a–c; Bevens et al. 1988 v. II pp. 1045–1216). Brief summaries of the eruption can be found in Jaggar (1930, 1947). The original descriptions are rich in detail; this paper attempts to collect them into a single account of surface and sub-surface activity, and present maps of features associated with the eruption. Aspects of the chronology

Table 1. Compilation of eruptive activity including volumes and volumetric flow rates, tilt activity including magma chamber volume changes calculated from NS tilt, and Halemaumau activity including volume changes and volumetric flow rates

Stage (date/s)	Lava lake	Lake vol. (million m^3)	Lake vol. rate (m^3/s)	EW tilt	NS tilt (cm)	NS tilt volume (million m^3)	Eruption?
pre-1 (11/28/19)	down 180 m in 4 h = 45 m/h	−14.2	−985	—	defl. 0.7	−4	none
pre-1 (11/29 to 12/14/19)	up 169 m in 17 days = 9.9 m/day	+13.3	+9	infl.	defl. 3	−17.5	none
1 (15/15/19)	down 34 m in 8.5 h = 4 m/h	−2.7	−88	—	defl. 0.75	−4.4	lava erupted in caldera
1 (12/16 to 12/23/19)	up 36 m in 7 days = 5 m/day	+2.8	+4.5	defl.	infl. 1	+5.9	cracks propagating downrift (mostly lava-filled), lava erupted in caldera
2a (12/24 to 12/29/19)	down 51 m in 6 days = 8.5 m/day	−4.0	−7.5	defl.	infl. 1.5	+8.8	low pahoehoe shield at Mauna Iki = 4.5 million m^3 at 8.7 m^3/s
2b (12/20/19–1/17/20)	down 32 m in 17 days = 1.5 m/day	−2.5	−1.4	barely defl.	defl. 4.5	−26.4	a'a flow 19.8 million m^3 at 13 m^3/s
3 (1/18 to 4/16/20)	up 67 m in 89 days = 0.74 m/day	+5.3	+0.7	variable	variable	no net change	pahoehoe shield 16.1 million m^3 at 2.1 m^3/s
4 (4/17 to 8/1/20)	down 60 m in 103 days = 0.6 m/day	−4.7	−0.5	defl.	infl. 5.5	+32	tube-fed pahoehoe 5.3 million m^3 at 0.6 m^3s
		21.5 gained−28.1 lost = 6.6 lost				46.7 gained −52.3 lost = 5.6 lost	45.7 million m^3 erupted

are summarized in Table 1 and Figs. 4 and 5. All times are local (HST) and original Imperial units have been converted to metric. At the end of each chronological section, we present a discussion of the eruptive products, Halemaumau activity, and tilt record of that particular eruptive stage.

Pre-eruption (prior to 15 December 1919)

The months prior to late November 1919 were characterized by a relatively stable Halemaumau lava lake. Its surface was about 2 m above the caldera floor, contained by levees; short overflows in all directions resulted in the construction of a small shield centered at Halemaumau. There were usually three separate convecting lakes present within Halemaumau, separated by 'crags' and 'islands' of solid to semi-solid lava. In about 4 h starting at 01:42 a.m. on 28 November, and accompanied by strong seismicity, the lake level dropped 180 m, a rate of 45 m/h (Figs. 4 and 5a). The shape of the Halemaumau crater after this event was described as a cylinder with a diameter of 366 m (Jaggar 1947). This is an important observation because it makes calculating volumetric changes simple: each meter of rise or drop corresponds to ~78750 m^3 of unvesiculated lava (Appendix). The volume lost from the lake during this event was therefore 14.2×10^6 m^3, at an average rate of 985 m^3/s (Fig. 4b, Table 1). Two cracks in the lower 120 m of the SW and NE walls of the 180-m-deep pit were exposed. These cracks did not extend to the surface along the pit walls; however, a new fuming fissure opened on the caldera floor ~100 m SW of the rim of Halemaumau. Except for this fissure, there was no surface manifestation of shallow dike emplacement that corresponded to this drop in lake level. Thus the loss of ~14×10^6 m^3 from the lava lake was accompanied only by seismicity and minor surface cracking. It is concluded that the lava drained into a cavity within the volcano, most likely into the fissures exposed in the walls of Halemaumau (Fig. 5a).

For the next 17 days, the actively fountaining lake surface rose, and the regained volume totalled 13.4×10^6 m^3 at an infilling rate of 3.7 m^3/s. NS tilt started a deflationary trend on 28 November, and over two weeks indicated a loss of 17.5×10^6 m^3 from deeper

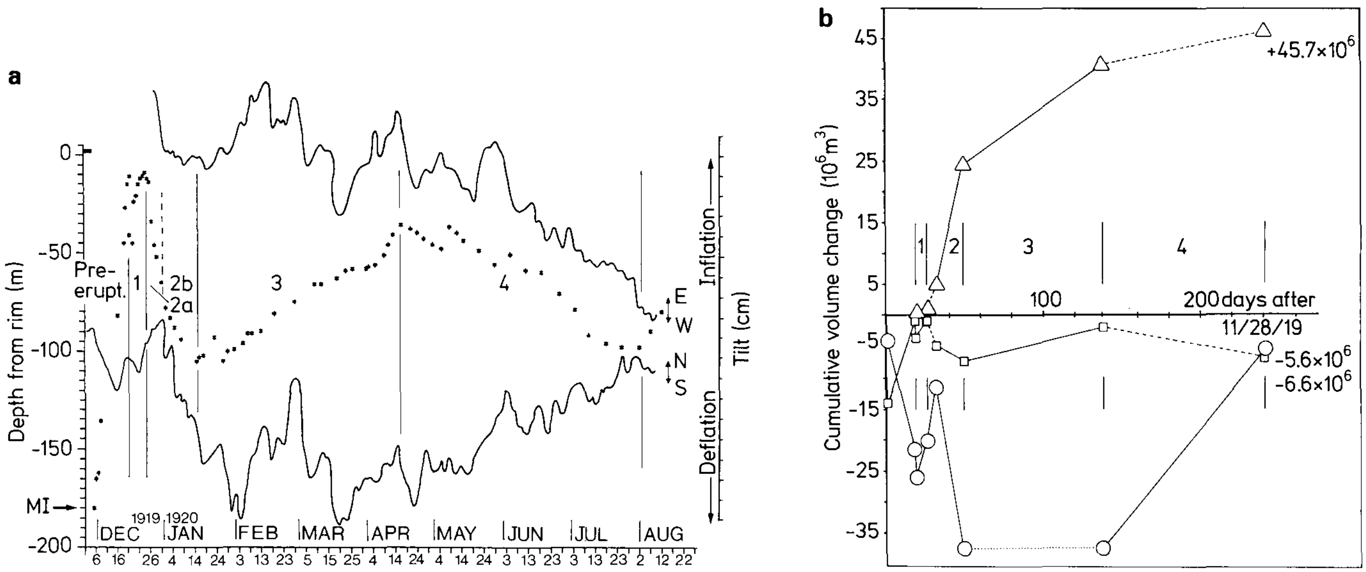


Fig. 4. **a** Compilation of measurements of the elevation of the Halemaumau lava lake the NS and EW components of tilt, and the stages of the Mauna Iki eruption. The lava lake data (dots) are from the monthly *Bulletins* of the Hawaiian Volcano Observatory for November 1919 to August 1920, and the tilt measurements are from Jaggar and Finch (1929) and some were kindly supplied by J Dvorak of the HVO. Tilt is plotted in cm of deflection of the seismograph needle: 1 cm of deflection equals 1.21 s or 4.848 microradians of tilt (see also Appendix). EW tilt is not available at high temporal resolution prior to stage 2. Note that prior to 28 November 1919 the Halemaumau lake was perched behind levees at a level above that of the actual pit crater rim. 'MI' at left (*arrow*) indicates elevation of Mauna Iki for comparison with Halemaumau lake levels. **b** Cumulative volumetric changes in Halemaumau (*squares*), deep storage (*circles*), and erupted lava (*triangles*). *Dashed lines* indicate periods of hydraulic draining (volumes and volumetric flow rates at Halemaumau and the vent are equal). *Dotted line* indicates steady-state with regard to deep storage (no net gain or loss)

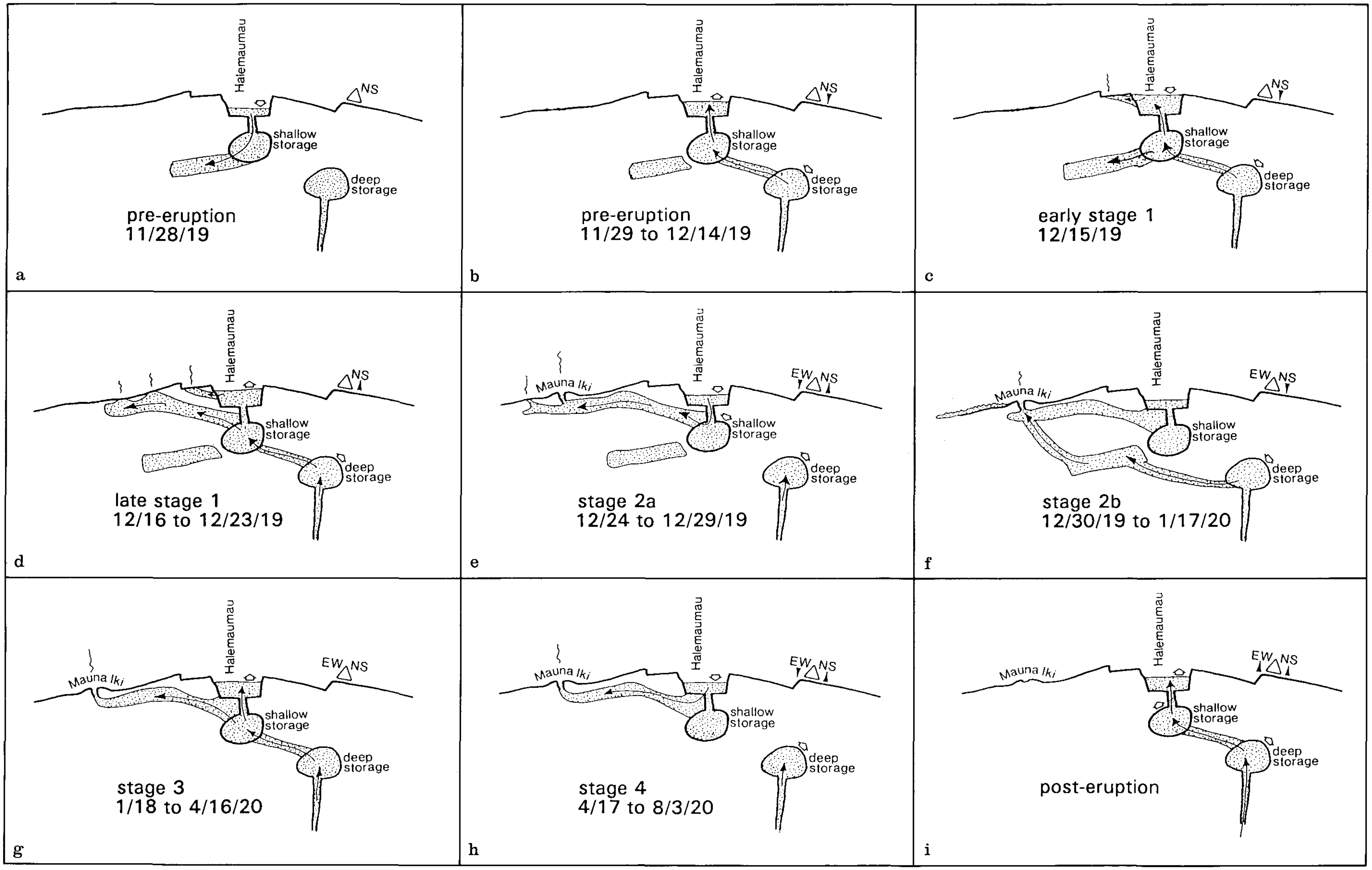
storage, similar to the volume gained by Halemaumau. NS tilt then changed to inflation about a week before Halemaumau had finished refilling.

Stage 1 (15 December 1919 to 23 December 1919)

On the morning of 15 December, Halemaumau lava lake had risen to within 11 m of the rim. Stage 1 (Fig. 5c) began at 11:25 a.m. when pahoehoe lava erupted from vents near the SW edge of the caldera in line with the 28 November fissures. These vents were at an elevation about 4 m below the level of the lake (thus 15 m below the Halemaumau rim). Lava could be seen flowing SW in a crack that ran from the rim of Halemaumau to the eruption site. As soon as the eruption in the caldera started, the lake level in Halemaumau began to drop; extrusion ceased as soon as the lake level reached the elevation of the vents, reflecting a simple hydraulic link beween the lava lake and the nearby vents (Jaggar 1947). However, the lake level continued to drop after the surface eruption ended.

During the first 8 h of stage 1, the lake level dropped 34 m at an average rate of ~4 m/h, equivalent to 2.7×10^6 m^3 at 88 m^3/s. The volume erupted onto the surface was not reported and most of it has been subsequently buried. 88 m^3/s is a volumetric flow rate associated with the production of a'a flows (Rowland and Walker 1990). The high rate of volume loss compared to the facts that pahoehoe was erupted and the lava lake continued to drop after the cessation of surface activity indicates that most of the lava was again being drawn off at depth (as on 28 November) and only a small fraction was draining out through the near-surface crack. NS tilt showed a short-lived deflation event corresponding to the lake draining (Fig. 4), and the calculated volume (4.4×10^6 m^3) is close to that lost from the lake.

After dropping to 45 m below the rim by the morning of 16 December, the lake began to rise again (Fig. 4), at an average rate of 5 m/day over the next five days, equivalent to re-filling at 4.7 m^3/s. It was during this rise in lake level that cracks were observed propagating down the SW rift zone (Figs. 5d and 6). Some of these cracks contained lava, others emitted fume or steam, and others were just open fractures. In general, they formed successively in a downrift direction at a propagation rate of roughly 0.5 km/day (Fig. 6). By 19 December, the lake level had risen to the elevation of the intra-caldera vents of 15 December (15 m below the Halemaumau rim), and they began to erupt again; this time, however, the lava lake continued to rise. Stage 1 of the eruption ended with the lava lake 9 m below the rim, a low-intensity eruption continuing in the caldera, and cracks having propagated 9.5 km to the SW. After the deflation associated with the draining event of 15 December, the NS component indicated inflation corresponding to a gain of 6×10^6 m^3 of magma.


Halemaumau
NS
shallow storage
deep storage
pre-eruption
11/28/19
a
Halemaumau
NS
shallow storage
deep storage
pre-eruption
11/29 to 12/14/19
b
Halemaumau
NS
shallow storage
deep storage
early stage 1
12/15/19
c
Halemaumau
NS
shallow storage
deep storage
late stage 1
12/16 to 12/23/19
d
Halemaumau
Mauna Iki
EW
NS
shallow storage
deep storage
stage 2a
12/24 to 12/29/19
e
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deep storage
stage 2b
12/30/19 to 1/17/20
f
Halemaumau
Mauna Iki
EW
NS
shallow storage
deep storage
stage 3
1/18 to 4/16/20
g
Halemaumau
Mauna Iki
EW
NS
shallow storage
deep storage
stage 4
4/17 to 8/3/20
h
Halemaumau
Mauna Iki
EW
NS
shallow storage
deep storage
post-eruption
i

Stage 2a (24 December 1919 to 29 December 1919)

Stage 2 began early in the morning of 24 December with an outbreak of lava at the site which was to become the Mauna Iki shield (Figs. 2, 5e, and 7). As soon as the extrusion began, the Halemaumau lake started to drop rapidly (Fig. 4) and the low fountaining at the caldera floor vents ceased; over the next six days the lake dropped 51 m at an average rate of 8.5 m/day resulting in a loss of $4.02 \times 10^6\ m^3$ at $7.5\ m^3/s$. The lava built a low, elongate ridge at the Mauna Iki site, and after cracks propagated 3 km farther downrift, an additional smaller shield, and three small pads of lava (C Neal personal communication; Figs. 3 and 7). The volume of the ridge is calculated to have been $4.5 \times 10^6\ m^3$, meaning that over these six days the volumetric flow rate was $8.7\ m^3/s$.

Thus in stage 2a the volume lost from Halemaumau was approximately equal to that erupted at Mauna Iki; the volumetric flow rates were also similar, suggesting a simple hydraulic draining of Halemaumau to Mauna Iki (Fig. 5e). Mauna Iki is at an elevation of ~180 m below the rim of Halemaumau, therefore the only time when hydraulic draining would have been impossible was after the initial drainout event of 28 November. At the start of stage 2a the lake level was ~170 m above the Mauna Iki elevation, and by the end of stage 2a it was still ~100 m above. EW tilt showed rapid deflation (sympathetic with Halemaumau lake level changes) whereas NS tilt showed continued inflation (Fig. 4), gaining a total of $9 \times 10^6\ m^3$, and indicating that magma was filling the deeper storage zone, but not replacing that lost from the lava lake.

Fig. 5a–i. Cross-sections (not to scale) showing the flow of magma (*stippled, thin arrows*), Halemaumau lava lake level changes (*open arrows*), tilt activity (shown at upper right for EW and NS components), and inferred magma storage inflation or deflation (*open arrows*) during the Mauna Iki eruption. The actual depths and locations of 'shallow' and 'deep' storage are conjectural (see text). **a** Rapid drop of Halemaumau lava lake, lava emplaced somewhere in the volcano without surface expression. **b** Recovery of the Halemaumau lava lake, deep storage showed deflation. **c** Short eruption in caldera accompanied dropping of the Halemaumau lava lake indicated draining into the volcano. Deep storage showed deflation. **d** Halemaumau lava lake rose and a shallow dike was emplaced down the SW rift indicated by ground cracking. Deep storage showed inflation, low intensity eruption in caldera. **e** Halemaumau lake dropped rapidly accompanied by first outbreak of pahoehoe at Mauna Iki. Shallow storage indicated deflation, deep storage indicated inflation. **f** a'a flow erupted at Mauna Iki, Halemaumau lake level drop and EW tilt deflation both became very slow. Deep storage indicated deflation, inferred to mean that it was supplying magma to displace (to the surface) that which was emplaced earlier. **g** Halemaumau lava lake rose, pahoehoe was erupted at Mauna Iki, no net inflation or deflation taken to indicate steady-stage flow-through of the summit plumbing system. **h** Halemaumau lava lake dropped and tube-fed pahoehoe flow erupted at Mauna Iki. EW tilt followed Halemaumau activity, NS tilt indicated deeper inflation. **i** Connection closed to Mauna Iki. Supply from depth inflated deep and shallow storage, and also supplied lava to Halemaumau

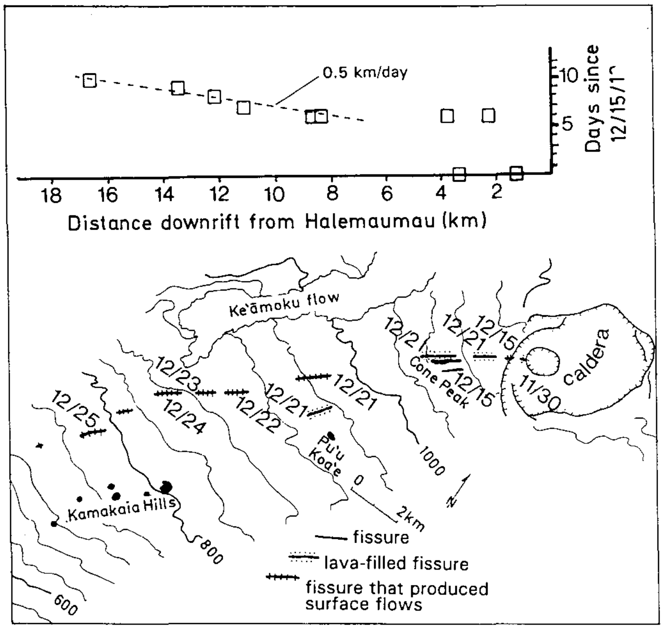

Fig. 6. Map showing the locations (from accounts, not field checked) and times of fractures formed during stage 1 of the eruption (contour interval 40 m). *Inset* shows time-distance plot yielding an average propagation rate of 0.5 km/day

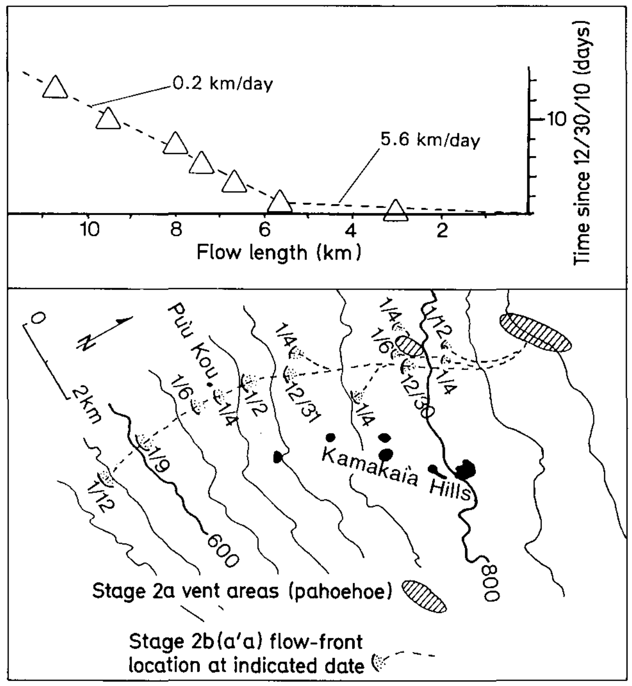

Fig. 7. Map of stage 2 features, including the elongate shield and downrift shield, as well as flow-front locations and times for the stage 2b a'a flow. The flow-front locations were determined by their reported elevations and positions relative to geographic features, and the time-distance plot indicates an initial high velocity (5.6 km/day) which slowed abruptly (to 0.2 km/day) after 31 December

Stage 2b (30 December 1919 to 17 January 1920)

After six days of building the elongate shield, the activity at Mauna Iki changed abruptly on the morning of 30 December. The low fountaining along the crest of the shield ceased and out of the E flank, halfway between its N and S ends (Fig. 7), a channel-fed flow issued quietly out from under a pahoehoe carapace and flowed to the SW. The lava made the transition from pahoehoe to a'a a few hundred meters from its origin. The flow-front velocity for the first two days was almost 5.6 km/day, after which it slowed to ~ 0.2 km/day (Fig. 7). The total volume was 19.8×10^6 m^3 (Appendix), and its average volumetric flow rate was 13 m^3/s, a 50% increase over that which had formed the low shield during stage 2a. At the same time (Jaggar 1919c), the rate of lowering of the Halemaumau lava lake decreased (Fig. 4) from 8.5 m/day (7.5 m^3/s) to 1.5 m/day (1.4 m^3/s). Thus at the vent site the volumetric flow rate increased and the lava became more gas-poor (fountaining ceased and a'a replaced vesicular pahoehoe), while simultaneously the rate of draining of the summit lava lake decreased by $>50\%$.The volume lost from Halemaumau during stage 2b was only 14% of the volume erupted as a'a. A 'feeble' earthquake was the only seismicity recorded at the onset of stage 2b.

The EW component of tilt reacted to the start of stage 2b by reducing its deflation rate (mimicking the Halemaumau activity). At the same time, the NS component changed from inflation to deflation, losing 26×10^6 m^3 of magma over the duration of stage 2b (Fig. 4; Jaggar 1919c, 1920a). One possible explanation of these events could be the opening of a direct link from the deeper magma reservoir directly to Mauna Iki, mostly bypassing Halemaumau. However, the a'a flow was described specifically as being gas-poor and erupting very quietly (Jaggar 1920a), an observation that is inconsistent with a direct influx of presumably gas-rich magma from depth.

We suggest that magma did bypass Halemaumau and invade the rift zone; however, instead of erupting it merely displaced magma that had been stored since the Halemaumau drain-out events of November and December (Fig. 5f). This magma would have been stored in the rift for up to 32 days and thus would have cooled and degassed. This physically evolved magma was pushed out by more gas-rich magma that didn't reach the surface and led to the change in eruptive style. Some magma probably also reached Halemaumau and slowed the net draining rate. Chemically, the a'a differs little from Mauna Iki pahoehoe samples (Wright 1971). This mechanism of displacing previously stored magma to the surface has also been proposed for the first part of the 1960 Kapoho eruption (Macdonald 1962), for the 1955 eruption (Ho and Garcia 1988), and for episode 1 of the Puu Oo eruption (Garcia et al. 1989).

During the 18 days that the a'a flow was active, the Halemaumau lake surface continued to drop, eventually reaching 105 m below the rim. When the a'a flow became inactive on 17 January, eruption of pahoehoe resumed at the N end of the Mauna Iki shield. At the same time, the lake in Halemaumau began to rise, EW tilt changed to inflation, and stage 2 was over. A 'very feeble' earthquake was registered the morning of 17 January.

Eruptive products of stage 2 were the elongate shield, the downrift shield, and the a'a flow (Figs. 2 and 3). The downrift shield has been largely buried by windblown sand since 1919 (Fig. 2). Only the SW-most end of the elongate shield from stage 2a survived the growth of the main shield during stage 3 (Fig. 2). It was also largely covered by 1971 lavas. The surviving portion is a low mound 400 m wide and 800 m long protruding SW out from under the stage 3 shield. A flat collapsed(?) area is found along the crest of this mound, and a'a/toothpaste lava breakouts emanate from its SW end.

The principal product of stage 2 was the downrift a'a flow (Figs. 2 and 3). Its E margin was partially buried by the tube-fed flows of stage 4 but it is otherwise well-preserved. Its source at the time of formation was at the middle of the elongate shield, but because the stage 3 activity extended the shield farther N, it now appears to emanate from near the S end. The upflow end of the a'a is a SE-trending depressed area of broken pahoehoe plates which marks the collapsed pahoehoe carapace described by Jaggar (1920a).

The transition to a'a takes place over a distance of about 250 m, and is manifested by a rapid decrease in the proportion of foundered pahoehoe blocks relative to surrounding a'a. By 800 m from the source the 'rafts' of pahoehoe become much less numerous, and the flow is essentially all a'a. The flow makes a turn from SE to SW about 600 m from its origin, and maintains this downrift direction for about 5 km, being partially confined by SW rift zone graben, as evidenced by straight sections of the W margin. Four arms a few hundred meters long trend towards the W; E-trending arms were buried by the pahoehoe of stage 4. Beyond the first few hundred meters, there are no well-defined channels or remnants of pahoehoe overflows (Fig. 2); however, poorly defined channels can be identified in the air photos. The a'a flow averages 3–5 m thick along its W margin and is of the proximal type (vesicular with a thin cover of clinker and few dense surface blocks; Rowland and Walker 1987); 6 km from its source the flow was fluid enough to consist largely of toothpaste lava.

Stage 3 (18 January 1920 to 16 April 1920)

Stage 3 was characterized at Mauna Iki by numerous small gas-rich pahoehoe overflows from a lava pond that developed at what was the N end of the stage 2a shield. During stage 3 the pond was described as '... a circular well 40 feet in diameter, covered with crust in the middle ...' (Finch 1920a). The pahoehoe flows either overflowed the rim of the pond or escaped through shallow tubes in the walls. This activity built the shield to its present size (Figs. 2, 3, and 5g). During stage 3 there were numerous instances of degassed lava breaking out of the shield flanks to form a'a and toothpaste lava flows. The volume of lava erupted during stage 3 was 16.1×10^6 m^3 (see Appendix), at an average output rate of 2.1 m^3/s (Table 1). At the onset of stage 3, the Halemaumau lake began to rise (Fig. 4). This continued throughout stage 3 at an average rate of 0.74 m/day, which converts to 5.2×10^6 m^3 at an inflow rate of 0.7 m^3/s.

The start of stage 3 was also marked by changes in the tilt record (Fig. 4). The EW component showed a change from deflation to inflation, mimicking the changes at Halemaumau. The NS component, however, continued the rapid deflationary trend of late stage 2 (at ~15 m^3/s), and since the combined surface eruption rate at Mauna Iki and Halemaumau during stage 3 was only 2.8 m^3/s, magma was apparently being emplaced elsewhere within the volcano from the deeper storage. About three weeks into stage 3, the NS tilt changed to indicate summit inflation, after which the two components acted in phase. There was a deflationary excursion from 15 March until the beginning of April, when inflation resumed. The lake level at Halemaumau rose constantly, showing no such fluctuations, meaning that during stage 3 magma was able to move into and out of the shallower storage zone (shown by EW tilt changes) without affecting the lava lake. This contrasted with stage 2 (and stage 4 later) during which EW tilt acted in concert with Halemaumau.

Overall, the tilt record during stage 3 shows no net inflation or deflation. It therefore appears that during this period steady-state conditions existed, and overall input from the magma source region was balanced by supply to the lava lake and Mauna Iki. The combined volume of lava erupted at Mauna Iki plus the volume gained by Halemaumau yields a supply rate to the surface of 2.8 m^3/s during stage 3. This value is close to the long-term supply rates to the Kilauea magma chamber calculated by Swanson (3.5 m^3/s; 1972), Dzurisin et al. (2.3–5 m^3/s; 1980), Dzurisin et al. (2.8 m^3/s; 1984), and implied by Rowland and Walker (5 m^3/s; 1990). However, the short-term input rates required to supply some of the inflationary fluctuations of stage 3 are much higher (i.e. up to 30 m^3/s).

Pahoeoe surface flows as well as some of the a'a and toothpaste lava breakouts from stage 3 are well preserved at Mauna Iki (Figs. 2 and 3). The largest breakout flowed towards the N, consists of broken and rotated blocks of shield lavas up to 10 m across and resembles a landslide with a scarp at its head and a toe 2–4 m high (Jaggar 1920b). The lava pond that was a prominent feature during stage 3 has been preserved as a relatively circular collapsed pit 10–15 m deep and ~50 m across (Fig. 8). Its W wall is 15 m high, and on its E side slabs of pahoehoe tilt inward to form a trapdoor-like surface. Many of the glassy surfaces of the lava around the summit of the shield have been oxidized by escaping gases to an orange-brown color, and show up as light patches on the stereo photos (Fig. 2).

Fig. 8. Photograph of the now-collapsed lava pond at the summit of Mauna Iki. View is to the SE, and note that the far rim (where figure is standing) is ~20 m lower than the near rim. Lava at bottom of pond erupted 2–3 weeks after cessation of flow-field activity (Jaggar 1920e)

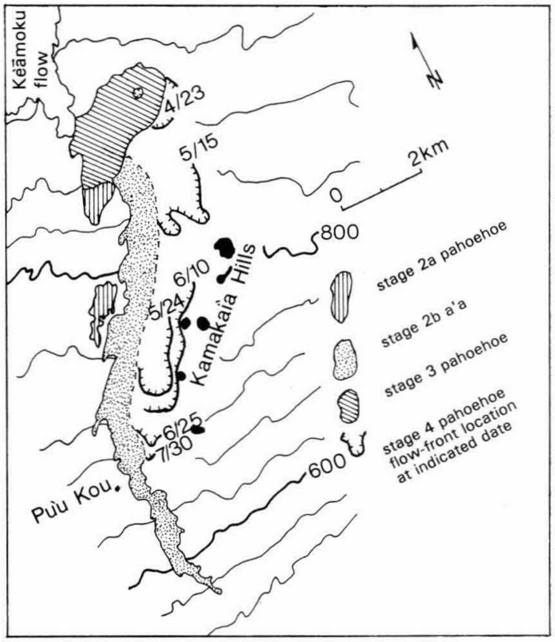

Fig. 9. Map showing positions through time of the flow front of the stage 4 pahoehoe flow. As in Fig. 7, flow-front positions were determined from accounts of their elevations and positions relative to geographic features; however, for this stage of the eruption, accounts are not very specific

Stage 4 (17 April 1920 to 3 August 1920)

The first reported observation of the majority of lava flowing in tubes was made on 17 April 1920, and we pick this as the start of stage 4. These tubes facilitated emplacement of pahoehoe lava well beyond the margin of the shield, eventually extending to an elevation of 680 m, ~8 km from the vent (Figs. 2, 3, and 9). During stage 4, the lava pond usually had a solid crust on which spatter cones occasionally developed. At times when the crust foundered, small fountains were noted to coincide with the locations of the spatter cones.

The volume of the tube-fed pahoehoe flow is 5.3×10^6 m^3, and it was erupted at a rate of 0.6 m^3/s (Appendix). At the start of stage 4, Halemaumau began to drain (Fig. 4). With minor perturbations, this draining continued throughout stage 4 at an average rate of 0.6 m/day, corresponding to a total of 4.7×10^6 m^3 drained at an average rate of 0.5 m^3/s. At the onset of stage 4, the EW tilt component began a deflationary trend while the NS component started an inflationary trend (Fig. 4). These persisted throughout stage 4. Again, the EW component mimicked the Halemaumau lake level while the NS component did not.

During stage 4, the volume loss and outflow rate at Halemaumau essentially equalled the lava volume and eruption rate, respectively, at Mauna Iki. This suggests that like stage 2a, stage 4 involved a direct hydraulic draining of lava from Halemaumau to Mauna Iki. This, combined with the change to inflation of the deeper storage indicated by the NS tilt, suggests that supply to Halemaumau from the deeper storage was disrupted (Fig. 5h). The relatively gas-poor nature of the stage 4 lava at Mauna Iki supports the idea that there was no fresh magma being supplied to the eruption site. If we assume that the connection from deeper storage to Halemaumau had been temporarily blocked, we can estimate a supply rate to the volcano from the NS tilt. The volume gained by NS tilt during stage 4 was 32×10^6 m^3, at a supply rate of 3.6 m^3/s, very similar to that calculated for stage 3 (2.8 m^3/s).

The main tube-fed pahoehoe flow of stage 4 is well preserved except where buried by windblown sand (Figs. 2 and 3). The flow had nearly reached its final length of ~8 km by 25 June (Fig. 9), yielding an average flow-front velocity of 0.1 km/day. Except for the skylights in the summit region that were observed during the eruption (now rubble-filled), they are otherwise exceedingly rare on the downrift pahoehoe flow. Only one was found off the shield in this study. It is located ~2 km from the vent and exposes a tube 1.5–2 m in diameter.

The end of the eruption. The lava pond at Mauna Iki began to subside during late July, and the tube-fed pahoehoe flow became barely active. By 3 August, only very hot cracks could be found on the Mauna Iki shield. The Halemaumau lake level began to rise on 28 July, and EW tilt changed from deflation to inflation (Figs. 4 and 5i). A slight perturbation in the inflation recorded by NS tilt accompanied the end of the eruption, but after a week it returned to the long-term inflation started at the end of stage 3.

We suggest that decreasing magma pressure at Halemaumau became unable to maintain an open pathway downrift, and the eruption ceased. No distinctive seismicity accompanied the end of the eruption even though it involved the closing of the conduit between Halemaumau and Mauna Iki. Magma from deeper storage immediately began to fill both Halemaumau and shallow storage even though there was no change in the inflation rate registered by NS tilt.

Discussion

Reconstruction of the eruption chronology, lake-level changes, and tilt records allows us to analyze characteristics of this shield-building eruption, including lava-flow mechanisms, storage and magma transport within the rift zone, the nature of magma ascent from depth, and magma supply rates.

Lava flows

The Mauna Iki eruption produced both a'a and pahoehoe, with the majority of the a'a erupted early on. This pattern is similar to the Mauna Ulu and Kupaianaha/Puu O'o eruptions; however, the details are very different. At both Mauna Ulu and Puu O'o (= early Kupaianaha), the a'a flows were produced during high fountaining episodes at volumetric flow rates of 20–300 m^3/s (Ulrich 1986; see compilation in Rowland and Walker 1990) and accompanied by rapid subsidence at the summit of Kilauea (e.g. Swanson et al. 1979; Wolfe et al. 1987, 1988). These lavas were gas-rich and the summit subsidence indicated that there was a direct hydraulic connection between the vent and summit storage.

At Mauna Iki, however, the early a'a stage was not accompanied by high fountaining. Rather, the low fountaining that had been occurring at the Mauna Iki shield (stage 2a) ceased at the start of the a'a activity, and the a'a flow is described specifically as having issued quietly from its source bocca (Jaggar 1920a). The slowing of the rate of Halemaumau draining and the decrease in the rate of EW deflation suggest that downrift supply in shallow conduits decreased corresponding to the onset of a'a activity. At the same time, NS tilt indicated relatively rapid subsidence (similar to the Mauna Ulu and Puu O'o examples) suggesting that there was a deep connection to the vent that bypassed Halemaumau. The distinctly gas-poor nature of the stage 2b eruption is the major difference from the Mauna Ulu and Puu Oo cases, and indicates that although a hydraulic link existed between the deep storage reservoir and Mauna Iki, fresh magma only displaced cooler degassed magma upwards and did not itself erupt.

The volumetric flow rate of the tube-fed pahoehoe at Mauna Iki was ~1 m^3/s. The average volumetric flow rates of the tube-fed pahoehoe stages of Mauna Ulu and Kupaianaha were 3–5 m^3/s (Swanson et al. 1979; C Heliker, personal communication). Thus the Mauna Iki pahoehoe flows are at the low end of the volumetric flow rate and flow-front velocity spectrum. As noted above, volume calculations suggest that the tube-fed stage of Mauna Iki was driven solely by draining of Halemaumau. The lower supply rate was not able to establish a thermally efficient conduit capable of sustaining the eruption for a long period of time, and additionally, the driving pressure decreased as the Halemaumau lake level dropped. Except near the vent, significant lava tubes were unable to form, and the one skylight found exposes a relatively small tube.

Magma storage and transport during the Mauna Iki eruption stages

The interplay between tilt components, the Halemaumau lake, and the Mauna Iki vent illustrates the complex nature of shallow magma storage and transport the

SW rift zone. The two large-volume Halemaumau draining events that took place in late 1919 without significant surface eruption or seismicity indicated that there was sufficient space within the volcano to inelastically accommodate large volumes of magma. It has been suggested that SW rift eruptions on Kilauea occur only when the rift zone has been propped open by numerous magma excursions into the (better-developed) E rift, or when pressure across the rift zone has been released by an eruption on Mauna Loa's SW rift zone (Duffield et al. 1982). There was such an eruption of Mauna Loa between 29 September and 11 October 1919 (e.g. Jaggar 1919a–c, 1947; Macdonald et al. 1983), so according to this model the SW rift zone of Kilauea was primed for activity in late 1919.

Stage 1 of the Mauna Iki eruption consisted of shallow propagation of a dike from the vicinity of Halemaumau down the SW rift. Magma was observed flowing SW in some of the fissures that opened during this stage showing that at least the top of the dike was near the surface along its entire course. This contrasts with the rapid Halemaumau drain-out events during which there was no surface evidence of dike intrusion. The existence of both deep and shallow conduits (at about 3 and 8 km below the surface, respectively) wthin the SW rift is suggested by seismic data (Klein et al. 1987 Fig. 43.12). The drainouts of 28 November and 15 December may have fed lava to the deeper conduit whereas the stage 1 dike (16–23 December) utilized the shallow conduit. During the propagation of this shallow dike, the Halemaumau lake rose and NS tilt indicated inflation meaning that magma was entering the volcano at a high rate, able to simultaneously propagate a shallow dike downrift, fill the Halemaumau lake, and fill deeper storage.

The onset of eruption at Mauna Iki (stage 2a) was accompanied by rapid draining of Halemaumau and deflation of EW tilt. As already noted, volume calculations illustrate a simple draining mechanism. The continued inflation shown by the NS tilt shows that magma was lost only from the shallow rift zone plumbing during stage 2a. This changed with the onset of stage 2b; a direct connection through deeper plumbing bypassed Halemaumau.

If the magma involved in the rapid drainout events of late 1919 went to deep (inelastic) storage, it would be a likely candidate for that pushed out through the deep conduit during stage 2b. The time interval between the 28 November Halemaumau draining event and the onset of stage 2b was 32 days. Bruce and Huppert (1989) showed that to avoid solidifying for 32 days, a flowing dike would have to be at least 1.3 m wide if the surrounding country rock was at a temperature of 100° C. The scenario presented here is different in that we suggest that the dike was emplaced and remained static before being displaced by a subsequent intrusion. Walker (1987) found an average dike width of 0.73 m for dikes of Koolau volcano. Thomas (1987) presented temperature-depth profiles for geothermal drill holes on the E rift zone of Kilauea in the range of 375° C at a depth of ~2 km. These temperatures could be extrapolated to ~400° C at 3 km (Thomas, personal communication), but might be somewhat lower in the less-active SW rift zone. Kauahikaua et al. (1986) used resistivity measurements to determine that at a depth of 5 km, the temperature is around 1000° C in the near-summit region. Given these constraints, and the evidence that batches of magma can remain fluid for years in the E rift zone (e.g. Macdonald 1962; Ho and Garcia 1988; Garcia et al. 1989), a dike emplaced early in the Mauna Iki eruption could probably have remained fluid for at least a month.

Stage 3, during which there was no net change in NS tilt, is the first indication in the Mauna Iki eruption of the establishment of a steady-state magma source-to-vent connection. Such a connection has been inferred from tilt and long-duration low output-rate lava production for stages of the Mauna Ulu (e.g. Swanson et al. 1979; Tilling et al. 1987) and Kupaianaha eruptions. Combining the volume erupted at Mauna Iki with that gained by Halemaumau, and averaging it over the duration of stage 3 yields 2.8 m^3/s, a rate similar to the estimates made for Mauna Ulu and Kupaianaha which have been considered to be long-term supply rates to the Kilauea (e.g. Swanson 1972). They are also essentially the same as those of historic tube-fed pahoehoe eruptions on Mauna Loa (Rowland and Walker 1990). If 3–5 m^3/s is indeed the long-term supply rate to Kilauea, based on the total volume erupted historically (Macdonald et al. 1983) it means that the ratio of intrusion to extrusion is possibly as high as 15:1. Previous estimates of this ratio were 2:1 (Dzurisin et al. 1984) and 5:1 (Walker 1987; for the subaerial part of Koolau volcano). The data of Furumoto (1978) can be converted to indicate that dikes make up 95–100% of Kilauea's E rift zone at a depth of ~3 km.

Stage 4 indicated a return to hydraulic draining of magma from Halemaumau downrift, and at the same time deeper storage (as indicated by NS tilt) showed inflation. The volume flow rate of this inflation (supply to the volcano) was 3.7 m^3/s, again similar to that determined during the steady-state stage 3.

Volume comparisons (Table 1) allow us to place further constraints on rift zone and summit plumbing. The total volume erupted at Mauna Iki was 46×10^6 m^3, and the total drained from Halemaumau was 28×10^6 m^3 so there had to have been 18×10^6 m^3 of magma supplied to Mauna Iki that did not show up as a change in lake level at Halemaumau. The total volume of deep storage loss was 52.3×10^6 m^3 and the total volume gained during rising events at Halemaumau accounts for only 21.5×10^6 m^3 of this, leaving an excess 30.8×10^6 m^3. If the 18×10^6 m^3 needed to make up the Mauna Iki volume is taken from this excess, there is still 12.8×10^6 m^3 remaining that was lost from deep storage and not accounted for at Mauna Iki or Halemaumau. It probably contributed to rift-zone storage. Deep storage only gained 46.7×10^6 m^3 while losing the 52.3×10^6 m^3 to Mauna Iki + Halemaumau + storage, for a net loss of 5.6×10^6 m^3. This net loss may not be significant given the uncertainty of our numbers.

The decoupling of NS and EW tilt (as discussed above) forms the basis of our hypothesis of separated storage zones within the summit magma chamber complex, and allows us to construct the model of the summit and SW rift zone plumbing system presented in Fig. 5. With only a single tilt station, we can only confidently suggest two magma storage zones. For many years prior to late 1919, magma fed directly to Halemaumau and its overflows. Possibly the release of confining pressure on the SW rift zone by the 1919 Mauna Loa eruption allowed magma to drain down the rift zone (pre-stage 1, early stage 1); however, the lack of surface deformation indicated that it travelled through deep or already-open conduits. The filling of these deep conduits possibly propped the SW rift zone open even more, so that after Halemaumau refilled, it then leaked out through a shallower dike (coincident with the ground cracking). At the end of stage 3, the connection from deep storage to both Mauna Iki and Halemaumau closed; deep storage began to refill while Halemaumau drained downrift through a shallow conduit (stage 4) until the magma head was unable to maintain an open pathway.

We are thus able to suggest that Mauna Iki, Halemaumau, and deeper storage were connected by both shallow and deep plumbing systems. We suggest that the combinations of which of these systems were open at any one time changed throughout the eruption. These changes led to the complexity of the tilt, lake-level, and eruption records, and provided information about the SW rift plumbing system.

Conclusions

This study illustrates the usefulness of compiling the chronology of an old eruption (as well as the need to carefully document modern events). We were able to reconstruct the Mauna Iki eruption by using a combination of written accounts of the activity and field mapping. By incorporating measurements of the Halemaumau lava lake and summit tilt, we extend our interpretation to events occurring at depth as well. We suggest that there were two storage zones actively connected to both the Mauna Iki vent and the Halemaumau lava lake, and that connections between all of these structures opened and closed during the eruption. The actual plumbing system was undoubtedly more complex than that presented here.

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Appendix

Volumes of Halemaumau lake level changes*, sub-surface changes from tilt data, and erupted lava*
(* Corrected for 25% vesicularity)

1. Volumes of lake level changes were calculated based on treating Halemaumau as a cylinder 366 m in diameter (as described by Jaggar 1919c):

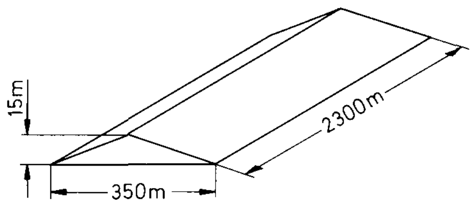
$\pi(366)^2 \Delta h (0.75) = 87750\ m^3$ of lava/m change in level

2. Tilt was measured as the deviation of a seismometer needle at the Whitney vault, and reported as 1 cm of deviation being equal to 1.21 s of arc (Jaggar and Finch 1929). This can be converted to a magma volume by using the conversion factor of:
1 microradian of tilt $= 1 \times 10^6\ m^3$ of magma (Dvorak 1992):

$$\left(\frac{1.21\ s}{cm}\right)\left(\frac{4.848\ \mu d}{s}\right)\left(\frac{1 \times 10^6\ m^3}{\mu d}\right) = 5.9 \times 10^6\ m^3/cm \text{ deflection}$$

3. The erupted volume of stage 2a was calculated as an elongate triangular ridge:

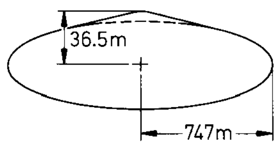
$1/2 \times 350 \times 15 \times 2300 \times 0.75 = 4.5 \times 10^6\ m^3$



4. The volume of stage 2b was calculated by digitizing the flow map to determine a surface area of 6.6 km^2 (including an estimate of the amount covered by later stages) and leveling the W flow margin (at 12 places) to get an average thickness of 4 m. These (multiplied by 0.75) yield a dense-rock volume of $19.8 \times 10^6\ m^3$.

5. The volume of stage 3 was calculated by assuming a right circular cone:

$1/3\, \pi (747\ m)^2 (36.5\ m)(0.75) = 16 \times 10^6\ m^3$



6. The volume of stage 4 was calculated by digitizing the flow map to determine a surface area of 7.1 km^2 and measuring the flow margin at five places to get an average thickness of 1 m. These (multiplied by 0.75) yield a dense-rock volume of $5.3 \times 10^6\ m^3$.

References

Bevens D, Takahashi TJ, Wright TL (eds) (1988) The early serial publications of the Hawaiian Volcano Observatory Volume 2. Hawaii Natural History Assoc 1273 pp

Bruce PM, Huppert HE (1989) Thermal control of basaltic fissure eruptions. Nature 342:665–667

Delaney PD, Fiske RS, Miklius A, Okamura AT, Sako MK (1990) Deep magma body beneath the summit and rift zones of Kilauea Volcano, Hawaii. Science 247:1311–1316

Duffield WA, Christiansen RL, Koyanagi RY, Peterson DW (1982) Storage, migration, and eruption of magma at Kilauea Volcano, Hawaii, 1971–1972. J Volcanol Geotherm Res 13:273–307

Dvorak JJ (1992) Mechanism of explosive eruptions at Kilauea Volcano, Hawaii. Bull Volcanol (in press)

Dvorak JJ, Okamura AT (1987) A hydraulic model to explain variations in summit tilt rate at Kilauea and Mauna Loa volcanoes. US Geol Surv Prof Pap 1350:1281–1296

Dzurisin D, Anderson SA, Eaton GP, Koyanagi RY, Lipman PW, Lockwood JP, Okamura RT, Puniwai GS, Sako MK, Yamashita KM (1980) Geophysical observations of Kilauea Volcano, Hawaii, 2. Constraints on the magma supply during November 1975–September 1977. J Volcanol Geotherm Res 7:169–241

Dzurisin D, Koyanagi RY, English TT (1984) Magma supply and storage at Kilauea Volcano, Hawaii, 1956–1983. J Volcanol Geotherm Res 21:177–206

Finch RH (1920a) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 3:33–49

Finch RH (1920b) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 4:51–57

Finch RH (1920c) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 5:59–67

Fiske RS, Kinoshita WT (1969) Inflation of Kilauea Volcano prior to its 1967–1968 eruption. Science 165:341–349

Furumoto AS (1978) Nature of the magma conduit under the east rift zone of Kilauea volcano, Hawaii. Bull Volcanol 41:435–453

Garcia MO, Ho RA, Rhodes JM, Wolfe EW (1989) Petrologic constraints on rift-zone processes. Bull Volcanol 52:81–96

Heliker CC, Wright TL (1991a) Lava flow hazards from Kilauea's current eruption. Geotimes 36, 5:16–19

Heliker CC, Wright TL (1991b) The Puu Oo-Kupaianaha eruption of Kilauea. EOS 72:521–530

Hill DP, Zucca JJ (1987) Geophysical constraints on the structure of Kilauea and Mauna Loa volcanoes and some implications for seismomagmatic processes. US Geol Surv Prof Pap 1350:903–918

Ho RA, Garcia MO (1988) Origin of differentiated lavas at Kilauea Volcano, Hawaii: implications from the 1955 eruption. Bull Volcanol 50:35–46

Holcomb RT (1987) Eruptive history and long-term behavior of Kilauea Volcano. US Geol Surv Prof Pap 1350:261–350

Jaggar TA (1919a) Monthly bulletin of the Hawaiian Volcano Observatory. 7, 10:127–159

Jaggar TA (1919b) Monthly bulletin of the Hawaiian Volcano Observatory. 7, 11:161–173

Jaggar TA (1919c) Monthly bulletin of the Hawaiian Volcano Observatory. 7, 12:175–199

Jaggar TA (1920a) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 1:1–14

Jaggar TA (1920b) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 2:17–30

Jaggar TA (1920c) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 6:96–77

Jaggar TA (1920d) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 7:79–85

Jaggar TA (1920e) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 8:89–95

Jaggar TA (1920f) Monthly bulletin of the Hawaiian Volcano Observatory. 8, 9:97–110

Jaggar TA (1930) When Kilauea Mountain broke open 1920. Volcano Letter 282:1–3

Jaggar TA (1947) Origin and development of craters. Geol Soc Am Mem 21:508 pp

Jaggar TA, Finch RY (1929) Tilt records for thirteen years at the Hawaiian Volcano Observatory. Seism Soc Am Bull 19:38–51

Kauahikaua J, Jackson DB, Zablocki CJ (1986) Resistivity structure to a depth of 5 km beneath Kilauea Volcano, Hawaii from large-loop-source electromagnetic measurements (0.04–8 Hz) J Geophys Res 91:8267–8283

Klein FW, Koyanagi RY, Nakata JS, Tanigawa WR (1987) The seismicity of Kilauea's magma system. US Geol Surv Prof Pap 1350:1019–1185

Macdonald GA (1962) The 1959 and 1960 eruptions of Kilauea volcano, Hawaii, and the construction of walls to restrict the spread of the lava flows. Bull Volcanol 24:249–294

Macdonald GA, Abbot AT, Peterson FL (1983) Volcanoes in the sea the geology of Hawaii. University of Hawaii Press, Honolulu. 517 pp

Peterson DW (1967) Geologic map of the Kilauea Crater quadrangle, Hawaii: US Geol Surv Geol Quad Map GQ-667 (1:24000)

Peterson DW, Moore JG (1987) Geologic history and evolution of geologic concepts, island of Hawaii. US Geol Surv Prof Pap 1350:149–189

Peterson DW, Tilling RI (1980) Transition of basaltic lava from pahoehoe to a'a, Kilauea Volcano, Hawaii: field observations and key factors. J Volcanol Geotherm Res 7:271–293

Rhodes JM, Wenz KP, Neal CA, Sparks JW, Lockwood JP (1989) Geochemical evidence for invasion of Kilauea's plumbing system by Mauna Loa magma. Nature 337:257–260

Rowland SK, Walker GPL (1987) Toothpaste lava: characteristics and origin of a lava structural type transitional between pahoehoe and a'a. Bull Volcanol 49:631–641

Rowland SK, Walker GPL (1990) Pahoehoe and a'a in Hawaii: volumetric flow rate controls the lava structure. Bull Volcanol 52:615–628

Rubin AM, Pollard DD (1987) Origins of blade-like dikes in volcanic rift zones. US Geol Surv Prof Pap 1350:1449–1470

Ryan MP, Koyanagi RY, Fiske RS (1981) Modeling the three-dimensional structure of macroscopic magma transport systems: application to Kilauea Volcano, Hawaii. J Geophys Res 86:7111–7129

Swanson DA (1972) Magma supply rate at Kilauea Volcano, 1952–1971. Science 175:160–170

Swanson DA, Duffield WA, Jackson DB, Peterson DW (1979) Chronological narrative of the 1969–71 Mauna Ulu eruption of Kilauea Volcano, Hawaii. US Geol Surv Prof Pap 1056:55 pp

Thomas D (1987) A geochemical model of the Kilauea east rift zone. US Geol Surv Prof Pap 1350:1507–1525

Tilling RI, Christiansen RL, Duffield WA, Endo ET, Holcomb RT, Koyanagi RY, Peterson DA, Unger JD (1987) The 1972–1974 Mauna Ulu eruption, Kilauea Volcano: an example of quasi-steady-state magma transfer. US Geol Surv Prof Pap 1350:405–469

Ulrich GE (1986) Geology section of Hawaiian Volcano Observatory monthly report for December 1986

Ulrich GE, Wolfe EW, Heliker CC, Neal CA (1987) Puu Oo IV: evolution of a plumbing system. Hawaii Symposium on How Volcanoes Work abstract vol p 259

Walker GPL (1987) The dike complex of Koolau volcano, Oahu: internal structure of a Hawaiian rift zone. US Geol Surv Prof Pap 1350:961–996

Walker GW (1967) Geologic map of the Kau Desert quadrangle, Hawaii. US Geol Surv Geol Quad Map GQ-827 (1:24000)

Wilson L, Head JW III (1988) Nature of local magma storage zones and geometry of conduit systems below basaltic eruption sites: Puu Oo, Kilauea east rift, Hawaii, example. J Geophys Res 93:14785–14792

Wolfe EW, Garcia MO, Jackson DB, Koyanagi RY, Neal CA, Okamura AT (1987) The Puu Oo eruption of Kilauea Volcano, episodes 1–20, January 1983–June 1984. US Geol Surv Prof Pap 1350:471–508

Wright TL (1971) Chemistry of Kilauea and Mauna Loa lava in space and time. US Geol Surv Prof Pap 735:40 pp

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