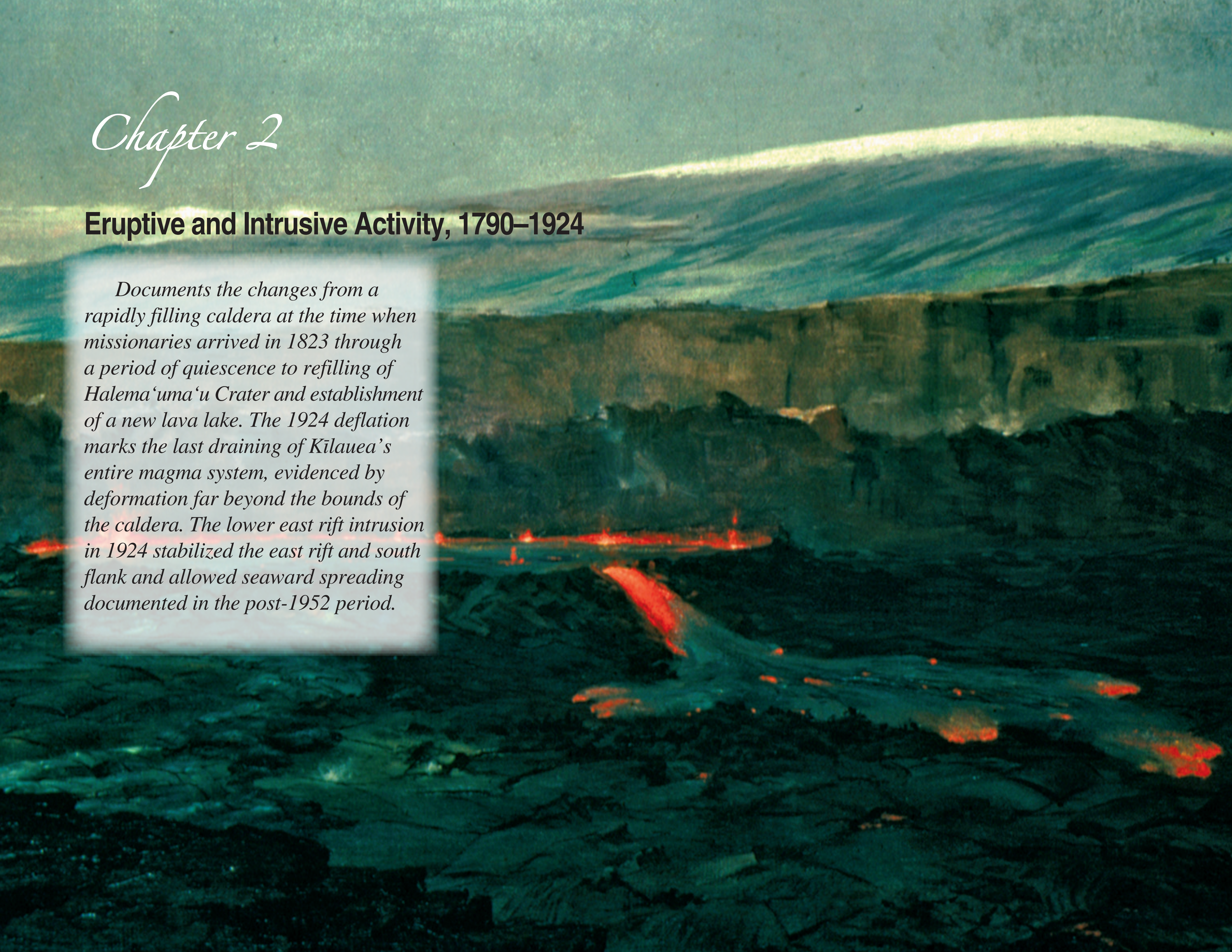

Chapter 2

Eruptive and Intrusive Activity, 1790–1924

Documents the changes from a rapidly filling caldera at the time when missionaries arrived in 1823 through a period of quiescence to refilling of Halema‘uma‘u Crater and establishment of a new lava lake. The 1924 deflation marks the last draining of Kīlauea’s entire magma system, evidenced by deformation far beyond the bounds of the caldera. The lower east rift intrusion in 1924 stabilized the east rift and south flank and allowed seaward spreading documented in the post-1952 period.

The historical period of direct observation in Hawai‘i begins with the European discovery of the islands in 1778–79 by Capt. James Cook (Wright and others, 1992). The written record of observations at Kīlauea Volcano begins in 1823 with the arrival of the missionary William Ellis (Ellis, 1825). The history can be extrapolated back to 1790 from oral reports that recount a great explosive eruption (Dibble, 1843; Swanson and Christiansen, 1973).

We subdivide this period into five segments, starting in 1790, 1840, 1868, 1895, and 1918, and ending in 1924. During the first three periods a lava lake was present within a broad region of Kīlauea Caldera, and filling rates diminished after 1840. Between 1840 and 1894 the lava lake was gradually reduced to a single vent at the position of the present-day Halema‘uma‘u. Within this period the great Ka‘ū earthquake of April 1868 (Wyss and Koyanagi, 1992, and references therein) was manifested at Kīlauea by intense shaking accompanied by loss of parts of the caldera wall, rapid withdrawal of magma from Kīlauea Caldera, eruptions in Kīlauea Iki and the southwest rift zone and by the occurrence of a possible strong aftershock beneath Kīlauea's south flank.

The disappearance of lava from Halema‘uma‘u from July through December 1894 marked the end of continuous activity in Kīlauea Caldera. During the period from 1895 to 1918 Halema‘uma‘u was gradually refilled to initiate a new era of lava lake activity. The lava lake ended with phreatic eruptions in May 1924 that accompanied emptying and enlargement of Halema‘uma‘u. A regional uplift in 1918–19 and a regional subsidence in 1924 bracketed several eruptions and intrusions both within and outside of the caldera.

1790–1840

Events of this period, including earthquakes with magnitudes ≥6.0, are summarized in table 2.1.

The earliest observations of Kīlauea in 1823 document the existence of a lava lake active over much of the summit caldera more than 400 m below the caldera rim. The subsequent history is marked by alternating episodes of filling and withdrawal, the latter sometimes accompanied by eruptions outside of Kīlauea Caldera. Withdrawal of magma left a ring of lava, termed a "black ledge", and subsequent filling occurred both within and over the previously existing black ledge. The active lava surface was often described as a broad dome with relief of as much as 90 m. We use areas within an inner and outer black ledge as well as the entire crater floor (Mastin, 1997; table A1) to calculate lava volumes that correspond to lava thicknesses added to the caldera over time, as cited in the various references. The thickness values are estimates, the most reliable coming from persons who made frequent visits to the crater, such as the missionary Titus Coan.

The occurrence of large earthquakes and earthquake swarms have been tabulated and their sources tentatively identified (Klein and Wright, 2000). In some cases earthquake locations are made more certain by viewing them within the context of documented filling and draining.

In this early period we estimate magma supply rates using data on caldera filling rates as shown in appendix A, "Calculation of magma supply" section. Filling rates within Kīlauea Caldera have been estimated from early drawings, crude maps, and measurement of the depth to the top of the lake surface (fig. 2.1; Mastin, 1997[4]). Filling is calibrated against maps made in 1825 (Byron, 1826) and 1840 (Wilkes, 1845). The pre-1840 eruption rate was very high; filling rates, corrected for vesicles, begin at values of 0.26 km^3/year, significantly higher than the 0.11–0.18 km^3/year vesicle-free eruption rate estimated at the start of the 1983 and ongoing eruption of Kīlauea (Dvorak and Dzurisin, 1993; Heliker and Mattox, 2003)[5]. The rates diminish to 1832, then increase as a result of refilling the very large volume lost in the 1832 draining, then diminish again after 1840. There are inconsistencies in reports of different persons on the same expedition, but any adjustments cannot deny the very high rates of filling before 1840 contrasting with a fivefold decrease in filling rate after 1840 (fig. 2.1)[6].

Two early eruptions from the southwest rift zone (1823) and east rift zone (1840) also had rates that were much higher than those measured in any modern eruption. Both eruptions were accompanied by rapid and temporary draining of Kīlauea's summit lava lake. Lava flows of the 1823 eruption were mapped and described by Harold Stearns, who noted that, although the lava flow was very thin, splash from the flow was found 10 m above the flow surface on cinder cones adjacent to the flow (Stearns, 1926). A flow velocity of 12–15 m/sec has been estimated by Guest and others (1995). This rate exceeds by about an order of magnitude the median velocity of 1–2 m/sec for flow in tubes feeding the current Pu‘u ‘Ō‘ō-Kupaianaha eruption (Hon and others,

[4]Mastin's calculations, summarized in his appendix table A3, are uncorrected for vesicularity. We use his volumes corrected to magma volume.

[5]We made new calculations of filling rate, based on reconciling the early reports of dimensions of the intra-caldera lava lake and the depth to active magma.

[6]Our estimates of filling rate are higher than those made by earlier workers (Finch, 1941; Macdonald, 1955) , but we are in full agreement with their conclusion that filling rates prior to 1840 were greater than those following 1840.

1994, p. 361). More recent work (Soule and others, 2004) suggests a lower emplacement rate closer to that of other channeled ʻaʻā flows.

The 1840 lava field was visited several months after the eruption by Titus Coan (1841) and James Dana (1849). Eruption took place at several points along the rift zone, extending from ʻAlae Crater, several kilometers from Kīlauea's summit, to the lower east rift zone about 12 km west-southwest of Kapoho Crater. Coan also reported steaming open fractures between Kīlauea's summit and the uppermost point where lava reached the surface[7]. The vents farthest from the summit erupted picritic lava that traveled rapidly to the ocean over a three-week period, producing a series of littoral cones that are still extant. Lava entering the ocean was dispersed downslope and has not been separately identified in recent bathymetry obtained adjacent to Kīlauea's south coast (for example, Smith and others, 1999)

The 1840 eruption also had unusually high flow rates for a channeled ʻaʻā flow at Kīlauea. Coan (1882) indicates that the final flow to the sea took place on 3 June at rates of 0.22–2.2 m/sec (0.5 to 5 miles per hour), consistent with the flow having reached the ocean in the same day from vents 9 to 15 km upslope. The areal extent of lava erupted from the lower vents is about 21 km^2, estimated from recent geologic mapping, and the flow thickness on land ranges from 1.2 to 12.2 m (Trusdell, 1991, fig. 5 and p. 18). Macdonald (1955) estimated the on-land volume to be 0.0618 km^3, which corresponds to an average flow thickness of 3 m. If we conservatively estimate that one-quarter of the total

[7]In 2010 D.A. Swanson discovered a previously unrecognized small lava patch in the western Koaʻe Fault Zone that has a chemistry consistent with other analyses of the 1840 eruption.

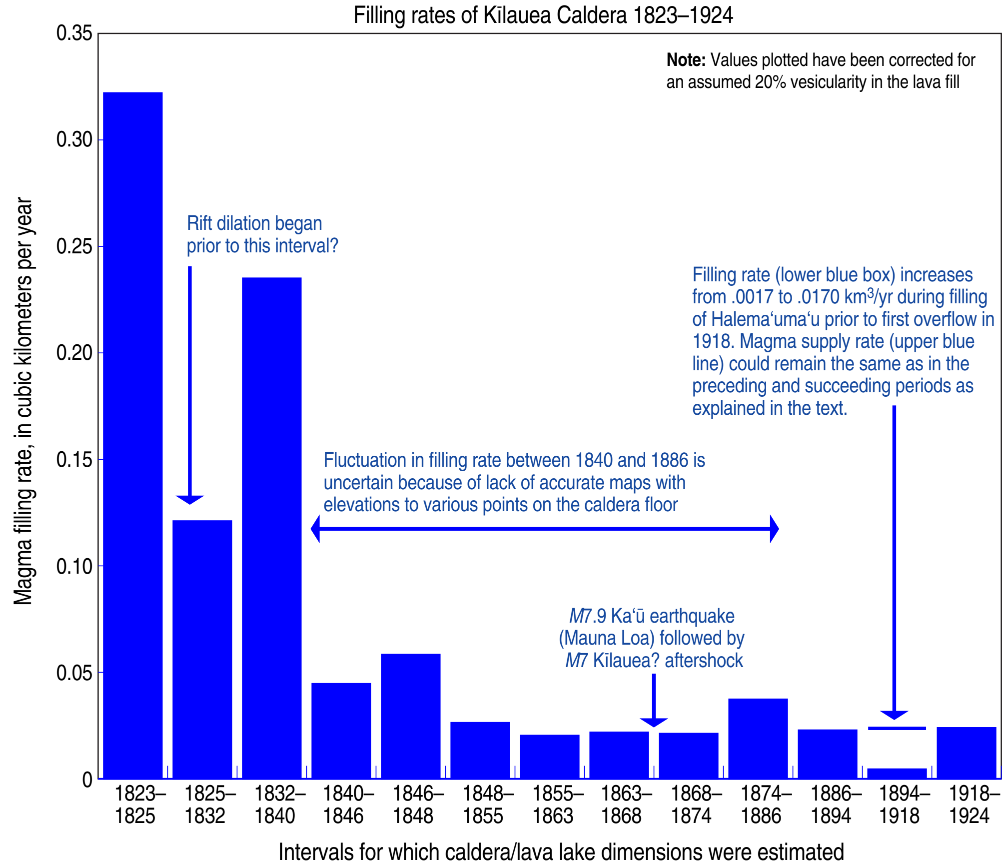

Figure 2.1. Graph of filling rates within Kīlauea Caldera 1823–1924. Magma filling rates calculated as cubic kilometers per year (within time periods of varying length) according to procedures discussed in the text. Lava volumes are corrected for 20-percent vesicularity. Uncertainties in the volume estimates are sufficiently large that we cannot deny the null hypothesis that rates could have been constant at different levels, both before and after 1840. However, the difference in rate of nearly an order of magnitude before and after 1840 is supported. The history after 1840 is critically dependent on a missing piece of data, the lack of an accurate figure for depth to the caldera floor before and after the 1868 earthquake. We use the estimate provided by James Dana (1888, p. 18). An assumption of an even greater amount of filling before 1868 would be more consistent with continuing decrease of the overall rate prior to disappearance of the caldera lava lake in 1894.

Table 2.1. Kīlauea eruptions, intrusions, and large earthquakes, 1790–1894.

[In rows with multiple entries text applies down to the next entry; data for eruptions and traditional intrusions are emphasized by grey shading; dates in m/d/yyyy format]

Start date	End date	Location[1]	Event-Type[2]	Comment	References
1790	1790	kc	E EQ	Last in a 300-year series of explosive eruptions at Kīlauea's summit *M*~6.4	Dibble, 1843; Mastin, 1997; Swanson and others, 1999
1790+	1894	kc	E	Continuous filling of Kīlauea Caldera	Brigham, 1909; Dana, 1887a; Dana, 1887b; Dana, 1888; Hitchcock, 1909
6/01?/1823		sf	EQ	Strong earthquake (*M*~7.0), reported to Ellis as preceding his visit by two months; probably located on the southwestern part of Kīlauea's south flank	Ellis, 1825; Klein and Wright, 2000
06?/1823	07?/1823	swr	E	Eruption still hot when seen by Ellis	Ellis, 1825
1/10/1832		sf	EQ	*M*5.6, 6.2—two damaging earthquakes, with aftershocks and many ground cracks	Dibble, 1843; Klein and Wright, 2000
1/10/1832	1/14/1832	kc erz?	E/C I?	Eruption on Byron's Ledge, Kīlauea's summit, strong earthquakes (see above) and a major collapse, magma withdrawing to the level first seen by Ellis	Dibble, 1839; Goodrich, 1833
11/5/1838	11/17/1838	erz/sf	EQS I	A series of 50–100 shocks felt in Hilo with magnitude range <4.5 to 5.9—probably an intrusion on the east rift zone with a south flank response	Klein and Wright, 2000
12/10/1838		Sf, erz	EQ, I	*M*6.1—preceded by elevated seismicity from 4 December; possible renewal of intrusion beneath the east rift zone	Klein and Wright, 2000
3/18/1839		kc??	EQ	*M*6.1—classified as "Hawai'i", possibly deep Kīlauea Caldera	Klein and Wright, 2000
2/1/1840		sf?	EQ	*M*6.1—classified as "south Hawai'i"	Klein and Wright, 2000
5/30/1840	6/7/1840	kc erz erz erz	C E EQS I	Eruption/intrusion migrated down the east rift zone, first appearing at 'Alae Crater and ending in Puna—accompanied by seismicity felt only near the eruption site and collapse and withdrawal of magma from Kīlauea's summit	Coan, 1841; Jarves, 1840; Jarves, 1844; Wilkes, 1845
4/5/1841	4/8/1841	sf?	EQ	*M*6.1 on 7 April preceded by *M*5.3 foreshock on 5 April and followed by several aftershocks	Klein and Wright, 2000
2/18/1844		sf?	EQ	*M*6.1	Klein and Wright, 2000
7/18/1860		sf??	EQ	*M*6.1	Klein and Wright, 2000
4/2/1868		ml	EQ	*M*7.9 Great Ka'ū earthquake. The source volume covered the entire south half of Island of Hawai'i, and the magnitude distribution of earthquakes occurring at Kīlauea and Mauna Loa up to the present are still part of the aftershock sequence following this earthquake (Klein and Wright, 2008). Alexander's map shows fractures generated by the 1868 shaking extending through the southwest flank	Anonymous, 1868a; Coan, 1868; Coan, 1869; Fornander, 1868; Hillebrand, 1868; Klein and Wright, 2000; Macdonald, 1952; Williamson, 1868b; Wyss and Koyanagi, 1992 Alexander, 1886

Table 2.1. Kīlauea eruptions, intrusions, and large earthquakes, 1790–1894.—Continued

[In rows with multiple entries text applies down to the next entry; data for eruptions and traditional intrusions are emphasized by grey shading; dates in m/d/yyyy format]

Start date	End date	Location[1]	Event-Type[2]	Comment	References
4/4/1868		sf?	EQ	*M*7? D. Cox (oral commun., 1992) notes that excessive damage on Kīlauea's south flank and an anomalous arrival of a 2nd tsunami in Hilo suggest that one of the strong aftershocks was beneath Kīlauea	Cox, 1980
4/8/1868		kc	C/E	Major collapse of Kīlauea's summit followed by eruption in Kīlauea Iki Crater	Coan, 1868; Coan, 1869; Fornander, 1868; Hillebrand, 1868
4/8/1868		erz?	I?	Report of eastern craters opening and smoke in the direction of Puna	Anonymous, 1868d
4/8/1868		swr	E/I?	Eruption (and intrusion?) on southwest rift zone	Anonymous, 1868b; 1868c; Coan, 1868
5/24/1868	5/29/1868	sf?	EQ	*M*6.2 mainshock with 8 aftershocks *M*3.5-5.9	Klein and Wright, 2000
3/21/1870 4/22/1872		sf??	EQ	*M*6.2; 6.1 aftershocks of the 1868 earthquake classified as "South Hawai'i"	Klein and Wright, 2000
5/4/1877	5/4/1877	kc	E/C	Draining of magma from Kīlauea Caldera coincident with eruption in Keanakāko'i	Anonymous, 1877a
5/5/1877	5/6/1877	sf?	I?	Possible south flank earthquakes associated with east rift intrusion?	Klein and Wright, 2000
5/31/1877		kc	EQ	*M*6.3 deep beneath Kīlauea Caldera—2 aftershocks	Klein and Wright, 2000
4/21/1879	4/21/1879	hm	C/I?	Collapse of several hundred feet—lava gone, no earthquakes	Anonymous, 1879; Coan, 1879; Wood, 1917
9/25/1880 ?		sf? ?	EQ I?	*M*6.0 with aftershocks Report of lava draining from Halema'uma'u before the Mauna Loa eruption	Klein and Wright, 2000 Maby, 1886; Wood, 1917
3/6/1886	3/6/1886	kc	C	Draining of Halema'uma'u lava lake	Klein and Wright, 2000; Maby, 1886
3/6/1886	3/7/1886	swr/sfswr	EQS/I	43 earthquakes, some felt at Kapāpala and Hilo map of Kīlauea Caldera made after the collapse	Emerson, 1887
8/6/1890	8/7/1890	sf?	EQ	*M*6.5 with at least 9 aftershocks, one *M*5.9	Klein and Wright, 2000
3/6/1891	3/6/1891	kc	C; I	Draining of Halema'uma'u Crater	Anonymous, 1891; Klein and Wright, 2000; Maby, 1891
3/6/1891	3/8/1891	swr/sfswr	EQS	Earthquake swarm of over 100 events, most felt at Kapāpala	Klein and Wright, 2000
7/12/1894	7/19/1894	kc	C	Halema'uma'u draining	Anonymous, 1894a; Thurston, 1894
7/13/1894		erz	EQS/I	At least 12 events; earthquakes felt at Hilo	
12/4/1894	12/6/1894	kc swr/sfswr	C EQS/I	Final breakdown of Halema'uma'u—lava disappears Earthquakes felt in Ka'ū	 Anonymous, 1894d

[1]Location abbreviations correspond to regions shown on chapter 1, figure 1.1*A*: kc, Kīlauea Caldera; hm, Halema'uma'u Crater; erz, east rift zone; swr, southwest rift zone; sf, south flank.
[2]Event abbreviations: E, Eruption; I, intrusion; EQ, Earthquake ≥*M*5; EQS, Earthquake swarm; fs, foreshock; C, Collapse of Kīlauea's summit or sharp summit tilt drop indicating transfer of magma to rift zone.

was emplaced in 18 hours on the first day, then the volumetric rate into the ocean is 0.02 km^3 per day (20 million m^3 per day). Another calculation, taking the cross-sectional area of the distributary tubes estimated by Trusdell at 360 m^2, and the median flow velocity seen in recent eruptions (1 m/sec), yields a volumetric flow rate of 0.031 km^3 per day. Even given the large uncertainties in these estimates imposed by required assumptions, we can say with confidence that the 1840 eruption exceeds by a considerable factor the discharge rate of other Kīlauea eruptions.

In addition to its high rate, the 1840 eruption was unlike any more recent Kīlauea eruptions in the following respects:

1. The distance that magma migrated along the east rift zone. The 1840 eruption propagated from Kīlauea's summit a total distance of 50 km. Only large east rift zone eruptions since 1840 have propagated more than 10 km within the rift zone and none has shown surface faulting propagating downrift beginning at Kīlauea's summit.
2. The rate of propagation down the rift. The total distance of 50 km was traversed in 4 days, or 12.5 km per day. Magma resupply from Kīlauea's summit to Puna during 1955 took 13–18 days to go approximately the same distance (Wright and Fiske, 1971). The 1840 rate may also be compared to rates of sustained downrift earthquake propagation over shorter (1 to 10 km) sections of rift accompanying emplacement of dikes at shallow depths. Well-defined rates range from 0.06 to 3.8 km/hr (1.4–91 km/day), the rate decreasing logarithmically with increasing time of propagation (Klein and others, 1987, table 43.1, p. 1056). The highest rates were sustained for times on the order of 1 hour over distances of 4 km or less; the lowest rates were sustained for as long as 48 hours over about the same distance. One of the best defined swarms, one that marked the beginning of the 1983 Pu‘u ‘Ō‘ō eruption, propagated 8 km in 12 hours, a rate of 16 km per day. This is the only swarm to have a propagation rate close to that inferred for 1840, but the propagation distance was far less.
3. The absence of significant seismic activity during or preceding the eruption. This is explained by looking at the earthquake history prior to 1840 (Klein and Wright, 2000). J.J. Jarves, editor of the Polynesian Magazine, visited the site of the 1840 eruption a few months after the eruption ended. Jarves concludes his narrative with comments on the eruptive process as it relates to earthquakes:

> It is singular that an eruption of this magnitude should occur without the slightest shock of an earthquake, at least none was noticed if any happened, which proves that this was the effect of no sudden, violent action, but one of long and gradual preparation. . . . . .
>
> Three years since, smoke and steam were seen issuing from near where the present eruption commenced, and two years ago a great rent was made in the ground, and all the springs in the vicinity dried up.

The latter statement is supported by the documentation of an earthquake swarm of hundreds of events, between 5 and 17 November 1838, culminating in a *M*5.9 earthquake beneath Kīlauea's south flank, and again in the first week of December, culminating in a *M*6.1 earthquake beneath Kīlauea's south flank (Klein and Wright, 2000, and references cited therein). It appears that a relatively slow intrusion into the east rift zone culminated in two large south flank earthquakes. The dilation of the rift that can be inferred from such an event made it possible for the eruption of 1840, two years later, to occur without an accompanying earthquake swarm.

A small eruption at Kīlauea's summit occurred in January 1832, between the two high-volume eruptions of 1823 and 1840. The eruption was located on Byron Ledge, which separates Kīlauea Caldera from Kīlauea Iki Crater, and was accompanied by a series of earthquakes felt in Hilo, culminating in an earthquake of *M*6.2 beneath Kīlauea's south flank (Klein and Wright, 2000, and references therein). This earthquake was strong enough to cause draining of lava from the caldera floor, subsidence adjacent to Kīlauea's summit, and fault opening over a wide region of the volcano (Dibble, 1839; Dibble, 1843). We interpret the 1832 event as an east rift intrusion triggering a broad draining of Kīlauea Caldera's lava lake and a possible lowering of the caldera floor (Dana, 1891).

1840–1868

Of inestimable help in our interpretations of the period between 1840 and 1887 are the excellent summaries of James Dana, who was a scientist on the U.S. Exploring Expedition that arrived at Kīlauea just after the 1840 eruption (Dana, 1887a,b, 1888).

The filling of Kīlauea caldera is imperfectly documented by (1) many anecdotal observations by visitors to the active lava lake, (2) more authoritative observations of scientists and missionaries who visited the caldera at several different times, and (3) the occasional production of maps and cross sections that define the depth to the caldera floor and the size of the active areas. From these observations both short- and long-term filling rates have been calculated (figs. 2.1, 2.2). Emerson's 1887 map (Emerson, 1887) is the only map on which elevations to various points on the caldera floor were accurately surveyed. The largest uncertainty in the caldera filling rates is before and after the events of 1868. W.T. Brigham made maps both before and following the 1868 draining, but he gives no elevations to indicate how much the caldera adjacent to its walls had filled since 1840. His one citation of vertical distance to the crater floor below the Volcano House differs only slightly from a similar estimate made in 1840, an observation at variance with many other reports. Dana also questioned Brigham's observation (Dana, 1888, p. 18) and assumed a filling rate of ~0.03 km^3/yr between 1840 and 1868, which we accept, even though it has no quantitative basis.

The filling process is inferred from the early descriptions and verified by observation of more recent lava lakes. It involves four distinct processes:

1. Filling of an empty crater. An active lava lake of some dimension is enclosed within a levee of previously cooled lava, termed "black ledge" in the early literature. The filling is calculated as the depth of fill multiplied by the area of the upper and lower bounds of the cone or cylinder assumed for the shape of the crater being filled within its black ledge.

2. Overflow beyond the confines of a crater being filled. In this instance the active lava spreads beyond the bounds of the initial crater to form a new black ledge. In some cases the overflow extends to the boundaries of the caldera. Fill is calculated as depth multiplied by the area covered. Reference areas (Mastin, 1997; appendix A, table A1) are given for the area within the inner black ledge before the 1840 draining and eruption (3.42 km^2), the area within the outer black ledge after the 1840 draining (8.13 km^2) and the area within the entire caldera (9.85 km^2).

3. Endogenous filling and dome growth. There are numerous early accounts of uplift in which the central active zone assumes the form of a dome whose height may be as much as 100 m. (for example, Brigham, 1887; Coan, 1851, 1854) The additional volume is calculated as half of a prolate spheroid. There are also numerous accounts of uplift of the central caldera floor with little or no evidence of active overflow (for example, Clarke, 1886; Coan, 1870; Lyman, 1851). This process was identified more recently during the partial filling of Halemaʻumaʻu in 1968 (Kinoshita and others, 1969, p. 62). There is no direct account of uplift at the margins of the caldera, so we have assumed that increase in elevation of the caldera floor at its edges is by overflow only.

4. The volumes of endogenous uplift are difficult to quantify because the dimensions of the uplifted area are generally not given. We have used the area within the pre-1840 black ledge in our calculations.

5. Draining, leaving an empty crater. For all such events an estimate of the drained volume has been made (table 2.2). Most of these are associated with earthquake swarms that include felt events far from the caldera, indicating intrusion beneath one or both rift zones. When earthquakes are felt in Hilo the intrusion is presumed to be beneath the east rift zone. When earthquakes are felt in Kaʻū, the intrusion is assumed to be beneath the southwest rift zone. In some instances reports of felt earthquakes suggest intrusion beneath both rift zones and (or) large earthquakes beneath the south flank.

Some of the best values for short-term filling rates come from descriptions of lava levels and crater dimensions following a draining. For the long-term calculations the draining volumes are added to increases in the caldera level; that is, it is assumed that new magma first fills the drained volume, then may flow into the broader caldera. The long-term estimates of filling of the caldera integrate the combination of exogenous and endogenous growth.

The Draining of 1868

An active lava lake returned to Kīlauea Caldera after the 1840 eruption, and caldera filling continued at a greatly diminished rate (fig. 2.1). The next major draining took place following the great Kaʻū earthquake of 2 April 1868. The magnitude 7.9 earthquake occurred beneath the Hīlea zone on Mauna Loa's south flank (Wyss and Koyanagi, 1992). Eyewitness reports of what happened at Kīlauea are quoted by Brigham (1868) and by Dana (1887a). From 20 January the lava lakes at Kīlauea were increasingly active, becoming even more markedly active following a felt foreshock of the Kaʻū earthquake on 27 March. On 28 March an earthquake sequence began beneath the Hīlea district of Mauna Loa. On 29 March the lava lakes overflowed and began to cover the caldera floor. The great earthquake occurred at 4 p.m. on 2 April. Recession of the lava began as parts of the caldera wall collapsed. By 6 p.m., lava was 30 m down in the main lake, the caldera floor was rent by gaping fractures, and a short eruption had taken place in Kīlauea Iki Crater. Over the next 3 days, lava continued to drain away; by 5 April, all active lava had left the caldera, leaving a double collapse—a central, empty pit about 150 m deep, surrounded by a broad sag with walls from 30 to 90 m high. There was an unconfirmed report of eruption on the east rift zone and a confirmed sighting of a glow emanating from the southwest rift zone. Later, fresh lava flows on the southwest rift zone were located and carefully described by Titus Coan (1869). The timing of the southwest rift eruption is not clear, although it undoubtedly took place within the 3-day period during which the caldera was draining. Following the *M*7.9 mainshock, Kīlauea's southwest rift zone and adjacent south flank were cracked, as documented by fault-related fractures shown on an early map of the island (Alexander, 1886) and the southern coast of Hawai‘i subsided 1–2 m (Coan, 1869). It is not known whether the east rift zone and eastern south flank were also affected.

The events of 1868 have been interpreted in the light of more recent knowledge by Wyss and Koyanagi (1992) and by Clague and Denlinger (1993). Both sets of authors place the epicenter of the foreshock on Mauna Loa's southwest rift zone. Wyss and Koyanagi placed the mainshock on the south flank of Mauna Loa and concluded that the mainshock rupture extended from the Hīlea area on Mauna Loa's south flank across Kīlauea's southwest rift zone and also ruptured Kīlauea's south flank. Clague and Denlinger place the mainshock near the lower end of Kīlauea's southwest rift zone. They interpret the ground cracking to indicate that a large landslide comprising the entire south flank of Kīlauea moved seaward during the *M*7.9 event. In our view the effects of the earthquake were not simple. The observation that propagation of magma down the full length of the east rift zone has not been seen at any time after 1868 suggest that the east rift zone was activated but later sealed as a consequence of the earthquake, but the mechanism is a matter of speculation.

One additional piece of modern analysis makes the events of 1868 more easily understandable. Doak Cox (1980 and oral commun., 2000) pointed to the timing of arrival in Hilo of a tsunami triggered by the great Ka‘ū earthquake as indicating the existence of a second tsunami source closer to Hilo. This is supported by comparing damage reports from (1) the south coast of Mauna Loa near the epicenter, (2) the city of Hilo, and (3) the summit of Kīlauea. It appears that Kīlauea had more damage than one would expect from damage at the other two localities. Wyss and Koyanagi (1992) concluded that the mainshock rupture extended from the Hīlea area on Mauna Loa's south flank across Kīlauea's southwest rift zone and ruptured Kīlauea's south flank also. Cox concluded that the 1868 earthquake aftershock sequence included a second earthquake of high magnitude (~*M*7) beneath Kīlauea's south flank, resulting in the generation of a second tsunami. The delay of at least one day in the major draining of Kīlauea Caldera and in the initiation of a southwest rift intrusion and eruption is more consistent with events local to Kīlauea than to the effects of a Mauna Loa earthquake, however large. The source volume estimated for the mainshock (Wyss and Koyanagi, 1992) includes all of Kīlauea and is consistent with the possibility of a large aftershock beneath Kīlauea.

1868–1895

During the remainder of the 19th century, lava was added to Kīlauea Caldera at a low and possibly decreasing rate (fig. 2.1) and the center of eruptive activity became more localized near the present site of Halema‘uma‘u Crater. Major, well documented draining of Kīlauea summit lava lake occurred in 1886, 1891, and 1894, each accompanied by felt earthquake sequences suggesting rift intrusion (table 2.1). Minor draining with less compelling evidence for intrusion occurred in 1871, 1877 (associated with an eruption in Keanakāko‘i Crater—a minor repeat of the 1868 sequence in Kīlauea Iki?), 1879, and 1880. The 1894 draining occurred in two stages, July and December, with increments of additional draining occurring between the two main events. Following the December 1894 earthquake swarm, lava disappeared from the crater, ending the 19th century period of near-continuous eruptive activity. Halema‘uma‘u was left as a circular pit of radius 180 m at the top and unspecified radius at its bottom.

1895–1918

Following the 1894 draining, the lava stored at shallow depth beneath the caldera remained relatively inactive, erupting sporadically deep within Halema‘uma‘u over the next decade (fig. 2.2). Halema‘uma‘u Crater also continued to deepen, reaching a maximum depth of 300 m in March 1899 (Wood, 1917). From 1899 on, we calculate the volume of fill as a frustum of a cone (the volume of part of a cone bounded by two horizontal planes) whose radius varies between 180 m at the surface to 120 m at 300-m depth. The altitude at the surface, used as a datum in figure 2.2, is 1,130 m (3,700 feet). Beginning at the end of 1906, filling became almost continuous and Halema‘uma‘u was nearly full toward the end of 1908 (fig. 2.2). However, reminiscent of the 19th century, the filling was punctuated by drainings, many of which occurred close in time to large Kīlauea earthquakes or earthquake swarms noted in the catalog (tables 2.3, 2.4; Klein and Wright, 2000). At the time of the founding of the Hawaiian Volcano Observatory in 1912 the lake was still nearly full (fig. 2.2).

Between 1912 and the first overflow in 1918, the level of the lake continued to fluctuate and most of the periods of draining were accompanied by earthquake swarms implying an intrusion (fig. 2.3*A*). In 1913, during a period when the lava lake was described as "dormant," there was a swarm of earthquakes beneath the south flank, possibly signifying a suspected deep intrusion (Klein and others, 1987; Wright and Klein, 2008). Filling rates (table 2.5, fig. 2.1) were much lower than in the 19th century, increasing from 0.0017 km^3/yr to 0.017 km^3/yr before overflow in 1918[8].

[8]When intrusions inferred during the refilling of Halema‘uma‘u (fig. 2.2) are taken into account, the magma supply rate could be close to that of periods preceding and following the refilling, as discussed in chapter 8, section on "Relation between eruption and intrusion expressed as eruption efficiency."

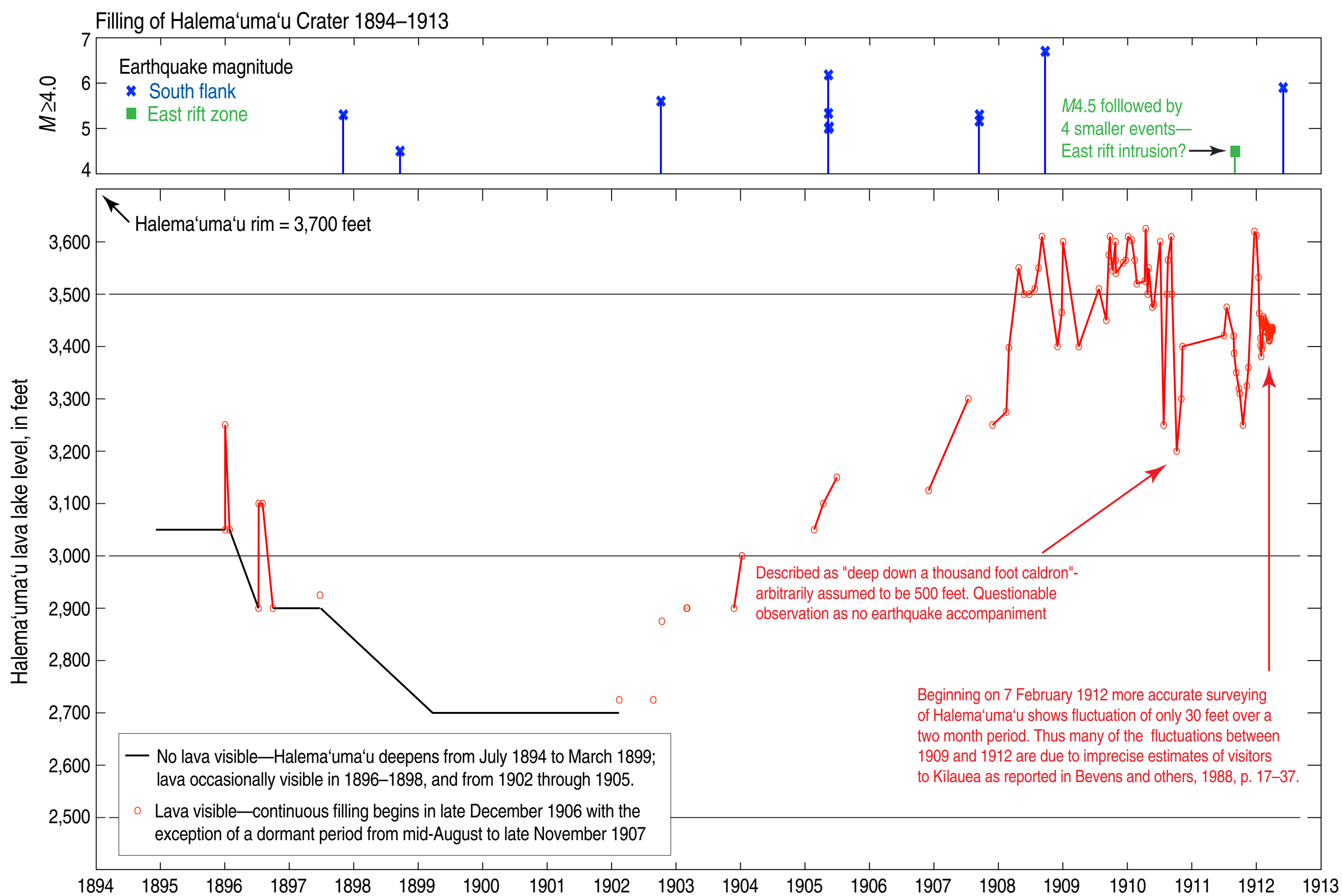

Figure 2.2. Graph showing refilling of Halemaʻumaʻu, 1895–1912. Dates and tick marks on the time (x) axis are centered at the beginning of the year. Elevation (above sea level) of the lava surface visible in Halemaʻumaʻu Crater, following disappearance of the caldera lava lake in December 1894 is plotted at times for which there exist published observations. The record is shown up to the founding of the Hawaiian Volcano Observatory in 1912. The pattern is one of gradual rise punctuated by periods of fall. The latter often correspond in time to large-magnitude earthquakes with aftershocks, tentatively assigned to Kīlauea's south flank. There is no evidence of preceding swarm activity that might suggest intrusion, and any possible swarm earthquakes would have to be large enough to be felt in this preinstrumental era. A single earthquake assigned to the east rift zone may be associated with intrusion. Estimates before 1912 have high errors as they are visual estimates made by visitors to the volcano without benefit of instruments. Instrumental measurements made after 1912 vary less than ±30 feet and probably represent the true variability between 1907 and 1912. Data from Bevens and others, 1988, v. 1, including Kīlauea activity from 1865–1011 (Wood, 1917), Kīlauea activity in 1909–1912, and F. Perret's observations in 1911, included in the first report of the Hawaiian Volcano Observatory.

Table 2.2. Kīlauea Caldera magma draining 1840–1900.

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format]

Start date	End date[1]	Return of lava[2]	Eqs yes/no	Volume (km^3)[3]	Comment[4,5]	References
5/30/1840	?	?	yes	0.22	Earthquake swarm on lower east rift zone. Eruption/intrusion?	Coan, 1841; Mastin, 1997
10/5/1855	10/6/1855			0.0371[6]		Dana, 1887a,b
4/2/1868	4/5/1868		yes	KC: 0.2658 Hm: 0.0537 Total: 0.3195[7]	Great Ka‘ū earthquake of 04/02/1868 preceded draining of lava from Kīlauea Caldera by more than 24 hours; many aftershocks, including one of *M*7+ located beneath Kīlauea(?)	Coan, 1869; Dana, 1887b
5/25/1871	5/25/1871	08/10/1871	yes	0.0267	Earthquakes felt in Hilo two days before lava disappeared	Anonymous, 1868, 1871a, 1871b; Wood, 1917
5/4/1877	5/4/1877	05/14/1877	yes	0.0278	Eruption in Keanakāko‘i accom. by intrusion beneath east rift zone.	Anonymous, 1877a, b; Wood, 1917
					Additional intrusion beneath southwest rift zone?	Anonymous, 1877b
4/21/1879	4/22/1879	04/23/1879	no	0.0500	Lava (assumed 300) feet down; probable intrusion	Coan, 1879; Dana, 1887a, b
9/1880	9/1880?	10/01/1880	yes?	0.0250	Lava draining from Halema‘uma‘u before the Mauna Loa eruption; associated with *M*6.1 south flank earthquake on 09/25/180?	Maby, 1886; Wood, 1917
3/6/1886	3/8/1886	03/20/1886	yes	0.056	Combine outer and inner collapses from elevations given on Emerson's map (plate)	Emerson, 1887
						Klein and Wright, 2000
			yes	0.109	Intrusion beneath upper east and sw rift	Anonymous, 1907; Klein and Wright, 2000
					Intrusion beneath southwest rift zone	
7/10/1894	7/15/1894	01/03/1896		0.0079	Initial collapse to depth of 275 feet; probable intrusion (east rift zone)	Armstrong, 1894; Anonymous, 1894b
	8/28/1894			0.0154	Further collapse to 600 feet	Anonymous, 1894e
12/3/1894	12/6/1894				All lava gone; probable intrusion (southwest rift zone)	Anonymous, 1894c, d
	3/24/1899			0.0225	Final collapse to 1,000 feet below rim	Anonymous, 1902; Wood, 1917

[1]Lava gone.

[2]Lava reappears.

[3]Volumes given as reported, estimated from cross-sections or description in reference(s). These are converted to magma volumes before calculation of caldera filling rates. KC, Kīlauea; Hm, Halema‘uma‘u Crater.

[4]Earthquake swarms are reported in Klein and Wright, 2000, Wyss and others, 1992 (Earthquake diary kept by the Lyman family), and Wood, 1917, in addition to anonymous newspaper reports cited in the table. Earthquakes felt in Hilo are presumed to indicate intrusion beneath Kīlauea's east rift zone. Earthquakes felt in Ka‘ū are presumed to indicate intrusion beneath Kīlauea's southwest rift zone.

[5]Intrusion locations estimated from felt earthquakes in earthquake swarms. If felt at Hilo, intrusion is beneath east rift zone. If felt in Ka‘ū, intrusion is beneath southwest rift zone. For some events, intrusion beneath both rift zones is indicated.

[6]Assume dome with area of inner black ledge (3.42 km^2 from Mastin, 1997) and height of 100 feet. Collapse reflects loss of dome and an additional loss of 50 feet of lava in Halema‘uma‘u (ellipse of 400 $\times$250 feet from Coan, 1910).

[7]The area of collapse (4.36 km^2) obtained from Lydgate's map (Dana, 1887b, p. 94) and depth of 300 feet from Coan (1869; quoted in Dana, 1887b, p. 92). Dimensions of Halema‘uma‘u (cone with 3,000 feet diameter at top and 1,500 feet at bottom and depth of 500 feet) from Dana (1887b, p. 92).

Table 2.3. Kīlauea eruptions, intrusions, and large earthquakes, 1895–1925.

[In rows with multiple entries text applies down to the next entry; data for eruptions and traditional intrusions are emphasized by grey shading; dates in m/d/yyyy format]

Start date	End date	Location[1]	Event type[2]	Comment	References[3]
1/3/1896	1/26/1896	hm	E	Lava returned briefly to bottom of Halema‘uma‘u	Wood, 1917
1/29/1896	1/31/1896	swr/sf	EQS/I?	Several earthquakes felt at Kapāpala	Anonymous, 1896
7/11/1896	9/30/1897	hm	E	Lava returned briefly to bottom of Halema‘uma‘u	Wood, 1917
6/24/1897	6/27/1897	hm	E	Lava returned briefly to bottom of Halema‘uma‘u	Wood, 1917
3/24/1899		hm	C	Halema‘uma‘u drained to 1,000 feet depth	KW; Wood, 1917
2/14/1902	2/15/1902	hm	E	Lava returned briefly to bottom of Halema‘uma‘u	KW; Wood, 1917
3/1/1903	3/5/1903	hm	E	Lava returned briefly to bottom of Halema‘uma‘u	KW
8/25/1903 10/13/1903 2/22/1905	9/12/1903 1/10/1904 9/15?/1905	hm	E	Intermittent addition of lava to the bottom of Halema‘uma‘u Crater	Wood, 1917
5/3/1905	5/7/1905	sf?	EQ	*M*6.18 preceded by M5.3 foreshock and followed by many aftershocks, some as strong as *M*≥5—classified as "Kīlauea south flank?"	KW
11/1905	5/1/1906	hm	E	Intermittent activity	Wood, 1917
12/2/1906 5/12/1907	4/15/1907 8/15/1907	hm	E	Intermittent but increasing activity from this date	Wood, 1917
11/30/1907	2/23/1918	hm	E	Continuous filling with occasional drawdown building to first overflow	Wood, 1917
9/2/1908	9/6/1908	kc?	EQS/C/I	Earthquakes classified as 5–10 km beneath Kīlauea Caldera—most likely east rift and south flank	KW
9/20/1908	9/30/1908	sf	EQ	*M*6.7 Kīlauea south flank w many aftershocks	KW
4/19/1910		kc? or sf?		*M*5.3 classified as Kīlauea?	KW
4/26/1910		kc?	EQ	*M*? classified as Hawai‘i—felt over entire island, might be deep beneath Kīlauea Caldera	KW
2/9/1911		kc?	EQ	do	KW
7/24/1911	8/7/1911	kc	EQS?	Kīlauea Caldera 0–5 km? Halema‘uma‘u lava lake falling between July 17 and August 7	ESPHVO, v. 1, p. 40; KW
8/25/1911	8/26/1911	erz/kc?	EQS	Classified as east rift—Ass. with modest subsidence of Halema‘uma‘u lava lake	ESPHVO, v. 1, p. 45; KW
12/26/1911	12/27/1912	kc	EQS	Kīlauea Caldera 0–5 km—associated with perturbations in Halema‘uma‘u lava lake	ESPHVO, v. 1, p. 57; KW
9/1/1912				Systematic earthquake reports from the Whitney Laboratory of Seismology begin	KW
9/2/1912	9/14/1912	kc erz/sf?	EQS I?	Kīlauea Caldera 0-5 km?—apparently preceded draining of magma in Halema‘uma‘u Possible east rift intrusion with south flank response on 09/15, 16, and 20	Jaggar, 1947, p. 37-40; KW

Table 2.3. Kīlauea eruptions, intrusions, and large earthquakes, 1895–1925.—Continued

[In rows with multiple entries text applies down to the next entry; data for eruptions and traditional intrusions are emphasized by grey shading; dates in m/d/yyyy format]

Start date	End date	Location[1]	Event type[2]	Comment	References[3]
9/12/1912	9/14/1912	kc erz/sf?	EQS I?	Kīlauea Caldera 0–5 km?—apparently preceded draining of magma in Halema‘uma‘u Possible east rift intrusion with south flank response on 09/15, 16, and 20.	Jaggar, 1947, p. 37-40; KW
3/25/1913	3/26/1913	erz?	EQS	Classified as “Lower east rift zone and Kīlauea south flank?”—probably related to subsidence of Halema‘uma‘u lava lake between 03/19 and 05/5, 1913	Jaggar, 1947, p. 79-81; KW
5/18/1913		sf?	EQ	Classified as “Kīlauea south flank”—Halema‘uma‘u still empty—revival near 10/01/1913	Jaggar, 1947, p. 86-88; KW
6/5/1913 7/9/1913 9/20/1913	6/16/1913 7/12/1913 9/26/1913	sf?	EQS/I?	Many earthquakes classified as “Kīlauea south flank?” during period when Halema‘uma‘u was empty—possible “suspected deep” intrusion?	Jaggar, 1947, p. 88; KW
11/29/1913 1/25/1914 3/4/1914 3/30/1914	12/9/1913 2/23/1914 3/9/1914 4/13/1914	sf?	EQS/I?	Many earthquakes classified as “Kīlauea south flank?” during period when Halema‘uma‘u was still minimally active—possible series of “suspected deep” intrusions?	KW
1/11/1915	1/18/1915	kc?	EQS?	Several earthquakes associated with beginning of withdrawal of magma from Halema‘uma‘u	KW
4/11/1915	4/18/1915	erz? kc?	EQS/I?	Possible east rift-south flank activity associated with the end of withdrawal of magma from Halema‘uma‘u	KW
8/27/1915 9/5/1915	8/31/1915 9/18/1915	erz sf	EQS/I? EQS	Swarm at distance of 20–25 km (middle east rift-south flank)—some events felt at Kīlauea’s summit and Hilo—“suspected deep?” intrusion preceding normal intrusion beginning on 09/25/1915	KW
9/19/1915	9/20/1915	kc	EQS	3 events at distance of 30–35 km (deep beneath Kīlauea Caldera?)	KW
9/22/1915 9/30/1915	9/29/1915 10/10/1915	erz, sf sf	EQS/C/I	Middle/upper? east rift intrusion (110 events) with south flank response (8 events) and some intercalation of events at 30–35 km. Continued south flank response (21 events)	KW
6/4/1916 6/12/1916	6/12/1916 6/25/1916	erz sf	EQS/C/I	Middle/upper? east rift intrusion (281 events) with south flank response (19 events) and some intercalation of events at 30–35 km. Continued south flank response (25 events)	KW
2/23/1918	3/10/1918	kc	E	Halema‘uma‘u overflow	KW
3/3/1918	3/5/1918	kc	EQS	5 events (0–5 km beneath Kīlauea Caldera?) associated with lowering of Halema‘uma‘u lake level	KW
3/26/1918	4/6/1918	hm	EQS/C	41 events (0–5 km beneath Kīlauea Caldera?) associated with lowering of Halema‘uma‘u lake level	KW
11/13/1918	11/17/1918	hm	EQS/C	72 events associated with lowering of Halema‘uma‘u lake level	KW
2/7/1919	11/28/1919	kc	E	“Postal Rift” eruption on Kīlauea Caldera floor	ESPHVO, v. 2, p. 888, 1055
6/18/1919		hm	EQS?/C	Earthquakes associated with lowering of Halema‘uma‘u lava lake level?	KW
8/26/1919		kc?	EQ	*M*5 deep beneath Kīlauea Caldera?	KW

Table 2.3. Kīlauea eruptions, intrusions, and large earthquakes, 1895–1925.—Continued

[In rows with multiple entries text applies down to the next entry; data for eruptions and traditional intrusions are emphasized by grey shading; dates in m/d/yyyy format]

Start date	End date	Location[1]	Event type[2]	Comment	References[3]
11/28/1919	12/4/1919	erz	EQS/C/I	> 200 events associated with draining of Halemaʻumaʻu lava lake. Assume middle east rift intrusion with south flank response	ESPHVO, v. 2, p. 1059; KW
12/15/1919	8/15/1920	swr	E	Mauna Iki eruption on southwest rift zone	KW
12/15/1919	12/19/1919	swr	EQS/I	Earthquake swarm of 79 events—probable intrusion into seismic southwest rift zone?	
12/22/1919	2/8/1920	sf	EQS	South flank response—25 events	
3/18/1921	3/27/1921	kc	E	Overflow onto caldera floor	ESPHVO, v. 3, p. 63-76
5/17/1922	6/1/1922	kc/ erz	EQS/ C/I	Earthquake swarm of 560 events (108 at 0–10 km beneath Kīlauea Caldera; 432 beneath east rift zone) associated with 850-foot lowering of lava lake	ESPHVO, v. 3, p. 287-290; KW
6/1/1922	6/8/1922	sf	EQS	South flank response (67 events)	
5/28/1922	5/30/1922	erz	E/I/C	Eruption at Makaopuhi and Nāpau Craters. Intrusion beneath upper and middle east rift zone; draining of Halemaʻumaʻu	ESPHVO, v. 3, p. 275, 282-285
11/21/1922	11/23/1922	sf	EQ	*M*5.5 classified as "Kīlauea south flank??" with several aftershocks	KW
12/31/1922	1/4/1923	erz	EQS/C/I	Earthquake swarm of 133 events—classified as upper east rift zone with minor south flank response	ESPHVO, v. 3, p. 375, 384-386; KW
4/1/1923	4/5/1923	kc	EQS	Earthquake swarm of 22 events 0–5 km beneath Kīlauea Caldera	ESPHVO, v. 3, p. 413; KW
8/3/1923	8/7/1923	erz	EQS	Earthquake swarm of 45 events beneath upper east rift zone?; draining of Halemaʻumaʻu	ESPHVO, v. 3, p. 457, 461-462; KW
8/24/1923	8/27/1923	erz	EQS/C	Earthquake swarm of 92 events beneath upper east rift zone; draining of Halemaʻumaʻu	ESPHVO, v. 3, p. 461-462; KW
8/25/1923	8/26/1923	erz	E	Eruption west of Makaopuhi Crater	ESPHVO, v. 3, p. 460
2/13/1924	2/20/1924	kc	EQS	Broken earthquake swarm of 22 events 0–5 km beneath Kīlauea Caldera?	KW
3/7/1924	4/17/1924	erz	EQS/I	Earthquake swarm migrating down east rift zone (83 events beneath east rift zone; 3 south flank) associated with Halemaʻumaʻu draining	ESPHVO, v. 3, p. 513; KW
4/17/1924	5/1/1924	erz	EQS/I	Continuation of earthquake swarm (324 events), now located beneath the lower east rift zone associated with intense ground deformation	ESPHVO, v. 3, p. 519-528; KW
5/1/1924	5/10/1924	kc	EQS	Continuing subsidence of Halemaʻumaʻu	ESPHVO, v. 3, p. 536-539; KW
5/10/1924	5/28/1924	kc	EQS/E	Explosive (phreatic) eruption from Halemaʻumaʻu Crater accompanied by continuing earthquake swarm	ESPHVO, v. 3, p. 540-560; KW
5/28/1924	6/30/1924			Earthquakes continue through the end of June	
7/19/1924	7/30/1924	hm	E	Return of lava to bottom of Halemaʻumaʻu	ESPHVO, v. 3, p. 576; KW

[1]Location abbreviations correspond to regions shown on chapter 1, figure 1.1a: kc, Kīlauea Caldera; hm, Halemaʻumaʻu Crater; erz, East rift zone; swr, Southwest rift zone; sf, South flank.

[2]Event abbreviation: E, Eruption; I, intrusion; EQ, Earthquake ≥*M*5; EQS, Earthquake swarm; C, Collapse of Kīlauea's summit or sharp summit tilt drop indicating transfer of magma to rift zone.

[3]ESPHVO, Early Serial Publications of the Hawaiian Volcano Observatory (Bevens and others, 1988); KW, Klein and Wright (2000).

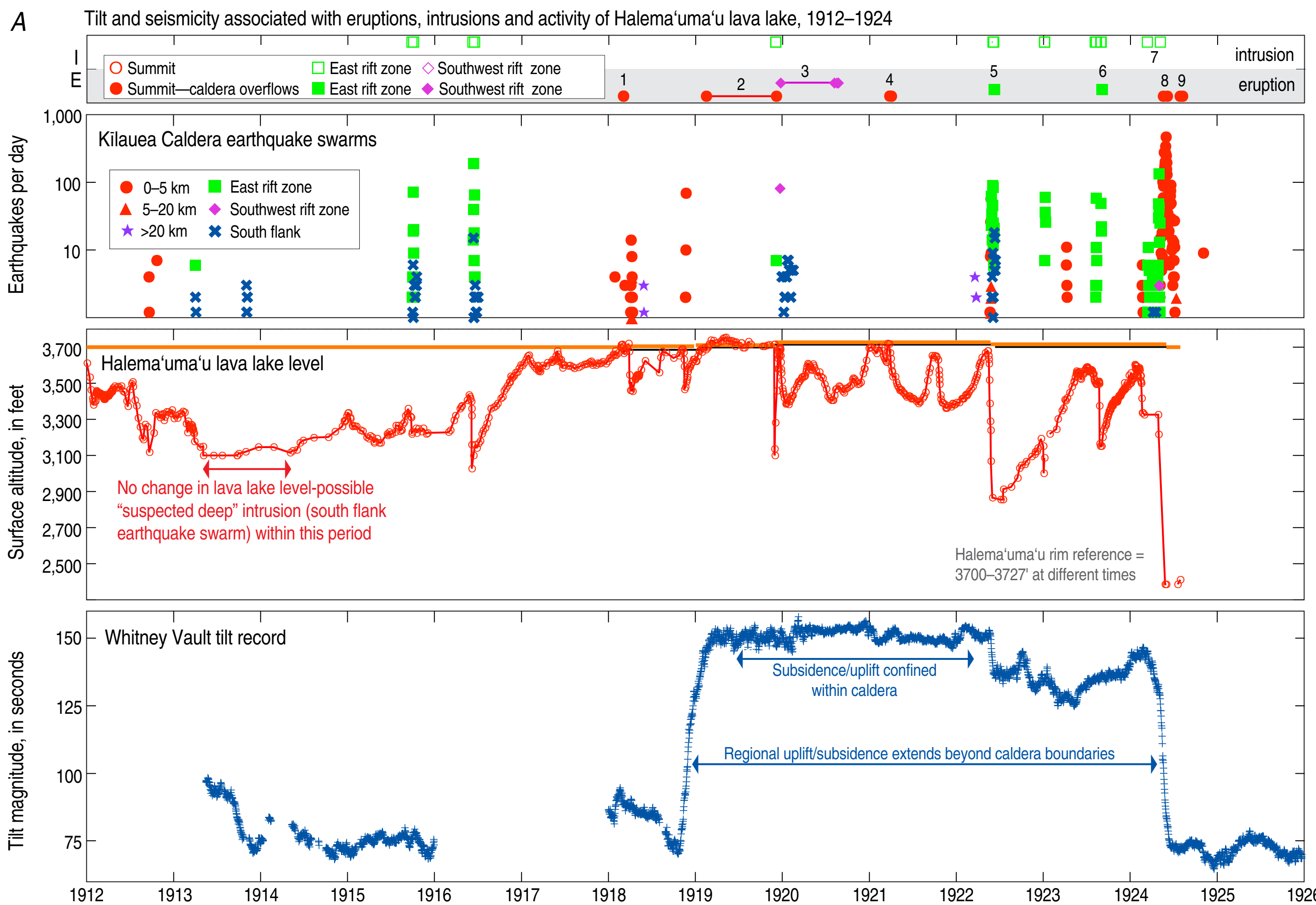

Figure 2.3. Graphs comparing Halemaʻumaʻu lava lake level, tilt magnitude, earthquake swarms, and times of eruption and intrusion. ***A***, 1912–1926. Panels show, from bottom to top: Whitney tilt magnitude, elevation of the surface of Halemaʻumaʻu lava lake, earthquake swarms, and eruptions(E)/intrusions(I), plotted against date. Dates on the time (x) axis are centered at the beginning of the year, as in figure 2.2. The rim of the lava lake is shown as a heavy orange line. The altitude varies within 20 feet or so (6 m) from overflows and subsidence over short time scales. Sites of intrusions are identified from the earthquake swarm locations. Numbers in the top panel identify selected eruptions and intrusions as follows: (1) First overflow of Halemaʻumaʻu. (2) 1919 Kīlauea Caldera "Postal rift" eruption. (3) 1919–1920 SW rift "Mauna Iki" eruption. (4) 1921 Halemaʻumaʻu overflow. (5) 1922 East rift eruption. (6) 1923 East rift eruption. (7) 1924 East rift intrusion migrates from upper to lower east rift zone. (8) 1924 explosive eruption associated with deepening of Halemaʻumaʻu and end of lava lake activity. (9) 1924 Return of lava to Halemaʻumaʻu. Eruptions on the east rift zone in May 1922 and May 1924 and an intrusion earlier in 1924 show a clear correlation of a drop in lava lake level with deflation and an earthquake swarm. The east rift eruption of August 1923 is accompanied by a drop in lava lake level and an earthquake swarm, but is accompanied by only a small tilt change at an unusual azimuth (appendix B, table B1). The large inflation at the end of 1918 occurs with no change in lava lake

level or increase in earthquakes. Both this tilt increase and the subsequent tilt decrease in 1924 are consistent with triangulation and leveling data that show changes extending well beyond the confines of Kīlauea Caldera. Data for all events are summarized in table 2.1. See text for interpretation of these events. ***B***, An expanded plot of earthquakes, tilt and lava lake level for the period between 1919 and 1924. Dates on scale are in m/d/yyyy format. Panels follow the same order as in figure 2.3*A*. Numbers in the top panel identify selected eruptions and intrusions as follows: (1) 1919 Kīlauea Caldera "Postal rift" eruption. (2) 1919 intrusion at end of the postal rift eruption. (3) 1919–1920 SW rift "Mauna Iki" eruption. (4) 1921 Halemaʻumaʻu overflow. (5) 1922 East rift eruption/intrusion (vertical dotted line). (6) Minor East rift zone intrusion. (7) Minor East rift zone intrusion. (8) 1923 East rift eruption/intrusion (vertical dotted line). The end of the 1919 "postal rift" eruption in Kīlauea Caldera is accompanied by a major draining of the lava lake, a moderately intense earthquake swarm beneath the east rift zone, and a small deflationary tilt change. The beginning of the "Mauna Iki" eruption on the southwest rift zone is accompanied by an intense earthquake swarm, after which there is a lowering of the lava lake level and a period of deflationary tilt. The tilt signal during these two events falls within the scatter for the longer period and, taken alone, would not identify eruption or intrusion. Likewise, the 1922 and 1923 eruptions/intrusions are both accompanied by a drop in lava lake level, but only the 1922 event shows a tilt drop. See text for further explanation.

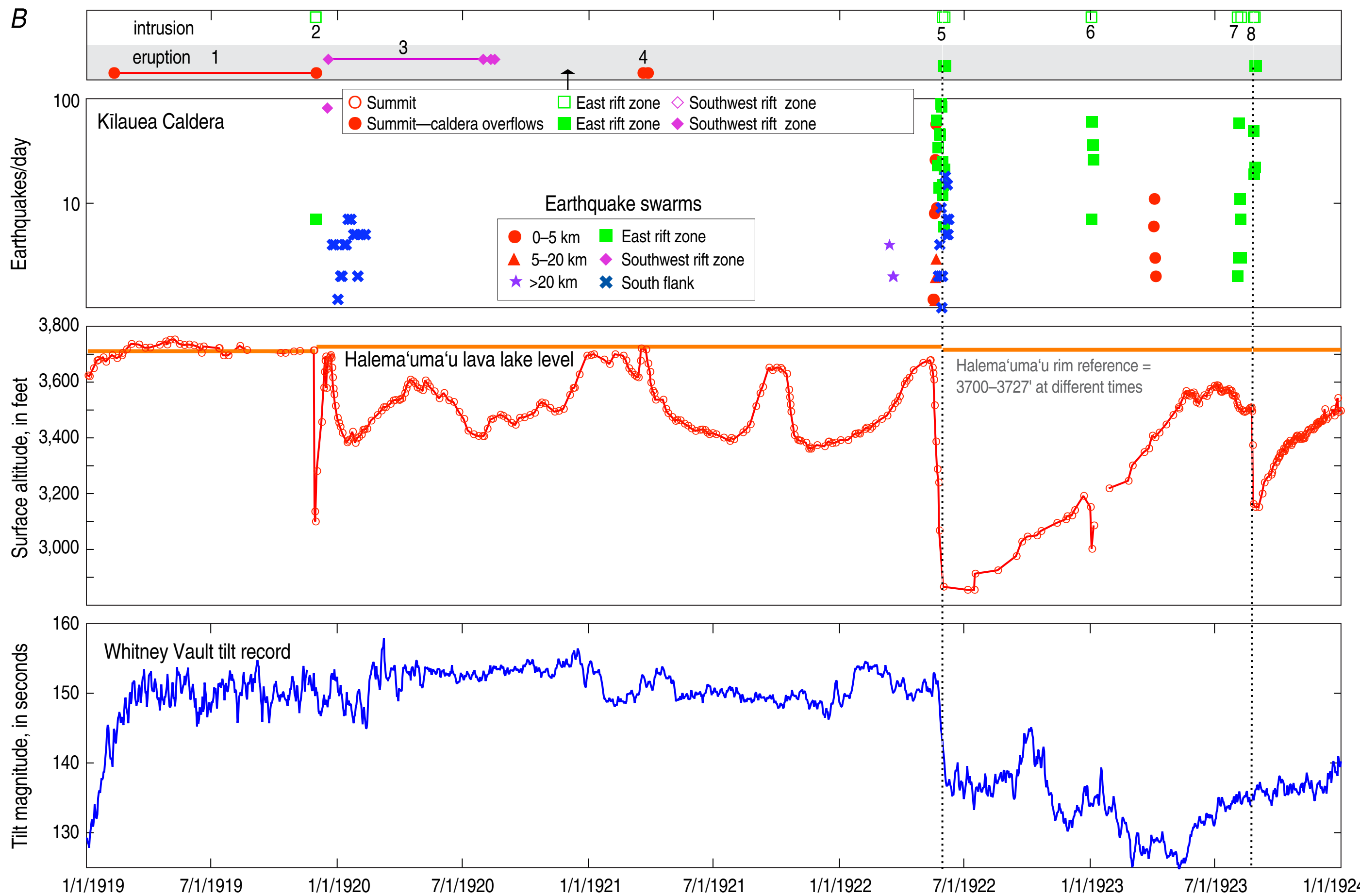

Table 2.4. Halemaʻumaʻu Crater filling and draining 1900–1924.

[Volume figures all represent net filling; in rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; Do., same as previous entry]

Start date	End date	Return of lava	Eqs[1] yes/no	Volume (km^3)	Comment	References[2]
					Filling of Halemaʻumaʻu Crater to first overflow on 2/23/1918	
1/10/1904	1/10/1904	2/22/1905	no	0.0091	Estimated from change of crater depth	Wood, 1917
5/1/1906?	5/1/1906?		no	0.0069	Maximum collapse calculated after 400 foot fill in 2005; amount of draining unspecified	
		12/2/1906			Initiation of continuous fill	Wood, 1917
9/7/1908	4/4/1909		yes	0.0059	Presumed intrusion beneath east rift zone; south flank slow intrusion??	KW; Wood, 1917
10/5/1909	10/15/1909		no	0.0019	Estimated from change of crater depth	Wood, 1917
1/1/1910	8/1/1910		no	0.0096	Estimated from change of crater depth	Wood, 1917
1/1/1912	2/1/1912		yes?	0.0115	Read from chart showing lava rise and fall in Halemaʻumaʻu	ESPHVO, v. 2, p. 295
7/12/1912	8/26/1912		no	0.0080	Local earthquakes in Jan., Sept., and 10/15 (accompanying. inflation?)	KW
2/8/1913	5/5/1913		no	0.0055	Read from chart showing lava rise and fall in Halemaʻumaʻu	ESPHVO, v. 2, p. 295
1/4/1915	5/13/1915		no	0.0038	Do.	ESPHVO, v. 2, p. 647
9/15/1915	9/28/1915		yes	0.0033	Read from chart showing lava rise and fall in Halemaʻumaʻu	ESPHVO, v. 2, p. 647
					Major earthquake swarm on 25–30 Sept.1915 tentatively identified as beneath east rift zone followed on 4–10 Oct. by south flank response	KW
6/4/1916	6/6/1916		yes	0.0119	Do.; last collapse before overflow 2/23/1918	ESPHVO, v. 2, p. 647
					Major earthquake swarm on 6/4–11/1916 tentatively identified as beneath east rift zone followed on 10/12–24 by south flank response	KW
3/11/1917	3/15/1917		yes	0.0008	Local earthquakes	ESPHVO, v. 2, p. 578; KW
					Halemaʻumaʻu lava lake active 2/23/1918–5/31/1924	
3/28/1918	4/15/1918		yes	0.0077	Local earthquakes 3/26–4/4/1918	ESPHVO, v. 2, p.748–751
11/5/1918	11/16/1918		yes	0.0064	Intrusion beneath east rift zone	ESPHVO, p. 844–845
11/28/1919	11/29/1919		yes	0.0154	End of postal rift eruption	ESPHVO, p. 1055–1059
12/22/1919	1/15/1920		yes	0.0098	Initiation of Mauna Iki eruption	ESPHVO, p. 1072–1092
5/14/1922	5/31/1922		yes	0.0358	East rift eruption	ESPHVO, v. 3, p. 297
8/23/1923	8/29/1923		yes	0.0266	East rift eruption	ESPHVO, v. 3, p. 461
2/9/1924	4/30/1924		yes	0.0227	Earthquake swarm and intrusion beneath lower east rift zone	ESPHVO, v. 3, p. 515–528[3]
4/30/1924	5/31/1924		yes	0.1304	Halemaʻumaʻu phreatic eruption	ESPHVO, v. 3, p. 529–560[3]

[1]Eqs, earthquake swarm. Yes/no refers to whether or not an earthquake swarm accompanied the activity listed.

[2]ESPHVO, Early Serial Publications of the Hawaiian Volcano Observatory (Bevens and others, 1988); KW, Klein and Wright (2000).

[3]Additional published summaries of 1924 activity are: (Finch, 1924, 1925, 1947; Jaggar and Finch, 1924).

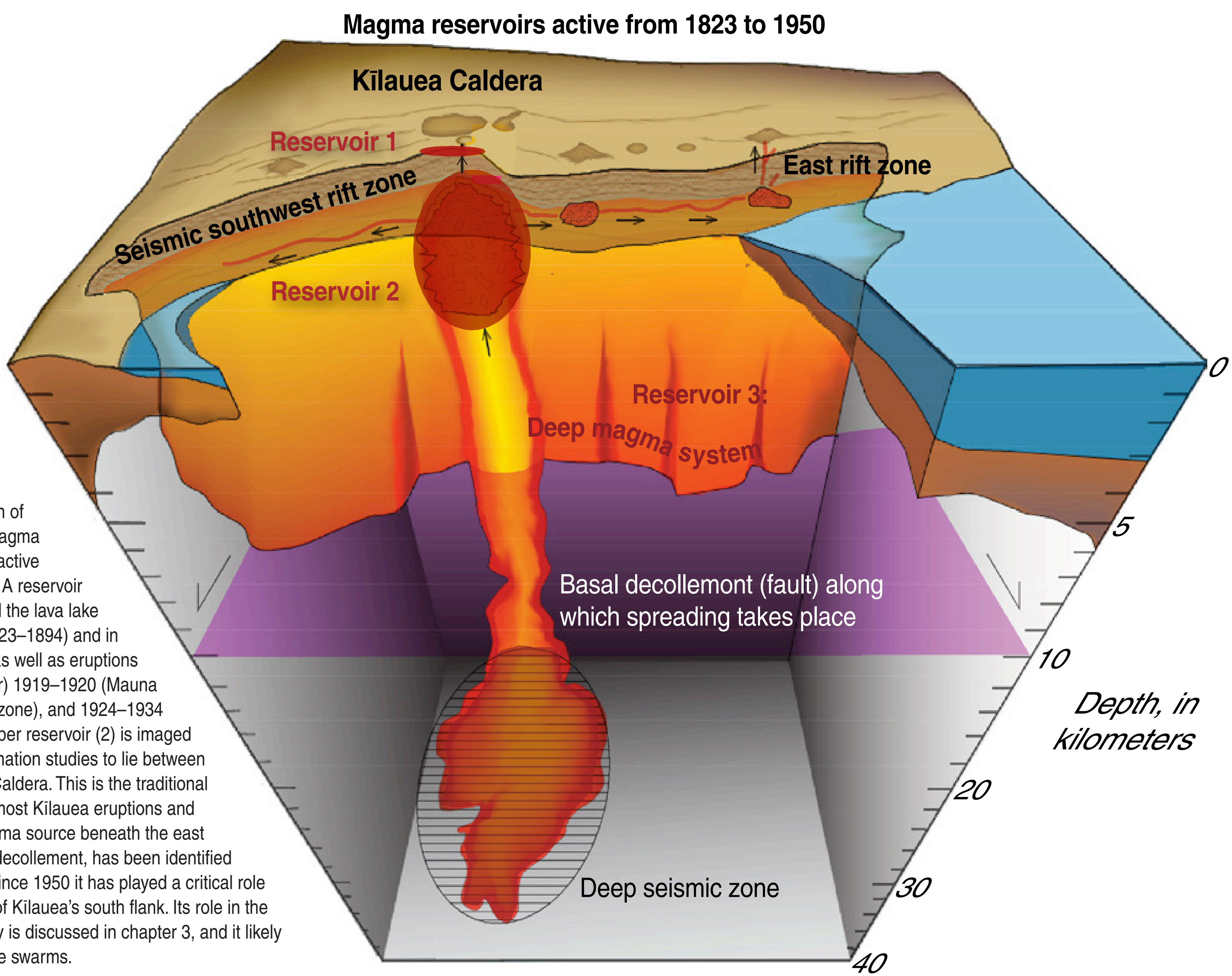

Figure 2.4. Cutaway diagram of Kīlauea showing location of magma reservoirs. Magma reservoirs active from 1823 to 1950 are shown. A reservoir at less than 1 km depth (1) fed the lava lake activity in Kīlauea Caldera (1823–1894) and in Halema‘uma‘u (1907–1924), as well as eruptions in 1919, (Kīlauea Caldera floor) 1919–1920 (Mauna Iki on Kīlauea's southwest rift zone), and 1924–1934 (Halema‘uma‘u Crater). A deeper reservoir (2) is imaged by modern seismic and deformation studies to lie between 2 and 6 km beneath Kīlauea Caldera. This is the traditional magma reservoir from which most Kīlauea eruptions and intrusions are fed. A third magma source beneath the east rift zone (3), extending to the decollement, has been identified (Delaney and others, 1990). Since 1950 it has played a critical role in driving seaward spreading of Kīlauea's south flank. Its role in the 1924 subsidence and recovery is discussed in chapter 3, and it likely triggers south flank earthquake swarms.

Table 2.5. Kīlauea Caldera filling rates 1823-1924.

[In rows with multiple entries text applies down to the next entry; dates in mm/dd/yyyy format]

Period	Start date	End date	D time (yr)	Volume (km^3)[1]	Filling rate (km^3/yr)[2]	Comment	Reference(s)
1823-1825	08/14/1823	06/30/1825	1.88	0.604	0.322	Average of Mastin volume range used	(Mastin, 1997)
1825-1832	0630/1825	01/01/1832	6.50	0.788	0.121[3]	Average of Mastin volume range used	(Mastin, 1997)
1832-1840	01/15/1832	05/31/1840	8.38	1.968	0.235	Average of Mastin volume range used	(Mastin, 1997)
1840-1846	05/31/1840	07/10/1846	6.108	0.2721	0.0446	1840 collapse volume (Mastin, 1997) added to crater fill	(Dana, 1887b; Lyman, 1851)
1846-1848	07/10/1846	08/10/1848	2.086	0.1216	0.0583	Endogenous growth between 1840 and 1848	(Coan, 1852; Dana, 1887b)
1848-1855	08/10/1848	10/05/1855	7.151	0.1886	0.0263		(Coan, 1856a, 1856b; Dana, 1887b)
1855-1863	10/5/1855	10/15/1863	8.027	0.1631	0.0203		(Coan, 1864; Dana, 1887b)
1863-1868	10/15/1863	04/01/1868	4.463	0.0973	0.0218	Central dome plus lava fill	(Coan, 1864, 1867; Dana, 1887b)
1868-1874[4]	04/01/1868	10/15/1874	6.535	0.1119	0.0212	Halema‘uma‘u dome + 200 feet filling of 1868 depression + 1871 collapse	(Coan, 1874; Dana, 1887b)
1874-1886[4]	10/15/1974	03/06/1886	11.389	0.4202	0.0373	Fill remainder of 1868 depression fill + 1877, 1879 and 1880 collapses + dome	(Brigham, 1868; Dana, 1887b, 1888; Emerson, 1887)
1886-1894	03/06/1886	07/10/1894	8.345	0.1899	0.0228	1886 + 1891 collapse + Halema‘uma‘u dome	(Anonymous, 1894a; Thurston, 1894)
1840-1894	05/31/1840	07/10/1894	54.108	1.4048	0.0307	Entire interval: fill + all collapses	
1894-1918	12/06/1894	12/02/1906	11.986	0.0043	0.0017	Halema‘uma‘u fill + collapses in 1904 and 1905-06; continuous filling;	(Bevens and others, 1988; Wood, 1917)
	12/02/1906	05/20/1916	9.465	0.0514	0.0054	includes 0.0042 km^3 fill and 0.0323 km^3 refill following collapses	
	05/20/1916	02/23/1918	1.763	0.0300	0.0170	Includes 0.0139 km^3 fill and 0.0082km^3 refill following collapses in 1916 and 1917	
1894-1918	12/06/1894	02/23/1918	23.214	0.1051	0.0045	Entire interval; includes 0.0214 km^3 fill and 0.0533 km^3 refill following collapses	(Bevens and others, 1988; Wood, 1917)
1918-1924	02/23/1918	02/9/1924	5.960	0.1425	0.0239	0.0617 km^3 erupted lava + 0.0808 km^3 refill after collapse[5]	(Bevens and others, 1988; Wood, 1917)

[1]Lava volume converted to magma volume by correction for 20% vesicularity. Volumes used are the sum of the net lava fill added to the volume of collapse (tables 2.3, 2.4) immediately preceding and within the filling period. Volumes of lava fill are calculated as cylinders or half spheroids to account for doming of the inner caldera (see text).

[2]Filling rate after correction of lava volume to magma volume.

[3]Mastin uses Malden's estimate that 50 feet of lava covered the black ledge in 1832. In order to support a declining fill rate from 1823 to 1840 Malden's depth must be increased by 200 feet or more or the altitude of the black ledge must be reduced by a similar amount. For example, an increase of lava depth of 250 feet between 1825 and 1832, matched by a corresponding decrease of 250 feet between 1832 and 1840 yields magma supply rates of 0.206 km^3/yr for 1825–1832 and 0.183 km^3/yr for 1832–1840.

[4]Brigham's estimate of depth to the caldera floor indicates no change since 1840. Emerson's 1886 map indicates a depth to the caldera floor yields an altitude close to the pre-1919 altitude. Accepting both maps gives a very low rate of caldera fill between 1874 and 1880 and a very high rate between 1880 and 1886. Dana (1888, v. 35, p. 18) corrects Brigham's estimate of fill by 50 feet; accepting this correction yields more reasonable values for the post-1868 filling rates.

[5]The volumes of the two east rift eruptions are very small. The volume of magma transfer is included in the collapse/refill figure.

1918–1924

The lava lake in Halema‘uma‘u overflowed onto the caldera floor numerous times between 1918 and 1921. A long eruption in Kīlauea Caldera, named "Postal Rift,"[9] occurred between February and December 1919, and a second eruption followed shortly thereafter to build the small Mauna Iki shield on Kīlauea's southwest rift zone. Both eruptions were fed directly from the Halema‘uma‘u lava lake, as evidenced by lava sighted at a few meters depth in the southwest rift preceding the beginning of surface eruption (Bevens and others, 1988; Rowland and Munro, 1993); likewise, the outlet for the Postal Rift eruption was visible during the draining of Halema‘uma‘u lava lake preceding the 1919–20 Mauna Iki eruption (Bevens and others, 1988). Small eruptions on Kīlauea's east rift zone near Nāpau and Makaopuhi Craters occurred in 1922 and 1923, associated with temporary draining of Halema‘uma‘u lava lake and large earthquake swarms (de Vis-Norton, 1922, 1923; Finch, 1926b; Jaggar, 1931). Extensive ground deformation near the eruption sites indicated significant intrusion beneath the east rift zone. These two eruptions are very similar to eruptions that occurred on the east rift zone during the 1960s. The seismicity was more intense (table 2.3), with higher average swarm magnitudes, expectable for a rift zone that had seen no activity since 1840.

Eruption rates were calculated for this period in the same way as filling rates were for the preceding period. Drainings in 1922 and 1923 were far larger than the volume of erupted lava, so the drained volumes have been used in combination with the 1919 and 1919–20 eruption volumes to calculate a magma supply rate of 0.0239 km^3/yr, similar to the rate prevailing in the latter part of the 19th century (fig. 2.1, table 2.5).

[9]Before the eruption the source was located within a hot and steaming crack that was a favorite place for tourists to singe postcards before mailing them.

Tilt Record 1913–1924

After 1913 HVO made continuous records of the tilting of the ground as measured by the Bosch-Omori seismometer installed in the Whitney Vault on the northeast rim of Kīlauea Caldera. Comparison of tilt magnitude with fluctuation in the level of Halema‘uma‘u lava lake is shown in figure 2.3. The correlation is not perfect, but is obvious for some major events, such as the 1922 and 1924 drainings.

The 1924 Crisis at Kīlauea

Sequence of Events

In 1924, continuous lava lake activity abruptly ended with a spectacular series of events, culminating in large phreatic explosions at Halema‘uma‘u. The sequence began in February with initial disappearance of lava from Halema‘uma‘u, followed by a series of felt earthquakes beneath the middle section of Kīlauea's east rift zone in March (Finch, 1924), and a major earthquake swarm farther east along the rift zone in April (Finch, 1925). Although both Jaggar (Bevens and others, 1988, v. 3, p. 515) and Finch (1924, 1925) report a progressive increase in epicentral distance along the rift zone, tabulated location data (Bevens and others, 1988, v. 3, p. 513) do not show an obvious time-distance progression. Rather, it appears that Jaggar and Finch were extrapolating eastward from a mild concentration of earthquakes in the vicinity of Kalalua Crater, spread over a period of about two weeks.

Three weeks after the last Kalalua earthquake, a swarm of small earthquakes felt locally began in the vicinity of Puu Kaliu, on the lower east rift zone, expanding within 3 days to an intense swarm with many widely felt earthquakes beneath the village of Kapoho. During the following 3 days the Kapoho graben subsided dramatically, accompanied by opening of fractures and uplift of the land on either side of the graben-bounding faults where they intersected the shoreline (Finch, 1925). Subsequent modeling of the triangulation done in 1933 (Wingate, 1933)[10] fits a dike emplaced beneath Kapoho (Paul Delaney, written commun., 1990). Jaggar and Finch also surmised the possibility of an undersea eruption in 1924. This is now considered unlikely, as dredging and diving on the offshore east rift zone has failed to confirm the existence of a flow of the appropriate age and chemistry.[11]

Meanwhile, at Kīlauea's summit, Halema‘uma‘u began draining in early February and lava disappeared by 21 February 1924 (Bevens and others, 1988, v. 3, p. 505). At the time of the peak in earthquake activity in lower Puna on 23 April, lava briefly reappeared at the bottom of Halema‘uma‘u, then disappeared again. On 30 April, following the Puna crisis, the summit began to collapse, accompanied by tens to hundreds of earthquakes per day. On 9 May a series of violent phreatic explosions at Halema‘uma‘u began, continuing to the end of the month. At this time observatory staff members and volunteers were sent to various locations to record the times of felt earthquakes, the location of falling lithic ash, and any other observations of interest. The contents of their notebooks were published

[10]Unpublished data obatined from the Hawai‘i State archives in Honolulu.

[11]Submarine exploration of Kīlauea's east rift zone has to date revealed no lavas of historical age, thus suggesting that the prior drainings and east rift eruptions of 1790 and 1840 did not reach the submarine surface of the east rift zone.

much later, as one chapter in a book discussing the mechanics of crater formation (Jaggar, 1947, p. 205–259). The events were summarized in the HVO Monthly Bulletin for May 1924 (Bevens and others, 1988, v. 3, p. 529–560). During 3 weeks of phreatic explosions the floor of Halemaʻumaʻu continued to collapse, accompanied by more widespread subsidence of Kīlauea's summit, leaving a greatly enlarged and empty pit 400 m deep (Finch, 1926b; Jaggar and Finch, 1924). The estimated volume by which Halemaʻumaʻu was enlarged exceeded the amount of material erupted, in a ratio of 253:1 (Jaggar, 1925). Later investigation of the products showed that no juvenile magma was involved (Finch, 1947), although some of the lithic ejecta were observed to glow at night, and molten lava was observed dripping from sills in the walls of the newly emptied Halemaʻumaʻu Crater.

Contemporary interpretations of the eruption were internally consistent, all invoking draining of magma from Kīlauea's summit into the east rift zone, followed by interaction of groundwater with the heated rocks surrounding the magma conduit. Harold Stearns (1925) ascribed the faulting at Kapoho to draining of magma emplaced in the rift during eruptions of 1922 and 1923. He further hypothesized that the lava column subsided more than 1,100 m (3,600 ft) during the subsidence preceding the explosions, (that is, down to about sea level and well below the local water table), permitting groundwater to enter the hot conduit. Steam accumulated under the plug of talus until explosive pressures were attained. Stearns explained the regularity of the steam blasts by a mechanism similar to that observed in geyser fields. John Dvorak (1992) has added to the interpretation of the 1924 events, concluding that withdrawal of magma alone is not sufficient to trigger explosions. He considers that the explosions were initiated at very shallow levels by interaction of perched ground water brought suddenly in contact with rocks preheated during extended lava lake activity. He also revises the amount of magma removed from Kīlauea's summit to 0.4 km^3, twice the figure estimated by Finch and Jaggar.

The events of 1924 were the most dramatic at Kīlauea since 1790 and 1868. The 1924 eruption, which contained only lithic material, contrasts with the explosive activity in 1790, which was marked by eruption of juvenile ash up to the final explosive surges. Jaggar claimed to have forecast the breakdown in 1924 on the basis of his belief in 130-year cycles of activity, the cycle beginning in 1790 (Bevens and others, 1988, v. 2, p. 721). Whether or not one subscribes to the cyclical theory, the 1924 events marked a change from dominant activity at Kīlauea's summit to increased activity on Kīlauea's east rift zone, a pattern borne out by geologic mapping and dating of Kīlauea flows (Holcomb, 1987). Modern study has also shown that the 1924 eruption represents a geochemical boundary; isotope signatures of lavas erupted before 1924 differ from those erupted after (Pietruszka and Garcia, 1999).

Ground Deformation

Surveys of Kīlauea's summit by triangulation and leveling were conducted in 1912, 1921, and 1926 (Mitchell, 1930; Wilson, 1935). Wilson showed that during both time periods, 1912–21 and 1921–26, the deformation field was very broad, extending more than half the distance to Hilo, at least 20 km from Halemaʻumaʻu Crater (see text table below). The Volcano House on the rim of Kīlauea Caldera rose more than 0.3 m (1 foot) between 1912 and 1921 and dropped 0.5 m (1.7 feet) between 1921 and 1926. The absolute elevation of the rim of Kīlauea Caldera attained in 1921 has not been exceeded as of 2010. Wilson's map also shows that stations within the caldera subsided, presumably in response to draining of magma to feed the 1919 caldera eruption and the 1919–20 Mauna Iki eruption. Wilson questioned the rod corrections applied to the 1912 data and concluded that if the rod corrections were discarded it was possible that the Volcano House benchmark had remained stable through the triangulation of 1921.

The tiltmeter installed in the Whitney Vault began systematic recording in 1913. As explained in appendix A, the Whitney Vault is more than 3 km from Halemaʻumaʻu and will not record draining of lava from Halemaʻumaʻu or from a source at less than 1-km depth beneath Halemaʻumaʻu, whereas it will record inflation or deflation from a source deeper than 3 km. Interpretation of the tilt and triangulation data for the period between 1913 and 1925 are given in the following text table.

Interpretation: The Youngest Summit Shield-Building Period Through May 1924

We interpret the extensive summit lava lake and the high caldera filling rates at the time of the western missionaries' arrival in 1823 (Ellis, 1825) as representing rebound from a massive draining of magma in 1790 that may be represented in Puna by 1790 lava (Trusdell and Moore, 2006) and a possible accompanying intrusion that may have extended beneath the undersea extension of Kīlauea's east rift zone. The eruption of 1790 was not a caldera-forming event (Dibble, 1843; Swanson and Christiansen, 1973; Swanson and Rausch, 2008), but it did drain Kīlauea's entire magmatic system and triggered a very high rate of resupply through lowered pressure above the magmatic system. We interpret the decline in filling rate after 1840 to be in part a return to a low equilibrium rate (low compared to Kīlauea's post-1950 history) and possibly in part a result of the increased activity at the adjacent Mauna Loa volcano (see chapter 8). We also infer from the occurrence of east rift eruptions and intrusions that, from at least 1790 onward, rift dilation becomes important in controlling the equilibrium magma supply rate (Wright and Klein, 2008).

Following the disappearance of lava in 1894 we interpret Kīlauea to have three different magma sources or reservoirs, as shown in figure 2.4. (1) A shallow magmatic system that fed the lava lakes in Kīlauea Caldera and Halema'uma'u lies at depths of less than a few hundred meters beneath the caldera. This source is evident in the occasional appearance of magma at the bottom of Halema'uma'u preceding the continuous refilling that began in 1907 and the observations cited above regarding the 1919 caldera and 1919–20 southwest rift eruptions. (2) The magma reservoir identified by later instrumental monitoring at between about 2 and 6 km depth beneath Kīlauea's summit (see, for example, Eaton, 1962, and many subsequent studies). (3) A deeper magma system, beneath the shallow summit reservoir at 2–6-km depth, and possibly above the decollement (Delaney and others, 1990). Sources at 3 depths (0.8, 3.5, and deeper than 10 km) are suggested by our modeling of levelling surveys surrounding the 1924 collapse (appendix I). We reinterpret Mogi's source beneath Kīlauea Caldera at 20-km depth (Mogi, 1958) as our source 3, distant from Kīlauea's summit and not directly beneath the caldera.

The period between the end of the large inflation in 1918–19 (following the first overflow of Halema'uma'u in 1918) and the eruption/intrusion of 1922 shows many fluctuations of lava lake level and little correlated tilt change at the Whitney Vault. We interpret this period to be dominated by removal of magma from and drainback into reservoir 1. The changing level of lava in Halema'uma'u associated with intrusion beneath the two rift zones may represent an additional contribution from draining of source 2. For example, a very rapid (3-day duration) episode of draining of the lava lake that followed the end of the Postal Rift eruption (28–30 November 1919) was accompanied by a small east rift earthquake swarm (fig. 2.3*A*) and deflationary tilt (azimuth 198, magnitude 16.2 µr) that suggested intrusion beneath the east rift zone. A second earthquake swarm beneath the southwest rift that took place at the beginning of the Mauna Iki eruption on 15 December 15 1919 showed a 34-m (113-foot) drop in lake level and no tilt response and is interpreted as breaking of rock as magma was draining along the shallow path connecting the summit and Mauna Iki. A slower draining of 90 m (300 feet) between 22 December 1919 and 18 January 1920 and deflationary tilt between 28 and 31 December 1919 (azimuth 194, magnitude 8.2 µrad) suggest a delayed response of the deeper source 2 to the southwest rift zone eruption.

The sharp deflation in 1922 (24 May to 6 June; azimuth 195, magnitude 75 µrad) associated with an east rift eruption and intrusion is correlated with large draining of the lava lake and are consistent with draining magma reservoir 2. The deflation began 4 days before the eruption began, indicating that the eruption was fed from the summit reservoir, consistent wth the absence of an east rift zone eruption since 1840. The 1923 eruption/intrusion, following closely on the similar event of 1922, shows a significant draining of the lava lake accompanied by a very small tilt change (15 µrad deflation at an azimuth of 260 between 25 and 27 August 1923). This azimuth is an unusual one for deflation, and the small tilt magnitude may suggest that eruption of new lava to the surface and further intrusion in 1923 are best interpreted as continued movement of magma that traveled out of the summit reservoir in 1922. Consistent with the idea of dual sources, there is a suggestion that, during intrusions beneath either rift zone, lava first disappears from Halema'uma'u during evacuation of source 1, while continuing to be withdrawn from source 2, much as Harold Stearns suggested for the 1924 collapse (Stearns, 1925).

Survey Data Relevant to 1924 Subsidence

Original values (elevations in feet)

Date Location	1912	1922	Δ 1912–1922	1927	Δ 1922–1927
Volcano House	3973.090	3974.107	+1.017	3972.541	-1.566
Kea'au	1266.425	1267.229	+ 0.804	1266.477	-0.752

Corrected (Wilson, 1935) values (elevations in feet)

Date Location	1912	1922	Δ 1912–1922	1927	Δ 1922–1927
Volcano House	3976.103	3976.103	0.000	3972.541	-3.562
Kea'au	1266.435	1266.673	+ 0.238	1266.477	-0.194

Whitney tilt values (arc-seconds)[1]

Date begin	Date end	Magnitude	Azimuth
10/22/1918	2/27/1919	85.2	354
4/28/1924	7/3/1924	64.1	198
7/3/1924	12/29/1924	5.3	127

[1]Conversion factors are: 1 arc-second = 4.8468 µrad; 1 µrad = 0.2063 arc-second

The large increase in tilt magnitude from 22 October 1918 to 27 February 1919 (413 µrad of inflation at an azimuth of 354) and the great deflation between 28 April and 29 December 1924 (320 µrad of deflation at an azimuth of 194) show tilt azimuths at variance with the other centers of inflation and deflation (appendix A, fig. A2; appendix B, table B3) and are interpreted to have involved source 3. The azimuth of the 1918–19 inflation (fig. 2.3*A*) corresponds to inflation east of the centers defined for the period preceding the 1967–68 eruption (appendix A, fig. A2; appendix B, table B3). The magnitude of the 1918–19 inflation cannot be quantitatively compared to the elevation changes because the 1911–12 leveling took place before the tiltmeter was installed. The azimuth of deflationary tilt up to July 1924 through the period of explosions is similar to the 1922 deflation, consistent with draining from source 2. However, an additional deflation of 25.8 µrad at azimuth 127 between 3 July and 29 December 1924 indicates a more easterly source.

The broad 1924 deflation indicates a source well below the depth of Halemaʻumaʻu Crater. The Japanese geophysicist Kiyoo Mogi modeled the 1924 collapse using the tilt values calculated from Wilson's triangulation to define centers of deflation (Mogi, 1958). Mogi's modeling suggested that two magma reservoirs were activated during the 1924 collapse, one at a depth of about 5 km, within current estimates of Kīlauea's shallow magma reservoir and appoximately consistent with our source 2 above, and one at about 25 km that has not been supported by geodetic and seismic instrumental measurements made in the modern era. Modern data show inflation and deflation confined to Kīlauea Caldera, with little or no change in benchmarks at or beyond the caldera rim. Our fit to the 1921–26 level changes requires two Mogi centers to fit the level changes inside the caldera and three sources to fit the broad caldera subsidence observed along the Kīlauea to Hilo level line (appendix I, fig. I6 and table I1). Mogi center depths of 0.8 and 3.5 km are required to fit the caldera level contours. These correspond to inflation-deflation sources 1 and 2, respectively. If one ascribes the altitude changes seen between the Volcano House and Hilo to a Mogi source, a source geometry which is unconstrained, an additional deflation at 30 km depth is required. John Dvorak's study (Dvorak, 1992) disregarded Wilson's conclusion of a large regional subsidence in 1924 (Wilson, 1935, figure 7), instead assuming the Volcano House benchmark as a fixed datum, citing Wilson's worries about rod corrections applied to the 1912 survey period (Wilson, 1935, p. 41 and following). Yet Wilson's corrections affect only the 1912–21 period and increase the amount that the Volcano House subsided in 1924 to more than 1 m (3.5 feet; see text table above). The large change of Whitney Vault tilt between 1918 and 1919 (figure 2.3*A*) argues for accepting Wilson's uncorrected data, including substantial elevation changes at Volcano House, in order to define a broad regional uplift between 1912 and 1921 and an equal volume of regional subsidence between 1921 and 1926, the latter assumed to have occurred mainly during the events of 1924. If accepted, this increases the volume of subsidence to more than the 0.4 km^3 calculated by Dvorak.

We conclude that the large Whitney Vault tilt changes in 1918–19 and 1924–25 are consistent with Wilson's initial conclusion of a 0.3-m (1-foot) increase in the altitude of the Volcano House benchmark before the 1921 triangulation and an even greater decrease in altitude across the 1924 collapse. The 1912–22 rise and 1922–27 fall of the Keaʻau benchmark, about 40 km from Kīlauea's summit along the road to Hilo, argue that its change is due to inflation and deflation of a deep magmatic source, rather than an irreversible tectonic change resulting from a source like south flank spreading. The large changes, extending at least as far as Keaʻau, amount to a regional inflation/deflation extending more than 20 km from Halemaʻumaʻu. A possible alternative to the 30-km-deep Mogi source modeled in appendix I, table I1, is additional draining of the deeper magmatic system of source 3, which lies above the decollement and below the east rift zone at depths of 10–12 km but is located at a lateral distance of several tens of kilometers from Kīlauea's summit. Unlike more recent collapses of Kīlauea's summit, the immediate recovery from the 1924 collapse, as measured by tilt, was only a fraction of the total collapse (fig. 2.3*A*), consistent with the need to refill a much larger magma volume than that occupied by sources 1 and 2 alone.

Finally, we test the hypothesis that a large earthquake could explain the 1918–19 tilt change at Kīlauea's summit. Late on the evening 1 November 1918 an earthquake of magnitude 6.4 occurred beneath Mauna Loa's Kaʻōiki Fault Zone (Klein and Wright, 2000, and references cited therein). A similar earthquake of magnitude 6.6 occurred on 16 November 1983 (Buchanan-Banks, 1987; Maley, 1986, Jackson and others, 1992) and produced a large instantaneous and permanent offset in the Uwēkahuna tiltmeter. There was extensive damage around the caldera rim.

The 1918 earthquake produced cracking on the floor of Kīlauea Caldera (Anonymous, 1918) but little damage around the rim (Bevens and others, 1988, v. 2, p. 840) and a small offset of the clinometer in the Whitney Vault (Bevens and others, 1988, v. 2, p. 843). However, the earthquake was an unlikely trigger for the inflation that had begun 10 days before (Anonymous, 1918; Bevens and others, 1988, v. 2, p. 836) and which continued for more than three months (see inset table above and fig. 2.3).

Supplementary Material

Supplementary material for this chapter appears in appendix B, which is only available in the digital versions of this work—in the DVD that accompanies the printed volume and as a separate file accompanying this volume on the Web at http://pubs.usgs.gov/pp/1806/. Appendix B contains the following figures and tables:

Tables B1a and B1b contain earthquakes of magnitudes between 5 and 6 for the same time periods as text tables 2.1 and 2.2, respectively.

Table B2 shows azimuth and distance from Uwēkahuna and Whitney Vaults to points within Kīlauea Caldera shown in text figure 2.4.

Table B3 contains Whitney Vault tilt data to support text figure 2.3.

Figure B1 plots occurrence of earthquakes designated as "south Hawai'i" on a timeline that also shows (1) Kīlauea eruptions and intrusions, (2) Mauna Loa eruptions, and (3) Kīlauea earthquake swarms.

Kīlauea Caldera at the time of missionary William Ellis' vist in 1823, showing activity extending over the entire caldera floor (Ellis, 1825 [1827 edition], plate facing p. 226). Image courtesy of Bishop Museum.

May 1924 explosive eruption in Halemaʻumaʻu viewed by tourists. Image courtesy of Bishop Museum.