Chapter 3

Eruptive and Intrusive Activity, 1925–1953

Kīlauea recovers from the 1924 deflation under a regime of increased magma supply rate and initiation of significant seaward spreading of the volcano's south flank, preceding the first documented long Halemaʻumaʻu eruption in 1952.

Kīlauea experienced seven eruptions and intrusions and large earthquakes from the time of the 1924 collapse through the Halemaʻumaʻu eruption of May-November 1952. These volcanic events and large earthquakes are summarized in table 3.1. Significant events before the beginning of reinflation in early 1950 include seven small eruptions between July 1924 and November 1934 confined to Halemaʻumaʻu (fig. 3.1), the formation of the "Puhimau thermal area," circa 1937, and two upper east rift intrusions in May and August 1938 (fig. 3.2). A possible summit intrusion in December 1944 (Finch, 1944; Klein and Wright, 2000) and several smaller events identified by shallow earthquake swarms beneath Kīlauea's summit are also shown in figure 3.1. During this time the volcano remained deflated, as the Whitney Vault tilt records an actual net drop of an additional 97 microradians (μrad) or 20 seconds of arc between 1925 and 1950.

Between 1925 and 1950 the Bosch-Omori tiltmeter in the Whitney Vault recorded cyclic variations, attributed by early authors to "seasonal" variations, but shown by us to be affected by periods of heavy rainfall[12]. Beginning in March 1950 up to the abandonment of the Whitney Vault in 1962, the Whitney tilt records show rapid deflations, inflations, and longer term trends that correlate well with volcanic events and are typical of modern water-tube tiltmeter observations.

During this time period the accurate location of intrusions and large earthquakes was still limited by the absence of a full seismic network and the short-term affects of rainfall on the Whitney tiltmeter. Major intrusions beneath the rift zones can be located from contemporaneous ground cracking. South flank activity is much less closely defined (Klein and Wright, 2000), and some felt events are classified as unsubdivided "south flank." There is also potential ambiguity in the earthquake swarms accompanying rift intrusion. Absent a large felt event, some of the swarm earthquakes may be a south flank response, but at this time the seismic network cannot discriminate between rift and flank.

[12]The Whitney tiltmeter is discussed in appendix A.

Halemaʻumaʻu Eruptions, 1924–1934

In the decade following the 1924 collapse, Kīlauea erupted seven times at the bottom of the newly deepened Halemaʻumaʻu Crater (table 3.1, figure 3.1). Eruptions in 1930, 1931–32 and 1934 were more voluminous than the others. Whitney Vault tilt signals near the times of eruption are not well-correlated with eruption times. It is likely that the eruptions of 1924–34 were fed from shallow pockets of magma remaining from the lava lake activity before the 1924 collapse (source 1 defined in fig. 2.4) with minor inflation/deflation of source 2. Changes in the shallow magma chamber are too far away to register at the Whitney tiltmeter. Unfortunately, this cannot be verified by the chemistry and petrography of the erupted lavas because only one sample of this series of Halemaʻumaʻu eruptions was collected—the 1931 eruption was sampled in conjunction with recovery of victims of a double suicide from the bottom of Halemaʻumaʻu (Fiske and others, 1987, Volcano Letter 388).

East Rift Intrusions in 1936–1938

Before the last eruption in Halemaʻumaʻu in 1934, the seismicity along the magma supply path and beneath the rift and south flank appeared to increase beneath several regions of the volcano (fig. 3.1, fig. C1). The seismicity increase may be believable, because the seismic network and presence of a staff seismologist were consistent through the 1930s (Klein and Wright, 2000). Earthquakes at shallow (0–5 km) and intermediate (5–15 km) depth beneath Kīlauea's summit and beneath the Koaʻe Fault Zone increased in the latter half of 1936 (fig. C1). In the Volcano Letter for May 1938 the HVO staff noted that steam appeared near Kōkoʻolau Crater accompanied by wilting of vegetation "within the last year or two" (Fiske and others, 1987, Volcano Letter 459. p. 2, 4). The steaming area was referred to as the "Kōkoʻolau hot area" (later called Puhimau thermal area) and identifies an area of intrusion beneath the east rift zone. Widening of

Figure 3.1. Graphs showing Kīlauea activity, 1925–1935. Dates on the time (x) axis are centered at the beginning of the year, as in figure 2.2. For example, the tick mark at 1926 is at 1 January 1926. Halemaʻumaʻu eruptions following 1924 collapse (first eruption in July 1924 not shown). Seismicity (bottom six panels) and Whitney tilt magnitude (second panel from top) related to times of eruption given in the top panel are emphasized by vertical dotted lines. Tilt magnitudes are given in arc-seconds (left axis) and microradians (right axis). Seismicity is plotted, from bottom to top, for the regions defined in appendix A, table A3 corresponding to the magma supply path, rift zones and Koaʻe, and south flank. Earthquakes per day (eq/day) and magnitudes (*M*) greater than or equal to 4.0 are given for each region. Region identifications for south flank earthquakes in this period are not well determined. Eruptions are associated with increase in shallow caldera earthquakes but are not correlated with changes in Whiney tilt. Additional times of of enhanced shallow summit seismicity are not accompanied by eruption. See text for further discussion.

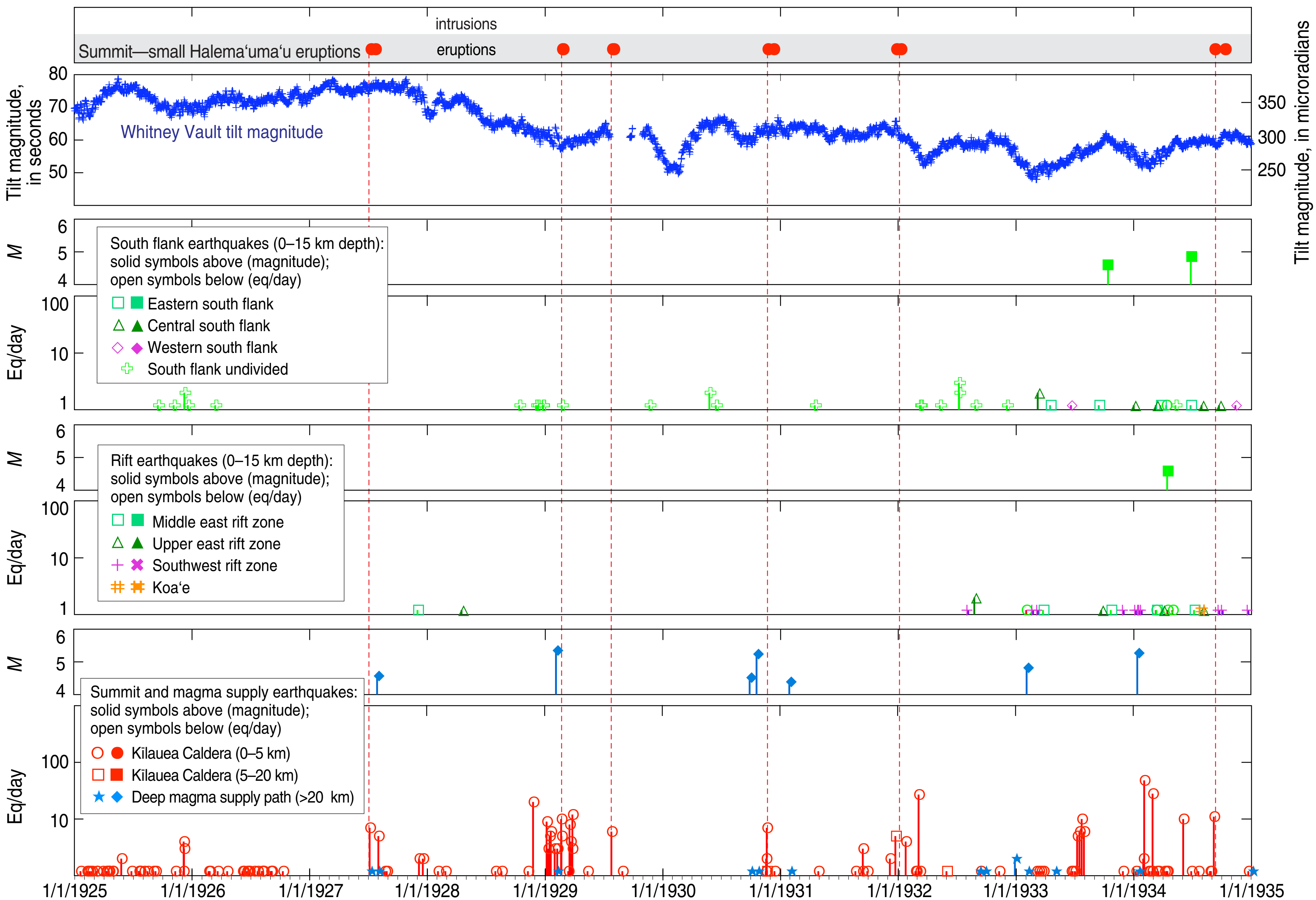

intrusions
eruptions
Summit—small Halema‘uma‘u eruptions
Tilt magnitude, in seconds
80
70
60
50
Whitney Vault tilt magnitude
Tilt magnitude, in microradians
350
300
250
M
6
5
4
Eq/day
100
10
1
South flank earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Eastern south flank
Central south flank
Western south flank
South flank undivided
Rift earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Middle east rift zone
Upper east rift zone
Southwest rift zone
Koa‘e
Summit and magma supply earthquakes:
solid symbols above (magnitude);
open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–20 km)
Deep magma supply path (>20 km)
1/1/1925
1/1/1926
1/1/1927
1/1/1928
1/1/1929
1/1/1930
1/1/1931
1/1/1932
1/1/1933
1/1/1934
1/1/1935

Table 3.1. Kīlauea eruptions, intrusions, earthquake swarms, and earthquakes $M \geq 4$, 1925–1953.

[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; closely related events nearby in time are grouped together]

Start date	End date	Location[1]	Activity[2]	Comment	References[3]
07/07/1927	07/20/1927	Hm	E	Eruption in Halema'uma'u Crater ; no precursory seismicity	ESPHVO , v. 3, p. 989 –1007
07/31/1927		KC?	EQ	*M* 4.58 deep beneath Kīlauea	KW; ESPHVO, v. 3, p. 1185
01/10/1928	01/11/1928	KC	EQS	7 precursory events 22:43, 01/10–00:26, 01/11/1928	ESPHVO, v. 3, p. 1059–1066
01/11/1928	01/11/1928	Hm	E	Lava from the 1927 eruption reactivated	
02/05/1929		KC?	EQ	*M* 5.4 deep beneath Kīlauea	KW; ESPHVO, v. 3, p. 1185
02/19/1929	02/20/1929	KC	EQS	15 precursory events 22:42, 02/19–00:46, 02/20/1929	ESPHVO, v. 3, p. 1184–1189
02/20/1929	02/21/1929	Hm	E	Eruption in Halema'uma'u Crater;	
07/25/1929	07/28/1929	KC	EQS	6 precursory events 4:20–5:31, 07/25/1929	ESPHVO, v. 3, p. 1209–1217
07/25/1929		Hm	E	Tilt data missing from 07/22–09/19/1929	
09/28/1930		KC?	EQ	*M* 4.53 deep beneath Kīlauea	KW; VL 301, p. 4
10/20/1930		KC?	EQ	*M* 5.25 deep beneath Kīlauea	KW; VL 305, p. 3
11/19/1930	11/19/1930	KC	EQS	83 precursory events at depths of 0–5 km	VL 309, p. 2–4
11/19/1930	12/07/1930	Hm	E	Eruption in Halema'uma'u Crater;	
01/29/1931		KC?	EQ	*M* 4.4 deep beneath Kīlauea?	KW; VL 364, p.3
12/23/1931	12/23/1931	KC	EQS	5 precursory events at depths of 6–8 km	VL 366–367
12/23/1931	01/05/1932	Hm	E	Eruption in Halema'uma'u Crater;	
03/04/1932	03/04/1932	Hm	EQS	37 events 0–5 km depth—no Whitney tilt signal	VL 376
02/04/1933		sf offshore?	EQ	*M* 4.83 deep beneath Kīlauea's offshore south flank	KW
01/13/1934		sf offshore?	EQ	*M* 5.28 deep beneath Kīlauea's offshore south flank	KW; VL 407, p. 2
02/02/1934	02/02/1934	KC	EQS	47 events at 0–5 km depth	VL 408
09/06/1934	09/06/1934	KC	EQS	9 precursory events at 0-5 km depth	VL 415–416
09/06/1934	10/08/1934	Hm	E	Eruption in Halema'uma'u Crater;	
01/02/1935		KC	EQ	*M*5.15; 30 km beneath Kīlauea Caldera	KW; VL 419, p. 2
06/25/1935		KC	EQ	*M*4.16; 10–20 km beneath Kīlauea Caldera	KW; VL 424, p. 2
04/15/1936		KC	EQ	*M*4.66; 30 km beneath Kīlauea Caldera	KW; VL 434, p. 2
05/28/1938	06/01/1938	ERZ	EQS/I	>88 precursory events (many felt) between 6:05 and 13:00; ground cracking near Devil's Throat	VL 459, p. 2–5; KW
05/28/1938		KC	EQ	*M*4.18; 30 km beneath Kīlauea Caldera	KW; VL 528, p. 2–5
06/01/1938		sf	EQ	*M*4.31	KW; VL 529, p. 3
06/02/1938		KC	EQ	*M*4.05 24 km beneath Kīlauea Caldera	KW; VL 529, p. 3
08/08/1938	08/13/1938	ERZ	EQS/I	>353 precursory events (many felt) 16:38–24:00, 08/08/1938; ground cracking near Devil's Throat	VL 462, p. 2–5
08/08/1939		KC?	EQ	*M*4.55; 30 km beneath Kīlauea Caldera	KW; VL 462, p. 3
10/25/1938		KC	EQ	*M*4.10; 25.6 km depth beneath Kīlauea Caldera	KW; VL 462, p. 5
04/12/1939		KC	EQ	*M*4.12; 28.8 km depth beneath Kīlauea Caldera	KW; VL 464, p. 5
05/24/1939		KC	EQ (2)	*M*5.39 and 4.19; 30 km beneath Kīlauea Caldera	KW; VL 464, p. 6
06/12/1939		KC	EQ	*M*4.65; 20.8 km beneath Kīlauea Caldera	KW; VL 464, p. 6
06/19/1939		KC	EQ	*M*4.29; 24 km beneath Kīlauea Caldera	KW; VL 464, p. 7
07/01/1939		KC	EQ	*M*4.39; 17.6 km beneath Kīlauea Caldera	KW

Table 3.1. Kīlauea eruptions, intrusions, earthquake swarms, and earthquakes *M*≥4, 1925–1953.—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; closely related events nearby in time are grouped together]

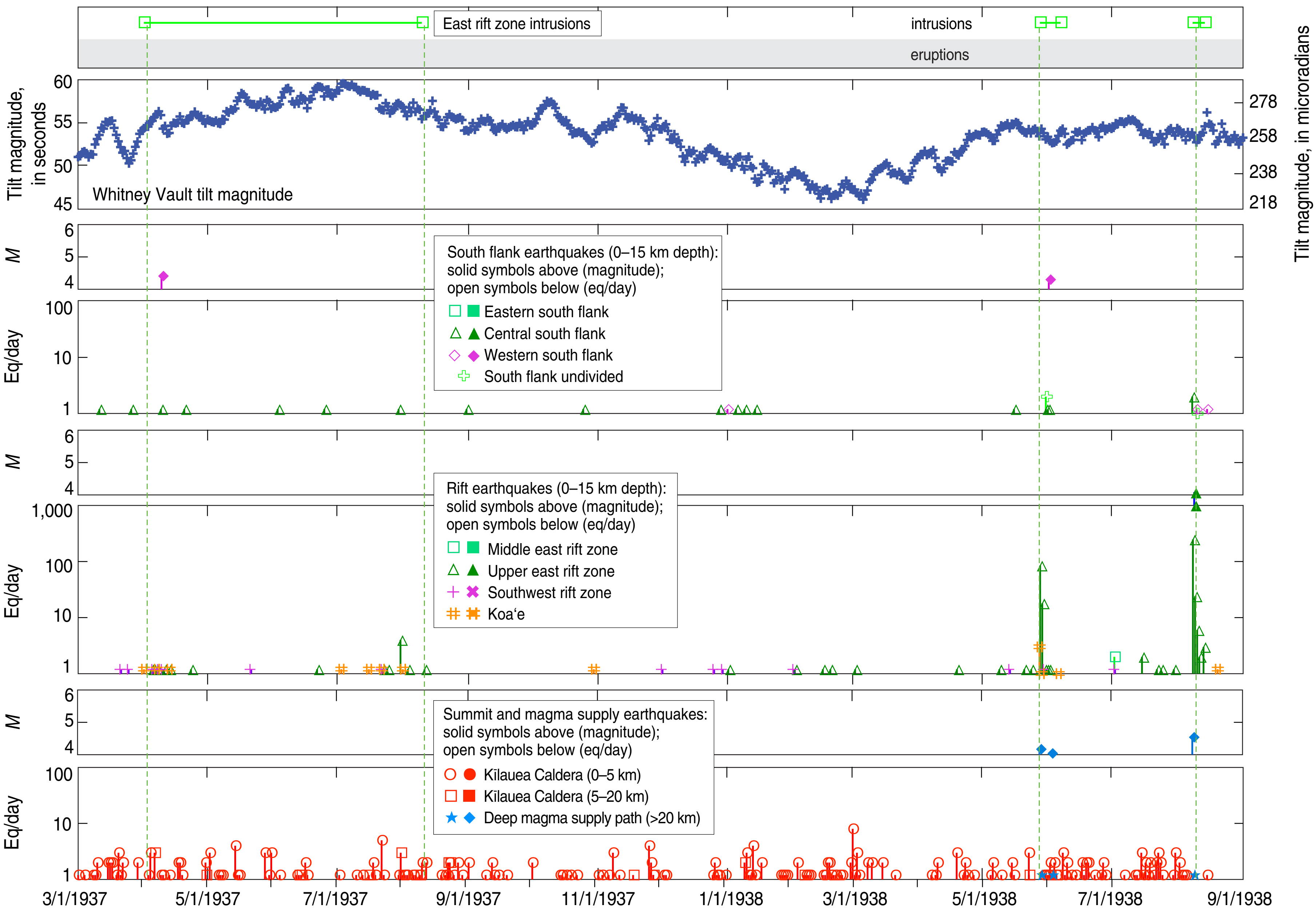
Start date	End date	Location[1]	Activity[2]	Comment	References[3]
04/20/1941		KC	EQ	*M*4.53; 25 km beneath Kīlauea Caldera	KW; VL 472, p. 3
02/18/1942		KC	EQ	*M*4.05; 12.8 km beneath Kīlauea Caldera	KW; VL 475, p. 2
11/12/1944		KC?	EQ	*M*4.58; 30 km beneath Kīlauea Caldera	KW; VL 486, p. 3
11/12/1944	12/06/1944	KC	EQS	Scattered earthquakes of decreasing depth after 11/15	Finch, 1944,
12/06/1944	12/07/1944		EQS/I	16 shallow events (some felt) beneath Kīlauea Caldera associated with subsidence near Halema‘uma‘u	Finch, 1944, KW
01/24/1945		KC	EQ	*M*4.32; 21 km beneath Kīlauea Caldera	KW; VL 487, p. 5
08/18/1947		KC	EQ	*M*4.27; 21 km beneath Kīlauea Caldera	KW; VL 497, p. 3
09/30/1947		KC	EQ	*M*4.74; 25 km beneath Kīlauea Caldera	KW; VL 497, p. 3
12/14/1947		KC	EQ	*M*4.69; 32 km beneath Kīlauea Caldera	KW; VL 498, p. 3
03/19/1948		KC	EQ	*M*4.35; 25 km beneath Kīlauea Caldera	KW; VL 499, p. 3
07/29/1948	07/31/1948	KC	I?	6 felt *M*2.8–4.1 on 7/30 at 5–15 km depth	KW; VL 501, p. 3
08/02/1950	08/02/1950	KC	I	3 felt out of 241 recorded; Whitney tilt 8/1–5: 5.8 µrad at azimuth 33.1	KW; 509, p. 6
12/08/1950	12/14/1950	Koa‘e[4]	EQS	*M*3.90 recorded in Honolulu; 16 *M*< 4	Finch, 1950;
12/09/1950			EQS	*M*4.40 and 5.12 recorded in Honolulu; 48 *M*< 4	Finch and Macdonald, 1953,
12/10/1950			EQS	*M*4.70 (3), 4.98, 5.26 recorded in Honolulu; 66 *M*< 4	KW: VL 510, p. 3–4
12/11/1950			EQS	*M*4.12 recorded in Honolulu; 36 *M*< 4	
12/12/1950			EQS	8, 6 and 6 *M*< 4 over 3 days	
04/22/1951		KC	EQ	*M*6.23 at 14:52 preceded by a *M*4.21 foreshock at 04:21 and followed by many aftershocks. Location east of Kīlauea Caldera is questionable; Interpreted as 35 km deep along the magma supply path	Macdonald, 1951; Macdonald and Wentworth, 1954; VL 512, p. 1–5
03/13/1952	04/21/1952	SF	EQS	Intense earthquake swarm beneath Kīlauea’s offshore south flank. Magnitudes range from 6.2 (2 events), 5–6 (19 events), 4–5 (36) and hundreds at *M*< 4. “Suspected deep intrusion”?	Macdonald, 1952, 1955; KW; VL 515, p.1–7
04/03/1952	04/12/1952	ERZ	EQS?	15 events beneath the onshore east rift zone	KW; VL 516, p. 7
04/12/1952		KC	EQ	*M*4.52 10–20 km beneath Kīlauea’s summit	KW; VL 516, p. 7
05/10/1952		KC	EQ	*M*4.04 5–10 km beneath Kīlauea’s summit	KW; VL 516, p. 7
06/19/1952		KC	EQ	*M*4.86 25 km deep beneath Kīlauea’s summit	KW; VL 516, p. 8
		SWR	EQ	*M*3.97, 4.03 beneath southwest rift zone	
06/27/1952	06/28/1952	KC	EQS	Precursory swarm 0–5 km	KW; VL 516, p. 8;
	11/09/1952	Hm	E	Eruption in Halema‘uma‘u Crater	Macdonald, 1952, 1955; VL 518, p. 1–10

[1]Location abbreviations correspond to regions shown on chapter 1, figure 1.1A: 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; C, Sharp summit tilt drop indicating transfer of magma to rift zone.

[3]ESPHVO, Bevens and others, 1988, Early serial publications of the Hawaiian Volcano Observatory; KW, Klein and Wright, 2000; VL number, Compilation of The Volcano Letter by Fiske and others, 1987.

[4]Epicenters of these earthquakes are across the Koa‘e fault zone from Kōko‘olau (east rift zone) to Kamakai‘a Hills (southwest rift zone). The larger events were recorded on O‘ahu. We interpret at least some to lie deeper than 20 km within the magma supply path. See second plot from bottom of figure 3.4.



East rift zone intrusions
intrusions
eruptions
Tilt magnitude, in seconds
60
55
50
45
Whitney Vault tilt magnitude
278
258
238
218
Tilt magnitude, in microradians
M
6
5
4
Eq/day
100
10
1
South flank earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Eastern south flank
Central south flank
Western south flank
South flank undivided
1,000
Rift earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Middle east rift zone
Upper east rift zone
Southwest rift zone
Koaʻe
Summit and magma supply earthquakes:
solid symbols above (magnitude);
open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–20 km)
Deep magma supply path (>20 km)
3/1/1937
5/1/1937
7/1/1937
9/1/1937
11/1/1937
1/1/1938
3/1/1938
5/1/1938
7/1/1938
9/1/1938

the area of steaming has occurred during the current post-1983 Kīlauea eruption (http://hvo.wr.usgs.gov/volcanowatch/2003/03_02_06.html), indicating that it remains a preferred area of intrusion and potential pit crater formation. The intrusion may have coincided with increased seismic activity beneath the upper east rift zone and Koa‘e Fault Zone (fig. 3.2). The inferred intrusion was not accompanied by ground cracking, indicating that emplacement was below 2-km depth.

In 1938 there were two intrusions into the east rift zone in the vicinity of Devil’s Throat, accompanied by major earthquake swarms (figs. 3.2 and 3.3, table 3.1) and by cracking and uplift of the Chain of Craters Road between Devil’s Throat and Aloi Craters (Fiske and others, 1987 Volcano Letters 459–460, 462). Apparent Whitney Vault tilt deflations were offset from the time of intrusion and smaller than the measurement uncertainty. The intensity of the ground deformation suggests that the intrusions were too shallow to be detected at Whitney and may have been fed in part from the deeper and earlier formed storage zone beneath the Puhimau thermal area. Cracks that opened in August were staked and the amount of opening measured. The movement continued for at least 6 months following the August intrusion and suggests that the intrusion was still being fed.

Figure 3.2. Graphs showing Kīlauea activity, 1 March 1937–1 September 1938. East rift intrusions including hypothesized formation of Puhimau thermal area. Panels as in figure 3.1. Dates on figure in m/d/yyyy format. Intrusion times are emphasized by dotted vertical lines. Formation of the Puhimau thermal area, probably sometime during 1937, is presumed correlated with occurrence of earthquakes in the upper east rift zone and Koa‘e regions. Whitney tilt is not correlated with either the Puhimau intrusion or the two 1938 intrusions. Earthquake locations are shown in figure 3.3. See text for further discussion.

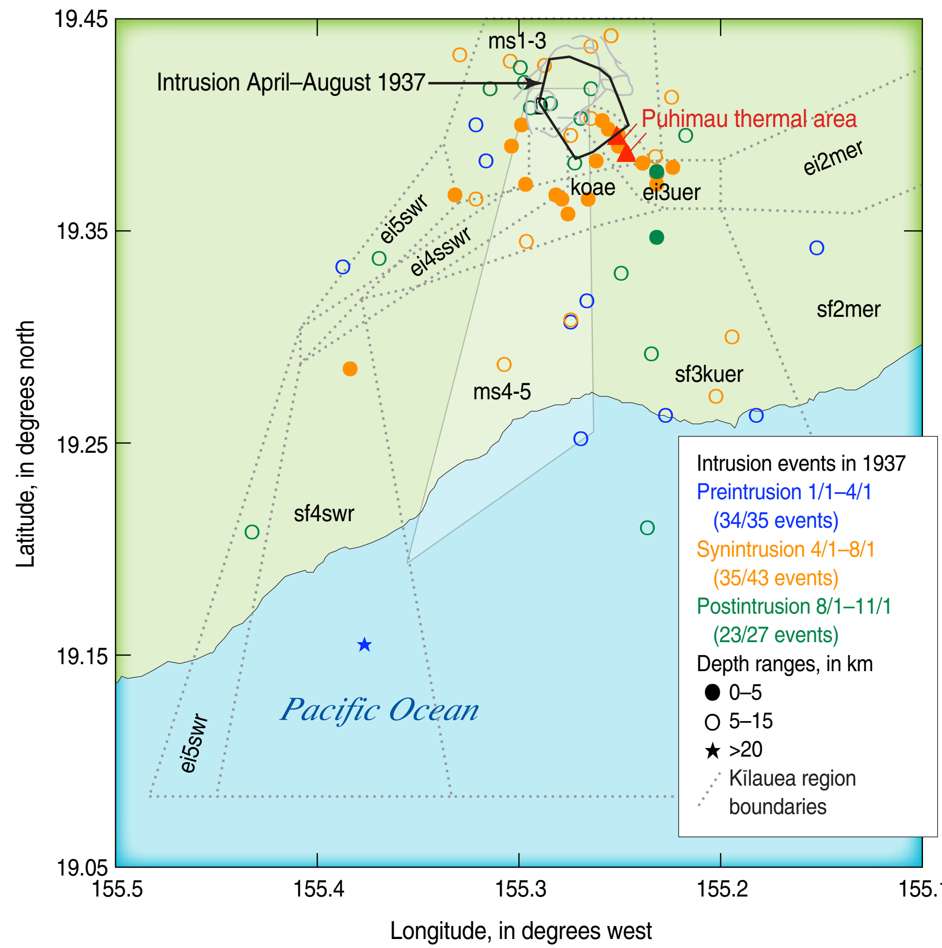


Figure 3.3. Map showing locations of earthquakes between 1 April and 1 August 1937 possibly associated with the formation of the Puhimau thermal area (fig. 3.2). Red triangles mark the location of Puhimau and Kōko‘olau Craters, near which vegetation died within 1–2 years before the May 1938 intrusion. Shallow summit earthquakes for periods before, during, and after the hypothesized intrusion occur within the area outlined in black. Dates on figure in m/d/yyyy format. Earthquake regions are defined in appendix A and shown in appendix A, figure A4. The black polygon outlines the region in which earthquakes presumed to be at depths less than 5 kilometers are present. Within this region there were swarms of events too small to precisely locate. The number of those events presumed to be within the black polygon are given on the figure as a fraction of the total number of events recorded. See text for further discussion.

Summit Intrusions of December 1944 and August 1950

A shallow earthquake swarm of 16 events on 6–7 December 1944 (table 3.1) was preceded by 4.7 µrad of inflation between 5 and 7 December and followed by deflation of 19 µrad ending on 17 December. Rainfall was low during both inflation and deflation, 0.35 cm/day (0.14 inches/day) and 0.25 cm/day (0.10 inches/day), respectively, so the Whitney tilt data can be trusted. Tiltmeters on the crater floor around Halemaʻumaʻu showed marked inflation before the earthquake swarm and deflation during the earthquake swarm, such that they went off scale (Finch, 1944). The data suggest a shallow intrusion beneath Halemaʻumaʻu Crater.

An earthquake swarm on August 2, 1950 consisted of 243 recorded events identified as being shallow beneath Kīlauea's summit (table 3.1, figure 3.4). Three earthquakes in the swarm were felt at the summit. This is probably an intrusion, too shallow to affect the Whitney tiltmeter.

Events Preceding the Return of Lava to Halemaʻumaʻu in June 1952

Summit Inflation

March 1950 marked the onset of continuous inflation measured at the Whitney Vault (fig. 3.4), easily separated from the preceding seasonal variation by lower signal noise and continuity over several months instead of days or weeks. The inflation was interrupted by an abrupt deflation in December 1950, followed almost immediately by reinflation. The reinflation continued without interruption through a *M*6.2 deep Kīlauea "magma supply" earthquake on 22 April 1951 and a major swarm of earthquakes beneath the offshore part of Kīlauea's south flank during March and April 1952 (table 3.1, fig. 3.4). Eruption broke out in Halemaʻumaʻu on 27 June 1952 (Macdonald, 1952).

The Koaʻe Crisis of 1950

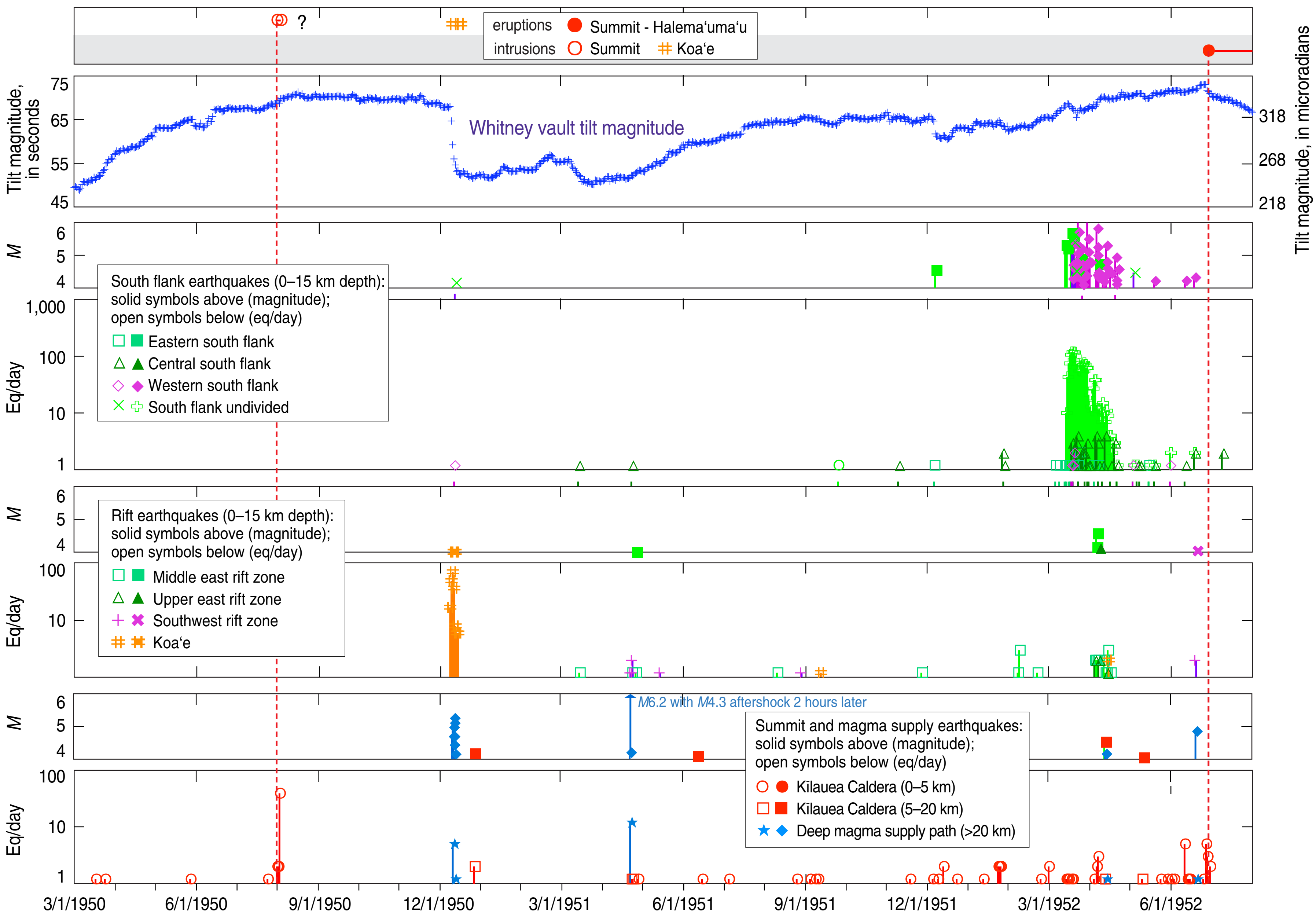
A major deflation of Kīlauea's summit in December 1950 was accompanied by an earthquake swarm beneath the western Koaʻe Fault Zone (table 3.1, fig. 3.5; Finch, 1950; Finch and Macdonald, 1953). This was the first event since the beginning of observation of the volcano in the early 19th century, and certainly since HVO's founding in 1912, in which the Koaʻe fault system was noticeably affected. The earthquake swarms of the 19th century were not precisely located, but the available data, including observations of ground cracking, suggest that they were associated with intrusion beneath the rift zones rather than activity between the rifts. The lack of uplift, earthquakes, and ground cracking on the Chain of Craters road suggests that the 1950 intrusion was considerably deeper and involved the east rift less than the intrusions of 1938. Apparently in 1950 no one walked across the Koaʻe Fault Zone along the earthquake zone to check for additional cracking and fault movement within the Koaʻe.

We don't fully understand how the patterns of the 1950 Koaʻe earthquake swarm fit into other events in Kīlauea's history. Many of the earthquakes lie along Kīlauea's magma supply path (Wright and Klein, 2006), and those with magnitudes greater than 4 were recorded on Oʻahu, suggesting that these larger events may be deeper than 20 km. The only comparable event in Kīlauea's modern history is the Christmas Eve 1965 eruption and intrusion (Fiske and Koyanagi, 1968). In 1965, the seismicity was shallow and the maximum earthquake magnitude was 3.6 (Bosher and Duennebier, 1985). Observed ground movements in 1965 were far more intense than in 1950 and included nearly 2 m of offset on the Kalanaokuaiki Fault separating the Koaʻe from the south flank (Fiske and Koyanagi, 1968, figure 8).

The Earthquake of 22 April 1951

Not long after the 1950 Koaʻe crisis a *M*6.2 earthquake occurred at a depth of more than 20 km beneath Kīlauea. Eissler and Kanamori (1986) estimated the depth as 35–50 km. The epicenter of this event was placed near and just northeast of Kīlauea Caldera, and aftershocks were located beneath the entire area of Kīlauea (Macdonald, 1951; Macdonald and Wentworth, 1954). It is likely that these locations have large errors, because modern earthquakes of similar magnitude and depth fall along the magma supply path and aftershock epicenters occur over a much smaller area.

Figure 3.4. Graphs showing Kīlauea activity, 1 March 1950–1 August 1952. Buildup to 1952 Halemaʻumaʻu eruption. Panels as in figure 3.1. Dates in m/d/yyyy format. Inflation of Kīlauea's summit begins circa 1 March 1950. There was a shallow summit earthquake swarm on 2 August 1950 (Klein and Wright, 2000), suggesting a summit intrusion. A large and intense seismic swarm beneath the Koaʻe Fault Zone in December 1950, including many earthquakes large enough to be recorded in Honolulu, was accompanied by a major deflation, after which inflation gradually resumed until beginning of Halemaʻumaʻu eruption on 27 June 1952. A deep magma supply earthquake occurred on 22 April 1951. A very large and prolonged earthquake swarm off the south shore of Kīlauea located beneath the midslope bench (chap. 1, fig. 1.1*C*) took place in March and April 1952. Locations of earthquakes are shown in figure 3.5.


eruptions
intrusions
Summit - Halemaʻumaʻu
Summit
Koaʻe
?
Tilt magnitude, in seconds
Tilt magnitude, in microradians
Whitney vault tilt magnitude
M
Eq/day
South flank earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Eastern south flank
Central south flank
Western south flank
South flank undivided
Rift earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Middle east rift zone
Upper east rift zone
Southwest rift zone
Koaʻe
M6.2 with M4.3 aftershock 2 hours later
Summit and magma supply earthquakes:
solid symbols above (magnitude);
open symbols below (eq/day)
Kilauea Caldera (0–5 km)
Kilauea Caldera (5–20 km)
Deep magma supply path (>20 km)
3/1/1950
6/1/1950
9/1/1950
12/1/1950
3/1/1951
6/1/1951
9/1/1951
12/1/1951
3/1/1952
6/1/1952

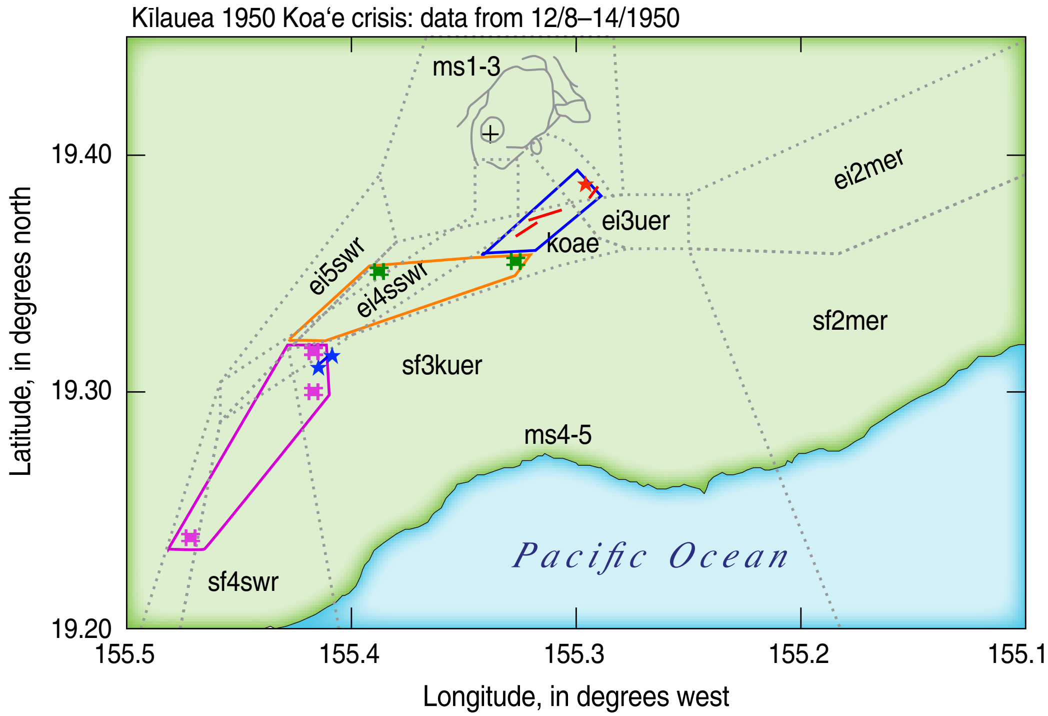


Figure 3.5. Map showing locations of earthquakes for the Koaʻe crisis of December 1950. Locations of earthquakes and ground cracking during the seismic swarm in December 1950 that was accompanied by dramatic subsidence of Kīlauea's summit (Finch, 1950; Finch and Macdonald, 1953; Klein and Wright, 2000). The swarm propagated from Kōkoʻolau Crater on Kīlauea's east rift zone across the Koaʻe to the vicinity of Kamakaiʻa Hills, then down the southwest rift zone and adjacent flank. Nine earthquakes of *M*4.16–*M*5.12 were recorded in Honolulu and were widely felt on the Island of Hawaiʻi. These earthquakes are assumed to be deeper than 20 km, hence located within the deep magma supply path. Earthquakes of *M*<4 are counted as belonging to the Koaʻe Fault Zone at depths sufficiently shallow to explain the observance of new cracking. Single earthquake location errors are unknown and probably large, but the general location of the swarm is well documented. Dates on figure in m/d/yyyy format.

The South Flank Seismic Crisis of March and April 1952

A few months before the 1952 Halemaʻumaʻu eruption a great earthquake swarm began beneath the offshore part of Kīlauea's south flank (table 3.1). Epicenters were located along a broad east-west-trending band extending from south of Kīlauea's middle east rift zone to the southwest rift zone (fig. 3.6). The principal swarm lasted for about 2 weeks, and many of the larger events were recorded on Oʻahu. Earthquakes continued at relatively high numbers through April and gradually declined up to the time of the eruption in Halemaʻumaʻu. The last confirmed earthquake in this swarm occurred on 16 November 1952, a week after the end of the Halemaʻumaʻu eruption. The net tilt change across the earthquake swarm reflected continued inflation leading up to eruption (fig. 3.4). This may qualify as an extreme example of a "suspected deep intrusion."

The Return of Lava to Halemaʻumaʻu in June 1952

On 27 June 1952 lava returned to Halemaʻumaʻu for the first time since 1934 (table 3.1; fig. 3.3). The eruption was immediately accompanied by a small earthquake swarm beneath Kīlauea Caldera and preceded by about 2 weeks of heightened shallow seismicity beneath the caldera. The summit eruption in Halemaʻumaʻu Crater lasted for nearly 6 months, ending on 9 November 1952. During the time of eruption there was a net deflation of 6.21 seconds (30 μrad) measured at the Whitney Vault, indicating that during the eruption additional magma was transferred to the rift zone (table 3.2).

1925–1952: Interpretation

This is a critical period in Kīlauea's history as it involves recovery from the 1924 collapse and the first of several increases in magma supply rate extending to the present. Magma supply calculations follow the procedures outlined in appendix A. The full history of magma supply rate for the entire period from 1950 to present is discussed in chapter 8.

Recovery from the 1924 Collapse

Analysis of the recovery from the 1924 collapse requires an evaluation of the volume lost during the collapse and how that was made up in subsequent years. It is important also to note that the Whitney tilt level stayed low after 1924, in contrast to rapid reinflation following many deflations observed during the modern era. The 1924 collapse created a reduction in summit volume of 0.4 km^3 to be filled (Dvorak, 1992). That volume divided by the 26 years between 17 June 1924 and 5 March 1950 yields a magma supply rate of less than 0.02 km^3/yr. This rate is less than the filling rate before 1924 and it seems unreasonably low.

If we calculate a collapse volume taking into account the deeper, broader source discussed in the last chapter, we obtain a volume of 1.26 km^3, more than three times that assumed by Dvorak[13]. Making up this volume in 26 years yields a magma supply rate of $1.26/25.714 = 0.05$ km^3/yr, a magma supply rate that is higher than rates before 1924 and less than a

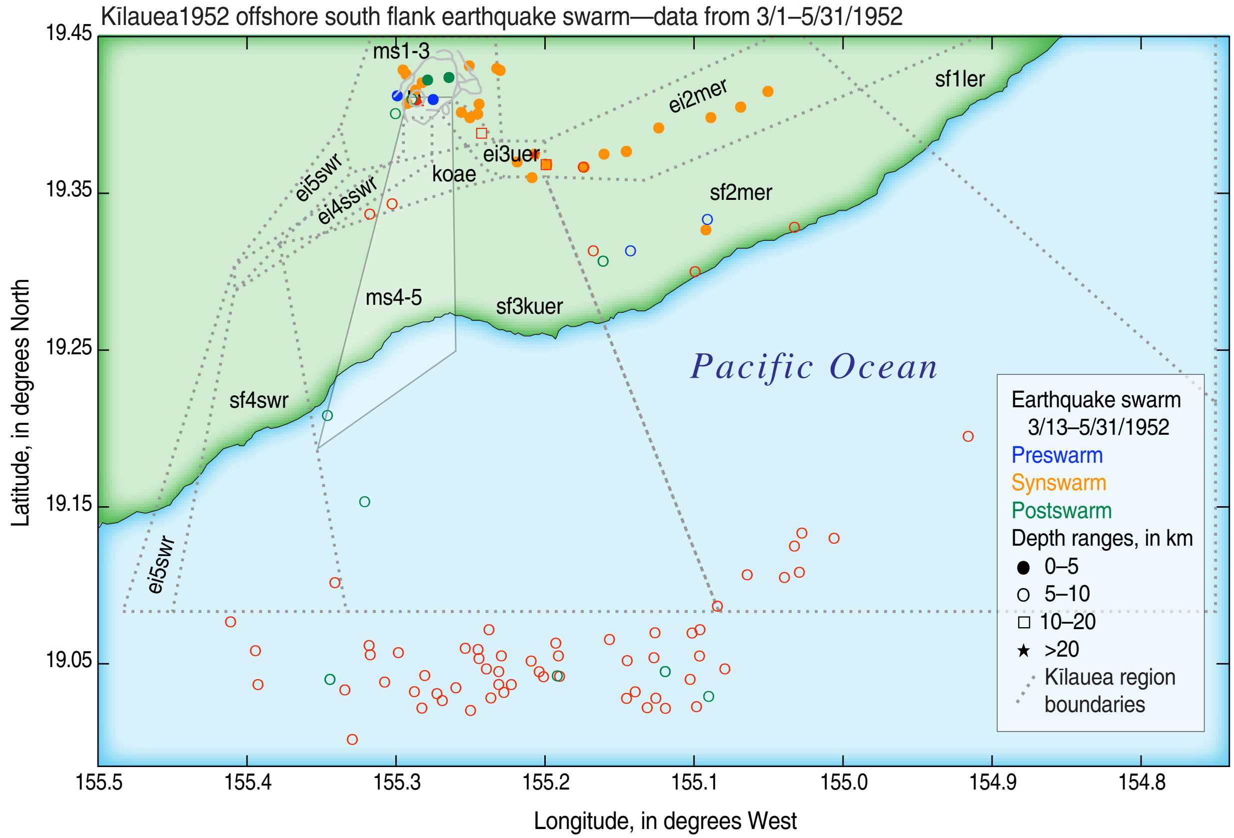


Figure 3.6. Map showing locations of earthquakes during March and April 1952 across a broad region of the offshore south flank (Fiske and others, 1987, Volcano Letter 515, fig. 1, p. 2). The smaller quakes are counted here as south flank undivided because precise locations are not known. The earthquakes of $M \geq 4$ are plotted at their given location. The linear trend is possibly an artifact of the limited seismic network, in which distance from Kīlauea's summit constituted the only reliable measurement. Earthquake locations are color-coded for pre-, syn- and postintrusion/eruption. Dates on figure in m/d/yyyy format. Only epicenters of the larger events in the offshore earthquake swarm are given in table 2 of Macdonald (1955). Additional earthquakes are given a time and a description ("off south shore of Hawai'i). For these events locations are randomly generated to match the published distribution of epicenters (Macdonald, 1955, fig. 5). The occurrence of many east rift earthquakes during the south flank swarm suggests that an intrusion may have occurred at the same time.

[13]We have calculated the volume of subsidence as a two-part cone, with very gentle slope over a broad area (almost disk-like in shape) and much steeper slope in the central area within 1 km of Halema'uma'u.

Table 3.2. History of tilt and volume changes prior to and associated with the 1952 eruption.

Cycle	Start date	End date	Time (years)	Tilt magnitude (µrad)	Tilt azimuth (degrees)	Tilt volume[1] (km³)	Eruption volume[2] (km³)	Magma supply rate (km³/year)	Comment msr = magma supply rate
	2/23/1918	2/9/1924	5.960			0.1425		0.0239	1918-1924 filling rate from table 2.5
1924-1934	6/1/1924	10/9/1934	10.36	flat			0.0211	0.0020	Filling rate for 1924–1934 eruptions
1924-1950	6/17/1924	3/5/1950	25.17	flat		1.26[3]		0.0490[3]	Filling of the 1924 collapse volume
1950-1952	3/5/1950	6/27/1952		135.5	27.85[4]	0.0870			Total inflation
	9/15/1950	12/8/1950		13.7	218.1	0.0088			Magma transfer to rift zone
	12/8/1950	12/16/1950		78.9	209.98	0.0507			Magma transfer to rift zone
Total			**2.313**			**0.1465**	**0.0021**	**0.0642**	**Pre-eruption magma supply rate**
1952	6/27/1952	11/9/1952	0.364				0.0370	0.1016	Filling rate 1952 Halema'uma'u
							0.0234		Volume added at preeruption msr
							-0.0136		Added volume minus erupted volume
	6/27/1952	11/9/1952		30.1	195.27	0.0193			Syneruption deflation
			0.364				0.0058	0.1176	Syneruption magma transfer to rift
							0.0428		Syneruption magma supply rate

[1]Tilt volume in cubic kilometers = Whitney tilt magnitude × 0.00064 after conversion from arc-seconds to microradians (see text for explanation).
[2]Equivalent magma volume obtained by multiplying published lava volumes by 0.8 to account for 20 per cent vesicles.
[3]Volume assumed; minimum magma supply rate calculated as described in text.
[4]Corrected for offset from the 1951 *M*6 earthquake.

rate calculated between 1950 and 1952 (table 3.2 and discussion below). This allows for a rapid recovery during a short time following the 1924 collapse, for example, the first year, followed by a gradual decrease in supply rate over the 1925–50 time period. The net deflationary tilt change of more than 20 arc-seconds (97 µad) from 1925 to 1950 cannot be explained by meteorological variations, and most likely represents continued regional subsidence[14].

We interpret that the discrepancy in volume during 1925–50 was made up through refilling of the deep magma system beneath the rift zone (source 3 in fig. 2.4), recovery being complete when the summit began to inflate in March 1950. The recovery of source 3 is consistent with the continuation of regional subsidence and the delayed reinflation of source 2.

[14]Long-term drift of the tiltmeter is not possible to confirm.

History of Magma Supply, 1925–1953

Estimates of magma supply for the entire period from 1925 to 1953 are shown in table 3.2. Magma for eruption and intrusion during this period came from the three sources shown in figure 2.4. We consider that the small eruptions in Halema'uma'u used up residual magma left at shallow depth beneath the caldera (source 1). The continued recovery after 1934 produced at least four east rift intrusions during 1937–38, all of which occurred with little tilt change (table 3.2; fig. 3.2). Only when all the volume lost in the 1924 collapse is restored to reservoir 3 (see above) does reservoir 2 become pressurized and show measurable inflation in the manner observed during post-1952 cycles of inflation and deflation. This hypothesized style of refilling following the massive and unusual 1924 collapse is similar to that invoked to explain gravity changes during the recovery from the 1975 earthquake (Dzurisin and others, 1980).

The filling rate from 1918 to 1924 of 0.024 km^3/yr (table 2.5) contrasts with the filling rate during the eruptions in Halemaʻumaʻu following the 1924 collapse, which are lower by a factor of 2, and during the 1952 eruption , which are higher by a factor of more than 4. The magma supply rate from March 1950 to the beginning of eruption in 1952, calculated from the volume derived from the Whitney Vault inflationary tilt (see appendix A), is 0.06 km^3/yr, a value falling between the filling rate for 1918–24 and the filling rate during the 1952 eruption, and somewhat greater than the estimated average rate for the entire 1925–53 period (table 3.2).

The low rate of filling between 1924 and 1934 can be explained in a number of ways. Perhaps the most likely is that magma was diverted to the east rift zone from below source 2 as part of the restoration of source 3. This hypothesis is consistent with the calculation of a higher overall magma supply rate for the entire period between 1925 and 1953, as discussed in the last section. Less likely would be a diversion of magma at this time to Mauna Loa in anticipation of its large southwest rift eruption in 1950.

Increased Kīlauea magma supply probably triggered the Koaʻe crisis of December 1950 and may have triggered the later occurrence of the deep *M*6.2 earthquake of 22 April 1951 that occurred near the postulated magma supply conduit from the mantle. Deep earthquakes near Kīlauea's conduit are caused by stress from the flexure of the lithosphere (Klein, 2007; Klein and others, 1987), but their timing could be influenced by increases in magma supply. Later the higher magma supply may have triggered the offshore south flank earthquake swarm of March and April 1952. We interpret the offshore swarm to have unlocked the south flank, potentially marking the beginning of much less constrained seaward spreading. We also can consider the south flank swarm as a massive suspected deep intrusion associated with an increase in rift dilation that in turn could provide a reason for deflation of about 50 µrad during the period of the 1952 eruption (table 3.2). Using a postearthquake dilation rate of ~0.005 km^3/yr , a calculated preeruption magma supply rate of ~0.07 km^3/yr can be compared to a syneruption filling rate of about 0.10 km^3/yr. The additional transfer of 0.006 km^3 of magma to the rift zone calculated from the deflation during the 1952 eruption yields a syneruption magma supply rate of 0.118 km^3/yr, which is larger than the filling rate. This pattern was repeated before and during the 1967–68 Halemaʻumaʻu eruption, at an assumed constant spreading rate, with a preeruption magma supply rate of 0.05km^3/yr, an eruption rate of 0.11 km^3/yr, and a syneruption magma supply rate of 0.12 km^3/yr (see chap. 5).

We interpret the differences among preeruption and posteruption magma supply rates, summit eruption filling rate, and syneruption magma supply rate to the effects of a confining pressure and its release on the rate of magma supply. Before eruption (1925–52) the magma is confined and the supply is throttled. As soon as eruption begins, magma is released at a rate compatible with the ability of the plumbing above the storage reservoir to deliver magma to the surface. When the magma supply rate exceeds the capacity of the delivery system, magma either continues to inflate the storage reservoir (inflationary tilt) or is released to the rift zone as part of the spreading process (deflationary tilt). If either value is greater than 0 the syneruption supply rate will exceed the Halemaʻumaʻu filling rate. When the eruption ends, the magma is again confined and the magma supply rate is temporarily reduced during subsequent inflation. The relationship between an open and closed magma supply system agrees with ideas previously expressed (compare Dvorak and Dzurisin, 1993).

Conclusions: (1) the Kīlauea magma supply rate from 1840 to 1950 (<0.03 km^3/yr) was far less than what we observe from 1950 and after; (2) in the period between the 1924 collapse and the March 1950 inflation, the volume lost in the collapse was regained at a rate still uncertain. The net magma supply rate before 1950 must have decreased as the pressure deficit caused by the 1924 collapse was equalized to a value greater than the 1918–24 filling rate; (3) summit inflation, driven by increased magma supply, began when the volume lost in the 1924 collapse was recovered, possibly augmented by a shift in the deep mantle plumbing to favor eruption at Kīlauea over eruption at Mauna Loa (see chapter 8).

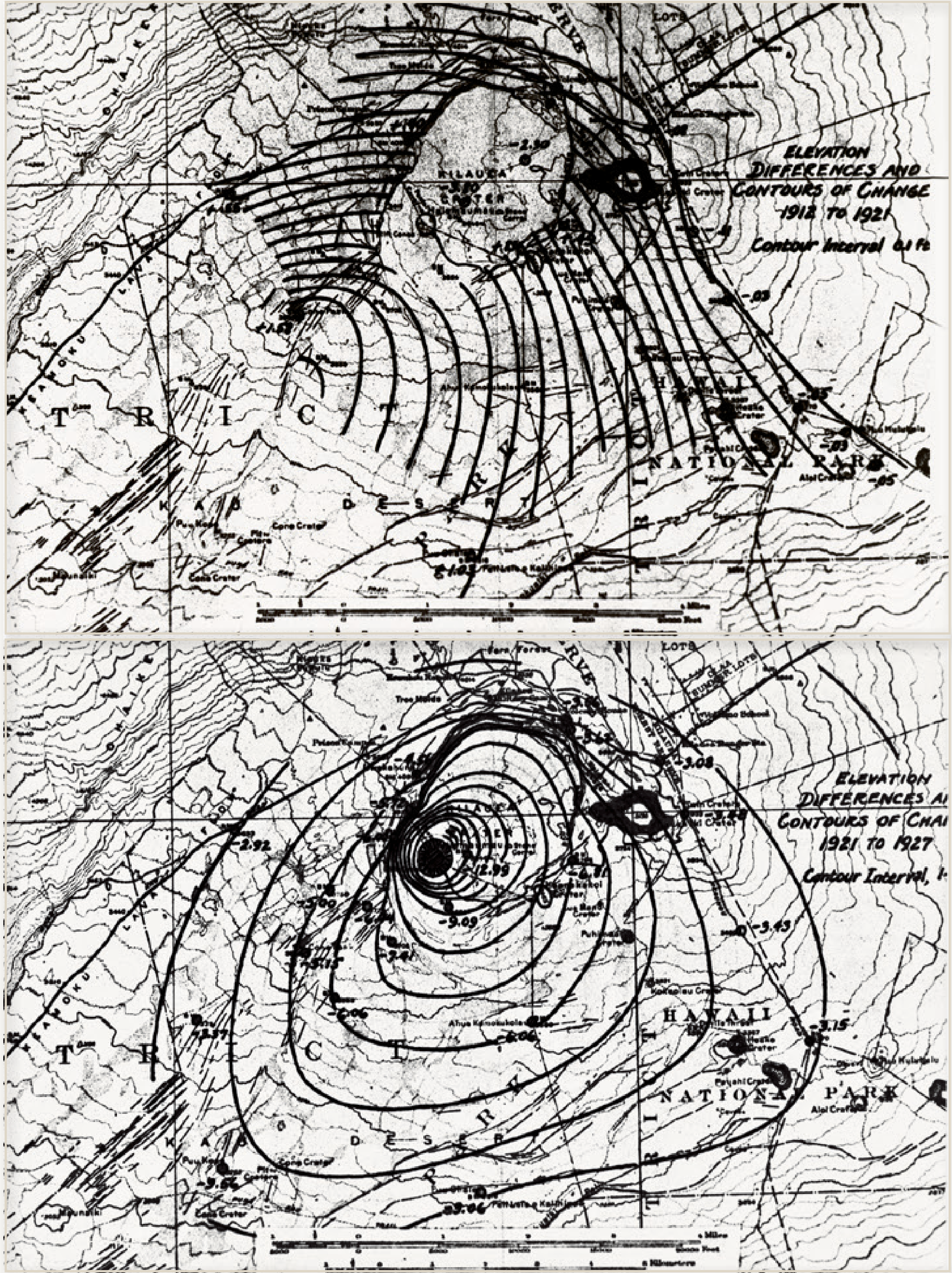
Supplementary Material

Supplementary material for this chapter appears in appendix C, 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 C includes the following supplementary material:

Table C1 contains earthquakes of magnitudes between 5 and 6 for the same time periods as text table 3.1.

Table C2 contains Whitney tilt data to support text figure 3.2.

Figures C1 and C2 show time series plots of earthquakes associated with eruptions and intrusions at Kīlauea from 1925 to 1953.



Elevation changes at Kilauea: (top) upward movement, 1912–1921; (bottom) subsidence, 1921–1927, associated with the great collapse of Halema'uma'u in May 1924. From Wilson (1935).