Chapter 4

Eruptive and Intrusive Activity, 1953–1967

In the interval between the Halemaʻumaʻu eruptions of 1952 and 1967–68, a unique eruption in Kīlauea Iki occurred in 1959. Rift eruptions between 1955 and 1965 are shown to be mixtures of fractionated magma residing in the rift zone and three magmas moving through the east rift zone earlier than, but in the same order as, eruptions of equivalent chemistry at the summit.

Lava lake formed in Kīlauea Iki Crater during eruption in 1959. USGS photo by J.P. Eaton.

The period 1953–67 was a very active time in Kīlauea's history, with pioneering research and monitoring and great leaps in understanding achieved at HVO. Kīlauea eruptions, intrusions, and large earthquakes following the 1952 eruption and through the end of 1960 are summarized in table 4.1 and figures 4.1. The 1961–67 period is covered later in this chapter. Additional seismic analysis for the period 1963–67 has been published in Klein and others (1987), and figures from that paper are cross-referenced in table 4.1.

The period following the 1952 eruption is unique in Kīlauea's known history because it involves many different eruption styles and eruption sequences, including (1) a short eruption in Kīlauea Caldera, (2) three longer eruptions in Halemaʻumaʻu, (3) one episodic eruption in Kīlauea Iki Crater, previously inactive for nearly a century, (4) two eruptions on Kīlauea's lower east rift zone, not active since the great eruption of 1840, and (5) a series of short east rift eruptions uninterrupted by summit activity.

It was also a time of great advances in HVO's ability to effectively monitor volcanic and seismic activity. Expansion and upgrading of the HVO seismic network (Klein and Koyanagi, 1980) began following the 1952 eruption with the arrival of Jerry Eaton. The expanded seismic network allowed earthquake locations to be determined with far more accuracy than in preceding periods. The arrival of Jerry Eaton at HVO also led to the installation of a water-tube tiltmeter permanently mounted in Uwēkahuna Vault and a network of portable water-tube tiltmeters around Kīlauea's summit (Eaton, 1959). Thus, for the first time HVO was able to verify, through monitoring of ground tilt and leveling, the location of a magma chamber at depths of 2–6 km beneath Kīlauea's summit (source 2 of fig. 2.4), from which all eruptions and intrusions were fed.

Tilt and Leveling Data[15]

During the time between the end of the 1965 east rift eruption and the beginning of the 1967–68 Halemaʻumaʻu eruption the leveling network in and near Kīlauea Caldera was measured numerous times, yielding a valuable record of changing epicenters of deformation during an extended period of inflation (fig. 4.2; Fiske and Kinoshita, 1969, figure 5). Deformation centers of nearly all subsequent inflations and deflations determined by a variety of methods fall within the grouping of centers for the 1965–68 period reported by Fiske and Kinoshita (fig. 4.2; Fiske and Kinoshita, 1969, figure 5). The range of deformation centers indicated by the long-base water-tube network (fig. 4.3) lie within a circle of approximately 1 km diameter in the south caldera.

Eruptions and Intrusions

The Eruption of 31 May–3 June 1954

The 31 May–3 June 1954 eruption in Halemaʻumaʻu (Macdonald and Eaton, 1957) was a short eruption during a long period of inflation that began following the end of the 1952 eruption and ended with the lower east rift eruption at the end of February 1955 (fig. 4.1). Inflation continued during the May 1954 summit eruption, with only a small deflection on the Whitney tilt record (fig. 4.4*A*). The eruption on 31 May 1954 was preceded on 30 March 1954 by an earthquake of *M*6.4 beneath Kīlauea's south flank (fig. 4.5) that did not seem to be directly connected to the summit eruption. However, immediately following the earthquake seismicity picked up beneath the lower east rift (fig. 4.4*A*), initially occurring at a rate of about 25 events per month (Macdonald and Eaton, 1964, p. 116, 120).

The Eruption of 28 February–26 May 1955

The 1955 eruption (Macdonald and Eaton, 1964) was the first historically documented eruption on Kīlauea's lower east rift zone since 1840 and is unique in the following respects, when compared to later eruptions: (1) the erupted lavas have a highly fractionated chemistry, (2) deflation of Kīlauea's summit that normally accompanies rift eruptions was delayed more than 1 week after the beginning of the eruption (fig. 4.4*B*), and (3) south flank seismicity adjacent to the eruption site was absent (table 4.1). Beginning two months before the 1955 eruption the number and magnitude of shallow earthquakes beneath the lower east rift zone increased from 1 per day to more than 1,000 per day in the week preceding eruption (fig. 4.4). A newly installed north-south tiltmeter at the Pāhoa schoolhouse registered 97 µrad (~20 arc-seconds) of inflation of the east rift zone beginning 2 days before lava reached the surface (fig. 4.4*A*).

The eruption took place in four stages punctuated by temporary cessation of eruptive activity and (or) shift of vent location (figs. 4.4, 4.5). Toward the close of stage 2, on 5 March 1955, an intrusion occurred near Kalalua Crater on the middle east rift zone (Macdonald and Eaton, 1964, p. 122). The rift deflated at the time of the Kalalua intrusion and resumed inflation through the opening of new vents associated with stage 3 (5 March–7 April 1955) as measured by the Pāhoa tiltmeter (fig. 4.4*A*). The rift zone continued to inflate intermittently before stabilizing within stage 4, a total of 291 µrad (60 arc-seconds) of change (fig. 4.4*A*). Deflation at

[15]A comprehensive review of tilt measurements, including discussion of uncertainties regarding locations of inflation and deflation centers and calculation of magma volume from tilt measurements, is given in appendix A.

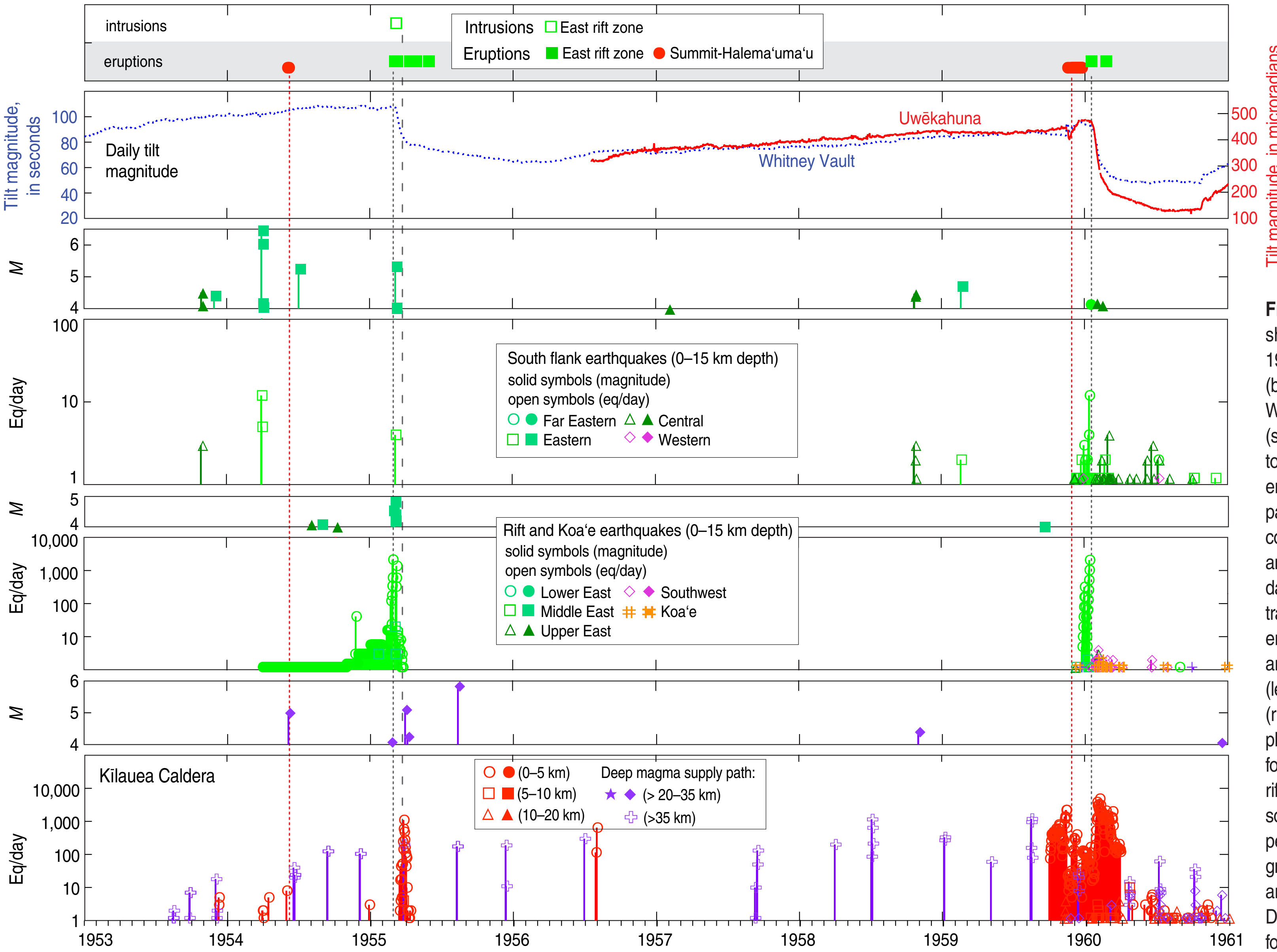

Figure 4.1. Graphs showing Kīlauea activity, 1953–1961. Seismicity (bottom six panels) and Whitney tilt magnitude (second panel from top) related to times of eruption given in the top panel. Vertical dotted lines connect data for eruptions and traditional intrusions; dashed lines connect traditional intrusions without eruption. Tilt magnitudes are given in arc-seconds (left axis) and microradians (right axis). Seismicity is plotted, from bottom to top, for the magma supply path, rift zones and Koaʻe, and south flank. Earthquakes per day and magnitudes greater than or equal to 4.0 are given for each region. Dates on figure in m/d/yyyy format.

Table 4.1. Kīlauea eruptions, intrusions, earthquake swarms and earthquakes $M \geq 4$, 1953–1967.

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; data for eruptions and traditional intrusions emphasized with gray shading; do, ditto (same as above)]

Time and Date		Region[1]	Event Type[2]	Number of events[3]	Tilt[4]		Lag[5]	Comment[6]	Figures[7]	References[8]
Start	End				Mag	Az				
07:50 9/23/1953	9/26/1953	ms5gln	EQS	15				First of several 40-60 km deep swarms north of Kīlauea Caldera; precursory to 1959 eruption and continuing to late 1960 as shown on figure 4.7	**4.1, 4.7,** table D1	1; VL 521, p. 6
06:40 3/30/1954	08:42 3/31/1954	sf2 sf2	EQ EQ		flat tilt			*M*6.03 foreshock; 3 aftershocks *M*6.45 mainshock, 17 as to 3/31	**4.5**	1, 2; VL 523, p. 7
4//1/1954	2/1/1955	ei1ler	EQS	~275				Precursors to 1955 eruption ~25/month, no date/time	**4.4**. D5	1, 3; VL 524, p. 10
03:42 5/31/1954	03:50 5/31/1954	ms1	EQS	7				Followed by 1 ms2 at 03:54	**4.1–4.4**, D5, 10	1, 4, 2; VL 524, p. 1–9
04:10 5/31/1954	03:00 6/3/1954	KC	E					1954 eruption in Kīlauea Caldera		
14:26 8/07/1954		ms4	EQ					*M*5.0, 25 km beneath Kīlauea Caldera	**4.1**	1; VL 525, p. 7
15:06 2/24/1955	22:30 2/24/1955	ei1ler	EQS	14				3 located; others no time	**4.1**	1; VL 527, p. 4–5
01:34 2/25/1955	22:10 2/25/1955	ei1ler	EQS	127				6 located; others no time	**4.1**	do
07:30 2/26/1955	18:56 2/26/1955	ei1ler	EQS	344				6 located; others no time	**4.1**	do
00:37 2/27/1955	23:12 2/27/1955	ei1ler	EQS	594				8 located; others no time	**4.1**	1, 3; VL 527, p. 4–5
07:45 2/28/1955	07:45 2/28/1955	ei1ler	EQS	691				2 located; others no time	**4.1, 4.4A–4.5**	3; VL 529–530, p. 1–10
08:00 2/28/1955	14:00 3/4/1955	LERZ	E					1955 eruption stage 1	**4.1, 4.4A–4.5**	
14:15 3/2/1955	06:00 3/7/1955		E					1955 eruption stage 2	do	do
12:39 3/5/1955	11:45 3/6/1955	ei2mer	EQS/I	23				*M*3.52-4.79 near Kalalua Crater	**4.1, 4.4*A***	do
22:21 3/7/1955	23:32 3/7/1955	sf2	EQS	4				*M*5.32, 3.95, 4.02, 4.00;	**4.1, 4.4*A***	1, 3; VL 527, p. 5–6
3/7/1955	3/30/1955				151.7	211		Summit def	**4.1, 4.4**	do
00:00 3/8/1955	23:59 3/8/1955	ei1ler	EQS	326				No time; 1 located at 20:03	**4.4**	do
00:00 3/9/1955	23:59 3/9/1955	ei1ler	EQS	601					do	
3/9/1955		sf2		2				09:16, 21:08, *M*3.5, 3.8		
00:00 3/10/1955	23:59 3/10/1955	ei1ler	EQS	1385				No time	do	do
00:00 3/11/1955	23:59 3/11/1955	ei1ler	EQS	76				No time	**4.4**	3; VL 527, p. 5–6
00:00 3/12/1955	23:59 3/12/1955	ei1ler	EQS	11				No time		1; VL 527, p. 5–6
17:05 3/12/1955	18:30 4/7/1955	LERZ	E					1955 eruption stage 3	**4.4–4.5**	1, 3; VL 527, p. 5–6
19:01 3/15/1955	19:02 3/15/1955	ms1	EQS	2				Initiation of summit subsidence	**4.1, 4.4**	1; VL 527, p. 5–6
00:00 3/16/1955	23:59 3/16/1955	ms1	EQS	21				No time	do	do
01:00 3/17/1955	13:35 3/17/1955	ms1	EQS	9				6 located; 3 unlocated eiler	do	do
09:54 3/18/1955	22:43 3/18/1955	ms1	EQS	48				3 located	do	do
00:00 3/20/1955	23:59 3/20/1955	ms1	EQS	6				1 located at 18:10	do	do
00:00 3/21/1955	23:59 3/21/1955	ms1	EQS	51				No times	do	do
00:00 3/22/1955	23:59 3/22/1955	ms1	EQS	52				No times; 2 eiler at 00:42, 20:46	do	do
00:00 3/23/1955	23:59 3/23/1955	ms1	EQS	324				2 at 00:10, 07:54	do	do

Table 4.1. Kīlauea eruptions, intrusions, earthquake swarms and earthquakes $M \geq 4$, 1953–1967.—Continued

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Time and Date		Region[1]	Event Type[2]	Number of events[3]	Tilt[4]		Lag[5]	Comment[6]	Figures[7]	References[8]
Start	End				Mag	Az				
3/23/1955	3/23/1955	ei1ler		3				3 at 02:06, 03:42, 12:08		
06:56 3/24/1955	10:27 3/24/1955	ms2		4						
23:26 3/24/1955	23:26 3/24/1955	ms3		1						
05:23 3/24/1955	11:02 3/24/1955	ei1ler		2						
04:27 3/25/1955	08:55 3/25/1955	ms1	EQS	590				8 located; 1 ms5 at 20:17	**4.1, 4.4**	1, 3; VL 527, p. 5–6
3/26/1955	3/26/1955	ms1	EQS	1103				No times	**4.1, 4.4**	1; VL 527, p. 5–6
3/27/1955	3/27/1955	ms1	EQS	482				1 at 09:23, 1 ms29 at 16:02	do	do
3/28/1955	3/28/1955	ms1	EQS	278				1 at 20:39	do	do
3/29/1955	3/29/1955	ms1	EQS	165				No time	do	do
3/30/1955	3/30/1955	ms1	EQS	111				End of summit subsidence	do	do
00:00 3/31/1955	23:59 3/31/1955	ms1	EQS	44				No time	do	do
04:24 4/1/1955		ms4	EQ					*M*5.1 at 30 km; *M*3.6 at 04:35	do	do
00:00 4/1/1955	23:59 4/1/1955	ms1	EQS	88				No time		
00:00 4/2/1955	23:59 4/2/1955	ms1	EQS	77				No time; 2 at 05:09, 06:37	do	1; VL 528, p. 5
00:00 4/3/1955	23:59 4/3/1955	ms1	EQS	10				End of intense ms1 EQS	do	do
13:28 4/4/1955	12:49 4/12/1955	ms1	EQS					8 located; intermittent activity to 6/1/1955		
01:27 4/07/1955		ms4	EQ					*M*4.25 at 30 km beneath Kīlauea Caldera	**4.1**	do
15:00 4/24/1955	11:15 5/26/1955	LERZ	E					1955 eruption stage 4; subsidence ended	**4.1, 4.4**	1, 3; VL 528, p. 5
02:28 8/14/1955		ms4	EQ					*M*5.84 at 25 km beneath Kīlauea Caldera Isoseismal map in Wyss and Koyanagi, 1992		1; VL 529–530, p. 12
10/1/1959	10/31/1959	ms1	EQS	12,543				Precusory swarm; 75-800 per day	**4.1, 4.4, 4.6**	10
11/1/1959	11/14/1959	ms1	EQS	12,323				Swarm continued; 90-2200 per day		
06:45 11/7/1959	07:53 11/7/1959	ms3	EQS	5				11/4, 6 2, 9, 13; 12.7-16.6 km depth	**4.6**	11
20:08 11/14/1959	08:00 12/20/1959	KI	E					Kīlauea Iki Crater eruption	**4.1-4.3, 4.6,** D6	7
20:08 11/14/1959	19:25 11/21/1959							Episode 1		
00:30 11/26/1959	16:35 11/26/1959	KI	E					Episode 2	do	do
16:30 11/28/1959	21:47 11/29/1959	KI	E					Episode 3	do	do
01:00 12/4/1959	09:27 12/5/1959	KI	E					Episode 4	do	do
14:40 12/6/1959	00:23 12/7/1959	KI	E					Episode 5	do	do
15:30 12/7/1959	02:45 12/8/1959	KI	E					Episode 6	do	do
13:00 12/8/1959	20:12 12/8/1959	KI	E					Episode 7	do	do
15:15 12/10/1959	11:40 12/11/1959	KI	E					Episode 8	do	do
10:07 12/12/1959	12/15/1959	ms5gln	EQS	56				Located; 43.57±2.24 km depth	do	do
05:08 12/13/1959	13:40 12/13/1959	KI	E					Episode 9	do	do
07:45 12/14/1959	15:36 12/14/1959	KI	E					Episode 10	**4.1, 4.6**	7
06:11 12/15/1959	10:25 12/15/1959	KI	E					Episode 11	do	do
19:30 12/15/1955	21:30 12/15/1959	KI	E					Episode 12	do	do
13:35 12/16/1959	17:19 12/16/1959	KI	E					Episode 13	do	do
11:10 12/17/1959	15:32 12/17/1959	KI	E					Episode 15	do	do

Table 4.1. Kīlauea eruptions, intrusions, earthquake swarms and earthquakes $M \geq 4$, 1953–1967.—Continued

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Time Date		Region[1]	Event Type[2]	Number of events[3]	Tilt[4]		Lag[5]	Comment[6]	Figures[7]	References[8]
Start	End				Mag	Az				
02:40 12/19/1959	06:16 12/19/1959	KI	E					Episode 16	do	do
20:45 12/19/1959	08:00 12/20/1959	KI	E					Episode 17	do	do
12/25/1959	12/31/1959	ei1ler	EQS	635				Increase from 5/ to 320/day	**4.6**	13
1/1/1960	1/7/1960	ei1ler	EQS	317				Decrease from 160 to 1/day	**4.6**	14
1/8/1960	1/13/1960	ei1ler	EQS	5100				Increase from 65 to 2,080/day	**4.6**	14
15:29 12/28/1959	17:32 1/12/1960	sf1/sf1os	EQS	8/9				South flank precursor to 1960 eruption; os, offshore	**4.6, 4.8b**	11
14:41 1/13/1960	20:13 1/13/1960	sf1/sf1os	EQS	2/10				Do; *M*4.13 at 16:30		
19:35 1/13/1960	14:00 2/19/1960	LERZ	E					Kapoho eruption	**4.6, 4.8,** D6	7
08:30 1/14/1960	08:30 1/21/1960				21.1	104		Summit subsidence Uwēkahuna tilt		
08:30 1/21/1960	08:30 1/26/1960				43.5	113		1/14-7/9/1960—Clockwise rotation		
08:30 1/26/1960	08:30 7/9/1960				299.8	127		1 arc-second = 4.848 microradians (μr)		
16:56 4/20/1960	08:32 4/22/1960	ms5gln	EQS	25				Continuation of pre-1959 swarms, now coincident with the beginning of 30 km deep swarms beneath Kīlauea Caldera	**4.1**, D6, 11	11
06:31 4/21/1960	09:03 4/22/1960	ms2	EQS	16				6 more on 5/27 (2), 6/7, 8, 7/6, 7		
10:31 4/21/1960	03:19 4/22/1960	ms4	EQS	10				3 more 5/8 2, 5/19		
21:26 4/21/1960	10:36 04/22/1960	ms3	EQS	4				First overlap ms5gln-ms4		
								Second overlap ms5gln-ms4	**4.1**, D6, 11	11
21:47 7/6/1960	01:13 7/8/1960	ms5gln	EQS	55				Continuation of pre-1959 swarms 40–60 km deep swarms; second overlap of ms5gin and ms4		
15:10 7/7/1960	13:53 7/8/1960	ms4	EQS	13				More events on 7/6 18:51, 19:11, 7/8-9 (4)		
17:17 7/8/1960	08:19 7/9/1960	ms5gln	EQS	13				1 more on 7/9 17:02		
02:32 10/5/1960	20:51 10/6/1960	ms5gln	EQS	64				End of pre-1959 40-60 km deep swarms	**4.1**, D6, 11	11
19:48 10/5/1960	03:52 10/6/1960	ms4	EQS	6				2 more on 10/6; last overlap ms5gln-ms4		
07:20 2/24/1961	15:08 2/24/1961	Hm[9]	E					Halema‘uma‘u Crater	**4.9**, D7	14
22:00 3/3/1961	20:00 3/25/1961	Hm[9]	E					Halema‘uma‘u Crater	**4.9**, D7	14
02:48 6/29/1961	02:45 6/30/1961	ms4	EQS	17				8 more on 6/30-7/3 (5), 7/9, 10, 14 (2)	**4.9**, D7, 19	11
20:15 7/10/1961	12:45 7/17/1961	Hm[9]	E					Halema‘uma‘u Crater	**4.9**, D7	14
04:19 7/23/1961	07:50 7/24/1961	ms4, 5	EQS	25				*M*4.07 on 7/23 05:24; 5 > 35 km deep	**4.9**, D7,20	11
13:17 9/21/1961	14:33 9/21/1961	sf3		4				South flank anticipation; 1 more on 9/22	**4.9**, D7	11
04:30 9/22/1961	05:00 9/25/1961	MERZ	E		173.6	136	-0h 54m	Heiheiahulu vicinity[10]	**4.9–10**, D12	11, 14
08:30 9/21/1961	08:30 9/22/1961				93.6	129				
08:30 9/22/1961	08:30 9/25/1961				72.6	143				
08:30 9/25/1961	08:30 10/1/1961				8.8	157				

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[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; data for eruptions and traditional intrusions emphasized with gray shading; do, ditto (same as above)]

Time Date Start	Time Date End	Region[1]	Event Type[2]	Number of events[3]	Tilt[4] Mag	Tilt[4] Az	Lag[5]	Comment[6]	Figures[7]	References[8]
19:29 9/24/1961	21:39 9/24/1961	sf2	EQS	11				*M*4.0, 4.32, 9/24 (2), 25, 26 (2), 27 (2)	**4.9**, D7	11
19:50 9/24/1961	21:14 9/24/1961	ei2mer		2				1 on 9/23	**4.9**, D7	11
16:29 11/23/1961	16:59 12/9/1961	ms4	EQS	48				Broken swarm; *M*4.19 12/2, 35.7 km	**4.9**, D7, 21	11
08:52 12/31/1961	23:21 12/31/1961	ms4	EQS	11				*M*4.10 28.34 km occurs as first EQ in swarm	D22	11
19:07 1/1/1962	16:19 1/3/1962	ms4	EQS	6				Broken swarm; diminished deep seismicity	D22	11
21:04 5/9/1962	06:37 5/11/1962	ms4.5	EQS	14					D23	11
19:11 12/6/1962	23:57 12/8/1962	sf3	EQS	10				South flank anticipation/response	**4.9**, D8	11
01:10 12/6/1962	15:00 12/9/1962	UERZ	E		20.5	130	-3h 20m	Aloi Crater; tilt 12/6–7	**4.9–10**, D8, 13	19
19: 31 12/6/1962	21:26 12/7/1962	koae	EQS	4				Koa‘e response		
07:13 12/7/1962	19:56 12/8/1962	sf2	EQS	7				South flank response		
13:12 12/10/1962	13:18 12/17/1962	sf3.4	EQS	12				South flank response shift to west		
07:56 1/8/1963	15:55 1/8/1963	ms4.5	EQS	10				*M*4.46, *M*4.11; 1/9 (3), 10, 11 (2), 12	**4.9**, D24	11
20:54 5/9/1963	20:01 5/12/1963	sf3	EQS	114				South flank anticipation/response; 5/13 (4)	43.21	8, 22
21:19 5/9/1963	19:32 5/11/1963	koae	I	62	35.0	126	-2h 56m	Koa‘e crisis; er3 on 5/10 (3), 11, 12; tilt 5/8–12		11, 15
23:51 5/9/1963	08:04 5/11/1963	sf4	EQS	5				Broken swarm		
04:31 5/10/1963	16:49 5/12/1963	ei4.5	I	5				Scattered	**4.9**, 11a	
03:56 5/12/1963	19:51 5/12/1963	koae	EQS	7				Continued tilting within the Koa‘e		
06:06 7/2/1963	08:04 74/1963	sf3	EQS	11				South flank anticipation/response	43.21	22
07:15 7/2/1963	06:38 7/31963	koae	EQS/I	15	19.0	122	-1h 55m[11]	Koa‘e crisis; tilt 7/1-2	**4.9**, 11b, D8	11
05:04 7/4/1963	20:32 7/4/1963	koae	EQS/I	8				Koa‘e crisis continued; tilting within the Koa‘e		
08:39 7/4/1963	16:56 7/4/1963	ei3kuer	EQS	3				East rift response		
17:01 7/4/1963	20:06 7/4/1963	sf3	EQS	3				South flank response continued		
18:15 8/21/1963	08:10 8/23/1963	MERZ	E		11.5	112	-0h 4m[12]	‘Alae Crater: lava lake; tilt 8/20–22	**4.9**, D8, 14	17
03:32 10/5/1963	05:44 10/5/1963	sf2/sf3	EQS	9/3				South flank anticipation/response		11
05:25 10/5/1963	10:00 10/6/1963	MERZ	E		75.7	121	-0h 4m[13]	Nāpau Crater; tilt 10/4-7, clockwise rotation	43.23; **4.9–10**	22, 18
20:43 10/5/1963	21:40 10/5/1963	koae	EQS	3				2 more on 10/6, 7	D8, 15	
00:38 10/6/1963	13:04 10/8/1963	sf2	EQS	25				South flank response		
04:06 10/6/1963	23:10 10/8/1963	ei2mer	EQS	7				East rift response; scattered; 10/6 (3), 7, 8 (3)		
21:47 10/6/1963	22:21 10/7/1963	sf3	EQS	15				South flank response continued		
08:35 10/8/1963	03:15 10/9/1963	sf3	EQS	7				South flank response continued		
18:45 10/9/1963	14:49 10/22/1963	sf3/sf2	EQS	18/7				South flank response continued		
22:29 12/2/1964	02:18 12/3/1964	ms4	EQS	12				*M*4.45; as on 12/3, 4 (4), 6 (2)	**4.9**, D25	11
09:16 3/5/1965	17:56 3/5/1965	sf2	EQS	8				South flank anticipation/response	**4.9**, D9	11
09:23 3/5/1965	23:00 3/15/1965	MERZ	E		87.8	128	-0h 28m[14]	Makaopuhi Crater: lava lake; tilt 3/5-9	43.24; D16	22, 19
18:50 3/5/1965	06:22 3/7/1965	sf3	EQS	6				South flank response; broken swarm		
13:06 3/6/1965	19:03 3/8/1965	sf2	EQS	18				South flank response continued; broken swarm		
23:53 8/21/1965	9:46 8/26/1965	sf3	EQS	9	3.4	122		Broken swarm; tilt 8/23–25	43.25; **4.9, 4.12**	22, 11

Table 4.1. Kīlauea eruptions, intrusions, earthquake swarms and earthquakes $M \geq 4$, 1953–1967.—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above).]

Time Date Start	Time Date End	Region[1]	Event Type[2]	Number of events[3]	Tilt[4] Mag	Tilt[4] Az	Lag[5]	Comment[6]	Figures[7]	References[8]
00:15 8/25/1965	12:58 8/25/1965	sf2	SDI	32				Also 8/23, 24; first suspected deep intrusion	D9	
22:35 8/25/1965	13:25 8/26/1965	sf2	SDI	5				8/26 (10), 27 (2), 28 (2), 30, 9/1 (2), 2 (2)		
00:31 8/25/1965	06:02 8/26/1965	ei2mer	I	4	3.4	121	+46h	I-A: 4 μrad deflation 8/23 02:11-8/26 08:34		
07:29 11/13/1965	18:21 11/13/1965	sf3	SDI	7				Additional earthquakes on 11/12 (3), 14 (2)		
13:04 12/25/1965	06:52 12/30/1965	sf3[15]	EQS	175				South flank anticipation/response	D9	21
13:53 12/25/1965	06:39 12/30/1965	koae	I	131				Koa‘e: tilting and ground cracking		21
21:30 12/24/1965	05:30 12/25/1965	UERZ	E		47.8	98	-0h 1m	Aloi Crater; tilt 12/23-28[16]	**4.2**; D9, 17	20, 11
11:18 12/28/1965	03:04 12/29/1965	sf3	EQS	7				USGS locations; south flank response		
11:35 12/28/1965	12:21 12/30/1965	koae	EQS	4				do; scattered		
15:16 12/28/1965	16:18 12/28/1965	sf4[15]	EQS	3				do; 12/25 (6), 26 (2), 27 (2), 28		
17:57 7/5/1966	01:34 7/6/1966	sf3	SDI?	6				Broken swarm	**4.9, 4.12**; 43.26	11, 22
23:52 7/5/1966	13:25 7/6/1966	sf2	SDI?	6						
23:59 7/5/1966	01:12 7/6/1966	ei3kuer	I?	4	3.9	132	+22h	I-A: sharp def of 3 μrad on 7/4-6		

[1]Earthquake classification abbreviations are given according to the classification in table A3A, and locations are shown on figure A4. Eruption location abbreviations correspond to regions shown on chapter 1, figure 1.1*A*; **KC**, Kīlauea Caldera; **SWR**, Southwest rift zone; **UERZ**, upper East rift zone, **MERZ**, middle East rift zone, **LERZ**, lower East rift zone; **KI**, Kīlauea Iki Crater.

[2]Event type abbreviations: **E**, Eruption; **I**, traditional intrusion; SDI, suspected deep intrusion; EQ, Earthquake $\geq M5$; EQS, Earthquake swarm.

[3]Minimum number of events defining a swarm: 5 for south flank; 3 for all other regions (see appendix table A3).

[4]Magnitude in microradians and azimuth of daily tilt measurements from the Bosch-Omori tiltmeter in Whitney Vault (1953–1957); water-tube tiltmeter in Uwēkahuna vault (1957–1967). 1 second of arc = 4.848 microradians (μrad).

[5]Lag times compare onset of tilt deflection and the beginning of an eruption or earthquake swarm. (+) tilt leads, (-) tilt lags. Readings from Press-Ewing seismometer in Uwēkahuna Vault in plain text, **bold** across eruptions; readings from Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault in *italic* text, ***bold/italic*** across eruptions.

[6]Abbreviations as follows: *M*, earthquake magnitude; fs, foreshock; as, aftershock; ant, anticipation; resp, response; inf, inflation; def, deflation; cw, clockwise; ccw, counterclockwise.

[7]Text figures **bold** text; Appendix figures plain text; 43.xx = figures in Klein and others, 1987

[8]Reference codes (for all tables in the report) as follows: 1; Klein and Wright, 2000, additional references given, 2; Macdonald and Eaton, 1957, 3; Macdonald and Eaton, 1964, 4; 8Macdonald and Eaton, 1954, 5; Macdonald and Eaton, 1956, 7: Richter and others, 1970, 8; Eaton and Fraser, 1957, 9; Eaton and Fraser, 1957, 10; HVO, unpub., 11; HVO seismic catalog, 12; Nakata, 2007, 13; Nakata, 2007, 14; Richter and others, 1964, 15; Kinoshita, 1967, 16; Peck and Kinoshita, 1976, 17; Moore and Koyanagi, 1969, 18; Moore and Krivoy, 1964, 19; Wright and others, 1968, 20; Fiske and Koyanagi, 1968, 21; Bosher, 1981, 22; Klein and others, 1987.

[9]Seismic summaries missing for six quarters between 4/1/1960-10/1/1961. Larger earthquakes were located by hand. There is no located seismicity for the three Halema‘uma‘u eruptions.

[10]Graben formed during eruption; tilt vectors in this row record the total deflationary tilt; the three succeeding rows record a clockwise rotation during deflation.

[11]Tremor and earthquake counts begin at 7/1 21:50, nearly 11 hours before first located earthquake—tilt lag calculated from the earlier time.

[12]Earthquake counts and tremor begin at 13:46 8/21/1963; tilt lag calculated from that time.

[13]Earthquake counts and tremor begin at 03:16 10/5/1963; tilt lag calculated from that time.

[14]Earthquake counts and tremor begin at 08:02 3/5/1965; tilt lag calculated from that time.

[15]Data from Bosher MS thesis cited in Bosher, 1985.

[16]Earthquake counts and tremor begin at 19:29 12/24/1965; tilt lag calculated from that time.

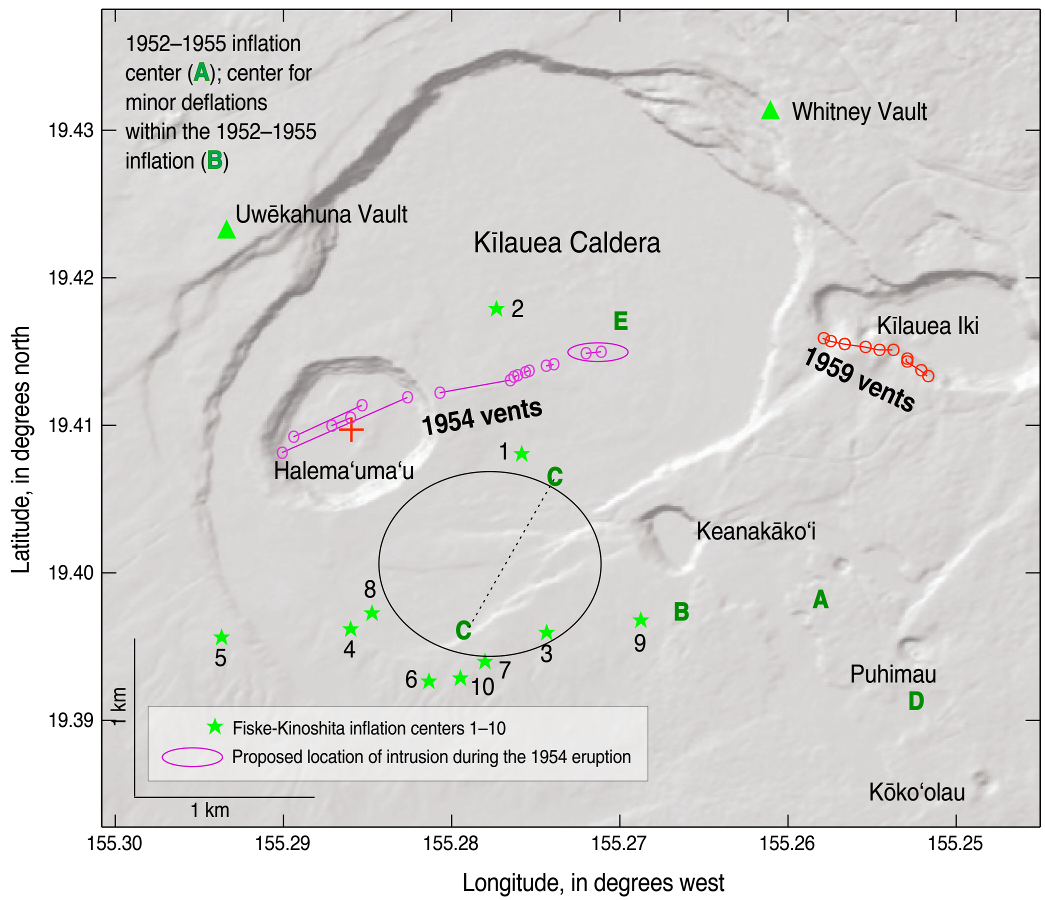


Figure 4.2. Map of Kīlauea activity, 1952–1959. Location of centers of inflation/deflation shown as dark green capital letters. Deformation centers determined from Whitney tilt azimuths are shown for: A, The center of inflation between 27 June 1952 and 27 February 1955 estimated from the tilt azimuth from Whitney to be between Halemaʻumaʻu and the east rift zone. B, Centers of small deflations within deflation period A estimated in the same way as for A and located near the eastern boundary of the Fiske-Kinoshita array. Location of the 1954 vents (small circles) and the oval surrounding the presumed 1954 summit intrusion are shown in purple. Vents for the 1959 eruption are shown as red circles. Fiske-Kinoshita centers of inflation are shown as light green stars, and upper east rift craters are labeled. C, Net deflation between the beginnings of the 1955 and 1959 eruptions. D, The major deflation accompanying and following the 1955 eruption. E, Inflation on the first day of the 1959 eruption. Tilt vectors are given in appendix D, table D3. Deflation center B lies east of the Fiske-Kinoshita array, C lies within the array, and A lies within the upper east rift zone. The black oval outlines the extent of deformation centers determined from the long-base watertube tilt network shown in appendix I, figure I5 . See text for further discussion.

Kīlauea's summit began 2 days after the intrusion. The intrusion triggered a strong south flank response, including a *M*5.3 flank earthquake later the same day (fig. 4.4).

The Eruptions of 1959 and 1960

The 1959 eruption in Kīlauea Iki was unusual for (1) its episodic eruption style, with 17 episodes (table 4.1, fig. 4.6), most lasting less than 24 hours, (2) fountains higher than seen in Hawaiʻi before or since (Richter and others, 1970), and (3) its hybrid chemistry (Wright, 1973). The eruption filled Kīlauea Iki Crater to a depth of about 110 m, forming the first of several "passive" lava lakes[16] formed during eruption (Helz, 1993). Subsequent drilling of the lava lake showed the lake to be considerably deeper than originally estimated, indicating a syneruption collapse of the crater floor amounting to more than 30 m (Helz, 1993, p. 12–14, figure 4).

Precursory to the 1959 eruption was the occurrence of deep earthquake swarms at 40–60 km depth located north of Kīlauea Caldera (fig. 4.7). Such swarms were first documented in September 1953 (fig. 4.7; Klein and Wright, 2000). These deep swarms were considered to be related to magma movement from a source region in the mantle (Eaton, 1962, p. 21; J.P. Eaton, unpub. data).

The 1959 erupted products were composed of mixtures of two kinds of magma defined by samples

[16] A passive lava lake is one formed during filling of a pit crater. The filling ends when the eruption ends. Active lava lakes are those within a pit crater or at the top of a shield that are connected to the feeding source and thus continuously filled from below.

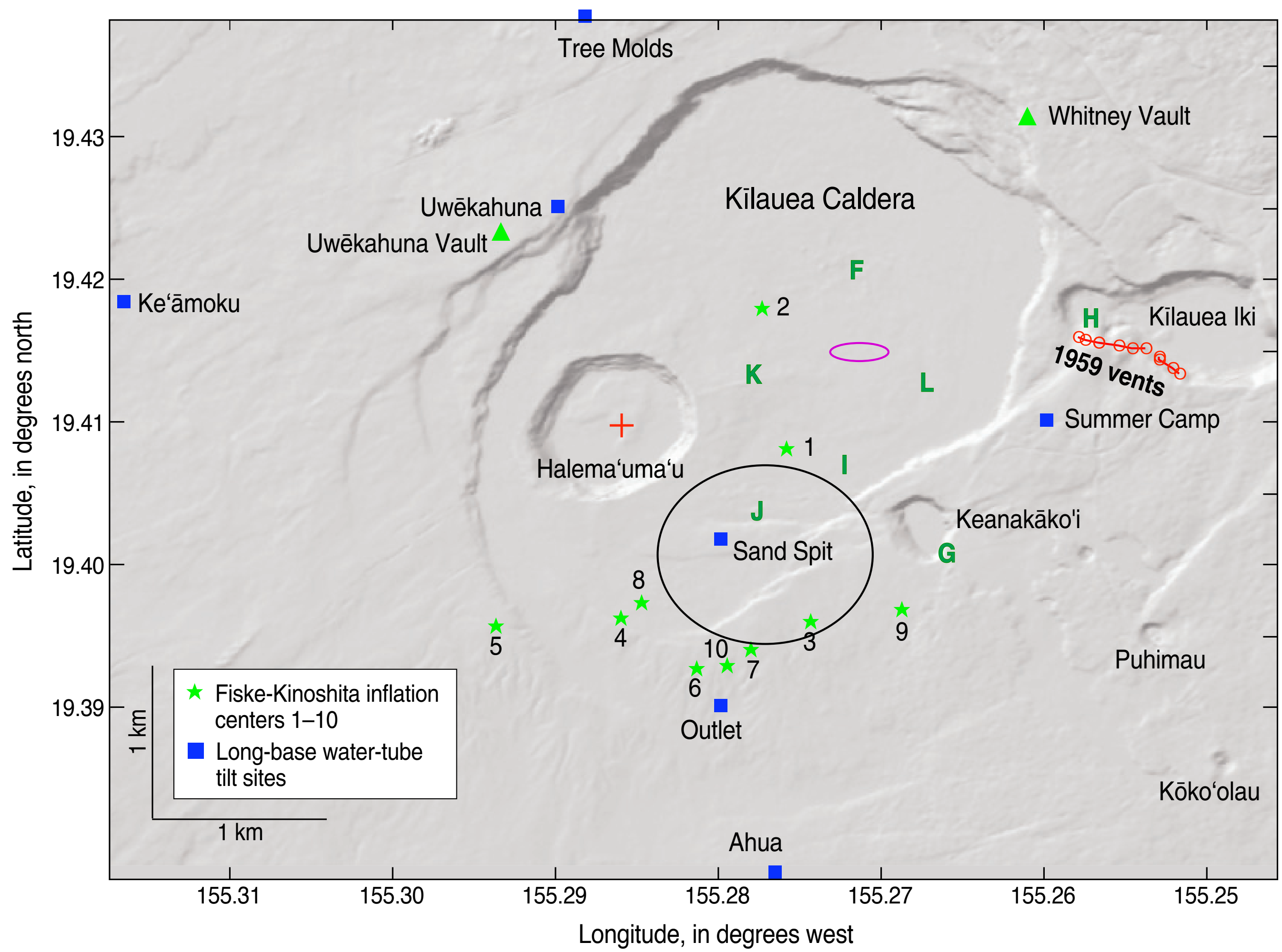


Figure 4.3. Map of Kīlauea activity, 1959–1960. Locations of centers of inflation/deflation are shown as dark green capital letters and continue the sequence begun in figure 4.2. The small purple oval indicates the area of the 1954 intrusion from figure 4.2. Deformation centers, unless otherwise indicated, are determined from the intersection of tilt vectors from Whitney and Uwēkahuna. (F) Deflation during episode 1 of the 1959 eruption followed by (G) inflation between episode 1 and the beginning of the 1960 eruption. Locations F and G are determined from intersection of tilt vectors from Uwēkahuna and Whitney Vaults (see appendix A). (H) Deflation during 21–24 November 1959 at the end of episode 1 recorded at Whitney Vault only. Using the Whitney azimuth, center H is placed at the west end of Kīlauea Iki and records the collapse of the crater at the end of episode 1. See text for further explanation. The center of deflation during the 1960 eruption is determined from (I) the intersection of tilt vectors from Uwēkahuna and Whitney Vaults, (J) the intersection of azimuths from the array of long-base water-tube tiltmeters, and (K) unpublished leveling data (appendix I, fig. I3; J.P. Eaton, written commun., 1999). Deflation most likely occurred near Fiske-Kinoshita center 1 and within the region defined by the three estimates I, J, and K. The scattering of these deflation center estimates (an area comparable to the size of Halema'uma'u) is an estimate of the minimum error in each location determination. (L) Post-1960 inflation, as defined by intersection of azimuths of short-base tiltmeters located at Uwēkahuna and Whitney Vaults, still lies east of the Fiske-Kinoshita array. Tilt vectors are given in appendix D, table D3. The black oval covers deformation centers determined from the long-base water-tube tilt network. See text for further discussion.

collected at the east and west ends of the initial line of erupting vents in episode 1[17]. The sample collected at the western end closer to the caldera (variant 1) had few olivine phenocrysts and a composition identical to that of magma erupted within Halemaʻumaʻu and Kīlauea Caldera in 1954. The sample at the eastern end (variant 2) had an unusual composition unmatched, for example, in its high ratio of CaO to MgO, by any other historical Kīlauea eruption. The eruption products also contained abundant phenocrysts of deformed and twinned olivine, indicating an origin considerably deeper than other Kīlauea eruptions (Helz, 1987). Products of subsequent episodes had chemistry that could be modeled as mixtures of variants 1 and 2 with varying amounts of additional olivine (Wright, 1973). Variant 2 is interpreted as related to the deep earthquake swarms originating north of the caldera as described above. Variant 2 later found its way into the east rift, where it was identified as a mixing component in hybrid lavas from the latter part of the 1960 eruption (Wright and Helz, 1996).

From 17 January through 19 February 1960 Kīlauea erupted again in the lower east rift zone to the east of the vents of the 1955 eruption (fig. 4.6; Richter and others, 1970). Lavas from this eruption destroyed the village of Kapoho. Precursory seismicity included many earthquakes beneath the south flank southeast of the 1960 vents, as well as shallow earthquakes beneath the eventual eruption site (fig. 4.8). Seismic network coverage of this eruption in this area was poor. The shallow earthquakes below the eruption site ended as the eruption began, because stress was relieved when magma escaped to the surface. As in 1955, the 1960 collapse of Kīlauea's summit occurred after a time delay, 4 days (instead of 8, as in 1955) following the beginning of eruption (fig. 4.6). The succeeding summit earthquake swarm also developed 8 days later, similar to the delay in 1955. The summit subsidence was the largest observed in the post-1924 tilt record and extended into midsummer of 1960.

During the period of maximum deflation, there was a dramatic collapse of Halemaʻumaʻu Crater itself, described in detail in the narrative report of the two eruptions (Richter and others, 1970, p. E68–E73, figures 76–81). The 1960 collapse of Halemaʻumaʻu took place in three stages, on 7 and 9 February and 11 March 1960 (fig. 4.6). During the first stage, the lava lake emplaced in 1952 first drained and then, as collapse proceeded, some of the 1952 lava was reextruded on the crater floor. The 7 February 1960 collapse was accompanied by a plume of explosively pulverized rock, and there was considerable apprehension that the collapse might develop into a major phreatic eruption, such as occurred in 1924. The second collapse, on 9 February, was heralded by a felt earthquake at shallow depth beneath Kīlauea Caldera and was succeeded by more felt earthquakes, some of which were located in the adjacent Koaʻe fault system and south flank (fig. 4.8). The third collapse, on 11 March, was again accompanied by a plume of dust but was otherwise uneventful. Fortunately the 1924 experience was not repeated[18].

Deep (45–55 km) earthquake swarms north of Kīlauea Caldera continued beyond the end of the 1960 eruption, the last one being recorded in October 1960. During this time interval earthquake swarms at 20–35 km depth began, marking a transition to frequent earthquake swarms at that depth beneath Kīlauea Caldera beginning in 1961 (fig. 4.9). The 1960 earthquake swarms shallower than 35 km are still north of the caldera, but with locations closer to the caldera than the earthquakes deeper than 35 km.

The Eruptions of 1961 Through 1965

The 1960 eruption was followed by three short eruptions in Halemaʻumaʻu (table 4.1, fig. 4.9), in turn followed by a series of six eruptions on the east rift zone without intervening summit activity (Fiske and Koyanagi, 1968; Moore and Koyanagi, 1969; Moore and Krivoy, 1964; Peck and Kinoshita, 1976; Richter and others, 1964; Wright and others, 1968). Vents for the east rift eruptions are shown in figure 4.10. Earthquake swarms at 20–35 km depth beneath Kīlauea Caldera also continued in 1961 and extended through and beyond 1965 at decreasing frequency and intensity (fig. 4.9).

No earthquakes associated with the 1961 summit activity were documented because they fall within the gap from 1 April 1960 to 1 October 1961, when no seismic summaries were published and no data for earthquakes with magnitudes less than 2 were recorded with information sufficient for later processing (J. Nakata, oral commun., 1992). The September 1961 rift eruption was preceded by an intense swarm of felt earthquakes originating near Nāpau Crater (fig. 4.9; see also Richter and others, 1964, p. D19). The larger events were located from unpublished seismic data that fell within the seismic summary gap mentioned above.

Intrusions into the eastern end of the Koaʻe Fault Zone (Klein and others, 1987) accompanied eruptions in December 1962, October 1963, and December 1965 (fig. 4.9). Koaʻe intrusions without eruption also occurred in May (figs. 4.9, 4.11*A*; Kinoshita, 1967) and July 1963 (figs. 4.9, 4.11*B*).

Suspected deep intrusions occurred in August and November 1965 and July 1966 (Fig. 4.12). From 25 February 1962 to 2 April 1963 similar small swarms of earthquakes were detected from the eastern south flank and were labeled "KT" (for

[17] Referred to colloquially as a "curtain of fire."

[18] Because the smaller summit collapses in the decades after 1960 did not cause a Halemaʻumaʻu floor collapse, we infer that summit caldera elevation drops of a meter or less can be sustained without completely evacuating magma from under Halemaʻumaʻu.

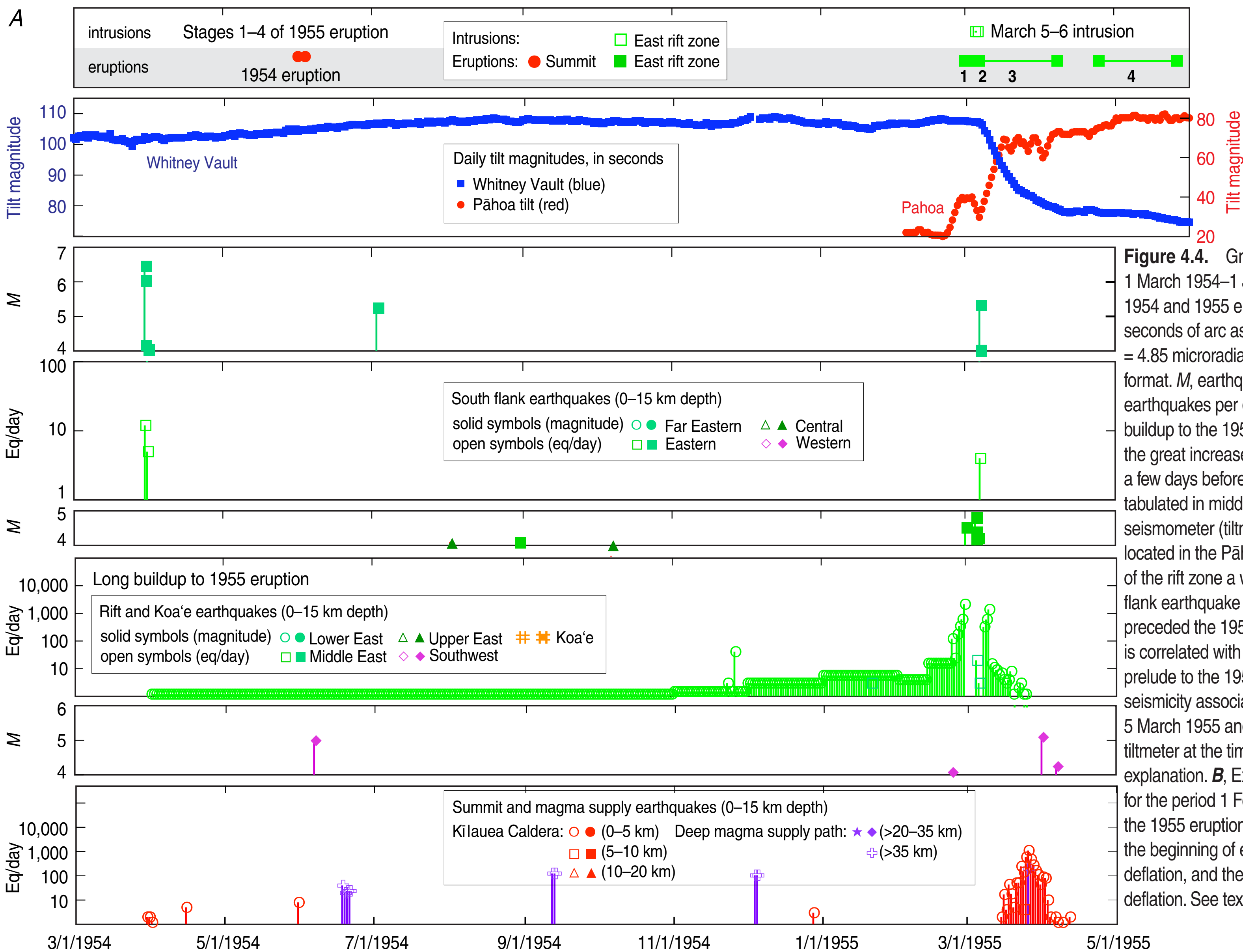
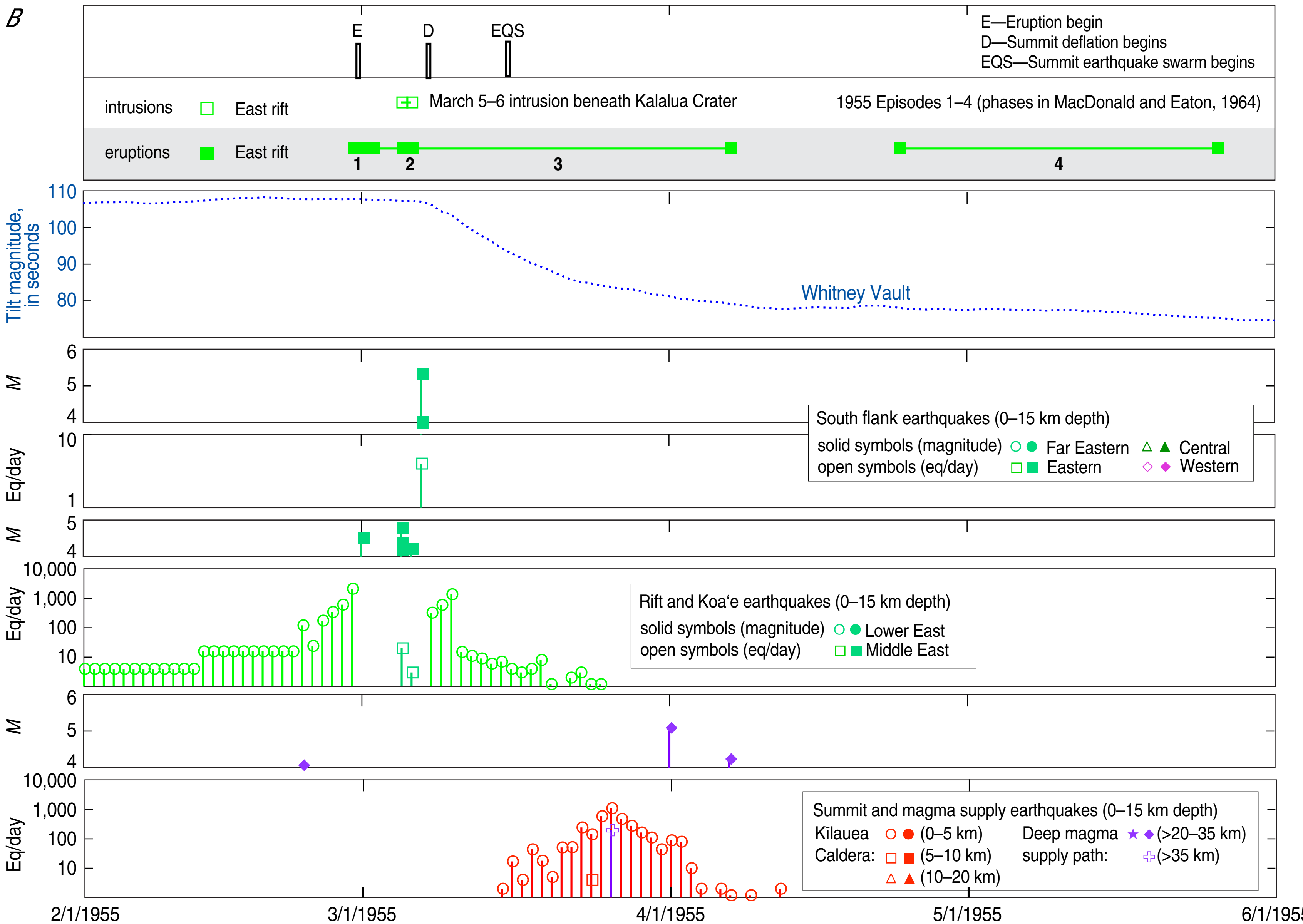


Figure 4.4. Graphs showing Kīlauea activity, 1 March 1954–1 June 1955. Seismic data for the 1954 and 1955 eruptions. Tilt magnitude shown in seconds of arc as originally reported. 1 arc-second = 4.85 microradians. Dates on figure in m/d/yyyy format. *M*, earthquake magnitude. ***A***, Number of earthquakes per day (eq/day), showing the long buildup to the 1955 lower east rift eruption and the great increase in lower east rift earthquakes a few days before the eruption (earthquakes not tabulated in middle of intense swarm). A pendulum seismometer (tiltmeter) oriented north-south, located in the Pāhoa School shows sharp inflation of the rift zone a week before the eruption. A south flank earthquake of *M*6.5 with a strong foreshock preceded the 1954 eruption by several months and is correlated with the beginning of the long seismic prelude to the 1955 eruption. Also shown is the seismicity associated with the Kalalua intrusion of 5 March 1955 and deflation recorded on the Pāhoa tiltmeter at the time of intrusion. See text for further explanation. ***B***, Expanded record of seismicity and tilt for the period 1 February to 1 June 1955, including the 1955 eruption, showing the time delays between the beginning of eruption, the beginning of summit deflation, and the earthquake swarm accompanying deflation. See text for further explanation.


B
E
D
EQS
E—Eruption begin
D—Summit deflation begins
EQS—Summit earthquake swarm begins
intrusions
East rift
March 5–6 intrusion beneath Kalalua Crater
1955 Episodes 1–4 (phases in MacDonald and Eaton, 1964)
eruptions
East rift
1
2
3
4
Tilt magnitude, in seconds
110
100
90
80
Whitney Vault
M
6
5
4
Eq/day
10
1
South flank earthquakes (0–15 km depth)
solid symbols (magnitude)
open symbols (eq/day)
Far Eastern
Eastern
Central
Western
M
5
4
Eq/day
10,000
1,000
100
10
Rift and Koa‘e earthquakes (0–15 km depth)
solid symbols (magnitude)
open symbols (eq/day)
Lower East
Middle East
M
6
5
4
Eq/day
10,000
1,000
100
10
Summit and magma supply earthquakes (0–15 km depth)
Kīlauea Caldera:
(0–5 km)
(5–10 km)
(10–20 km)
Deep magma supply path:
(>20–35 km)
(>35 km)
2/1/1955
3/1/1955
4/1/1955
5/1/1955
6/1/1955

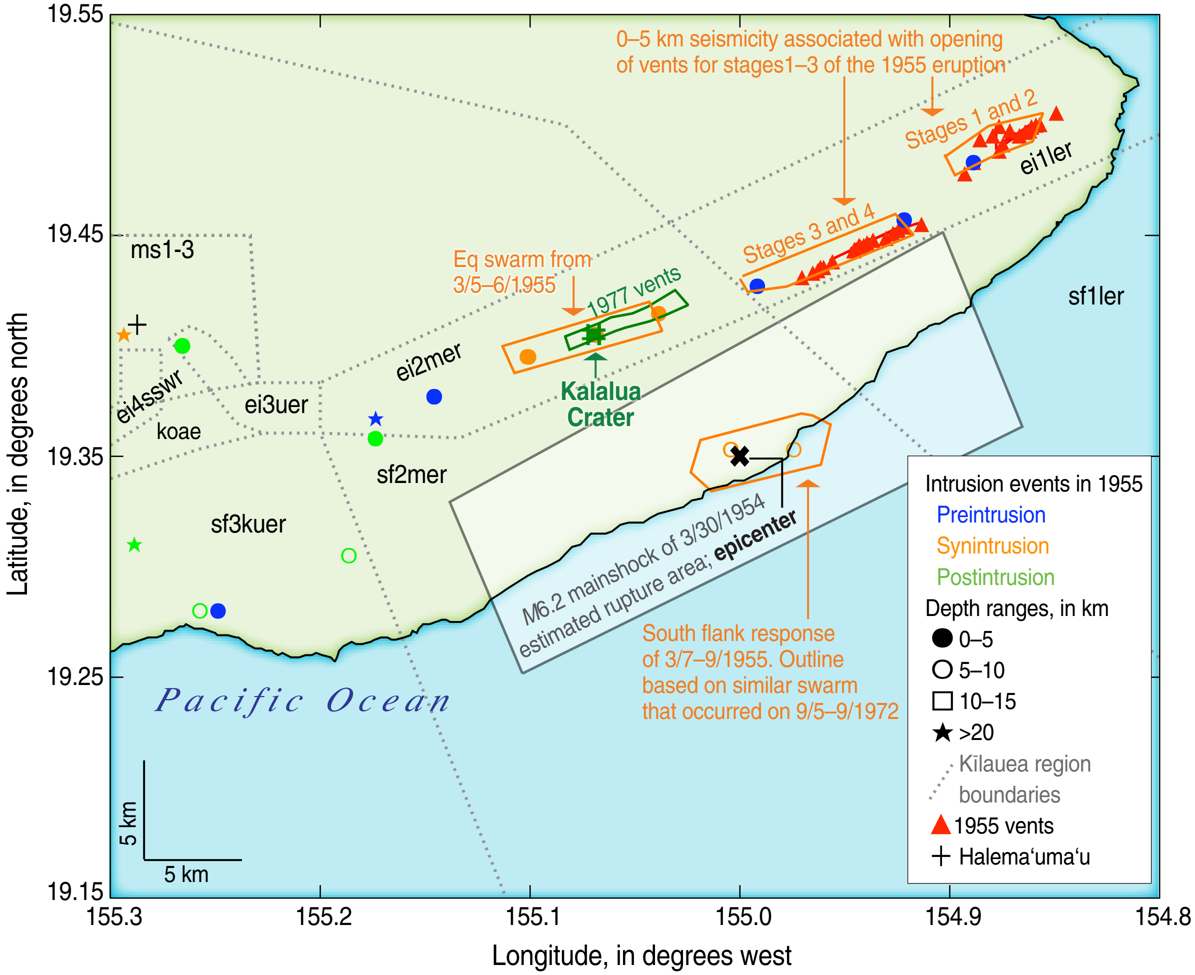


Figure 4.5. Map showing locations of earthquakes (circles and dots) associated with the 1955 Kīlauea lower east rift eruption and Kalalua intrusion. Vents for that eruption are shown as solid red triangles and three rift and one south flank swarms are approximately outlined in orange. Shown for comparison is the area of the 1977 vents. A parent magma for fractionated lavas erupted in 1977 is inferred to correspond to magma emplaced in the 1955 Kalalua intrusion. The south flank region activated in response to the March 1955 Kalalua intrusion is compared with the estimated rupture zone of the 30 March 1954 south flank earthquake. Dates on figure in m/d/yyyy format.

Kalapana Trail) in the HVO seismic summaries (Koyanagi and others, 1963; Krivoy and others, 1964; Okamura and others, 1963, 1964). The earthquakes were all assigned to a single approximate location listed in the HVO seismic summaries and shown in figure 4.12.

Interpretations 1952–1967

Events of this period, bracketed by the 1952 and 1967–68 eruptions in Halemaʻumaʻu Crater, can be better interpreted than was possible for the events in the preceding period because of (1) the expansion of seismic and ground deformation networks and (2) the acquisition of high-quality chemical data for every eruption. The relative timing of earthquake swarms and summit tilt deflections relative to the beginning of eruption and intrusion can now be calculated for this period, as can magma supply rates and eruption efficiencies for the intervals separating eruptions and intrusions. Petrologic study has established that magmas erupted at Kīlauea's summit enter the summit reservoir in their order of eruption and move through the rift plumbing to (1) serve as parents for fractionated lavas and (2) appear as components of mixed magma eruptions (Helz and Wright, 1992; Wright and Fiske, 1971; Wright and Helz, 1996; Wright and others, 1975; Wright and Tilling, 1980). Compositional differences among the summit magmas are small, but they can be clearly discriminated using petrologic mixing calculations (Wright and Fiske, 1971). It is evident that these "magma batches" retain both their chemical identity and low phenocryst content as they move through the Kīlauea plumbing, as shown in figure 4.13. In this section we interpret each eruption in terms of patterns of seismicity (figs. 4.1, 4.9), ground

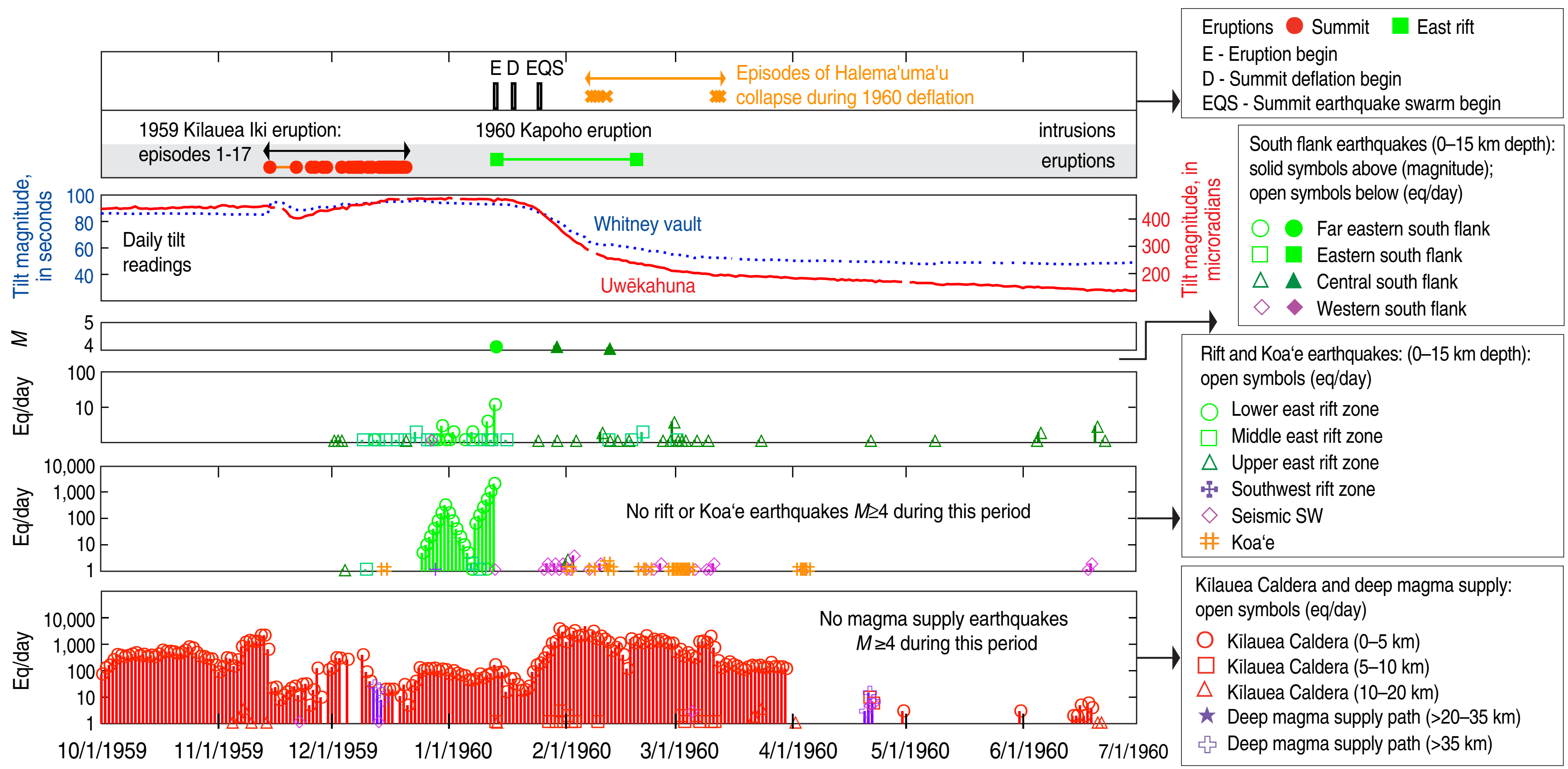


Figure 4.6. Graphs showing seismicity and tilt changes associated with the 1959 Kīlauea Iki and 1960 Kapoho eruptions. Earthquake counts and earthquakes of *M*>4 are shown for all regions and compared with eruption times and tilt changes measured at both the Uwēkahuna and Whitney Vaults. The 1959 eruption in Kīlauea Iki Crater had 17 short episodes. The mismatch between the Whitney and Uwēkahuna tilt reflects a late surge of magma to shallow depth beneath Kīlauea Iki and a later syneruption collapse of the crater floor, both evident only on the Whitney instrument. See text for further explanation. The 1960 eruption shows similar but shorter delays separating the beginning of eruption, summit collapse, and summit earthquake swarm compared to the 1955 sequence shown in figure 4.4*B*. Earthquake swarms at 40-60 km depth north of Kīlauea Caldera continued through both eruptions. Unlike the 1955 eruption and more similar to later rift eruptions, south flank earthquakes occur as a precursor to and, to a lesser extent, as a delayed response to the 1960 eruption. Dates on figure in m/d/yyyy format.

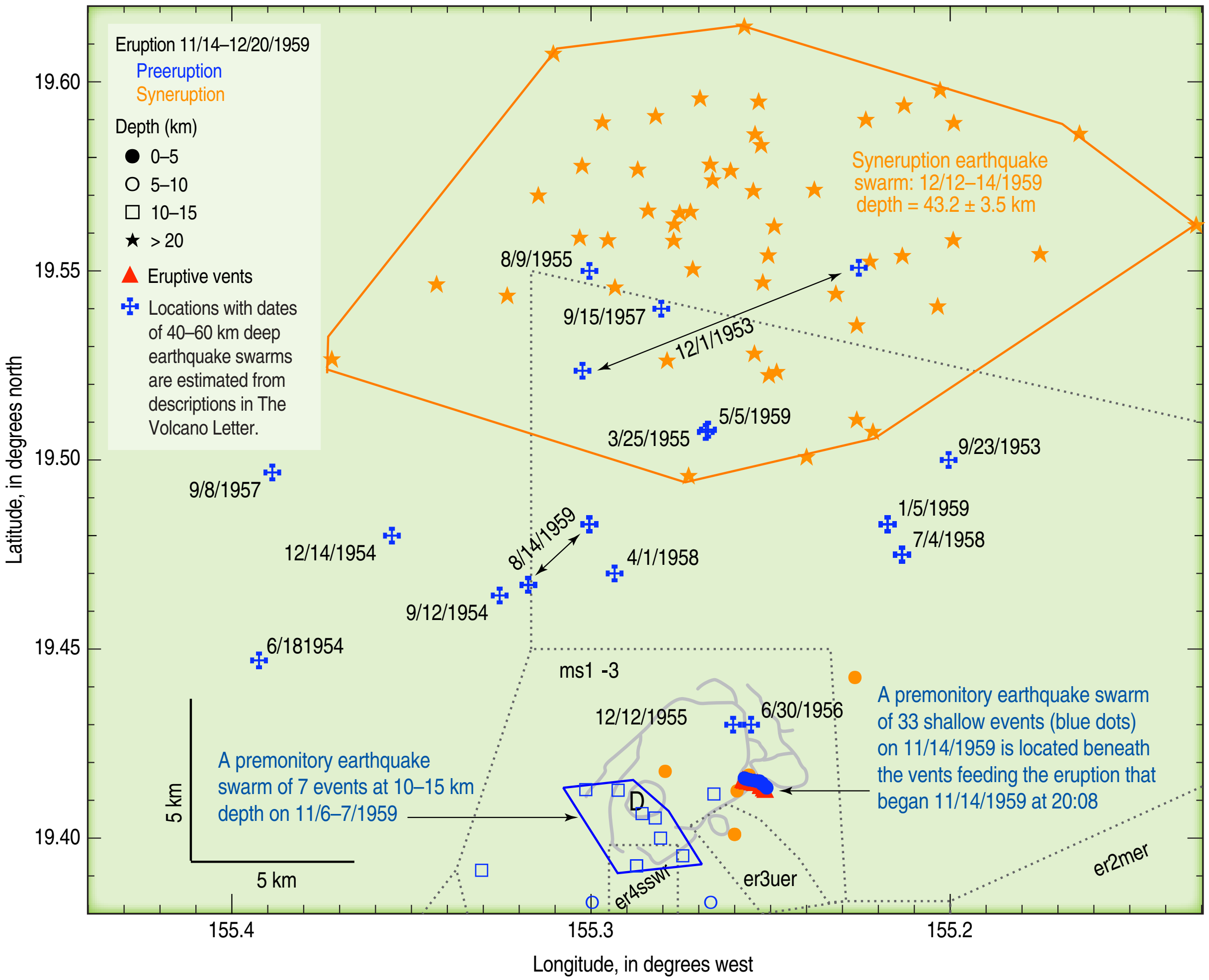


Figure 4.7. Map showing locations of earthquakes associated with the 1959 Kīlauea Iki eruption. Most swarms before December 1959 were reported as consisting of several hundred events at depths of 40–60 km, only approximately located by hand as less than 10 km north (toward Mauna Loa) from the Uwēkahuna seismometer. The orange polygon outlines the computer-located deep earthquake swarm of 12–14 December 1959 and is a likely representation of the spread of epicenters for the larger swarms before 1 October 1959 that are labelled with the date of the swarm next to a blue cross. Dates on figure in m/d/yyyy format.

deformation, and eruption chemistry for the entire sequence of eruptions and intrusions. A quantitative evaluation of where magma is stored beneath Kīlauea's summit and how it moves into the east rift plumbing is given in chapter 8.

1954 Eruption and Intrusion

The 1954 eruption differed from eruptions before and after. Between 1952 and 1955, the upper east rift zone inflated, suggested by the azimuth of the Whitney Vault tilt vector pointing east of the pre-1967 array of inflation centers (fig. 4.2; location "A" assumed). Inflation of the upper east rift zone contrasted with the summit inflation preceding the 1952 eruption, and with post-1960 inflations and deflations (table 4.1). Minor deflations within the overall 1952–55 inflation also lie east of the principal center of inflation and deflation (fig. 4.2; location "B" assumed). The line of 1954 vents extends within the caldera to a point north of Keanakāko'i (location "E" in fig. 4.2).

The relation of the 1954 magma to the Kīlauea plumbing is problematic. The eruption was of small volume, and the magma does not appear as a mixing component of any subsequent rift eruptions (see, for example, Wright and Fiske, 1971). It is possible that the eruption was fed from the postulated shallow intrusion at the eastern end of the line of vents, which may have been emplaced at the top of a path from the mantle closer to the east rift zone that bypassed the reservoir feeding the larger Halema'uma'u eruptions (fig. 4.13*C*). The line of vents on the caldera floor opened minutes after the fountaining in Halema'uma'u (Macdonald and Eaton, 1954), but the initiation of eruption in Halema'uma'u may have been because the floor of Halema'uma'u was lower in altitude.

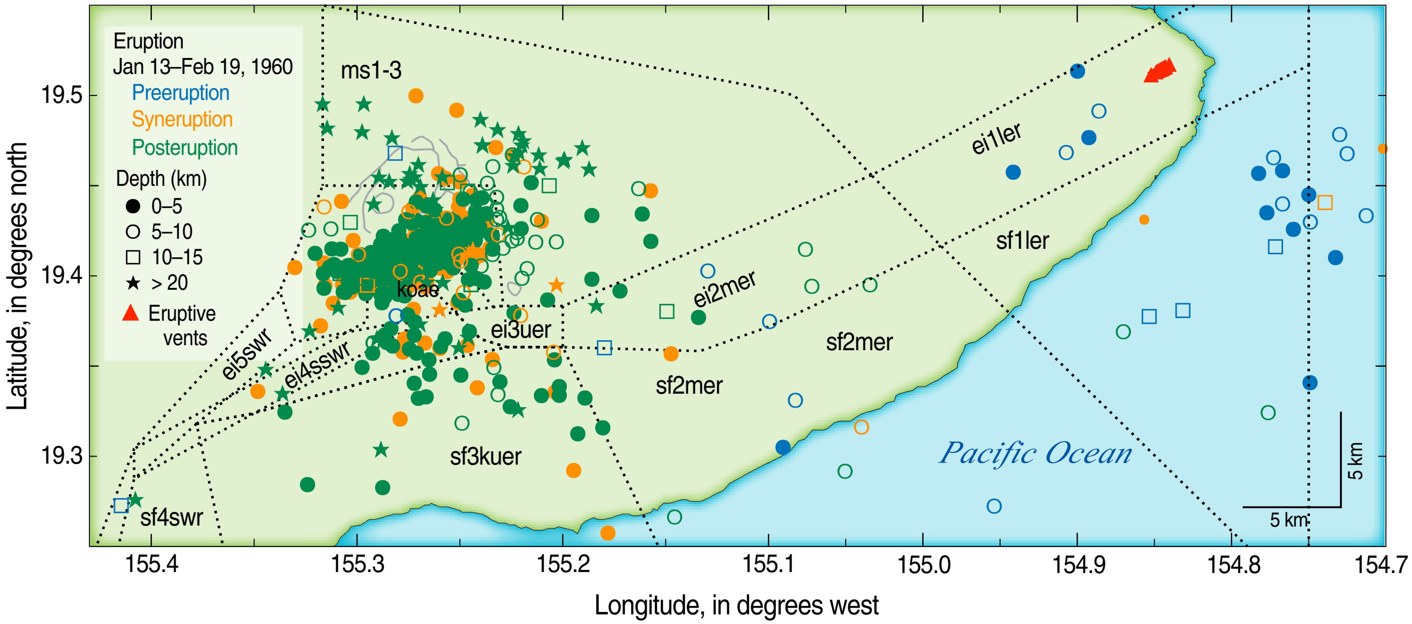


Figure 4.8. Map showing locations of earthquakes and earthquake swarms associated with the 1960 Kapoho eruption. A few south flank earthquakes before the eruption (blue dots and circles) are located southeast of the eruption site, but poor earthquake location precision this far from Kīlauea Caldera means that their location closer to the vents can't be ruled out. The magma supply seismicity at 5–10 km depth occurring during the eruption, as well as the south flank earthquakes during and following the eruption, are associated with the collapse of Kīlauea's summit, beginning about 10 days following the beginning of eruption.

We interpret the 1954 summit eruption as a minor, and almost accidental, event between the 1952 summit eruption and the 1955 east rift eruption. We propose that the 1954 eruption occurred when the edifice above the summit magma reservoir cracked during a time of inflation to allow an eruption, but was quickly healed because the small volume of stored magma was insufficient to sustain a longer eruption. In the longer historical context, we reject the idea of a pairing of the 1954 summit and 1955 flank eruptions (compare Macdonald, 1959, p. 4; Macdonald and Abbott, 1970). The failure of consistent pairing or alternation of summit and flank eruptions is demonstrated by a statistical runs test (Klein, 1982); some summit/flank eruption pairs like 1954/1955 and 1959/1960 may be linked by the volcano's response to gradual increase of its current stress state, but pairing is not a feature of the historical record.

1955 Eruption

The 1955 eruption differed from all previous Kīlauea eruptions in that the erupted magma was highly fractionated and therefore not fed directly from the summit magma reservoir. Instead, it was fed from the body of cooling magma emplaced below the lower east rift zone during the intrusion of April 1924. The erupted magma represents a liquid composition obtained by ~50-percent crystallization of a magma similar in chemistry to what was erupted at Kīlauea's summit in 1924 (table 4.2). Left alone, this body of magma would have cooled and crystallized past the point where it could erupt (compare Marsh, 1981). Instead, the *M*6.5 south flank earthquake of 30 March 1954 was instrumental in making possible the subsequent 1955 lower east rift eruption[19]. The accelerating preeruption lower east rift seismicity may have been caused by slow, downrift magma flow to fill rift voids left by stress release from the 1954 earthquake. The leveling off of summit tilt and inferred stop of summit magma accumulation, after a period of inflation and before the 1955 eruption (fig. 4.4) suggest that magma slowly entered the rift zone to increase pressure on the 1924 magma already in residence. At the same

[19]Flank earthquakes sometimes encourage subsequent eruptions (see, for example, Walter and Amelung, 2006), but at other times they promote unclamping of the rift zone, as happened during the 1975 Kalapana earthquake, thus encouraging intrusions rather than eruptions (Klein, 1982).

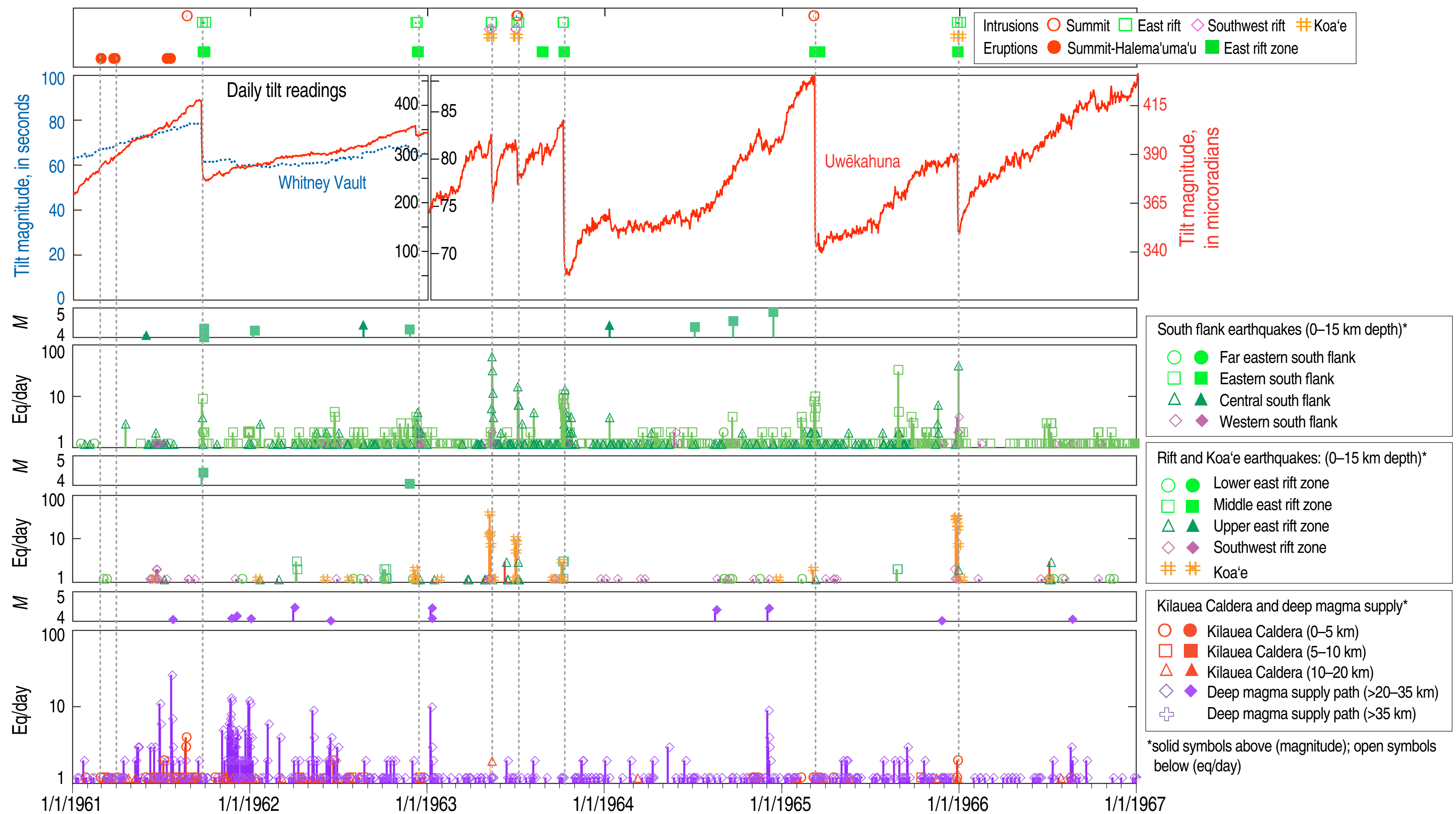


Figure 4.9. Graphs showing Kīlauea activity, 1961–1967. Seismicity (bottom six panels) and Whitney tilt magnitude (second panel from top) related to times of eruption given in the top panel. Vertical dotted lines connect data for eruptions and traditional intrusions; dashed lines connect traditional intrusions without eruption. Tilt magnitudes are given in arc-seconds (left axis) and microradians (right axis). Seismicity is plotted, from bottom to top, for the magma supply path, rift zones and Koa'e, and south flank. Earthquakes per day (eq/day) and magnitudes (*M*) greater than or equal to 4.0 are given for each region. The tilt plot is divided at 1 January 1963 following abandonment of the Whitney tilt site. The scale is also changed at that date to emphasize the smaller deflations associated with eruptions and intrusions after 1961. Dates on figure in m/d/yyyy format.

Table 4.2. Parentage of 1955 and 1977 differentiated lavas.[1]

[Fo = forsterite content of olivine; An = anorthite content of plagioclase; MgO in weight percent]

	Parent	Differentiate	Minerals removed from parent				Residuals	
			Olivine[2]	Augite[3]	Plagioclase	Ilmenite	Max.	Min.
1955 components								
Name	1924	1955E: MgO = 5.39						
Wt %	100	49.84	5.24	23.10	20.52	1.29	0.053	0.003
Composition			Fo 77.1		An 66.1			
1977 components using least magnesian differentiate								
Name	1961	1977: MgO = 5.43						
Wt %	100	62.97	3.85	17.31	15.29	0.58	0.006	0.001
Composition			Fo 77.1		An 68.4			
1977 components using most magnesian differentiate								
Name	1961	1977: MgO = 5.89						
Wt %	100	73.39	3.20	12.80	10.31	0.29	0.010	0.001
Composition			Fo 77.1		An 69.8			

[1]Petrologic mixing calculations modified from a program described by Wright and Doherty, 1970.
[2]Olivine chemistry fixed.
[3]Augite chemistry averaged from two analyzed augites from similar rocks.

time the earthquake slip on the flank decollement acted to both reduce the confining stress on the rift zone and to reduce the pressure above the stored magma body below, thus promoting eruption. The eruption occurred while the summit was still inflating. The earthquake location beneath the eastern south flank also relieved confining stress on the rift near the March 1955 Kalalua intrusion (fig. 4.5).

Seismicity and ground deformation before, during, and following the 1955 eruption differ markedly from subsequent east rift eruptions and intrusions. At that time, it was not possible for HVO to locate earthquakes with magnitudes less than 3, or discriminate rift earthquakes associated with dike formation from triggered flank events. Therefore we cannot plot earthquakes on the map (fig 4.5) but can plot daily counts (figs 4.4). The occurrence in time of earthquakes in the days before the eruption started are typical of earthquake swarms accompanying dike propagation. The March 1955 Kalalua intrusion was accompanied by an intense swarm

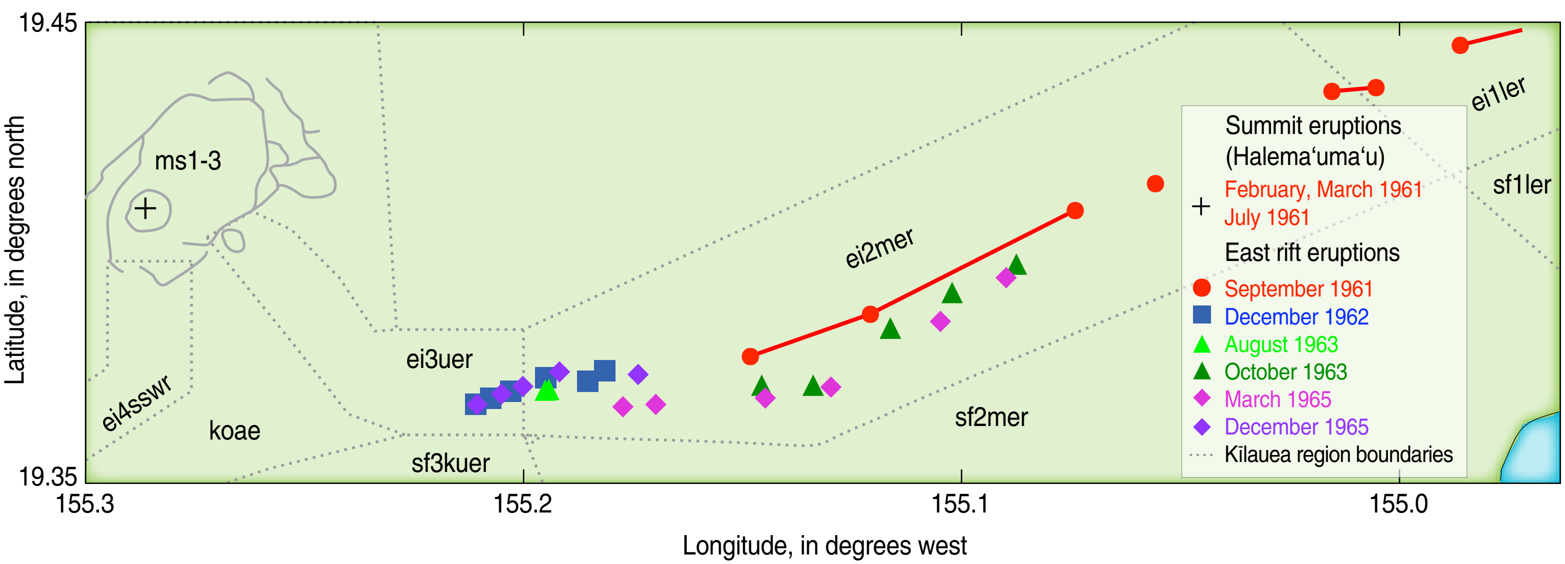
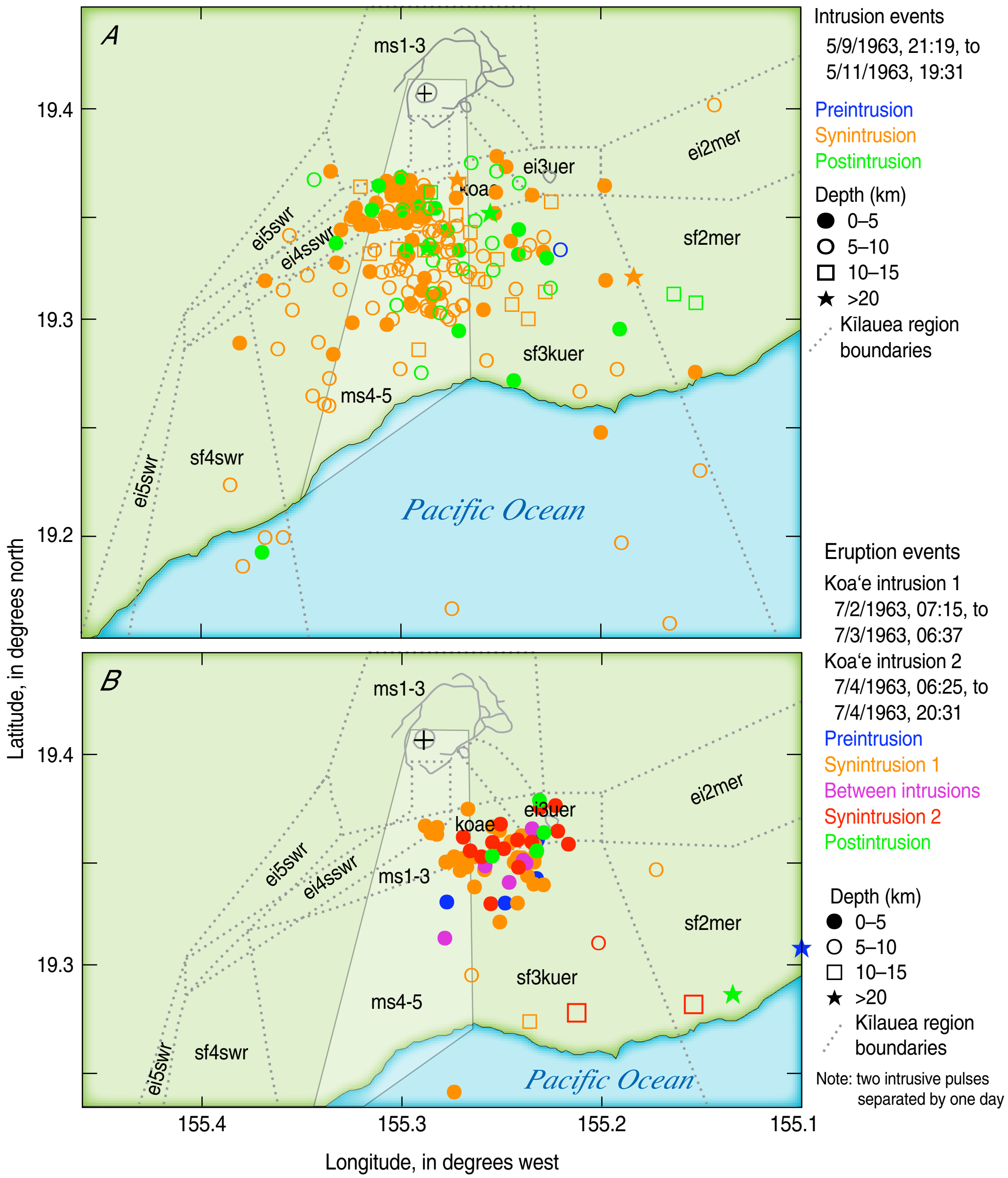


Figure 4.10. Map showing Kīlauea activity, 1961–1965. Vent locations for 1961–1965 eruptions on Kīlauea's east rift zone. Many eruptions took place at several locations along the rift zone.



of rift earthquakes of *M*3 to *M*>4 and a delayed south flank response with one earthquake of *M*5.5 about 2 days after the intrusion began (fig. 4.4). The early Kalalua intrusion phase was neither preceded nor accompanied by draining of Kīlauea's summit magma reservoir, as has been the case for every rift eruption beginning in 1961. However, the east rift zone did later deflate about 10 arc-seconds (50 µr), as shown by the Pāhoa tiltmeter record (fig. 4.4*A*). The large summit deflation that followed the beginning of eruption showed a deformation center somewhat east of the Fiske-Kinoshita array (fig. 4.2, point labeled "D").

Petrologic calculations made for the fractionated magmas of the 1977 eruption indicate that the chemistry of the parent magma, assumed to be emplaced beneath the 1977 eruption site in 1955, matches the chemistry of lavas erupted at Kīlauea's summit during 1961 (table 4.2). We infer that magma of 1961 composition moved upward beneath Kalalua in 1955 to cause the deflation coincident with intrusion observed on the Pāhoa tiltmeter in 1955 (fig. 4.4*A*). Subsidence of Kīlauea's summit began 2 days after the Kalalua intrusion, and 8 days after the beginning of the 1955 eruption (fig. 4.4*B*). This implies the 1955 eruption was initally fed from magma stored within the rift. After another 8 days a major earthquake swarm began beneath Kīlauea's summit, with epicenters extending to 10–km depth. We associate these

Figure 4.11. Maps showing seismicity associated with 1963 Koa'e intrusions. Symbols for pre-, during-, and postintrusion are explained in text preceding figure 4.7*D*. Dates on figure in m/d/yyyy format. Times given represent the beginnings and endings of intrusions. ***A***, Locations of earthquakes associated with the May 1963 Koa'e intrusion. ***B***, Locations of earthquakes associated with the July 1963 Koa'e-east rift intrusion. This intrusion occurred to the east of the May event, filling in the relatively aseismic area left from the May intrusion. Both intrusions have a strong south flank response.

summit earthquakes with caldera subsidence and magma flow from the summit magma reservoir. Notably, the deflation was not accompanied by seismicity beneath the east rift zone, indicating that magma moved aseismically downrift below the seismic zone of shallow intrusion without breaking rock along the path.

Petrologic study indicates that lava erupted during the latter part of the 1955 eruption had mixed with magma having a chemistry identical to that of Kīlauea's 1952 summit eruption (Helz and Wright, 1992). The timing and chemistry of magmas emplaced in 1955 are summarized in Wright and Helz (1996, table 3a). The relative ages and inferred position of magmas within Kīlauea's plumbing during the 1955 eruption are shown in figures 4.13*D* and 4.13*E*. We infer that the 1952 magma occupied only that part of the rift zone east (downrift) of Kalalua. Mixing of 1952 with the early 1955 magma began before pressure was applied from summit deflation and this mixture was the only magma occupying the rift zone beneath the site of the 1955 eruption.

We interpret the delay in summit collapse in 1955 to the distance between the eruption site and Kīlauea's summit. The loss of magma from the 1955 section of the lower rift was too far away to be immediately detected at the summit, but the pressure drop drove eventual replacement from the summit storage reservoir, which was then recorded by the tilt drop.

We can compare the volume erupted in 1955 (0.07 km^3) with the volume of magma moving into the rift plumbing from the summit magma reservoir. Before the 1955 eruption, Kīlauea's summit reservoir received an estimated volume of magma of about 0.036 km^3, based on inflation of 73 µrad (16.3 arc-seconds) measured at the Whitney Vault between the beginning of the 1952 eruption and the beginning of the 1955 eruption. The volume of subsidence calculated from the Whitney tilt record is 0.0952 km^3. The difference of these two values represents net loss from the summit of 0.059 km^3, and within measurement error this is equal to or less than the magma volume of 0.07 km^3 for the 1955 erupted lava after correcting the lava volume for 20 percent vesicles. The volume comparison, which implies no additional intrusion over and above replacing what was lost during eruption, is consistent with the scarcity of south flank seismicity during magma recharge.

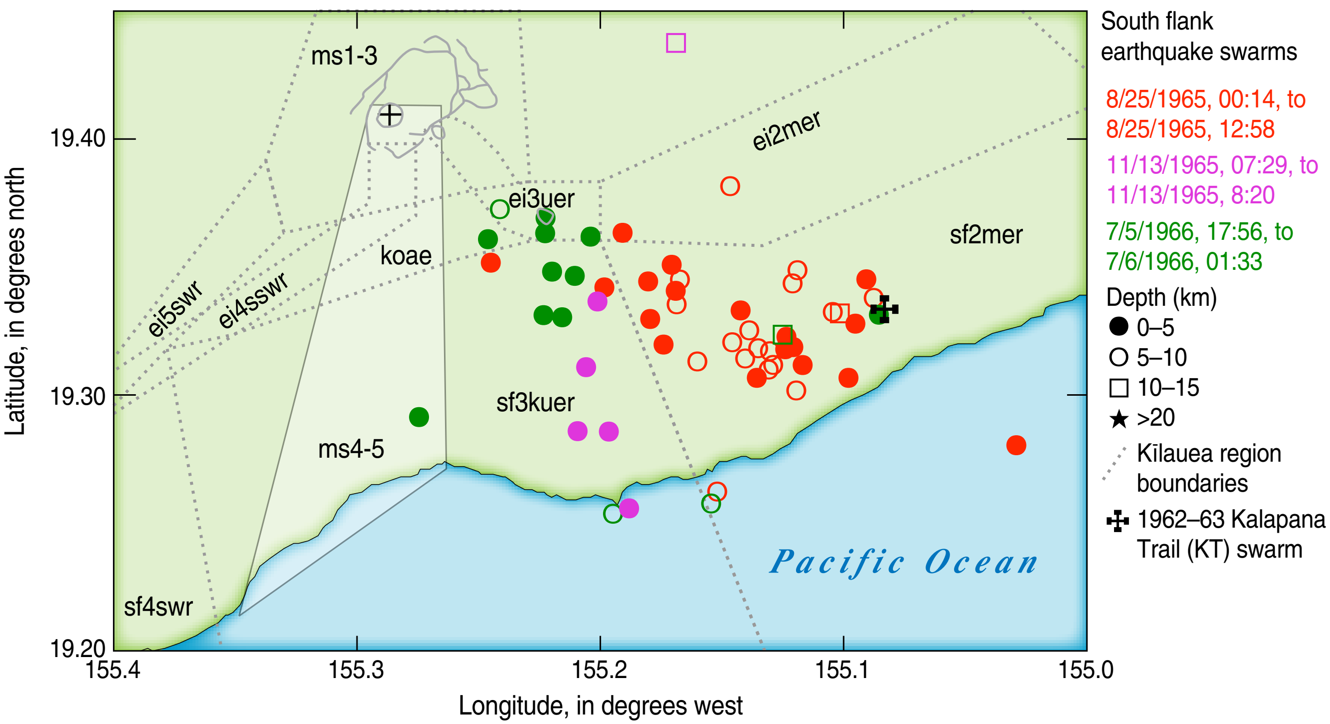


Figure 4.12. Map showing seismic activity in 1965–1966 associated with two suspected deep intrusions and one minor rift intrusion with a similar pattern in its south flank response. The patterns shown fit later documented examples of suspected deep intrusions in which earthquakes are distributed at a high angle to the east rift zone. Also shown are the imperfectly located earthquakes designated "Kalapana Trail" or "KT" in the HVO seismic summaries for 1962, which may be the earliest cataloged occurrence of south flank earthquake swarms without accompanying rift activity, and could be the earliest examples of suspected deep intrusions. Dates on figure in m/d/yyyy format.

1959 Eruption

Tilt data between the beginning of the 1955 eruption and the beginning of the 1959 eruption failed to recover the net deflation located beneath the upper east rift zone (fig. 4.2, point labeled "C"). This was the last time that an inflation or deflation vector lay outside of the Fiske-Kinoshita array. The 1959 eruption has been interpreted as a mixed-magma eruption, and different models have been offered to explain the origin and mixing of the two magmas erupted in 1959 (Helz, 1987; Wright, 1973). As indicated in the section interpreting the 1954 eruption, a postulated intrusion below the eastern end of the line of 1954 vents lies close to the westward projection of the initial line of vents for the 1959 eruption (purple oval in figs. 4.2 and 4.3). As the altitudes of the 1959 vent openings at Kīlauea Iki were lower than the altitude of the caldera floor we infer that the opening of the Kīlauea Iki fracture could draw the magma erupted at the western end of the 1959 vents (variant 1) from this caldera source, even though magma erupted at the eastern end of the 1959 vents (variant 2) came from a deeper, distinctive source (see below).

An additional observation suggests the 1954 and 1959 magmatic plumbing systems were connected. On the day before the 1959 eruption began, the Whitney tilt magnitude showed a sharp upward excursion at an azimuth of about 31° east of north (tilt down to the northeast). Intersection with a smaller inflation vector at Uwēkahuna indicates inflation of a source close to the inferred location of the magma intruded in 1954 (fig. 4.2, point labeled "E"). This may have been the final magma-pressure increase that caused the 1959 fractures to open.

Meanwhile the magma component of the 1959 eruption associated with the deep (40–60 km) earthquake swarms north of Kīlauea Caldera (variant 2) must have been accumulating from the time of initial detection of deep seismicity in 1953. This component is inferred to have flooded the shallow caldera reservoir containing the magma of 1954 chemistry to produce the hybrid magma compositions seen during the 1959 eruption (fig. 13*F*). Upward movement of this component is presumed to have occurred rapidly to preserve the deformed and twinned olivine.

The collapse of Kīlauea Iki Crater during the 1959 eruption can also be detected in the tilt record at the Whitney Vault. During 1959 episode 1 both the Whitney and Uwēkahuna isntruments recorded deflation at a point less than 1 km north of the proposed 1954 intrusion (fig. 4.3, label "F"). We conclude that this represents removal of magma from the 1954 intrusion. In the pause between eruptive episodes 1 and 2, the Whitney tilt difference for 21–24 November 1959 shows a 1.1 arc-second (5.3 µrad) deflation at an azimuth of 161° pointing toward the west end of the Kīlauea Iki vents (fig. 4.3, point labeled "H"), whereas the Uwēkahuna vector over the same interval shows inflation. This is the only evidence to corroborate the collapse of the floor of Kīlauea Iki documented above, and the timing was logical, occurring at the end of the long and large-volume initial episode of the Kīlauea Iki eruption (Richter and Moore, 1966). This shallow collapse was too far away from the Uwēkahuna Vault to be recorded by the Uwēkahuna tiltmeter and barely above the noise level at Whitney.

Tilt during and following the 1959 eruption signifies the end of inflation and deflation located close to the upper east rift zone. The intersection of Uwēkahuna and Whitney tilt vectors for the period between the onset of the Kīlauea Iki eruption on 14 November 1959 and the onset of the 1960 eruption falls within the caldera (fig. 4.3, point labeled "G") and is consistent with a source within the summit reservoir rather than a shallow center in the eastern caldera or beneath Kīlauea Iki.

1960 Eruption

The January-February 1960 Kapoho eruption is linked chemically and petrographically to the 1955 lower east rift eruption and to the 1959 eruption in Kīlauea Iki. During the summit deflation following the 1955 eruption, most but not all of the 1952 magma mixed with the unerupted 1955 magma to refill the 1955 storage volume (fig. 4.13*E*), producing a hybrid magma that was erupted at the beginning of the 1960 eruption (fig. 4.13*G*).

The earliest 1960 lavas are chemically identical to those erupted from the east rift in late 1955 but have about 5 percent more phenocrysts formed during the 5 years separating the two eruptions (Helz and Wright, 1992; Murata and Richter, 1966; Wright and Fiske, 1971). The earliest recharge in 1960 involves only magma having the 1952 chemistry, which is interpreted as the last remnant of the 1952 magma that was not intruded in 1955, and which occupied a region east of the easternmost 1955 vents. Subsequent recharge involved the other two summit magma batches in a sequence matching their appearance in later eruptions at Kīlauea's summit, that is, 1952⇒1961⇒1967–68 (fig. 4.13*G*; Wright and Helz, 1996), but carrying more olivine than was seen in the corresponding Halema'uma'u eruptions. A final component of the 1960 recharge matched the eastern (mantle) component of the preceding 1959 eruption, distinguished both by chemistry and by the twinned and deformed olivine (fig. 4.13*G*). Addition of this 1959 component contributed further to the olivine-rich character of the 1960 eruption.

Deformation data indicate that the patterns of inflation and deflation in 1959–61 represent a transition from centers located to the east of the Fiske-Kinoshita array to centers within the Fiske-Kinoshita array. The intersection of tilt vectors and the center of leveling contours for the 1960 collapse (fig. 4.3, points labeled “I,” “J,” and “K”) are located in the central caldera surrounding inflation center 1 of the Fiske-Kinoshita array of inflation sites. The differences in the centers determined for the 1960 collapse arise from different time intervals for the measurements and, in the case of the short-base tilt, from continued influence of the east rift zone on the Whitney tilt azimuths, as well as higher error in tilt vector inversions. The tilt intersection of the pre-1961 inflation (fig. 4.3, label “L”) likewise falls near center 1 of the Fiske-Kinoshita array.

The south flank seismicity adjacent to the lower east rift zone preceding and accompanying the 1960 eruption (fig. 4.8), and lack of much seismicity in the middle rift or flank, is consistent with expansion of the 1960 magma reservoir by addition of magma already in the lower east rift zone underneath the reservoir. Finally, the volume of collapse during and following the 1960 eruption, as estimated from the Uwēkahuna tilt (0.1405 km^3), is nearly twice the erupted volume after correction for 20 percent vesicles (0.0906 km^3). This volume difference suggests that significant additional rift intrusion took place, even after refilling of the summit reservoir evacuated during the eruption. In this case the absence of posteruption south flank seismicity is puzzling and may indicate that the intruded volume was small and (or) that the eruption volume was underestimated by the amount that flowed into the ocean (Richter and others, 1970).

History of Magma Mixing in 1955 and 1960

The identification of the sequence of chemical changes associated with magma mixing in the period from the 1952 summit eruption through the 1960 east rift eruption was possible only through the acquisition of very high quality major-oxide chemical data from well-sampled eruptions. The interpretations cartooned in figure 4.13 are rendered credible by the observation that the time sequence of compositions identified as mixing components matches the time sequence of the three chemically distinguishable summit eruptions of 1952, 1961, and 1967–68. The mixing calculations force a further inference that these magmas entered the east rift zone along parallel paths beginning even before their appearance in the three summit eruptions. The mixing calculations also indicate that (1) the 1954 summit magma, also chemically distinct, never moved through the main Kīlauea plumbing feeding the summit reservoir from below and (2) a magma of unique chemistry moved from great depths at a location far from the usual mantle source region to be erupted only in 1959 and 1960. In chapter 8 we augment the interpretations illustrated in figure 4.13 with consideration of volumes and residence times for the three summit magmas in order to specify the nature of magma storage at Kīlauea’s summit during this period.

Unique Deep Magma Pathways

The events of the 1954–60 period stand apart from the rest of Kīlauea’s recorded history. The vertical changes observed during the 1960 collapse record the integrated movement of summit, east rift, and south flank. The deep (40–60 km) seismicity during 1953–60 and the unique chemistry of the Kīlauea Iki eruption strongly suggest that the magma being supplied was from an alternate deep mantle source above the normal Hawaiian mantle source and that movement of magma from this source to the surface did not follow the typical magma conduit feeding Kīlauea’s shallow reservoir. Instead, the deep earthquakes and magma movement toward Kīlauea Iki were independent of Kīlauea’s typical plumbing, but instead they were assisting inflation of Kīlauea’s summit from a position eccentric to the main plumbing geometry. We thus think of the deep Kīlauea conduit as being multistranded (Wright and Klein, 2006, fig. 10 and discussion, p. 63–64). On arriving at shallow depth beneath the eastern caldera, the deeper magma (variant 2 of the 1959 eruption) mixed with and pushed out a shallow pocket of magma (variant 1 of the 1959 eruption) that also may have followed a different path to be stored some distance away from the primary Kīlauea reservoir. The absence of shallow rift seismicity, the migration of flank seismicity to the far eastern south flank, and the appearance of the deep component of the 1959 Kīlauea Iki eruption during the latter part of the 1960 eruption all suggest that magma pressure was being applied at a deeper (>5 km?) level beneath the east rift zone than in other typical eruptions (2–4 km). Finally, the movement of magma out of the shallow summit reservoir in 1960 was triggered by downrift movement of magma batches within the deeper parts of the rift zone.

Comparison with Other Time Periods

The rift activity between 1961 and 1966 is similar to the earlier 20th century east rift zone eruptions (1922 and 1923) and intrusions (1938). During the time (1956–62) that both Whitney and Uwēkahuna Vaults were in use, tilt measurements were consistent, the respective vectors defining centers of inflation and

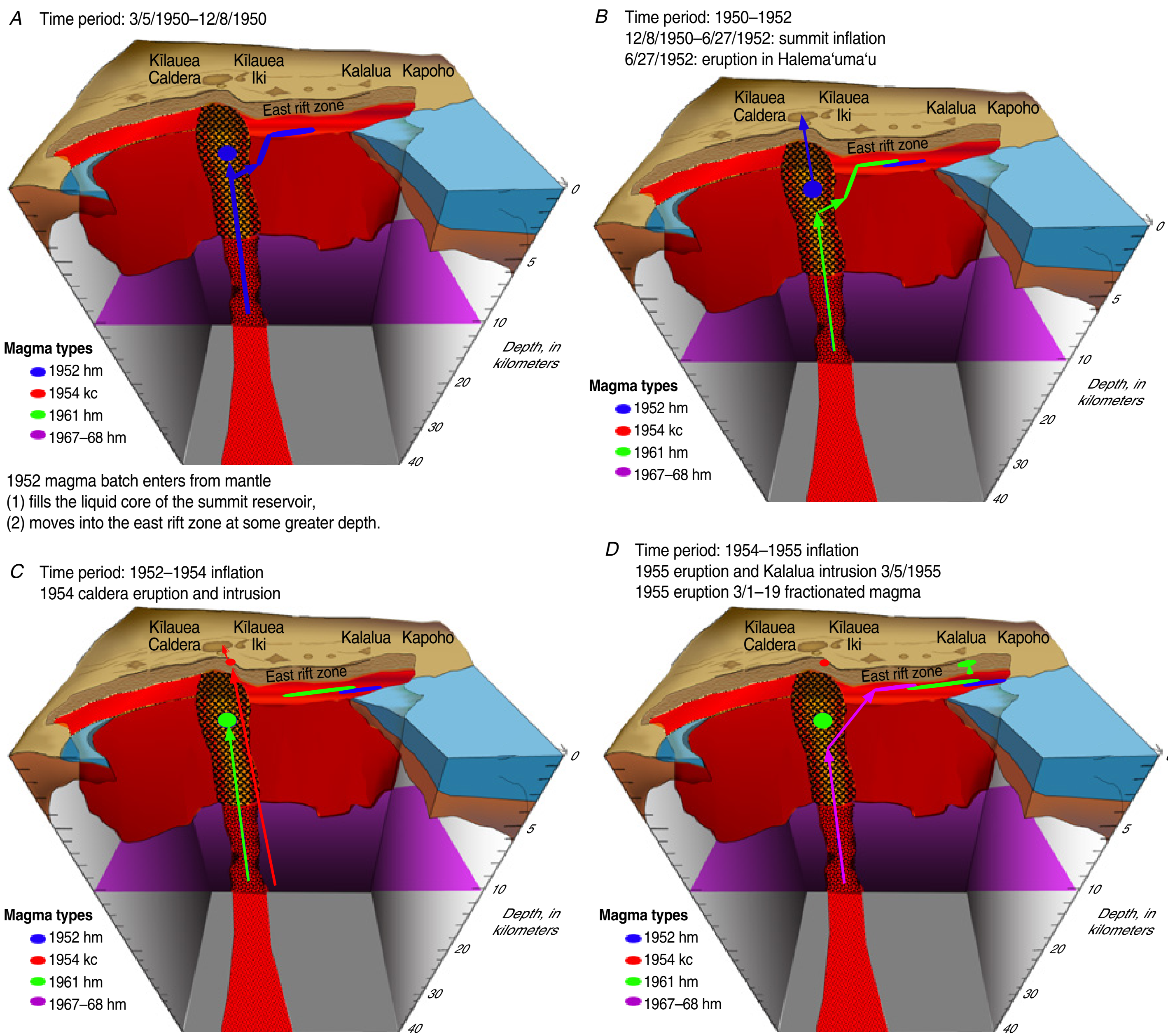
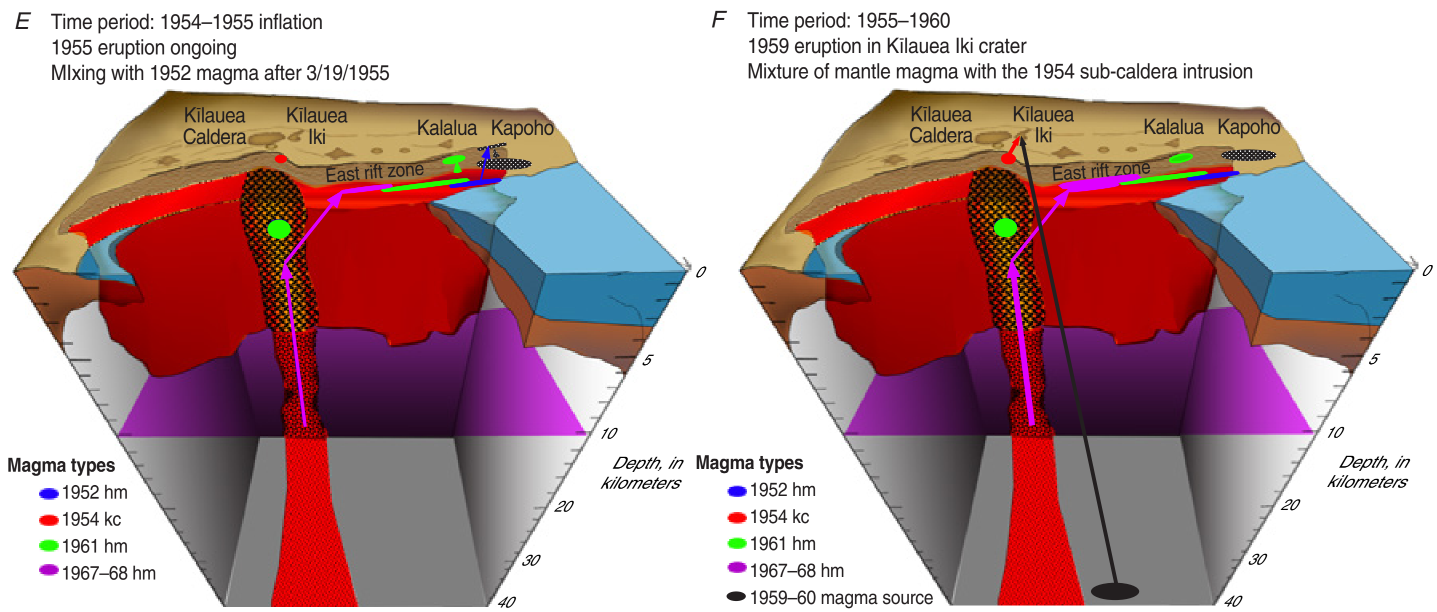
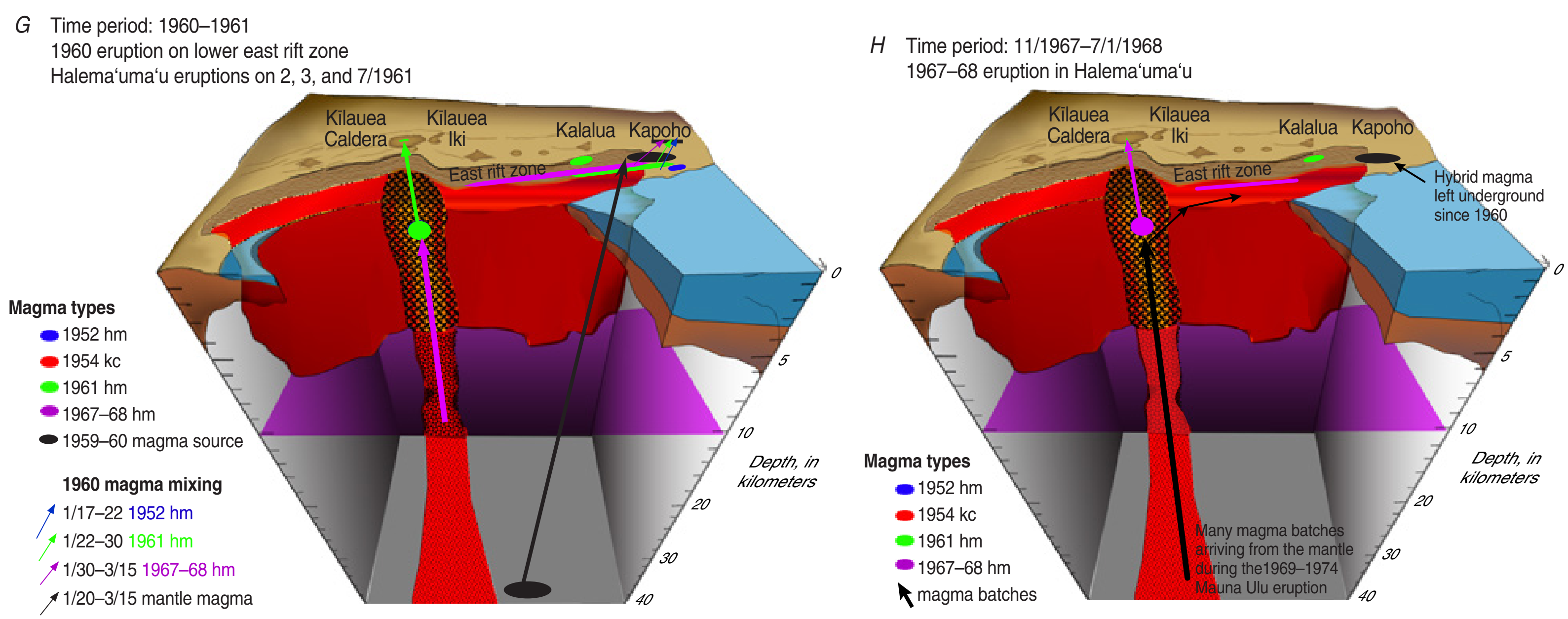


Figure 4.13. Cutaway diagram of Kīlauea showing transport paths of chemically distinct magma batches through the volcano's plumbing. Dates on figure in m/d/yyyy format. Four different magma chemistries are distinguished by color. The "1952 hm", "1961 hm" and "1967-68 hm" magma chemistries erupted in Halemaʻumaʻu and also entered the east rift zone. The "1954 kc" magma chemistry erupted in Kīlauea Caldera in 1954 and its intruded equivalent was identified as a mixing component of the 1959 eruption, but never entered the east rift zone. ***A***, 5 March 1950 to 8 December 1950. Possible distribution of 1952 magma beneath both the summit and east rift zone. ***B***, 8 December 1950 to 27 June 1952. Introduction of 1954 and 1961 magma following the Koaʻe collapse in December 1950. The 1952 eruption is fed from the top of the summit reservoir. ***C***, Inflation between 1952 and 1954 eruptions. The 1952 Halemaʻumaʻu eruption used up the 1952 magma in the summit reservoir. The small-volume 1954 magma is erupted and intruded at Kīlauea's summit without any transport into the east rift zone. ***D***, The 1961 magma moves up and outward into the rift zone and is intruded beneath Kalalua on 5 March 1955. Introduction of 1967–68 magma into the east rift zone. ***E***, 1955 eruption. During the latter part of the 1955 eruption, 1952 magma stored beneath the lower east rift zone is mixed with previously stored 1961 magma. ***F***, 1955–1960. The 1959 eruption is a mixture of magma from a mantle source (black oval

at lower left) with magma of 1954 chemistry intruded west of Kīlauea Iki. ***G***, The 1960 eruption on the east rift zone initially erupts the mixed magma produced in 1955, then is mixed with additional rift magma in the following sequence: 1952–1961–1967–1968. A component of the mantle-derived magma is also a component of the latter part of the 1960 eruption (black arrow, unknown path from mantle). ***H***, The 1967-68 eruption and afterward. 1967-68 magma erupts in Halema'uma'u. Subsequent east rift hybrid eruptions are mixed with new magma batches arriving from the mantle at more frequent intervals, illustrated schematically by the solid black arrows.





deflation around the Sand Spit tilt station (fig. 4.3). The pattern of inflation before rift eruptions, and deflation associated with rift eruptions and intrusions, of this 1956–1962 period is similar to that of later post-1961 periods in which deformation data were more numerous and locations more accurate.

Deep Magma Supply Seismicity

Earthquake swarms in the 20–35-km depth zone dominantly represent response to variable stresses associated with magma supply, whereas larger single earthquakes at this depth may be triggered by flexural stresses in the lithosphere under the volcanic load and by lateral shear stresses from the south flank. The incidence of earthquake swarms at 20–35-km depth sharply decreased following the December 1962 eruption (fig. 4.9). A similar decrease in earthquake rate only for the year 1963 occurs in the eastern south flank sector at 5–10-km depths adjacent to the middle east rift zone. The rate of seismic release beneath the various rift segments and Koaʻe, however, does not diminish until 1966.

Supplementary Material

Supplementary material for this chapter appears in appendix D, 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 D comprises the following:

Table D1 shows additional earthquake swarms and earthquakes of *M*4–6 from 1953 to 1967.

Table D2 summarizes tilt volume, eruption efficiency, and magma supply rate for the period 1950–67

Table D3 summarizes tilt data for deformation centers plotted in text figures 4. 2 and 4.3.

Figures D1 and D2 show earthquake swarms using the same data as in text figures 4.1 and 4.9.

Figure D3*A*–*N* shows the same data as text figures 4.1 and 4.9 plotted at 1-year intervals.

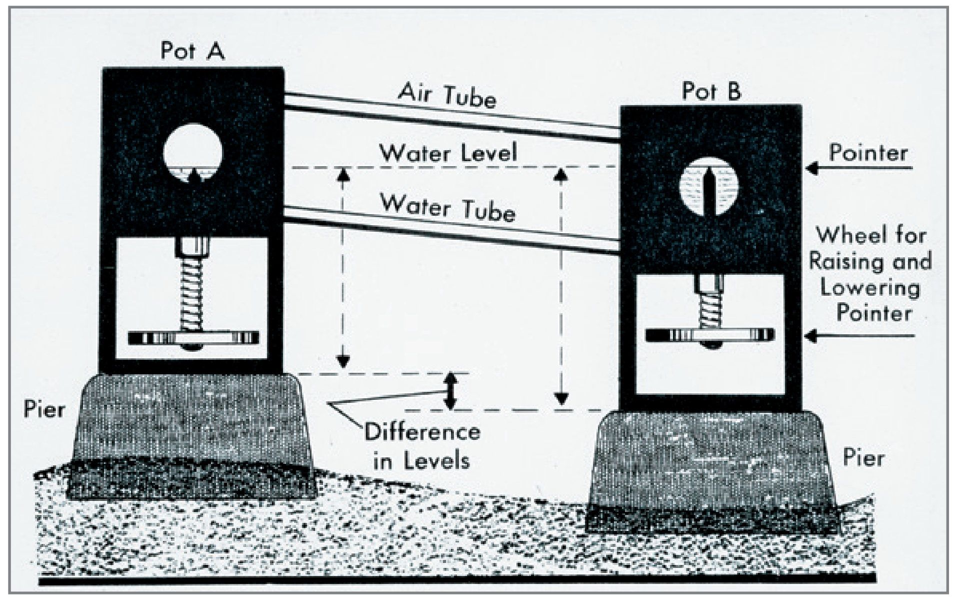
Figure D4*A*–*N* shows earthquake swarm data as in figures D1 and D2 plotted at 1-year intervals, but beginning 3 years earlier at 1 February 1950.

Figures D5–9 show time series plots of earthquakes associated with eruptions and traditional intrusions between 1954 and 1965.

Figures D10–17 show map plots of earthquakes associated with eruptions and traditional intrusions between 1954 and 1965.

Figures D18–25 show map plots of deep (20–35 km) earthquake swarms in and near the magma supply path, organized chronologically.

Reading of wet tilt. USGS photograph by R.S. Fiske, January, 1968.



Field measurement of watertube (wet) tilt at Kīlauea as pioneered by Jerry Eaton showing instrument setup (Herbert, D., and Bardossi, F. , 1968, Kīlauea: Case History of a volcano, New York, Harper & Row, p. 106).