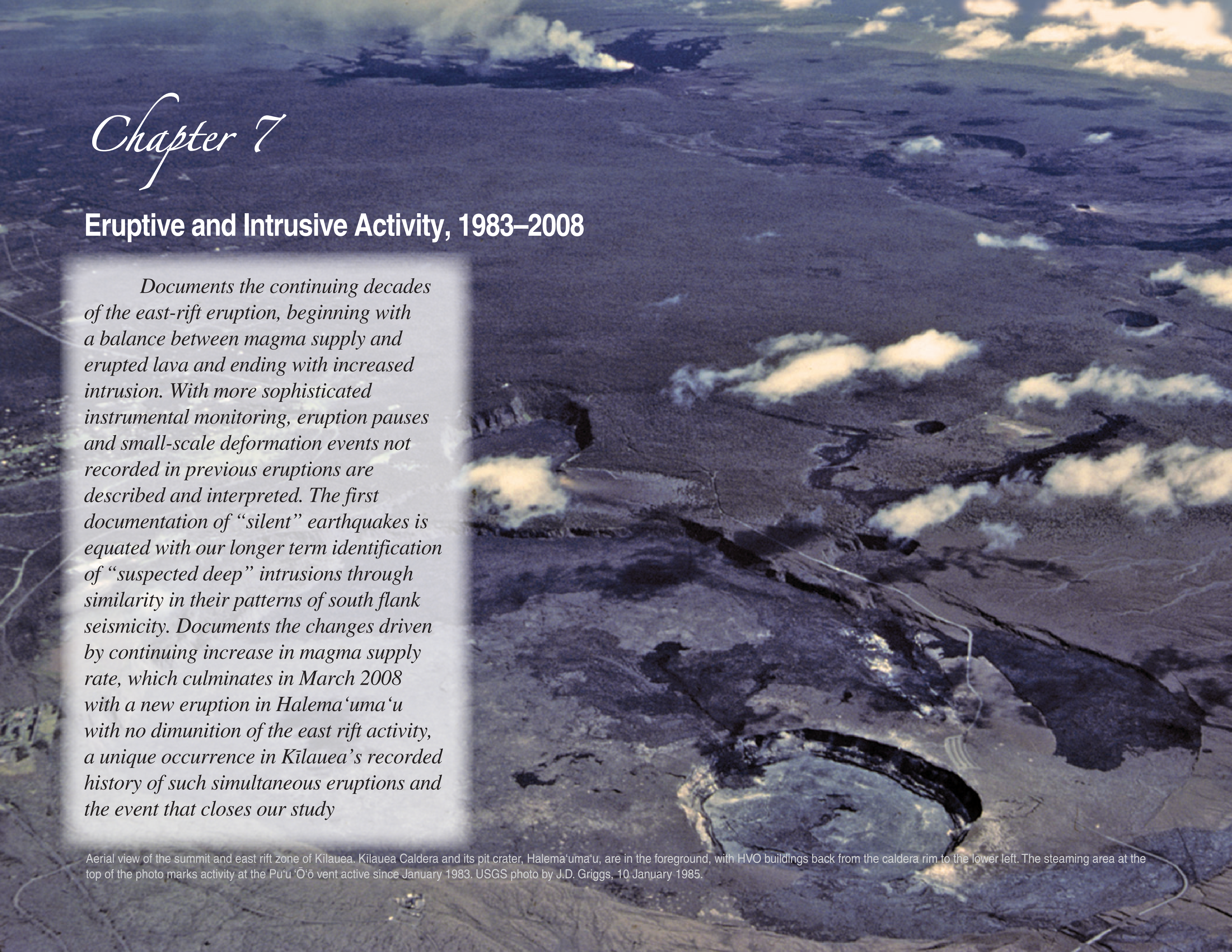
Chapter 7

Eruptive and Intrusive Activity, 1983–2008

Documents the continuing decades of the east-rift eruption, beginning with a balance between magma supply and erupted lava and ending with increased intrusion. With more sophisticated instrumental monitoring, eruption pauses and small-scale deformation events not recorded in previous eruptions are described and interpreted. The first documentation of "silent" earthquakes is equated with our longer term identification of "suspected deep" intrusions through similarity in their patterns of south flank seismicity. Documents the changes driven by continuing increase in magma supply rate, which culminates in March 2008 with a new eruption in Halemaʻumaʻu with no dimunition of the east rift activity, a unique occurrence in Kīlauea's recorded history of such simultaneous eruptions and the event that closes our study



Aerial view of the summit and east rift zone of Kīlauea. Kīlauea Caldera and its pit crater, Halemaʻumaʻu, are in the foreground, with HVO buildings back from the caldera rim to the lower left. The steaming area at the top of the photo marks activity at the Puʻu ʻŌʻō vent active since January 1983. USGS photo by J.D. Griggs, 10 January 1985.

Early on 2 January 1983, an earthquake swarm and summit subsidence heralded the beginning of what was to be long-term activity in the middle east rift zone—activity that continues to the present time (2014). The eruption took place at several vents over a 3-week time period (table 7.1; figs. 7.1, 7.2). An intense south flank earthquake response occurred adjacent to the erupting vents and also south of the upper east rift zone and for several hundred meters downrift from the erupting vents. The complexity in rate of both downrift and uprift migration of earthquakes from different points beneath the rift indicates that this eruption was fed from a series of separate intrusions (Klein and others, 1987, figure 43.97, discussion on p. 1167). In order to understand this period we build on the recently published summary of the first 20 years of this eruption (Heliker and others, 2003).

On 28 March 2008 a small explosive eruption occurred at Halemaʻumaʻu, followed within weeks by identification of an active magma body just below the Halemaʻumaʻu floor (Orr and others, 2008; Poland and Sutton, 2008; Wilson and others, 2008). The ongoing eruption on Kīlauea's east rift zone continued through this event, yielding the first instance in Kīlauea's historical period of simultaneous eruption at two different sites. The Halemaʻumaʻu eruption provides a convenient closing date for our study and also provides a context for this chapter—that is, we seek to answer the question of how Kīlauea's plumbing evolved between 1983 and 2008 to allow simultaneous eruption at Kīlauea's summit and east rift zone.

Episode 1 of the ongoing Puʻu ʻŌʻō-Kupaianaha eruption is interpreted as the culminating event of recovery from the 1975 earthquake, as indicated in chapter 6. For convenience we have divided the eruption into three stages. Stage I comprises 9 years: the 4 years of episodic eruption at Puʻu ʻŌʻō beginning with episode 2 (stage IA), followed by more than 5 years of continuous eruption from a lava lake developed at Kupaianaha (stage IB). Stage II begins on 8 November 1991, during the dying of the Kupaianaha vent and just before the return of activity to Puʻu ʻŌʻō in episode 49. The early events of stage II feature several short episodes at different places on the Puʻu ʻŌʻō cone (episodes 49–51), and the period ends just before the beginning of reinflation of Kīlauea's summit in December 2003. Stage II is arbitrarily divided into stages IIA and IIB at 1 January 1997, before the intense eruption and intrusion of January–February 1997 and the beginning of the long-lived episode 55 at Puʻu ʻŌʻō. Stage III begins on 1 December 2003, a date preceding the beginning both of reinflation and of a dramatic increase in CO_2 emission at Kīlauea's summit. Stage III ends with the explosive eruption in Halemaʻumaʻu on 19 March 2008. In order to emphasize the year of intense activity precursory to the Halemaʻumaʻu eruption, we divide stage III into stages IIIA and IIIB at 18 May 2007, a date which precedes the east rift intrusion of 24 May 24, the following Father's Day eruption and intrusion of 17 June, and the renewal of east rift eruption downrift from Puʻu ʻŌʻō on 21 July.

The terminology used here to describe eruptive and intrusive events is as follows:

Episode: An eruption event that forms part of a series repeated at the same site. Stage IA comprised 47 episodes of high-fountaining (figure 7.1) that built the 260-m-high cone Puʻu ʻŌʻō (Heliker and Mattox, 2003; Wolfe and others, 1987; Wolfe and others, 1988). The Hawaiian Volcano Observatory (HVO) continues to use the term episode to apply to every new eruption. We emphasize the change in location of the eruption with a name in addition to the episode designation for eruptions within the Puʻu ʻŌʻō edifice and use other naming terminology to refer to eruptions outside of Puʻu ʻŌʻō. Thus episode 48 refers to the fissure eruption that led to continuous eruption at Kupaianaha (Heliker and Mattox, 2003; Heliker and Wright, 1991), thereafter designated in this paper as the "Kupaianaha" eruption. Eruption terminology for this chapter is listed in the following text table.

Stage	Begin	End	Location	Eruption name*
Episode 1	1/3/1983	1/23/1983	Various, including Puʻu ʻŌʻō	Puʻu ʻŌʻō; episode 1
IA	2/13/1983	7/18/1986	Puʻu ʻŌʻō	Puʻu ʻŌʻō; episodes 2–47
IB	7/18/1986	11/8/1991		*Kupaianaha* (episode 48)
	7/18/1986	2/7/1992	Kupaianaha	
IIA	11/8/1991	1/1/1997		
	11/8/1991	1/29/1997	Puʻu ʻŌʻō	Puʻu ʻŌʻō episodes 49–53
IIB	1/1/1997	12/1/2003		
	1/30/1997	1/31/1997	Nāpau	*1997 Nāpau* (episode 54)
	2/24/1997	6/17/2007	Puʻu ʻŌʻō	Puʻu ʻŌʻō episode 55
IIIA	12/1/2003	5/18/2008	Puʻu ʻŌʻō	Puʻu ʻŌʻō episode 55
IIIB	5/18/2007	3/19/2008		
	6//19/2007	6/19/2007	Kane nui o Hamo	*Father's Day* (episode 56)
	7/2/2007	7/21/2007	Puʻu ʻŌʻō	Puʻu ʻŌʻō episode 57
	7/21/2007	present	East rift	*2007 fissure* (episode 58)

* Proposed name in italic; current name in parentheses.

Table 7.1. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IA—2/1/1983–7/20/1986 (see fig. 7.1).

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

Date and time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
2/10/1983 10:30	2/25/1983 09:00	MERZ	E					Episode 02—low-level fountaining	
2/25/1983 09:00	3/4/1983 14:51	do	do		13.9	117	+6h	do—vigorous fountaining; tilt 2/24–3/3	
2/12/1983 07:21	2/12/1983 12:37	sf4swr	EQS	9				Possibly a suspected deep intrusion (SDI)?	
	3/21/1983 13:12	sf2mer	EQS	10				South flank anticipation	
3/21/1983 6:00	3/28/1983 1:00	MERZ	E		14.9	115	+0h	Episode 03—low-level fountaining	
3/28/1983 1:00	4/9/1983 02:57	do	do		19.2	133		do—vigorous fountaining; tilt 3/27–4/2; Tilt 4/2–9-clockwise rotation	
6/13/1983 10:25	6/17/1983 14:13	MERZ	E		16.2	113	-4h 35m	Episode 04; tilt 6/12–17	
6/29/1983 12:51	7/3/1983 7:15	MERZ	E		9.3	120	-10h 9m	Episode 05; tilt 6/30–7/3	
7/22/1983 15:30	7/25/1983 16:30	MERZ	E		16.7	117	-8h 30m	Episode 06; tilt 7/22–25	
8/15/1983 7:41	8/17/1983 16:00	MERZ	E		19.7	117	-4h 19m	Episode 07; tilt 8/15–18	
8/15/1983 22:51	8/16/1983 22:49	sf3kuer	EQS	18				South flank response—*M*3.7 with aftershocks	
9/6/1983 5:11	9/7/1983 5:26	MERZ	E		14.8	117	-5h 49m	Episode 08; tilt 9/5–7	
9/9/1983 06:30 9/9/1983 06:37	9/9/1983 23:02 9/10/1983 23:35	sf2mer sf2.3	EQ					*M*5.7; 3 foreshocks? from 9/8 20:26 26 aftershocks extending to the west from mainshock in regions sf2mer and sf3kuer	
9/15/1983 15:41	9/17/1983 19:20	MERZ	E		16.2	115	-3h 19m	Episode 09; tilt 9/15–17	
10/5/1983 1:06	10/7/1983 16:50	MERZ	E		16.9	108	-4h 54m	Episode 10; tilt 10/5–7	
11/5/1983 23:50	11/7/1983 18:45	MERZ	E		21.1	110	-2h 10m	Episode 11; tilt 11/5–8	
11/16/1983 06:13 11/16/1983 10:02	 11/18/1983 10:52	 all	EQ					Ka‘ōiki mainshock *M*6.7 Triggered Kīlauea aftershock sequence	 **7.3**
11/30/1983 4:47	12/1/1983 15:45	MERZ	E		24.6	111	-1h 13m	Episode 12; tilt 11/30–12/2	
12/18/1983 11:39	12/18/1983 18:27	ms2	EQS	9	flat			Nāmakanipaio[9]	
1/20/1984 17:24	1/22/1984 11:23	MERZ	E		10.0	111	-3h 36m	Episode 13; tilt 1/19–23	
1/30/1984 17:45	1/31/1984 13:18	MERZ	E		12.1	112	-2h 15m	Episode 14; tilt 1/29–2/1	
2/14/1984 19:40	2/15/1984 15:01	MERZ	E		15.7	110	-1h 20m	Episode 15; tilt 2/12–17	
3/3/1984 14:50	3/4/1984 22:31	MERZ	E		18.2	105	-2h 10m	Episode 16; tilt 3/3–5	
3/30/1984 4:48	3/31/1984 3:24	MERZ	E		14.6	120	-4h 12m	Episode 17; tilt 3/30–31	

Table 7.1. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IA—2/1/1983–7/20/1986 (see fig. 7.1).—Continued

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

Date and time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
4/18/1984 18:00	4/21/1984 5:33	MERZ	E		30.1	112	-4h 0m	Episode 18; tilt 4/18-22	
4/21/1984 21:15	4/22/1984 09:00	sf3kuer	EQS	7				south flank response; *M*3.8 (2) with aftershocks	
5/16/1984 5:00	5/18/1984 0:50	MERZ	E		8.6	127	-5h 0m	Episode 19; tilt 5/14–18	
6/7/1984 21:04	6/8/1984 6:25	MERZ	E		21.8	124	-0h 56m	Episode 20; tilt 6/6–11	
6/30/1984 10:28	6/30/1984 18:27	MERZ	E		12.7	107	-0h 32m	Episode 21; tilt 6/30–7/1	
7/8/1984 19:30	7/9/1984 10:17	MERZ	E		11.3	117	-1h 30m	Episode 22; tilt 7/7–10	
7/28/1984 12:00	7/29/1984 5:40	MERZ	E		16.2	113	-1h 0m	Episode 23; tilt 7/28–29	**7.4**
8/19/1984 21:52	8/20/1984 17:25	MERZ	E		12.0	117	-1h 8m	Episode 24; tilt 8/19–21	**7.4**
9/19/1984 16:04	9/20/1984 5:32	MERZ	E		20.9	114	-0h 56m	Episode 25; tilt 9/19–20	
11/2/1984 11:40	11/2/1984 16:36	MERZ	E		9.9	112	-0h 20m	Episode 26; tilt11/2–4	
11/20/1984 0:05	11/20/1984 10:06	MERZ	E		10.5	106	-0h 55m	Episode 27; tilt 11/19–20	
12/3/1984 19:05	12/4/1984 9:41	MERZ	E		10.4	124	+0h 5m	Episode 28; tilt 12/3–4	
12/23/1984 06:14	12/23/1984 13:37	sf4swr	SDI	24	flat			*M*3.2 and aftershocks during inter-Episode inflation	G5
1/3/1985 13:15	1/4/1985 5:04	MERZ	E		16.5	113	-0h 45m	Episode 29; tilt 1/2v7	
2/4/1985 5:46	2/5/1985 2:46	MERZ	E		31.1	108	-2h 14m	Episode 30; tilt 2/3–5	
2/21/1985 19:48		sf3kuer	EQ					*M*4.8[10] with aftershocks	
3/13/1985 6:00	3/14/1985 4:55	MERZ	E		30.9	117	-3h	Episode 31; tilt 3/11–14	
4/21/1985 15:16	4/22/1985 9:06	MERZ	E		21.4	114	-4h 44m	Episode 32; tilt 4/21–23	
5/20/1985 06:16	5/20/1985 08:10	ms2	EQS	6	flat			Nāmakanipaio[9]	
6/11/1985 05:19	6/11/1985 19:12	sf3kuer	EQS	9				South flank anticipation	
6/12/1985 23:06	6/13/1985 4:53	MERZ	E		7.7	110	-0h 54m	Episode 33; tilt 6/12–14; 2-step def	
6/13/1985 11:13	6/13/1985 16:58	sf3kuer	EQS	9				South flank response	
7/6/1985 19:03	7/7/1985 8:50	MERZ	E		18.3	118	-3h 57m	Episode 34; tilt 7/6–8	
7/26/1985 2:52	7/26/1985 9:52	MERZ	E		10.5	119	+0h 52m	Episode 35; tilt 7/25–26	
7/27/1985 4:14	8/12/1985 4:30	MERZ	E					Episode 35a—fissure continuation	
9/2/1985 14:00	9/2/1985 23:35	MERZ	E		14.4	110	-3h	Episode 36; tilt 9/2–3	
9/24/1985 18:08	9/25/1985 6:19	MERZ	E		14.3	104	-5h 52m	Episode 37; tilt 9/24–25	

Table 7.1. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IA—2/1/1983–7/20/1986 (see fig. 7.1).—Continued

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

Date and time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
10/5/1985 21:12	10/6/1985 20:44	sf3.2	SDI??	8, 4	flat			Possibly a suspected deep intrusion	G6
10/21/1985 3:00	10/21/1985 11:24	MERZ	E		17.2	113	+1h	Episode 38; tilt10/20–22	
11/13/1985 15:34	11/14/1985 1:24	MERZ	E		16.0	110	-1h 26m	Episode 39; tilt 11/13–15	
12/31/1985 13:35	12/31/1985 17:55	ms2	EQS	8				Nāmakanipaio[9]	
1/1/1986 13:09	1/2/1986 2:38	MERZ	E		14.5	114	-1h 51m	Episode 40; tilt 1/1–2	
1/27/1986 20:35	1/28/1986 7:57	MERZ	E		14.0	112	-0h 25m	Episode 41; tilt 1/27–28	
1/27/1986 13:36	1/30/1986 06:54	sf3kuer	EQS	11				Weak south flank anticipation/response	
2/22/1986 15:15	2/23/1986 4:20	MERZ	E		6.4	111	-1h 45m	Episode 42; tilt 2/22–23	
3/22/1986 4:50	3/22/1986 15:56	MERZ	E		12.7	107	-0h 45m	Episode 43; tilt 3/21–23	
4/13/1986 20:54	4/14/1986 7:56	MERZ	E		24.5	102	-3h 6m	Episode 44; tilt 4/11–14	
5/7/1986 15:45	5/7/1986 21:07	sf3kuer	EQS	8				Weak south flank anticipation	
5/7/1986 22:41	5/8/1986 11:06	MERZ	E		13.3	123	no data	Episode 45; tilt 5/7–8	
6/2/1986 2:29	6/2/1986 13:20	MERZ	E		14.6	105	no data	Episode 46; tilt 6/1–2	
6/26/1986 4:19	6/26/1986 16:35	MERZ	E		23.5	116	no data	Episode 47; tilt 6/25–29	
7/18/1986 12:05	7/19/1986 09:30	MERZ	E		17.9	106	no data	Episode 48 fissure eruption	G7

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai‘i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword “kl.erz.1983”.

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3, and locations are shown on appendix figure A4.

[3]Event types defined in chapter 1 are abbreviated as follows: **E**, Eruption; intrusion (“traditional” **I;** “inflationary” **II;** “suspected deep” **SDI**); **EQS**, earthquake swarms; EQ, earthquake $M\geq4$; “surge”—abrupt inflation at Kīlauea’s summit followed by an increase in magma output at Pu‘u ‘Ō‘ō. These later become “d-i-d” events in which there is a preliminary deflation at Kīlauea’s summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu‘u ‘Ō‘ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (µrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna vault.

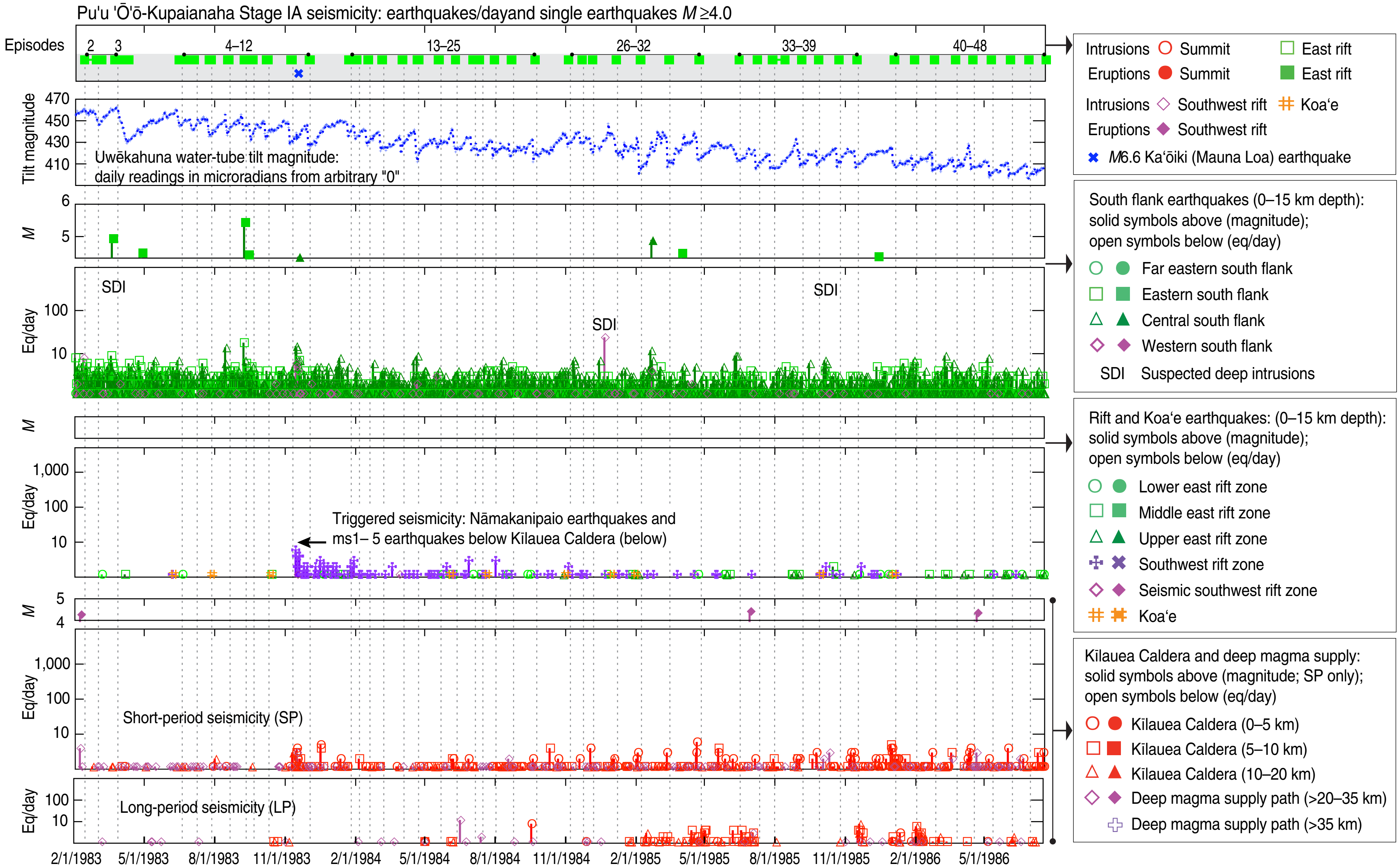
[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu‘u ‘Ō‘ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu‘u ‘Ō‘ō vent (E) time lag in hours.

[7]Abbreviations as follows: ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); I-A, Ideal-Arrowsmith continuously recording tiltmeter in Uwēkahuna vault; drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix figures plain text.

[9]Continuation of earthquakes triggered by the 1983 Ka‘ōiki earthquake. Locations are beneath the Nāmakanipaio campground in Hawai‘i Volcanoes National Park.

[10]Klein and others, 2006.


Pu'u 'Ō'ō-Kupaianaha Stage IA seismicity: earthquakes/dayand single earthquakes $M \geq 4.0$
Episodes
2
3
4–12
13–25
26–32
33–39
40–48
Tilt magnitude
Uwēkahuna water-tube tilt magnitude:
daily readings in microradians from arbitrary "0"
M
Eq/day
SDI
Triggered seismicity: Nāmakanipaio earthquakes and
ms1– 5 earthquakes below Kīlauea Caldera (below)
Short-period seismicity (SP)
Long-period seismicity (LP)
2/1/1983
5/1/1983
8/1/1983
11/1/1983
2/1/1984
5/1/1984
8/1/1984
11/1/1984
2/1/1985
5/1/1985
8/1/1985
11/1/1985
2/1/1986
5/1/1986
Intrusions Summit East rift
Eruptions Summit East rift
Intrusions Southwest rift Koa'e
Eruptions Southwest rift
M6.6 Ka'ōiki (Mauna Loa) earthquake
South flank earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Far eastern south flank
Eastern south flank
Central south flank
Western south flank
SDI Suspected deep intrusions
Rift and Koa'e earthquakes: (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Lower east rift zone
Middle east rift zone
Upper east rift zone
Southwest rift zone
Seismic southwest rift zone
Koa'e
Kīlauea Caldera and deep magma supply:
solid symbols above (magnitude; SP only);
open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–10 km)
Kīlauea Caldera (10–20 km)
Deep magma supply path (>20–35 km)
Deep magma supply path (>35 km)

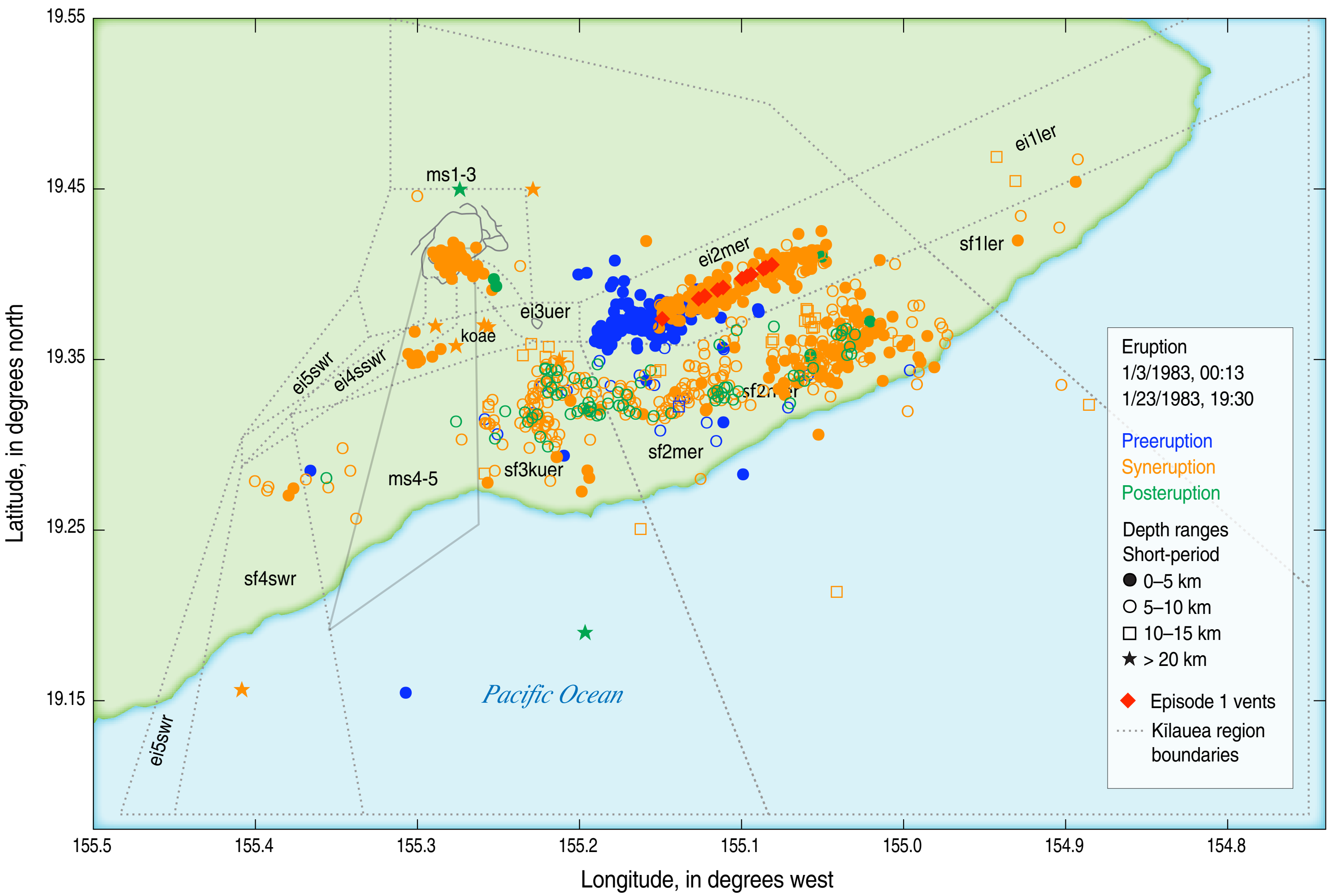


Figure 7.2. Map showing Kīlauea activity, January 1 through January 31, 1983: Puʻu ʻŌʻō-eruption episode 1. Preeruption intrusion is uprift of the vents, and intrusion during the eruption occurs beneath the erupting vents on the upper east rift zone and extends somewhat farther east. The zone due south of the upper east rift zone, which is the locus of many suspected deep intrusions, was apparently activated by a seismic passage of magma on the way to being erupted. Dates on figure in m/d/yyyy format.

Figure 7.1. Graphs showing Kīlauea activity, 1 February 1983–20 July 1986: Stage IA of the Puʻu ʻŌʻō-Kupaianaha eruption. Time-series plots show the number of earthquakes per day and magnitudes (*M*) ≥4 plotted against times of eruption and intrusion and the Uwēkahuna tilt magnitude. Symbols are given on the plots. Seismic regions are shown in figure A4 of appendix A. Top panel: Times of eruption and traditional intrusion. Numbered episodes of the Puʻu ʻŌʻō-Kupaianaha eruption are shown. Vertical dashed lines connect seismicity associated with eruptions and associated traditional intrusions. Second panel from top: Uwēkahuna tilt magnitude related to times of eruption and intrusion emphasized by vertical dotted lines. Tilt magnitudes are given in microradians. Bottom seven panels: seismicity is plotted, from bottom to top, for the magma supply path (divided into short-period and long-period earthquakes), 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. Three types of intrusions are defined in chapter 1. Traditional intrusions are shown as intrusion symbols. Inflationary intrusions are labeled (II), and suspected deep intrusions are labeled (SDI) but are not plotted as intrusions. Dates on figure in m/d/yyyy format.

Pause: A temporary cessation in eruptive activity. The earliest pauses were accompanied by significant tilt and earthquake signals, whereas later pauses gradually came to lack such association.

Surge: A visible increase in eruptive activity at Puʻu ʻŌʻō. The earliest surges followed a pattern of correlated gradual deflation at Kīlauea's summit and Puʻu ʻŌʻō, followed by rapid inflation of several microradians and a subsequent less rapid deflation, as measured by continuously recording tiltmeters. Once the tilt correlation was recognized, these become known as "deflation-inflation-deflation" (D-I-D) events. Eventually the D-I-D events were no longer associated with visible changes in eruptive activity and the tilt signal shifted to a smaller paired and nearly simultaneous rapid deflation and inflation at Kīlauea's summit and at Puʻu ʻŌʻō.

Earthquake swarm (eqs): Located earthquakes are from the HVO catalog and consist of both brittle-failure (short-period) and long-period events. A continuous sequence consisting of at least 10 earthquakes of one type within a single region separated by times of less than 6 hours is designated as an earthquake swarm. Most earthquake swarms consist of more than 10 events occurring at rates exceeding one earthquake per hour. Swarms are caused by a sustained increase in stressing rate and are almost always associated with magma movement of some kind.

Silent earthquakes: "Silent" or "slow" earthquakes (see, for example, Cervelli and others, 2002b; Segall and others, 2006) represent an abrupt increase in the rate of south flank spreading and are accompanied by a sequence of south flank earthquakes not related to a rift intrusion.

Intrusion: We recognize three types of intrusions, "traditional," "inflationary." and "suspected deep," as defined in chapter 1. Traditional and inflationary intrusions are associated with earthquake swarms at depths of 2 km or less. Traditional intrusions have a sharp tilt drop at Kīlauea's summit and may occur alone or as part of an eruptive sequence. Inflationary intrusions occur during stable tilt or continuing inflation and are confined to the near-summit parts of the rift zones. The suspected deep intrusions were originally named "slow" (Klein and others, 1987; Wright and Klein, 2008). The name change is made to emphasize their association with deeper magmatic processes and to avoid confusion with traditional intrusions that evolve slowly.

Tilt changes: Tilt changes are measured daily by the short-base water-tube tiltmeter located in the Uwēkahuna Vault and are expressed as an azimuth in degrees measured clockwise from north and a magnitude in microradians. The water-tube results are compared with readings from a single component (east-west) continuously recording Ideal-Aerosmith ("I-A") tiltmeter co-located in the Uwēkahuna Vault from June 1965 to May 1992. Beginning in January 1999, a two-component continuously recording borehole tiltmeter ("UWE") was installed near the Uwēkahuna Vault site.

"Lag" times (in tables): The difference in time, given in hours (h) and minutes (m) between (1) the onset of an earthquake swarm near the site of eruption and a deflection on the continuously recording tiltmeters I-A and UWE or (2) the difference in time between the onset of sharp inflation or deflation at Kīlauea's summit and observed increase in eruptive activity. Most intrusions have a negative value for (1), which means that the onset of the earthquake swarm began before the change in tilt. All values for (2) are positive because tilt changes begin at Kīlauea's summit before changes on the rift zone.

Stage IA: Episodic Eruption at Puʻu ʻŌʻō, 1 February 1983–20 July 1986

Table 7.1 and figure 7.1 summarize all eruptions, intrusions, earthquake swarms, and other significant events for stage IA. Figures showing earthquake locations for selected events are referenced in the right-hand column of the table 7.1. Some figures may show the near-simultaneous occurrence of more than one type of event.

Following the end of episode 1, the eruption devolved into a series of 46 high-fountaining events, each lasting for 6–60 hours, separated by quiet intervals of about a month. The tilt and seismicity patterns of individual Puʻu ʻŌʻō episodes during stage IA mimic the behavior of previous small rift eruptions and of early episodes of Mauna Ulu in 1969. Each episode was immediately preceded by a sharp drop in summit tilt, with partial recovery in between. Each episode shows a remarkably similar deflation azimuth, ranging from 102 to 127 degrees, mostly between 110 and 120 degrees, closely matching the initial deflation azimuth of episode 1. By the end of stage IA the net deflation at Kīlauea's summit was more than 190 µrad at an azimuth of 150 degrees.

Mauna Loa's Ka'ōiki Earthquake of 16 November 1983: Triggered Seismicity at Kīlauea

On 16 November 1983 a *M*6.7 earthquake occurred on Mauna Loa's Ka'ōiki Fault Zone[25] (see Buchanan-Banks, 1987; Jackson and others, 1992). The earthquake triggered seismicity beneath Kīlauea, shown well by the earthquake counts (fig. 7.1). Counts of earthquakes deeper than 20 km increased dramatically, as did located events immediately west of Kīlauea Caldera, referred to as "Nāmakanipaio" for their proximity to a Kīlauea campground of that name (Okubo and Nakata, 2003, p. 178)[26]. The latter occur in two regions (fig. 7.3), which became active because they are part of the aftershock zone (not shown). The southern region may correspond to a Ka'ōiki fault plane, now concealed beneath lava erupted from Kīlauea's southwest rift zone. The northern region may correspond to either the northern continuation of the same Ka'ōiki fault or a concealed former Kīlauea Caldera boundary fault now covered by lava erupted from Kīlauea's summit (A. Miklius, oral. commun., 2005). Both of these regions are active over the first 4 days following the 1983 earthquake. The southern region was not active again, but the northern region has shown periodic swarms during the entire Pu'u 'Ō'ō eruption (events labeled Nāmakanipaio in table 7.1) and nonswarm activity at many other times. The counts of events deeper than 20 km decrease and reach background levels by February 1984 (fig.7.1).

[25] Located on the lower slopes of Mauna Loa's south flank adjacent to Kīlauea.

[26] Nāmakanipaio can be regarded as an extension of the aftershock zone.

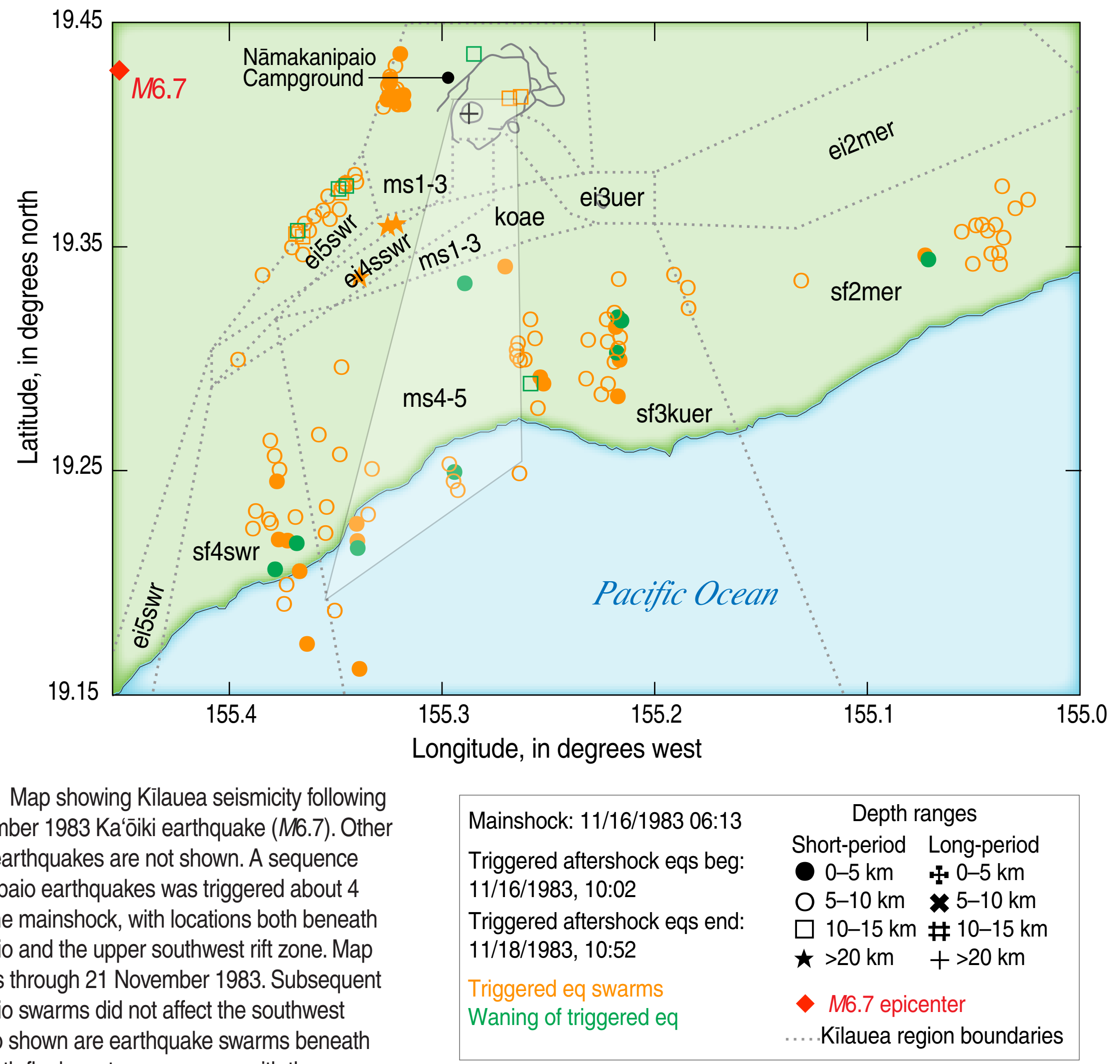


Figure 7.3. Map showing Kīlauea seismicity following the 16 November 1983 Ka'ōiki earthquake (*M*6.7). Other Mauna Loa earthquakes are not shown. A sequence of Nāmakanipaio earthquakes was triggered about 4 hours after the mainshock, with locations both beneath Nāmakanipaio and the upper southwest rift zone. Map shows events through 21 November 1983. Subsequent Nāmakanipaio swarms did not affect the southwest rift zone. Also shown are earthquake swarms beneath Kīlauea's south flank contemporaneous with the Nāmakanipaio swarm, which have the characteristics of suspected deep intrusions at four different places from the western to the eastern south flank. Dates on figure in m/d/yyyy format.

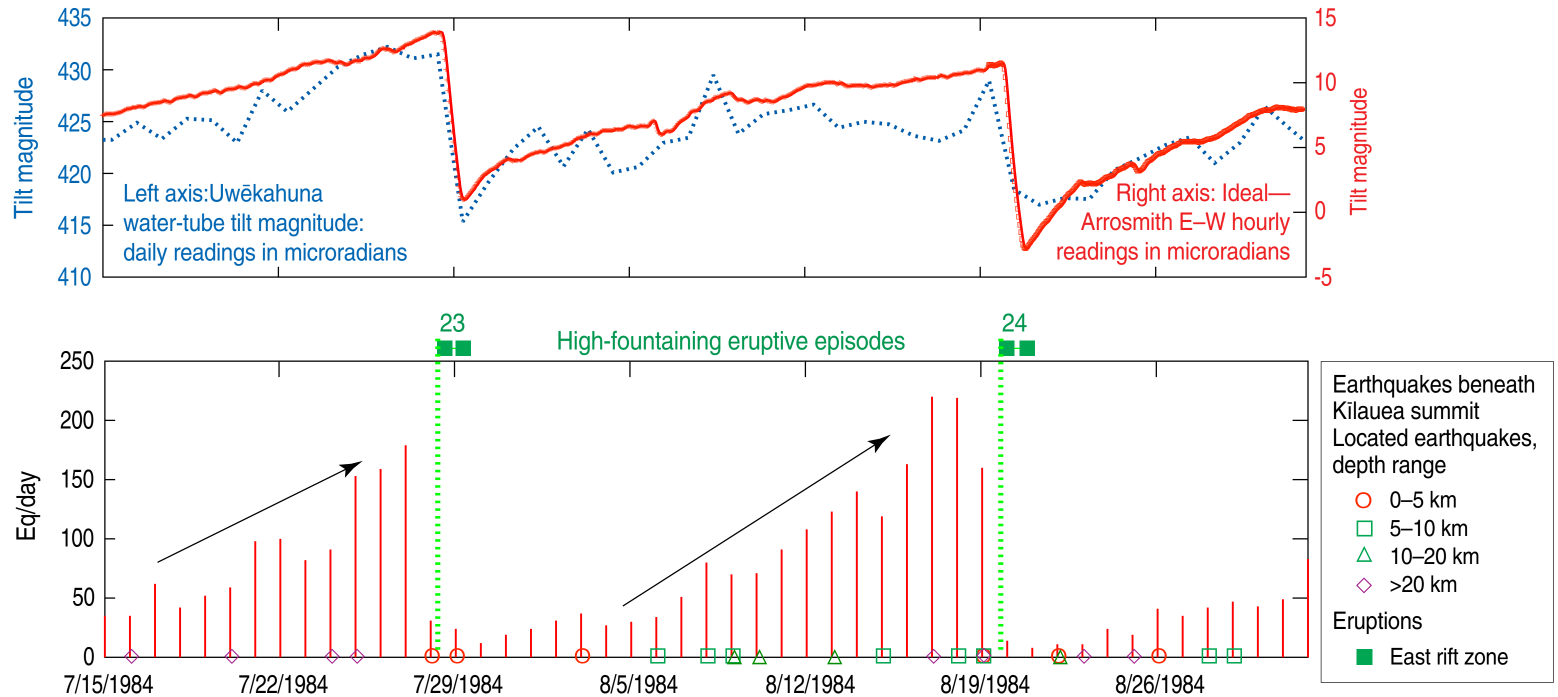


Figure 7.4. Plots showing cyclic variation of summit tilt (top panel) and numbers of short-period earthquakes per day (eq/day) too small to locate (red bars, bottom panel) at 0–5 km beneath Kīlauea's summit during stage IA of the Pu‘u ‘Ō‘ō-Kupaianaha eruption. Shown here are patterns for episodes 23 and 24; data from 15 July to 1 September 1984. Earthquake counts increase before each episode, then decrease during the eruptive fountaining. The cyclic variation of summit tilt is shown by both water-tube tilt measured daily and Ideal-Aerosmith electronic tilt measured continuously but recorded hourly. Dates on figure in m/d/yyyy format.

Located earthquakes at 10–20 km depth beneath Kīlauea's summit (ms3, defined in appendix A, table A3) increase following the Ka'ōiki earthquake, but then die off quickly.

Several rhythmic variations in earthquake counts are associated with eruptive episodes. Short-period daily counts of summit earthquakes above 5-km depth increase before eruptive episodes (fig. 7.4). Long-period counts at the same depth show a less steady rhythmic pattern. The rhythmic increase in shallow short-period counts before eruptive episodes is less obvious in the period preceding episodes 12 and 13, immediately following the Ka'ōiki earthquake.

There were no traditional intrusions, as revealed by rift earthquake swarms, associated with any of the high-fountaining episodes following episode 1. Two periods of increased south flank seismicity between episodes, which are classified as potential suspected deep intrusions, are listed in table 7.1. The lack of continuously recorded deformation data precludes the identification of spreading steps associated with these earthquake swarm events.

Stage IB: Continuous Eruption at Kupaianaha, 20 July 1986–8 November 1991

A fissure eruption extending downrift from Pu'u 'Ō'ō on 18 and 19 July 1986 (HVO episode 48) marks the transition from episodic eruption at Pu'u 'Ō'ō to continuous eruption at Kupaianaha, which is at the eastern or lower end of the fissure system (Heliker and Mattox, 2003). There is no obvious precursory seismicity to indicate that emplacement of a new dike caused a change of eruption style and location. A small shield surmounted by an active lava lake was built over the Kupaianaha vent, and Kupaianaha grew both by endogenous processes and by periodic overflow. Activity at Kupaianaha gradually declined toward the end of stage IB. Its demise on 7 February 1992 was predicted several months before that by extrapolation of its declining flow rate (Kauahikaua and others, 1996). Events of this period are summarized in table 7.2 and figure 7.5.

Kīlauea seismic activity continued at near-normal levels during stage IB as the summit continued to deflate. The average daily Uwēkahuna tilt azimuth for the entire Kupaianaha period (1986–92) is 198 degrees, near the westernmost Fiske-Kinoshita inflation-deflation centers defined in chapter 4, figure 4.2. This is consistent with the shift of summit subsidence to include Kīlauea's southwest rift zone (see, for example, HVO monthly report for February 1990; (Delaney and others, 1998)). The overall rate of seismicity beneath the shallow summit, rift zones, and Koa'e in stage IB increases relative to stage IA, but the south flank seismicity decreases and magma supply seismicity deeper than 5 km remains about the same.

The following events (table 7.2) occurred within stage IB: (1) the onset of located long-period earthquake swarms deeper than 5 km beneath Kīlauea's summit (lpc-c), beginning in May 1987[27] and continuing throughout stage IB (fig. 7.5), (2) a suspected deep intrusion on 22–24 March 1990 (fig. 7.6), (3) pauses in the continuous eruption beginning in April 1988 (fig. 7.4), (4) a magnitude 6.2 south flank earthquake on 26 June 1989 with aftershocks, and (5) four intrusions into the upper east rift zone.

Pauses in the supply of magma to the eruption have a seismic as well as a tilt signature. The first eruption pause occurred at the end of April 1988. Subsequently there was a series of pauses in 1990 that showed variation in summit tilt and seismic signature within a specific time sequence. All pauses were preceded by an increase in lpc-c (5–13 km) earthquake counts, followed shortly (except for the 1988 pause) by a small deflation measured on the continuously recording Ideal-Aerosmith tiltmeter. The pause in eruption began following the end of deflation and ended sometime after the summit began to reinflate. Tilt and seismicity associated with two typical pauses are shown in figure 7.7. This pattern gradually disappeared in the pauses of stage II.

Swarms of long-period earthquakes (lpc-c) greatly increased after May 1987 and became continuous between March 1989 and March 1990 (fig. 7.5). They were unusual in that all previous long-period swarms had been shallow, as documented for the 1977 eruption in chapter 6. The deep long-period earthquake swarms decreased to background levels by the end of 1991.

The earthquake of 26 June 1989 (Arnadottir and others, 1991; Delaney and others, 1993; Dvorak, 1994) occurred within a normal seismic background (fig. 7.5). The earthquake was followed by an aftershock sequence extending offshore and produced a south flank displacement of more than 25 cm and an almost equal amount of subsidence south of the lower east rift zone (Delaney and others, 1993; Dvorak, 1994). Focal mechanisms indicate that offset occurred on planes shallower than the decollement (Arnadottir and others, 1991; Bryan, 1992). Although not recognized at the time, the declining occurrence rate of such $M\geq5$ south flank earthquakes may have been influenced by the declining residual stress field of the 1868 $M8$ event (Klein and Wright, 2008) that occurred more than a century earlier. The 1989 earthquake had no apparent effect on the eruption.

The intrusion of 4 December 1990 (table 7.2; fig. 7.5) was the first large intrusion to occur in the

[27] Previous to 1987, long-period earthquakes deeper than 5 km had occurred individually, but not in noticeable swarms.

Table 7.2. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IB—7/18/1986–11/8/1991 (see fig. 7.5).

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
7/18/1986 12:05	7/19/1986 9:30	MERZ	E[9]		23.5	106	no data	Episode 48[9] tilt 7/18–19	G8
7/20/1986 8:30	2/7/1992 0:00	MERZ	E[10]		5.4	122	no data	Episode 48[10]; tilt 7/25–27	
9/13/1986 12:15	9/13/1986 19:58	ms2.1	EQS	13, 1	4.8	303		Nāmakanipaio[11]; tilt 9/12–15 inflation	G9
5/19/1987 3:13	5/19/1987 7:30	sf3kuer	SDI	8				Weak swarm	
6/7/1987 20:26	6/8/1987 08:55	lpms3	EQS	22					
6/11/1987 13:12	6/13/1987 09:03	lpms3	EQS	27					
8/8/1987 21:23	8/9/1987 02:37	sf3.2	SDI	9, 3					
2/17/1988 00:02	2/18/1988 21:52	lpms3	EQS	37					
3/11/1988 03:13	3/14/1988 07:44	lpms3	EQS	44					
7/11/1988 17:43	7/12/1988 01:19	ms1-2	EQS	16				Nāmakanipaio[11]	G10
8/16/1988 16:29	8/17/1988 03:57	lpms3	EQS	23					
9/17/1988 12:56	9/17/1988 15:41	ei3uer	I	9	3.4	160		Tilt 9/18–20	G11
6/25/1989 17:27			EQ					*M*6.21 mainshock[12]	G12
6/25/1989 17:32	6/29/1989 01:23			152				Aftershocks continue to 7/10	
7/25/1989 20:04	7/30/1989 17:45	lpms2.3	EQS	104					
8/5/1989 00:23	8/6/1989 03:59	lpms2	EQS	11					
8/6/1989 18:05	8/7/1989 17:08	do	do	17					
8/8/1989 04:07	8/9/1989 08:04	do	do	11					
8/29/1989 03:14	8/31/1989 12:22	lpms2	EQS	27					
9/10/1989 17:36	9/11/1989 15:30	lpms2	EQS	24					
10/1/1989 17:54	10/6/1989 09:45	lpms2	EQS	61					
10/10/1989 08:50	10/12/1989 06:10	lpms2	EQS	78					
10/10/1989 10:59	10/12/1989 09:45	lpms3	EQS	62					
10/18/1989 03:27	10/20/1989 03:13	lpms3	EQS	92					
10/19/1989 05:25	10/20/1989 03:04	lpms2	EQS	79					
11/21/1989 14:13	11/25/1989 01:41	lpms3	EQS	44					
11/24/1989 09:35	11/27/1989 11:49	lpms2	EQS	45					
11/27/1989 02:22	11/29/1989 09:14	lpms3	EQS	30					
12/6/1989 19:42	12/9/1989 16:36	lpms2	EQS	46					
12/28/1989 20:50	12/30/1989 04:35	lpms2	EQS	33					
12/28/1989 21:12	12/30/1989 07:10	lpms3	EQS	29					

Table 7.2. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IB—7/18/1986–11/8/1991 (see fig. 7.5).—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
1/17/1990 22:06	1/19/1990 10:47	lpms2	EQS	27					
2/4/1990 07:14	2/5/1990 22:04	lpms3	EQS	45					
3/22/1990 22:54	3/24/1990 06:15	sf3kuer	SDI	22					**7.6**
5/4/1990 23:09	5/5/1990 12:49	lpms3	EQS	27					
8/8/1990 16:06	8/9/1990 09:27	sf2mer	EQ					*M*4.7	
11/11/1990 18:20	11/11/1990 23:10	ms1.2	EQS	2, 4				Precursory Nāmakanipaio[11, 13]	G13
12/4/1990 16:29	12/4/1990 19:29	ms1	I	11	9.2	302	no data	Tilt 12/3–4	G13
12/4/1990 17:13	12/4/1990 22:24	er3.2	I	29, 4				Downrift migration 6.3 km/hr	
1/7/1991 17:04	1/15/1991 06:29	lpms3	EQS	204	8.8	101		Tilt 1/5–19	
3/13/1991 10:27	3/13/1991 11:33	ms1.2	EQS	7, 6				Precursory Nāmakanipaio[11, 13]	G14
3/26/1991 05:33	3/26/1991 15:27	ei3uer	I	97	17.7	107	+1h 33m	Tilt 3/21–26; downrift migration 1.3 km/hr; uprift migration 0.53 km/hr	G14
3/26/1991 05:39	3/26/1991 11:55	sf3kuer	EQS	13				South flank accompaniment—6 eq on 3/28	
8/10/1991 19:08	8/10/1991 23:05	ms1.2		1, 6				Precursory Nāmakanipaio[11, 13]	G15
8/21/1991 11:05	8/21/1991 15:23	ei3uer	I	58	5.0	291	+0h 05m	Tilt 8/20–24—inflation; I-A: < 1 μrad deflation 8/21 11:00–12:00	G15

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai‘i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword "kl.erz.1983".

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3 and locations are shown on appendix figure A4.

[3]Event types defined in chapter 1 are abbreviated as follows: **E**, Eruption; intrusion ("traditional" **I;** "inflationary" **II;** "suspected deep" **SDI**); **EQS**; earthquake swarms; EQ, Earthquake $M \geq 4$; "surge"—abrupt inflation at Kīlauea's summit followed by an increase in magma output at Pu‘u ‘Ō‘ō. These later become "d-i-d" events in which there is a preliminary deflation at Kīlauea's summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu‘u ‘Ō‘ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (μrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna Vault.

[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu‘u ‘Ō‘ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu‘u ‘Ō‘ō vent (E) time lag in hours.

[7]Abbreviations as follows: ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); I-A, Ideal-Arrowsmith continuously recording tiltmeter in Uwēkahuna Vault; drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix figures plain text.

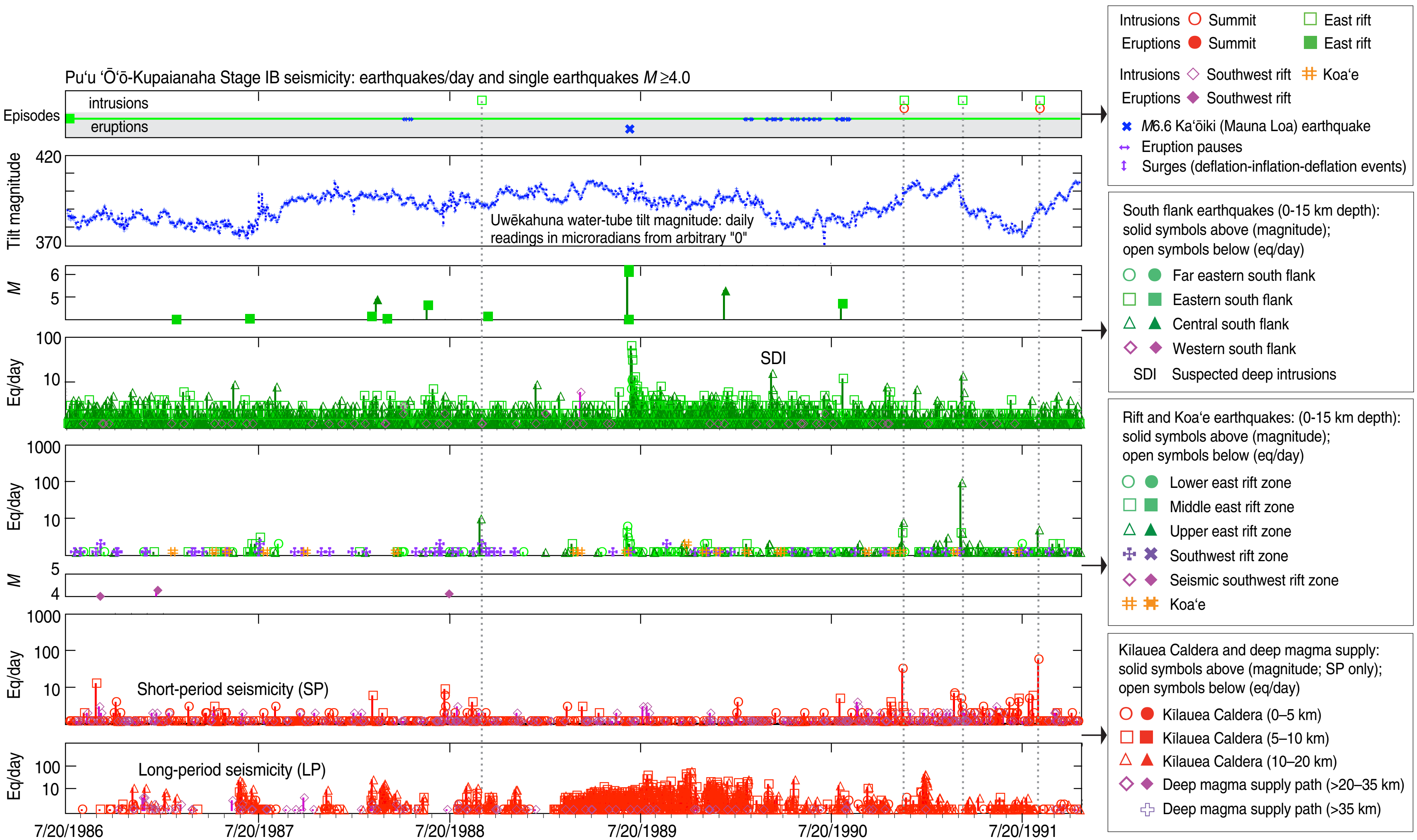
[9]Fissure eruption.

[10]Continuous eruption.

[11]Continuation of earthquakes triggered by the 1983 Ka‘ōiki earthquake. Locations are beneath the Nāmakanipaio campground in Hawai‘i Volcanoes National Park.

[12]Klein and others, 2006.

[13]Identified as precursor to following east rift intrusion (Okubo and Nakata, 2003).



Pu‘u ‘Ō‘ō-Kupaianaha Stage IB seismicity: earthquakes/day and single earthquakes $M \geq 4.0$
Episodes
intrusions
eruptions
Tilt magnitude
420
370
Uwēkahuna water-tube tilt magnitude: daily readings in microradians from arbitrary "0"
M
6
5
Eq/day
100
10
SDI
1000
100
10
M
5
4
1000
100
10
Short-period seismicity (SP)
100
10
Long-period seismicity (LP)
7/20/1986
7/20/1987
7/20/1988
7/20/1989
7/20/1990
7/20/1991
Intrusions Summit East rift
Eruptions Summit East rift
Intrusions Southwest rift Koa‘e
Eruptions Southwest rift
M6.6 Ka‘ōiki (Mauna Loa) earthquake
Eruption pauses
Surges (deflation-inflation-deflation events)
South flank earthquakes (0-15 km depth): solid symbols above (magnitude); open symbols below (eq/day)
Far eastern south flank
Eastern south flank
Central south flank
Western south flank
SDI Suspected deep intrusions
Rift and Koa‘e earthquakes: (0-15 km depth): solid symbols above (magnitude); open symbols below (eq/day)
Lower east rift zone
Middle east rift zone
Upper east rift zone
Southwest rift zone
Seismic southwest rift zone
Koa‘e
Kīlauea Caldera and deep magma supply: solid symbols above (magnitude; SP only); open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–10 km)
Kīlauea Caldera (10–20 km)
Deep magma supply path (>20–35 km)
Deep magma supply path (>35 km)

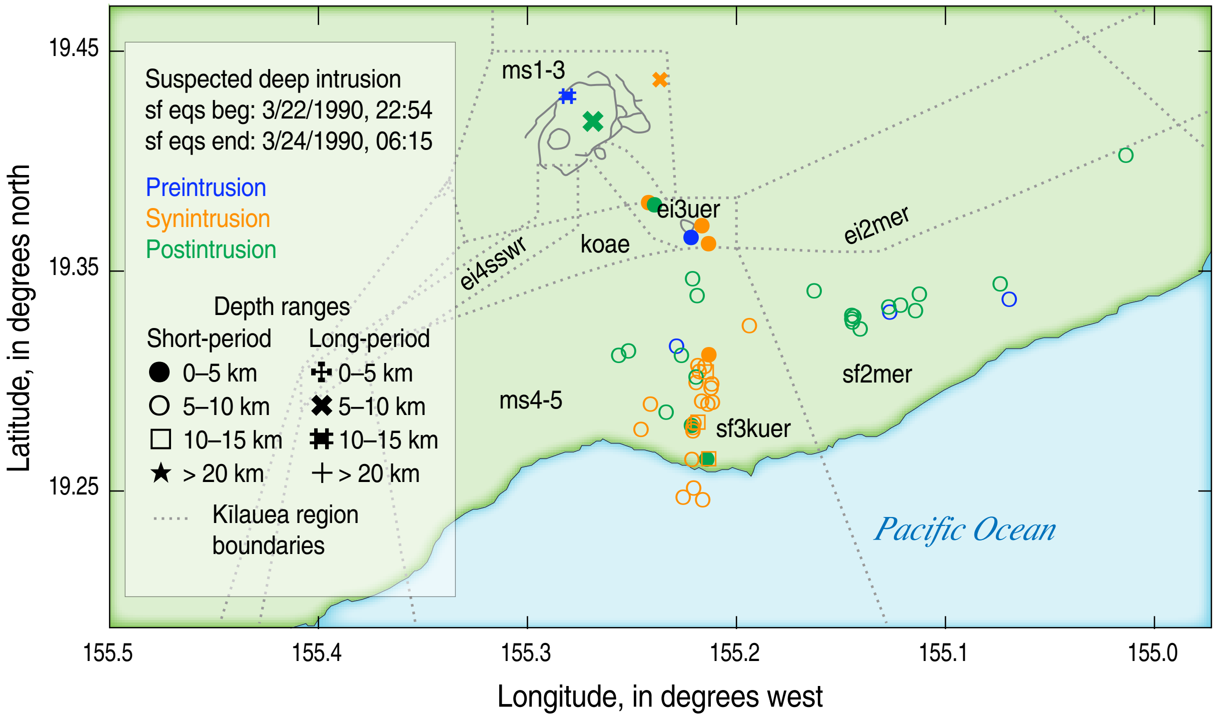


Figure 7.6. Map showing seismicity on Kīlauea, 22–28 March 1990 associated with a strong suspected deep intrusion beneath the central south flank from 22 to 24 March, possibly associated with weak intrusive activity beneath the upper east rift. Dates on figure in m/d/yyyy format.

Figure 7.5. Graphs showing Kīlauea activity, 20 July 1986–8 November 1991: Stage IB of the Pu‘u ‘Ō‘ō-Kupaianaha eruption. Time-series plots show the number of earthquakes per day (eq/day) and magnitudes (*M*) ≥4 plotted against times of eruption and intrusion and the Uwēkahuna tilt magnitude. Symbols are given on the plots. Seismic regions are shown in figure A4 of appendix A. Three types of intrusions are defined in chapter 1. Traditional intrusions are shown as intrusion symbols. Inflationary intrusions are labeled (II), and suspected deep intrusions are labeled (SDI) but not plotted as intrusions. Panels from top to bottom show the following: (a), Times of eruption and intrusion. Vertical dotted lines connect seismicity associated with eruptions and associated traditional intrusions. Vertical dashed lines connect traditional and inflationary intrusions not associated with an eruption. (b), Uwēkahuna tilt magnitudes in microradians. (c), South flank earthquake magnitudes. (d), South flank earthquakes per day. (e), Rift and Koa‘e earthquake magnitudes. (f), Rift and Koa‘e earthquakes per day. (g), Kīlauea Caldera and deep magma-supply earthquake magnitudes. (h), Kīlauea Caldera and deep magma-supply earthquakes per day—short-period data. (i), Kīlauea Caldera and deep magma-supply earthquakes per day—long-period data. Dates on figure in m/d/yyyy format.

more than 7 years since the initial intrusion associated with the beginning of eruption in January 1983, and it was the second of four intrusions during stage IB. Less than a month before the December 1990 intrusion, a swarm of Nāmakanipaio earthquakes occurred west of Kīlauea Caldera (Okubo and Nakata, 2003; table 7.2). During the intrusion of 4 December 1990 the daily tilt at Uwēkahuna recorded a sudden inflation east of Halema‘uma‘u between Fiske-Kinoshita centers 1 and 2. Earthquakes began beneath the summit and extended southeast to the upper east rift zone. A few south flank earthquakes occurred both before and after this intrusion.

The intrusion of 26 March 1991 also was preceded by a Nāmakanipaio earthquake swarm west of Kīlauea Caldera (table 7.2). The summit began deflating several days before the intrusion, and the rate of deflation accelerated about 1.5 hours before the east rift earthquake swarm. The extent of uplift and horizontal displacement are not known, because ground deformation data were not available close to the time of intrusion. The earthquake swarm was concentrated in the upper east rift zone near the eastern termination of the previous intrusion. South flank seismicity during the intrusion was focused parallel to and south of the rift zone.

A fourth intrusion in the same upper east rift region occurred on 21 August 1991, preceded by Nāmakanipaio seismicity on 10 August 1991 (table 7.2). The intrusion was preceded and followed by very few south flank earthquakes.

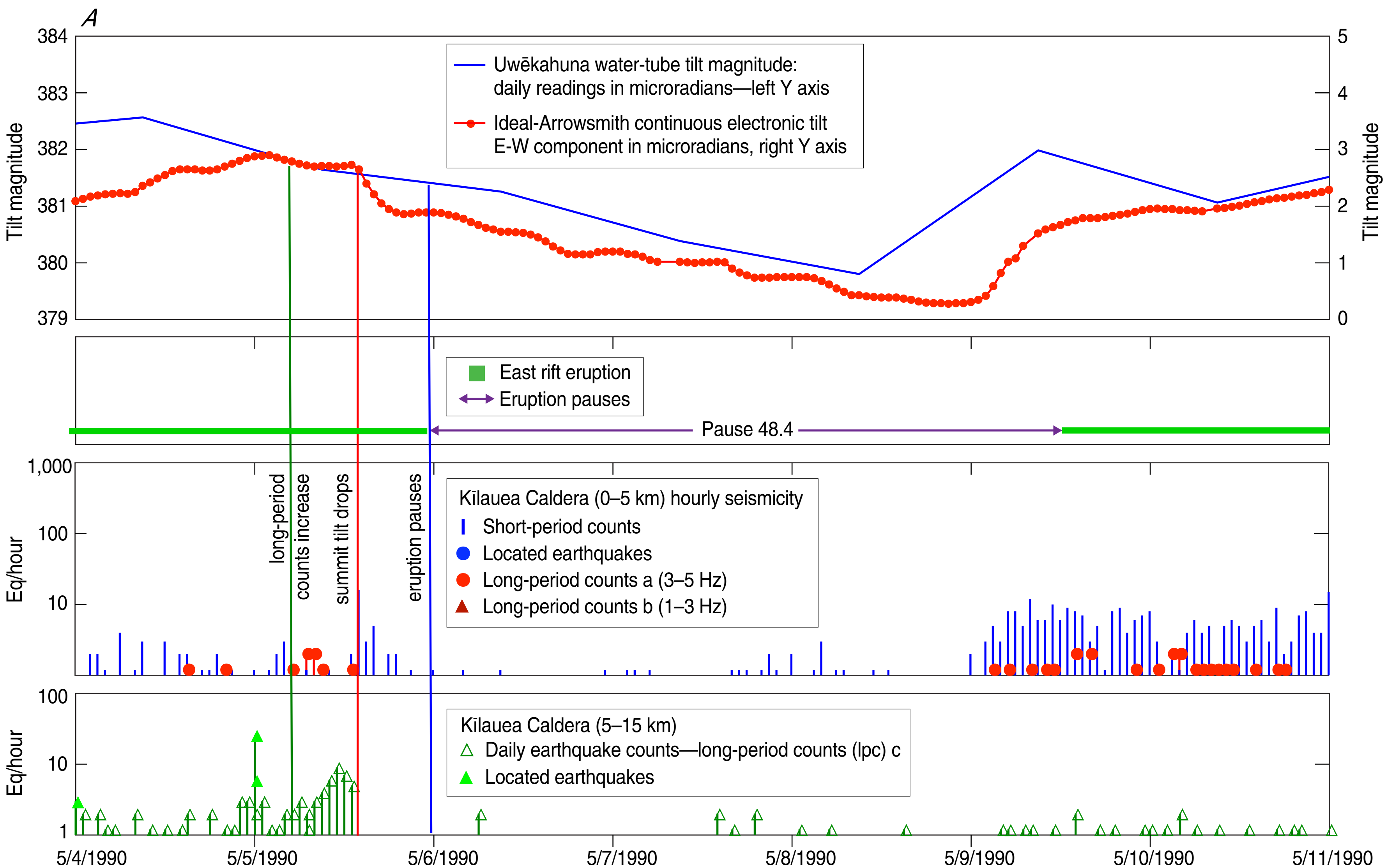


Figure 7.7. Plots of long-period earthquakes per hour (eq/hour) beneath Kīlauea's summit associated with pauses in the eruption during stage IB of the Pu'u 'Ō'ō-Kupaianaha eruption. Pauses began in 1988 (pause 48.1), and eight more occurred in 1990 (pauses 48.2–48.9). See Heliker and Mattox (2003). Each pause was preceded by an increase in lpc-c earthquakes beneath Kīlauea's summit, followed by a small deflation at Kīlauea's summit. lpc-c earthquakes are mostly absent during the pause, and shallow short-period earthquake counts pick up before the eruption resumes. See text for further explanation. Dates on figure in m/d/yyyy format. ***A***, Seismic sequences for pause 48.4, 6–9 May 1990. ***B***, Seismic sequences for pause 48.7, 31 July–2 August 1990.

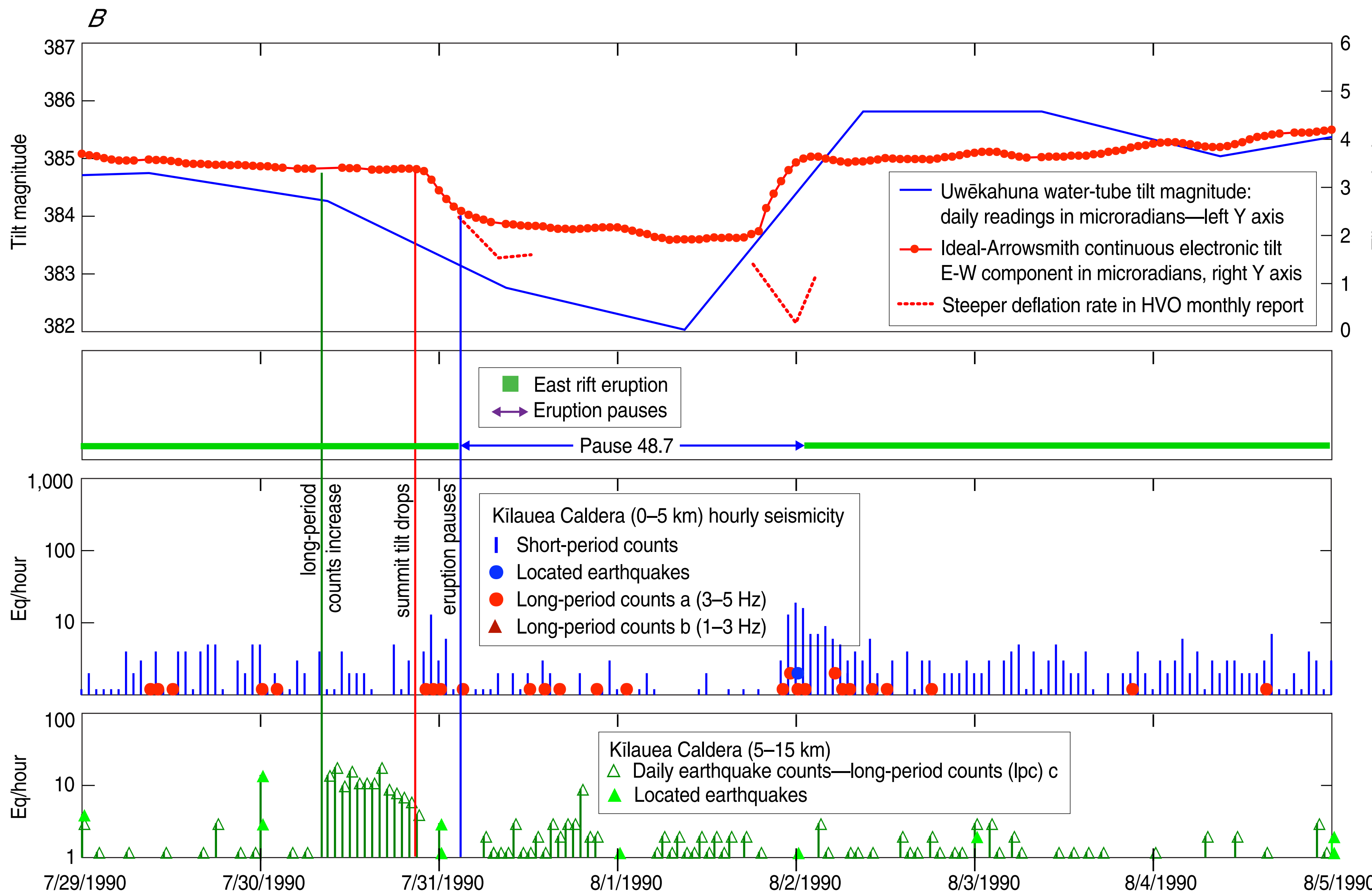


Figure 7.7.—Continued

Stage IIA: Return of Eruption to Puʻu ʻŌʻō, 8 November 1991–1 January 1997

Lava returned to the flanks of Puʻu ʻŌʻō on 8 November 1991 in episode 49 (Heliker and others, 1998; Mangan and others, 1995). Episode 49 was preceded by about 3.5 months of summit inflation, with no increase in seismicity anywhere on the volcano (figs. 7.5, 7.8), and was accompanied by a sharp summit deflation (table 7.3, fig. 7.8) and by a few long-period earthquakes down to 10 km beneath Kīlauea's summit. Episode 50 began on 17 February 1992, 10 days after the cessation of activity at Kupaianaha. Episode 50 was also accompanied by a sharp summit deflation and was preceded by steady inflation and increased earthquake activity beneath the upper and middle east rift during the week before. Episode 51 began on 7 March 1992, preceded on 3–4 March by a traditional intrusion. The eruption a few days later took place quietly, accompanied by no tilt change and only a few earthquakes beneath the upper east rift zone. The onset of episode 52 on 3 October 1992 (Heliker and Mattox, 2003, table 2) was accompanied by a moderate summit deflation and scattered south flank seismicity.

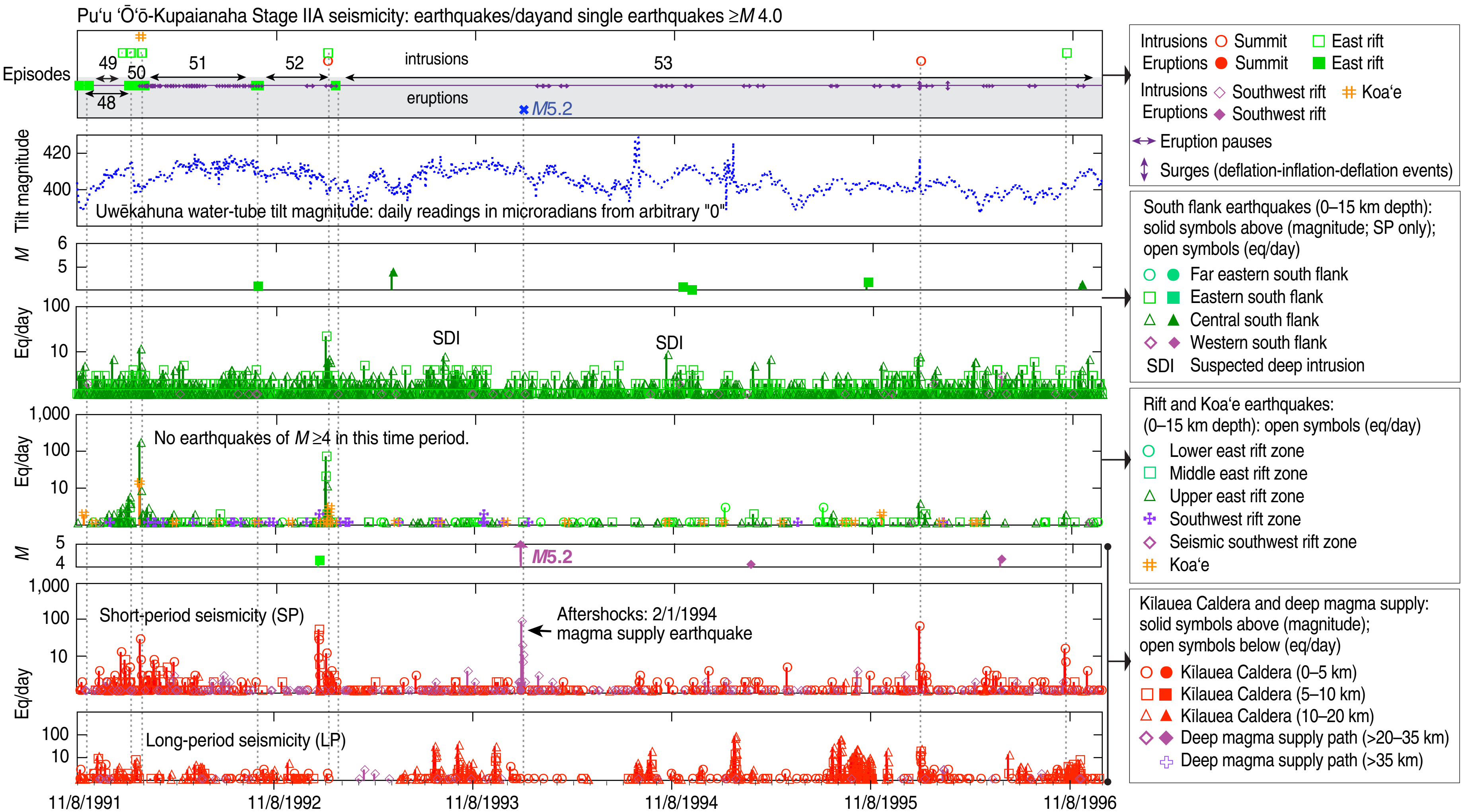
The intrusion of 7–9 February 1993 was accompanied by a sharp deflation of Kīlauea's summit, but it differed from the preceding two intrusions in combining an earthquake swarm beneath Kīlauea's summit with activity on the upper east rift and an intense swarm of earthquakes beneath the middle east rift (figs. 7.8, 7.9). A very large sequence of Nāmakanipaio earthquakes on 24–26 January preceded the intrusion (table 7.3). South flank seismicity during the February intrusion was focused beneath the eastern south flank. Following the intrusion, earthquakes were again focused in the uppermost east rift, accompanied by an earthquake swarm beneath the central south flank. The east rift seismicity extended to the site of later eruption and intrusion in January 1997. The February 1993 intrusion led to the end of episode 52. Following an eruptive pause of less than 2 weeks duration, episode 53 began on 20 February 1993 from yet another fissure system on the flanks of Puʻu ʻŌʻō.

The remainder of 1993 through the end of 1995 was seismically quiet with the exception of a major deep-magma supply earthquake on 1 February 1994 and two possible suspected deep intrusions in September 1993 and October 1994 (table 7.3). Most of the eruptive pauses during stage IIA (fig. 7.8) lacked the definitive seismic signatures that characterized the pauses of 1990. All but the first pause in March 1992 lacked rapid precursory deflation and only a few pauses were preceded by lpc-c seismic activity. Unlike the pauses of 1990, the 1993–95 pauses that were preceded by lpc-c seismic activity are not distinguished from periods of enhanced lpc-c activity that did not result in an eruptive pause.

Installation of a Broadband Seismic Array

A broadband seismic array was installed at Kīlauea's summit in 1994 to study tremor and long-period seismicity in more detail than had been previously possible (Dawson and others, 1998). Early studies with this array identified a shallow upward extension of Kīlauea's summit magma reservoir close to the northeast margin of Halemaʻumaʻu at a depth of less than 1 km (Almendros and others, 2002a,b; Dawson and others, 2004). This shallow reservoir was not detected by earlier ground deformation studies, at least through the end of episodic high-fountaining and summit deflation characterizing stage IA. Subsequently the existence of this shallow reservoir was confirmed by the installation of continuously recording tiltmeters around Kīlauea's summit (see below).

Figure 7.8. Graphs showing Kīlauea activity, 8 November 1991–1 January 1997: Stage II A of the Puʻu ʻŌʻō-Kupaianaha eruption. Time-series plots show the number of earthquakes per day (eq/day) and magnitudes (*M*) ≥4 plotted against times of eruption and intrusion and the Uwēkahuna tilt magnitude. Symbols are given on the plots. Seismic regions are shown in figure A4 of appendix A. Three types of intrusions are defined in chapter 1. Traditional intrusions are shown as intrusion symbols, and inflationary intrusions are labeled (II). Suspected deep intrusions are labeled (SDI) but not plotted as intrusions. Dates on figure in m/d/yyyy format. Panels from top to bottom show the following: *(a)*, Times of eruption and intrusion. Vertical dotted lines connect seismicity associated with eruptions and associated traditional intrusions. Vertical dashed lines connect traditional intrusions not associated with an eruption. *(b)*, Uwēkahuna tilt magnitudes in microradians. *(c)*, South flank earthquake magnitudes. *(d)*, South flank earthquakes per day. *(e)*, Rift and Koaʻe earthquakes per day. *(f)*, Kīlauea Caldera and deep magma supply earthquake magnitudes. *(g)*, Kīlauea Caldera and deep magma-supply earthquakes per day—short-period data. *(h)*, Kīlauea Caldera and deep magma-supply earthquakes per day—long-period data.



Pu‘u ‘Ō‘ō-Kupaianaha Stage IIA seismicity: earthquakes/dayand single earthquakes ≥M 4.0
Episodes
48
49
50
51
52
53
intrusions
eruptions
M5.2
Tilt magnitude
420
400
Uwēkahuna water-tube tilt magnitude: daily readings in microradians from arbitrary "0"
M
6
5
Eq/day
100
10
SDI
SDI
1,000
No earthquakes of M ≥4 in this time period.
M
5
4
M5.2
Short-period seismicity (SP)
Aftershocks: 2/1/1994 magma supply earthquake
Long-period seismicity (LP)
11/8/1991
11/8/1992
11/8/1993
11/8/1994
11/8/1995
11/8/1996
Intrusions Summit East rift
Eruptions Summit East rift
Intrusions Southwest rift Koa‘e
Eruptions Southwest rift
Eruption pauses
Surges (deflation-inflation-deflation events)
South flank earthquakes (0–15 km depth): solid symbols above (magnitude; SP only); open symbols (eq/day)
Far eastern south flank
Eastern south flank
Central south flank
Western south flank
SDI Suspected deep intrusion
Rift and Koa‘e earthquakes: (0–15 km depth): open symbols (eq/day)
Lower east rift zone
Middle east rift zone
Upper east rift zone
Southwest rift zone
Seismic southwest rift zone
Koa‘e
Kīlauea Caldera and deep magma supply: solid symbols above (magnitude); open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–10 km)
Kīlauea Caldera (10–20 km)
Deep magma supply path (>20–35 km)
Deep magma supply path (>35 km)

Table 7.3. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IIA—11/8/1991–1/1/1997 (see fig. 7.8).

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; “no data” in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
11/8/1991 4:45	11/26/1991 0:00	MERZ	E		15.5	117	+1h 45m	Episode 49[9]—Tilt 11/7–15	G17
1/28/1992 07:18	1/29/1992 03:15	ei3uer	II	13	0.8	135	+4h 18m	Tilt 1/28–29; I-A: 1/28 8.4 µrad deflation	G18
2/4/1992 08:36	2/4/1992 17:09	ms1.2	EQS	1, 7				Precursory Nāmakanipaio[10, 11]	G19
2/11/1992 00:30	2/13/1992 13:22	ei2.3	I	18	flat			Broken swarm	
2/17/1992 19:30	3/3/1992 1:30	MERZ	E		18.0	103	+2h 30m	Episode 50[12]—Tilt 2/17–22	G19
3/3/1992 00:45	3/4/1992 22:20	ei3uer	I	225	3.9	132	+0h 45m	Tilt 3/2–3	G20
3/3/1992 02:28	3/3/1992 07:41	koae	I	12					
3/3/1992 06:08	3/4/1992 15:04	sf3kuer	EQS	16				South flank response similar to SDI[3]	
3/7/1992 12:45	9/27/1992 6:00	MERZ	E		flat		+ 5h 45m	Episode 51[12]	
10/3/1992 3:30	2/20/1993 14:50	MERZ	E		7.1	122	no data	Episode 52[12]—Tilt 10/4-6	
1/24/1993 19:22	1/24/1993 22:13	ms1.2	EQ	41,10				Foreshocks for earthquake below	
1/24/1993 22:14		ms 2	EQ		flat			Precursory Nāmakanipaio[10]; *M*4.3	**7.9**
1/24/1993 19:48	1/26/1993 07:34	ms 2	EQ	83				Aftershocks for earthquake above	
2/7/1993 23:28	2/9/1993 02:23	ei2mer	I	96	5.1	128	no data	Tilt 2/7–8 deflation; 2/9–10 missing	**7.9**
2/7/1993 23:28	2/8/1993 13:23	ei3uer	I	13					
2/7/1993 23:35	2/8/1993 20:35	ms1	EQS	14					
2/7/1993 23:35	2/8/1993 16:46	sf2mer	EQS	23				South flank response similar to SDI[3]	
2/10/1993 18:01	2/14/1993 06:59	sf3kuer	EQS	22				Broken swarm	
2/20/1993 14:50	1/29/1997 18:52	MERZ	E		7.6	127		Episode 53[12]—Tilt 2/23–3/2	
6/8/1993 02:57			EQ					Ka‘ōiki *M*5.3 with aftershocks[13]	
8/22/1993 22:51	8/23/1993 14:14	lpms3	EQS	34					
8/24/1993 13:17	8/27/1993 00:59	lpms3	EQS	39					
9/11/1993 12:27	9/12/1993 12:13	sf3.2	SDI?	13, 5					G21
10/5/1993 14:53	10/8/1993 12:48	lpms3	EQS	68					
12/12/1993 23:40	12/15/1993 00:11	lpms3	EQS	43					
1/31/1994 21:29	1/31/1994 23:00	ms4.5	EQ	2				Foreshocks for earthquake below	
2/1/1994 01:55		do	EQ					*M*5.2, 35 km; magma supply path	G22
2/1/1994 04:03	2/3/1994 06:01	do	EQ	113				Aftershocks for earthquake above	
2/3/1994 17:57	2/4/1994 18:37	do	EQ	13				do	
9/25/1994 02:18	9/26/1994 05:20	lpms3	EQS	24					
10/25/1994 23:20	10/26/1994 14:22	sf3.2	SDI?	9, 2					G23
2/24/1995 12:54	2/28/1995 11:00	lpms3	EQS	233				Mixed deflation/inflation	
2/25/1995 17:40	2/27/1995 05:17	lpms2	EQS	21					
5/3/1995 12:28		sf3kuer	EQ					*M*3.9 mainshock; 2 foreshocks, 4 aftershocks	

Table 7.3. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IIA—11/8/1991–1/1/1997 (see fig. 7.8).—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; “no data” in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
8/24/1995 16:33	8/26/1995 05:53	lpms3	EQS	52					
9/5/1995 11:42	9/9/1995 18:58	lpms3	EQS	207				Tilt—9/5–8 missing	
9/27/1995 05:47	9/29/1995 16:04	lpms3	EQS	28					
10/2/1995 18:42	10/10/1995 17:20	lpms3	EQS	129	flat				
10/29/1995 10:25	10/31/1995 22:40	lpms3	EQS	22					
12/1/1995 23:29	12/3/1995 12:06	lpms3	EQS	26					
2/1/1996 08:09	2/1/1996 12:10		surge				E: 3h	I-A: 15 µrad 08:24–11:45 deflation	G23 A
2/1/1996 08:53	2/2/1996 05:41	ms1	I	70	18.5	307		Tilt 1/31-2/1	G23 A
2/1/1996 13:17	2/2/1996 05:43	sf3kuer	EQS	10					
2/1/1996 14:48	2/2/1996 23:45	lpms3	EQS	33					G23B
2/1/1996 16:16	2/2/1996 06:51	lpms1	EQS	11					G23B
2/1/1996 17:28	2/2/1996 14:17	lpms2	EQS	84					G23B
3/24/1996 10:36	3/24/1996 11:51		surge				E: ~3h	I-A: 4.3 µrad inflation 10:36–11:33 deflation	
5/13/1996 11:00	5/13/1996 20:37	sf3kuer	SDI	7				Weak swarm	
10/25/1996 21:41	10/26/1996 12:46	ei3uer	I	22	0.93	117		Tilt 10/25–28	G24

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai‘i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword “kl.erz.1983”.

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3, and locations are shown on appendix figure A4.

[3]Event types defined in Chapter 1 are abbreviated as follows: **E**, Eruption; intrusion (“traditional” **I;** “inflationary” **II;** “suspected deep” **SDI**); **EQS**, earthquake swarms; EQ, Earthquake $M \geq 4$; “surge”—abrupt inflation at Kīlauea’s summit followed by an increase in magma output at Pu‘u ‘Ō‘ō. These later become “d-i-d” events in which there is a preliminary deflation at Kīlauea’s summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu‘u ‘Ō‘ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (µrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna Vault.

[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu‘u ‘Ō‘ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu‘u ‘Ō‘ō vent (E) time lag in hours.

[7]Abbreviations as follows: sf, south flank; ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); I-A, Ideal-Arrowsmith continuously recording tiltmeter in Uwēkahuna Vault, drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix figures plain text.

[9]Eruption described by Mangan and others, 1995.

[10]Continuation of earthquakes triggered by the 1983 Ka‘ōiki earthquake. Locations are beneath the Nāmakanipaio campground in Hawai‘i Volcanoes National Park.

[11]Identified as precursor to following east rift intrusion (Okubo and Nakata, 2003).

[12]Eruption described by Heliker and others, 1998.

[13]Klein and others, 2006.

Table 7.4. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IIB—1/1/1997–12/1/2003 (see fig. 7.10).

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Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
1/29/1997 18:52	1/31/1997 12:14	ei2mer	I	48	26.8	118		Tilt 1/27-30; I-A no data	**7.11**
1/29/1997 19:34	2/16/1997 13:00	lpms1	EQS	2318				2 7–8 hour pauses in swarm	**7.11**
1/30/1997 2:40	1/31/1997 0:33	MERZ	E					Episode 54: 1997 Nāpau	**7.11**
2/9/1997 08:48	2/10/1997 20:17	lpms2	EQS	21					
2/24/1997 7:00	6/17/2007 9:30	MERZ	E		flat			Episode 55	
6/2/1997 03:35	6/3/1997 19:45	ms1-2	EQS	34				Nāmakanipaio sequence[9]	G26
6/30/1997 05:47		sf2mer	EQ		flat			*M*5.5 with aftershocks[10]	
7/28/1997 16:19	7/29/1997 13:11	lpms2	EQS	45					
7/28/1997 19:28	7/30/1997 01:49	lpms1	EQS	15					
8/14/1997 15:54		sf2mer	EQ		flat			*M*5.0 with aftershocks[10]	
9/16/1997 22:59	9/18/1997 10:31	lpms2	EQS	63					
9/17/1997 01:41	9/18/1997 07:14	lpms3	EQS	47					
9/17/1997 03:27	9/17/1997 14:41	lpms1	EQS	10					
9/20/1997 14:47	9/21/1997 10:27	lpms2	EQS	28					
10/1/1997 10:18	10/2/1997 07:28	lpms3	EQS	50					
10/1/1997 11:42	10/2/1997 08:13	lpms2	EQS	56					
1/14/1998 18:20	1/14/1998 20:35		Surge[6]				E 4h	I-A:7.2 µrad inflation 18:20-20:35 deflation	G27*A*
1/14/1998 18:57	1/14/1998 23:00	ei3/kc	I	17	8.0	129		Tilt 1/13-15	G27*A*
1/15/1998 00:30	1/15/1998 14:26	lpms3	EQS	21					G27*B*
1/27/1998 16:55	1/28/1998 08:33	ms1.2	EQS	9, 36				Nāmakanipaio sequence[9]—2 *M*4, many *M*3+	G28
2/20/1998			SE?[11]					2 sf with no located eq 2 days before and after	
3/8/1998 08:30	3/9/1988 22:40	lpms3	EQS	20					
9/19/1998 06:08	9/20/1998 03:12	sf3kuer	SE[11]	17	2.4	166		Tilt 9/19-21; 9/20 missing; SE on 9/19; also classified as SDI	G29
9/27/1998 21:56		ms1	EQ		2.7	148		Glenwood *M*4.6[10]; Tilt 9/27–29	G30
9/28/1998 20:39	9/29/1998 22:29	sf2mer	EQ					*M*4.8 with aftershocks[10]	
1/10/1999			SE?[11]					2 widely separated south flank eq	
3/18/1999 11:42	3/18/1999 18:36	sf3kuer	SDI/EQ	9				*M*3.3 mainshock at 11:42 with 8 aftershocks?	
4/16/1999 14:46			EQ					Hīlea *M*5.6[10]	G31
4/16/1999 15:48	4/17/1999 05:23	ei5swr	EQ	15				Triggered Kīlauea aftershocks	
5/26/1999 06:01		ms2	EQ					Nāmakanipaio[9] mainshock *M*4.3	G32
5/26/1999 06:04	5/27/1999 01:27	ms2	EQ	34				Aftershocks	
9/12/1999 01:31	9/12/1999 15:17	ei3uer	I	61	7.1	159	0h 03m	Tilt 9/11–13	G33

Table 7.4. Puʻu ʻŌʻō-Kupaianaha eruption[1]: Stage IIB—1/1/1997–12/1/2003 (see fig. 7.10).—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
9/12/1999 01:40	9/12/1999 05:01	sf3kuer	EQS	11				South flank accompaniment; sf seismicity rate increases following this intrusion	
11/21/1999 11:38			SE?[11]					No located sf eq on this date	
2/23/2000 13:41	2/24/2000 19:45	ei3uer	I	107	8.5	147		Tilt 2/20–22 deflation; uprift migration 8.6 km/hr	G34 a
2/23/2000 15:09	2/24/2000 01:47	sf3kuer	EQS	7				South flank accompaniment	
2/23/2000 15:58	2/24/2000 17:58	lpms2.3	EQS	7				Broken swarm 2/17–2/29	G34 b
4/1/2000 20:18			EQ					*M*5.0 mainshock with at least 6 aftershocks	
4/24/2000 13:59	4/25/2000 03:16	lpms2	EQS	20	7.6	115		Tilt 4/19–28	
5/4/2000 21:38	5/7/2000 18:27	lpms2	EQS	45	4.2	124		Tilt 5/3–9	
5/5/2000 22:07	5/8/2000 06:09	lpms3	EQS	39					
5/8/2000 21:14	5/11/2000 03:56	lpms2	EQS	51	5.7	319		Tilt 5/14–19 inflation?	
5/29/2000 16:10	5/30/2000 15:00	sf3kuer	SE[11]	23	7.2	124		Tilt 5/29–6/2; *M*3.9 with aftershocks; SE at 5/29 11:23?; SE at 6/2 12:00?; also classified as SDI	**7.12**
6/1/2000 17:17	6/2/2000 21:47	do	do	11					
9/24/2000 10:30	9/25/2000 17:38		Surge[6]				POC 22 m E 3h	I-A: >6 µrad inflation 9/24 21:00-21:47 deflation[11]!	G35
11/8/2000 22:24	11/9/2000 10:53	sf3kuer	SE[11]	10	3.0	119		Tilt 11/5-7 SE on 11/9; also classified as SDI	G36
1/26/2001 10:44	1/27/2001 21:04	lpms3	EQS	20					
4/25/2001 17:34		ms2						*M*4.4[10], depth 6.34 km	
5/20/2001 04:02	5/21/2001 16:40		Surge[6]				POC 18m E 1.5h	I-A: 11 µrad inflation 5/20 1629-1743 deflation	G37
5/20/2001 20:43	5/20/2001 23:42	lpms3	EQS	11					
6/23/2001 21:57	6/24/2001 06:10	sf3.2	SDI	10, 3					G38
9/19/2001 04:03	9/19/2001 22:24	sf2	SE?[11]	4				SE at 11:40–9/19	G39
9/17/2001 01:14	9/22/2001 19:15	sf2.3		18				Scattered seismicity	
12/8/2001 10:40	12/10/2001 09:00		D-I-D		6.3	294	POC 41m	Inflation 12/9 08:54–09:50; no effect on eruption	G40
12/8/2001 12:00	12/8/2001 16:45	lpms2.3	EQS	5, 3					
12/9/2001 09:31	12/9/2001 09:54	ei3uer	I	5				Summit intrusion	
12/9/2001 20:54	12/10/2001 11:03	ms1-3	I	11					
12/19/2001 08:49	12/19/2001 11:24	ei3uer	I	6	4.1	129		Tilt 12/20–21; no rift deformation	G41
2/12/2002 06:47	2/12/2002 20:41	sf3kuer	SDI	7					G42
4/4/2002 20:50	4/6/2002 12:00		D-I-D				POC 11m E 94m	Inflation 4/5 15:56–16:47; no eqs but increased eruption ~4/5 17:30[13]	G43
8/21/2002 15:55	8/21/2002 20:00	sf3kuer	SDI	6				2 suspected deep intrusions	G44
8/28/2002 12:02	8/29/2002 03:21	sf3kuer	SDI	8					G44

Table 7.4. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IIB—1/1/1997–12/1/2003 (see fig. 7.10).—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith tiltmeter]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
12/15/2002 18:54	12/16/2002 15:19	sf3.2	SE[11]	7, 3	5.2	171		Tilt 12/14–16; 12/15 missing; SE 12/17; also classified as SDI	G45
1/20/2003 17:00	1/22/2003 06:50		D-I-D				POC 26m E 4h 25m	Inflation 1/21 16:16–16:52	G46
4/6/2003 21:27	4/7/2003 03:23	ms1	EQS	13				Nāmakanipaio[9]	G47
6/23/2003 16:30	6/23/2006 23:07	lpms2	EQS	10					
6/23/2003 19:04	6/25/2003 02:16	lpms3	EQS	16					
7/1/2003 16:56	7/2/2003 00:00	sf2mer	SE[11]	10	4.8	115		Tilt 6/30–7/1; SE 7/1; also classified as SDI	G48
7/11/2003 20:09	7/12/2003 16:35	lpms3	EQS	19					
7/15/2003 12:07	7/15/2003 18:37	lpms3	EQS	11					
8/4/2003 07:24	8/4/2003 18:03	lpms2	EQS	11					
8/7/2003 22:36	8/10/2003 00:00		d-i-d[6]				POC 69m E 19h	Inflation 8/8 19:32–22:48; 4 ms1 eq	G49
11/5/2003 06:54	11/5/2003 23:16	lpms2	EQS	14					
11/18/2003 09:34	11/21/2003 02:45	lpms2	EQS	36	6.4	117		Tilt 11/17–18	

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai‘i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword "kl.erz.1983".

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3, and locations are shown on appendix figure A4.

[3]Event types defined in chapter 1 are abbreviated as follows: **E**, Eruption; intrusion ("traditional" **I;** "inflationary" **II;** "suspected deep" **SDI**); **EQS**, earthquake swarms; EQ, Earthquake $M \geq 4$; "surge"—abrupt inflation at Kīlauea's summit followed by an increase in magma output at Pu‘u ‘Ō‘ō. These later become "d-i-d" events in which there is a preliminary deflation at Kīlauea's summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu‘u ‘Ō‘ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (µrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna Vault.

[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu‘u ‘Ō‘ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu‘u ‘Ō‘ō vent (E) time lag in hours.

[7]Abbreviations as follows: sf, south flank; ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); I-A, Ideal-Arrowsmith continuously recording tiltmeter in Uwēkahuna Vault, drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix figures plain text.

[9]Continuation of earthquakes triggered by the 1983 Ka‘ōiki earthquake. Locations are beneath the Nāmakanipaio campground in Hawai‘i Volcanoes National Park.

[10]Klein and others, 2006.

[11]Silent earthquakes documented in 4 papers—summary in (Montgomery-Brown and others, 2009, table 1), including earthquakes with a small deformation step and scant seismic expression designated "SE?": (Brooks and others, 2006; Cervelli and others, 2002b; Montgomery-Brown and others, 2009; Segall and others, 2006).

[12]Recorded on strainmeter on the West side of Mauna Loa.

[13]Tilt source was determined ESE of Halema‘uma‘u Crater near Fiske-Kinoshita site 2 (see fig. 4.2) at a depth of ~0.45 km.

Narrative of Later Intrusion and Eruption During Stage IIA

Seismic activity increased dramatically in 1996, with a major intrusion beneath Kīlauea's summit on 1 February defined by a swarm of short-period earthquakes (table 7.3). This swarm was accompanied by a small swarm of long-period earthquakes shallower than 5 km, and by a very large swarm of long-period earthquakes deeper than 5 km. This date also marks the first of several "surges" in eruptive activity (Thornber and others, 1996) that were later defined as deflation-inflation-deflation (D-I-D) events from the pattern seen on continuously recorded tiltmeters in the Uwēkahuna vault and at the eruption site (Cervelli and Miklius, 2003). The 1996 surges were defined by a sharp inflation at the summit followed about 3 hours later by a noticeable increase in eruptive activity at the Puʻu ʻŌʻō vent and its associated tube system delivering lava to the ocean. The location of a magma source shallower than 1 km and southeast of Halemaʻumaʻu was modeled by three continuously recording tiltmeters operating during a surge on 24 March 1996, and this may be the source of other surges as well. The location of the shallow reservoir agreed with that determined by the broadband seismic array (Dawson and others, 1999).

Ten eruptive pauses took place over a period of 6 weeks in early 1997. These pauses show some positive correlation with the lpc-c seismicity, but there are times of elevated lpc-c seismicity both before and after this time during which the eruption didn't pause.

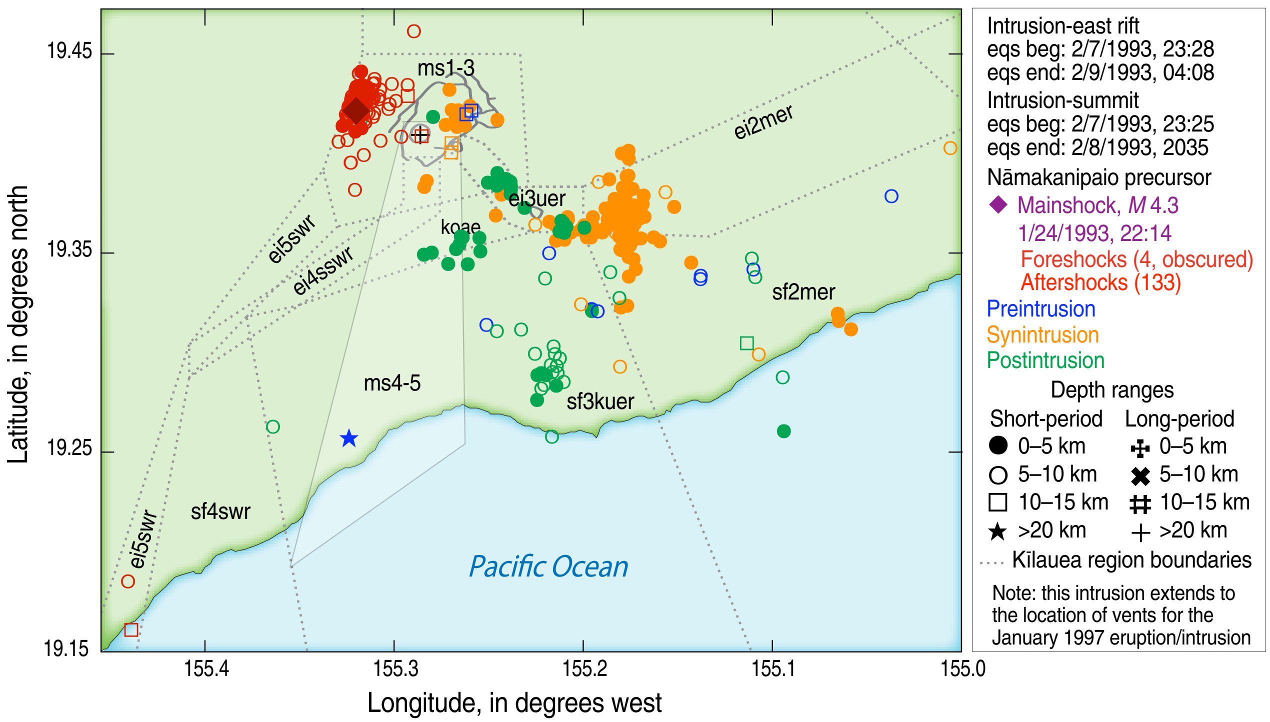
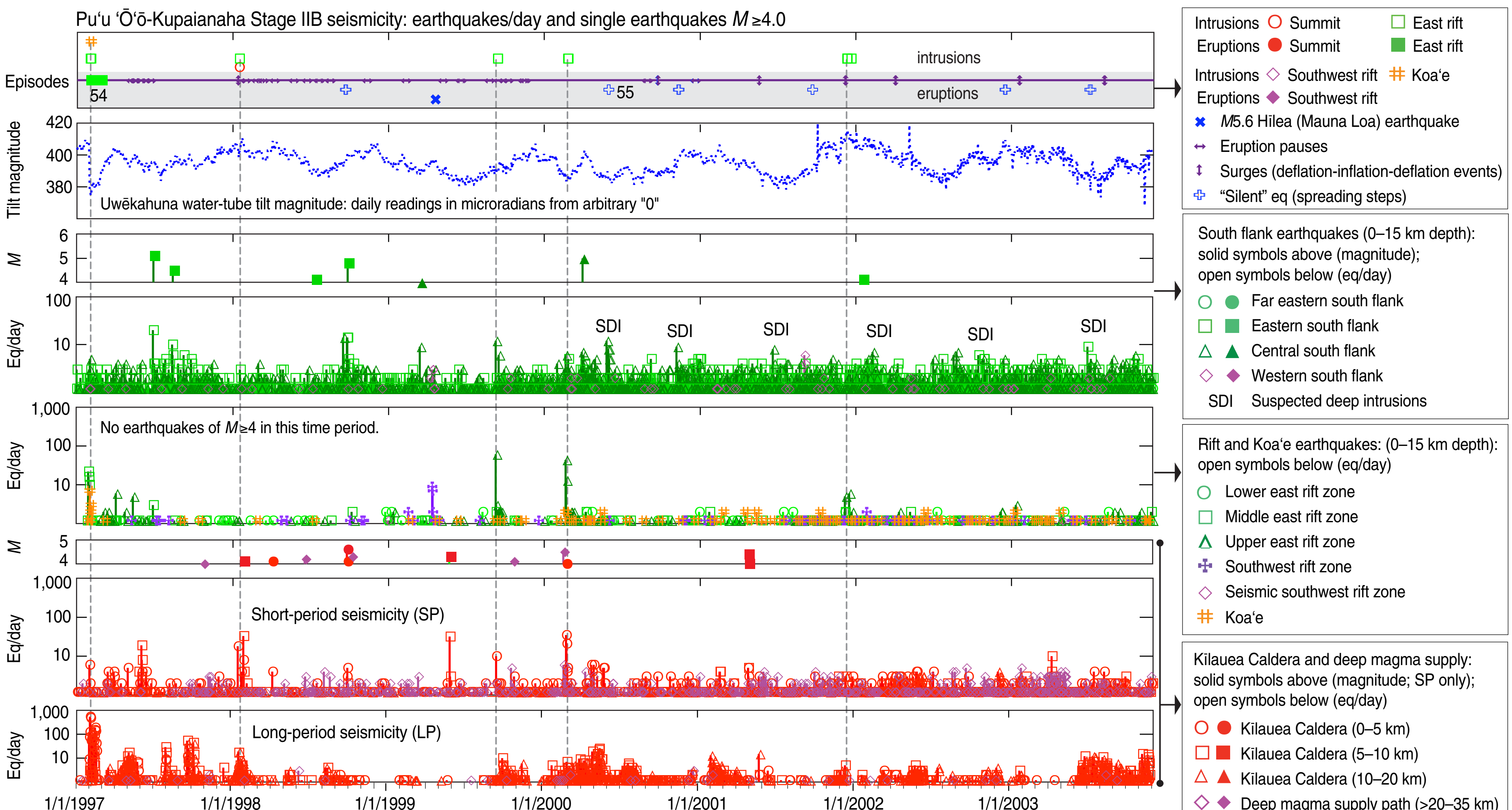


Figure 7.9. Map showing seismicity on Kīlauea, 4–15 February 1993, associated with east rift and summit intrusions during 7–9 February 1993. A large middle east rift intrusion was accompanied by a small summit intrusion. These seismic swarms were preceded by a Nāmakanipaio swarm and followed by seismicity beneath the upper east rift and Koaʻe Fault Zone and a possible suspected deep intrusion beneath the central south flank. Dates on figure in m/d/yyyy format.

Stage IIB: 1 January 1997–1 December 2003

Events in this period are summarized in table 7.4 and figure 7.10. Stage IIB marks the beginning of an increase in seismicity beneath the southwest rift zone and western south flank that is accentuated in stage III. Stage IIB began with the east rift eruption/intrusion near Nāpau Crater (fig. 7.11) that took place over the period 29–31 January 1997 (Desmarais and Segall, 2007; Owen and others, 2000b). The activity at Puʻu ʻŌʻō (episode 53) ended with the onset of an earthquake swarm beneath and slightly uprift of the eventual eruption site. Seismicity and Uwēkahuna daily tilt are tabulated in table 7.4 and shown in figure 7.10. Although HVO refers to this event as episode 54 of the eruption that began in 1983, we prefer to refer to it as the 1997 Nāpau eruption, because it was distant from Puʻu ʻŌʻō.

The 1997 Nāpau eruption/intrusion is noteworthy for the occurrence of a small swarm of Koaʻe earthquakes that followed the eruption (fig. 7.10), the



Pu‘u ‘Ō‘ō-Kupaianaha Stage IIB seismicity: earthquakes/day and single earthquakes M ≥4.0
Episodes
54
55
intrusions
eruptions
Tilt magnitude
420
400
380
Uwēkahuna water-tube tilt magnitude: daily readings in microradians from arbitrary "0"
M
6
5
4
Eq/day
100
10
SDI
No earthquakes of M≥4 in this time period.
1,000
Short-period seismicity (SP)
Long-period seismicity (LP)
1/1/1997
1/1/1998
1/1/1999
1/1/2000
1/1/2001
1/1/2002
1/1/2003
Intrusions Summit East rift
Eruptions Summit East rift
Intrusions Southwest rift Koa‘e
Eruptions Southwest rift
M5.6 Hilea (Mauna Loa) earthquake
Eruption pauses
Surges (deflation-inflation-deflation events)
“Silent” eq (spreading steps)
South flank earthquakes (0–15 km depth): solid symbols above (magnitude); open symbols below (eq/day)
Far eastern south flank
Eastern south flank
Central south flank
Western south flank
SDI Suspected deep intrusions
Rift and Koa‘e earthquakes: (0–15 km depth): open symbols below (eq/day)
Lower east rift zone
Middle east rift zone
Upper east rift zone
Southwest rift zone
Seismic southwest rift zone
Koa‘e
Kīlauea Caldera and deep magma supply: solid symbols above (magnitude; SP only); open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–10 km)
Kīlauea Caldera (10–20 km)
Deep magma supply path (>20–35 km)
Deep magma supply path (>35 km)

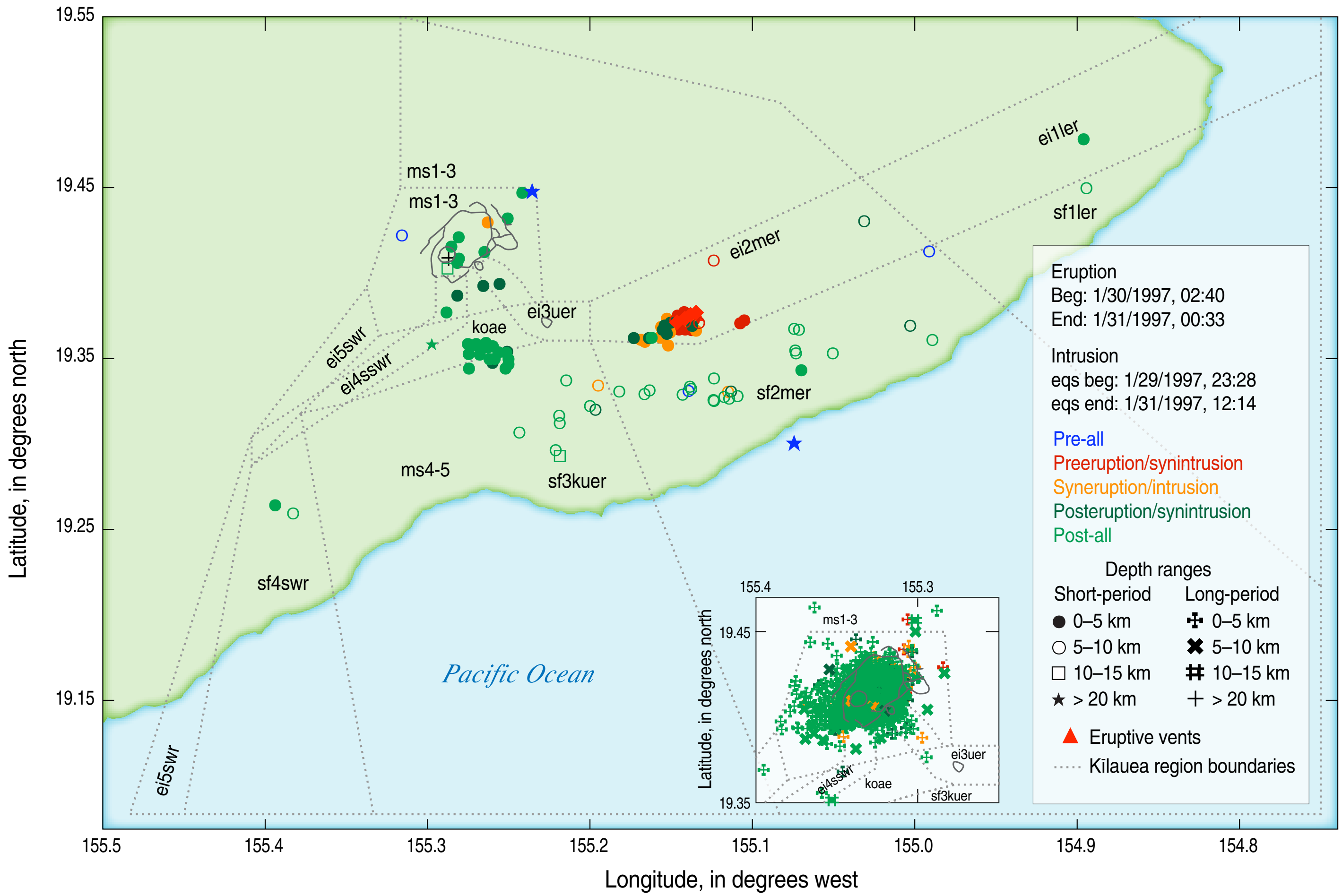


Figure 7.11. Map showing seismicity on Kīlauea, 28 January-16 February 1997. Short-period seismicity associated with the Nāpau eruption and intrusion of–29–31 January (Owen and others, 2000b; Thornber and others, 2003). An intense long-period earthquake swarm accompanied the intrusion and continued for another 3 months. The Koa‘e Fault Zone was briefly activated following the end of eruption. Dates on figure in m/d/yyyy format. Inset shows long-period seismicity associated with the eruption and intrusion of 29–31 January 1997.

Figure 7.10. Graphs showing Kīlauea activity, 1 January 1997–1 December 2003: Stage II B of the Pu‘u ‘Ō‘ō-Kupaianaha eruption. Time-series plots show the number of earthquakes per day (eq/day) and magnitudes(*M*) ≥4 plotted against times of eruption and intrusion and the Uwēkahuna tilt magnitude. Symbols are given on the plots. Seismic regions are shown in figure A4 of appendix A. Three types of intrusions are defined in chapter 1. Traditional intrusions are shown as intrusion symbols, and suspected deep intrusions (SDI) are not plotted as intrusions. Dates on figure in m/d/yyyy format. Panels from top to bottom show the following: *(a)*, Times of eruption and intrusion. Vertical dotted lines in panel below connect seismicity associated with eruptions and associated traditional intrusions. Vertical dashed lines connect traditional and inflationary intrusions not associated with an eruption. *(b)*, Uwēkahuna tilt magnitudes in microradians. *(c)*, South flank earthquake magnitudes. *(d)*, South flank earthquakes per day. *(e)*, Rift and Koa‘e earthquakes per day. *(f)*, Kīlauea Caldera and deep magma-supply earthquake magnitudes. *(g)*, Kīlauea Caldera and deep magma-supply earthquakes per day—short-period data. *(h)*, Kīlauea Caldera and deep magma supply earthquakes per day—long-period data.

lack of preeruption summit inflation, and the absence of seismicity beneath the rift zone between Kīlauea's summit and the eruption site. It is tempting to interpret the lack of preeruption seismicity to opening of the rift zone during the February 1993 intrusion (see above), but apparently no extension occurred across the east rift zone at the time of the earlier intrusion (Heliker and others, 1998, p. 391).

The event was accompanied by a large summit deflation and by a long-period earthquake swarm above 5-km depth that consisted of more than 2,000 located and thousands of additional shallow lpc-a events spanning a period of nearly 3 weeks. A pause in seismicity occurred on 16 February, after which the lpc-a earthquake counts continued to decay, but they still exceeded preeruption levels until about 15 April 1997.

The 29 January 1997 eruption marked only a temporary shift in the eruption site. Lava returned to Pu'u 'Ō'ō on 24 February 1997 (episode 55) before the end of seismic activity associated with the 1997 Nāpau eruption/intrusion (fig. 7.10).

Long-period seismicity, principally deeper than 5 km, continued during stage IIB, as did intervals of pauses, surges, and Nāmakanipaio seismicity. Pauses during stage IIB have the same character as those during stage IIA (see above). The numbers of eruption pauses decreased in 2000 and 2001. Swarms of Nāmakanipaio earthquakes, mostly at depths of 5–10 km, occurred in June 1997, January 1998, and May 1999.

An intrusion occurred on the uppermost east rift on 14 January 1998, associated with a surge in eruptive activity and long-period seismicity at depths of 10–15 km (table 7.4). Large intrusions on 12 September 1999 (Cervelli and others, 2002a) and 23–24 January 2000 extended somewhat farther down the upper east rift (table 7.4). In April 1999, a Mauna Loa earthquake of magnitude 5.6 occurred beneath the Hīlea region and triggered seismicity adjacent to Kīlauea's lower southwest rift zone.

Additional surges occurred on 24–25 September 2000 and 20–21 May 2001. With the installation of continuous, digital recording tiltmeters at Kīlauea's summit (UWE tiltmeter) and at Pu'u 'Ō'ō (POC tiltmeter), the surges could now be more precisely defined by their character of gradual deflation (D) followed by inflation over about one hour (I) followed by decay to the value before the event (D). Later D-I-D events occurred on 9 December 2001, 5 April 2002, and 21 January and 8 August 2003. The time lag between the onset of the event at Kīlauea's summit and Pu'u 'Ō'ō was shown to be usually less than 30 minutes (table 7.4), and a noticeable increase in eruptive activity began a few hours after the beginning of inflation. Little seismic activity is associated with these events.

With the advent of a continuously recorded and telemetered GPS network, events of a new type—"slow" or "silent" earthquakes (Brooks and others, 2006; Cervelli and others, 2002b; Montgomery-Brown and others, 2009; Segall and others, 2006)—were identified on 19–20 and 28–29 September 1998, 29 May 2000 (fig. 7.12), 8–9 November 2000, 15–16 December 2002, and 1–2 July 2003 ("SE" in the "type" column of table 7.4, plotted as Greek crosses in figure 7.10). The largest of these events are associated with seaward movement of Kīlauea's south flank by several centimeters, with geodetic moments calculated as equivalent to an *M*5 or greater earthquake. The silent earthquakes are accompanied by swarms of low-magnitude south flank earthquakes of variable location and number of events.

Stage IIIA-B: Reinflation and Acceleration of Eruptive/Intrusive Activity, 1 December 2003–19 March 2008

Events of this period are given in tables 7.5 and 7.6 and figure 7.13. Stage III traces the evolution of Kīlauea from the end of continuous deflation to the explosive eruption in Halema'uma'u. We have arbitrarily divided the period at 1 May 2007 to isolate the buildup to the Father's Day eruption in June 2007.

Long-period earthquake swarms at the summit continued through 2004 (table 7.5). Nāmakanipaio events continued from late 2004. D-I-D events died out by September 2004 and the character changed to typical rapid deflation instead of inflation. Intrusions continued, increasing dramatically in 2006 (table 7.5).

An important change in the seismicity patterns associated with intrusions begins in 2005. Paired intrusions on the east rift zone and seismic southwest rift zone are seen in January 2005, the first time since before the beginning of the eruption in 1983 (table 7.5; fig. 7.13). This dual intrusion is accompanied by an apparent silent earthquake with an earthquake pattern identified with suspected deep intrusions and is followed within 3 days by a Nāmakanipaio sequence. Seismic southwest rift seismicity increases in 2006, particularly during a period of almost continuous unrest from 1 February through 2 March 2006 (fig. 7.13), and continues through March 2007. An additional suspected deep intrusion occurs on 3–5 April 2007, with no spreading step documented (Montgomery-Brown and others, 2009, table 1). A silent earthquake associated with a small spreading step is documented on 16 April, but there is very little seismic accompaniment and the few located earthquakes are scattered.

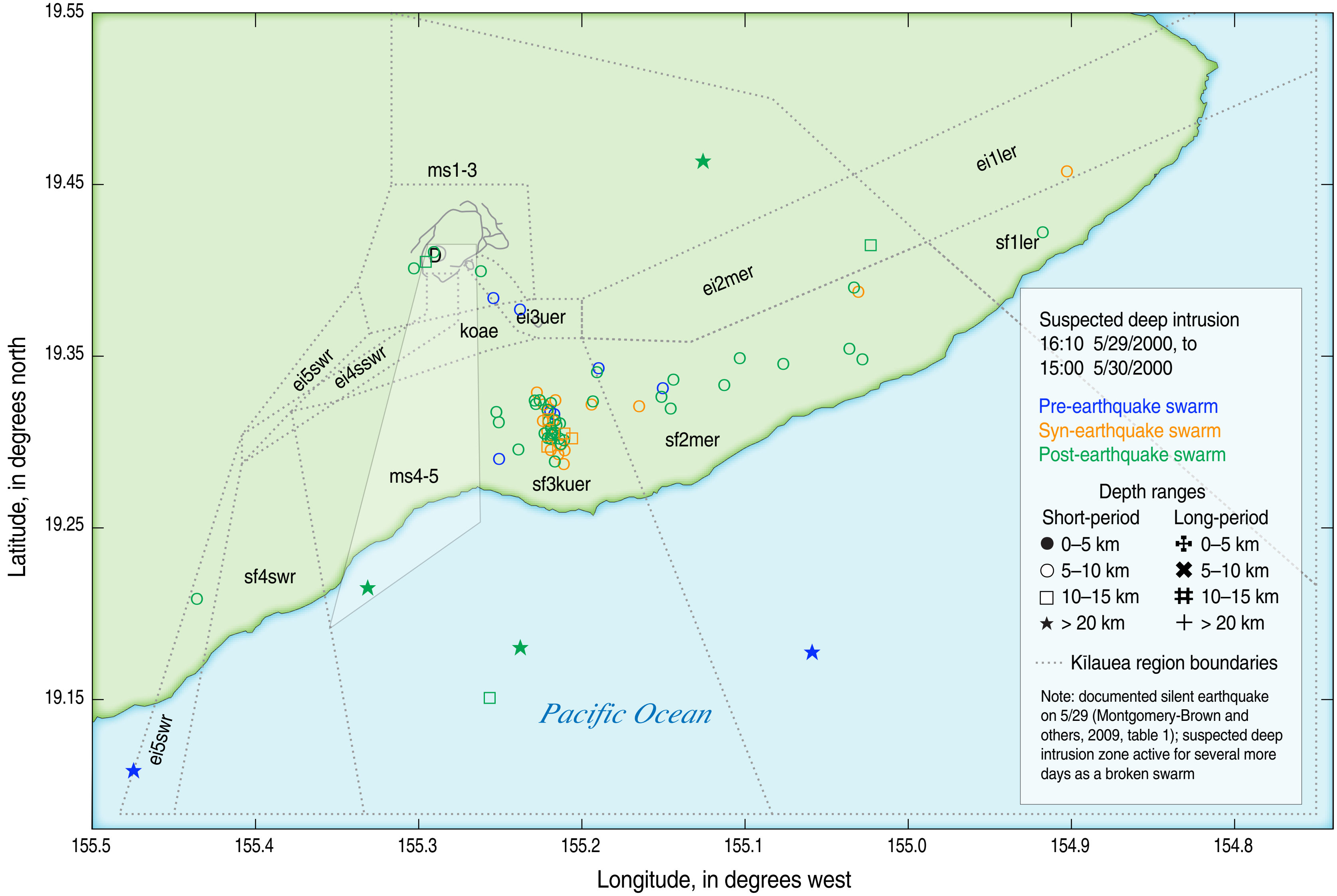


Figure 7.12. Map showing seismicity on Kīlauea, 26 May–6 June 2000. 5/29/2000: A suspected deep intrusion on 29–30 May beneath the central south flank was independently documented as a silent earthquake accompanied by a spreading step (Montgomery-Brown and others, 2009). Dates on figure in m/d/yyyy format.

Table 7.5. Pu'u 'Ō'ō-Kupaianaha eruption[1]: Stage IIIA—12/1/2003–5/18/2007 (see fig. 7.13).

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
12/5/2003 03:29	12/5/2003 18:25	lpms2	EQS	14	5.9	141		Tilt 12/4–5; 12/7–8 missing	
12/6/2003 07:56	12/6/2003 20:25	do	do	18					
12/10/2003 23:31	12/12/2003 20:13	lpms3	EQS	20				Break 12/11–12	
12/10/2003 23:32	12/13/2006 04:15	lpms2	EQS	61					
12/22/2003 11:16	12/22/2003 16:09	sf3kuer	SDI?	7					G51
12/27/2003 01:10	12/27/2003 11:33	lpms2	I?	12					
1/12/2004 19:58	1/12/2004 23:16	lpms2	I?	12					
1/23/2004 08:37	1/23/2004 15:20	lpms2	I?	10					
3/3/2004 03:00	3/5/2004 12:00		D-I-D				POC 30m E <3h	I-A: 17.5 µrad inflation 3/4 02:52–04:14 Tilt 3/2–3	
3/4/2004 03:39	3/4/2004 07:08	ei3uer	I	10	4.0	111			G52
3/20/2004 02:00	3/21/2004 15:50		D-I-D				POC 36m E 4h	I-A: 5.4 µrad inflation 3/20 13:49–15:41; no swarm	G53
5/6/2004 11:45			SE?[9]					2 widely separated sf eq on 5/5–6; probable SDI	
5/12/2004 08:05	5/13/2004 01:28	ei3uer	I	10	6.4	117	POC 26m	Tilt 5/12–14	G54
5/15/2004 06:06	5/17/2004 01:16		D-I-D				E ~8h	I-A: 6 µrad inflation 5/15 16:11–17:22	
6/4/2004 00:06	6/4/2004 17:18	ei3uer	I	8	8.0	116		Tilt 6/3-9 deflation	G55
7/9/2004 03:13	79/2004 18:24	ei3uer	I	8	6.9	135		Tilt 7/8–11; downrift migration of 0.19 km/hr[10]	G56
7/10/2004 04:00	7/10/2004 15:12	ei3uer	I	8				South flank eq scattered in time	
7/26/2004 18:00	7/28/2004 13:44		D-I-D				POC 56m	I-A: 6 µrad inflation 7/27 7:32–09:34	G57
7/27/2004 04:17	7/27/2004 17:27	ei3uer	I	10	9.8	130	E 8h	Tilt 7/27–30; downrift migration 8.2 km/hr[10]	G57
9/14/2004 03:13	9/16/2004 12:00		D-I				POC 71m	~2.5 µrad inflation 9/15 follows 5 lpms3 by 6 hr; d-i-d surges end	
11/2/2004 05:33	11/2/2004 09:32	ms4.5	EQS	5	flat			Tilt 11/2-3	G58
11/2/2004 12:45	11/2/2004 16:33	ms2	EQS	6					
11/2/2004 13:02	11/2/2004 16:56	ms1	EQS	17				Nāmakanipaio[11]	G58
11/24/2004 14:35	11/25/2004 12:45	lpms2	EQS	12					
12/1/2004 01:04	12/1/2004 03:22	lpms3	EQS	10					
12/13/2004 20:46	12/14/2004 11:38	lpms2	EQS	11	3.9	312		Tilt 12/13-14 inflation	
12/14/2004 02:33	12/14/2004 12:24	lpms3	EQS	15					
12/22/2004 07:07	12/23/2004 10:25	ei3uer	I	23	3.1	131		Tilt 12/23-27; downrift migration 1.2 km/hr[10]	G59
1/24/2005 18:35	1/25/2005 04:00	ei4swr	II	7	2.4	135		Tilt 1/24-26; inflation-deflation event	G60
1/24/2005 22:42	1/25/2005 04:00	ei3uer	II	13				UWE: 1/25 01:16 5.3 µrad 322.7	G60
1/25/2005 01:19	1/25/2005 11:17	ei3/kc	II	10					G60

Table 7.5. Pu‘u ‘Ō‘ō-Kupaianaha eruption[1]: Stage IIIA—12/1/2003–5/18/2007 (see fig. 7.13).—Continued

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith]

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
1/25/2005 17:54	1/27/2005 02:37	sf3kuer	SDI?	57				SE 1/26; broken swarm	
1/26/2005 16:34	1/30/2005 09:28	sf2mer	EQS	18				Continuation of SE?	G60
1/27/2005 10:23	1/28/2005 05:18	ms1	EQS	19				Nāmakanipaio[11]	
1/29/2005 00:32	1/29/2005 16:35	ms2		14					
12/29/2005 15:54	12/29/2005 23:46	ei3.2	I	7, 4	flat				G61
1/15/2006 05:39	1/16/2006 01:50	ei3uer	II	10	1.7	149		Tilt 1/20–23 deflation; 1/21–22 missing	G62
1/22/2006 23:07	1/23/2006 11:40	ms1	EQS	16				Nāmakanipaio[11]	G63
1/25/2006 06:23	1/26/2006 22:36	ei3uer	II	15	4.7	308		Tilt 1/25–27 inflation	G64*A*
1/29/2006 11:31	1/30/2006 11:22	ei3uer	II	15	5.5	129		Tilt 1/27–2/3 deflation	G64*B*
1/30/2006 21:24	1/31/2006 18:13	ei3uer	II	12				UWE: flat	G64*B*
2/1/2006 04:47	2/8/2006 22:50	ei3uer	II	191				No rift deformation	G64*C*
2/9/2006 15:36	2/18/2006 07:02	ei3uer	II	113	flat			40, 38, 10, 12 and 48 events	G64*D*
						301		UWE: 2/10-17 2.3 µrad inflation	
2/22/2006 16:41	2/23/2006 09:47	ms2	EQS	23				Nāmakanipaio[11]	G65
2/23/2006 07:30	2/24/2006 17:29	ei4sswr	II	12				Tilt 2/23–28 inflation	G65
2/23/2006 21:08	2/24/2006 08:25	er3uer	II	12				No rift deformation	G65
2/26/2006 18:05	3/2/2006 20:05	ei4swr	II	17				Broken swarm ; Tilt 2/25–27 missing	G66
2/27/2006 22:42	3/1/2006 17:03	ei3uer	II	22				UWE: flat; no rift deformation	G66
3/1/2006 01:55	3/4/2006 20:25	ms1-2	EQS	65	5.1	297		Nāmakanipaio[11]	G67
3/1/2006 03:40	3/1/2006 17:03	er3.4	I	7, 3				Tilt 3/1-3; inflation	G67
3/6/2006 05:56	3/7/2006 02:07	ms2	EQS	17	8.8	128		Nāmakanipaio[11]	G68
3/6/2006 20:27	3/7/2006 03:49	ei4sswr	II	9				Tilt 3/3–8; deflation	G68
3/11/2006 02:00	3/16/2006 01:08	ms1-2	EQS	24	9.3	112		Tilt 3/10–13 deflation broken swarm	G69
3/16/2006 02:02	3/16/2006 22:51	sf3kuer	SDI	18	3.9.	132		Tilt 3/15–17 deflation; no spreading step recorded	G70
3/22/2006 18:37	3/22/2006 21:38	ei3uer	I	13	5.9	129		Tilt 3/20–22; UWE flat	G71
5/4/2006 12:18	5/5/2006 12:44	sf2mer	EQS	9	3.4	290			
5/9/2006 14:27	5/10/2006 00:10	ei3uer	I	12				Tilt 5/9–10	G72
7/29/2006 15:30	7/30/2006 10:21	ei4sswr[12]	II	13	9.5	290		Tilt 7/27–8/1; 7/29–31 missing	G73
8/3/2006 08:07	8/4/2006 02:30	ei3uer	I	11	flat			Tilt 8/3–7; 8/4–6 missing; UWE flat	G74
8/6/2006 10:18	8/6/2006 18:35	do	do	7					
4/3/2007 13:40	4/5/2007 07:20	sf3kuer	SDI	28	flat			No spreading step recorded	G75
4/16/2007			SE?[9]					Very few eq—resembles south flank response to intrusion; also classified as SDI	G76

Table 7.5. Pu'u 'Ō'ō-Kupaianaha eruption[1]: Stage IIIA—12/1/2003–5/18/2007 (see fig. 7.13).—Continued (footnotes)

[In rows with multiple entries text applies down to the next entry; dates in m/d/yyyy format; do, ditto (same as above); data for eruptions and traditional intrusions are emphasized by grey shading; "no data" in Lag column refers to gaps in the record of the Ideal-Arrowsmith]

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai'i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword "kl.erz.1983".

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3, and locations are shown on appendix figure A4.

[3]Event types defined in chapter 1 are abbreviated as follows: **E**, Eruption; intrusion ("traditional" **I**; "inflationary" **II**;"suspected deep" **SDI**); **EQS**, earthquake swarms; EQ, Earthquake $M \geq 4$; "surge"—abrupt inflation at Kīlauea's summit followed by an increase in magma output at Pu'u 'Ō'ō. These later become "d-i-d" events in which there is a preliminary deflation at Kīlauea's summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu'u 'Ō'ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (µrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna vault.

[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu'u 'Ō'ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu'u 'Ō'ō vent (E) time lag in hours.

[7]Abbreviations as follows: sf, south flank; ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); Continuously recording tiltmeters in Uwēkahuna Vault: I-A, Ideal-Arrowsmith, UWE, Uwēkahuna; drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix G figures plain text.

[9]Silent earthquakes documented in 4 papers—summary in (Montgomery-Brown and others, 2009, table 1), including earthquakes with a small deformation step and scant seismic expression designated "SE?": (Brooks and others, 2006; Cervelli and others, 2002b; Montgomery-Brown and others, 2009; Segall and others, 2006).

[10]After January 1983 earthquake migration rates are measured from plots similar to those in Klein and others (1987) that show migration rates of earthquakes between 1968 and 1983.

[11]Continuation of earthquakes triggered by the 1983 Ka'ōiki earthquake. Locations are beneath the Nāmakanipaio campground in Hawai'i Volcanoes National Park.

[12]er4 seismicity continues until 10/2006.

Table 7.6. Pu'u 'Ō'ō-Kupaianaha eruption [1]: Stage IIIB—5/18/2007–3/19/2008 (see fig. 7.13).

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

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
5/24/2007 07:40	5/25/2007 14:07	ei3uer	I	30	1.56	131	+ 1h 36m	Tilt 5/22–29; 5/26–28 missing	G77
5/25/2007 23:01	5/27/2007 11:25	ei3uer	I	19					
5/31/2007 21:29	6/1/2007 04:08	ei4sswr	II	8					G78
6/17/2007 02:16	6/18/2007 12:46	ei3uer	I	121	7.18	123	+ 0h 21m	Tilt 6/15–20 6/16–17 missing	
6/17/2007 02:31	6/17/2007 13:00	lpms1	EQS	27				Location beneath upper east rift—first ever long-period earthquake swarm in this region!	
6/17/2007 02:54	6/17/2007 12:22	sf3.2	EQS	14, 8				South flank response	
6/17/2007 03:01	6/17/2007 08:11	ms1	EQS	7				9 more ei2mer to 6/21/2007 19:24; 9 ei3uer from 6/19 11:58 to 6/22 07:56	
6/17/2007 03:03	6/18/2007 23:24	ei2mer	I	88				Silent earthquake; one 10-hr break	

Table 7.6. Pu‘u ‘Ō‘ō-Kupaianaha eruption [1]: Stage IIIB—5/18/2007–3/19/2008 (see fig. 7.13).—Continued

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

Date and Time		Reg.[2]	Event Type[3]	No.[4]	Tilt[5]		Lag[6]	Comment[7]	Fig.[8]
Start	End				Mag	Az			
6/17/2007 20:52	6/18/2007 17:47	sf3kuer	SE[9]	30				South flank anticipation	G79
6/18/2007 14:12	6/18/2007 15:35	ms1	EQS	4					
6/20/2007 12:37	6/21/2007 12:27	sf3, sf2	EQS	5/5				South flank anticipation	
6/22/2007 18:35	6/22/2007 23:23	MERZ	E					Fathers day eruption (Episode 56)	**7.14**
6/22/2007 18:35	6/23/2007 02:56	sf3, sf2	EQS	6,1				South flank accompaniment/response	
7/2/2007 07:50	7/20/2007 22:23	MERZ	E					Ep 57; renew activity at Pu‘u ‘Ō‘ō	
7/3/2007 23:16	7/4/2007 12:37	ei3uer	I	28	0.97	133		Tilt 7/6-16; 58 er3 events 7/4–16	G80
7/5/2007 06:11	7/6/2007 01:38	ei3uer	I	13					G81
7/16/2007 21:07	7/17/2007 13:23	ei3uer	I	16				UWE 7/15–17 5.3 µrad deflation	G82
7/21/2007 00:39	6/1/2009	MERZ	E		flat			Ep 58; fissure East of Pu‘u ‘Ō‘ō	**7.15**
7/26/2007 12:29	7/26/2007 22:52	ms4.5	EQS	8					
8/13/2007 19:38	8/19/2007 08:26	sf2mer	EQS	74				Several swarm breaks after first day	
9/23/2007 16:05	9/24/2007 13:13	sf2mer	EQS	10					
11/4/2007 02:01	11/4/2007 14:59	sf3kuer	SDI	14				*M*3.3, 3.2 double mainshock? followed by aftershocks	

[1]References as follows: Wolfe and others (1987, 1988) cover the first 20 episodes. Heliker and others (2003) summarize the first 20 years of eruption. Other references to the eruption are covered in the Hawai‘i bibliographic database (Wright and Takahashi, 1998) from which all references pertaining to the eruption may be obtained by searching on the keyword “kl.erz.1983”.

[2]Earthquake classification abbreviations are given according to the classification in appendix table A3, and locations are shown on appendix figure A4.

[3]Event types defined in chapter 1 are abbreviated as follows: **E**, Eruption; intrusion (“traditional” **I**; “inflationary” **II**;“suspected deep”**SDI**); **EQS**, earthquake swarms; EQ, Earthquake $M \geq 4$; “surge”—abrupt inflation at Kīlauea’s summit followed by an increase in magma output at Pu‘u ‘Ō‘ō. These later become “d-i-d” events in which there is a preliminary deflation at Kīlauea’s summit followed by sharp inflation and then deflation. This pattern is matched by the electronic tilt at Pu‘u ‘Ō‘ō with a slight time delay.

[4]Minimum number of events defining a swarm: 20 for south flank; 10 for all other regions.

[5]Magnitude in microradians (µrad) and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna vault.

[6]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) or eruption (in the absence of a precursory swarm) for a given event and the beginning of deflation or inflation measured by the continuously recording Ideal-Arrowsmith tiltmeter in Uwēkahuna Vault. (+) tilt leads, (-) tilt lags. For the later eruption surges (Deflation-Inflation-Deflation events) lag times (+) are given for the delayed response of the tiltmeter at Pu‘u ‘Ō‘ō (POC) time lag in minutes, and the increase in eruptive activity at or near the Pu‘u ‘Ō‘ō vent (E) time lag in hours.

[7]Abbreviations as follows: sf, south flank; ftn, fountaining; eq, earthquake; eqs, earthquake swarm; fs, foreshock; as, aftershock; ms, mainshock; sf, south flank; inf, inflation; def, deflation; ant, anticipation (preceding event); acc, accompaniment (during event); resp, response (following event); Continuously recording tiltmeters in Uwēkahuna Vault: I-A, Ideal-Arrowsmith, UWE, Uwēkahuna; drm, downrift migration of earthquakes; urm, uprift migration of earthquakes; abs, missing data.

[8]Text figures **bold text**; appendix G figures plain text.

[9]Silent earthquakes documented in 4 papers—summary in (Montgomery-Brown and others, 2009, table 1), including earthquakes with a small deformation step and scant seismic expression designated “SE?”: (Brooks and others, 2006; Cervelli and others, 2002b; Montgomery-Brown and others, 2009; Segall and others, 2006).

A major paired intrusion occurred in May 2007 (table 7.6), marking the beginning of stage IIIB. One month later the most dramatic event of this stage occurred, the Father's Day east rift eruption and traditional intrusion of 19 June 2007 (Poland and others, 2008). The volume of lava erupted was very small compared to the volume of intrusion. A silent earthquake accompanied the precursory intrusion (fig. 7.14; Montgomery-Brown and others, 2010). Eruption stopped at Puʻu ʻŌʻō on the day of the intrusion, ending episode 55.

Puʻu ʻŌʻō activity resumed on 2 July (episode 57) and ended on 20 July, one day before the fissure eruption (episode 58) located downrift of Puʻu ʻŌʻō (Poland and others, 2008)) Two intrusions occurred between the Father's Day eruption and episode 58 (table 7.6). South flank seismicity increased as rift seismicity moved eastward toward the site of fissure eruption. Rift seismicity virtually ended before the fissure eruption began. South flank seismicity continued through the time of fissure eruption and was focused both south of the eruption site and south of the uppermost east rift zone (fig. 7.15).

Volatile Release During Stage IIIB

East rift sulfur dioxide (SO_2) emissions at Puʻu ʻŌʻō increased dramatically following the 1997 Nāpau eruption and again in 2005 and 2006 (Elias and Sutton, 2002, 2007; Elias and others, 1998). Sulfur dioxide emissions at Kīlauea's summit showed only small changes through 2006, but emissions increased briefly during the Father's Day eruption and increased steadily before and during the eruption at Halemaʻumaʻu in March 2008 (Wilson and others, 2008). Carbon dioxide (CO_2) emissions at Kīlauea's summit increased in 2004, peaking in 2005, and remained high through 2007 (J. Sutton, written commun., 2009).

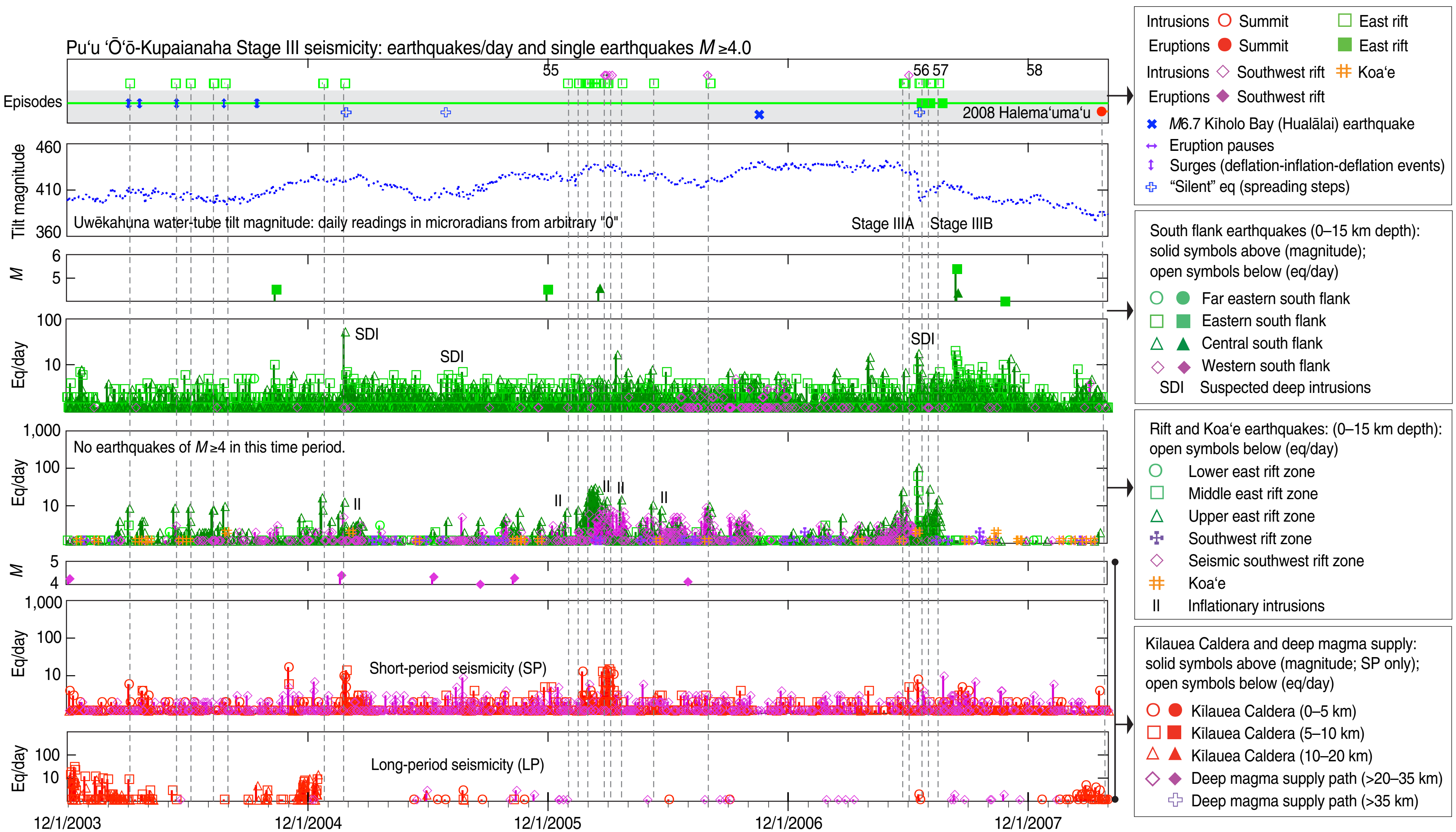
Interpretations, 1983–2008

The onset of the Puʻu ʻŌʻō eruption in January 1983 (episode 1) is interpreted as the culminating event in the series of eruptions and intrusions marking the recovery from the 1975 earthquake. The succeeding eruption history is governed by the adjustment of the rift plumbing to accommodate an increasing magma supply (see chap. 8, figure 8.5). The current activity is unique in Kīlauea's historical period in that increased magma supply eventually resulted in two concurrent eruptions.

A broad comparison between seismicity in the year preceding and including episode 1 and the remainder of stage I (episodes 2–47) is shown in table 7.7, which counts all located earthquakes in the HVO catalog sorted into different regions. As a consequence of the 1975 earthquake and its aftershocks, the rate of south flank seismicity increased greatly and the rate of deep magma-supply seismicity was reduced (Klein and others, 1987, p. 1034, 1038, figure 43.8H, p. 1054). The release of magma to the surface and accompanying summit deflation in January 1983 resulted in a release of the stress on Kīlauea's south flank engendered during magma refilling under the east rift during the recovery from the 1975 earthquake (Delaney and others, 1993, 1998; Dieterich and others, 2003). The average number of earthquakes per day above 5-km depth beneath the summit (ms1), rift zones, and Koaʻe at depths extending to the decollement is also greatly reduced following the end of episode 1. In contrast, the average number of earthquakes per day along the magma supply path at depths greater than 5 km, which was low during recovery from the 1975 earthquake, again increases in the period following episode 2.

The entire seismic and eruptive history from 1982 through 2007 is summarized in figures 7.16 and 7.17. The daily radial tilt component at Uwēkahuna vault is plotted with yearly averages of located short-period and long-period earthquakes, number of intrusions, SO_2 and CO_2 emission rates, and south flank spreading rates. Kīlauea's summit continued to deflate until the end of stage II (fig. 7.17*A*).

Figure 7.13. Graphs showing Kīlauea activity, 1 December 2003–19 March 2008: Stage III of the Puʻu ʻŌʻō-Kupaianaha eruption. Stage III is arbitrarily divided into IIIA and IIIB at 18 May 2007, preceding the east rift intrusion of 24 May and the Father's Day eruption in June. These events begin the final precursory period before the Halemaʻumaʻu eruption of 19 March 2008. Time-series plots show the number of earthquakes per day (eq/day) and magnitudes (*M*) ≥4 plotted against times of eruption and intrusion and the Uwēkahuna tilt magnitude. Symbols are given on the plots. Seismic regions are shown in figure A4 of appendix A. Three types of intrusions are defined in chapter 1. Traditional intrusions are shown as intrusion symbols. Inflationary intrusions are labeled (II), and suspected deep intrusions are labeled (SDI) but are not plotted as intrusions. Dates on figure in m/d/yyyy format. Panels from top to bottom show the following: (a), Times of eruption and intrusion. Vertical dotted lines connect seismicity associated with eruptions and associated traditional intrusions. Vertical dashed lines connect traditional intrusions not associated with an eruption. (b), Uwēkahuna tilt magnitudes in microradians. (c), South flank earthquake magnitudes. (d), South flank earthquakes per day, Rift and Koaʻe earthquake magnitudes. (e), Rift and Koaʻe earthquakes per day. (f), Kīlauea Caldera and deep magma-supply earthquake magnitudes. (g), Kīlauea Caldera and deep magma-supply earthquakes per day—short-period data. (h), Kīlauea Caldera and deep magma-supply earthquakes per day—long-period data.



Pu‘u ‘Ō‘ō-Kupaianaha Stage III seismicity: earthquakes/day and single earthquakes M ≥4.0
Episodes
55
56 57
58
2008 Halema‘uma‘u
Tilt magnitude
460
410
360
Uwēkahuna water-tube tilt magnitude: daily readings in microradians from arbitrary "0"
Stage IIIA
Stage IIIB
M
6
5
Eq/day
100
10
SDI
SDI
SDI
1,000
100
10
No earthquakes of M ≥4 in this time period.
II
M
5
4
1,000
100
10
Short-period seismicity (SP)
100
10
Long-period seismicity (LP)
12/1/2003
12/1/2004
12/1/2005
12/1/2006
12/1/2007
Intrusions Summit East rift
Eruptions Summit East rift
Intrusions Southwest rift Koa‘e
Eruptions Southwest rift
M6.7 Kīholo Bay (Hualālai) earthquake
Eruption pauses
Surges (deflation-inflation-deflation events)
“Silent” eq (spreading steps)
South flank earthquakes (0–15 km depth):
solid symbols above (magnitude);
open symbols below (eq/day)
Far eastern south flank
Eastern south flank
Central south flank
Western south flank
SDI Suspected deep intrusions
Rift and Koa‘e earthquakes: (0–15 km depth):
open symbols below (eq/day)
Lower east rift zone
Middle east rift zone
Upper east rift zone
Southwest rift zone
Seismic southwest rift zone
Koa‘e
II Inflationary intrusions
Kīlauea Caldera and deep magma supply:
solid symbols above (magnitude; SP only);
open symbols below (eq/day)
Kīlauea Caldera (0–5 km)
Kīlauea Caldera (5–10 km)
Kīlauea Caldera (10–20 km)
Deep magma supply path (>20–35 km)
Deep magma supply path (>35 km)

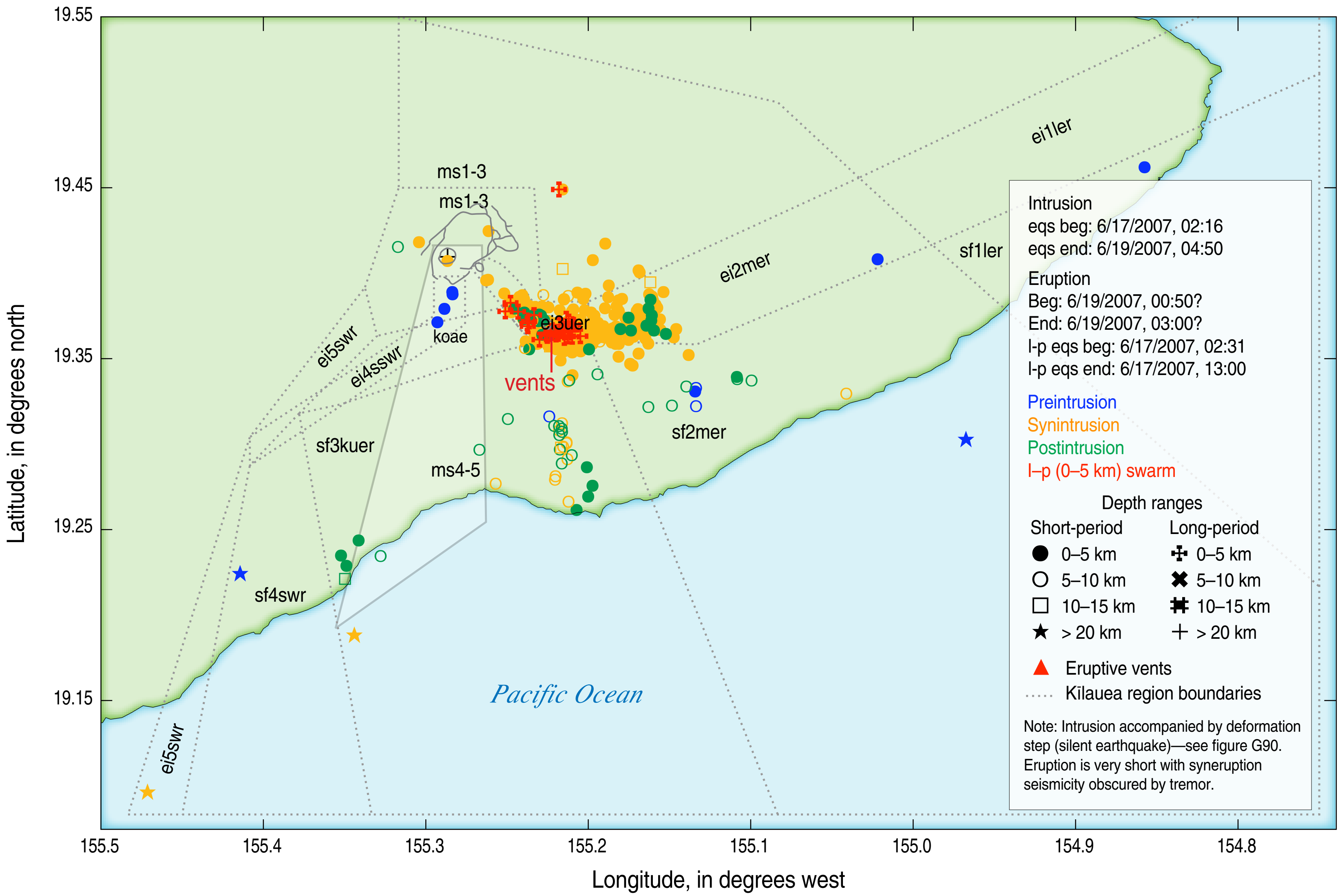


Figure 7.14. Map showing seismicity on Kīlauea, 13–23 June 2007: before, during, and after the "Father's Day eruption." That small eruption on 19 June was accompanied by a major intrusion on 17–19 June beneath the upper and middle east rift, accompanied and followed by a suspected deep intrusion beneath the central south flank. Other than that accompanying the suspected deep intrusion, the south flank seismicity is very sparse and distributed over a wide area. Dates on figure in m/d/yyyy format.

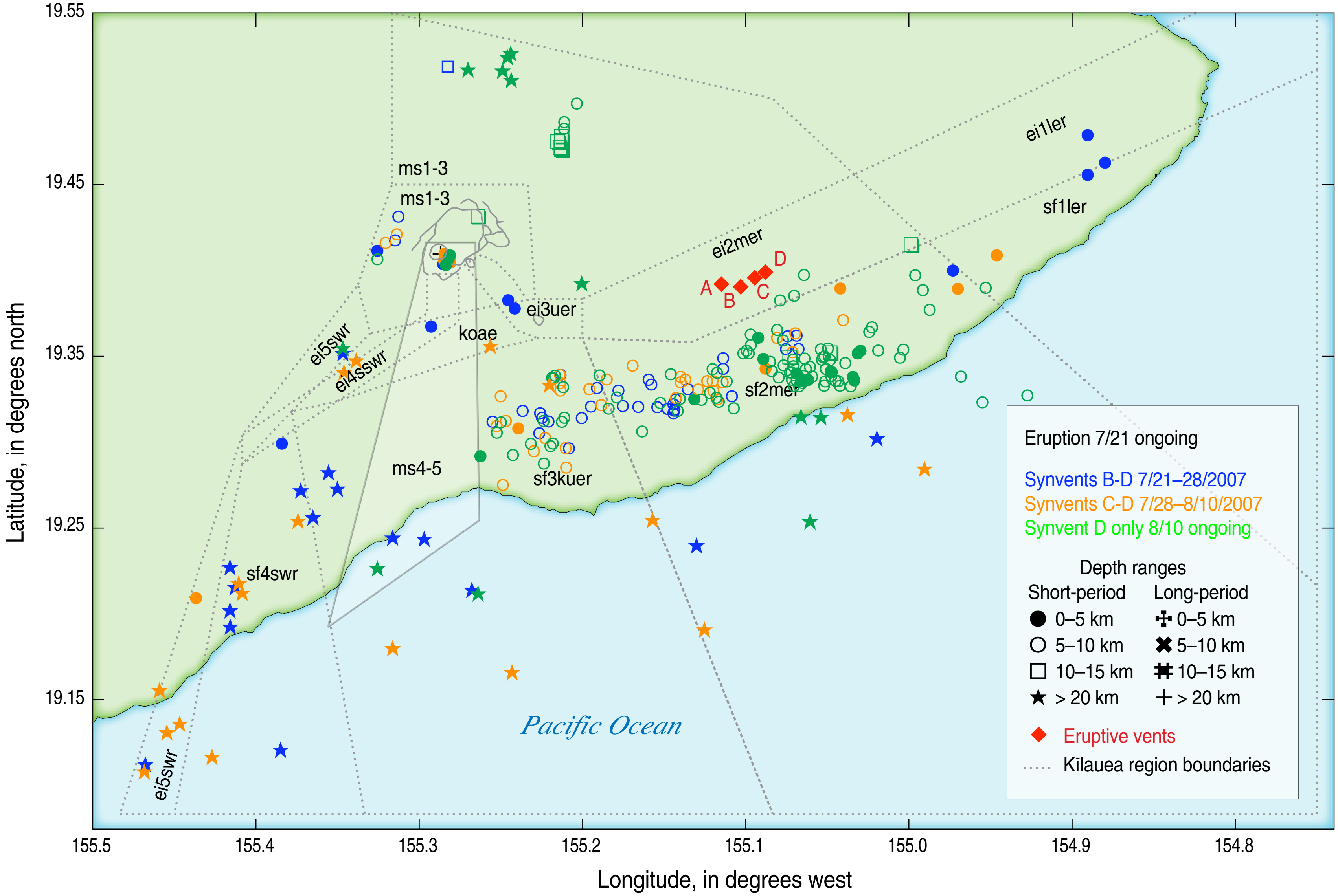


Figure 7.15. Map showing seismicity on Kīlauea, 22 July–19 August 2007. A fissure eruption on 21 July was accompanied and followed by very little rift seismicity, but it was followed by a very strong swarm of south flank earthquakes. Dates on figure in m/d/yyyy format.

Table 7.7. Number of short-period earthquakes per day in different regions through stages I–III of the Pu‘u ‘Ō‘ō–Kupaianaha eruption.

[Earthquake region abbreviations are given according to the classification in appendix A, table A3, and locations of regions are shown in appendix A, figure A4]

Regions Depth (km)	ms1[1] 0-5	ms1 all[2]	ms2.3[1] 5–15	ms2.3 all[2]	ms4.5 > 20	ei2.3 0-15	ei4 0-15	ei2.3.4 0-15	koae 0–15	sf2.3 0–15	sf4 0–15	sf all
Stages												
Pre: 2/1/1982-2/1/1983	0.57	0.57	0.04	0.04	0.04	3.28	1.6	4.90	0.09	6.97	0.86	7.83
IA: 2/1/1983-7/18/1986	0.13	0.22	0.06	0.16	0.12	0.03	0.01	0.03	0.01	2.78	0.11	2.89
IB: 7/18/1986-11/8/1991	0.26	0.28	0.04	0.14	0.15	0.19	0.00	0.19	0.01	1.90	0.04	1.94
IIA: 11/8/1991-1/1/1997	0.26	0.29	0.35	0.15	0.18	0.30	0.002	0.30	0.03	1.15	0.02	1.17
IIB: 1/1/1997-8/1/2003	0.32	0.34	0.09	0.22	0.32	0.20	0.01	0.31	0.09	1.17	0.04	1.54
III: 8/1/2003-3/18/2008	0.27	0.35	0.07	0.34	0.52	1.21	0.49	1.70	0.02	2.62	0.18	2.62

[1]Excluding seismicity triggered by the earthquake of 11/16/1983 and subsequent seismicity beneath the Nāmakanipaio region.

[2]Including seismicity beneath the Nāmakanipaio region.

Kīlauea’s south flank continued to relax through the end of stage IIA, as indicated by decreasing numbers of earthquakes, but those numbers then increased through the beginning of eruption in Halema‘uma‘u in 2008 (figure 7.17*B, C*). The deep magma-supply seismicity matches the later south flank seismicity, and both began to increase in 1998–2000, several years before the beginning of inflation in 2004. The number of earthquakes beneath the rift zones and the number of intrusions, particularly on the southwest side of the volcano, increased coincident with the beginning of inflation. CO_2 emissions at Kīlauea’s summit were low and constant until a spike in 2003–2004, also coincident with the beginning of inflation. SO_2 emissions measured on the east rift zone show a large increase associated with the 1997 eruption/intrusion and a smaller increase during stage III of the eruption. SO_2 emissions at the summit show little change until the advent of the March 2008 Halema‘uma‘u explosions, and the rate of SO_2 release has remained high since that time. The south flank spreading rate has varied little except for a spike associated with the January 1997 intrusion.

Magma Supply and the Evolution of Kīlauea’s Plumbing, 1983–2008

Within the period from 1983 to 2008, Pu‘u ‘Ō‘ō-Kupaianaha stage I represents an approximate equilibrium between magma supply, spreading, and eruption rates at an estimated magma-supply rate of 0.18 km^3/yr (Cayol and others, 2000), which is higher than magma-supply estimates prior to the 1975 earthquake (Wright and Klein, 2008). During stage IA there were no intrusions, and eruptive episodes were fed from the traditional summit reservoir at 2–6-km depth depicted in chapter 2, figure 2.5. Intrusions began in 1988 and have been frequent since (fig. 7.17*D*).

Magma supply rates during stages I and II have been estimated using a variety of methods. Eruption rates during this time were estimated by mapping flow distribution, by measurement of SO_2 emission, by electromagnetic profiling over active lava tubes (Heliker and Mattox, 2003, table 1; Sutton and others, 2003, table 1, figures 2–4), and by estimating volume changes during D-I-D events (Cervelli and Miklius, 2003, table 1). Magma supply rates were calculated for the first 20 years of eruption and show good agreement among the various methods. When rift dilation is taken into account, magma supply rates agree with the 0.18 km^3/yr magma supply rate estimated for stage IA (Cayol and others, 2000), which may have increased to more than 0.2 km^3/yr by 2001(Cervelli and Miklius, 2003, table 1). A microgravity study indicates that mass was added to Kīlauea’s summit reservoir in 1983–85 and 1991–93 and subtracted from it during1985–91 (Kauahikaua and Miklius, 2003, figure 2). Mass was also added following the December 1990 intrusion through the transition from stage I to stage II. A full discussion of the long-term history of magma supply and the evolution of Kīlauea’s plumbing is given in the next chapter (see fig. 8.5).

A new magma source just southeast of Halema‘uma‘u at a depth of less than 1 km was identified in 1996 by the broadband seismic array and by continuous recording tiltmeters located around Kīlauea’s summit (see section above on

"Installation of a Broadband Seismic Array"). This magma source supplied Puʻu ʻŌʻō during stages II and III (Cervelli and Miklius, 2003). Earthquakes associated with the summit eruption in April 1982 and the intrusion of December 1990 lie very close to the new magma center and may bracket the time when this source first became active. Subsequent eruptions at Puʻu ʻŌʻō may have been fed from this new shallow magma chamber. On the other hand, the large intrusion of 26 March 1991 appears to be more similar to earlier intrusions fed from the traditional reservoir at depths of 2–6 km. The March 1991 intrusion and others accompanied by a sizable summit deflation observed on the Uwēkahuna tiltmeter must be fed from the 2–6-km deep reservoir to produce the observed summit collapse. We suggest that subsequent intrusions continued to be fed from the deeper reservoir, whereas magma erupted from Puʻu ʻŌʻō followed the shallower path.

We suggest that a small increase in magma supply may have caused the transition from episodic (stage IA) to continuous (stage IB) eruption, in agreement with Parfitt and Wilson (1994). The supply increase caused a nonlinear transition from an oscillator to a continuous flow mechanism. A change in conduit geometry could also cause a transition from oscillator to continuous, but we prefer magma-supply increase as the cause because other evidence supports a supply increase. Another increase in magma supply triggered the 1997 eruption and intrusion. In the latter case the summit was not pressurized before the intrusion, because there was no prior inflation, indicating that pressure was applied from the deeper magma system beneath the rift zone. The application of magma pressure originating in the deep rift resulted in dilation of the rift and a temporary increase in spreading rate (fig. 7.17*B*; Owen and others, 2000b), as well as a temporary increase in SO_2 emission measured at the east rift zone (fig. 7.17*C*). The steady increase in short-period earthquakes deeper than 20 km from 1996 through 2007 (figure 7.16*D*) suggests that the magma supply from depth was increasing continuously during this period but that conditions within the crust caused the increase in magma supply to be manifested in a discontinuous fashion.

A further large increase in magma supply occurred in late 2003, evidenced by summit inflation (fig. 7.16*A*), an increase in CO_2 emission at Kīlauea's summit to double or triple the average values measured earlier in the eruption (fig. 7.17*C*; Poland and others, 2007, 2008; Sutton and others, 2009), and a great increase in the frequency of traditional and inflationary intrusions (figure 7.17*D*). Additional evidence for a magma-supply increase is provided by gravity measurements that show addition of mass beneath Kīlauea's summit through periods of both inflation and deflation (Eggers and Johnson, 2006; Tikku and others, 2006). Finally, the activation of Kīlauea's seismic southwest rift zone to accommodate increased magma supply, manifested as increased seismicity (table 7.7; fig. 7.16*B*), uplift (Poland and others, 2007), and increased intrusion beneath both rift zones (fig. 7.17*D*), mimics a pattern seen earlier in the Mauna Ulu period that preceded major changes in the eruptive regime (this paper, chap. 5; (Wright and Klein, 2008)).

The final events concluding stage III and leading to the 2008 Halemaʻumaʻu explosions begin with the Father's Day eruption. The great increase of sulfur dioxide emission at Kīlauea's summit during and following that eruption (Poland and others, 2009a) is a function of the greatly increased magma supply. In our interpretation, the ever-increasing magma supply resulted in the upward migration of the magma system to the surface through stoping of the weakened and formerly resistant rocks above the magma reservoir roof. At some time before the Halemaʻumaʻu explosions of March 2008, the shallow reservoir broke upward to yield a single magma source extending from the surface to 1 km depth (see chap. 8, fig. 8.1). In chapter 8 we interpret the monitored data in terms of this three-stage magma chamber evolution.

Long-Period Seismicity

Long-period earthquakes at different depths offer a clue to changes in plumbing during the Puʻu ʻŌʻō eruption. Long-period earthquakes at depths of 0–5 km represent excitation of the hydrothermal system around Kīlauea's summit reservoir (Almendros and others, 2001; Chouet, 1996). Before the current eruption, shallow long-period seismicity was seen below the caldera several days after the beginning of eruption and intrusion in September 1977 and persisted for many days after the eruption ended. Shallow long-period seismicity again dominated the response to the 1997 intrusion, this time persisting for many weeks after the end of eruption. Notably, shallow long-period seismicity was absent from every other eruption and intrusion since 1972, including episode 1 of the current eruption.

Long-period earthquakes below the magma chamber must reflect the flow regime along the vertical magma path connecting the magma chamber to its mantle source. Long-period earthquake swarms (at 5–15 km depth) become important beginning in 1985, reaching a maximum in 1989 and 1990, during stage IB (figure 7.16*D*). The seismicity most likely reflects a response to increased and consistent use of a single magma path in this depth range. As basalt is a good insulator, it is not likely

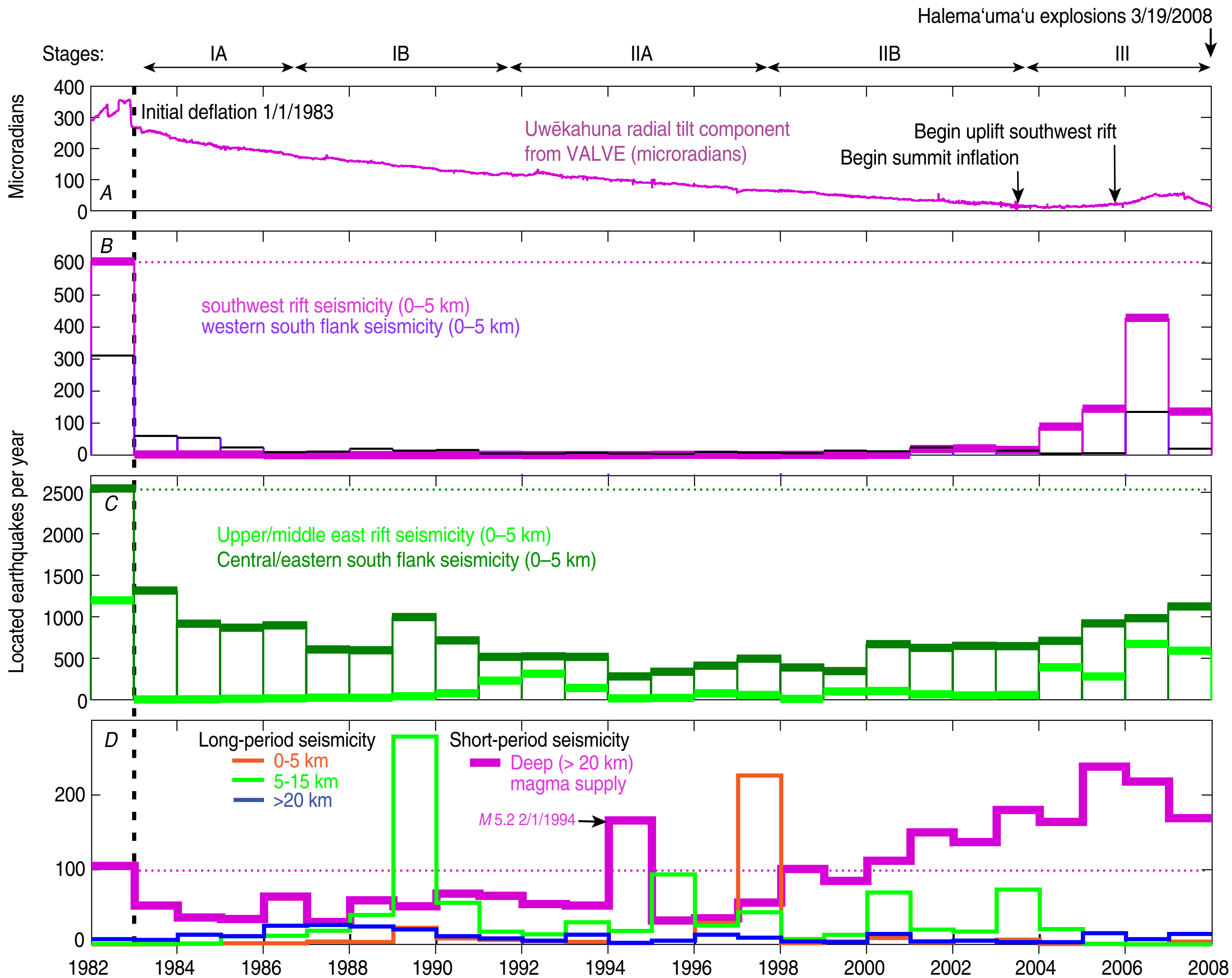


Figure 7.16. Graphs showing Kīlauea seismicity and tilt data, 1982–2008. The heavy dashed line separates data on the left covering a 1-year precursory period through episode 1 of the ongoing east rift eruption (1 February 1982–1 February 1983) from data on the right covering yearly data from 1 February 1983 to 1 February 2008. Arbitrarily defined stages of the Pu'u 'Ō'ō-Kupaianaha eruption are given across the top. Horizontal dotted lines represent the level of activity in the precursory period for comparison with the later eruption stages. Dates on figure in m/d/yyyy format. ***A***, Uwēkahuna water-tube tilt, radial component, from the Hawaiian Volcano Observatory's computer database (VALVE). ***B***, Southwest rift zone and western south flank earthquakes per year. ***C***, Upper/middle east rift and adjacent south flank earthquakes per year. ***D***, Long-period seismicity (thin bars) at 0–5, 5–15, and >20 km depth compared with short-period seismicity deeper than 20 km (thick bars). Earthquakes from 0 to 15 km depth are located beneath Kīlauea's summit. Earthquakes deeper than 20 km extend south and southwest from Kīlauea's summit along Kīlauea's magma supply path (Wright and Klein, 2006).

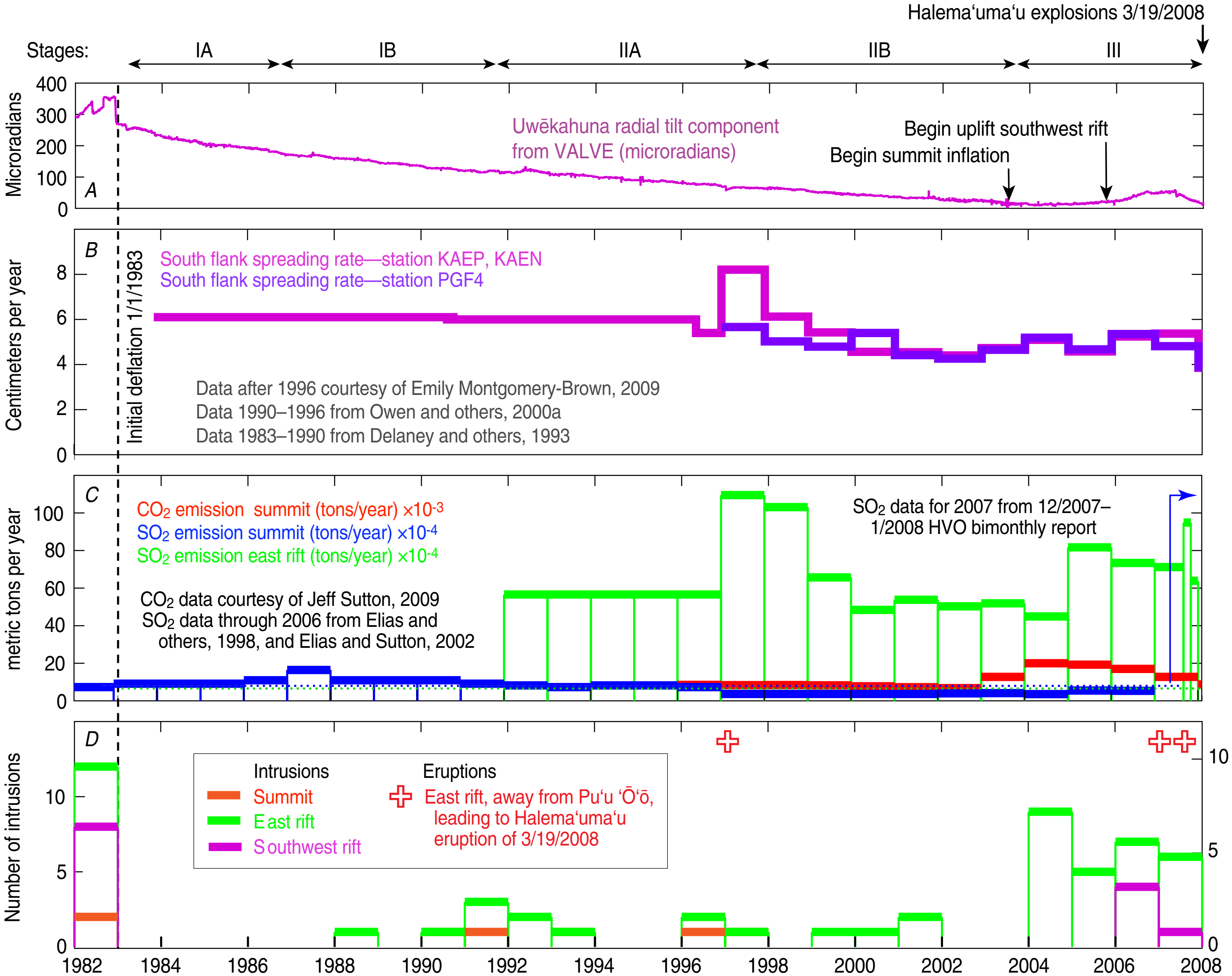


Figure 7.17. Graphs showing Kīlauea south flank spreading, gas emissions, intrusions, eruptions away from Pu‘u ‘Ō‘ō, and tilt data, 1982–2008. The heavy dashed line separates data on the left covering a 1-year precursory period through episode 1 of the ongoing east rift eruption (1 February 1982–1 February 1983) from data on the right covering yearly data from 1 February 1983 to 1 February 2008. Arbitrarily defined stages of the Pu‘u ‘Ō‘ō-Kupaianaha eruption are given across the top. Horizontal dotted lines represent the level of activity in the precursory period for comparison with the later eruption stages. Dates on figure in m/d/yyyy format. ***A***, Uwēkahuna water-tube tilt, radial component, from the Hawaiian Volcano Observatory's computer database (VALVE). ***B***, South flank spreading rates estimated from episodic and continuous Global Positioning System measurements modeled at two locations. ***C***, Yearly CO_2 and SO_2 emissions from Kīlauea's summit and yearly SO_2 emissions from Kīlauea's east rift zone. The blue arrow points to the very high rate of SO_2 release at Kīlauea's summit following the beginning of the March 2008 eruption in Halema‘uma‘u that ends our study. ***D***, Number of intrusions beneath Kīlauea's summit, east rift zone, and seismic southwest rift zone and timing of eruptions away from Pu‘u ‘Ō‘ō.

that softening of the rocks surrounding the magma conduit through heating could yield a broad distribution of long-period seismicity (Bruce Julian, oral commun., 2009). Mechanical disruption of the rocks surrounding the conduit is considered more likely (P. Dawson, oral commun., 2009), perhaps accompanying conduit widening as a response to long and continued use of the conduit at an ever–increasing magma supply rate. In any case, the physical or thermal environment of the conduit dramatically changed in the years after 1985.

More difficult to explain is the great decrease of long-period earthquakes deeper than 5 km in 2005 and their complete absence thereafter. This requires a process that would restore a stable physical and thermal structure of a possibly wider conduit noted above. It is also possible that the decrease is an artifact related to changes in seismic staffing at HVO, because the notation for long-period earthquakes is done through visual inspection by the analyst as part of normal earthquake processing.

Nāmakanipaio Earthquake Sequences

The ongoing occurrence of swarms of earthquakes a few kilometers west and north of Kīlauea Caldera in the vicinity of the Nāmakanipaio Campground is an interesting aspect of the eruption that began in 1983. Such earthquakes were first identified as Kīlauea seismicity triggered by the 16 November 1983 Kaʻōiki earthquake. Five swarms in 1990–92 were identified as precursors to several intrusions on the east rift zone (Okubo and Nakata, 2003). However, such swarms have occurred both earlier and later and sometimes accompany east rift intrusion (tables 7.1–7.5). Their origin remains uncertain. One possibility is that they are triggered by increase in magma pressure beneath Kīlauea's summit on an older caldera ring fracture (A. Miklius, oral commun., 2009), which was weakened from the effects of the 1983 Kaʻōiki earthquake.

Supplementary Material

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

Table G1. Tilt volume, eruption efficiency, and magma supply rate from 1983 to 2008.

Figures G1–G3. One-year time series plots between 1 February 1982 and 1 February 2008, showing details of numbers of both short-period and long-period earthquakes shown in text figures.

Figures G4–G7. Time series plot of earthquake swarms and plots of earthquake locations for the events of stage IA.

Figures G8–G15. Time series plot of earthquake swarms and plots of earthquake locations for the events of stage IB.

Figures G16–G24. Time series plot of earthquake swarms and plots of earthquake locations for the events of stage IIA.

Figures G25–G49. Time series plot of earthquake swarms and plots of earthquake locations for the events of stage IIB.

Figures G50–G82. Time series plot of earthquake swarms and plots of earthquake locations for the events of stage III.

Webcam setup on the rim of Puʻo ʻŌʻō, part of the monitoring improvements following the period covered in this paper. Images from the camera are continuously transmitted to HVO to allow staff to remotely assess changes in the eruption. USGS photo by B. Gaddis, 18 November 2010.