Chapter 6

Eruptive and Intrusive Activity, 1975–1983

Recovery from the 1975 earthquake, in a series of intrusions on both sides of the volcano, culminates in the intrusion associated with episode 1 of the east-rift eruption that continues in the second decade of the 21st century. The spreading regime also changes from one driven by magma supply to one where spreading rates are decoupled from changes in magma supply rate.

A coconut grove at Halapē on Kīlauea's south coast, under water because of coastal subsidence following the 29 November 1975 earthquake. USGS photo by R.T. Holcomb, 4 December 1975.

Kīlauea eruptions and intrusions following the *M*7.2 earthquake on 29 November 1975 are summarized in table 6.1; seismic data from that earthquake through the end of 1979 are shown in figure 6.1, and earthquake locations related to the 1977 eruption are shown in figure 6.2. Seismic data covering the rest of the period, from 1 January 1980 to episode 1 of the Pu‘u ‘Ō‘ō-Kupaianaha eruption, are shown in figure 6.3 These are supplemented by online figures that are cross-referenced in table 6.1. Additional seismic analysis for the entire period is included in Klein and others (1987), and figures from that paper are also cross-referenced in table 6.1. In the following paragraphs we briefly summarize the eruptive activity of this period and its interpretation.

The Kalapana Earthquake of 29 November 1975

The second largest earthquake in recorded Hawaiian history ruptured Kīlauea's south flank on 29 November 1975 (Klein and others, 2001). This earthquake had a surface-wave magnitude (M_S) of 7.2, and it has recently been assigned a moment magnitude (M_W) of 7.7. Motion in this Kalapana earthquake caused as much as 3.5 m subsidence at the south coast, as much as 1.5 m slip on the normal Hilina Pali faults, as much as 8 m of lateral motion of the coast, a tsunami with maximum run-up of 15 m along the south coast (causing two deaths), maximum shaking intensities (Modified Mercalli) of VIII in Puna and Hilo, including building damage, aftershocks that extended at least into late 1976, and a small eruption in Kīlauea Caldera (Tilling, 1976).

The 1975 Kalapana earthquake is unlike the more common strike-slip, thrust, and normal faulting seen in continental and plate-boundary environments. Fault slip in the Kalapana earthquake was at about 9-km depth on the decollement surface at the oceanic sediment layer between the oceanic crust and the overlying volcanic rocks, with a slight 5–10º northward dip of the fault plane (Ando, 1979). Lateral, compressive stress applied for decades by the east rift zone on the south flank enabled thrust motion on the decollement (Swanson and others, 1976a). Gravity aided slip on the Hilina Pali normal faults, subsidence at the coast, and slumping along the submarine toe of the Hilina slump block (Denlinger and Okubo, 1995; Morgan and others, 2000). The aftershocks defining the rupture extend for 40 km along most of the south flank at depths of 8–9 km and show focal mechanisms with slip on near-horizontal fault planes with slip vectors directed south-southeast and the upper block moving seaward (Crosson and Endo, 1982). An isoseismal map of shaking intensity also shows slip along the south flank, with areas of high intensity extending northward from the rupture zone to Hilo (Wyss and Koyanagi, 1992). Rupture during the mainshock was relatively slow and jerky, with secondary slip probably corresponding to high-stress fault asperities or stiff patches (Harvey and Wyss, 1986). Horizontal slip of benchmarks at the south coast, relative to the stable north flank of Kīlauea, was as much as 8 m south-southeast (Lipman and others, 1985). The surface deformation, teleseismic Love wave records, and tsunami recordings can be modeled by seaward slip on a subhorizontal fault of length 40 km and width of 20–40 km, extending offshore to give upward motion of the seafloor and an initial compression motion to the tsunami (Ando, 1979; Owen and Būrgmann, 2006). The interpretation of the tsunami mechanism is improved by modeling a rotating toe and slumping of the submarine extension of the south flank block, with subsidence at the coast and uplift 15–20 km offshore (Ma and others, 1999). Modeling of benchmark displacement during the earthquake involves both dilation of the east rift and subhorizontal slip in the buried decollement surface, similar to that modeled by Dvorak and others (1994) for 1976–88 and by Owen and Būrgmann (2006) for 1990–93.

The 29 November 1975 earthquake was anticipated because of the understanding and thoughtful analysis of the repeated dike injections in the east rift zone and geodetically measured compression of the south flank before the earthquake occurred (Swanson and others, 1976a). Several earthquake precursors were studied after the earthquake occurred, including seismic quiescence, foreshocks, earthquake clustering, lower P-wave velocities seen by teleseismic P residuals, and reversal of the compression of a geodetic line crossing a hypothesized asperity (Wyss and others, 1981), though the latter was not as strong an effect as first believed (Delaney and others, 1992).

Although magma pressure applied to the south flank over the preceding decades had set up conditions for the earthquake to occur, magma movement at the time of the earthquake was an effect of the earthquake, rather than a cause of it. The summit collapsed 1.2 m (Lipman and others, 1985), and about 0.1 km^3 of magma flowed into the east rift zone (Owen and Būrgmann, 2006). No east rift eruption took place, and most of the magma thus filled voids created by the earthquake. No direct measurements of the amount of rifting exist, but benchmarks separated by 3–6 km spanning the rift separated by 0.5 to 0.7 m (Lipman and others, 1985), and a geodetic inversion indicates that as much as 3–5 m of rifting took place (Owen and Būrgmann, 2006). There was a minor Kīlauea Caldera eruption that erupted about 250,000 m^3 of lava starting about 1 hr after the earthquake (Tilling, 1976). We interpret this summit eruption as magma moving upward from

Table 6.1. Earthquake swarms 11/29/1975 to 2/1/1983 (see figs. 6.1 and 6.3).

[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 gray bands]

Date and time		Class[1]	Event Type[2]	No.[3]	Tilt[4]		Lag[5]	Comment[6]	Fig.[7]
Start	End				Mag	Az			
11/29/1975 04:48		sf2mer	EQ					*M*7.2 with aftershocks	F4
11/29/1975 05:32	11/29/1975 22:00	Hm	E[8]					Halema‘uma‘u; induced by earthquake	
6/21/1976 09:15	6/22/1976 08:33	ei3uer	I	66	7.6	120	-4h45m	Tilt 6/20–22; uprift migration 1.3 km/hr	F5a; 43.68
7/14/1976 09:36	7/15/1976 08:54	ei3uer	I	49	6.6	108	-4h24m	Tilt 7/14–15	F5b; 43.69
1/22/1977 05:28	1/23/1977 02:39	ei3uer	II	17	5.3	299	-4h32m	Tilt 1/20–24; downrift migration 0.7 km/hr	F6; 43.70
2/7/1977 20:28	2/9/1977 00:44	ei3uer	I	65	6.6	108	-22h33m	Tilt 2/7–11; downrift migration 0.37 km/hr	F7; 43.71
2/8/1977 19:04	2/8/1977 22:43	koae	I	6				Koa‘e events aligned along east rift boundary	
9/12/1977 19:01	9/20/1977 05:25	sf2mer	EQS	302				South flank anticipation/response	
9/12/1977 21:33	9/17/1977 05:04	ei2mer	I	84	43.7	107	-0h27m	Tilt 9/11-13; downrift migration 1.23 Ð0.23 km/hr	43.72
9/13/1977 00:38	9/16/1977 09:41	lpms1	EQS	277	26.3	123		Tilt 9/13-14; magma recharge?	**6.2**
9/13/1977 19:13	9/17/1977 20:45	MERZ	E[9]		30.8	130		Stage 1; Tilt 9/14-16	**6.2**
9/14/1977 00:20	9/14/1977 10:08	koae	EQS	8					
9/18/1977 10:15	9/20/1977 12:00	MERZ	E[9]		12.9	163		Stage 2; Tilt 9/16–22	**6.2**; 43.73
9/25/1977 23:50	10/1/1977 15:30	MERZ	E		14.4	145		Stage 3; Tilt 9/26–10/9	
9/27/1977 10:35	10/8/1977 06:45	lpms1	EQS	130	14.4	145	-7h25m	Tilt 9/26–10/9; lp response; earthquake swarms of 47, 14, 23, 23 and 23 events; downrift migration 0.01 km/hr	**6.2 inset**; F8
5/29/1979 16:21	5/29/1979 21:06	sf3kue	EQS	22				South flank anticipation/response	F9; 43.75
5/29/1979 17:15	5/30/1979 04:36	ei3uer	I	33	4.3	133	+1h15m	Tilt 5/28–30; uprift migration 0.77 km/hr; downrift migration 0.65 km/hr	
5/29/1979 18:59	5/30/1979 00:34	ei2mer	I	27					
8/12/1979 06:02	8/12/1979 22:18	ei3uer	I	54	3.5	100	-3h58m	Tilt 8/11–13; downrift migration 1.6 km/hr	F10; 43.76
9/21/1979 21:59			EQ					*M*5.7; 3 foreshocks? from 17:16; >100 aftershocks	F11; 43.77
9/22/1979 13:33	9/22/1979 16:01	lpms1	II	22			+15h33m	I–A: 3.9 µrad inflation over 6 h	
10/11/1979 13:04	10/12/1979 19:03	ei3uer	II	21	nd		na	I–A: gradual inflation	F12
11/15/1979 00:06	11/15/1979 05:32	ei3uer	I	11					F13
11/15/1979 06:10	11/16/1979 21:51	sf3kuer		25				South flank anticipation/response	
11/15/1979 20:27	11/16/1979 21:51	ei3uer	I	138	8.2	101	-1h33m	Tilt 11/15–16; complex uprift migration/downrift migration	43.78
11/15/1979 22:21	11/17/1979 01:38	koae	I	33				I–A: deflation to 11/17, 03:00	F13
11/16/1979 08:18	11/17/1979 07:30	UERZ	E[10]					Pauahi Crater	F13
11/19/1979 23:30	11/21/1979 14:06	ei3uer	I	16					F13
1/16/1980 15:35	1/17/1980 04:06	ei3uer	II	11	nd		-6h25m	I–A: small deflation	F14
2/2/1980 00:57	2/2/1980 15:41	ei3uer	II	11	nd			Gradual inflation from 2/1, 22:00	F15
3/1/1980 00:31	3/1/1980 23:58	sf2mer	EQS	9				South flank anticipation	
3/2/1980 07:51	3/2/1980 20:55	ei3uer	I	114	2.7	122	+0h 51m	Tilt 3/1-3	F16; 43.79
3/2/1980 08:51	3/3/1980 05:50	sf3kuer	EQS	9				South flank accompaniment/response	
3/2/1980 14:12	3/3/1980 07:27	sf2mer	EQS	10				South flank accompaniment/response	

Table 6.1. Earthquake swarms 11/29/1975 to 2/1/1983 (see figs. 6.1 and 6.3).—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 gray bands]

Date and time		Class[1]	Event Type[2]	No.[3]	Tilt[4]		Lag[5]	Comment[6]	Fig.[7]
Start	End				Mag	Az			
3/10/1980 07:48	3/12/1980 23:05	sf3kuer	EQS	88	13.0	112	-3h 39m	South flank anticipation/response, tilt 3/10–11; uprift migration 0.25 km/hr	F17; 43:80
3/10/1980 18:21	3/11/1980 22:38	er2mer	I	43					
3/10/1980 21:55	3/12/1980 03:46	er3uer	I	130					
3/11/1980	3/12/1980	UERZ	E[11]					Near Devil's Throat	
3/11/1980 17:41	3/12/1980 07:58	koae		8					
7/30/1980 07:24	7/30/1980 08:44	ei3uer	I	36	1.6	158		Tilt 7/29–30; on I-A: gradual inflation	F18; 43.81
8/27/1980 14:30	8/28/1980 09:49	ei3uer	I	172	9.7	113	-0h 30m	Tilt 8/26–27; I-A: 8.6 µrad deflation; uprift and downrift migration	F19; 43.82
8/27/1980 15:01	8/28/1980 03:31	ms1	EQS	24					
10/21/1980 19:01	10/21/1980 22:04	ei2mer	I	12	9.0	135	-0h 04m	Tilt 10/20–22	F20; 43.83
10/22/1980 18:41	10/22/1980 21:36	ei3uer	I	34					
11/2/1980 14:11	11/3/1980 01:32	ei3uer	I	142	8.5	123	-0h 19m	Tilt 11/2–3; uprift migration and downrift migration	F21; 43.84
1/20/1981 03:10	1/21/1981 06:18	ei4sswr	I	94	2.7	147	32h 23m	Tilt 1/20–21; uprift migration 0.04 km/hr I-A: 1/18–20 slow deflation;	F22A;
1/24/1981 20:23	1/25/1981 18:45	ei4sswr	I	24	flat			I–A: slight inflation	43.86
1/26/1981 02:31	1/28/1981 01:05	ei4sswr	I	29	flat		22h	I–A: deflation from 1/25–1/26	F22B; 43.87
2/10/1981 13:19	2/13/1981 21:03	sf4swr	EQS	60				South flank anticipation/accompaniment	F23
2/13/1981 07:59	2/14/1981 06:24	ei4sswr	I	14	2.9	127		Tilt 2/9-10	F23; 43.88
2/14/1981 09:55	2/17/1981 01:17	sf4swr	EQS	40				South flank accompaniment/response	
2/14/1981 14:40	2/16/1981 02:20	ei4sswr	I	17	13.4	104		Tilt 2/12–18; I-A: ~15 µrad deflation 2/8–17	
2/16/1981 09:18	2/16/1981 22:59	ei4sswr	I	10					
3/19/1981 00:18	3/20/1981 4:14	sf2mer	SDI?	8				Scattered earthquakes	
3/19/1981 1:21	3/20/1981 3:58	sf3kuer	SDI?	5				Scattered earthquakes	
3/19/1981 4:32	3/20/1981 5:28	sf4swr	SDI	15				Concentrated earthquake swarm	
4/25/1981 01:02	4/27/1981 11:29	sf3kuer	SDI?	21	flat			I-A: gradual inflation	F24
6/25/1981 15:17	6/25/1981 17:15	ms1	I	5	13.8	301		Tilt 6/23-29; summit intrusion	F25
6/26/1981 18:48	6/27/1981 02:55	ms1	I	5			+1h 17m	I-A: sharp inflation on 6/25, gradual inflation on 6/26	
7/20/1981 19:56	7/21/1981 13:13	ei4sswr	II	10	flat		+8h 56m	I-A: ~1 µrad deflation	F26
8/1/1981 16:33	8/4/1981 05:26	ei4sswr	I	40			+2h 33m	I-A : deflation 8/1-8/4	F27
8/4/1981 19:39	8/7/1981 03:01	ei4sswr	I	22	7.0	289		Tilt 8/1-7	
8/9/1981 17:20	8/15/1981 04:53	ei4sswr	I	277	28.9	86	-11h 10m	Tilt 8/10; uprift migration 3.5 km/hr	F28; 43.89
8/10/1981 07:23	8/13/1981 08:32	sf3kuer	EQS	50	22.2	118		Tilt 8/10 07:40-09:30; south flank response	
8/10/1981 17:36	8/13/1981 11:36	sf4swr	EQS	76	46.6	128		Tilt 8/10; downrift migration 2.6, 0.28 km/hr	F28; 43.90
8/13/1981 23:30	8/14/1981 20:58	lpms1	I	13	20.3	157		Tilt 8/11–14; summit intrusion?	
11/10/1981 03:03		sf3kuer	EQ					*M*4.5 ms with >10 aftershocks	

Table 6.1. Earthquake swarms 11/29/1975 to 2/1/1983 (see figs. 6.1 and 6.3).—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 gray bands]

Date and time		Class[1]	Event Type[2]	No.[3]	Tilt[4]		Lag[5]	Comment[6]	Fig.[7]
Start	End				Mag	Az			
1/15/1982 18:44	1/16/1982 16:16	ei4sswr	II	10	flat		na	I-A : < 1 µrad inflation	F29[12]
2/27/1982 22:44	2/28/1982 07:56	ei4sswr	II	11	flat		-1h	I–A: ~ 1 µrad inflation	F30
3/3/1982 07:35	3/3/1982 17:29	ei4sswr	II	11	flat		+30m	I–A: ~ 1 µrad inflation	F31
3/9/1982 01:24	3/9/1982 15:08	ei4sswr	II	11	flat		+6h 24m	I–A: ~ 1 µrad r inflation	F32
3/23/1982 09:05	3/23/1982 16:10	ei4sswr	II	22	8.3	314		Tilt 3/22–25; I-A: ~ 2 µrad gradual inflation following earthquake swarm	F33[12]; 43.91
4/30/1982 08:55	4/30/1982 11:41	ei3uer	I	10	10.1	323		Tilt 4/30-5/2; uprift migration 14 km/hr	F34; 43.92
4/30/1982 08:55	4/30/1982 12:46	ms1	I	30			+17m	I-A: 5.6 µrad inf	
4/30/1982 11:37	5/1/1982 06:30	KC	E[13]/I					Kīlauea Caldera	
6/8/1982 15:30	6/9/1982 07:45	ei4sswr	II	13	8.6	340		Tilt 6/7-12; I-A shows <1 µrad inf/def	F35
6/22/1982 02:57	6/27/1982 15:38	sf3kuer	EQS	447	21.0	120		Tilt 6/21-23; South flank anticipation/response	F36
6/22/1982 07:04	6/24/1982 19:25	ei4sswr	I	131	32.8	141	+27h	Tilt 6/23-24; I-A: 39 µrad gradual deflation 6/21–25; downrift migration 0.37 km/hr	43.93
6/23/1982 17:55	6/24/1982 20:21	sf4swr	EQS	31	9.6	134		Tilt 6/24-30; continuing south flank response	
6/28/1982 17:04	7/1/1982 13:35	sf3kuer	EQS	37				Continued south flank response?	
8/10/1982 1:21	8/10/1982 1:37	sf3kuer	EQ					Double mainshock *M*3.8, 3.6 with aftershocks	
9/19/1982 2:21	9/19/1982 14:20	sf3kuer	EQS	11				South flank ant?	
9/25/1982 16:51	9/25/1982 20:24	ei4sswr	I	54	23.3	330	+0h 26m	Tilt 9/23-25 17:40; I-A: ~15 µrad sharp inflation	F37
9/25/1982 16:52	9/26/1982 0:12	ms1	I	30				Tilt 9/25; downrift migration 1.4 km/hr	43.94
9/25/1982 17:19	9/27/1982 13:51	ei3uer	I	180	10.1	320			
9/25/1982 18:45	9/26/1982 08:30	KC	E/I[13]					Kīlauea Caldera	
10/1/1982 14:46	10/3/1982 08:34	ei3uer	II	24	6.0	335		Tilt 9/2710/3; a series of small inflationary intrusions; I-A shows cyclic	F38
10/5/1982 01:50	10/6/1982 13:12	ei3uer	II	24	flat			inflation-deflation of 0.21.4 µrad that does not matching intrusion times	
10/7/1982 20:15	10/8/1982 21:27	ei3uer	II	20	flat				
10/10/1982 10:54	10/11/1982 10:36	ei3uer	II	27	flat				
12/9/1982 17:46	12/11/1982 10:54	ei3uer	I	185	4.4	148	+0h 27m	Tilt 12/9 08:4521:00; IA: 3 µrad sharp deflation; downrift migration 6.4 km/hr	**6.4***A*; 43.96
12/9/1982 17:49	12/10/1982 01:13	ms1	EQS	10					
12/21/1982 02:15	12/21/1982 14:44	Sf2.3	EQS	9		flat		South flank ant?	
12/21/1982 14:06	12/21/1982 23:42	ei3uer	II	10				I-A; no change	**6.4***A*
12/30/1982 01:36	1/3/1983 00:31				flat			Precursory sequence to ep. 1	**6.4***A-B*
12/30/1982 01:36	12/30/1982 20:25	ei2mer	II	10	flat		-2h 12m	I-A: ~1.2 µrad gradual deflation through both intrusions	**6.4***A*
12/29/1982 20:08	12/31/1982 04:56	ei3uer	II	10					43.97
12/30/1982 17:21	12/31/1982 23:37	sf3kuer	EQS	12				South flank anticipation/response	
1/1/1983 04:52	1/6/1983 11:32	sf2mer	EQS	95					

Table 6.1. Earthquake swarms 11/29/1975 to 2/1/1983 (see figs. 6.1 and 6.3).—Continued

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Date and time		Class[1]	Event Type[2]	No.[3]	Tilt[4]		Lag[5]	Comment[6]	Fig.[7]
Start	End				Mag	Az			
1/1/1983 22:36	1/6/1983 13:59	ei2mer	I	324	45.6	119	-5h 24m	Tilt 1/2–1/3; downrift migration 0.6 km/hr followed by uprift migration 0.06 km/hr	**6.5**
1/2/1983 15:32	1/3/1983 09:10	ms1	EQS	11	86.3	134		Tilt 1/3 13:50-1/8 07:15	
1/3/1983 00:31	1/3/1983 15:21	MERZ	E/I					Episode 1 Puʻu ʻŌʻō eruption	
1/4/1983 11:01	1/5/1983 11:45	sf3kuer	EQS	19				South flank response	
1/5/1983 11:44	1/5/1983 23:17	ms1	EQS	14					
1/5/1983 11:23	1/6/1983 09:55	MERZ	E				+8h 44m	Reactivate episode 1	**6.5**; 43:97
1/6/1983 10:11	1/6/1983 20:49	MERZ	E					do	
1/6/1983 18:19	1/6/1983 20:07	sf2mer	EQS	58				South flank response	
1/7/1983 00:07	1/7/1983 21:33	ei2mer	I	81				Downrift migration 0.61 km/hr	**6.5**; 43.97
1/7/1983 01:19	1/8/1983 01:05	ms1	EQS	18					
1/7/1983 09:57 1/8/1983 19:57	1/8/1983 15:04 1/8/1993 23:22	MERZ MERZ	E E					Reactivate episode 1; I–A: flat do	
1/10/1983 05:02 1/11/1983 01:30 1/15/1983 03:12	1/10/1983 14:50 1/11/1983 12:30 1/15/1983 18:35	MERZ MERZ MERZ	E E E		8.8	161		Do; Tilt 1/9-14; I–A: flat do do	**6.5**
1/18/1983 12:38	1/19/1983 23:32	sf2mer	EQS	18				South flank response	
1/23/1983 10:11	1/23/1983 23:04	sf2mer	EQS	14				South flank anticipation/response	**6.5**
1/23/1983 18:30	1/23/1983 19:30	MERZ	E					Episode 1 end; I–A: flat	

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

[2]Event types defined in chapter 1 are abbreviated as follows: Eruption (E); intrusion (“traditional” I; “inflationary” II; “suspected deep” SDI); earthquake swarms EQS; Earthquake ≥ *M*4 (EQ).

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

[4]Magnitude in microradians and azimuth of daily tilt measurements from the water-tube tiltmeter in Uwēkahuna Vault; nd, record not available.

[5]Lag times separating the onset of the earliest earthquake swarm (excluding south flank) 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.

[6]Abbreviations as follows: 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); during an earthquake swarm: drm, downrift migration of epicenters; urm, uprift migration of epicenters; I–A, Ideal-Arrowsmith continuously recording tiltmeter in Uwēkahuna Vault.

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

[8]See Tilling (1976) for a description of the eruption.

[9]See Moore and others (1980) for a description of the eruption.

[10]Eruption information in unpublished HVO monthly reports.

[11]Eruption discovered in March 1982 as documented in unpublished HVO monthly reports.

[12]See also figure 43.85 in Klein and others (1987).

[13]Eruption information in unpublished HVO monthly reports and in Nancy Baker’s unpublished Honor’s thesis at the University of Hawaiʻi at Manoa (Baker, 1987).

the reservoir a short distance through cracks shaken open by the earthquake and the movement of magma into the rift as a passive magma flow resulting from breaking of a magma barrier separating the reservoir and the rift zone.

Effects of the Kalapana Earthquake

The Kalapana earthquake profoundly altered stress on the south flank and "softened" it to the stress imposed by magma traversing the east rift. Aftershocks initially followed a normal $t^{\text{-p}}$ time decay with p = 0.82 for the first 100 days (Klein and others, 2006), but did not return to pre-1975 levels until stage II of the Puʻu ʻŌʻō eruption (see chap. 7; Dvorak, 1994; Klein and Wright, 2008). The high rate of aftershocks in the 17 years following 1975 means the stress released by the mainshock was large, but the relatively high rates of seismicity in the south flank before the earthquake also means that the rate of stress accumulation on the flank actually decreased at the time of the earthquake (Klein and others, 2006). This means that rift eruptions and intrusions stressed the flank more before the Kalapana earthquake than they did after it. Thus the flank was stiffer and offered more resistance before November 1975, but became softer and offered less resistance afterward.

When magma intrudes into the rift zone, it may stop before it erupts if the rift can accommodate all of the magma. But if conditions are right, the intrusion can turn into an eruption, in which case the magma pressure is partly relieved. After the 1975 earthquake, intrusions outnumbered eruptions (Klein, 1982), and movement of magma in the rift was often at a slower rate (Decker, 1987). This geologic change is another effect of the flank becoming more pliable and able to absorb magmatic stress without offering resistance to a dike, making magma less likely to be forced up to the surface. The "softening" of the flank as a result of the earthquake can also be seen in the change of the rate of extension or compression measured in the south flank: The line lengths, measured within the flank before the earthquake, showed extension of about 1 cm/yr during 1970–75 (Swanson and others, 1976a), but this changed to compression of about 6 cm/yr during 1976–80 (Delaney and others, 1998; Dvorak and others, 1994). Thus, after the flank suddenly expanded during the earthquake, intrusions could more easily squeeze the "soft" flank and compress it.

Following the earthquake, Kīlauea has been unable to sustain the high levels of magma in its summit reservoir as it did in 1971–75 (Lipman and others, 1985). Kīlauea's summit inflated almost 2 m between 1965 and 1975, but it deflated by almost 2.5 m between 1976 and 1997 (Delaney and others, 1998, figure 2a). Except for the collapse associated with the 1977 eruption, Kīlauea neither inflated nor deflated from 1976 to 1983, but it steadily deflated at 7.8 cm/yr after the Puʻu ʻŌʻō-Kupaianaha eruption began (see chap. 7).

Intrusions in the 1½ Years Following the 1975 Earthquake

A series of four east rift intrusions in the 18 months after the Kalapana earthquake followed typical patterns for Kīlauea intrusions (table 6.1; fig. 6.1). The east rift intrusions of 21 June and 14 July 1976 were similar in that the intense earthquake swarms began near Pauahi Crater and earthquakes then migrated about 5 km uprift. Earthquakes also migrated upward from the seismically defined conduit at a depth of 3 km, but the dike did not reach the surface. Minimum intruded magma volumes were 3.4×10^6 m^3 and 3.0×10^6 m^3. In both intrusions the summit reservoir began deflating about 4 hours after an intense earthquake swarm began beneath the rift zone.

We interpret the 1976 intruded magma, and hence the new or rejuvenated dike, as having originated at the rift zone magma reservoir under Pauahi Crater (fig. 6.5) that has also fed many other uprift and downrift migrating east rift intrusions (Klein and others, 1987). Intruded magma was ultimately resupplied from the summit reservoir. Dzurisin and others (1980) used Kīlauea's approximate magma supply rate of 9×10^6 m^3/month and the 40–90×10^6 m^3 void space created during the 1975 earthquake to infer that rift voids were filled in the 7 months before the June 1976 intrusion. We believe it took much longer than 7 months to fill all the 1975 void space because there was no summit inflation prior to the 1977 east rift eruption and no net inflation from the bottom of the 1975 collapse until after 1981 (figs. 6.1, 6.3).

Aftershocks of the Kalapana earthquake continued during 1976, but there were some small changes in south flank seismicity resulting from the intrusions that year. There was minor triggered seismicity in the flank immediately after the 21 June 1976 intrusion, but the amount is typical of day-to-day fluctuations and may not be related to the intrusion. A brief but noticeable spike in south flank activity occurred on the day of the 14 July 1976 intrusion, indicating that the intrusion incrementally added to south flank stress. The level of south flank seismicity was noticeably reduced during the 2–3 weeks after the 21 June 1976 intrusion (fig. 6.1), raising the possibility that redistribution of magma within the rift during the intrusion may have lessened stress on the flank.

Two intrusions in early 1977 are related to each other. Earthquakes in the primary east rift zone conduit during the 22 January 1977 inflationary intrusion (table 6.1) extended downrift to the vicinity of Kōkoʻolau Crater, and depths were confined between

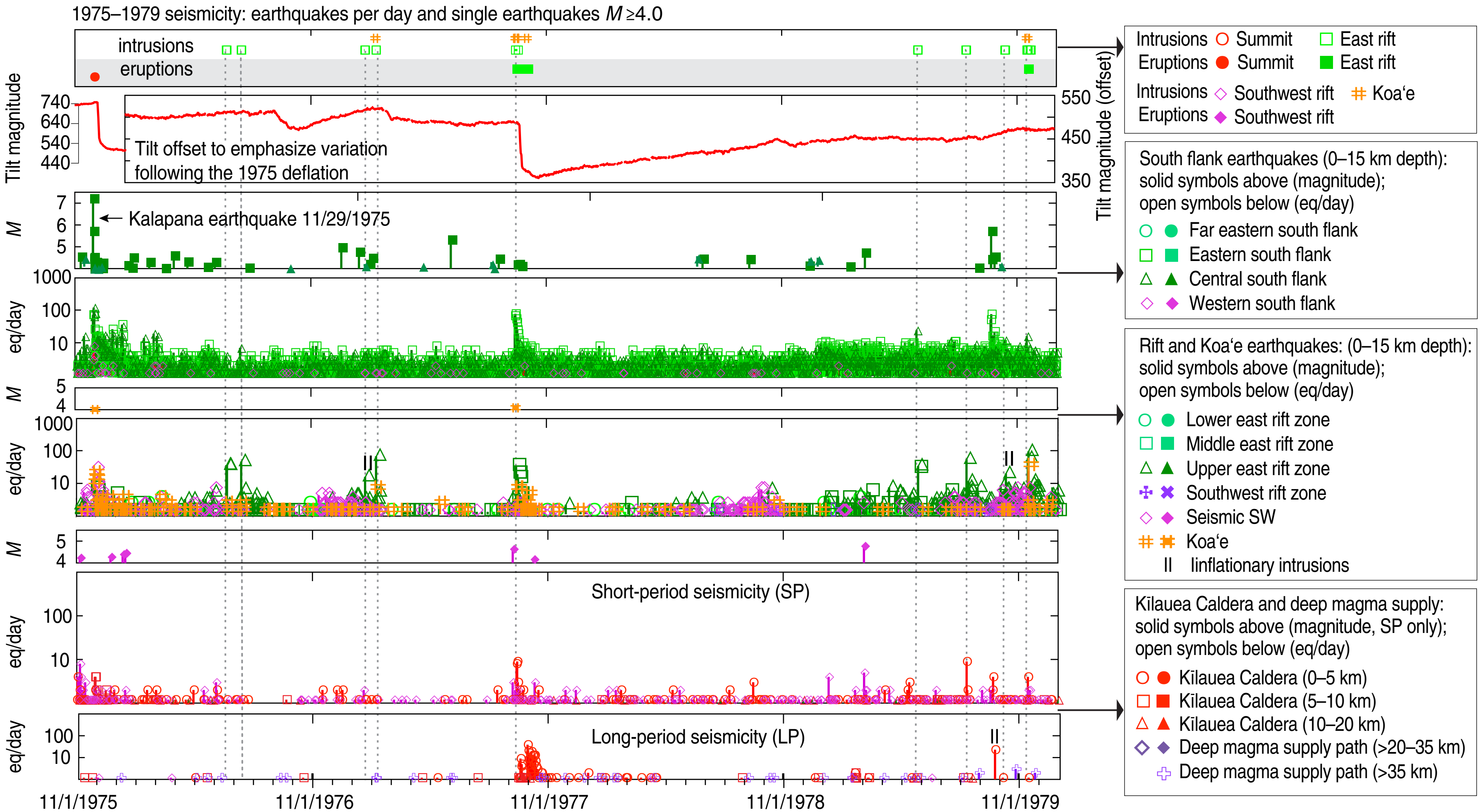

Figure 6.1. Graphs showing Kīlauea activity, 1 November 1975–1 January 1980. Time series plots show Uwēkahuna tilt magnitude, and times of eruption and intrusion, and seismic activity. Symbols are given on the plots. Top panel: Times of eruption and traditional intrusion. Second panel from top: Uwēkahuna 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, 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 and the following information applies to all time series figures in this chapter. Traditional intrusions are shown as intrusion symbols. Inflationary intrusions are labeled (II), and suspected deep intrusions are labeled (SDI) but not plotted as intrusions. Dates on figure in m/d/yyyy format.

2 and 4 km. The 8 February 1977 intrusion (table 6.1) began just uprift of Kōkoʻolau Crater and extended the newly intruded magma of 22 January downrift to Pauahi. Rift earthquakes associated with the February intrusion occurred between 4-km depth and the surface, a much larger cross sectional area than during the January intrusion. Both intrusions showed downrift earthquake migration (Klein and others, 1987, figure 43.70D and 43.71D). Neither of the early 1977 intrusions caused a south flank earthquake response.

We interpret the initial January 1977 inflationary intrusion as low volume and low pressure because the summit actually inflated while an earthquake swarm migrated away from the summit. In this and similar instances magma can leak into the rift zone at rates equal to or less than the rate of resupply. Earthquakes were confined to the main conduit near 3-km depth without expanding to form a larger dike. Earthquakes and magma stopped near Kōkoʻolau Crater, perhaps at a barrier within the rift or because of insufficient magma pressure. An opening in the reservoir complex on 8 February 1977 permitted a larger and more pressurized volume of magma to extend the intrusion downrift to the next rift barrier below Pauahi (fig. 6.5).

East Rift Eruption of 13 September–1 October 1977

What was then the largest Kīlauea eruption since the 1969–74 Mauna Ulu eruption began on 13 September 1977 (table 6.1, figs. 6.1, 6.2). An eruption had not occurred this far down the middle east rift since September 1961. The erupted lava had a fractionated chemical composition indicating that it had been stored in the rift (Moore and others, 1980). In chapter 4 (table 4.2) we suggested that the erupted magma had been emplaced in 1955 and cooled and fractionated in the intervening 22 years.

The eruption in September 1977 was accompanied by a large summit deflation that continued for 4 days, indicating that an uprift intrusion from the summit had forced the stored magma to the surface. Earthquakes produced by the intrusion immediately before the September 1977 eruption occurred in four main zones (fig. 6.2). Three zones, the southern Kīlauea Caldera, the Koaʻe Fault Zone, and the Makaopuhi section of the middle east rift zone, started producing earthquakes at essentially the same time late on 12 September 27 minutes before the summit began rapid deflation (table 6.1). The simultaneity of seismicity in these separate zones and the lack of earthquakes along the rift between them suggest that the part of the rift that is uprift of the eventual intrusion and vent area was open, fluid, and saw magma pressure and flow transmitted easily (Klein and others, 1987, figure 43.72). From Makaopuhi Crater to the eruption site, earthquake hypocenters migrated downrift at about 1.2 km/hr along the main conduit at 2–3-km depth. Earthquakes then slowed to 0.23 km/hr downrift, as the earthquakes traced the upward growth of the dike to the surface vents.

Earthquakes were triggered immediately in the south flank adjacent to the east rift zone, especially in the sections that saw no shallow rift earthquakes (fig. 6.2). This demonstrates that the growth of the dike in this section was by widening of an already fluid-filled dike: had there been voids in the rift or a destressed flank, magma filling would have occurred for some time before the flank accumulated enough stress to make earthquakes. The large number of triggered flank earthquakes implies that there was a great increase in stress rate in the south flank adjacent to the vents, suggesting that the stress applied by the November 1975 Kalapana earthquake was not fully released in this area[23]. The rate of earthquakes beneath the central and eastern flank during the 4 months following the September 1977 eruption was about twice that before and after the September–December period (fig. 6.1). The flank seismicity suggests that flank spreading was temporarily accelerated by the intrusion of new summit magma, although there were no geodetic measurements to confirm this.

Unlike other recent east rift zone eruptions, the September 1977 eruption was accompanied by a large earthquake swarm in and under Kīlauea Caldera. Many of these were long-period earthquakes but with seismogram onsets impulsive enough to time and locate the earthquakes in the upper 3 km of brittle rock above the summit magma reservoir (fig. 6.1). The swarms of long-period earthquakes continued through the deflation (fig. 6.2 inset) and, in decreasing numbers, beyond the end of the eruption (fig. 6.1). This was the first eruption to be accompanied by a large swarm of shallow long-period earthquakes beneath the caldera since HVO began counting them.

Earthquakes in the Koaʻe Fault Zone accompanied both the initial east rift zone intrusion on 13–19 September 1977 and the later pulse on 27 September–1 October 1. We do not believe that new magma entered the Koaʻe from the east rift zone because (1) the earthquakes were located in the central Koaʻe south of the caldera and not near the east rift zone from which new magma would be fed as it was in May 1973 (chap. 5, fig. 5.10) and (2) the earthquakes during 13–19 September 1977 started in the central Koaʻe and migrated toward instead of away from the east rift zone. This suggests that the Koaʻe can respond to major south flank movements by tectonic rifting unaccompanied by magma intrusion.

[23] This may explain why the 1977 magma was not erupted immediately following the 1975 earthquake.

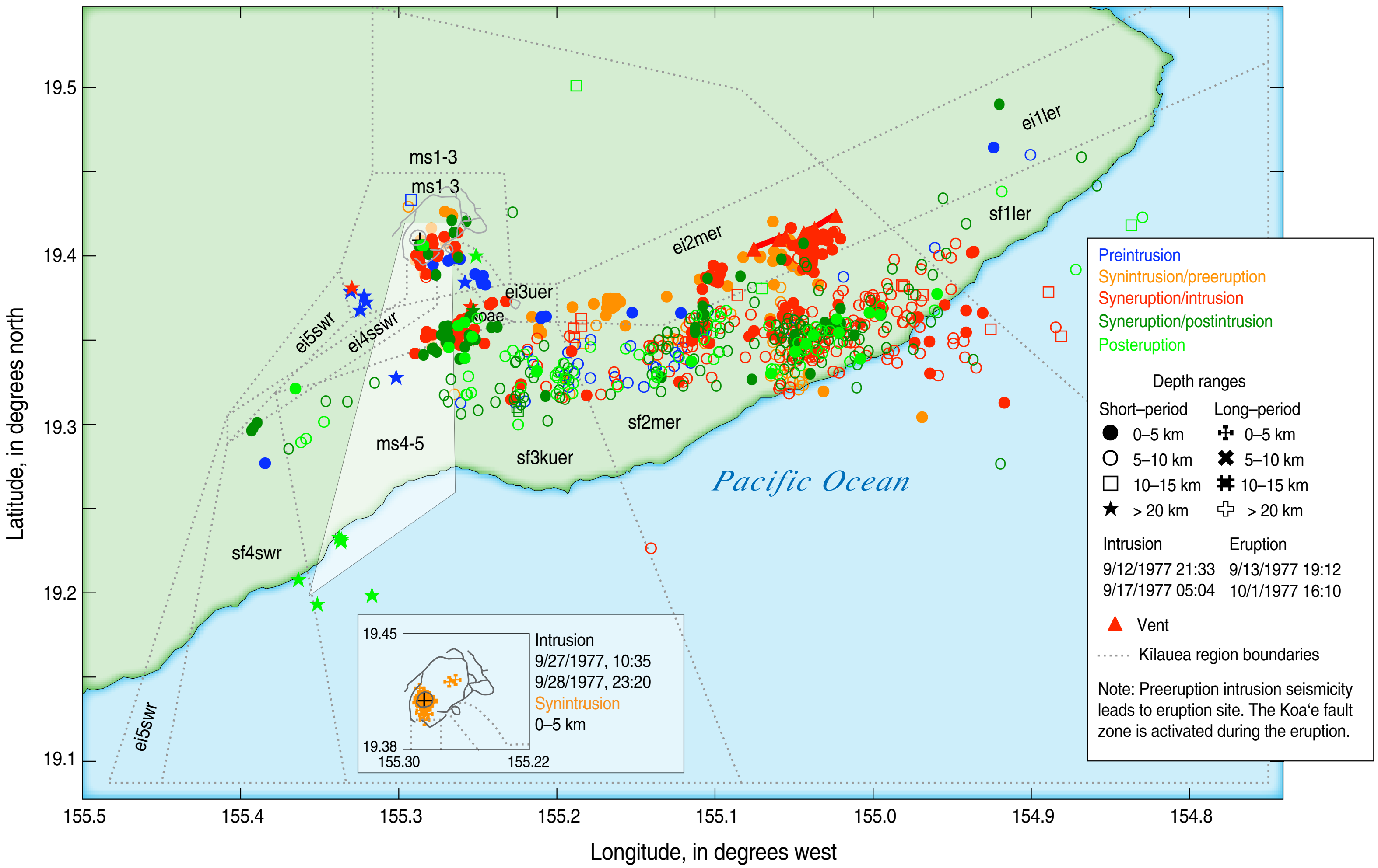

Figure 6.2. Map showing Kīlauea activity, 5 September 1977–13 October 1977. Main plot shows locations of short-period earthquakes during the September 1977 eruption and the surrounding time period. Eruption was preceded by nonswarm earthquakes beneath the rift zone to the west of the vents and was accompanied by intense south flank seismicity and intrusion beneath the Koa‘e Fault Zone and the uppermost seismic southwest rift zone. Intrusion occurred in two pulses separated by seven hours and in the same location. Data are shown for periods before (blue), during (orange), and after (green) the intrusion and eruption, and eruptive vents are plotted as red triangles. Inset shows a long-period earthquake swarm on 27–28 September. The unusually tight cluster of epicenters combined with inflationary tilt indicates a small zone of magma movement beneath Kilauea's summit. Dates on figure in m/d/yyyy format.

East Rift Intrusions and Eruption, 1979

The summit reservoir very slowly but steadily inflated in the 2 years after the major deflation of the September 1977 eruption and before the intrusions of 1980. The relative slowness of the inflation suggests that magma was still filling voids in the east rift zone left by the major south flank movement during the November 1975 Kalapana earthquake. The deflation of September 1977 was so large, and subsequent reinflation so slow, that there was not a single recognized intrusion until 29 May 1979.

The 29 May 1979 intrusion began 3 km below Mauna Ulu on the east rift zone (table 6.1), and earthquakes migrated uprift, downrift, upward, and downward during the 6-hour-long swarm. This intrusion fed a dike, 2 by 5 km in extent, initially supplied with magma from a reservoir located in the rift below Mauna Ulu and about 1 km uprift of it. This apparent magma reservoir was located near the bend in the east rift zone and its junction with the Koaʻe Fault Zone, and it is the starting point for many other intrusions (fig. 6.5; Klein and others, 1987).

Kīlauea inflated during September and October 1979, accompanied by inflationary earthquake swarms (1) in the south caldera area on 22 September and (2) in the uppermost east and southwest rift zones in the first half of October 1979 (table 6.1), culminating in intense seismicity on 11–12 October. The high sustained inflation rate of September was comparable to the inflation of the eruption recovery after September 1977, suggesting that more intrusions were possible and that the voids in the east rift zone left by the 1975 earthquake were mostly filled.

The largest intrusive event in 1979 started on 15 November and culminated with a small eruption in and near Pauahi Crater (table 6.1). The November 1979 intrusion was the first sizable one to occur after the installation of an Eclipse computer at HVO, which resulted in more precise timing of earthquake arrivals within a dense part of the seismic network. This improvement in earthquake location resolved individual horizontal magma conduits at 1-km and 3-km depths, defined the blade of the dike that pushed upward toward the surface vent, and provided details of the earthquake migration and dike propagation in time (Klein and others, 1987, fig. 43.78, discussion, p. 1133). The 15 November eruption did not trigger earthquakes in the adjacent south flank, suggesting that the intrusion may have lessened stress on the flank. We interpret the November 1979 event dominantly as a redistribution of magma within the rift, with minimal contribution from the summit.

East Rift Intrusions of 1980

The seismic network and accurate earthquake locations enabled intrusions of the early 1980s to be studied in great detail. Kīlauea inflated steadily after the 15 November 1979 eruption, at a very low rate of about 2 µrad per month. Inflationary seismicity was in the caldera and uppermost east rift zone, with representative swarm peaks on 16–17 January 1980 and 2 February 1980 (table 6.1, fig. 6.3).

The east rift intrusions of 2 March and 10–12 March 1980 (table 6.1) are probably linked. The first, and smaller, intrusion in the upper east rift on 2–3 March 1980 was followed a week later by intrusion in the middle east rift on 10–12 March. The latter intrusion was accompanied by significant summit deflation and south flank earthquake response. An accompanying eruption (table 6.1) was inferred from discovery of a small pad of lava in March 1982 near the site of the earthquake swarm. The 10–12 March 1980 earthquake swarm and magma migration preceded summit deflation by nearly 4 hours, suggesting that stored east rift magma fed the eruption and intrusions, to be later resupplied from the summit via a different, parallel, and probably deeper conduit. This resupply conduit produced few if any earthquakes and was probably an open and hot conduit in direct connection to the summit reservoir.

East rift activity was temporarily suspended following four more intrusions fom August to November 1980 (table 6.1). A pair of linked east rift intrusions occurred on 30 July and 27 August 1980. The first, smaller intrusion (no measurable deflation) began uprift of Puhimau Crater on 30 July 1980. On 27 August a larger intrusion started at Puhimau where the previous intrusion terminated. We interpret the first intrusion as stopping at a rift conduit barrier, where magma initially pooled but then broke through the barrier 28 days later and enlarged a dike in both uprift and downrift directions. The final two intrusions were on 21–22 October and 2 November 1980.

Southwest Rift Intrusions of 1981–1982

1981 marked a shift in magmatic activity from the east rift zone to the seismic southwest rift zone (sswr). The first intrusion in this period was in January–February 1981, followed by almost continuous sswr earthquake activity from February through August, which culminated in a large sswr intrusion on 10 August 1981. Intrusions extended into 1982, ending with a large event on 22 June (table 6.1; fig. 6.3). Each of these three intrusion sequences had different earthquake and time-development characteristics, implying different sswr pathways.

Earthquake swarms between January and August 1981 show an erratic progression down the sswr. During the first intrusion on 20 January 1981,

Figure 6.3. Graphs showing Kīlauea activity, 1 January 1980–1 February 1983. Time series plots show Uwēkahuna tilt magnitude and times of eruption and intrusion. Symbols are given on the plots. Three types of intrusions are defined in chapter 1. Traditional intrusions and inflationary intrusions are shown as intrusion symbols and inflationary intrusions are labeled (II). Suspected deep intrusions are labeled (SDI) but not plotted as intrusions. See also caption of figure 6.1. Dates on figure in m/d/yyyy format.

earthquakes ventured no more than 2 km south of the south caldera boundary into the sswr. On 24 January magma and earthquakes progressed 5 km further down the rift zone. During 9–16 February, the intrusion progressed to and activated a patch near Puʻukou at a bend and possible blockage in the rift zone, about 20 km from the caldera. During the next intrusions earthquake swarms were again concentrated in the uppermost sswr.

Unlike the rapid deflation characteristic of east rift zone intrusions, during which the beginning of deflation followed by minutes to hours the onset of earthquake swarms, deflation during these sswr intrusions was both gradual and began a day or more before the rift earthquake swarms. This suggests that the sswr offered resistance to magma flow in a conduit that was not open and liquid filled, and that the adjacent flank offered some resistance to spreading.

August 1981 Intrusion

A much larger sswr intrusion began on 10 August 1981 and followed a pattern very similar to the intrusion associated with the December 1974 eruption (chap. 5, figs. 5.15 and 5.16). The August 1981 intrusion was preceded by nearly continuous elevated sswr seismicity from March through July 1981, including a possible suspected deep intrusion in April (fig. 6.3). Summit inflation was low through mid-June, then accelerated in the 2 months following the minor summit intrusion of 25–27 June 1981. That intrusion marks a time when magma largely ceased flowing down the sswr and inflated the summit reservoir instead. Clearly the sswr and summit were building for a possible event. On 2 August 1981, the gradual buildup of earthquakes in the upper sswr increased to more than 10 per day, and earthquakes suddenly advanced down the sswr to a point 5 km from the caldera.

The August intrusion started from a point just south of the caldera and moved along the sswr at a speed of 2.6 km/hr, twice the speed of the similar December 1974 intrusion, perhaps because the rift had been opened during the 1974–75 intrusion, making it easier for further intrusion in 1981. A dike cross section of 1 m width by 1.5 km height is consistent with the earthquake migration speed, deflation rate, earthquake cross section, and geodetic observations (Klein and others, 1987, page 1153). Shallow sswr earthquakes stopped on 15 August, but the triggered flank earthquakes continued above background for about a month (fig. 6.3).

Early 1982 Intrusions

Kīlauea reinflated steadily in the 10 months following the 10 August 1981 sswr intrusion (fig. 6.3). Inflationary intrusions increased in frequency as the caldera reservoir swelled with magma. Peaks of intrusive activity occurred in 1982 on 15 January, 27 February, 3, 9, and 23 March, and 8 June. Because earthquakes did not migrate down the rift, the magma buildup was confined to the near-summit region.

A small caldera eruption occurred on 30 April 1982 during this inflationary period. Earthquakes were confined to the vent area within the caldera (Klein and others, 1987, fig 43.92). The Uwēkahuna tiltmeter showed an “inflationary” jump of 10 µrad (table 6.1; figure 6.3), suggesting that magma moved rapidly upward to a shallower depth as it would for a new dike under the caldera vents, creating an “inflationary” bulge from a shallow source. On 22 June 1982, another intrusion started—the last sswr intrusion before the Puʻu ʻŌʻō-Kupaianaha eruption. This was a major intrusion accompanied by a downrift seismic progression similar to that shown by the August 1981 and 1974–75 intrusions.

Latter 1982 Intrusions and Return to the East Rift Zone

A caldera eruption and an upper east rift zone intrusion in the latter half of 1982 signaled a return of volcanism from the sswr to the east rift zone. The 25 September 1982 eruption formed a small, short-lived fissure in the southern caldera and was accompanied by an intrusion beneath the fissure (table 6.1). Modeling the eruption as inflation of a shallow source and deflation of a deeper source yields outward tilt at nearby stations. The outward tilt of nearly 35 mrad (table 6.1) did not recover (fig. 6.3), which indicated a permanent September 1982 dike emplacement rather than reservoir inflation.

Following the summit eruption/intrusion of 25 September 1982, inflationary intrusions into the upper east rift zone occurred as the summit continued to inflate. Four small intrusions between 1 and 11 October repeat the seismic patterns seen in September. A series of three intrusions occurred on 9, 21, and 29–30 December (table 6.1; fig. 6.4). The first intrusion was an intense upper east rift zone intrusion with downrift earthquake migration between the caldera and Hiiaka Crater. The latter two were slow moving and less intense inflationary intrusions, which did not interrupt the inflation (fig. 6.3).

Episode 1 of the Puʻu ʻŌʻō-Kupaianaha Eruption

The earthquake swarm of 29–30 December 1982 continued into 1983 and was the immediate precursor to the long-lived Puʻu ʻŌʻō-Kupaianaha eruption that began on 3 January 1983 and is still continuing as of this writing (2014). We consider episode 1 to be the culminating event in the recovery from the 1975 earthquake,

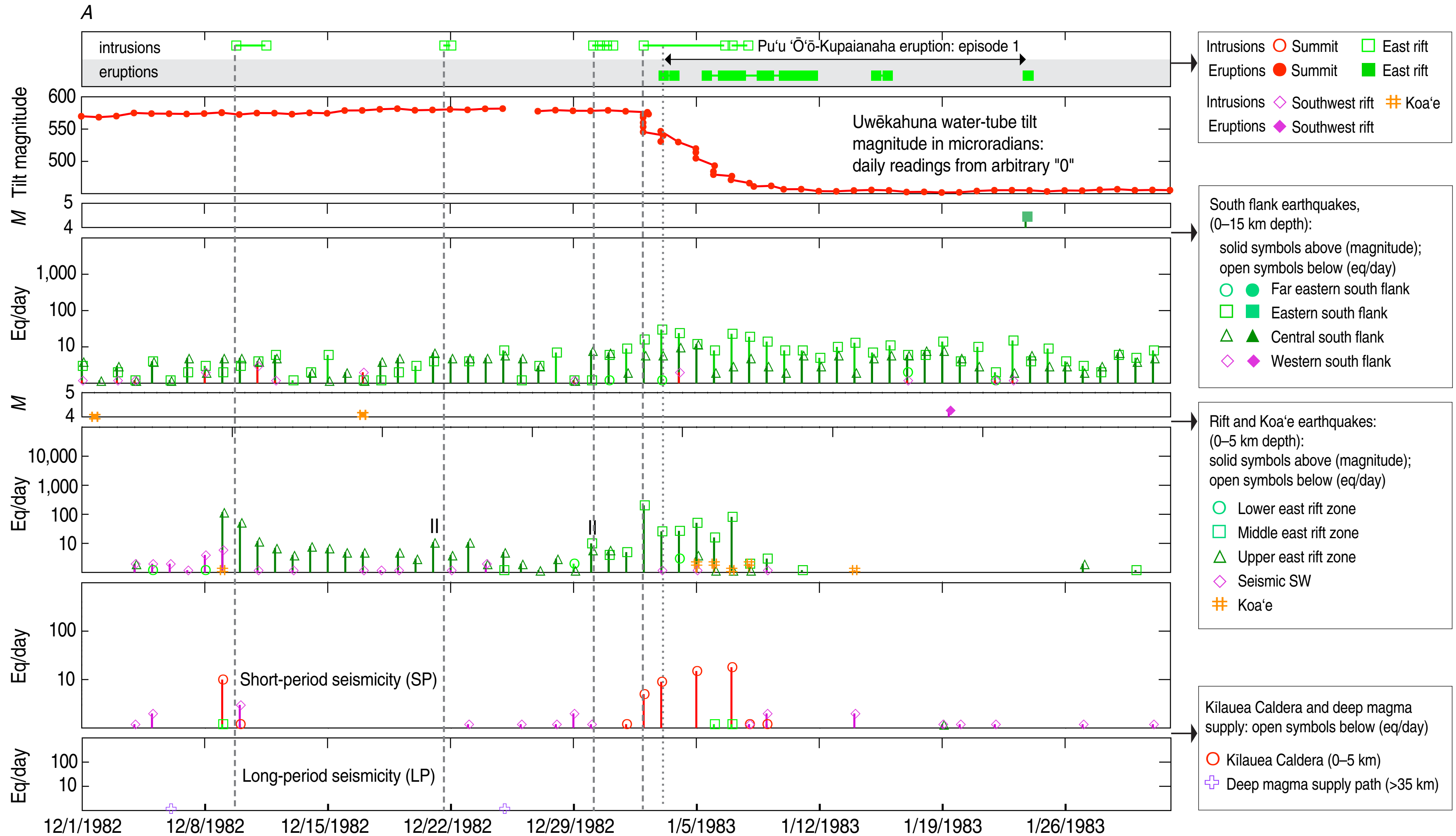

Figure 6.4. Graphs and map showing Kīlauea activity, 1 December 1982–1 February 1983. Precursors to episode 1 of the Pu‘u ‘Ō‘ō-Kupaianaha eruption. Dates on figure in m/d/yyyy format. ***A***, Time series plot for 1 December 1982–1 February 1983. Pu‘u ‘Ō‘ō-Kupaianaha eruption episode 1 and precursory intrusions. The last intrusion precedes eruption by about 1 day, and the summit begins to deflate after the beginning of the intrusion earthquake swarm (table 6.1). See also caption to figure 6.1. ***B***, Map showing earthquake locations for the period 7–31 December 1982. Each intrusion moves progressively downrift toward the episode 1 vents.

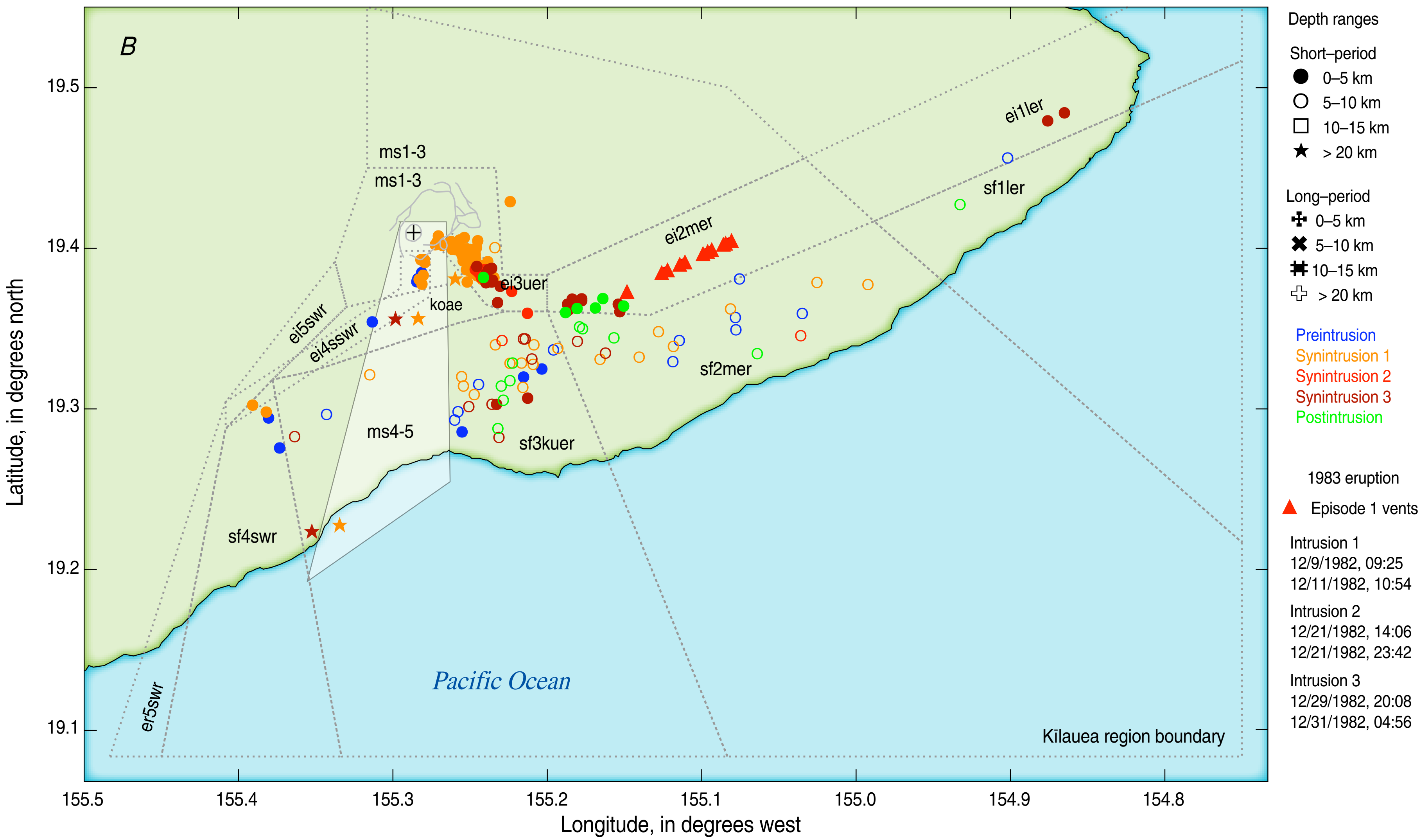

Figure 6.4.—Continued

because the character of seismic activity in all regions of the volcano as well as deformation patterns changed dramatically following episode 1. Further discussion of episode 1 leads off the description of the entire Puʻu ʻŌʻō-Kupaianaha eruption in the next chapter.

Interpretations 1975–1982

Stages of recovery from the 29 November 1975 earthquake can be summarized as follows:

November 1975–September 1977: no inflation, east rift intrusions refilling the volume formed by dilation of the rift zones during the earthquake.

September 1977–May 1979: rapid reinflation without further shallow intrusion following the 1977 eruption and deflation of Kīlauea's summit.

May 1979–December 1980: continued rapid inflation accompanied by frequent east rift zone intrusions.

January 1981–June 1982: continued rapid inflation accompanied by seismic southwest rift zone intrusions.

June 1982–January 1983: rapid inflation accompanied by east rift zone intrusions precursory to deflation of Kīlauea's summit during episode 1 of the Puʻu ʻŌʻō-Kupaianaha eruption.

East Rift Intrusions and Uprift/Downrift Migration of Associated Earthquake Swarms

Zones of identified magma storage are shown in fig. 6.5. The summit caldera reservoir is principally defined by inflation and deflation seen at the surface and as the source of intrusions revealed by earthquakes, as well as numerous geophysical and geological studies. The Pauahi magma reservoir was identified by Tilling and others (1987, fig. 16.41, 16.43) from localized inflation prior to the Pauahi eruptions of 1973, in the pause of the 1969–74 Mauna Ulu eruption. Klein and others (1987) identified the Pauahi reservoir as an origin point of intrusions in the 1960s, 1970s, and 1980s, evidenced by earthquakes migrating uprift (west) and downrift (east) initially fed from the Pauahi reservoir. The Mauna Ulu reservoir was suggested by Tilling and others (1987, fig. 16.43) as the site of deflation during 1973–74 within the Mauna Ulu eruption, but it is less well expressed from other evidence and may only be short lived. The Makaopuhi reservoir was identified by Jackson and others (1975, figs. 32, 35) and Swanson and others (1976, fig. 20) from local magma differentiation and fractionation before and after the October 1968 eruption and from uplift before the February 1969 eruption seen by leveling and seismicity. The intense seismicity and tremor under and just before the eruption cited by these authors do not necessarily require a local magma reservoir as a source, but are certainly the result of dike propagation from the conduit to the surface. Other unrecognized or temporary magma reservoirs undoubtedly exist, but the summit, Pauahi, and Makaopuhi reservoirs are the most persistent and best documented. The shape of the reservoirs is approximate. The reservoirs within the rift have unknown shape and may be only zones where the conduit widens and stores liquid magma for a period of time. An approximate minimum magma volume of 0.001–0.003 km^3 is consistent with the temporary magma storage behavior, which could be any shape or combination of liquid and solid having a minimum dimension of 50–100 m, necessary to minimize cooling between times of magma replenishment. Wyss and others (2001, fig. 6) found indirect evidence for persistent Pauahi and Makaopuhi reservoirs because b-value anomalies (a relative excess of small magnitude earthquakes suggesting heterogeneous fractures and stress or high pore pressure) are in the south flank adjacent to both reservoirs.

During the 1977–82 inflation period, the summit reservoir was in magmatic communication with the upper east rift zone down to a conduit barrier located near Mauna Ulu (fig. 6.5). This barrier was active during 1976–82 as a stopping point of earthquake swarms progressing downrift. In addition, there was aseismic passage of magma along upper rift pathways to the central and lower rift preceding the eruption of 13 September 1977. Earthquake migration with time shows that more than half of the intrusions during the period from June 1976 to early 1982 began near Mauna Ulu and migrated both uprift and downrift simultaneously, with resupply from Kīlauea's summit. Because the summit was deflating at the same time as magma was actually moving uprift from Mauna Ulu, it is likely that intrusions were forming dikes within a shallow pathway originating beneath Mauna Ulu, while magma was being resupplied aseismically from Kīlauea's summit via another, deeper east rift zone pathway .

Magma pathways in the upper east rift between the caldera and Mauna Ulu are seismically defined by earthquake bands at depths of 1.5 and 3 km (fig 6.5*B*). Many larger intrusions, such as that of 15 November 1979, produce earthquakes in both depth zones (Klein and others, 1987, figure 43.78). Typical intrusions, especially those associated with eruption, first show earthquakes in the 3-km-deep zone that migrate upward through the 1.5-km-deep zone to the surface, but there is no simple pattern of the seismic zones at the two depths that would indicate that they operate as independent conduits (Klein and others, 1987). Multiplet relocation of shallow background (nonintrusion) earthquakes in the upper east rift (Gillard and others, 1996) and the January 1983 intrusion in the middle east rift (Rubin

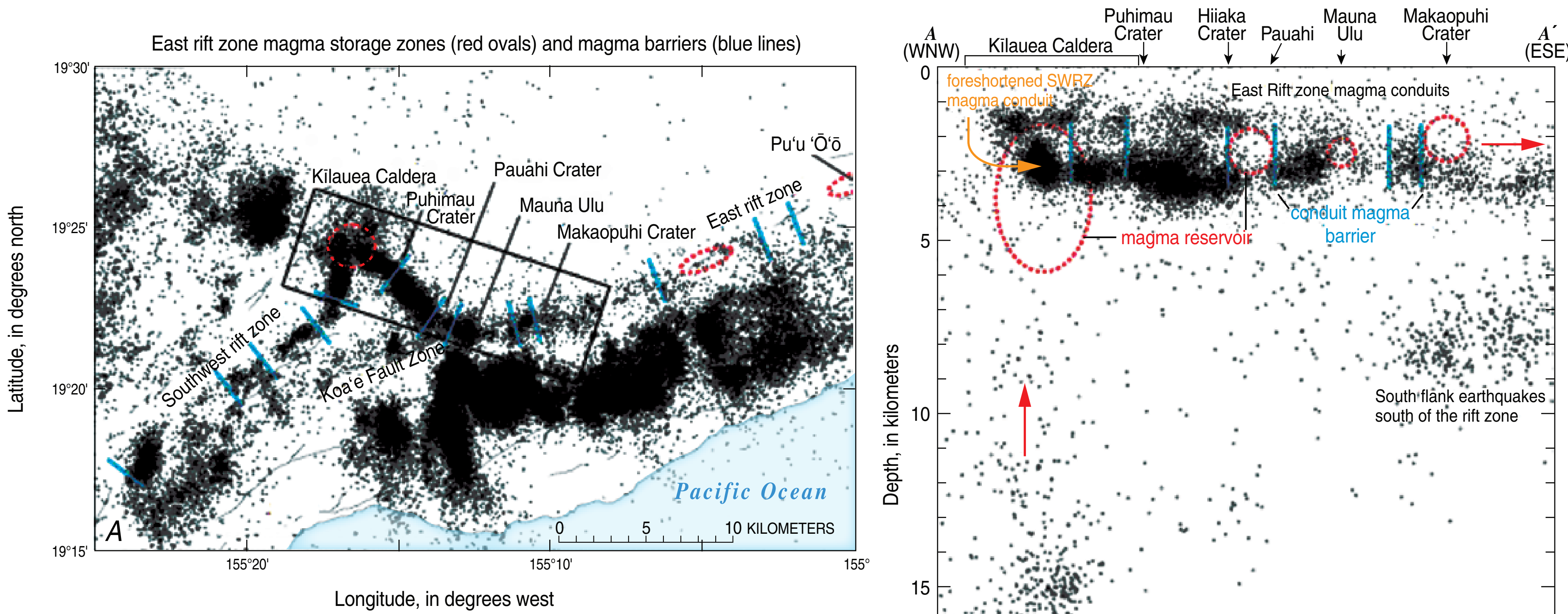

Figure 6.5. Map and cross-section showing location of east rift magma storage zones and magma barriers. ***A***, Map of Kīlauea earthquakes from 1976 through 2007. Earthquakes shown are short period (brittle fracture), and those designated as long period are excluded. ***B***, Cross-section of earthquakes of the east rift zone from Kīlauea Caldera to below Makaopuhi Crater. Rectangle on *A* is the cross-section A-A' shown in *B*. Red dashed circles in both *A* and *B* mark the locations of magma storage areas within the rift zone and the summit magma reservoir, defined by reduced seismicity, magnetic anomalies (Kauahikaua, 1993), self potential (Kauahikaua, 1993; Zablocki and Koyanagi, 1979; Zablocki, 1976) or by other factors. Blue lines on both *A* and *B* indicate inferred magma barriers, which are often points where intrusions start and stop. Barriers and the magma reservoir at long 155°5´W. outside the section zone are from Klein and others (1987). The reservoir near longitude 155°0'W. (Pu‘u ‘Ō‘ō-Heiheiahulu region) is inferred from accumulated magma before the Pu‘u ‘Ō‘ō eruption (Wolfe and others, 1988) and the eruption of differentiated lava in the 1977 eruption (Moore, 1983). The bands of earthquakes centered near 1.5 and 3 km depth on *B* show the magma conduits that produced earthquakes by brittle fracture through dike propagation along the subhorizontal magma conduit. Red arrows on *B* show direction of magma flow to replenish the summit reservoir from depth and feed eruptions and intrusions in the east rift zone.

and others, 1998) show the deeper zone as a narrow ribbon, with earthquakes at depths of about 3 km ± 50 meters. They interpret this 3-km-deep seismicity as the region of high stress concentration above the deep rift magma body. It is possible that the 1.5-km and 3-km depths are the brittle, dike-forming zones above and below a fluid filled, aseismic conduit, but this cannot be proven because the relative absence of earthquakes near 2-km-depth indicates the absence of brittle rock under stress—that rock may or may not be fluid. The 3-km-deep earthquake zone is narrow and responds to stresses from intrusions propagating uprift and downrift as well as from rift growth between intrusions, and the earthquakes reveal dikes that propagate upward from to 2–3-km depth to the surface.

Another barrier closer to Kīlauea's summit is under Hiiaka Crater and appears to have stopped intrusions migrating downrift on 12 August 1979 and 27 August 1980. The Hiiaka barrier may help contain the Mauna Ulu magma storage reservoir just downrift of it. The Pauahi magma reservoir, just uprift of Mauna Ulu, is visible as a gap in seismicity and may feed intrusions up and down rift (fig 6.5).

Some barriers, such as that under Mauna Ulu, are structurally controlled by a junction with the Koa‘e Fault Zone and the eastward bend of the rift and may persist for long periods of time. Other barriers may have a short lifetime as the rift grows and evolves. The relation of intrusions to rift barriers is not always straightforward. In some cases an intrusion may stop at a barrier and be followed by an intrusion that breaches the barrier as magma moves downrift in discrete pulses. An example is the 22 January 1977 inflationary intrusion that paused uprift of the Hiiaka barrier, then continued downrift in the 8 February 1977 intrusion. A general discussion of rift zone barriers and magma storage reservoirs is given by Klein and others (1987).

Intrusion Pathway, Speed, and Flank Resistance on the Seismic Southwest Rift Zone

The June 1982 sswr intrusion was different in depth and time compared with other rift intrusions. The main intrusive seismic zone started on 22 June and was between 7 and 16 km distant from the caldera. Earthquakes defining the connecting magma pathway adjacent to the caldera occurred 2–4 days earlier on 18–20 June, rather than being part of the larger earthquake swarm defining the intrusion. Deflation began at a slow rate on 21 June, about 1 day before the downrift earthquakes started. The deflation rate accelerated about 18 hours later, but still more slowly than in previous intrusions. This suggests that magma moved slowly and aseismically through the upper 7 km of rift, probably through the still-molten dike formed in August 1981.

Unlike most other rift intrusions, the June intrusion's seismic zone was mostly at depths between 6 and 9 km, with few earthquakes defining the shallow sswr magma pathway near 3–4 km depth revealed in the August 1981 intrusion. The June 1982 intrusion was thus similar to but smaller than the December 1974 intrusion and did not produce earthquakes in the shallow rift conduit as in the December 1974 and August 1981 intrusions. The 22–24 June 1982 intrusion was relatively slow, taking 3 days to deflate compared to the 1 day of the December 1974 and August 1981 intrusions. This slow deflation and deeper earthquake location suggests a deeper magma pathway. The deeper conduit of 1982 offered more flow resistance than the shallower conduits of December 1974 and August 1981, as evidenced by (1) the slowness of deflation (taking 3 times as long) and (2) slower earthquake migration speed, 0.2 km/hr for 1982 vs. 1.3 km/hr for 1974 (table 6.1). The last and farthest part of the August 1981 intrusion slowed from 2.6 km/hr to 0.28 km/hr (table 6.1; Klein and others, 1987, figure 43.90), suggesting that it too encountered the higher flow resistance of an intrusion that must push against the deeper parts of the adjacent south flank.

Restoration of the Magmatic System Following the Kalapana Earthquake

During the earthquake of 29 November 1975 the flank moved several meters seaward and the summit deflated by 225 µrad, sending about 0.08–0.12 km^3 of magma into the east rift zone[24]. This was at least 10 percent of the rift dilation volume of 0.8–0.9 km^3 created during the earthquake (Owen and Būrgmann, 2006). After the earthquake, the tilt record shows no net inflation or deflation until the eruption of September 1977. We interpret the lack of summit magma accumulation to indicate that all of Kīlauea's magma supply during this 1975–77 period went to fill voids or volumes in the east rift left by the flank slip to the south. The four east rift zone intrusions during this period were of small magma volume compared to the 1975 collapse, and they encountered a rift and flank that offered little resistance to intrusion and easy ability to accommodate subsurface magma without eruption.

The 1977 eruption served to further delay the recovery from the 1975 earthquake. The 91 µrad Uwēkahuna deflation in 1977 means approximately

[24] The lower value represents deflation below the central caldera. The higher value represents the sum of volumes calculated as the deflationary tilt varied in azimuth. Our tilt to volume factors may not apply to the entire range of azimuths. The lower value falls within the range of 0.04–0.09 km^3 estimated from gravity measurement made after the earthquake (Dzurisin and others, 1980). Our values are higher than a model estimate of 0.04 km^3 used by Owen and Būrgmann (2006).

0.04 km^3 left the summit reservoir, leaving that volume to be filled. Reinflation of the summit took 2 years, up to the eruption in November 1979, to recover the magma lost from the summit reservoir in the September 1977 eruption. The slow reinflation suggests that magma was also still refilling the volume loss produced during the earthquake as well as the added volume of rift dilation from continued spreading (Delaney and others, 1998). After this 1978–79 recovery and during 1980, tilt was approximately level, indicating that the magma supply was still filling the remaining rift volume lost during the earthquake. Magma did not leak into the east rift zone steadily but in pulses, as tilt oscillated once or twice per month with amplitudes of 3 to 5 µrad (Klein and others, 1987, fig 43.74). Earthquakes also showed this oscillation, with caldera earthquakes peaking at times of peak inflation as the caldera extended and rift earthquakes swarming at times of deflation. This was a time of stable oscillation of filling and draining when no volcanic event was large enough to alter the equilibrium or change the level or pressure in the magma column. There were no large, forceful intrusions during this 1978–79 time period, and Kīlauea was in a steady reinflation mode.

The beginning of summit reinflation above the level of the bottom of the 1975 collapse (including recovery from the 1977 collapse) signified the end of passive intrusion and the beginning of a different filling mode. The new filling mode found intrusions moving into the volume produced during ongoing spreading and also occasionally breaking through barriers to complete the filling of volume lost during the 1975 earthquake. Our interpretation of the recovery from the 1975 earthquake is similar to our interpretation of the recovery from the 1924 collapse as described in chapter 3.

The shift to the southwest rift zone in 1981 and early 1982 signified that the east rift volume deficit was effectively made up, and the remaining volume deficit was made up by intrusion beneath the seismic southwest rift zone (sswr). We view the sswr as a region of overflow that is only activated when the east rift zone can no longer accept magma and the summit is not fully inflated. A similar sequence occurred at the end of both stages of the Mauna Ulu eruption in 1971 and 1974 as described in chapter 5.

The year 1982 marked the end of the post-1975 earthquake recovery era. The summit caldera underwent intrusion and eruption in April 1982, and the last significant southwest rift intrusion was in June 1982. It was not until the summit eruption of September 1982, and simultaneous intrusions into both rifts, that magmatic intrusions switched back to the east rift zone, which had undergone further dilation during spreading over the previous 1.5 years of 1981–82 southwest rift and summit intrusions. East rift intrusions in the latter part of 1982 prepared the way for release of magma to the surface of the east rift in January 1983. The large and continuing deflation and the long-lived 1983 and later eruption indicated that the recovery from the 1975 earthquake was complete and an equilibrium was established between the magma supply rate and eruption.

Supplementary Material

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

Table F1 presents tilt volume, eruption efficiency, and magma supply rate for the period 1975–83.

Figure F1 shows short-period and long-period earthquake swarms for all regions.

Figure F2A–H. shows short-period earthquake counts and earthquakes of $M \geq 4$ at 1-year intervals from 1 Feburary 1975 to 1 February 1983.

Figure F2I–P shows long-period earthquake counts and earthquakes of $M \geq 4$ at 1-year intervals from 2/1 February 1975 to 1 Feburary 1983

Figure F3 shows time series plots at 1-year intervals for 1975–1983.

Figure F4 presents the *M*7.2 south flank earthquake of 29 November 1975. Aftershocks are shown through 5 December 1975.

Figures F5–F38 show locations of earthquakes for eruptions and intrusions between June 1976 and December 1982.

High fountaining at Puʻu ʻŌʻō. USGS photo by C.C. Heliker, 19 September 1984.