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Deep magma transport at Kilauea volcano, Hawaii

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Abstract

The shallow part of Kilauea's magma system is conceptually well-understood. Long-period and short-period (brittle-failure) earthquake swarms outline a near-vertical magma transport path beneath Kilauea's summit to 20 km depth. A gravity high centered above the magma transport path demonstrates that Kilauea's shallow magma system, established early in the volcano's history, has remained fixed in place. Low seismicity at 4–7 km outlines a storage region from which magma is supplied for eruptions and intrusions.

Brittle-failure earthquake swarms shallower than 5 km beneath the rift zones accompany dike emplacement. Sparse earthquakes extend to a decollement at 10–12 km along which the south flank of Kilauea is sliding seaward. This zone below 5 km can sustain aseismic magma transport, consistent with recent tomographic studies.

Long-period earthquake clusters deeper than 40 km occur parallel to and offshore of Kilauea's south coast, defining the deepest seismic response to magma transport from the Hawaiian hot spot. A path connecting the shallow and deep long-period earthquakes is defined by mainshock–aftershock locations of brittle-failure earthquakes unique to Kilauea whose hypocenters are deeper than 25 km with magnitudes from 4.4 to 5.2.

Separation of deep and shallow long-period clusters occurs as the shallow plumbing moves with the volcanic edifice, while the deep plumbing is centered over the hotspot. Recent GPS data agrees with the volcano-propagation vector from Kauai to Maui, suggesting that Pacific plate motion, azimuth 293.5° and rate of 7.4 cm/yr, has been constant over Kilauea's lifetime. However, volcano propagation on the island of Hawaii, azimuth 325°, rate 13 cm/yr, requires southwesterly migration of the locus of melting within the broad hotspot. Deep, long-period earthquakes lie west of the extrapolated position of Kilauea backward in time along a plate-motion vector, requiring southwesterly migration of Kilauea's magma source. Assumed ages of 0.4 my for Kilauea and 0.8 my for Mauna Loa are consistent with this model. Younger ages would apply if Kilauea began its growth south of the locus of maximum melting, as is true for Loihi seamount.

We conclude that Kilauea is fed from below the eastern end of the zone of deep long-period earthquakes. Magma transport is vertical below 30 km, then sub-horizontal, following the oceanic mantle boundary separating plagioclase- and spinel-peridotite, then near-vertical beneath Kilauea's summit. The migration of the melting region within the hotspot and Kilauea's sampling of different sources within the melting region can explain (1) the long-term geochemical separation of

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Kilauea from neighboring volcanoes Mauna Loa and Loihi, and (2) the short-term changes in trace-element and isotope signatures within Kilauea.

Keywords: Magma transport; Kilauea; Age; Long-period earthquakes; Brittle-failure earthquakes; Hawaiian hotspot

1. Introduction

We focus this paper on magma transport beneath Kilauea volcano. We seek to understand the path by which magma moves from the melting site in the aesthenosphere at a depth of 80–100 km to a shallow magma reservoir 4–6 km beneath Kilauea's summit, known to be the source of all eruptions at Kilauea. The connection is made through consideration of (1) long-period (LP) earthquakes and tremor at depths of 40–60 km, (2) LP earthquake swarms extending to 20 km beneath Kilauea caldera (3) short-period, or brittle-failure (BF) mainshocks (*M*4.4–5.2; depth >25 km) and aftershock sequences that are unique to Kilauea, and (4) BF earthquake swarms deeper than 20 km beneath Kilauea's summit. BF earthquake swarms shallower than 5 km define magma pathways associated with eruption and intrusion. Our conclusions build on the pioneering work of Koyanagi et al. (1987) and Klein and co-authors (Klein et al., 1987; Klein and Koyanagi, 1989) to provide a more detailed definition of deep magma pathways that feed Hawaii's active volcanoes.

Kilauea volcano has grown on the southern flank of its larger sister volcano Mauna Loa (Fig. 1). A summit caldera is flanked by rift zones extending to the east and southwest. South of Kilauea's summit, the Koae fault zone connects the two rift zones. Kilauea's north

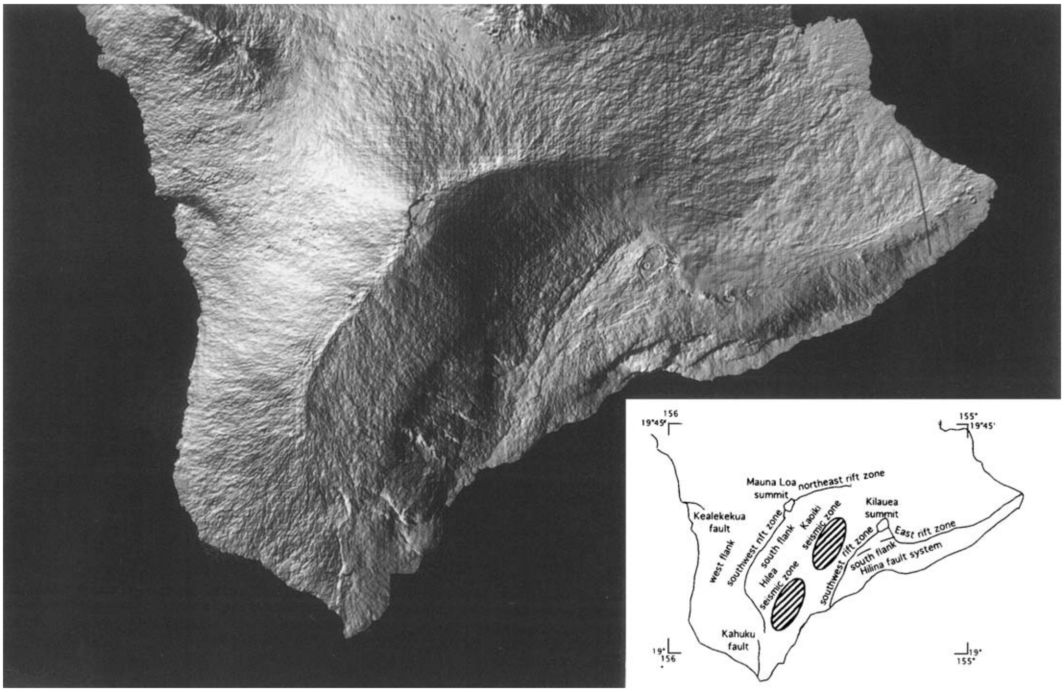


Fig. 1. Index map showing location and structural features of Kilauea and Mauna Loa volcanoes (from (Moore and Mark, 1992). Volcano-tectonic features are labeled on the inset below the digitally produced slope map of the island of Hawaii. Mauna Loa seismic zones are shown in a hatched pattern. A third active center, Loihi, is located beneath 1 km of water south of the area shown (see Fig. 11).

flank, a region of low seismicity, occurs north of the caldera and rift zones. A highly seismic, seaward-moving flank is located south of the rift zones and Koae fault zone. To clarify magma transport and storage, we have reclassified the location code for earthquakes in the Hawaiian Volcano Observatory (HVO) catalog (2001) to correspond to tectonically distinct regions within Kilauea (Fig. 2 and Appendix).

Our study is based mainly on earthquake data from the catalog of the Hawaiian Volcano Observatory (Hawaiian Volcano Observatory, 2001) for a 10-year interval, from 1966 to November 29, 1975, when a $M7.2$ earthquake struck Kilauea's south flank. The aftershocks from this earthquake obscured other seismic patterns for the following several years. We have supplemented these data with selected earthquake data sets before 1966 and after 1975. Long-period (LP) earthquakes were separately designated at Kilauea beginning in 1972. Seismic patterns preceding the beginning of Kilauea's ongoing eruption on January 1, 1983 were similar to those seen before 1975. During the eruption, still continuing as of this writing, long-period seismicity beneath Kilauea's summit has become much more frequent and extends to greater depths. Focusing on an earlier and shorter time period allows the magma plumbing to be more easily evaluated. The results of this study are consistent with subsequent observations using relocated earthquakes.

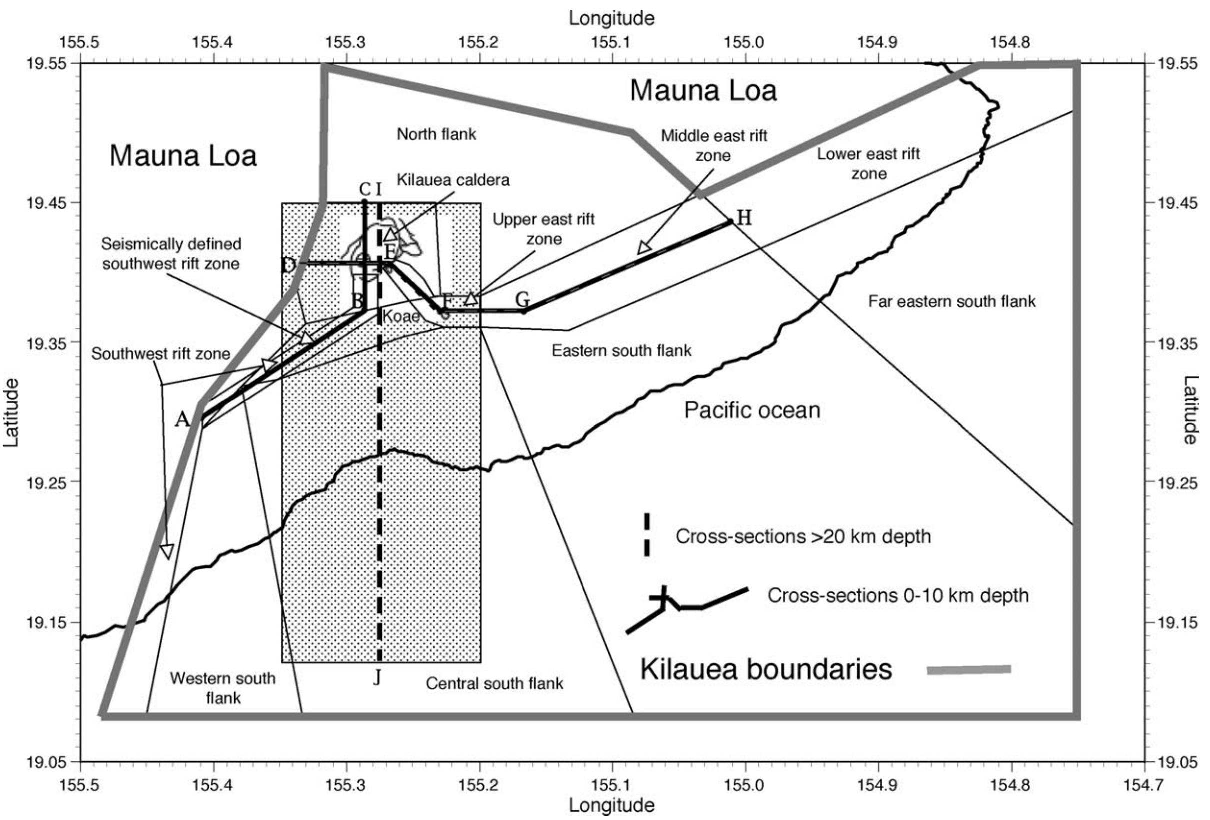


Fig. 2. Earthquake classification regions and locations of cross-sections. The thicker gray line outlines Kilauea volcano. Mauna Loa lies to the north and west of Kilauea's north flank and rift zones. A plus (+) marks the center of Halemaumau crater. (a) Earthquake classification. Region boundaries are shown as light solid lines. Labels are either inside or adjacent to region boundaries. Descriptions are given in Appendix Table 1. Deep earthquake swarms preceding the 1959 eruption of Kilauea lie within the "north flank" box. (b) Cross-sections that follow the plumbing shallower than 20 km are labeled A-B-C and D-E-F-G-H. Cross-sections of the plumbing deeper than 20 km are oriented N–S, labeled I–J. The deep cross-sections show only earthquakes within the shaded box, i.e., between longitude 155.2 and 155.35 W, latitude 19.12 and 19.45 N.

Our interpretations build on the following ideas developed by many authors over the past several decades:

(1) Seaward spreading of Kilauea's south flank, the region south of the rift zones and Koae fault system, along a low-angle decollement at 9–12 km depth (Crosson and Endo, 1981; Lipman et al., 1985; Dieterich, 1988; Borgia and Treves, 1992; Borgia, 1994; Delaney et al., 1998).
(2) An interconnected magmatic plumbing beneath Kilauea's summit and rift zones that extends to the decollement (e.g., Delaney et al., 1990).
(3) A direct connection between LP seismicity and presence of magma (e.g., Julian, 1994; Chouet, 1996). LP seismicity and tremor deeper than 40 km lie over the magma source for Hawaii's three active volcanoes, Loihi, Kilauea and Mauna Loa (Aki and Koyanagi, 1981; Koyanagi et al., 1987). LP seismicity shallower than 20 km outlines the magma transport path beneath Kilauea's summit (Koyanagi et al., 1974).
(4) Shallow magma storage beneath Kilauea's summit defined by absence of seismicity within an otherwise seismic region (Koyanagi et al., 1974) and by modeling deformation data from inflation–deflation cycles following methods originally outlined by Mogi (1958).
(5) The association of intense earthquake swarms with magma movement (Hill, 1977; Klein et al., 1987).
(6) The prevalence of aseismic magma transport (Aki and Koyanagi, 1981), reinforced by Koyanagi et al. (1987), who concluded:

> ...These aseismic regions connecting the seismic sources along the expected magma transport paths may be relatively open, low-stress passages in which magma can maintain a state of quasi-steady flow that does not generate measurable seismic signals.

(7) Recent work (Tilmann et al., 2001; Wolfe et al., 2003) on the structure of the mantle beneath Kilauea. Tilmann's tomographic study identifies a broad and deep low-velocity anomaly beneath Kilauea. Wolfe, using relocated seismicity beneath Kilauea's south flank, identifies a near-horizontal tectonic fault plane at about 30 km depth.

Kilauea's seismicity is related to magma supply from depth, which helps to drive spreading by dilating the rift zones in a seaward direction. Earthquakes beneath the summit and rift zones accompany breaking of rock during inflation or deflation of magma storage regions, and as magma moves toward sites of eventual eruption or intrusion. Seismic release beneath Kilauea's south flank, down to the depth of the decollement, is a function of the pressure resulting from supply of magma to the deep magma system beneath the rift zones, the resistance to spreading offered by the submarine toe of the south flank, and the mechanical friction on the decollement slip surface.

Seismicity associated with shallow magma storage and transport at Kilauea volcano was comprehensively examined by Klein et al. (1987), who showed how earthquakes in the upper 10 km of Kilauea's edifice were temporally and spatially related to specific eruptions or intrusions. Interpretation of the seismicity below 20 km is more problematic. We ask the following questions: (1) What is the path by which magma moves from the vicinity of the melting region to shallow storage beneath Kilauea's summit?, and (2) What is the relationship of deep, BF and LP seismicity to magma transport? Answering these questions allows us to identify the source of Kilauea magma within the broad Hawaiian hotspot and to define, using the seismicity, an upward directed transport path. We conclude by considering the interaction of plate motion and melting source dynamics during the construction of Kilauea volcano.

2. Observations

2.1. Location errors

Location errors (2σ) associated with the earthquakes used in this study vary with time and type of event, depending on the number of stations in the expanding HVO seismic network and the nature of the seismic trace. Brittle-failure locations are known to within 1–2 km in the 1970s. Aftershocks of the deep earthquake on February 1, 1994 are about 0.5–2 km. LP events are located to within 2–7 km in the 1970s, dependent on the degree of emergence. Errors are reduced to about 2 km in the 1980s and 1990s. Wolfe et al. (2003) have shown that relocation of deep earthquakes beneath Kilauea using modern methods significantly reduces the scatter, although the patterns

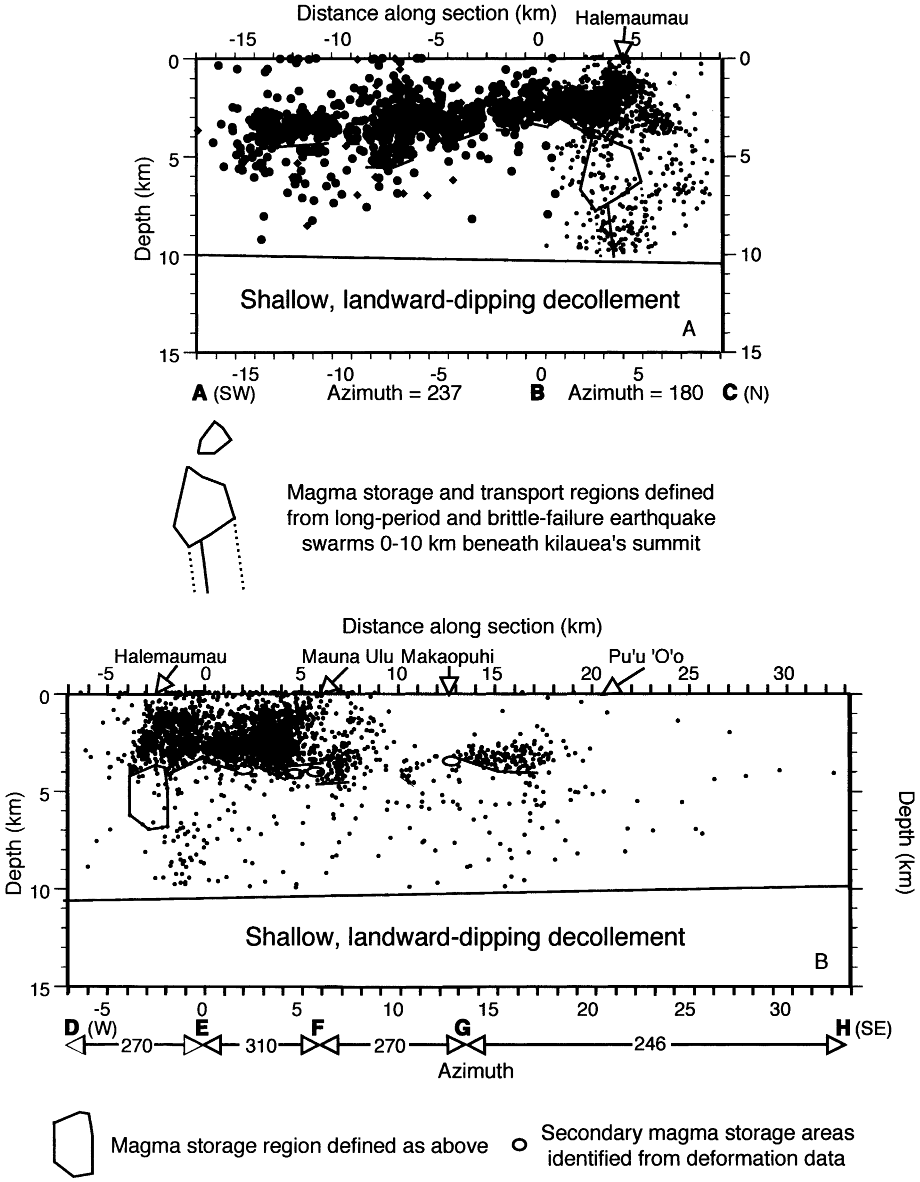
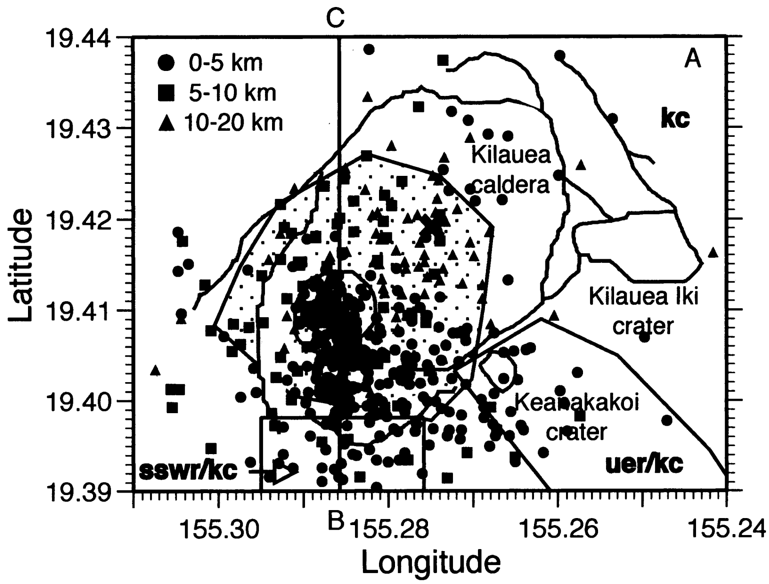


Fig. 3. Brittle-failure earthquake swarms (s1 classification in Appendix Table 1) shallower than 10 km beneath Kilauea's summit and rift zones as taken from the HVO earthquake catalog for a 10-year period 1966–1975. Earthquake selection is made such that no earthquake is included on more than one segment. Short solid line segments separate regions of intense seismicity above from regions of more sparse seismicity below. Irregular polygons outline regions of low seismicity beneath Kilauea's summit. The decollement along which Kilauea's south flank is moving seaward is labeled at a depth of about 10 km. (A) Cross-section A-B-C; seismic southwest rift zone through Kilauea's summit (N–S section). The boundaries separating Kilauea caldera from the Koae region (left) and north flank region (right) occur at points B and C, respectively, in the cross-section. (B) Cross-section D-E-F-G-H; Kilauea's summit (E–W section) through east rift zone. Small ellipses outline areas of magma storage below the east rift zone.



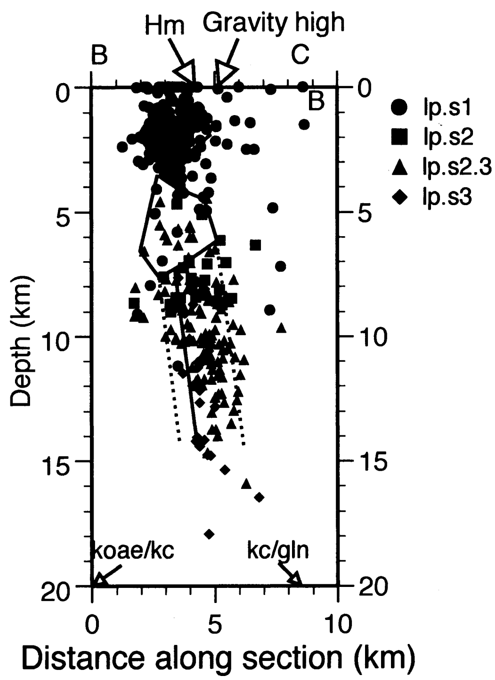


Fig. 4. Map and cross-section of long-period earthquake swarms 0–20 km beneath Kilauea's summit. Caldera and other structural boundaries are shown as irregular lines; region boundaries (Fig. 2a) are shown as straight line segments with abbreviations in bold type. Areas where regions overlap (Fig. 2a) are shown by an abbreviated double region designation, e.g., uer/kc. Earthquakes in cross-sections are coded according to the classification in Appendix Table 1. The location of Halemaumau crater is shown as a circle within Kilauea caldera in the map view and is labeled "Hm" in the cross-section. The maximum contoured Bouguer gravity value (J. Kauahikaua, pers. comm, 2000; Kauahikaua, 1993) is shown as a heavy cross (1) in the map view and is labeled "Gravity high" in the cross-section. Only earthquakes within the shaded area on the map view are shown on the cross-section. An irregular polygon outlines Kilaueas shallow magma reservoir. (A) Map view, long-period earthquake swarms, 0–20 km, 1972–1982 (data from Hawaiian Volcano Observatory, 2001). (B) Data of (A) projected onto cross-section B–C.

remain the same. Because not all earthquakes have been relocated, we use the unrelocated seismicity and assume that these patterns, albeit with greater scatter, can be used to draw valid conclusions regarding deep magma transport.

2.2. Shallow seismicity beneath Kilauea's summit and rift zones

Seismicity above 20 km is related to magma transport and storage beneath Kilauea's summit and rift zones (Figs. 3 and 4). The uppermost 5 km is highly seismic, extending east and southwest from the shallow magma storage reservoir. The zone between 5 km and the decollement is weakly seismic and secondary magma storage occurs just below the zones of elevated seismicity (Fig. 3).

LP earthquake swarms beneath Kilauea's summit occur both above and below the shallow magma chamber (Fig. 4). Those deeper than 6 km define a nearly vertical pipe down to at least 20 km. Wolfe et al. (2003, Fig. S3) show relocated LP earthquakes between 12 and 24 km (mostly 13–16 km) that occupy the same region and also define a vertical pipe.

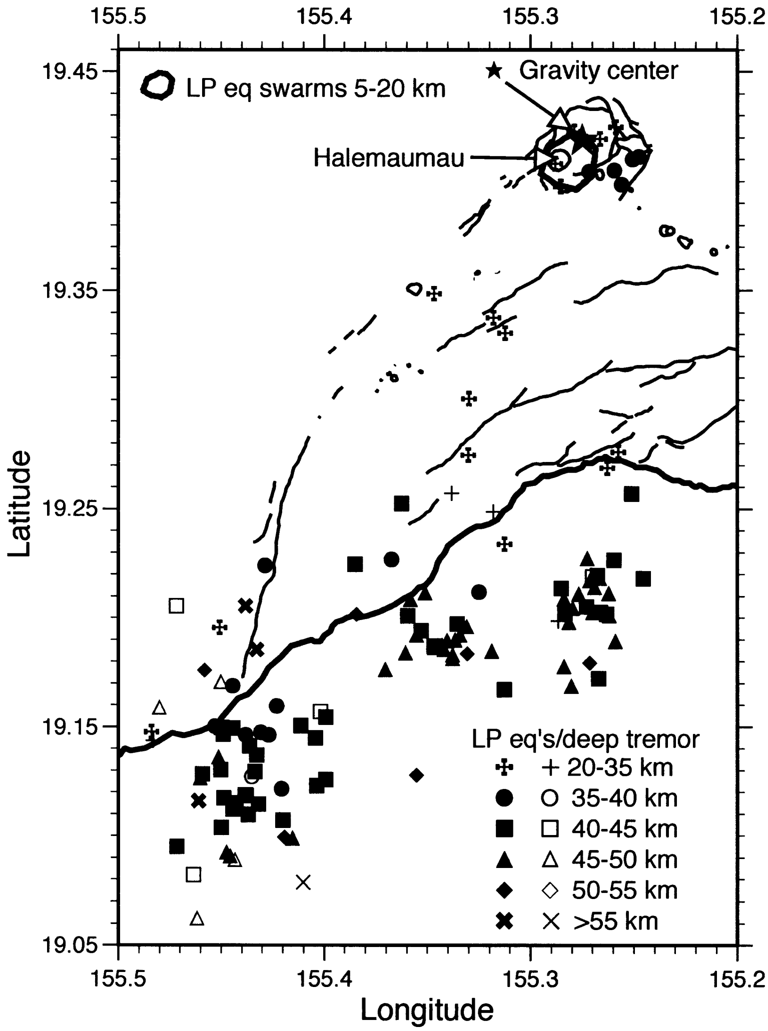


Fig. 5. Location of deep (>20 km) long-period earthquakes (1972–1983) and tremor (1973–1977 beneath Kilauea volcano. For reference the positions of Halemaumau crater, the Bouguer gravity high and the locus of LP earthquakes shallower than 20 km are labeled. A bold line represents the coastline and other lines show traces of faults. The same background is used in Figs. 6A–10A.

2.3. Deep, long-period seismicity

Tabulation of LP seismicity in the Hawaiian Volcano Observatory seismic catalog began in May 1972. We have analyzed the location of LP earthquakes and deep tremor events (Aki and Koyanagi, 1981; Koyanagi et al., 1987) from 1972 through 1982 (Fig. 5). A gap of more than 20 km, both vertically and horizontally, separates the deep LP seismicity located offshore of Kilauea's south flank (Fig. 5) from the shallower LP seismicity beneath Kilauea caldera (Fig. 4).

2.4. Deep, brittle-failure seismicity

Brittle-failure seismicity deeper than 20 km occurs beneath all regions of Kilauea volcano. An average of about 10 temporally isolated deep earthquakes of $M \geq 2$ occur each year. Some are of large enough magnitude to have aftershocks (Table 1). Deep earthquakes also occur in swarms of five or more events spread over several hours or days. Larger swarms of over 15 events. Such swarms were prevalent from 1961–1965, less common from 1966–1973 and absent from 1974–1983 (Table 2). We searched the deep, BF seismicity for a connection between the deep and shallow LP earthquake zones to define a preferred path or paths through the lithosphere by which magma reaches Kilauea's summit.

2.4.1. The earthquake of February 1, 1994

An earthquake of particular importance to our understanding of deep seismicity occurred on February 1, 1994, located nearly due south of Kilauea's summit, just offshore beneath Kilauea's south flank, with a depth of nearly 35 km and a magnitude of 5.2. A total of 132 aftershocks ($M \leq 3.0$) took place, over half within the first nine hours following the mainshock. Compared to shallower Kilauea aftershock sequences, or to deep aftershock sequences away from Kilauea, aftershocks were much more numerous

Table 1
Deep ($Z > 25$ km) brittle-failure earthquakes of $M \geq 4.5$ with and without aftershocks

Date y/m/d	Time (UT) hr:m:s	Lon W	Lat N	Z km	Loc	Pmag	Aftershocks		As dur days	Remarks
							$M>2$	All		
1961/08/25	08:45:34.93	155 05.20	19 49.84	43.53	KEAF	4.6L	none		0	Mauna Kea
1971/05/11	16:00:03.13	155 33.01	18 57.14	37.08	DLS	4.7L	none		0	Mauna Loa offshore
1971/08/15	15:36:09.14	155 16.71	19 21.95	34.04	DEP	4.9L	5	18	3	Kilauea; deep quakes continue—13 events 8/21–27/71
1973/04/22	21:07:51.85	154 35.67	20 01.33	33.72	DIS	5.0L	none		0	50 km offshore. Aftershocks of M <2.7 not detectable
1973/04/26	10:26:31.64	155 09.17	19 51.92	38.71	KEA	6.2S	73	169	9	Mauna Kea offshore. Aftershocks expected because of high Pmag
1973/10/09	01:53:45.27	155 16.07	19 20.24	32.50	DEPF	4.8L	19	28	5	Kilauea; largest aftershock (M4.2) 7 min after mainshock; deep quakes continue—14 events 10/16–26/73
1973/12/13	04:25:56.08	155 17.55	19 22.44	34.84	DEPF	4.8L	6	8	2	Kilauea
1974/12/25	07:47:49.41	155 16.84	19 20.86	32.30	DEPF	4.6L	14	16	5	Kilauea; deep quakes continue—13 events 1/2–13/75
1975/11/06	02:05:28.35	155 18.83	19 20.56	31.90	DEPF	4.6L	8	11	2	Kilauea; 7 foreshocks 11/3–6; largest aftershock M4.2, 76 min after ms; deep quakes continue—5 events 11/10–18/75
1977/09/07	13:51:06.86	155 19.34	19 22.37	31.42	DMLF	4.6L	3	3	4	Kilauea; foreshock on 7/6; aftershocks to 9/15
1978/08/31	13:07:21.37	155 28.97	18 59.97	35.26	DLSF	4.5L	5	5	3	Mauna Loa offshore
1979/03/06	05:07:58.53	155 16.20	19 31.23	27.53	DEP	4.8L	4	7	4	Mauna Loa
1979/08/14	02:51:41.75	156 19.95	20 50.11	26.14	DISF	4.6L	–	–	–	Near Maui
1980/01/19	15:28:48.56	155 32.42	19 18.67	26.84	DLS	4.5L	none		0	Mauna Loa offshore
1981/01/12	04:18:10.61	155 18.28	19 21.33	31.19	DEPF	4.9L	12	12	4	Kilauea
1981/01/13	18:20:16.50	155 19.41	19 22.12	28.97	DMLF	4.7L				Largest of 4 aftershocks $M>4$

Table 2
Deep earthquake swarms of over 15 events, 1961–1983

Date			Depth		Magnitude		Number		Remarks
Year	Begin	End	Min	Max	High	Low	$M \geq 2$	Total	
1961	6/27	7/2	24.6	32.4	4.2	2.3	18	20	
1961	7/23	7/28	20.0	36.5	4.4	2.0	18	32	
1961	11/16	11/27	21.9	33.3	3.8	2.3	44	56	
1961	11/30	12/17	25.7	34.2	3.9	2.0	23	32	
1961	12/28	1962/1/3	21.3	30.9	3.8	1.4	11	33	
1962	2/4	2/7	24.1	35.3	3.5	2.0	18	18	
1962	5/7	5/13	21.4	32.4	4.0	0.9	21	25	Event on 5/8 has depth of 41.8 km
1962	6/7	6/16	21.1	32.5	4.1	1.2	8	17	Event on 6/7 has depth of 47.6 km
1963	1/8	1/15	23.2	33.2	4.6	1.3	29	34	Event on 1/7 has depth of 38.7 km; eq w aftershock?
1964	12/2	12/10	24.2	34.1	4.5	1.3	18	28	Eq w aftershocks?
1965	5/30	6/10	23.7	34.0	3.4	1.3	11	18	Event on 6/7 has depth of 37.0
1969	11/8	11/11	38.9	51.4	3.4	2.4	2	16	Swarm > 35 km; 3 events at depths of 28.0–30.9 km
1970	5/20	6/1	20.9	44.4	2.5	1.0	26	44	associated with events at 5–20 km beneath Kilauea's summit; 8 events deeper than 35 km
1970	9/30	10/10	21.9	36.0	2.9	1.0	10	23	5 events at depths of 41.9–45.8 km
1970	10/13	10/20	21.0	35.8	3.2	1.2	8	26	8 events at depths of 37.9–51.7 km
1971	4/25	4/30	21.6	32.3	4.4	2.0	8	32	Eq w aftershocks? Event on 4/29 at depth of 40.9 km
1971	5/4	5/12	20.5	44.7	3.1	2.3	6	28	Event on 5/6 at depth of 49.5 km
1973	9/12	9/24	27.8	33.0	3.9	2.2	10	31	
			36.9	45.7	2.5	2.4			

("productive") and decayed much more rapidly (Klein and others, 2002). This earthquake is the largest representative of a unique class of deep Kilauea earthquakes of moderate magnitudes (4.5–5.2) that are accompanied by productive aftershock sequences (Table 1).

The aftershocks trace a N–S band extending from offshore to near Kilauea's summit (Fig. 6A), thus occupying the zone between the deep and shallow LP earthquakes (Figs. 4 and 5). A focal mechanism determined for this quake yielded a sub-horizontal fault (Wolfe et al., 2003, Fig. 1E) The aftershocks in cross-section (Fig. 6B) lie mainly above the mainshock, trace a horizontal N–S band at a depth of about 30 km, and suggest a horizontal slip-plane consistent with the focal mechanism. Relocation of the aftershocks using the double-difference technique (Wolfe et al., 2001) shows a horizontal zone of reduced thickness and strengthens the interpretation of a sub-horizontal fault plane.

2.4.2. Other deep earthquakes with aftershocks

Deep, BF earthquakes with productive aftershock sequences also occurred several times before 1994 (Table 1; Fig. 7). These can be compared to deep earthquakes in this magnitude range, drawn from the entire island chain (Table 1). The latter earthquakes all have fewer aftershocks compared to the same magnitude mainshock and show a less rapid decay when compared to the shallow Kilauea examples. These deep Kilauea mainshocks lie south of Halemaumau crater, and aftershocks scatter around the mainshocks (Fig. 7). Mainshocks and aftershocks lie within or near the northern boundary of the aftershock sequence for the February 1, 1994 event (Fig. 6B).

2.4.3. Deep, brittle-failure earthquake swarms 1961–1973

Intense earthquake swarms beneath Kilauea caldera deeper than 20 km were first documented in 1961 (Krivoy et al., 1963). Dates of deep earthquake swarms which have more than 15 events are listed in Table 2. Many of the earliest swarms (1961–1965) contained one or more earthquakes exceeding $M4$, and were located beneath Kilauea caldera and the Koae fault zone. A few events scatter to the south and these swarms from the 1960s (Fig. 8A) scatter more and are less well-located because of a sparser seismic station network than in the 1970s. Most swarm events lie at depths of 25–35 km and, compared to the earthquakes with aftershocks, lie more directly beneath the

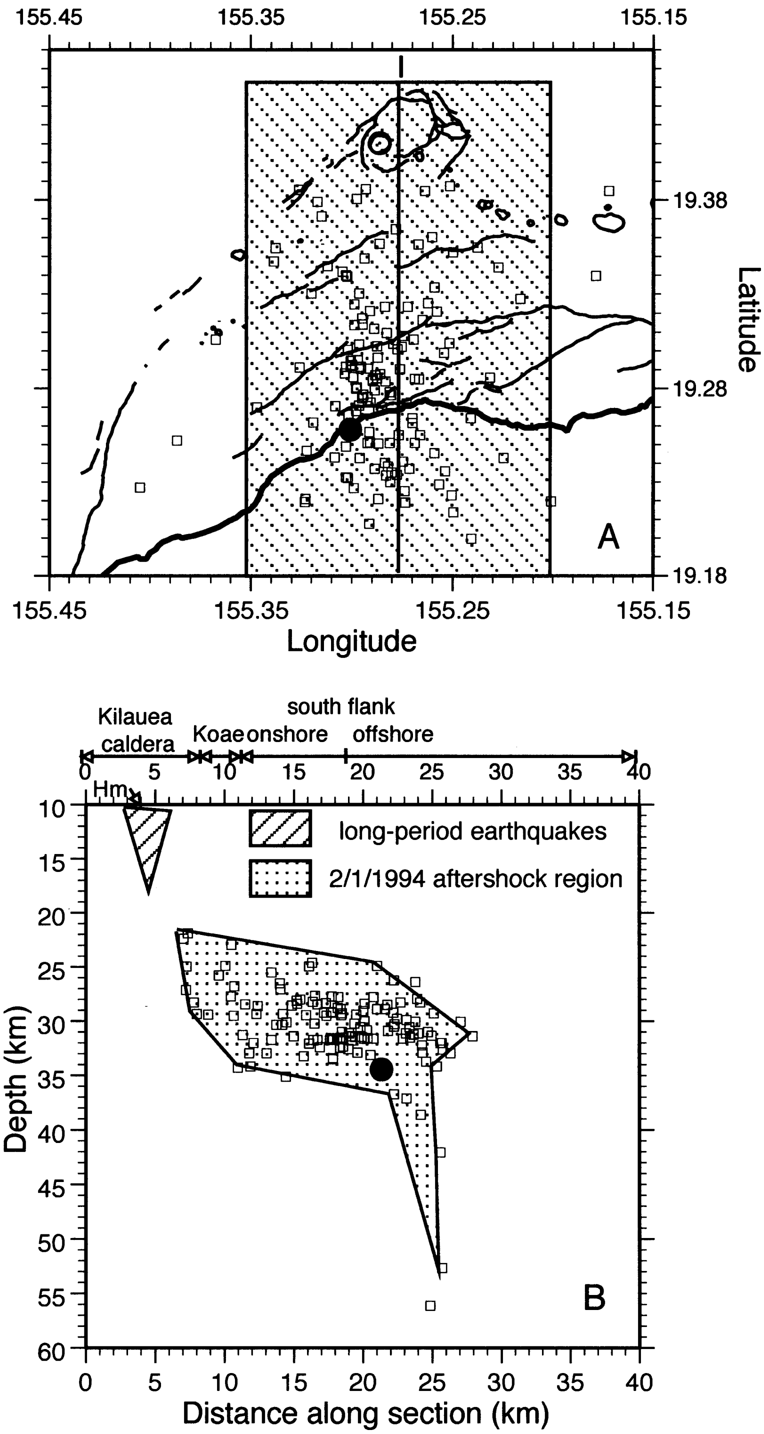


Fig. 6. Deep, brittle-failure earthquake of February 1, 1994 and its aftershocks. The mainshock is shown as a solid circle, aftershocks as open squares. (A) Map view. (B) Earthquakes within the rectangular box on (A) are projected onto cross-section I–J. The aftershock region is outlined. The zone of LP earthquakes beneath Kilauea's summit is shown schematically.

5–15 km depth LP earthquakes (Fig. 4). The swarm events also overlap the northern edge of the February 1, 1994 aftershock zone.

Earthquake swarms beneath Kilauea caldera gradually gave way in the mid 1960s to less frequent and more widely distributed deep swarm activity. Some epicenters extend to the east and west of the region defined by the 1961–1965 swarms and the deep mainshock–aftershock sequences. By the time of the *M*7.2 1975 south flank earthquake, deep swarms beneath Kilauea caldera were no longer seen and have not reappeared up to the present writing.

3. Discussion: deep magma transport

3.1. Geophysical and volcanological setting

Kilauea is built on the Pacific Ocean floor on top of the southern flank of Mauna Loa. Kilauea's south flank is actively moving seaward on a sliding surface (decollement) located at the surface of the pre-volcano ocean floor at about 10 km depth. The oceanic crust extends several kilometers deeper, to about 13 km beneath Kilauea and 18 km beneath Mauna Loa (Hill and Zucca, 1987). The lithosphere extends to at least 60 km beneath the island of Hawaii, as defined by the deepest earthquakes. Most contemporary workers on Hawaii have concluded that the thickness of the lithosphere beneath Hawaii is not substantially different from its thickness away from the Hawaiian chain, i.e., 80–100 km (e.g., Woods and Okal, 1996). Magma is supplied to Kilauea from the partly molten aesthenosphere, termed the Hawaiian hot spot. Although magma is stored within the Kilauea edifice, the feeding channels from the hotspot must penetrate the terrain upon which Kilauea is constructed, including the oceanic mantle, oceanic crust and Mauna Loa edifice.

3.2. Seismic response in the mantle beneath Kilauea

Brittle-failure earthquakes deeper than 20 km represent release of strain within the lithospheric mantle that is potentially related to one or more of the following mechanisms:

(1) Lithospheric adjustments associated with plate movement.
(2) Lithospheric adjustment to stress gradients associated with an uncompensated volcanic load imposed on the mantle. The actively growing volcanoes Mauna Loa and Kilauea are rapidly loading the lithosphere before it has a chance to respond, thus providing stress for deep seismicity. The shear stress load of a volcano no longer in a constructional phase diminishes as it subsides and becomes isostatically compensated (e.g., Klein and Koyanagi, 1989; Wessel, 1993).
(3) Stress imposed by the seaward spreading of Kilauea's south flank. As the south flank moves seaward, a tractive stress is imposed on the mantle underlying the decollement along which the spreading takes place. This effect was dramatically demonstrated by the sharp drop in the deep earthquake rate after south flank stress was relieved by the 1975 Kalapana earthquake (Klein et al., 1987; Klein and Koyanagi, 1989).
(4) Stresses related to the magma conduit feeding Kilauea and Mauna Loa from the deep mantle. These could result from magma overpressure, or from the effect of the conduit on the regional stress field. The heterogeneity of the conduit and the fact that a fluid-bearing conduit is unable to support strong shear stress, serves to concentrate stresses around the conduit. These stresses are imposed on a mantle that is already stressed by factors 1–3.

3.3. Seismically defined magma transport path

The deep LP earthquakes and tremor (Fig. 5) represent the deepest seismically detectable response of the lithosphere beneath Kilauea to the upward movement of magma from the Hawaiian hotspot. Accepting a lithospheric thickness of at least 80 km requires that much of the magma collection and initial upward movement be aseismic.

The aftershocks of deep earthquakes of moderate magnitude (4.5–5.2) outline a possible path connecting deep and shallow LP seismicity (Figs. 6 and 7). Aftershock numbers decay at the rate t^{-p}, and the 2/1/1994 sequence has the highest p value (1.39) and hence the fastest decay rate of the two large deep and three largest shallow sequences with enough aftershocks to provide an accurate measurement (Klein et al., 2002) A rapid aftershock decay rate indicates

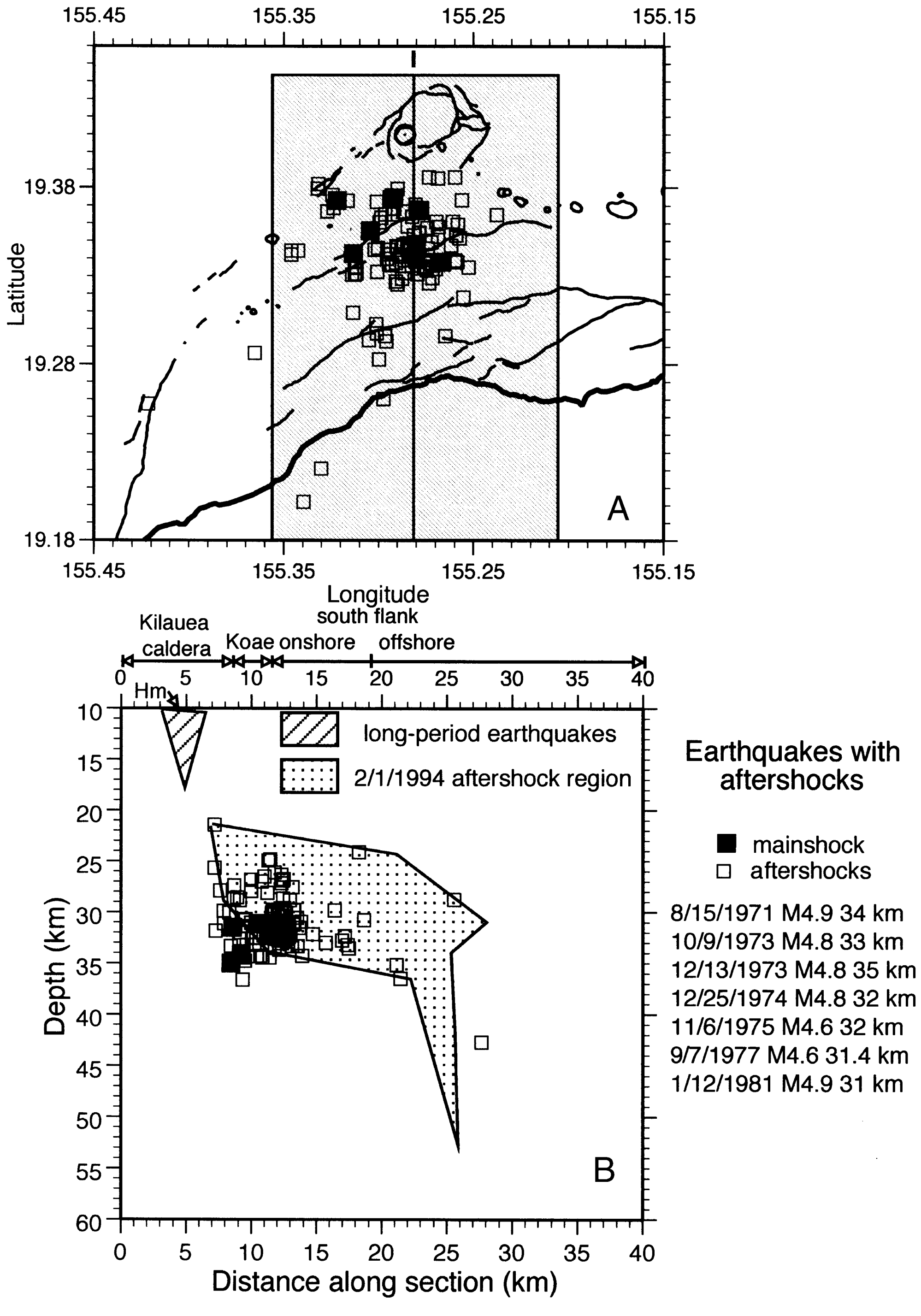
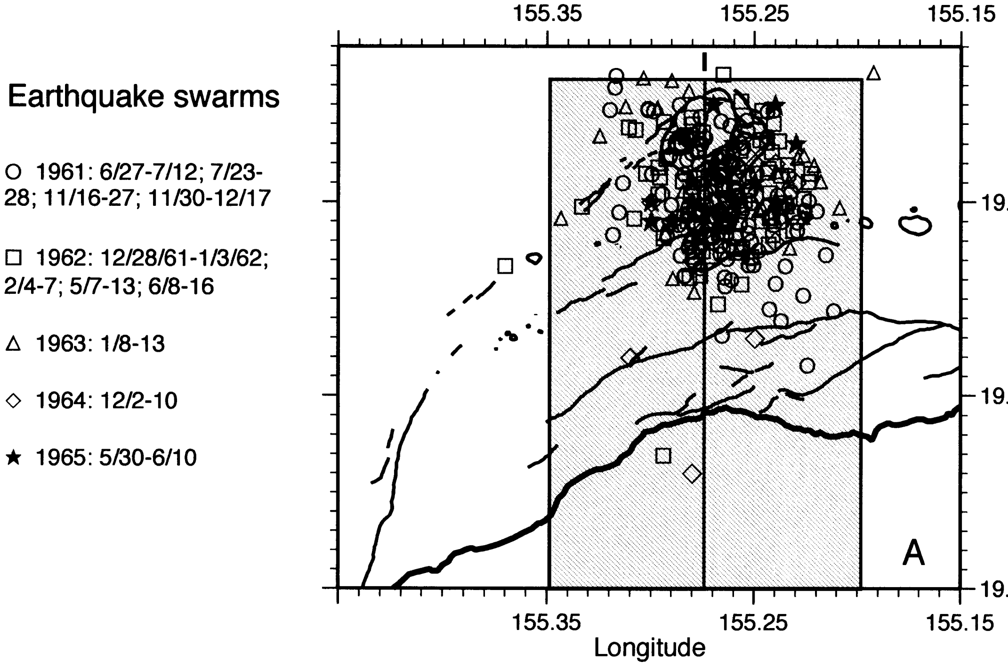


Fig. 7. Deep (30–35 km) Kilauea brittle-failure earthquakes with aftershocks. (A) Plan view. (B) Cross-sections I–J. Only earthquakes within the stippled rectangle on (A) are plotted. Crosshatched regions of long-period earthquakes and the stippled aftershock region for the earthquake of February 1, 1994 is shown for reference in this figure and in Figs. 8B–10B.



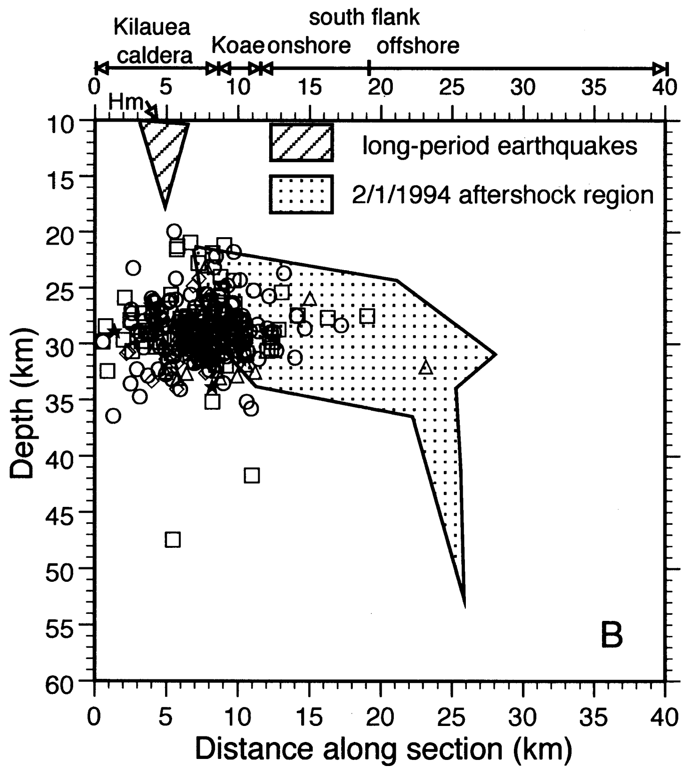


Fig. 8. Deep (20–35 km) Kilauea brittle-failure earthquake swarms. (A) Plan view. (B) Cross-sections I–J. Only earthquakes within the stippled rectangle on (A) are plotted.

rapid stress relaxation or high temperatures (Kisslinger and Jones, 1991; Dieterich, 1994). High aftershock productivity, coupled with the persistent seismicity of the deep Kilauea conduit, makes it likely that faults in the conduit area are continually stressed and remain close to failure because of high pore fluid pressures or greater crack density. We interpret the aftershock distribution shown in Figs. 6 and 7 to indicate a region of high fluid pore pressure, and thus a possible magma transport path. The association with magma is reinforced by the occurrence of earthquake swarms in the same region (Fig. 8).

Our inferred magma transport path (Fig. 9) is vertical through and above the deep LP earthquakes and also below the shallow LP earthquakes. The vertical zones are connected along the "long-lived tectonic fault zone near 30 km depth" identified in the distribution of relocated deep Kilauea earthquakes (Wolfe et al., 2003, Fig. 2A, discussion on p. 479). Our analysis agrees with their statement (p. 479):

The association of this highly active seismic zone with the frequently erupting Kilauea volcano implies that tectonic faulting is related to stresses of magmatic origin, although the background stresses from volcano loading and flexure may help bring faults close to failure.

Our proposed transport path coincides with a mineralogical change in the oceanic mantle, from spinel peridotite below to plagioclase peridotite above (Sen, 1983). The change in mineralogy may help to focus both the fault planes and the magma transport path. Alternatively, a turbulently convecting olivine-rich magma may find during upward transport through the mantle a region of neutral buoyancy within which lateral transport is favored. This implies that further vertical transport beneath Kilauea's summit requires loss of olivine to create a progressively more buoyant magma body.

Not all deep earthquake swarms are located south of Kilauea's summit (Fig. 10, Table 2). The swarm on November 8–11, 1969 shows a vertical distribution of

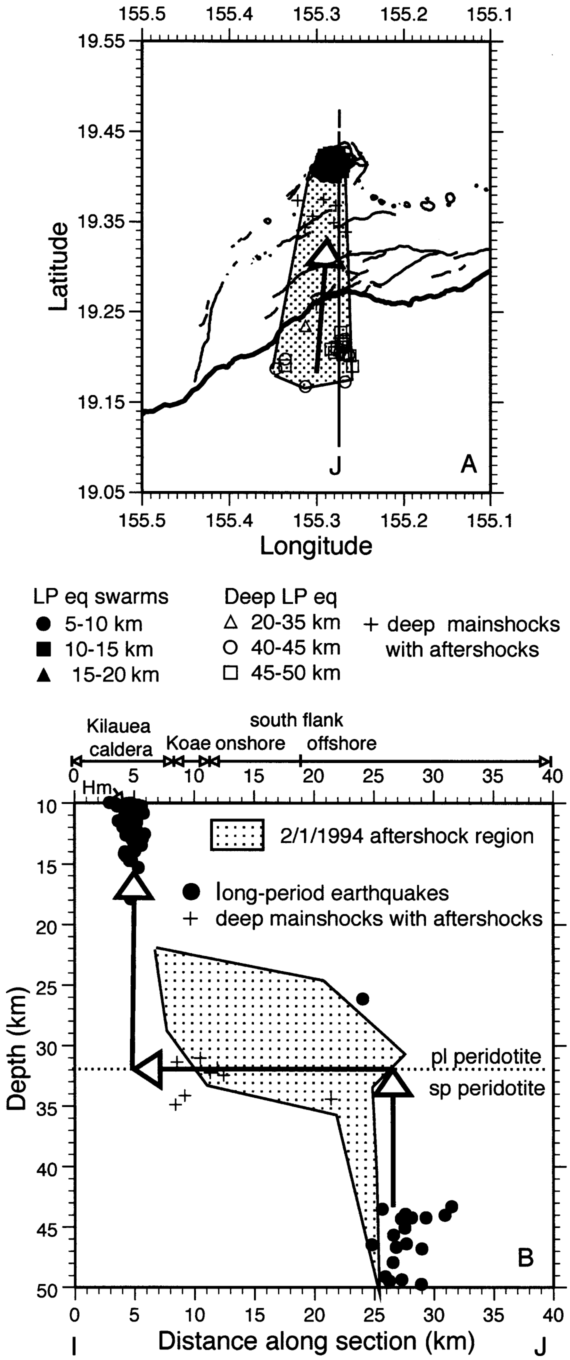


Fig. 9. Preferred deep magma transport path(s). (A) Plan view. Shaded region encloses epicentral area of long-period earthquakes and deep earthquakes with aftershocks. Arrow indicates generalized magma transport direction. (B) Data of (A). Arrows show proposed magma transport path through the upper lithosphere. The plagioclase peridotite–spinel peridotite transition depth is from Sen (1983).

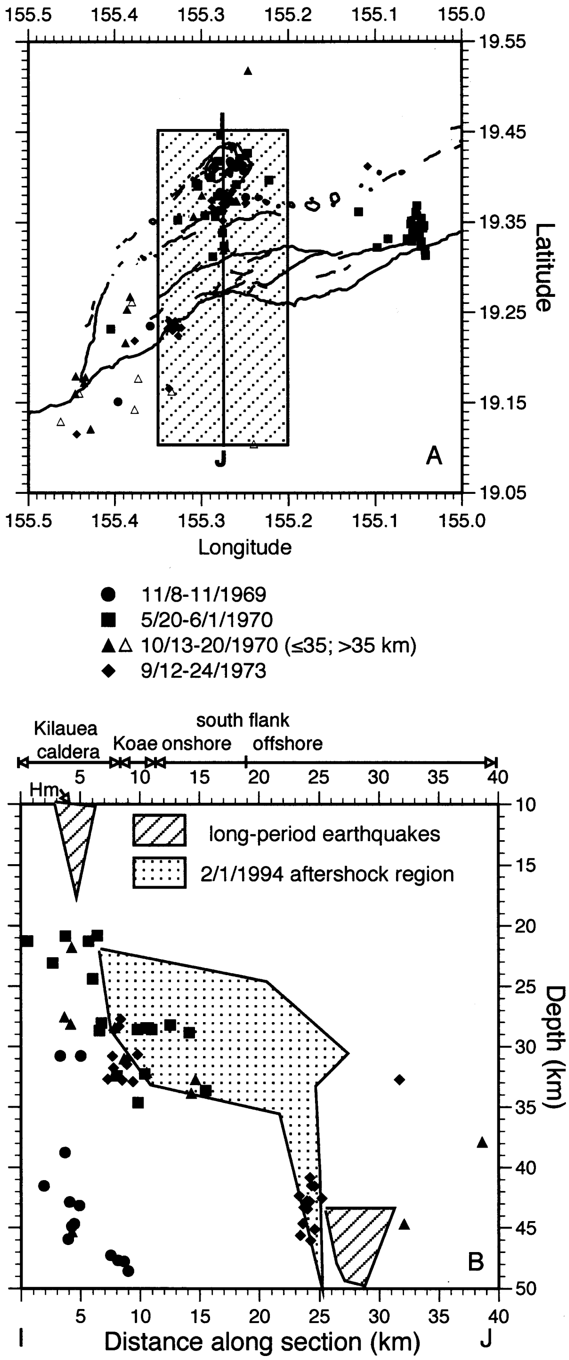


Fig. 10. Alternate deep magma transport paths. (A) Plan view of alternate magma transport paths and possible triggering of deep seismicity away from the primary magma transport path. (B) Data within stippled area on (A) projected onto cross-section I–J.

hypocenters extending to 49 km beneath Kilauea's summit, suggesting that during this brief time magma was supplied from a part of the hotspot directly below Kilauea's summit. The 1959 eruption in Kilauea Iki crater was preceded by several years of earthquake swarms to the north of Kilauea caldera (Eaton and Murata, 1960; Eaton, 1962), indicating a different deep, and nearly vertical path connecting the hotspot with an eruption.

The swarm of September 12–24, 1973 shows a bimodal grouping of hypocenters. In plan view the deep epicenters plot near the more westerly concentration of LP earthquakes (Fig. 5) within our proposed magma transport zone (Figs. 9 and 10A). This suggests a more westerly magma supply path compared to that originating from the LP swarms that plot due south of Kilauea's summit. An even more westerly path is represented by the swarm of October 10–13, 1970. In this swarm the southerly epicenters plot to the west of the shaded region, whereas those near Kilauea's summit are within the shaded region.

The swarm of May 20 to June 1, 1970 followed the intrusion of magma into Kilauea's east rift zone on May 15–16, 1970 (Duffield et al., 1974) and represents an exceptionally widespread seismic response. Earthquakes at depths of 21 to 33 km plot near the north edge of the February 1, 1994 aftershock volume (Fig. 10B) and suggest a magmatic connection between the aftershock volume and a shallow zone of LP earthquakes. Within the same time interval events deeper than 35 km occurred beneath the eastern south flank (Fig. 10A). We interpret this as shallow magma intrusion beneath Kilauea's summit and east rift zone that triggered deeper magma transport beneath the central south flank and, in turn, triggered stress release in a part of the mantle distant from the primary magma transport path.

The magma paths illustrated in Fig. 10 are consistent with deep seismic tomographic evidence for a low velocity anomaly beneath Kilauea. The pioneering study of the deep seismic structure beneath Kilauea (Ellsworth and Koyanagi, 1977) identified a low-velocity zone deeper than 30 km beneath Kilauea's summit that extended offshore south of the island. A more recent tomographic study (Tilmann et al., 2001) confirms a low-velocity anomaly between 40 and 80 km that narrows beneath Kilauea.

3.4. Long-term history of the source region for Kilauea magma and its supply path

The analysis of the magma supply path in the preceding section applies to only a few decades of Kilauea's history. Because the magma source is in the aesthenosphere and the volcano and all its associated earthquakes lie within the lithosphere, we must consider the effects of motion of the Pacific plate and the dynamics of the Hawaiian hotspot to assess a longer history of magma supply. The related questions involve whether (1) the direction and rate of Pacific plate motion have remained constant, and (2) the Hawaiian hotspot has remained fixed in its position within the aesthenosphere.

3.5. Pacific plate motion

Volcanoes at the southern end of the Hawaiian chain are arranged along two parallel locus lines, called the "Kea" and "Loa" trends (Dana, 1849; Clague and Dalrymple, 1987). The orientation of the chain and locus lines between the islands of Kauai and Maui is about 292°, younging to the southeast at about 8 cm/yr. The island of Hawaii falls south of this trend, and locus lines on Hawaii are oriented approximately 325° (Fig. 11). Controversy exists in the literature as to whether the change of locus line orientation requires a recent shift of Pacific plate motion, or whether the change in volcano propagation direction is best explained by movement of the hotspot. One group argues for a recent shift in plate motion (e.g., Wessel and Kroenke, 1997) and volcano propagation has been modeled on this basis (Hieronymus and Bercovici, 1999). In contrast, a ten-year history of GPS data shows the Pacific plate at several Hawaiian stations to be consistently moving northwestward at 295° at about 7 cm/year , obtained from a web search for GPS plate motions. These data match the Kauai–Maui trend (Table 3) and suggest that Pacific plate motion has not changed. A model of volcano propagation consistent with no change in plate motion (Cox, 1999) involves migration of the melting source due to decoupling of the deep mantle flow from the plate. The long-period earthquake sources are more consistent with a shift in the melting source than with a shift in plate motion.

3.6. Plume source defined by long-period earthquakes

At its inception, Kilauea grew on the sea floor, with magma rising from the hotspot through the lower lithosphere, ocean crust, and the flank of Mauna Loa. We assume that magma transport was initially vertical and that vertical magma transport should be preferred throughout the lifetime of a volcano. However, plate motion has carried Kilauea and its magmatic plumbing to the northwest of the source region in the aesthenosphere. The gravity high centered over the magma transport path shallower than 20 km (Figs. 4 and 5) indicates that the upper part of the plumbing has moved with the volcano, and thus the shallow transport path has remained nearly vertical.

The deeper plumbing responds to the location of the melting source below the plate. We assume that the transport path through the lower lithosphere will lie vertically above the region of highest temperature within the hotspot. Because plate motion carries Kilauea and its shallow plumbing away from its source, the deep and shallow magmatic plumbing will be separated, necessitating a horizontal or oblique component of magma transport as argued above.

We can expand the arguments to include Mauna Loa and Loihi. Fig. 11A shows all the LP seismicity deeper than 20 km for a 28-year period from 1972–2000. The earthquakes deeper than 40 km (mainly 40–55 km) define three clusters located off the south shore of the Island of Hawaii. As argued above, the two eastern clusters are interpreted to be associated with magma supply to Kilauea.

The large southwestern cluster lies south of Mauna Loa's summit and the deep seismicity becomes somewhat shallower in the direction of Mauna Loa's summit. This cluster may belong to a deep magma transport path feeding Mauna Loa. Seismic tomography shows distinct high-velocity anomalies for Kilauea and Mauna Loa down to 9 km (Okubo et al., 1997, Fig. 2). The Mauna Loa anomaly deepens to the southeast toward the southwestern cluster of deep LP earthquakes (Okubo et

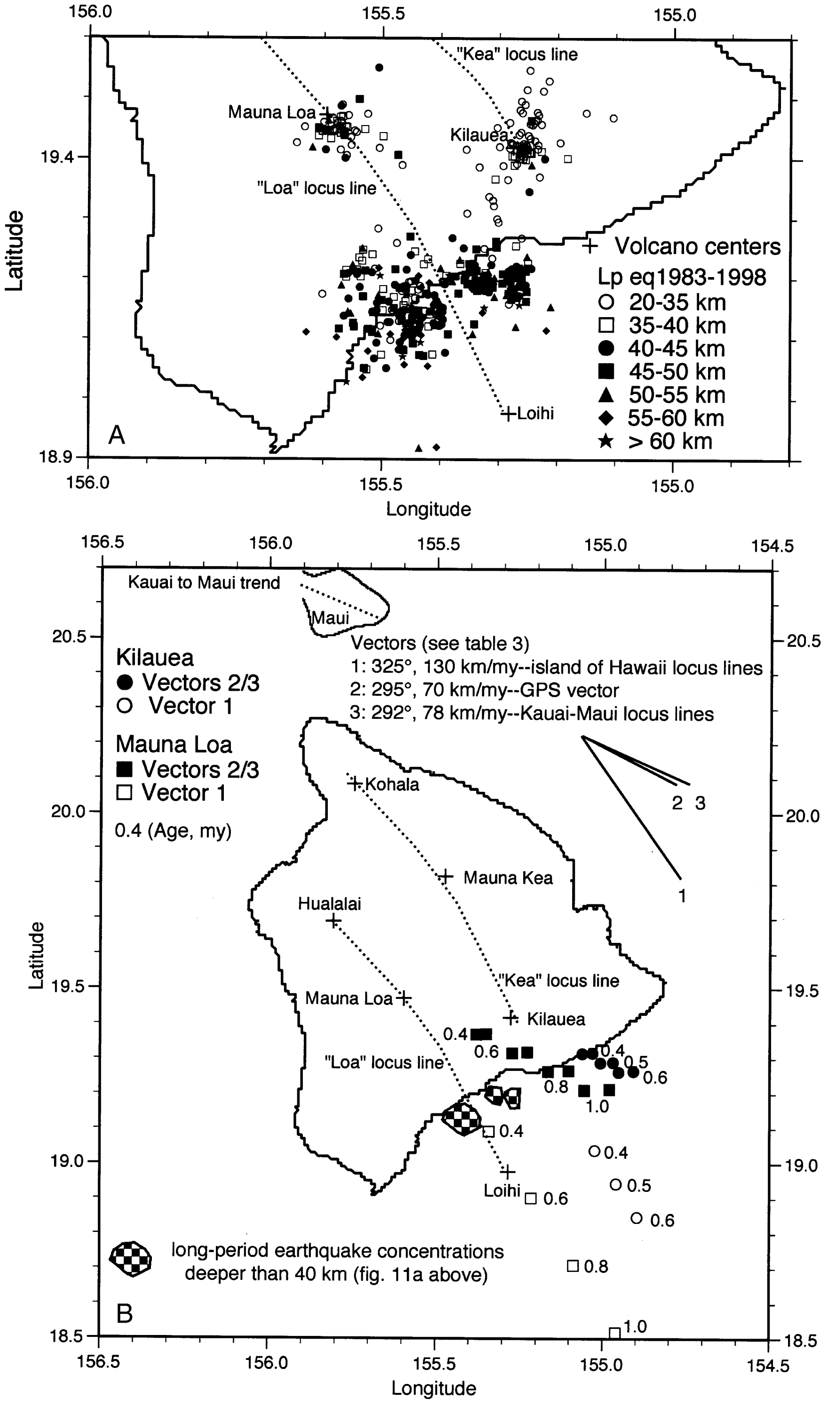


Fig. 11. Relationship of magma transport to plate motion. (A) Deep, long-period seismicity clusters related to magma transport to Kilauea and Mauna Loa. (B) Ages of Kilauea and Mauna Loa volcanoes are obtained by backward extrapolation along the three plate motion vectors of Table 3. Current long-period seismicity deeper than 40 km lies WSW of the plate motion extrapolations. See text for further discussion.

Table 3
Pacific plate motion vectors

Vector source/reference	Azimuth	Rate (km/my)
10-year GPS record (http://sideshow.jpl.nasa.gov/mbh/series.html)	295	70
Volcano propagation vector—Kauai to Maui (Clague and Dalrymple, 1987)	292	78
Volcano propagation vector—Haleakala to Hualalai (Moore and Clague, 1992)	325	~130

al., 1997, Fig. 3), consistent with the inferred deeper magma transport path. LP seismicity extends to 35 km south of Mauna Loa's summit. There is a lateral gap in which LP seismicity is rare or absent, similar to that seen for Kilauea.

Loihi shows a fairly well-defined cluster of LP earthquakes shallower than 15 km (Koyanagi et al., 1987; Caplan et al., 1997), but no obvious deep LP earthquakes are observed on the land-based seismic network. The magma source may still lie vertically beneath Loihi with aseismic transport through most of the lithosphere. Alternatively, the geochemical similarity between Loihi and Kilauea suggests that they may share a common source (Garcia et al., 2000). In this case, magma transport to Loihi would be a mirror image of that proposed for Kilauea.

3.7. Relationship of the melting source to plate motion

Using the data of Table 3, we can infer where in the aesthenosphere Kilauea and Mauna Loa originated relative to the present sea floor by assuming an age and extrapolating a distance along the various plate motion vectors (Fig. 11B), similar to the approach used previously (DePaolo and Stolper, 1996) to infer volcanic growth rates on the island of Hawaii. Extrapolation using either the recent GPS results or the Kauai–Maui volcano propagation trend (Table 3) place the inception of both Kilauea and Mauna Loa just off the south shore of the island. Extrapolating from present to original volcano location along the locus line vector for the island of Hawaii, including the much higher estimated rate of volcano propagation, places both volcano origin locations much farther offshore.

Extrapolations of Kilauea's origin along any of the assumed vectors lie to the east of the deep LP seismicity, which we interpret as to lie vertically above the current melting source for each volcano. This requires migration of the melt source since the inception of the volcano, consistent with recent study of the earliest volcanism in the Hawaiian chain (Tarduno and Cottrell, 1997; Sager, 2002). On the assumption of constant plate motion along the Kauai–Maui locus lines, the source would have moved WSW. This direction is consistent with a clockwise rotation of the volcano propagation vector needed to explain the change in orientation of the locus lines for volcanoes on the island of Hawaii. Thus, the evidence of long-period earthquake locations favors the hypothesis of constant plate motion and migration of the melting source. The distribution of deep earthquake source zones for Kilauea and Mauna Loa during the past 40 years, combined with the present location of the active Loihi volcano, requires a hotspot whose diameter is at least 30 km (Fig. 11).

3.8. Age of Kilauea and Mauna Loa

The two oldest apparent ages obtained for Kilauea's subaerial tholeiitic shield stage are 0.37 my (Quane et al., 2000) and 0.44 my (Guillou et al., 1997), obtained on the core from recent deep drilling beneath Kilauea's east rift zone. Recent dating of submarine alkalic rock fragments sampled off Kilauea's south shore suggests an age of 0.33 my for the beginning of Kilauea (Lipman et al., 2001). An age of 0.2 my for transitional basalt fragments suggests an even younger age for the beginning of the submarine shield stage.

In constructing Fig. 11B we make three assumptions: (1) that Kilauea's summit and shallow magmatic system originally lay vertically above the point where Kilauea originated on the seafloor; (2) that Kilauea has moved northwest along the GPS vector of plate motion or the Kauai–Maui locus line, and (3) that the locus of Kilauea's deep LP seismicity has remained on the WSW trend defined by the current deep LP seismicity off Kilauea's south coast.

A consequence of these assumptions is that Kilauea's point of origin on the seafloor lies on a northeasterly extrapolation of the trend of deep, LP seismicity. Derived ages of about 0.4 my for the origin of Kilauea and about 0.8 my for the origin of Mauna Loa are consistent with these assumptions, and with a recent estimate of the length of time from birth to the end of subaerial shield-building at a typical Hawaiian volcano (Moore and Clague, 1992). Our extrapolations are consistent with the data of Lipman et al. (2001) if their ages represent a minimum age of Kilauea or if Kilauea originated south of the present position of its summit, similar to the southerly offset of Loihi seamount from the assumed hotspot center located below Kilauea. Our extrapolations are not consistent with the drill-core data in agreement with the suggestion of Lipman et al. (2001) that the drill core ages are too old.

Fig. 12 illustrates our preferred position of Kilauea at its inception. As Kilauea grew, its source migrated to the WSW, while the volcanic edifice was moving WNW, necessitating adjustment in the supply path away from the vertical. We suggest that a segmented vertical-horizontal-vertical supply path utilizing a plane or planes of mantle weakness would be more efficient than attempting to traverse the mantle obliquely. Such a scenario suggests that the preferred supply path has remained approximately due south of Kilauea's summit.

3.9. Application to the geochemistry of the active volcanoes

Kilauea, Mauna Loa and Loihi volcanoes each have a unique isotopic signature that appears to have remained so over the time available for sam-

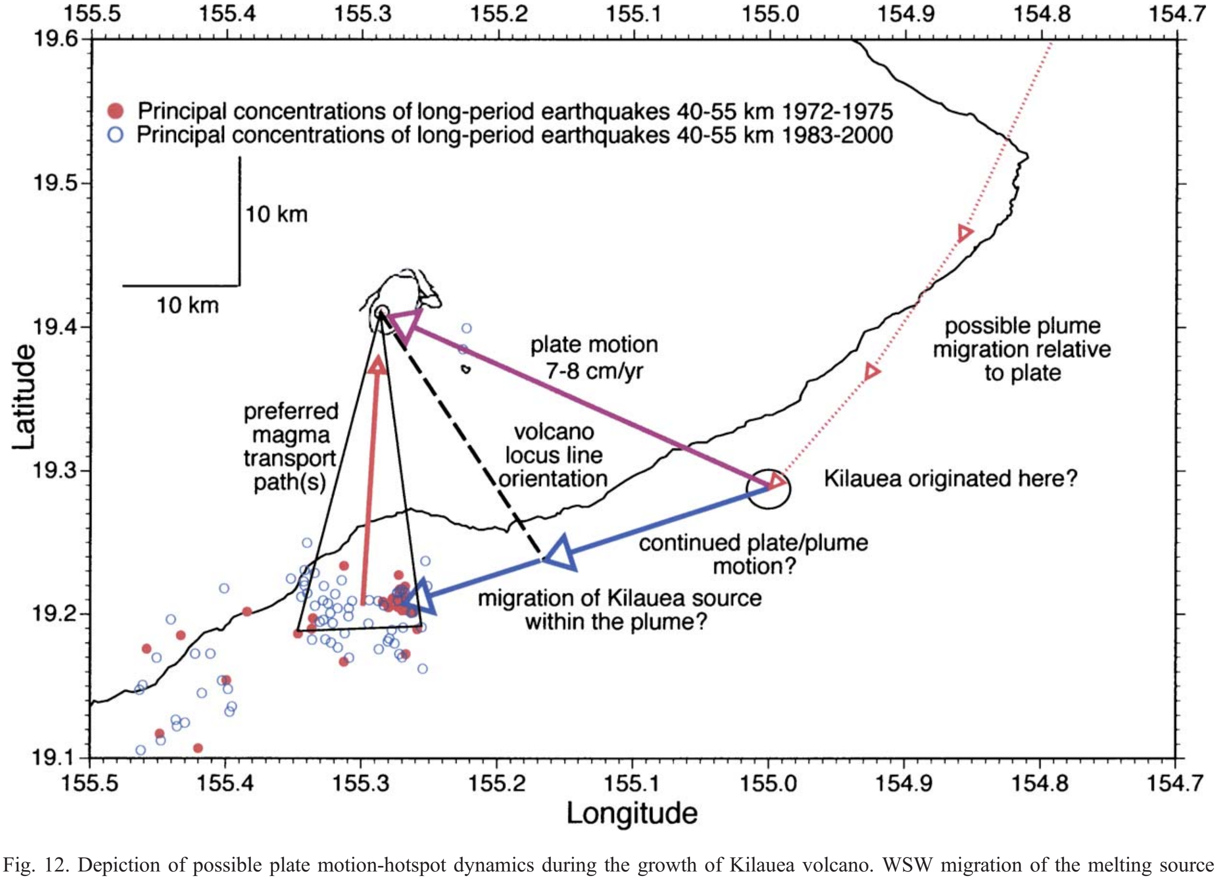


Fig. 12. Depiction of possible plate motion-hotspot dynamics during the growth of Kilauea volcano. WSW migration of the melting source within the lifetime of Kilauea matches the longer-term clockwise migration of the melting source to explain the shift of locus line orientation. See text for further explanation.

pling (e.g., helium isotopes, Kurz et al., 1983). It has long been known that Kilauea's major and trace-element chemistry has remained distinct from that of its sister volcano Mauna Loa (Wright, 1971; Tilling et al., 1987), while within Kilauea major oxide chemistry has changed over time (Wright, 1971). There have also been times when a separate source region seems indicated. One example is the 1959–1960 eruption, in which one source component arrived directly from mantle depths, bypassing Kilauea's summit storage region (Wright, 1973; Helz, 1987). The unique source for this magma batch was confirmed by studies that showed that it did not participate as a summit mixing component in any rift eruption other than 1960 (Wright and Fiske, 1971; Wright and Helz, 1996).

Recent work has confirmed that variation of trace-elements and isotopes at Kilauea has occurred over both short times, within a single eruption (Hofmann et al., 1984; Garcia et al., 2000) and longer times, spanning several decades (Pietruszka and Garcia, 1999). The changes are interpreted to reflect a heterogeneous melting regime within the Hawaiian hotspot (Pietruszka et al., 2001).

The present study offers a possible explanation for the petrologic and geochemical observations. If Kilauea is fed only from the easternmost clusters of deep LP earthquakes, as shown in Fig. 11, this would ensure separation of Kilauea's source from source regions for Mauna Loa farther west. The southwestward migration of Kilauea's melting source within a heterogeneous source region provides an explanation for the temporal variations of chemistry within Kilauea.

4. Summary

The immediate magma source for Kilauea's eruptions, as defined by LP and BF earthquake swarms, lies at 4–7 km depth directly beneath Kilauea's summit. The conduit feeding this source from depth is near-vertical and well-defined to 15 km depth. The coincidence of the magma transport path with the position of the gravity high suggests that the shallow plumbing has remained vertically beneath Kilauea caldera over most of the lifetime of the volcano.

Plate motion during the construction of Kilauea is inferred to match the long-term volcano propagation trend from Kauai to Maui. LP earthquakes from 40 to 55 km depth, assumed to vertically overlie the present mantle hotspot source for Kilauea's magma, are displaced more than 20 km to the south of the well-defined shallow plumbing. We propose a horizontal component of magma transport to take into account this offset. This lateral offset of the conduit coincides with the aftershock zone of the *M*5.2 February 1, 1994 earthquake at about 30 km depth, suggesting a weakened zone capable of faulting. Aftershocks of this earthquake decay in time more rapidly than other deep and shallow Hawaiian aftershock sequences, an observation explained by rapid stress decay in a region of elevated temperature. The February 1, 1994 earthquake and other deep mainshocks within the conduit zone produce slightly more aftershocks than other mainshocks at similar depths and magnitudes, which is consistent with a greater crack density and faults that remain close to failure.

If the plate motion has not changed, the melting source must have migrated in a clockwise (SW) direction to explain volcano propagation along the locus lines connecting the volcanoes the island of Hawaii. The WNW vector connecting the points of origin of Kilauea and Mauna Loa with the clusters of LP seismicity that overlie the current position of the hotspot is consistent both with the SW source migration and with reasonable ages for Kilauea (0.4 my) and Mauna Loa (0.8 my).

The interpretation that the LP clusters overlie separate melting regions within the hotspot explains the geochemical separation of Kilauea from Mauna Loa and Loihi, Hawaii's other currently active volcanoes. Finally, the location of deep, BF earthquake swarms indicates that within the last few decades of good seismic monitoring Kilauea has sampled different parts of the hotspot. Sampling of a heterogeneous source provides an explanation for the geochemical variation seen within Kilauea that cannot be ascribed to shallow crystallization and mixing.

Acknowledgements

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Appendix A. Earthquake classification

In order to better understand how earthquakes relate to magma transport within the Kilauea edifice, we classify earthquakes according to the geology and tectonics of the volcano. Boundaries between regions are defined by a combination of surface features (e.g., active faults, pit craters) and seismicity (e.g., repeated locations of earthquake swarms associated with eruption and intrusion).

Our defined regions are described in Appendix Table 1a and shown in Fig. 2. Fig. 2 also shows the location of cross-sections, designated by the letters A to J, used in Figs. 3–9. The Koae fault system is defined by the most northerly south-facing active fault traces and by the Kalanaokuaiki north-facing fault scarp on the south. The southern boundary of Kilauea caldera is coincident with the northern boundary of the Koae. The east rift zone is divided into three parts, an upper northeast-trending portion, a middle east-trending portion that extends to Heiheiahulu shield, and a lower portion extending eastward to the east point of the island and far offshore. The southwest rift zone is divided into two parts—a northern segment extending approximately to the Kamakaia Hills, and a southern portion encompassing "the great crack." Kilauea seismicity plots from the late 1960s (Klein et al., 1987, e.g., Fig. 43.67, p. 1118) show swarms extending south from Halemaumau, then turning to the southwest to join the southwest rift zone near the Kamakaia Hills. We have designated the locus of such swarms as the "seismic southwest rift zone" to distinguish it from the southwest rift zone defined by surface fractures, pit craters and cones. Kilauea's mobile south flank is defined in four segments bounded on the north by the southwest rift zone, Koae fault zone and east rift zone. Boundaries between south flank segments are arbitrarily placed to match the divisions of the rift zone.

Two of the regions, the upper east rift zone, and the seismic southwest rift zone overlap other regions. Beginning in 1968 we see paired earthquake swarms south and southeast of Halemaumau. The eastern swarms begin within Kilauea caldera in the vicinity of Keanakakoi crater (Klein et al., 1987, e.g., Fig. 43.66, p. 1116), but are clearly part of activity on the upper east rift zone. The seismic southwest rift zone swarms overlap Kilauea caldera, Koae fault zone, southwest rift zone and the adjacent south flank. We give these events a dual classification, with the rift region leading for swarm events, e.g. sswr/koae; uer/kc, and the other region leading for non-swarm events, e.g., kc/uer; sfswr/sswr.

We focus exclusively on earthquakes that could be associated with magma transport at Kilauea. These are:

(1) LP earthquakes at all depths.
(2) Brittle-failure earthquakes beneath Kilauea caldera and rift zones (including the seismic southwest rift zone) shallower than 20 km.
(3) Brittle-failure earthquakes deeper than 20 km beneath all regions of the volcano.

We group earthquakes within the defined geographic regions into 5 depth ranges, appending a number from 1 to 5: 0–5 km (1); 5–10 km (2); 10–20 km (3); 20–35 km (4); >35 km (5). Finally, we consider five time relationships, related to the occurrence of earthquake swarms in different depth ranges. Criteria for defining these time periods are given in Appendix Table 1b.

s0—Earthquakes *not* associated in time with eruption, intrusion or swarm activity
s1—times of shallow (0–5 km) earthquake swarms associated directly with eruption and shallow intrusion beneath Kilauea's summit and rift zones
s2—times of occurrence of earthquake swarms at 5–10 km depth, independent of times of eruption or intrusion
s3—times of occurrence of earthquake swarms at 10–20 km depth, independent of times of eruption or intrusion
s4—times of earthquake swarms at 20–35 km depth in the absence of earthquakes shallower than 20 km

s5—times of deep earthquake swarms at depths >35 km in the absence of earthquakes shallower than 35 km

sf—times when seismic activity beneath Kilauea's south flank at depths of 0–20 km dominates

x.y.z etc—times when heightened activity occurs in more than one region or depth range.

Deep earthquakes in all categories except s0 may occur either singly or in small swarms. By definition, s0 earthquakes at all depths occur as isolated events not meeting any of the swarm criteria outlined in Appendix Table 1b.

Appendix Table 1a
Tectonic regions of Kilauea volcano

Code	Description
gln	North flank: region north and east of Kilauea caldera; site of deep (>45 km) earthquake swarms before 1961
kc	Kilauea caldera: extends somewhat beyond the bounding faults that define the surface expression of Kilauea's central depression
koae	Koae fault zone: the region between the southwest and east rift zones; bounded on the north by the northern most set of active East–West fractures; bounded on the south by the Kalanaokuaiki North-facing fault scarp
swr	Southwest rift zone: defined by surface fractures, cones and pit craters; locus of eruptions
sswr	Seismic southwest rift zone: defined by earthquake swarms extending south from Halemaumau, then south west to join southwest rift zone in the vicinity of the Kamakaia Hills
uer	Upper east rift zone: southeast-trending rift zone defined by surface fractures, cones and pit craters. Turns east at intersection with Koae fault system; active vents extend from Puhimau to Mauna Ulu
mer	Middle east rift zone: east-trending east rift zone defined by surface fractures, shields and cinder cones and pit craters; active vents extend from Mauna Ulu to Heiheiahulu
ler	Lower east rift zone: continuation of east rift zone east from Heiheiahulu; continues offshore for 50 km
sfswr	Western south flank: east of southwest rift zone and southwest of Koae fault zone
sfkuer	Central south flank: south of Koae fault zone and west of upper east rift zone
sfmer	Eastern south flank: south of middle east rift zone; site of large-magnitude south flank earthquakes
sfler	Far eastern south flank: south of lower east rift zone

Appendix Table 1b
Criteria for earthquake swarm activity, 2/1/1966–11/28/1975

Class depth	Regions	Description criteria
s1 0–5 km	gln1; kc1; uer1/kc; uer1; mer1; koae1; sswr1/kc; sswr1/koae; swr1	**Periods of eruption and/or shallow intrusion**. A contiguous period within which at least one day has 5 events and all days have 2 or more events
s2 5–10 km	gln2; kc2	**Elevated sub-caldera activity**. Average 2 events per day for minimum of two days or 5 events/day for a minimum of one day
s3 10–20 km	gln3; kc3	Do
s4 20–35 km	all	**Elevated Deep activity**. Average one event per day for a minimum of five contiguous days; a contiguous sequence of any length featuring at least one day with three events; non-contiguous sequences allowed only when there is little activity elsewhere on the volcano
s5>35 km	all	Do
sf 0–20 km	sfmer; sfkuer; sfswr	**Elevated South flank activity**. Counting all south flank regions, at least an average of 5 earthquakes/day in a contiguous time span of at least two days. Days within span, including beginning and ending days, may drop below five as long as average is maintained. Earthquakes at 10–20 km depth are added to the count from 5–10 km as most are close to 10 km
s0 all depths	all	**Background seismicity**. Periods of time not meeting any of the above criteria.
x.y all depths	all	**Mixed swarm activity**. Events meeting criteria for more than one category; listed in order of dominance; e.g., s3.4, s1.sf, sf. s4.5

Appendix Table 2a

Date	Total	Used[a]	Depth	Code[b]	Comment
Long-period earthquakes (020 km depth) 5/25/197211/28/1975					
1/2/1975	10	4	0–5.8	lp.s1	1 (5–10)—not used
10/4–8/1975	19	19	2.2–4.9	do	
6/29–7/1/1975	24	17	4.7–10.2	lp.s2	1 (0–5); 1 (10–20)
10/15–18/1973	17	13	5.6–15.9	lp.s2.3	7 (5–10); 10 (10–20)
10/31–11/2/1973	18	18	7.8–12.4	do	8 (5–10); 10 (10–20)
6/11–13/1974	23	17	4.5–14.0	do	1 (0–5); 18 (5–10); 4 (10–20)
3/20–25/1975	34	26	5.7–13.8	do	19 (5–10); 15 (10–20)
4/7–11/1975	12	12	4.6–13.8	do	4 (5–10); 8 (10–20)
4/14/15/1975	7	7	7.1–14.7	do	3 (5–10); 4 (10–20)
5/25–27/1972	15	15	8.1–17.9	lp.s3	
5/30–31/1972	5	5	7.7–12.1	do	
1/2–3/1973	7	6	9.0–16.5	do	1 (5–10)
Long-period earthquakes not in swarms (not plotted)					
3/22/74–6/17/75	9	7	0–5	s0	Background seismicity
6/7/72–11/9/75	33	25	5–10	do	
6/2/72–10/20/75	31	22	10–20	do	
1/9/74–8/29/74	5	4	10–20	sf	Periods of south flank seismicity following
6/3/74–11/21/75	11	8	5–10	do	some s1 swarms
Long-period earthquakes associated with brittle-failure swarms (not plotted)					
1/3–4/1975	2	2	0.7, 2.0	s1	Long-period earthquakes (5–20 km) associated with brittle-failure earthquake swarms shallower than 5 km
11/10/73–1/4/75	5	3	0–5	do	
5/22/73–8/28/74	6	4	5–10	do	
5/10/73–5/30/74	10	7	10–20	do	
12/20/72	1	1	6.8	s3	Brittle-failure swarms have fewer than five earthquakes
9/10/72	1	1	10.1	do	
9/25/72; 7/3/75	2	2	7.9; 8.8	s3.4	Long-period earthquakes (5–20 km) associated with brittle-failure earthquake swarms deeper than 20 km
3/26/74	1	1	7.9	s4	
12/25/72; 2/8/74	1	1	18.6; 11.4	s4	
9/19, 23/73	2	2	8.0; 11.9	s4.5	
6/3–4/75	2	2	8.5; 9.2	s4.5	
6/3/75	1	1	12.0	s4.5	
6/22–23/75	2	2	8.7; 7.0;	s4.5	
9/9/75	3	3	8.4	s5	

[a] Number of earthquakes falling within the shaded area on Fig. 3A. Only these are plotted in cross-section (Fig. 3B).

[b] See Appendix text for explanation of codes.

Appendix Table 2b
Brittle-failure earthquake swarms

Date	Total[a]	Used[b]	Depth	Code[c]	Comment
1. 5–20 km depth from 1969 to 1975					
2/25–26/1969	6	5	10–20	s3	Accompanying East rift eruption of 2/22–28/1969
1/2–3/1970	4	4	10–20	s3	
5/24–6/1/1970	46	21	5–10	s2.3.4 ± .5	Post-intrusion response
	74	41	10–20		
6/8–11/1970	7	6	5–10	s2.3.4	No 0–5 km activity; Mauna Ulu I
	15	15	10–20		
4/27/1971	3	1	5–10	s3.4	
4/26–30/1971	9	6	10–20		
5/14–15/1971	2	2	5–10	s3.4	
	3	3	10–20		
5/23/1971	5	5	5–10	s2.3	No 0–5 km activity; Mauna Ulu I
	6	4	10–20		
6/20–21/1971	5	5	10–20	sf.s3	Post Mauna Ulu I; no 0–10 km activity
6/25–26/1971	4	4	5–10	s2.3	
	4	2	10–20		
8/25–27/1971	6	5	5–10	s2.3.4	
	9	7	10–20		
8/28/1971	7	7	5–10	s2.3	
	9	7	10–20		
8/30–31/1971	2	1	5–10	s2.3	
	4	2	10–20		
10/27–28/1971	3	3	5–10	s2.3	
	2	2	10–20		
11/17–18/1972	–		5–10	s3	Mauna Ulu II
	11	11	10–20		
11/25–26/1972	–		5–10	s3	Do
	5	5	10–20		
4/21–28/1974	–		5–10	s3	Mauna Ulu II
	15	15	10–20		
5/16–18/1974	4	4	10–20	s1	Mauna Ulu eruption declines during May; summit
5/20–21/1974	5	5	10–20	s3	deflation on 5/29 followed by largest eruptive
5/22–25/1974	4	4	10–20	s1.sf	episode of 1974 (Tilling et al., 1987, p. 441)
5/26–27/1974	5	5	10–20	s3.sf	
5/28–30/1974	3	3	10–20	s1.sf	
7/20–28/1974	–		5–10	s3	kc1; kc1/uer; Acc. and following summit eruption
	27	27	10–20		of July 19–22; Mauna Ulu eruption ends July 22
9/21–24/1974	–		5–10	s3	Following summit eruption of 9/19/1974
	6	6	10–20		(Lockwood et al., 1999)
10/13/1974	1	1	5–10	s1	
10/3–13/1974	10	9	10–20		

(continued on next page)

Appendix Table 2b (*continued*)

Date	Total[d]	Used[e]	Depth	Code[f]	Comment
12/2–13/1974	1	1	5–10	s1	Precursory to slow intrusion into uppermost east rift zone/seismic southwest rift zone on 12/24/1974
	5	3	10–20		
12/16–22/1974	5	5	10–20		
12/31/74–1/11/75	6	6	10–20	s1.sf	Accompanying and following southwest rift eruption 12/31/1974 (Lockwood et al., 1999)
1/14–15/1975	9	9	10–20	s3	Continued post-eruption response
2/6/1975	5	5	10–20	s3.sf	
4/29/1975	3	3	10–20	s3	
7/12/1975	3	3	10–20	s3	
7/29–30/1975	4	4	10–20	s3	
9/25/1975	3	3	10–20	s3	
11/29/1975					*M*7.2 Kilauea south flank eq

2. Shallow (0–20 km) swarms associated with eruption and intrusion (plotted on Fig. 4)

Cross-section	Eq's used	Depth code	Azimuth	Lat max	Lat min	Lon max	Lon min
A–B Fig. 4A	sswr/koae	1, 2	237	19.375	19.287	155.408	155.276
	koae			19.38	19.318	155.338	155.285
	swr			19.363	19.287	155.408	155.330
B–C Fig. 4A	sswr/kc	1, 2	180	19.398	19.370	155.295	155.2758
	kc/sswr			do	do	do	do
	kc			19.45	19.363	155.300	155.268
D–E Fig. 4B	kc	1, 2	270	19.4265	19.3995	155.338	155.267
E–F Fig. 4B	kc	1, 2	310	19.427	19.363	155.267	155.229
	kc/uer			19.409	19.380	155.272	155.234
	uer/kc			do	do	do	do
	uer			19.383	19.358	155.253	155.229
	koae			19.380	19.353	155.276	155.227
F–G Fig. 4B	uer	1, 2	270	19.383	19.358	155.229	155.2
	mer			19.395	19.358	155.200	155.167
G–H Fig. 4B	mer	1, 2	246	19.358	19.456	154.988	155.229
I–J	kc kc/sswr kc/uer	3, 4, 5 do do do	0	19.45	19.0	155.35	155.20
	uer koae koae/sswr sfkuer	4, 5 do do					

[a] Minimum of four events during the period.
[b] Cross-sections (Fig. 3D,F) show only earthquakes whose epicenters fall within the shaded area on Fig. 3C and E.
[c] See Appendix text for explanation of codes.
[d] Minimum of four events during the period.
[e] Cross-sections (Fig. 4B) show only earthquakes whose epicenters fall within the shaded area on Fig. 4A.
[f] See Appendix text for explanation of codes.

Appendix Table 2c
Additional deep (≥20 km) brittle-failure earthquake swarms beneath Kilauea, 1961–1975

Date			Depth		Magnitude		Number		Remarks
Year	Begin	End	Min	Max	High	Low	$M \geq 2$	Total	
1961	6/17	6/18	23.2	29.3	3.2	–	1	4	
1961	6/27	7/2	24.6	32.4	4.2	2.3	18	20	
1961	11/16	11/27	21.9	33.3	3.8	2.3	44	56	
1961	11/30	12/17	25.7	34.2	3.9	2.0	23	32	
1961	12/21	12/24	26.7	30.9	3.0	2.4	2	6	
1961	12/28	1962/1/3	21.3	30.9	3.8	1.4	11	33	
1962	1/7	1/10	22.9	31.3	2.9	2.0	6	6	
1962	2/4	2/7	24.1	35.3	3.5	2.0	18	18	
1962	3/23	3/24	24.7	29.0	3.7	2.0	5	5	
1962	3/30	4/5	26.7	34.2	4.0	2.0	5	8	
1962	4/11	4/12	26.4	30.7	2.0	1.4	1	6	
1962	5/7	5/13	21.4	32.4	4.0	0.9	21	25	Event on 5/8 has depth of 41.8 km
1962	6/7	6/16	21.1	32.5	4.1	1.2	8	17	Event on 6/7 has depth of 47.6 km
1962	6/24	6/30	25.7	31.0	2.5	1.5	7	10	
1963	1/8	1/15	23.2	33.2	4.6	1.3	29	34	Event on 1/7 has depth of 38.7 km; eq w aftershock?
1963	11/13	11/20	20.9	31.4	3.8	1.9	8	9	
1964	12/2	12/10	24.2	34.1	4.5	1.3	18	28	Eq w aftershocks?
1965	5/30	6/10	23.7	34.0	3.4	1.3	11	18	Event on 6/7 has depth of 37.0
1965	9/12	9/17	27.3	33.3	3.0	1.4	9	14	Event on 9/12 has depth of 35.8
1965	11/22	11/30	27.2	33.0	3.7	1.0	9	10	
1966	8/19	8/23	28.3	35.7	3.0	2.5	8	10	
1966	9/20	9/21	27.6	32.7	3.6	2.3	9	9	
1966	12/30	12/31	28.1	32.5	4.2	2.8	4	4	
1967	4/6	4/9	26.4	32.7	3.9	2.3	4	6	
1967	7/31	8/1	26.7	30.9	2.6	2.2	3	5	3 more quakes on 8/4–5; event on 7/31 has depth of 39.6 km
1967	9/24	9/29	24.2	35.5	3.5	2.5	7	8	Event on 9/26 has depth of 44.6 km
1968	5/28	6/1	30.8	35.7	2.5	2.1	2	5	
1968	6/27	7/5	22.9	35.3	3.2	1.7	4	14	5 events at depths of 38.1–47.7 km
1968	7/23	7/27	21.5	31.8	2.5	1.8	3	6	
1968	9/15	9/21	21.4	33.6	2.1	2.0	2	7	3 events at depths of 36.8–39.9 km
1968	11/19	11/22	31.4	34.0	3.7	2.6	2	5	Event on 11/21 has depth of 39.5 km
1968	11/28	12/3	29.4	35.4	2.9	2.4	6	10	Event on 11/28 has depth of 45.2 km
1969	1/15	1/20	29.3	34.0	2.6	2.1	7	10	3 events 40–54.5 km
1969	3/4	3/11	22.2	31.2	3.7	2.1	7	11	2 events 47.2, 49.4 km
1969	5/26	5/28	20.4	33.7	3.2	2.4	5	8	
1969	6/26	6/30	22.4	34.1	2.5	1.9	4	7	
1969	7/20	7/24	24.3	32.4	2.2	–	1	8	3 events 41.8–49.7 km
1969	8/4	8/5	20.7	32.8	2.0	–	1	6	
1969	8/18	8/22	20.5	34.7	2.6	1.6	4	9	Event on 8/20 has depth of 47.8 km
1969	9/13	9/18	25.4	35.4	3.7	1.0	4	14	Events at depths of 36.7, 39.5 km
1969	9/23	9/26	28.0	32.5	–	–	0	5	Associated with events at 10–20 km beneath Kilauea's summit
1969	10/20	10/23	22.5	33.6	2.3	–	1	5	do; additional deep events on 10/24 and 10/27–28
1969	11/8	11/11	38.9	51.4	3.4	2.4	2	16	Swarm > 35 km; 3 events at depths of 28.0–30.9 km
1969	12/23	12/27	23.3	32.3	3.3	1.7	4	9	
1970	2/17	2/20	20.1	30.4	3.2	1.8	5	10	Event on 2/19 at a depth of 40.2 km
1970	2/26	2/27	30.2	33.5	2.4	0.8	4	6	
1970	4/10	4/16	25.2	45.7	3.6	1.5	5	11	5 events > 35 km depth

(continued on next page)

Appendix Table 2c (*continued*)

Date			Depth		Magnitude		Number		Remarks
Year	Begin	End	Min	Max	High	Low	$M \geq 2$	Total	
1970	4/28	5/3	14.2	47.9	3.8	1.7	8	11	5 events > 35 km depth
1970	5/20	6/1	20.9	44.4	2.5	1.0	26	44	Associated with events at 5–20 km beneath Kilauea's summit; 8 events deeper than 35 km
1970	6/8	6/11	22.2	32.9		9	11	Event on 6/8 at depth of 37.4 km	
1970	6/17	6/17	45.9	49.1	2.5	2.4	3	5	Event at 32.9 km
1970	6/23	6/30	22.8	33.9	2.6	1.2	9	11	3 events at depths of 38.7–45.1 km
1970	7/16	7/19	28.9	32.8	2.5	2.4	5	6	Event on 7/18 at depth of 41.7 km
1970	8/5	8/9	36.9	48.2	2.7	1.1	5	7	2 events at depths of 25.9, 34.4 km
1970	9/7	9/9	29.6	35.2	2.8	1.5	3	7	Event on 9/9 at depth of 49.7 km
1970	9/30	10/10	21.9	36.0	2.9	1.0	10	23	5 events at depths of 41.9–45.8 km
1970	10/13	10/20	21.0	35.8	3.2	1.2	8	26	8 events at depths of 37.9–51.7 km
1970	11/3	11/8	21.0	34.3	2.5	1.0	4	7	2 events at depths of 39.9, 43.1 km
1970	11/29	12/3	25.8	35.8	1.9	1.0	2	7	Event on 11/30 at depth of 51.4 km
19701	2/15	12/16	22.4	37.6	2.4	1.8	3	5	
1970	12/31	1/1/71	21.7	33.4	1.5	–	1	8	Event on 12/31 at depth of 47.5 km
1971	3/25	3/27	22.5	29.1	2.5	2.1	2	8	3 events at depths of 40.8–44.8 km; 1 event at 62.6 km
1971	3/31	4/1	24.5	31.2	–	–	0	7	
1971	4/9	4/12	23.9	30.9	2.2	0.7	5	7	
1971	4/25	4/30	21.6	32.3	4.4	2.0	8	32	Eq w aftershocks? Event on 4/29 at depth of 40.9 km
1971	5/4	5/12	20.5	44.7	3.1	2.3	628	Event on 5/6 at depth of 49.5 km	
1971	5/27	6/6	20.1	35.9	2.9	2.1	4	13	3 events at depth of 41.6–48.1 km
1971	6/15	6/16	21.5	35.7		6	2	Event on 6/16 at depth of 39.5	
1971	7/9	7/11	30.9	36.7	2.5	–	5	1	Event on 7/10 at depth of 45.6 km
1971	8/25	8/27	20.3	33.5	2.3	–	1	8	3 events at depths of 43.3–45.8 km
1971	9/30	10/4	24.8	34.0	2.4	1.7	2	7	
1971	12/14	12/16	27.7	40.1	3.3	2.8	4	6	
1972	1/23	1/24	25.0	28.9	2.5	2.1	6	10	
1972	2/2	2/4	23.6	33.8	2.8	1.9	5	13	3 events at depth of 43.8–44.9
1972	4/8	4/9	26.8	34.7	3.7	1.8	7	10	
1972	4/25	4/30	22.3	39.0	2.4	–	1	10	
1972	7/29	8/6	26.0	37.8	2.3	2.2	2	12	3 events at depths of 40.6–48.5 km
1972	9/12	9/16	25.2	39.9	2.2	2.1	2	6	Event on 9/16 at a depth of 45.3 km
1972	11/19	11/22	25.9	39.9	3.6	2.1	4	6	
1972	12/13	12/15	24.4	37.4	2.1	–	1	7	
1973	2/6	2/12	30.9	38.6	4.0	2.2	7	10	Events at depths of 43.1, 43.9
1973	4/26	4/28	20.2	36.7	1.9	–	2	12	
1973	7/2	7/5	21.8	33.2	2.5	–	2	8	
			41.4	47.7	2.5	–			
1973	9/12	9/24	27.8	33.0	3.9	2.2	10	31	
			36.9	45.7	2.5	2.4			
1973	10/20	10/21	25.0	31.8	2.2	2.1	3	7	Event on 10/19 at depth of 37.2 km
1974	3/26		23.4	26.6	2.6	2.0	6	9	
1974	8/10	8/11	21.9	46.0	2.7	2.4	3	5	
1975	1/9	1/13	27.3	32.0	2.2	2.1	8	8	
1975	1/23	1/28	26.1	38.5	2.5	1.8	6	10	Event on 1/27 at depth of 58.1 km
1975	2/23	3/3	24.7	35.5	3.2	1.6	9	11	

Appendix Table 2c (*continued*)

Date			Depth		Magnitude		Number		Remarks
Year	Begin	End	Min	Max	High	Low	$M \geq 2$	Total	
1975	5/27	5/31	26.4	36.0	2.3	1.4	6	11	2 events at depths of 40.9, 43.6 km
1975	6/8	6/14	27.5	33.3	3.0	1.4	8	9	2 events at depths of 47.8, 58.3
1975	6/21	6/25	24.0	30.6	2.0	1.5	3	7	
			42.8	45.3					
1975	7/3	7/5	30.8	36.3	4.2	1.7	5	8	
1975	10/29	10/31	26.5	35.9	2.4	1.2	6	8	2 events at depths of 44.0. 45.0 km

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