Tectonic Pulses During Kīlauea’s Current Long-Term Eruption

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Abstract

The 20-year-old eruption of Kīlauea Volcano at Pu‘u ‘Ō‘ō and Kūpaianaha in the east rift zone has afforded unprecedented opportunities to observe and monitor sustained, long-term eruptive behaviors. In Hawai‘i, surface deformation rates are such that, over the course of this eruption, tectonic processes might significantly influence or couple with volcanic processes. When the eruption shifted its center of activity uprift to Pu‘u ‘Ō‘ō, the principal vent, from downrift Kūpaianaha, we observed magmatic pulses, in the form of intrusions, into Kilauea’s summit caldera or east rift zone. These pulses were apparently coupled with occasional earthquake swarms or sequences of faulting along the Ka‘ōiki system of normal faults bordering Kīlauea’s summit caldera. These normal faults have experienced a renewed rate of seismogenic activity since the 1983 M6.6 Ka‘ōiki earthquake beneath Mauna Loa’s southeast flank. We present our observations suggesting that the Ka‘ōiki faulting does indeed couple with the series of dike intrusions that marked a transitional eruptive stage.

Introduction

As of 2003, Pu‘u ‘Ō‘ō-Kūpaianaha eruption has continued for 20 years. It has featured numerous distinct episodes (Wolfe and others, 1987; Mangan and others, 1995; Heliker and others, 1998). The different eruptive styles and shifting vent locations in these episodes are suggestive of different eruptive stages. The detailed observations associated with present eruption monitoring will no doubt lead to improved insights on the evolution of, and transition between, these different eruptive stages. Perhaps as important, given the high average rates of measured surface displacements (Owen and others, 1995), tectonic plate motions, and recurrence of large earthquakes (Klein and others, 2001) in Hawai‘i, the 20-year duration of the Pu‘u ‘Ō‘ō-Kūpaianaha eruption can be productively studied in terms of the relationship and possible interactions between magmatic and tectonic processes.

In late 1990, an earthquake swarm signaled a magmatic intrusion into Kīlauea’s summit caldera following more than 4 years of steady, effusive eruption from Kūpaianaha—a vent 3 km downrift of Pu‘u ‘Ō‘ō. Such earthquake swarms had been absent from Kīlauea since the earliest stages of the eruption. Between 1990 and 1993, four more magma intrusions—announced by their respective earthquake swarms—occurred between Kīlauea’s summit and Pu‘u ‘Ō‘ō. This paper describes these intrusions and points out their association with a family of tectonic earthquakes reactivated by a M6.6 earthquake in 1983 beneath the flank of Mauna Loa (P. Okubo and J. Nakata, unpub. data, 2002). The work uses data from catalogs of hypocentral parameters and other seismic observations, derived according to standard HVO seismic data processing practice (for example, Nakata, 2002).

Overview of Eruption-Related Seismicity

Seismicity patterns preceding the January 3, 1983, beginning of the current eruption have been described in Klein and others (1987) and Koyanagi and others (1988). We agree with those authors in interpreting some of the patterns in microseismicity, especially increased seismicity in the summit and rift zones, to indicate magma transport through Kīlauea’s magma storage and transport complex. Figure 1 is a map of the summit and rift zones of Kīlauea, showing various geologic features and locations of seismographic stations.

The early stages of the eruption were marked by repeating episodes of high lava fountains from Pu‘u ‘Ō‘ō. Koyanagi and others (1988) describe their characteristic seismic pattern: (1) an increase in the level of short-period summit earthquake activity (SPC), coincident with inflation of the caldera region as monitored via an electronic tiltmeter on the northwest side of the caldera; (2) shallow long-period (LPC-A) earthquakes beneath the summit caldera, following the rapid deflation of the summit region accompanying the onset of a fountaining episode; and (3) the emergence of deeper long-period (LPC-C) earthquakes within the summit caldera, with lower dominant frequency of oscillation than the LPC-A earthquakes. Hypocentral coordinates, calculated from seismic-wave first-arrival times for larger LP events

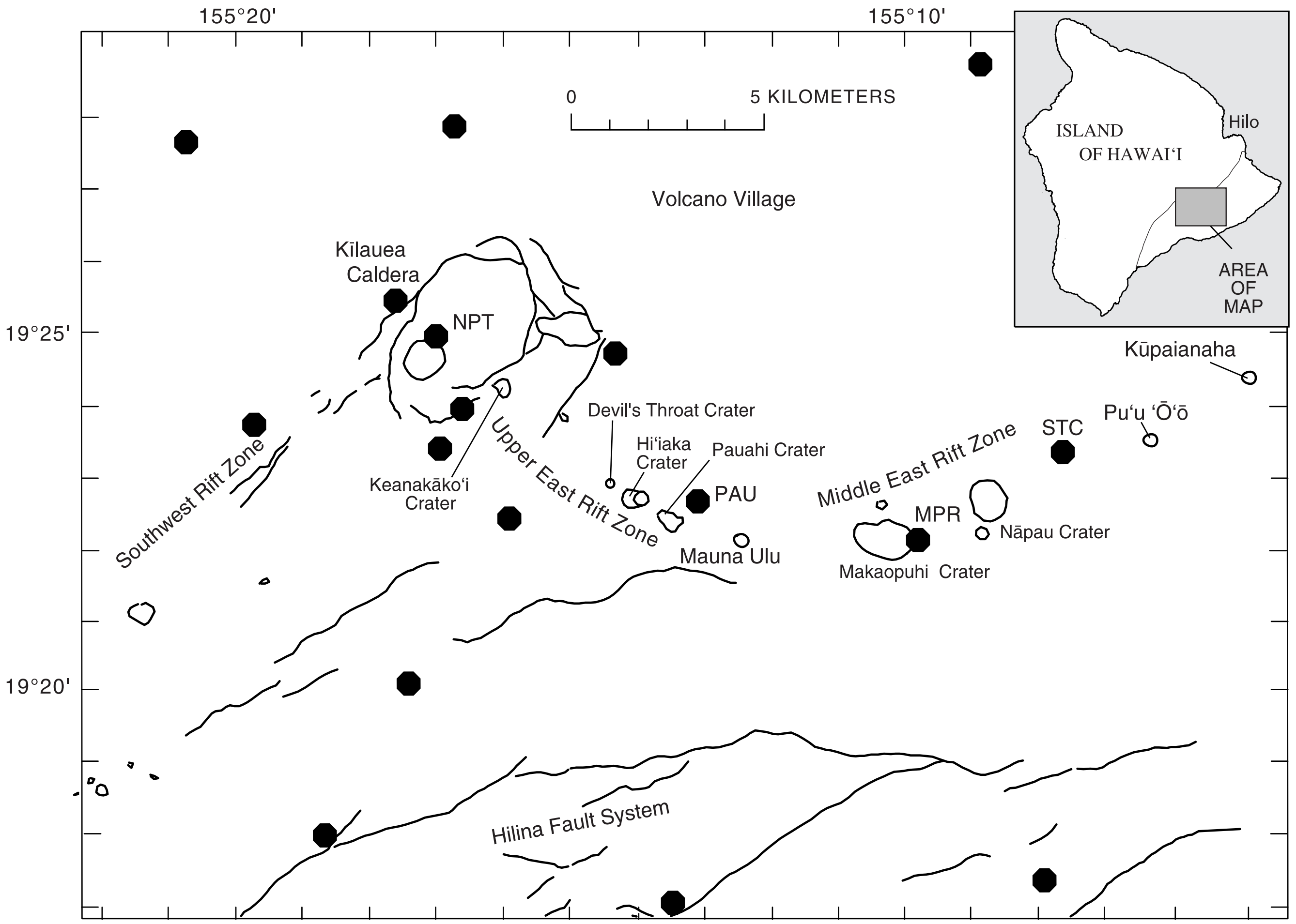


Figure 1. Map showing Kīlauea summit and east rift zone, including seismographic stations (black octagons), faults (lines), craters, and other features.

and events whose first-arrivals were adequately identified, show that LPC-A earthquakes have focal depths of 0–5 km and LPC-C earthquakes, 5–13 km (Koyanagi and others, 1988).

This pattern of seismicity is illustrated in figure 2, which shows 1985 earthquake-count data derived from the daily scanning of a continuous recording of seismic data traces on a Develocorder microfilm recorder. Event counts were compiled by recognizing combinations of waveform characteristics and dominant frequencies of oscillation, principally at station NPT in Kīlauea's caldera; distributions of waveform arrivals and amplitudes about the broader network were used to distinguish between SPC and LPC-A or LPC-C. These scanning procedures and classification criteria result in a qualitative compilation of Kīlauea seismicity. The overall trends in earthquake number, and the ability to calculate hypocentral coordinates for subsets of these earthquakes, afford some confidence toward incorporating these observations into a broader volcanic context. Also included in figure 2 are daily counts of earthquakes from the upper to middle east rift (UER/MER) zone of Kīlauea.

In July 1986, activity shifted from Pu'u 'Ō'ō to Kūpaianaha, a vent that developed a standing lava pond 3 km downrift of Pu'u 'Ō'ō. Flows from this lava pond built a shield and eventually extended downslope via a system of lava tubes (Mangan and others, 1995; Heliker and others, 1998). During the period from July 1986 through November 1990, earthquake swarm activity typically associated with magmatic dike intrusion was absent, consistent with the steady rates of lava production from the eruptive vents.

Figure 3 shows daily earthquake counts for the years 1986 through 1993. This period spans most of Kūpaianaha's eruptive duration of July 1986 to February 1992. The first half of 1986 shows the repeating pattern of earthquake variation beneath Kīlauea's summit caldera associated with the last of the 44 Pu'u 'Ō'ō fountaining episodes. Through much of Kūpaianaha's span, seismicity in the east rift zone, as recorded by counted UER/MER microseismicity, averaged approximately 100 events per day.

Clear departures from the steady UER/MER counts of earthquakes in Kīlauea's east rift zone are seen beginning in June 1987, in September 1988, in June 1989, and at several times during 1990 (see fig. 3). In June 1987, the eruptive vent at Pu'u 'Ō'ō enlarged significantly, and the elevated levels of counted UER/MER microearthquakes are largely due to numerous earthquakes and rockfalls associated with the collapse of the walls of the newly formed crater. On September

17, 1988, a swarm of earthquakes occurred in Kīlauea's upper east rift zone, extending between Kīlauea's caldera and Mauna Ulu. No other observations indicative of magmatic intrusion were associated with these earthquakes. On June 25, 1989, at 1727 H.s.t., the steady seismicity levels in the east rift zone were punctuated by the mainshock/aftershock sequence of a M6.1 Kīlauea south flank earthquake near Kalapana. Despite the size of that earthquake, no direct influence on the eruption was observed. The fluctuations in east-rift seismicity through 1990 are associated with a series of pauses in the eruption, when the extrusion of lava through the Kūpaianaha tube system stopped for different lengths of time and subsequently restarted (Okubo, 1994; Heliker and others, 1998; Heliker and Mattox, this volume).

Kīlauea's summit microseismicity, classified in the manner described above, shows greater variability during the time period from 1986 through 1990. Overall SPC counts appear to decrease from 1987 through 1990. In April 1988, a week-long pause in lava-flow activity was observed at Kūpaianaha. The large numbers of SPC earthquakes in late April, continuing into May 1988 (fig. 3), are associated with this pause. The sporadic spikes in SPC counts registered through 1990 are related to the series of eruption pauses at Kūpaianaha (Heliker and others, 1998). Long-period caldera earthquakes (both LPC-A and LPC-C) occurred in swarms not clearly related to changes in the eruption. Beginning in February 1989, elevated levels of LPC-C counts became apparent. These higher levels continued into early 1990, ending with the onset of the series of eruptive pauses mentioned above. Like other aspects of the eruption, summit microseismicity appeared relatively unaffected by the M6.1 earthquake in June 1989.

Intrusive Swarms

The Kūpaianaha eruptive pauses during 1990 have been described as precursory to the eventual demise of the downrift vent (Mangan and others, 1995). From mid-1990 through 1991, activity gradually shifted from Kūpaianaha back to Puʻu ʻŌʻō, and the last Kūpaianaha pause was observed in November 1990. Shortly after that pause a series of magma intrusions began while both Kūpaianaha and the lava pond at Puʻu ʻŌʻō remained active. The period of Kūpaianaha pauses and rift-zone intrusions has been described as a transitional stage as the eruption returned to Puʻu ʻŌʻō (Mangan and others, 1995).

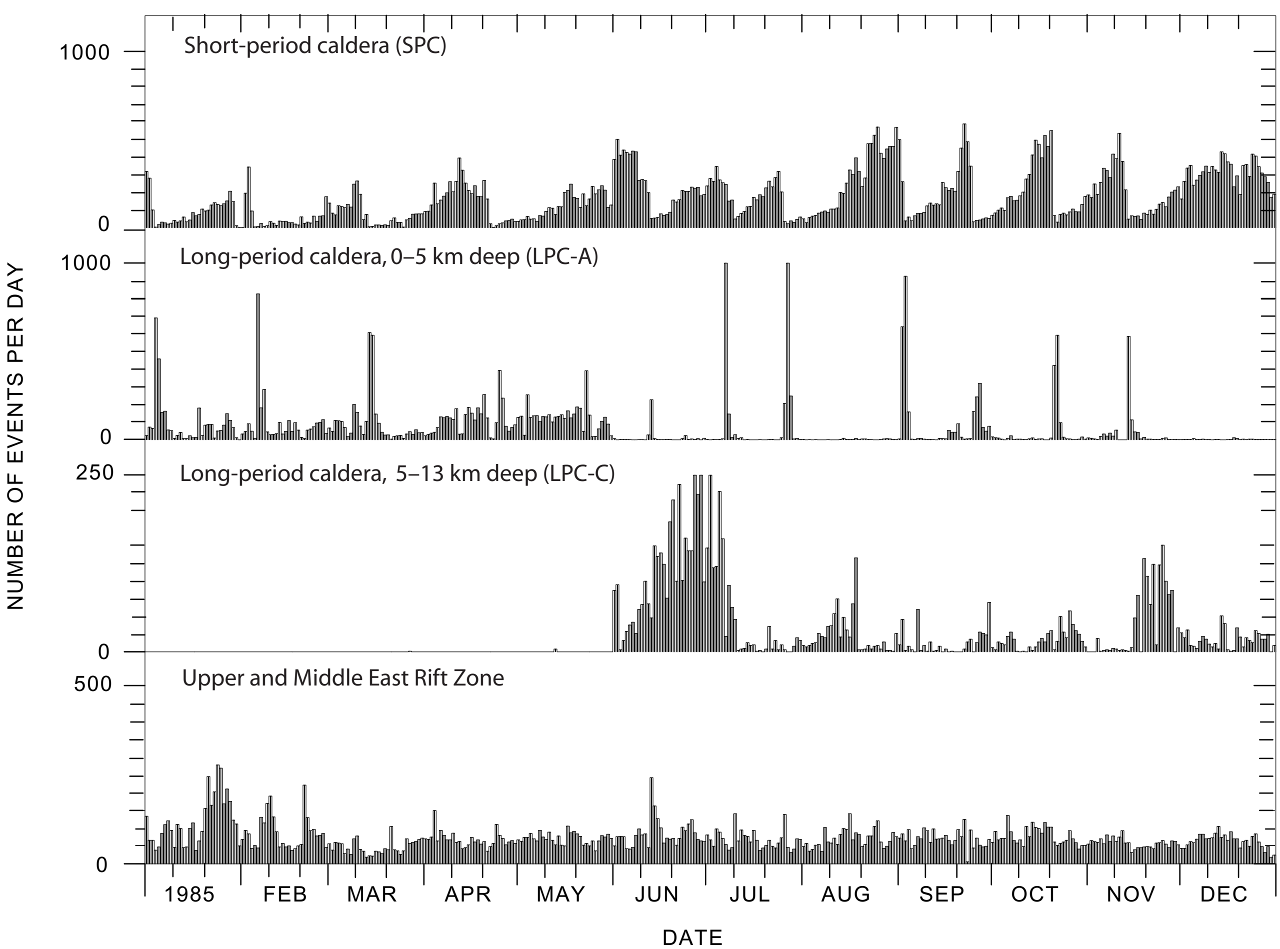


Figure 2. Daily earthquake classification for Kīlauea during 1985, assembled from daily scanning of HVO Develocorder microfilm record.

On December 4, 1990, an intrusion occurred beneath the eastern portion of Kīlauea summit and extended into the uppermost east rift zone. At approximately 1630 H.s.t., a microearthquake swarm started near Keanakāko‘i Crater. This activity was immediately preceded by a small M2 earthquake near Makaopuhi Crater. Approximately 15 minutes after the onset of the swarm near Keanakāko‘i, rapid summit inflation started, and both the amplitude of continuous tremor and summit earthquake activity increased. Maximum tremor amplitude occurred between 1735 and 1810 H.s.t. on December 4. Following this peak, the microearthquake activity continued beneath the summit and extended southeastward toward Mauna Ulu (fig. 4*A*). Elevated seismicity beneath the summit and upper east rift zone continued into the next morning, and the peak in microearthquake activity was followed by another burst of intermediate-depth long-period earthquakes (fig. 3).

This intrusion appears to have involved principally the upward transport of magma to shallower depths beneath the summit and into the adjacent east rift zone of the volcano. Following the intrusion on December 4, Kīlauea’s summit gradually reinflated through the month without marked variations in seismicity.

Shallow LP activity continued through the first 3 months of 1991 (fig. 3). This pattern changed with the second intrusion into the east rift zone in March 1991. At approximately 0532 H.s.t. on March 26, a shallow earthquake swarm (depths less than 5 km) started in the upper east rift zone, between Pauahi Crater and Mauna Ulu, 6 km southeast of the caldera rim and 15 km uprift of the active Kūpaianaha vent (fig. 4*B*). Five minutes later, a very sharp deflation of the summit began, and, in two stages, 7–8 microradians of deflation was registered at the summit by late March 27. Intense seismic activity occurred between 0530 and 0830 H.s.t. on March 26 before tapering off. Many of these earthquakes were felt, both in Volcano village and by field workers near Pauahi Crater. Seismicity along the upper east rift zone continued through the end of March at a higher level than the average rate for the early part of the month. On March 28, three earthquakes in the magnitude-4 range occurred beneath Kilauea’s south flank, along the Hilina fault system. These

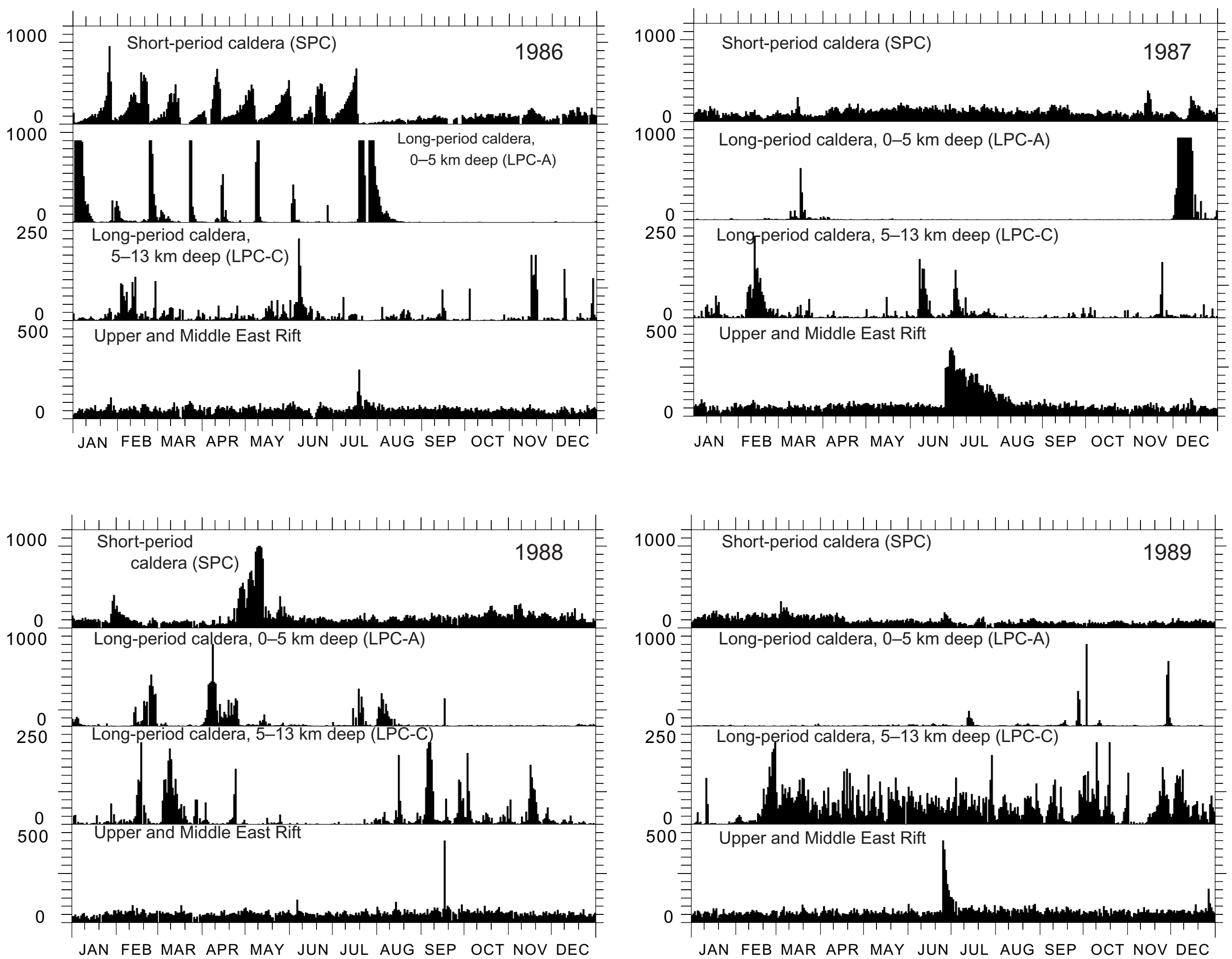


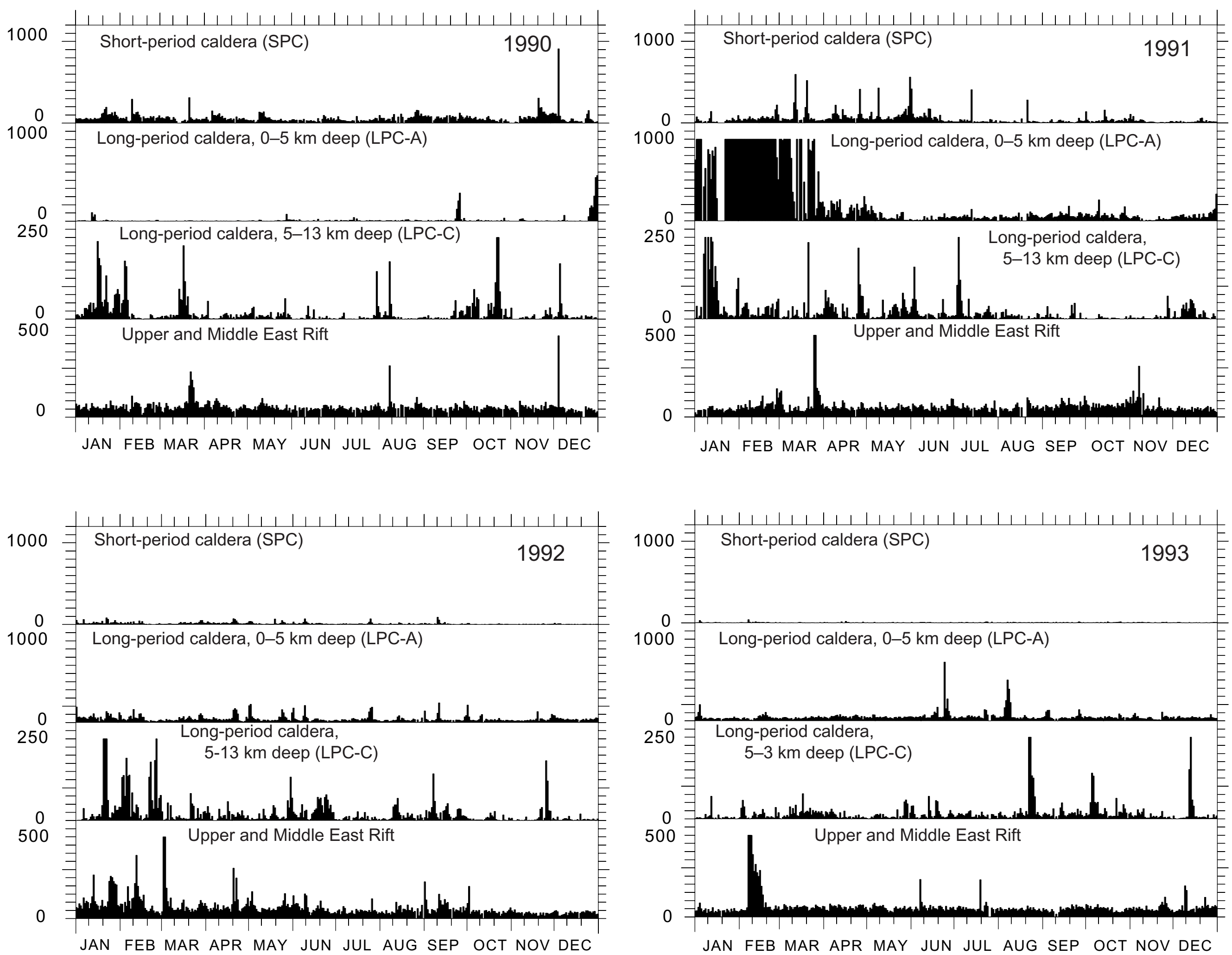
Figure 3. Daily earthquake classification for Kīlauea, 1986 to 1991, assembled from daily scanning of Develocorder microfilm record.

earthquakes were possibly triggered by the intrusion into the upper section of the east rift zone.

The third intrusion accompanied by a swarm of shallow rift-zone microearthquakes occurred on August 21, 1991. Between 1100 and 1200 H.s.t., more than 200 shallow summit microearthquakes were registered. The earthquake count quickly dropped off in the next hour, but elevated levels of seismicity continued in the upper east rift zone through the next day. The largest concentration of events was just southeast of Kīlauea's caldera, and very few events were located beyond Hiʻiaka Crater (fig. 4*C*). Most of the events beneath the summit and uppermost section of the east rift zone were related to the intrusive swarm.

The next intrusion, in March 1992, was accompanied by an intense swarm of shallow earthquakes along the rift zone between Devil's Throat and Pauahi Crater (fig. 4*D*). The swarm began at approximately 0045 H.s.t. on March 3, with more than 2,000 events listed in the hourly counts obtained from the HVO Develocorder between 0000 and 0500 that day. During these hours, 139 events were recorded well enough to allow precise computer estimation of hypocentral parameters. The intrusion and the earthquake swarm were coincident with summit deflation and apparent downrift inflation. Seismicity did not migrate either uprift or downrift. These events are also linked to the termination of eruptive episode 50 (Mangan and others, 1995). Renewed eruptive activity, designated as eruptive episode 51 (Heliker and others, 1998), began on March 7 following a period of elevated volcanic tremor at Puʻu ʻŌʻō that registered at the STC seismographic station. With the onset of episode 51, seismicity along the Devil's Throat-to-Pauahi Crater segment returned to levels observed before episode 50.

The fifth intrusive swarm occurred in February 1993 (fig. 4*E*). A dramatic increase of activity occurred at 2325 H.s.t. on February 7. Strong responses were observed both at Kīlauea's summit and in the rift zone. High-amplitude volcanic tremor began at 2325 H.s.t. and essentially saturated the record at station MPR for two hours. During this period, the amplitude of volcanic tremor at NPT and throughout Kīlauea's summit area gradually increased as the summit rapidly deflated. At



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0100 H.s.t. on February 8, decreasing amplitude of continuous tremor made it possible to distinguish discrete events on the upper east rift seismic records as the summit continued to register strong tremor and deflation. By 0400 H.s.t. on February 8, eruption tremor had dropped to quiet background levels in the east rift zone.

From the morning of February 8, earthquake activity continued to taper to lower, steady levels. Through the first 48 hours of the swarm, more than 5,000 events were counted. Many of the located events clustered near Makaopuhi Crater (fig. 4*E*). The strong shallow tremor beneath Kīlauea caldera, registered at station NPT, continued for approximately 18 hours before gradually returning to background levels. As the intensity of activity near Makaopuhi Crater decreased, increased numbers of deeper (6 km and greater) earthquakes were recorded beneath the south flank.

Ka‘ōiki Earthquakes

On November 16, 1983, a M6.6 earthquake occurred in the Ka‘ōiki fault system, which lies between the summits of Kīlauea and Mauna Loa volcanoes (fig. 5). In addition to the immediate effects of this earthquake, Lockwood and others (1987) suggested that it was a precursor to the 1984 eruption of Mauna Loa. The earthquake was followed by numerous aftershocks, including seismicity extending eastward toward Kīlauea's summit caldera.

Earthquakes located between the Ka‘ōiki fault system and Kīlauea's caldera are referred to as Nāmakani earthquakes because of their proximity to the Nāmakani Paio Campground. Figure 6 shows the cumulative numbers of Nāmakani earthquakes between January 1974 and December 2001. One effect of the 1983 M6.6 mainshock is to introduce a jump in the number of Nāmakani earthquakes. After 1983 the rate of Nāmakani earthquakes remains elevated compared to the pre-1983 rate. The typical aftershock decay evident after 1983 is interrupted by a swarm of microearthquakes in mid-November 1990, 2 weeks before the December 1990 summit intrusion.

Each of the five intrusive swarms of earthquakes from December 1990 to February 1993 was preceded by a recognizable cluster of Nāmakani earthquakes. Windows for each swarm are defined to begin 1 month before and to end 1 month after the swarm. For example, for the February 7, 1993 swarm, earthquakes that occurred between January 7, and March 7, 1993, are plotted. The located seismicity for the 5 intrusive swarms is combined in figure 7. The timing of the intrusive swarms and the Nāmakani earthquakes is seen in figure 8, where epicenters are projected onto plane A–A′ shown in figure 7, and plotted as a function of time. In the case of each intrusive swarm, a cluster of Nāmakani earthquakes occurs precursory to the dike intrusion by 2 to 3 weeks.

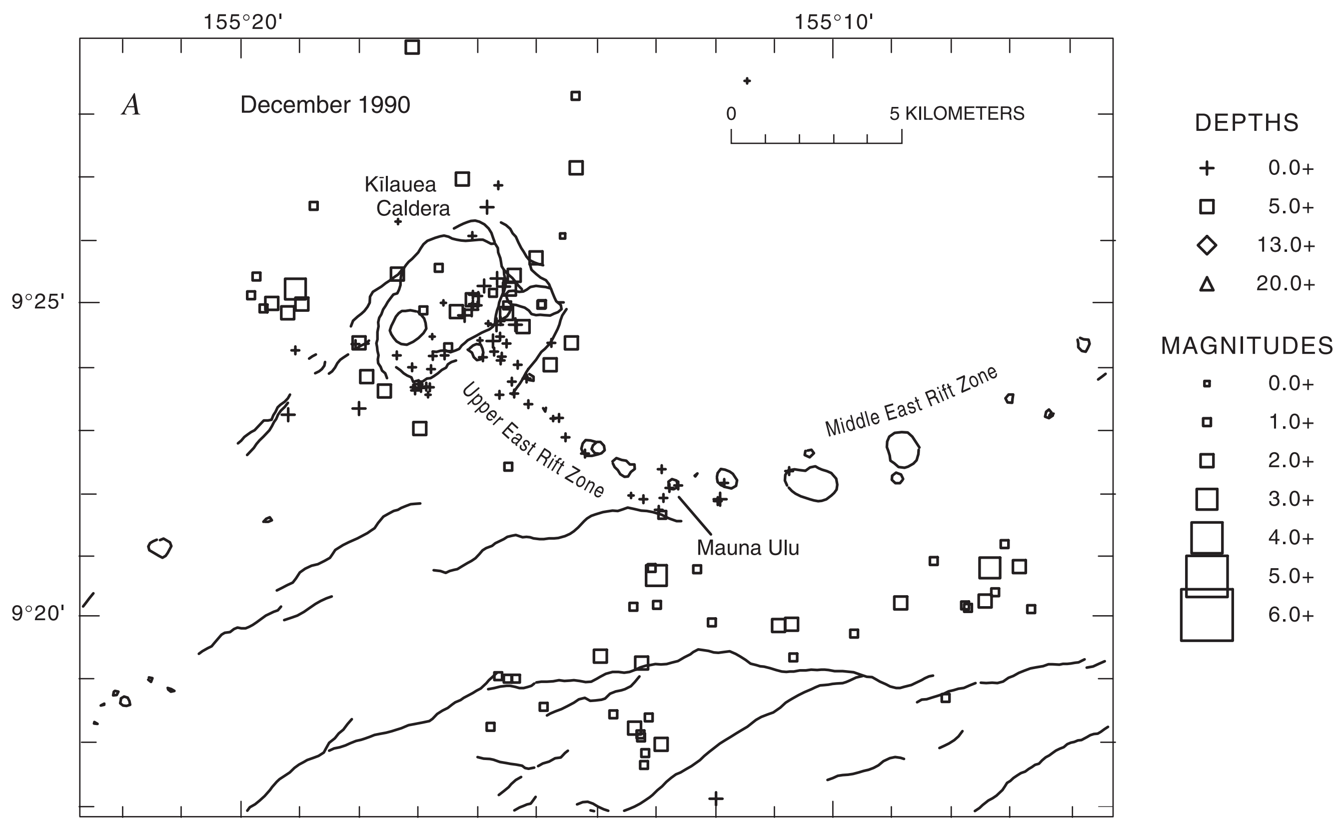
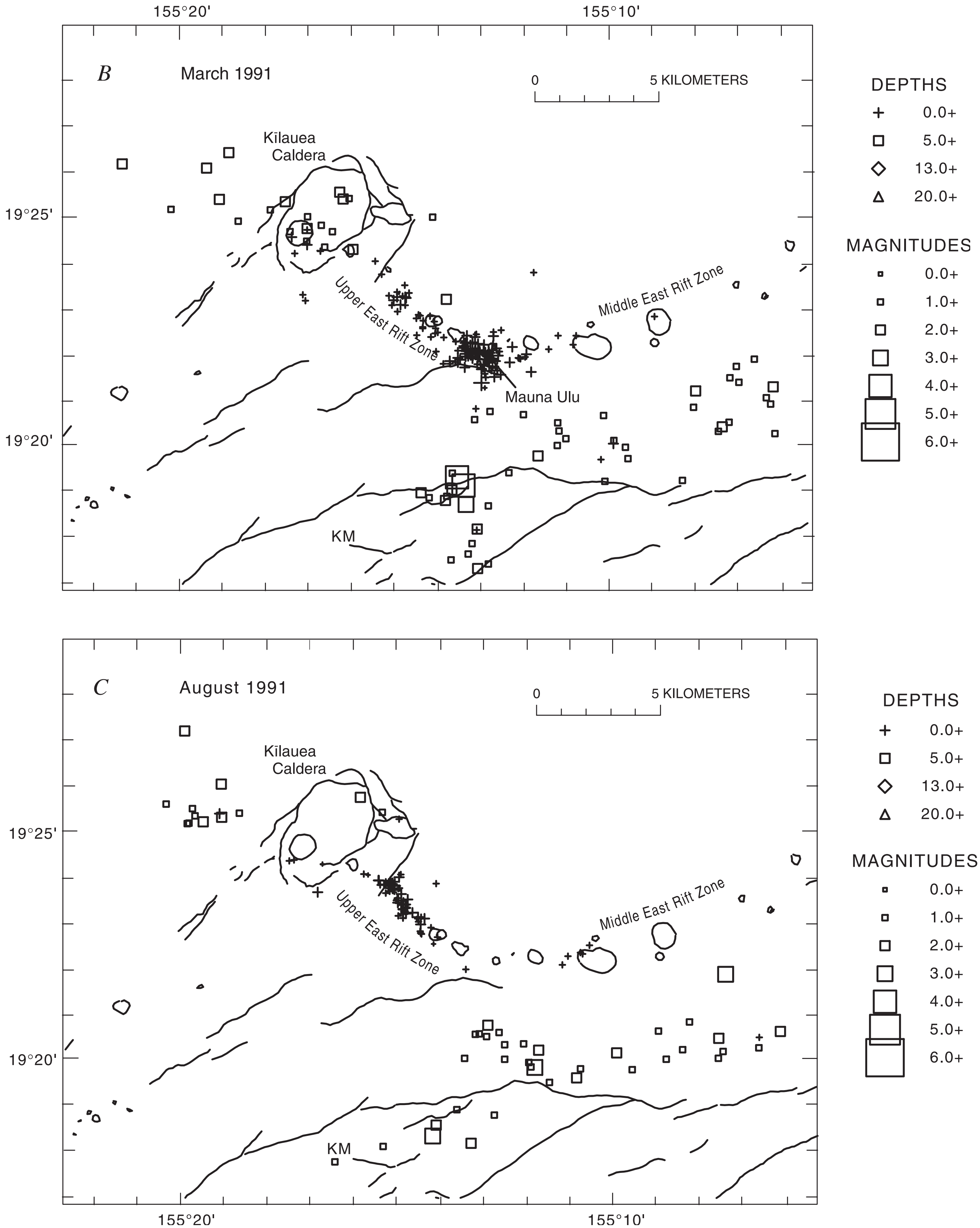


Figure 4. Seismicity, presented as earthquake epicenters coded according to earthquake focal depth and sized according to magnitude, for intrusive swarms, 1990 to 1993. *A*, December 1990. *B*, March 1991. *C*, August 1991. *D*, March 1992. *E*, February 1993.



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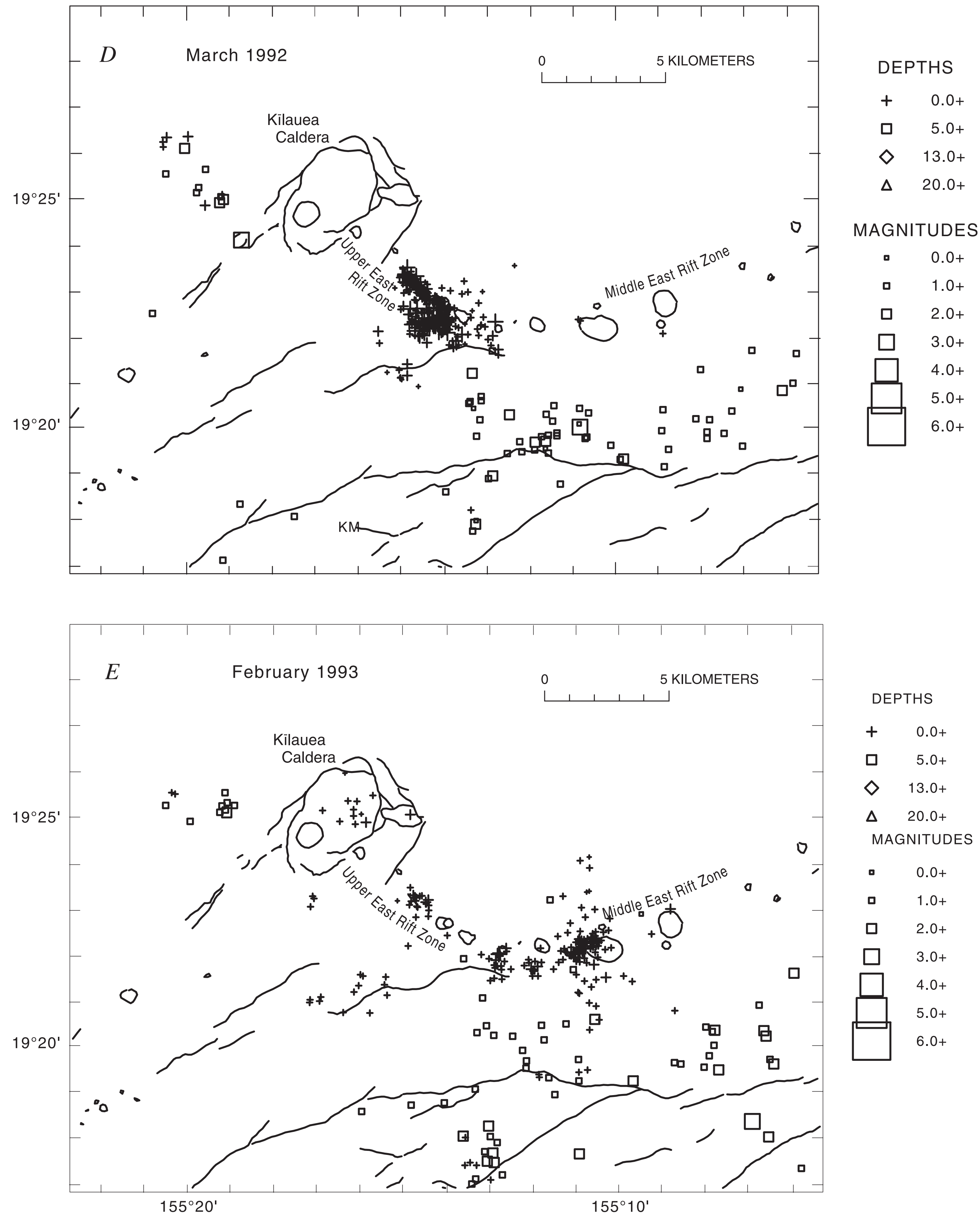

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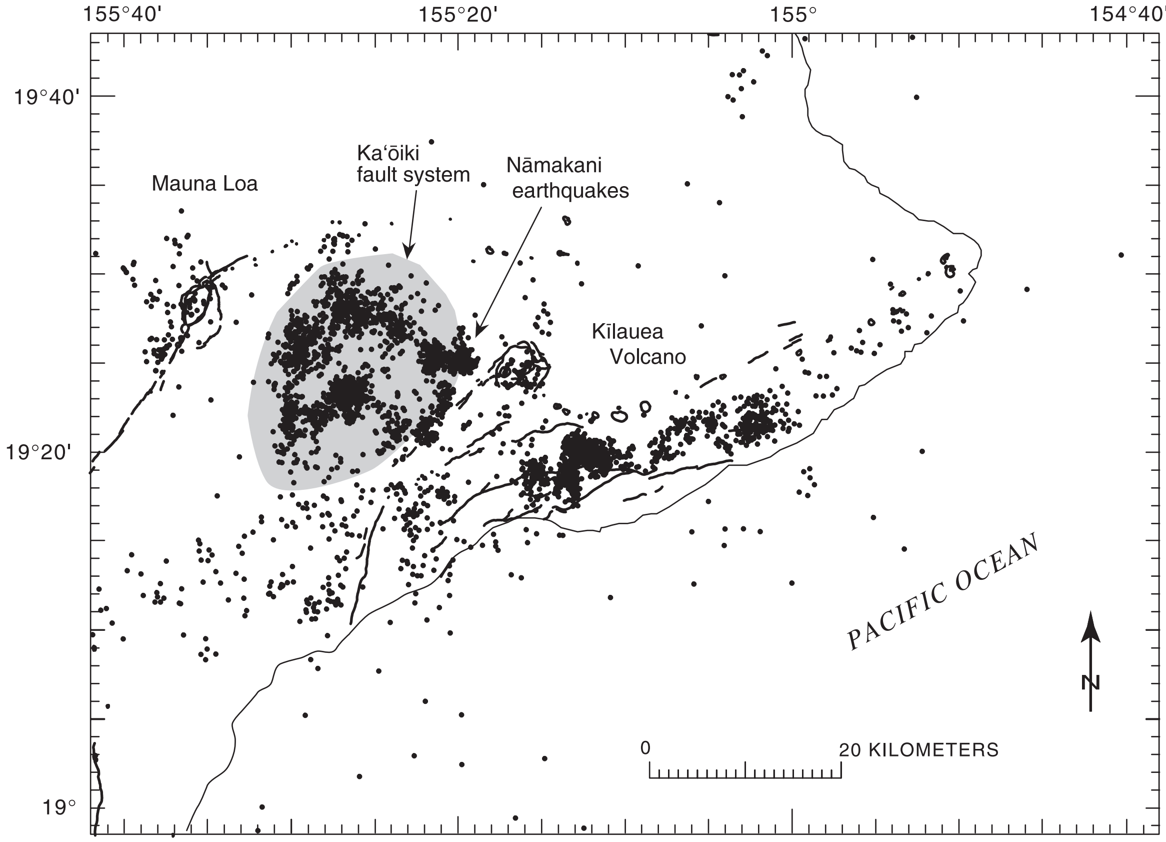


Figure 5. Southeast Hawai'i earthquakes (black dots), November 16, 1983–November 16, 1984, including aftershocks of the M6.6 November 16, 1983, Ka'ōiki earthquake. Gray area encloses Ka'ōiki fault system.

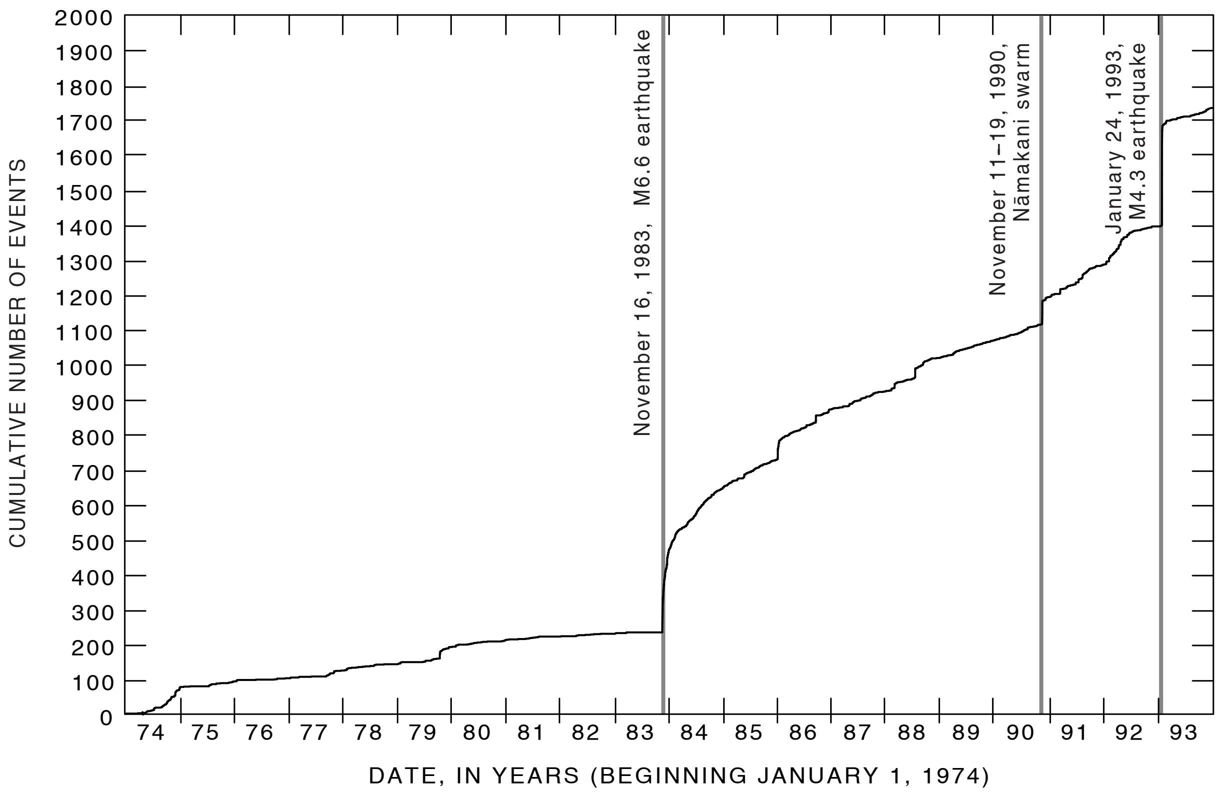


Figure 6. Cumulative number of Nāmakani earthquakes, 1974–1993.

Discussion

The composite seismicity of figure 7 is shown in cross section in figure 9. The levels of seismicity beneath the summit caldera of Kīlauea during these periods are lower than those in the neighboring regions. The caldera earthquakes shallower than 5 km are of the SPC type, and those extending to 13 km are LPC-C. The relatively aseismic region between the two sparse groups of hypocenters beneath Kīlauea's summit caldera has traditionally been interpreted as Kīlauea's principal magma-storage complex.

Seismicity clusters in different parts of the east rift zone activated during the different intrusions. Between the summit caldera and Mauna Ulu are three larger clusters of shallow earthquakes. The weakly seismic zone that separates the upper and the lower clusters of shallow earthquakes may represent an active conduit or a storage reservoir. The southeasternmost shallow cluster of earthquakes at 3-km depth is beneath the west side of Makaopuhi Crater. Swanson and others (1975) suggested that a secondary magma-storage chamber underlies Makaopuhi, so the swarm seismicity there might indicate occasional activation of this feature.

Gillard and others (1996) have examined the 1991 seismic swarms in detail using waveform-correlation techniques. This analysis allows precise relative relocation of earthquakes whose waveforms strongly correlate with waveforms of other earthquakes. In the March and August 1991 swarms, the relocated seismicity defines streaks within the rift zone at approximately 3 km below the surface, and the focal mechanisms are consistent with right-lateral strike-slip faulting between Kīlauea's caldera and Mauna Ulu. Gillard and others (1996) interpret the seismicity to define a transition between the stably active, deeper rift zone (e.g., Delaney and others, 1990) and an overlying elastic-brittle crust, not the propagating tip of a dike. The presumed increased presence of magma during the intrusions facilitated this faulting.

We see the Nāmakani seismicity in figure 9 as a cluster of epicenters west-northwest of Kīlauea's summit caldera. In cross-section, the hypocenters align along a moderately

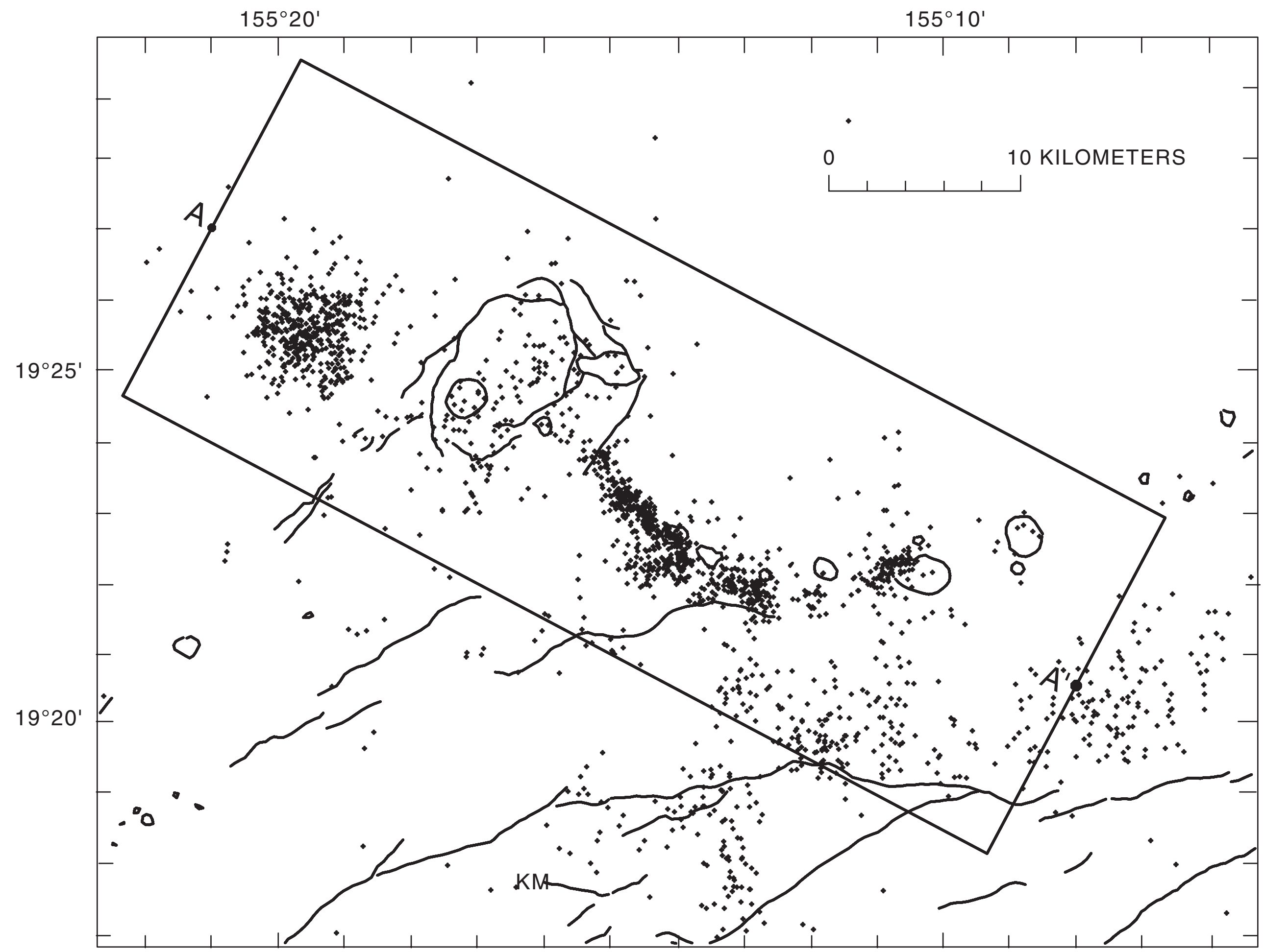
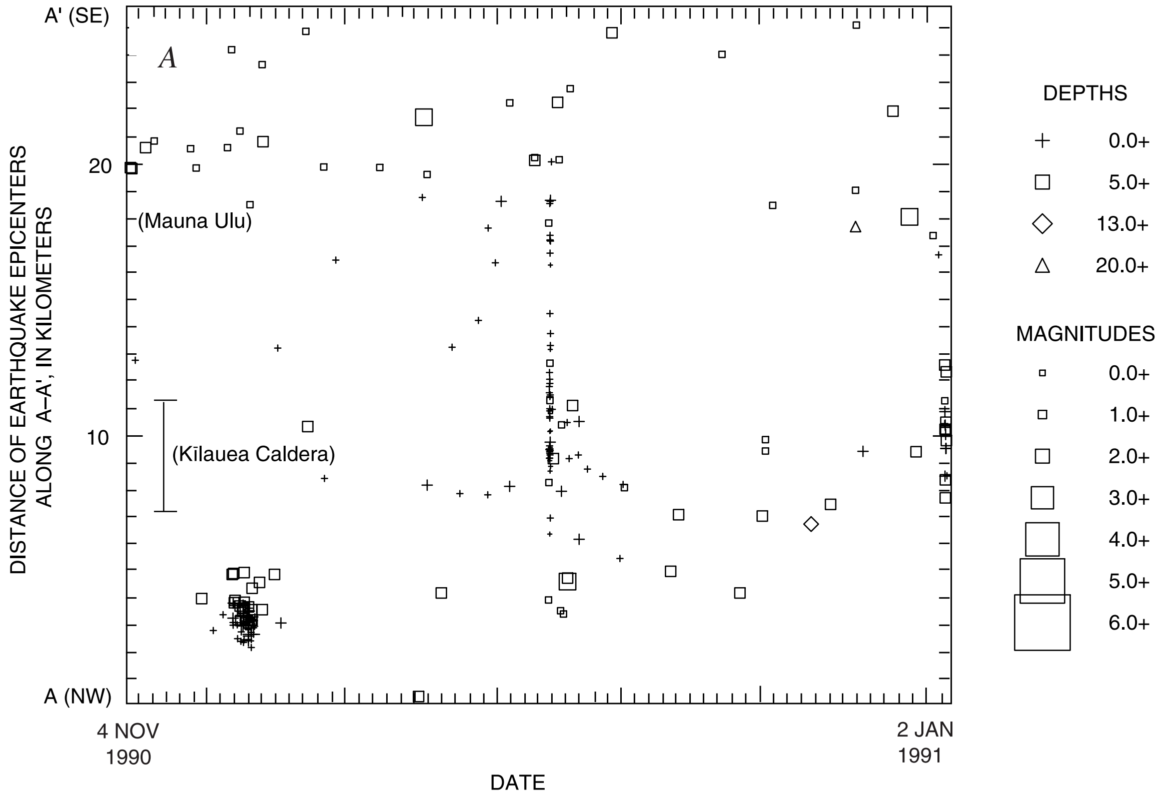


Figure 7. Composite seismicity map of Kīlauea showing epicenters of earthquakes associated with five intrusive swarm periods, 1990 to 1993 (see also figure 8). Earthquakes within box labeled A–A′ used for plots in figures 8 and 9.



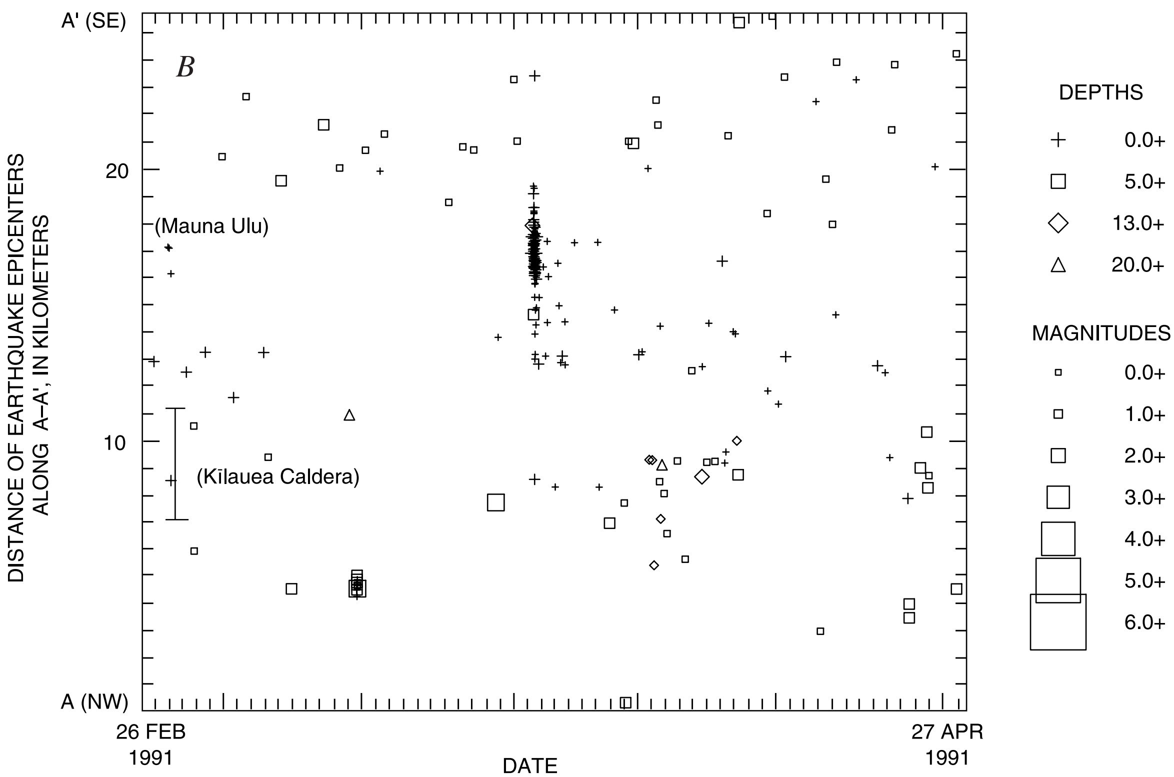


Figure 8. Distance-versus-time plots of earthquake epicenters. Symbols for geologic features as in figure 1. Earthquakes within box labelled A–A′ (fig. 7) for 2-month windows centered about five east-rift-zone intrusions. Epicenters are projected onto a plane parallel to A–A′ shown in figure 7. Epicentral symbols coded as in figure 4. Nāmakani earthquakes appear as cluster at lower left of figures, and east rift intrusions appear as nearly vertical streaks of shallow earthquake symbols. *A*, December 1990. *B*, March 1991. *C*, August 1991. *D*, March 1992. *E*, February 1993.

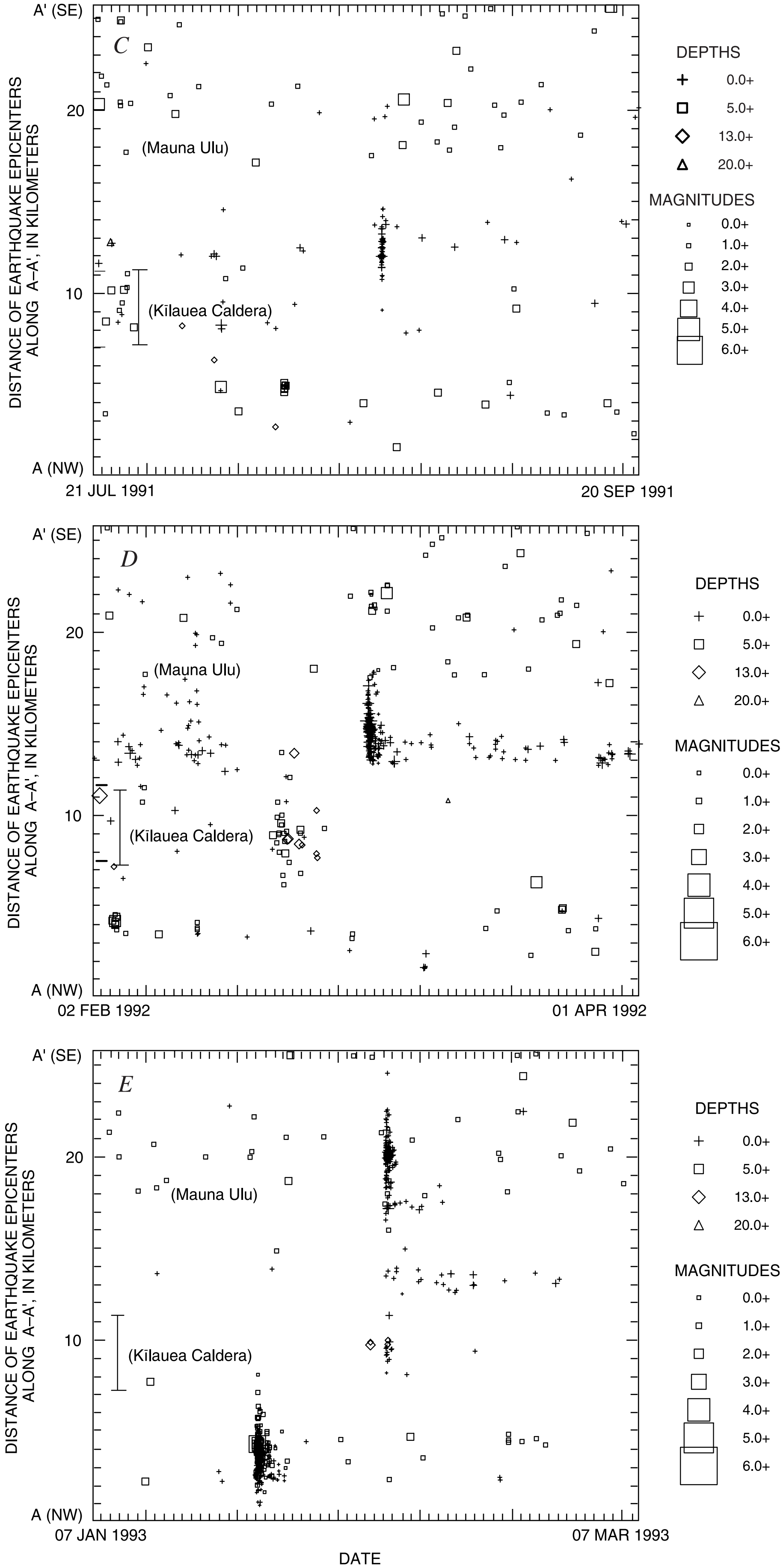


Figure 8. Continued.

southeast-dipping structure that, if projected updip toward the surface, would coincide with part of the Kaʻōiki fault system. P-wave first motions of the largest of the Nāmakani earthquakes show a nodal plane that is consistent with normal faulting along a fault dipping to the southeast at approximately 60°.

The hypocentral cross-section (fig. 9) suggests an explanation for the association between the Nāmakani earthquakes and the east-rift-zone intrusions. The predominant structure defined by the Nāmakani earthquakes is a southeast-dipping normal fault, extending to 8-km depth toward Kīlauea's caldera. The focal mechanisms of the Nāmakani earthquakes are not restrictively dip-slip, but those of the largest Nāmakani earthquakes are consistent with normal faulting. We suggest that a swarm of Nāmakani earthquakes indicates normal faulting along the southeast-dipping fault. Thus, either a relatively large Nāmakani earthquake or a Nāmakani swarm has the effect of changing stresses near Kīlauea's summit caldera. We infer that, for these stress changes to then lead to dike intrusions along the east rift zone, stress conditions in Kīlauea's summit magma-storage complex, and possibly through the east-rift-zone magma conduit, must be finely balanced.

Since 1993, additional Nāmakani earthquake sequences and east-rift-zone intrusions have occurred. In February 1996, a summit intrusion closely resembling the December 1990 intrusion took place. In January 1997, lava erupted in and near Nāpau Crater, uprift of Puʻu ʻŌʻō (Thornber, 2001). On January 27, 1998, an energetic Nāmakani sequence, with 2 M4.1 earthquakes followed by numerous aftershocks, was observed. Another M4.3 Nāmakani earthquake occurred on May 26, 1999. The pattern of Nāmakani earthquakes preceding east-rift-zone intrusions is not as clearly apparent as it was before 1994 (Okubo and others, 1996).

Conclusions

Swarms of tectonic Nāmakani microearthquakes preceded magma intrusions on Kīlauea's east rift zone from 1990 to 1993. This association, admittedly qualitative, suggests the potential to integrate aspects of Kīlauea's eruptive behavior into a broader regional context. Somewhat paradoxically, swarms or sequences of microearthquakes were directly linked

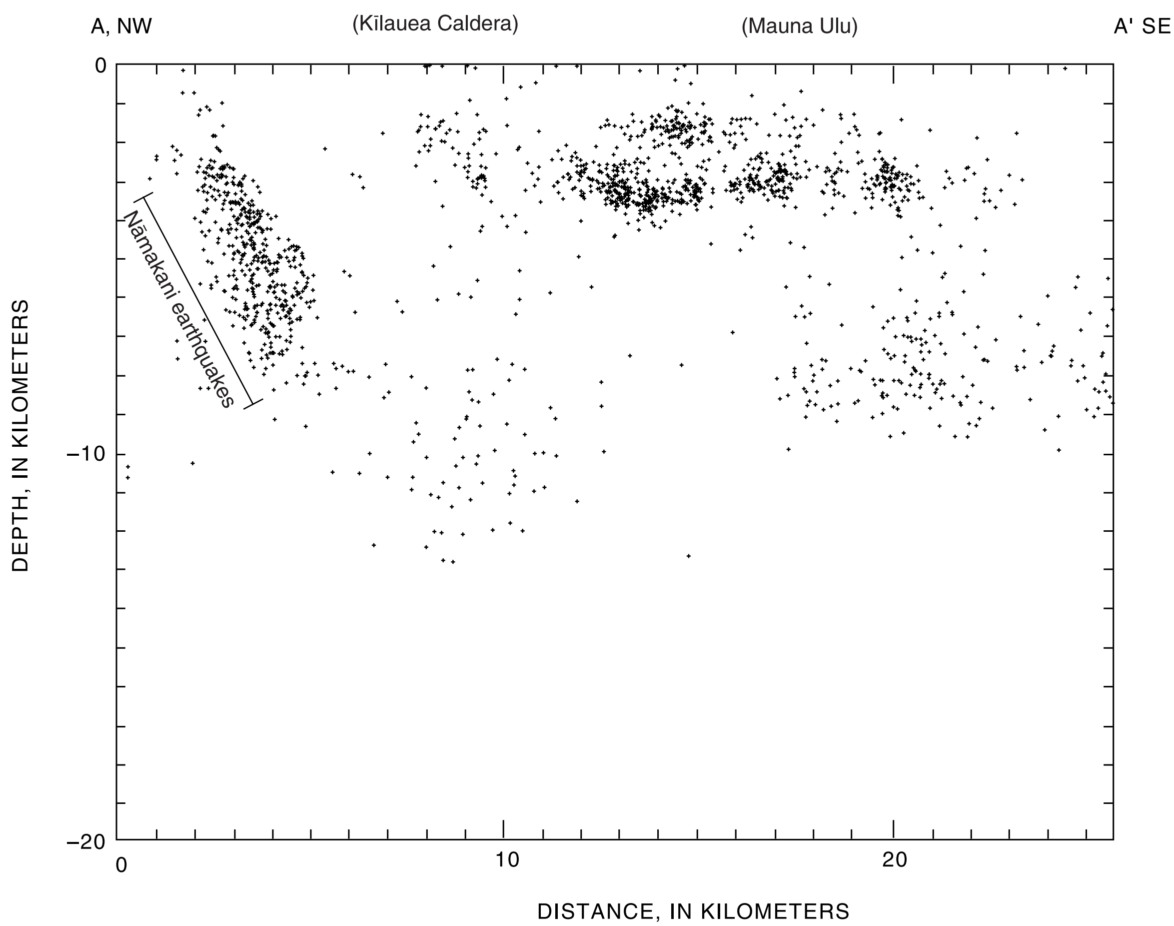


Figure 9. Hypocenters of earthquakes shown in box labeled A–A′ in figure 7, projected onto a vertical plane parallel to A–A′. The cross-section extends from the Kaʻōiki fault system (NW) to Kīlauea's east rift zone (SE).

to visible eruptive changes, but moderate earthquakes in 1983 and 1989 had no apparent effects on the eruption.

The rate of Nāmakani earthquakes increased dramatically as part of the 1983 M6.6 Ka‘ōiki aftershock sequence. Ongoing high rates of seaward displacement of Kīlauea’s south flank, and extension and subsidence of its summit caldera persist (Owen and others, 1995; Cervelli and Miklius, this volume), suggesting that continuing Nāmakani seismicity reflects extension reaching inland to Mauna Loa’s flank. If the Pu‘u ‘Ō‘ō-Kūpaianaha eruption helps fuel Kīlauea’s flank deformations, it can be expected that the Nāmakani seismicity will continue as the eruption continues. With the eruption again in a stable mode at Pu‘u ‘Ō‘ō, we have apparently lost the direct link between Nāmakani seismicity pulses and east-rift-zone intrusions.

Quantitative descriptions of the effects of the Nāmakani earthquakes remain problematic. The source depths, focal mechanisms, and low magnitudes of even the largest of these earthquakes (M4.3) are not likely to produce large surface deformations. No comprehensive and continuous geodetic monitors of Mauna Loa and the Ka‘ōiki fault system were in place in the early 1990s, when Kīlauea’s east-rift-zone eruption was adjusting back from Kūpaianaha to Pu‘u ‘Ō‘ō. Ongoing improvements in such monitors afford the possibility of more detailed modeling of future Nāmakani earthquakes and of similar interactions of tectonic and magmatic processes.

Acknowledgments

The ability to study and discuss long-term seismicity patterns and behaviors is only afforded by ongoing field maintenance and data processing and archiving performed by the electronics and seismic data analysis teams at the Hawaiian Volcano Observatory. The efforts of Robert Koyanagi, George Kojima, Kenneth Honma, Renee Ellorda, Gary Honzaki, Steven Fuke, Wilfred Tanigawa, and Alvin Tomori are appreciated and gratefully acknowledged.

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