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New Episodes of Volcanism at Kilauea Volcano, Hawaii

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Mid-2007 was a time of intense activity at Kilauea Volcano, Hawaii (see Figure 1). In June, the long-lived Pu‘u ‘Ō‘ō–Kupaianaha eruption, a dual-vent system along the east rift zone (ERZ) that has been erupting since 1983 [*Heliker et al.*, 2003], paused due to the outbreak of a new vent farther up the rift (see Figure 2). The Pu‘u ‘Ō‘ō vent collapsed following that activity, and the resulting reorganization of the magma plumbing system led to the formation of a second new eruptive vent 2 kilometers downrift of Pu‘u ‘Ō‘ō.

These events were well documented by geological, geophysical, and geochemical monitoring. This article summarizes results from these monitoring efforts and interprets the changes that have occurred at Kilauea since June 2007.

Before 17 June 2007: Setting the Stage

Kilauea's summit deflated throughout most of the sustained Pu‘u ‘Ō‘ō–Kupaianaha eruption. In late 2003, however, the summit started to inflate, accumulating 0.55 meters of extension and 0.25 meters of uplift by mid-2007. Sulfur dioxide (SO_2) emissions from the ERZ, which indicate the volume of magma degassing at Pu‘u ‘Ō‘ō, doubled in early 2005 and remained elevated through mid-2007. Both the summit inflation and the heightened SO_2 emissions suggest increased magma supply to the shallow volcanic system.

From 17 to 30 June: ERZ Activity and Aftermath

A new episode of activity began at 0216 local time (LT) on 17 June 2007, when summit tiltmeters on Kilauea began recording rapid deflation. At the same time, increased earthquake activity and ground tilt were measured along the ERZ between Pauahi Crater and Mauna Ulu (Figure 3b, time T_1), suggesting the intrusion of magma in that region. Deflationary tilt began at Pu‘u ‘O‘ō a few minutes later, indicating that magma supply there had been disrupted. Because of this deflation, Pu‘u ‘Ō‘ō began to collapse on the morning of 17 June, and within a few days parts of the crater floor had dropped as much as 80 meters.

Seismic and geodetic data suggest that over approximately the next 48 hours there were three additional pulses of intrusion to the ERZ (Figure 3b, starting at times T_2, T_3, and T_4). Between 18 and 19 June, a small eruption (area, 2211 square meters; volume, about 1500 cubic meters) occurred north of Makaopuhi crater (see Figure 2). The chemistry and temperature of the erupted lava (Figure 3a) suggest that the magma that fed the eruption came directly from Kilauea's summit without incorporating magma stored in the rift zone. At 1030 LT on 19 June (about 57 hours after the onset of intrusion), summit tilt switched from deflation to inflation, and deformation and swarm seismicity in the ERZ were minimal.

Between 20 June and 1 July, active lava was not visible anywhere on the surface of Kilauea Volcano. The combined SO_2 emission rate from Pu‘u ‘Ō‘ō and the 18–19 June eruption site declined through this time period to less than 200 tons per day (Figure 3a), and deflationary tilt at Pu‘u ‘Ō‘ō continued until 27 June.

From 1 to 20 July: Lava Returns to Pu‘u ‘Ō‘ō

Eruptive activity resumed at Pu‘u ‘Ō‘ō on 1 July, and lava had filled the crater to within 30 meters of the rim by 12 July. On 13 July, new vents appeared high on the crater walls, well above the lava lake, and webcam images recorded piston-like uplift of about 1 meter per day along the interior crater walls. Inflation of Pu‘u ‘Ō‘ō was documented by ground tilt and Global Positioning System data (GPS; see Figures 3a and 3c).

SO_2 emission rates during 1–20 July remained low. The temperature and chemistry of lava lake samples (Figure 3a) are indicative of shallow magma storage and crystallization prior to eruption, as opposed to direct transport from Kilauea's summit as is inferred for the 18–19 June eruption near Makaopuhi crater.

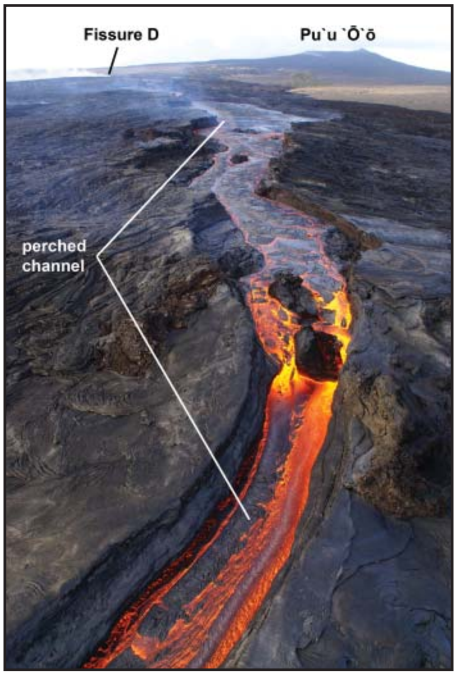

Fig. 1. View to the south of the perched lava channel emanating from fissure D, with Pu‘u ‘Ō‘ō in the background. USGS photograph by Jim Kauahikaua taken on 7 October 2007.

From 21 July to 31 October: Downrift Migration of the Eruption

Just before midnight on 20 July, tilt and GPS measurements at Pu‘u ‘Ō‘ō indicated cone deflation as well as a deformation source to the east (Figure 3c). Webcam imagery revealed draining of the Pu‘u ‘Ō‘ō lava lake, followed by glow that indicated the start of a fissure eruption on the east flank of Pu‘u ‘Ō‘ō a few minutes after midnight. The fissure system consisted of four segments (designated A–D) that extended 2 kilometers east from near the east rim of Pu‘u ‘Ō‘ō crater (Figure 3c). No unusual seismicity accompanied the new outbreak, and deformation associated with fissure opening, as seen from interferometric synthetic aperture radar (InSAR) and GPS data, is highly localized (Figure 3c), suggesting a shallow source.

Immediately following fissure opening, SO_2 emissions from the ERZ increased by

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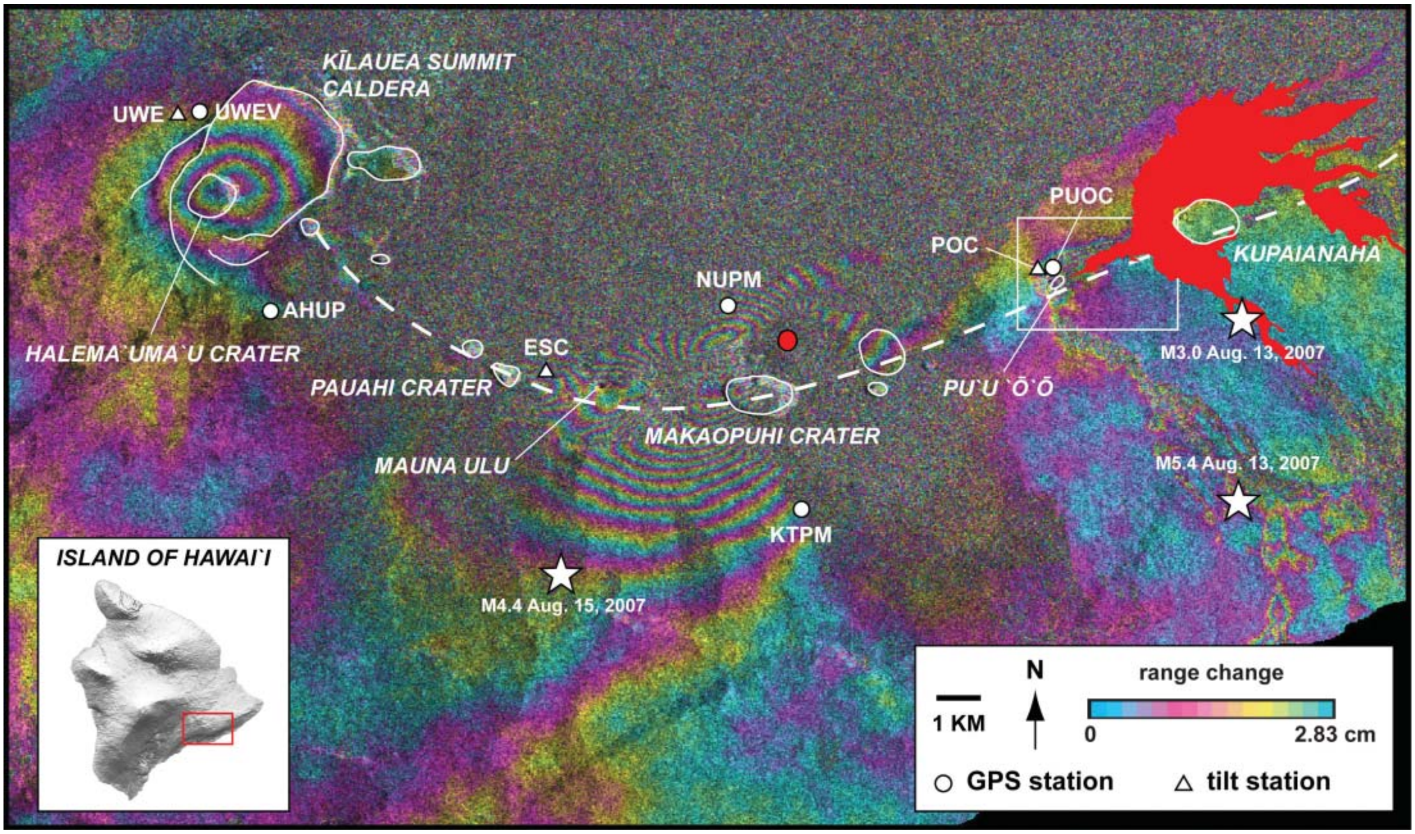

Fig. 2. Envisat interferogram spanning 12 April to 21 June 2007. Craters and other geographic features are outlined by white solid lines. Dashed white line indicates the ERZ axis. Red dot shows the location of the 18–19 June eruption. Red area shows lava erupted between 21 July 2007 and 17 January 2008. Tilt and GPS stations discussed in the text are labeled as white dots and white triangles, respectively. Earthquakes are noted by white stars. Inset shows the extent of the Figure 3c map.

an order of magnitude and, following a brief decline, rose to more than 2000 tons each day by the end of August. Lava that erupted from the fissure system was initially similar to that from the Pu'u 'Ō'ō lava lake, although a slight but steady increase in magnesium oxide content through the end of October (Figure 3a) may reflect an increasing component of Kilauea summit-derived magma mixed with rift-stored, crystallizing magma.

The erupted lava initially built a series of ponds between Pu'u 'Ō'ō and Kupaianaha that were perched as much as 15 meters above surrounding terrain. By 10 August, all eruptive activity focused on fissure D, which formed an open lava channel (Figure 1) and fed a series of northeast directed 'a'ā flows (rough-textured blocky lava) that extended a maximum distance of 6 kilometers from the vent by mid-August. Subsequent lava flows consisted of channel overflows, breakouts from the base of the channel walls, and short-lived flows fed through breaches at the end of the lava channel.

Characteristics of Intrusive and Extrusive Activity During Mid-2007 at Kilauea

ERZ intrusions in 1997 and 1999 grew in single pulses and were accompanied by relatively little seismicity, suggesting passive magma emplacement facilitated by seaward motion of Kilauea's south flank [*Cervelli et al.*, 2002; *Owen et al.*, 2000]. In contrast, the June 2007 intrusion had several distinct pulses, released relatively more seismic energy, and erupted lavas characteristic of summit-derived magma (the eruption that resulted from the 1997 intrusion was clearly derived from rift-stored magma [*Thornber et al.*, 2003]), all of which suggest forcible intrusion in June 2007. The difference in styles between the 2007 activity and past intrusions (both eruptive and noneruptive) is probably related to the inflated state of the summit magma system in 2007.

Interferograms formed from radar images acquired by the European Space Agency's Environmental Satellite (Envisat) that span mid-2007 indicate subsidence of Kilauea's summit and a butterfly-shaped pattern of uplift centered on the ERZ that is indicative of dike intrusion (Figure 2). A simple model of the deformation using a point source of volume loss at Kilauea's summit and an opening dislocation source between Pauahi and Makaopuhi craters suggests 1–2 million cubic meters of volume loss from a shallow magma reservoir near Halema'uma'u crater during 17–19 June and an ERZ intrusion volume of about 15 million cubic meters. The discrepancy in volumes introduces the possibility that magma from other sources (for example, Pu'u 'Ō'ō, where the volume of collapse was of the order of 5 million cubic meters) contributed to the ERZ intrusion.

When the magma supply to Pu'u 'Ō'ō was cut off on 17 June, the resulting collapse disrupted the local magma plumbing system. As the connection between Kilauea's summit and Pu'u 'Ō'ō was reestablished, high rates of uplift and the formation of vents on the crater walls indicated increasing pressure beneath the Pu'u 'Ō'ō cone. The 21 July fissure eruption was a response to the pressure increase. Formation of a highly efficient vent allowed increased magma flow from the summit to the eruption site and resulted in summit deflation (Figure 3a). Field measurements and SO_2 emissions suggest an effusion rate from the 21 July vent of 0.5–0.8 million cubic meters each day through the end of October, compared with about 0.4 million cubic meters each day prior to 17 June.

In addition to changing the character of Kilauea's eruptive activity, the June intrusion and eruption caused local widening of the ERZ, which increased compressive stress on the volcano's south flank. Heightened seismicity during the second half of 2007 and an unusually strong series of earthquakes between Pu'u 'Ō'ō and the coast in mid-August (Figure 2) were probably a result of this stress.

Kilauea's Current Status

Starting on 21 July 2007, lava erupting from fissure D built and fed a 1.4-kilometer-long,

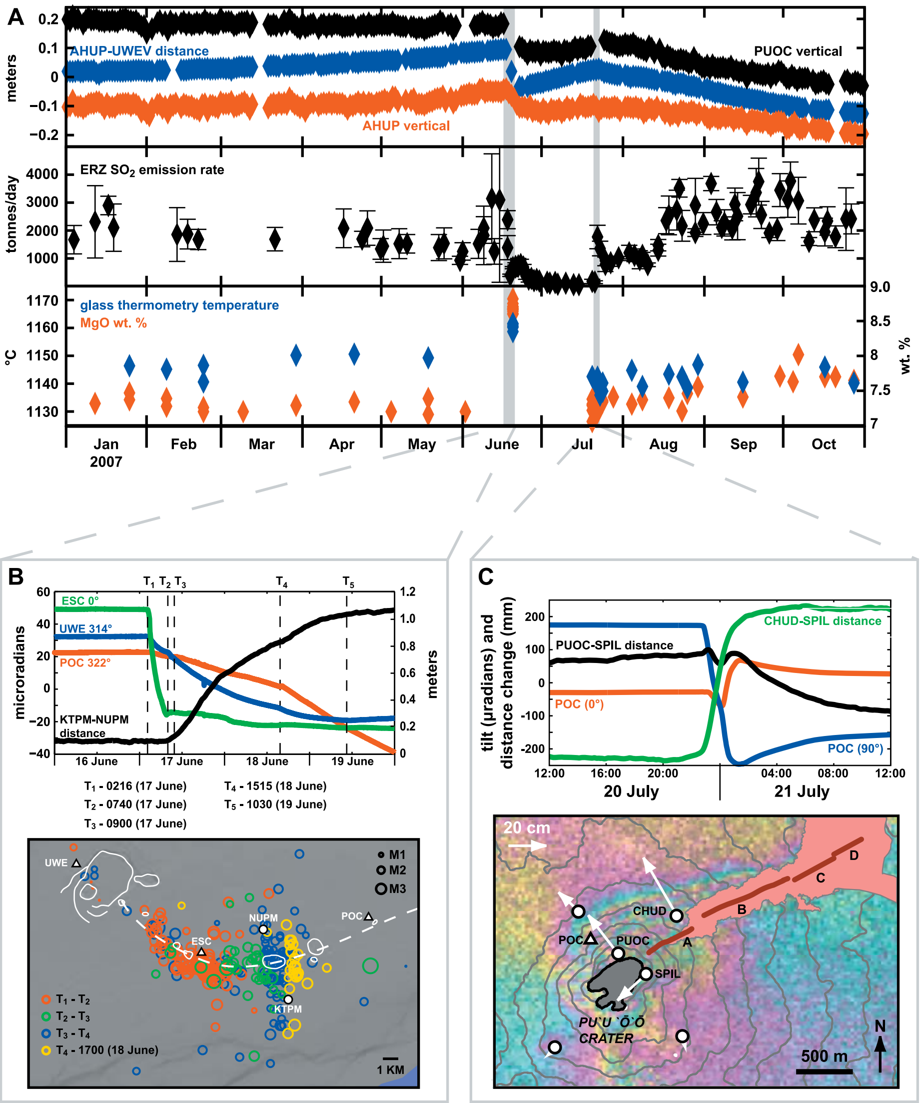

Fig. 3. Time series showing the chronology of the mid-2007 events at Kilauea Volcano. GPS and tilt station locations are shown in Figures 2 and 3c, with the same labeling conventions. (a) Daily GPS solutions, SO$_2$, and petrology data from 1 January to 31 October, 2007. Distance change between AHUP and UWEV is a proxy for summit inflation/deflation (positive/negative). Note dramatic changes in established trends of deformation, lava chemistry and temperature, and gas emissions during and following both the mid-June and mid-July eruptive events (noted by grey bars). (b) Tilt (top, left axis), 4-minute GPS solutions (top, right axis), and seismicity (bottom; circle size and scale in upper right indicate earthquake magnitude, and color indicates timing) during June 2007 ERZ intrusion and eruption. Times are Hawaii Standard Time (UTC minus 10 hours). Components of tilt are in degrees, with the positive tilt toward that azimuth. The map coverage and symbols are as in Figure 2. Note the downrift progression of seismicity and correlation with changes in deformation over time, both indicating the propagation of a dike from Kilauea's summit to east of Makaopuhi crater during 17–19 June. (c) Tilt and 4-minute GPS solutions (top) from Pu‘u ‘Ō‘ō during a 24-hour period spanning 20–21 July. Map (bottom) shows the interferogram from Figure 2 with 10-meter topographic contours, GPS and tilt station locations (symbols are as in Figure 2), GPS horizontal displacements (white arrows), fissure segments (red lines), and lava erupted after 21 July (red). Note the high rate and magnitude of the deformation that preceded and accompanied the 21 July fissure eruption.

northeast directed open channel (Figure 1). Frequent overflows from the edges of the channel built levees that elevated the lava stream up to 45 meters above the pre–21 July ground level. From 21 November 2007 to early January 2008, however, the channel has been mostly abandoned, with lava building a series of shields to the southeast of the fissure. About 3 weeks ago, one of the shields sent a lava flow to within a few hundred meters of the Royal Gardens subdivision (segment of lava flow extending farthest southeast in Figure 2). Although the subdivision was mostly deserted after lava inundated and isolated the area in the 1980s and 1990s, there are still homes standing and one permanent resident. The lava flow stagnated before reaching the subdivision, but the current shield-building activity continues to threaten the region.

Kilauea's summit has continued to deflate slowly since 21 July. Although gas emissions and observational evidence suggest a subtle decrease in effusion rate since the end of October, the ongoing extrusion from fissure D and the persistence of summit deflation imply a strong connection between the summit magma system and vent, so we expect erupted lavas to show an increasing component of summit-derived magma over time. The new eruption site has replaced Pu‘u ‘Ō‘ō as the locus of lava effusion, and is likely to remain active for months to years.

The lava poses no immediate threat to communities on the island of Hawaii (besides the mostly empty Royal Gardens subdivision), although the situation may change if the character of the eruption allows for long lava flows fed by tubes and directed at populated areas [*Kauahikaua*, 2007]. Updates, maps, live webcam views, and images of the most recent activity are available at http://volcano.wr.usgs.gov/hvostatus.php.

Acknowledgments

The response to the mid-2007 activity of Kilauea Volcano was a team effort and would not have been successful without the hard work of colleagues at the U.S. Geological Survey's Hawaiian Volcano Observatory. We acknowledge collaborations with Stanford University and the Pacific GPS Facility at the University of Hawai‘i on GPS results. Kristine Larson (University of Colorado, Boulder) assisted with kinematic GPS processing. The European Space Agency provided rapid access to Envisat radar data through Cat-1 project 2765. The Pu‘u ‘Ō‘ō GPS network was supported by a NASA New Investigator Program grant and aided by equipment loans from Ben Brooks (University of Hawai‘i, Manoa). Dan Dzurisin, John Power, and Gordon Keating provided constructive and timely reviews.

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MEETINGS

Converting Raw Data Into Ecologically Meaningful Products

Data-Model Assimilation in Ecology: Techniques and Applications; Norman, Oklahoma, 22–24 October 2007

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A U.S. National Science Foundation workshop brought together more than 40 researchers from different disciplines to discuss applications of data assimilation techniques in ecology, define major scientific questions to be addressed, and identify future research challenges.

The field of ecology has become a data-rich enterprise, due largely to rapid development of measurement sensors and long-term accumulation of data from research networks. With the implementation of the National Ecological Observatory Network (NEON), a network with different kinds of sensors at many locations over the nation, large volumes of ecological data will be generated every day. There will be an unprecedented demand to convert the massive raw data into ecologically meaningful products using data assimilation techniques.

Data assimilation is a technique that combines observational data into ecological models to improve ecological forecasting. Data assimilation becomes a valuable tool to improve model parameterization, choose between alternative model structures, better design sensor networks and experiments for data collection, and analyze uncertainty of ecological forecasts.

Applications of data assimilation in ecology have been made in recent years. In this workshop, for example, one study evaluated how the distribution and abundance of species were influenced by climate and land use change using a Bayesian hierarchical approach. By integrating observed net ecosystem carbon exchange (NEE) and a measure of surface reflectance into an ecosystem carbon model with a Kalman filter method, it was possible to retrieve complete estimates of carbon stocks and fluxes, with errors, for Arctic tundra. Growth, mortality, and NEE estimations at Harvard Forest (an ecological research site affiliated with Harvard University, Cambridge, Mass.) were improved using an optimized ecosystem demography model.

Also presented at the workshop was a study that used a deconvolution method to partition soil respiration into contributions by plants with different pathways of carbon fixation during photosynthesis (C_3 forb and C_4 grass) and other sources. In addition, a simplified analytical model predicted that reduced maximum evapotranspiration (ET_{max}) results in longer soil moisture memory and an out-of-phase relationship between rainfall and soil moisture variations.

One presentation highlighted how regional streamflow in Australia was simulated using a three-dimensional variational assimilation approach. Several researchers discussed advancements in understanding uncertainty related to measurements and optimization methods on model prediction. Another important application discussed at the workshop involved how to extract information from manipulative experiments in order to advance predictive understanding.

The workshop also highlighted research challenges. One major challenge, for example, is how to get the community ready within 5–10 years for ecological forecasting using NEON data. It is urgent to develop our data assimilation capability so as to advance ecological understandings and generate