COOPERATOR REPORT TO HAWAI`I VOLCANOES NATIONAL PARK

Volcanic Hazard at the Summit of Kīlauea: June 29, 2018 Update

U.S. Geological Survey

Introduction

This document is a guide for understanding current activity and hazard at and around the summit of Kīlauea Volcano. Here, we summarize activity from late April through the present, detail possible future outcomes, and review hazards associated with these outcomes. Few processes outlined below are known sufficiently well for us to be able to assign quantitative probabilities to possible future events. Instead, we rank future possibilities in qualitative terms of likelihood based on our understanding of current data. We stress that our understanding of Kīlauea and the current eruption is continually evolving as we obtain new information and that our analyses may change in response.

Current activity

In a general model of the 1983-present eruptions of Kīlauea, magma from the mantle rises beneath the summit, passes through the magma storage system, and ultimately exits the summit towards the East Rift Zone (ERZ). If the rate of magma evacuation towards the ERZ exceeds the rate of magma supply to the summit, the reservoir depressurizes ("deflates"), and vice versa. This causes subsidence of rock in and around Kīlauea Caldera.

Deflation of Kīlauea's shallow summit magma reservoir began in early May and continued at a near-constant rate through the middle of the month. Deflation was triggered by the intrusion of magma into Kīlauea's lower ERZ, and also possibly changing conditions in the rift itself which have enabled increased rates of magma storage (for instance due to rift opening associated with the M6.9 earthquake). Reservoir deflation caused the floor of the caldera to subside at a rate of 6-8 cm/day (2-3 inches/day) near the Overlook vent within Halema`uma`u, and the lava lake to drop out of sight around May 10, more than 320 m (1,000 ft.) below its high point in late April. Deflation and subsidence stressed the rock in and around the caldera, causing more than

800 earthquakes during the first two weeks of May, and withdrawal of the lava lake destabilized the Overlook vent, causing rockfalls which produced short-lived ash emissions.

More powerful explosions accompanied by ground slumping and ash emission began on May 16. The most notable explosions – and the type discussed here – have produced relatively high levels of ground shaking, are apparently associated with abrupt pressurization of the magma reservoir, and through late May emitted relatively vigorous ash plumes. We here refer to these as *Collapse/Explosion (CE) events*.

Early CE events (before late May) ejected ash and gas to heights above 25,000 ft. and large (ballistic) fragments tens of centimeters in size to the area immediately surrounding the vent (Figure 1). Observations and preliminary models suggest that these explosions may have been caused not by interaction of magma with groundwater, as previously believed to have occurred at Kīlauea in 1924, but rather by exsolution, expansion, and release of gases which were dissolved in the magma. CE events have occurred semi-regularly with repose periods (time between events) of roughly 1/2 to 2 days. Seismicity increases in the hours preceding explosions, leading to cycles of earthquakes that are felt in the summit area (Figure 2).

Figure 1: Parking lot of the former Halema`uma`u Overlook (closed since 2008) taken on June 8, 2018, showing changes due to 2018 explosive eruptions. The rocks were ejected from the vent as ballistic projectiles – those in the median (center of the photo) in both 1924 and 2018, and those in the parking bays (left and right) in 2018. The gray color is due to 2018 ash, which coats the parking lot and surrounding areas to a depth of 2-4 centimeters (less than 1.5 inches). Large cracks and uplifted blocks are due to stresses and slumping associated with the widening of Halema`uma`u crater.

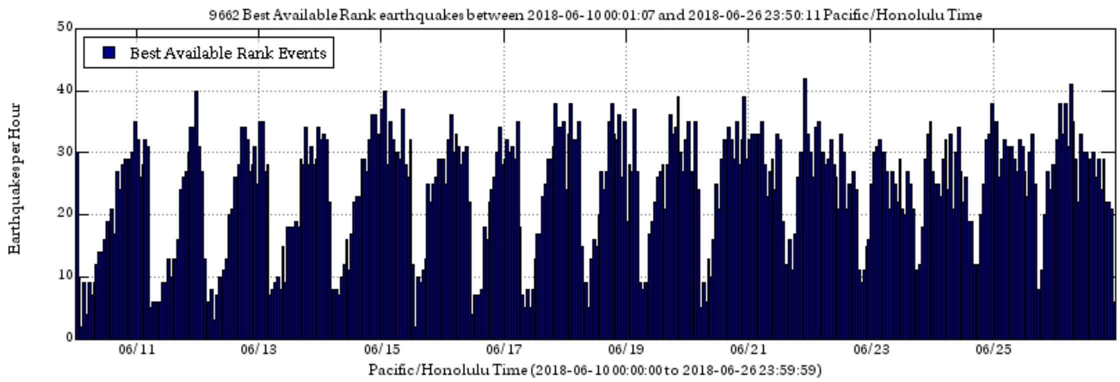

Figure 2: Number of earthquakes recorded per hour at the summit of Kīlauea from June 10 to June 26. A clear pattern of high and low seismicity rates is evident. Most of these earthquakes are far too small to be felt by nearby residents.

The mechanism producing CE events is not well understood. We infer that withdrawal of magma towards the ERZ continually works to reduce pressure in the shallow reservoir. When the reduction in pressure becomes too great, the rock that forms the floor of Halema`uma`u and parts of surrounding Kīlauea Caldera[1] slump down into the shallow magma reservoir in a CE event. The rock which slumps down into the reservoir replaces magma that has migrated into the ERZ, and abruptly increases reservoir pressure (as measured by ground deformation instruments). Similar processes have been observed during caldera formation at other volcanoes (see “Historical analogs” section).

In this way, magma evacuation is accompanied by relatively non-hazardous slumping and enlargement of Halema`uma`u, rather than sudden large-scale collapses and more powerful explosions. Since the beginning of May, the crater’s volume has more than quadrupled (Figures 1 and 3), and since May 29, a GPS station near the north rim of Halema`uma`u crater dropped more than 100 meters (330 ft.) during CE events.

At the end of May, collapse of rock from surrounding crater walls blocked the Overlook vent (which formerly contained the lava lake) and changed the character of summit activity. Since then, background gas emissions at the summit have greatly decreased, CE events generally have produced only weak ash plumes that do not rise higher than 6000 feet above the crater rim, and no ballistic fragments are known to have been ejected. Although the plumes have become less vigorous, these more recent events have been preceded and accompanied by larger amounts of seismic shaking, and reservoir pressurization (as measured by ground deformation instruments) during the events has increased. The character of subsidence at the summit has also changed, with deformation becoming more localized around Halema`uma`u

[1] For the purposes of this document, “Kīlauea Caldera” refers to the obvious pre-existing topographic depression at the volcano’s summit, which has about half the diameter of the complete caldera. The larger Kilauea caldera formed about 500 years ago. To date, all evidence suggests that the current activity is confined to the topographic depression and is not activating the larger structure.

crater but occurring at a higher rate. At the current time, subsidence of the caldera continues at a high rate due to magma withdrawal from the Halema`uma`u magma reservoir.

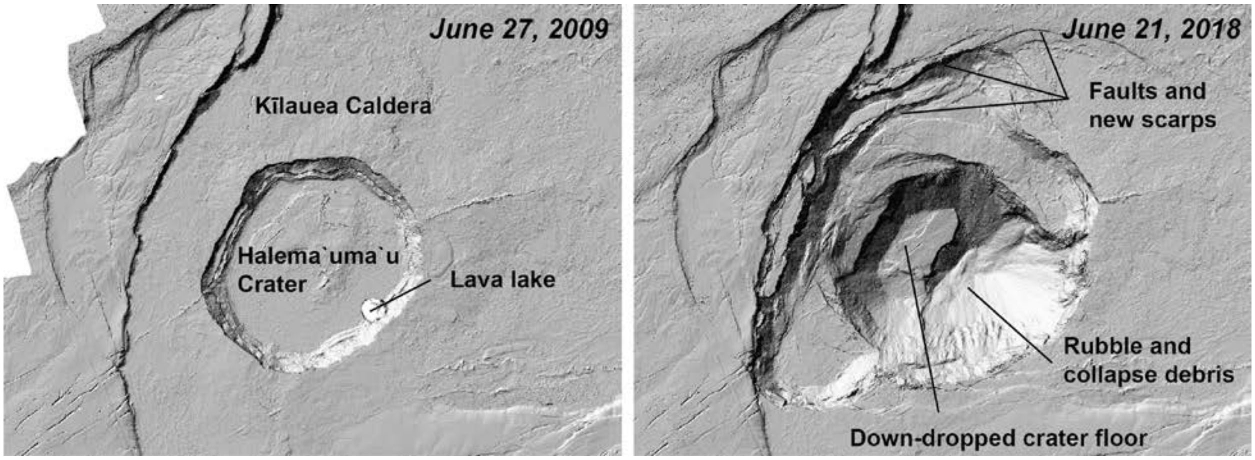

Figure 3: Comparison of the topography of Halema`uma`u Crater in 2009 (left) and on June 21 2018 (right). The 2018 data, from a photogrammetric survey of Kīlauea's summit by the U.S. Department of Interior Unmanned Aircraft Systems' (UAS) Kīlauea response team, show the topography of Halemaʻumaʻu as of June 21. Extensive cracking and faulting has occurred around the crater, and the crater has enlarged through collapses of wallrock. The depth of the crater floor has increased by more than 350 meters (1100 feet) since early May. Limited UAS flights into the summit area are conducted with permission and in coordination with Hawaiʻi Volcanoes National Park to collect quantitative and qualitative data needed for updated hazard assessments, all of which are shared with emergency managers. Image courtesy of the U.S. Geological Survey and Office of Aviation Services, Department of the Interior, with support from the Hawaiian Volcano Observatory and Hawaiʻi Volcanoes National Park.

Possible outcomes

Ground subsidence will continue for as long as magma is withdrawn from the summit reservoir(s) at a rate exceeding the rate of magma supply, but the rate, style, and geographical extent of the subsidence – along with associated hazards – may vary. The scenarios below are considered under the condition of continued net magma withdrawal. For a discussion on how long this might occur, see the later section “Time frames of activity”.

#1: MOST LIKELY OUTCOME FOR THE IMMEDIATE FUTURE (UP TO TWO MONTHS)

The most likely activity for the immediate future is continued subsidence of Kīlauea Caldera, episodic slumping into a widening Halema`uma`u crater, felt earthquakes (some large enough to be damaging), and small to intermediate ash plumes that remain below 10,000 feet above sea level. As the reservoir deflates, cracking and slumping is gradually engulfing a broader extent of Kīlauea Caldera (as observed in high rates of ground deformation and propagating cracks around Halema`uma`u); this process will likely continue to enlarge Halema`uma`u and may involve larger slump blocks than previously. This activity is impressive in scale—and may ultimately involve much or even all of the current Kīlauea Caldera—but it need not necessarily involve new or more hazardous explosive activity.

Hazardous explosive activity cannot be ruled out, however. It is possible that a large section of the Halema`uma`u wall could abruptly collapse into the crater. Because a broad region E and NE of Halema`uma`u is currently deforming, it is difficult to predict how large such a collapse might be or its impact on the explosion hazard. Most likely, such an event would generate only strong seismic shaking and a robust ash plume.

Should activity continue as described, primary hazards of concern are:

- Damaging earthquakes (potentially exceeding equivalent M5). Hazards associated with earthquakes are detailed more fully in the section "Potential Hazards"
- Ash plumes, ashfall (associated with CE events and large rockfalls)
- Large and sudden collapses into the expanding Halema`uma`u crater
- Ground cracking and continued rockfall activity along steep caldera walls
- Vog (although sulphur dioxide output is approaching low pre-2008 levels)

#2: LESS LIKELY OUTCOMES FOR THE IMMEDIATE FUTURE (UP TO TWO MONTHS)

Several mechanisms could change the nature of activity and associated hazards. <u>These are considered less likely but cannot be ruled out</u>. The likelihood of some of these processes may increase if the net rate of magma outflux from the summit increases.

Below we consider the possibility of 1) more hazardous explosions occurring during ongoing subsidence and enlargement of Halema`uma`u, and 2) sudden collapse of the larger caldera system. This list may not include all possible future outcomes and hazards.

1. *Larger explosion during ongoing subsidence in and around Halema`uma`u*. Activity could become more hazardous over short time scales. This could be triggered in one of several ways, including a) rapid pressure change or other perturbation of the reservoir, b) opening of new pathways between the reservoir and the surface, or c) interaction of magma with groundwater. Rapid pressure change could be caused by a large, sudden landslide from the crater's steep, faulted rim; alternatively, sudden larger-scale collapse of rock into the reservoir could perturb reservoir pressure above levels seen during previous CE events. New pathways could be formed by explosive ejection of rubble in the vent or downward propagation of cracks. Groundwater could enter the magmatic system at sufficient rates to produce steam-driven explosive eruptions. Some of these mechanisms could be preceded by detectable changes in monitoring data, but others could happen with no warning. If larger explosions do occur their style and magnitude cannot be predicted; it is possible that they could produce more ballistics and ash, and possibly also pyroclastic surges (defined below).

2. *Sudden collapse of the broader caldera system and catastrophic failure of high caldera walls*. Even less likely but more hazardous scenarios exist. Large explosive eruptions

have occurred in Kīlauea's past after caldera formation or during the last stage of its formation. It is possible that these eruptions were triggered by rapid collapse of broad regions of the caldera along caldera-bounding faults due to withdrawal of large quantities of magma from the summit storage system. Based on our understanding of the magmatic system, this activity should be preceded by significant changes in earthquake activity and ground deformation. At this time, satellite radar data show that high rates of deformation are concentrated in a well-defined area bordered by caldera-boundary faults on the west and south and on the east and northeast along a line roughly 600-900 meters (yards) from the caldera walls. These data do not suggest that extensive deformation is occurring outside of the caldera. Additionally, we currently see no evidence that major caldera-bounding faults are moving, although some cracks have been detected that probably result from ground shaking. Additional hazards associated with rapid, broad-scale caldera collapse could include high lava fountains and larger and more dangerous explosions producing pyroclastic surges (defined below). *However, we emphasize that current data do not suggest that a larger, sudden collapse scenario is likely at present.*

Historical analogs

For additional insight into possible outcomes we can examine past scenarios at other basaltic volcanoes. While every eruption is unique, these events can help inform our thinking about the current situation at Kīlauea. Collapses of summit calderas – caused by the lateral subsurface removal of magma from the underlying storage reservoir rather than the explosive removal of magma into the atmosphere – have been observed in human history only a handful of times. Examples include eruptions at Fernandina (Galapagos; 1968), Tolbachik (Russia; 1975-1976), Miyakejima (Japan; 2000), Piton de la Fournaise (Réunion Island; 2006-2007), and Bárdarbunga (Iceland; 2014-2015).

Each of these historical collapses were preceded by flank eruptions/intrusions similar to what is occurring in the Lower East Rift Zone (LERZ) at Kīlauea. Moderate to large summit explosions at Miyakejima and Fernandina produced widespread ashfall and ballistics up to 2 km (1.2 miles) from the vent, as well as cool, slow-moving pyroclastic surges at Miyakejima (this unusual type of flow was not hazardous) and potentially-deadly high-velocity surges at Fernandina.

As at Kīlauea, various combinations of summit explosions, deformation, and earthquake activity often occurred in repeating cycles during these episodes at other volcanoes; these observations have been interpreted as indicative of piecemeal caldera subsidence over a period of days to months. Collapse volumes ranged widely from 0.1 to 2 km^3 (0.02 - 0.5 cubic miles), compared to roughly 0.3 km^3 of collapse (as of June 21) at Kīlauea. These caldera collapses were all largely controlled by pre-existing caldera bounding faults and did not significantly enlarge pre-existing caldera structures.

Potential hazards

For both scenarios, primary hazards are due to earthquakes and explosions. These hazards are closely related but here we address them separately.

1. **Earthquakes and ground cracking**. During recent weeks, earthquakes at Kīlauea's summit have occurred in swarms associated with CE events.

    A. *Earthquake swarms.* As many as 40 earthquakes per hour have been recorded during earthquake swarms preceding CE events (Figure 2). Most of these are small and cannot be felt by people, but magnitude 3 and larger earthquakes do occur at increasing rates through the course of individual swarms (Figure 4). Overall, more than 500 earthquakes per day have been recorded in the Kīlauea summit region during recent weeks. Felt event rates have exceeded 30 earthquakes per day at and around the summit.

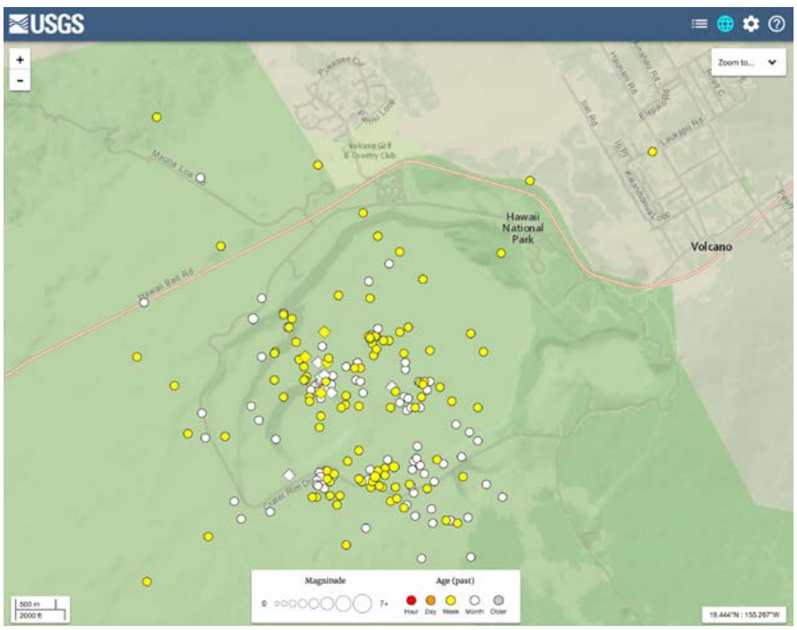

Figure 4: Map location of earthquakes with magnitude 3 and greater at the Kīlauea summit from June 1 to June 15, 2018.

    B. *Collapse/Explosion (CE) Events*. Energy release during CE events is equivalent to earthquake magnitudes of low- to mid-magnitude-5. These types of events emit most of their energy at low frequencies and so are not felt as strongly as typical non-volcanic M5 earthquakes. Regardless, shaking can be strong and possibly damaging near the summit.

    C. *Other tectonic earthquakes*. Strong earthquakes can occur at any time, and the risk of these events is larger now due to ongoing stress changes in and around the caldera. These earthquakes will not necessarily occur during swarm seismicity or in association with CE events, may be large, and may happen outside of the caldera.

The exact location and timing of earthquakes cannot be predicted, but if recent patterns continue, earthquake activity will increase gradually over the course of an individual swarm, culminating in a CE event. After these events, earthquake activity will drop rapidly before gradually increasing again. However, earthquakes can occur at any time.

Historically, high rates of earthquake activity were observed during the 1924 summit subsidence and explosions. However, based on known historical records, no earthquakes related to summit subsidence caused significant damage in 1924. In 1960, earthquakes occurring in the summit area during subsidence caused some minor damage in Volcano.

Residents should continue to be prepared for strong seismic shaking and, in the vicinity of the caldera, ground cracks (see https://www.shakeout.org/hawaii/)**.** During earthquakes it is wise to drop, cover, and hold on. With over six weeks of heightened seismic activity, structures are in some cases already weakened from strong earthquakes. Ongoing earthquake activity can damage these further, especially close to the summit in the National Park and Volcano Golf Course areas. Ground cracks, rockfalls, and damage to roads, trails, rock walls, buildings, utilities, and water pipes may also occur.

2. **Gas emissions**. Emissions of sulfur dioxide (SO_2) from Kīlauea's summit are currently relatively low, possibly due to collapses into the vent in late May which have likely inhibited gas escape and discouraged the exsolution of gases from shallow magma (currently, most of Kīlauea's SO_2 is emitted at the LERZ eruption site). Gas emissions remain a hazard at the summit, however. If larger explosions occur that tap magmatic gases, surges in SO_2 emissions may occur. SO_2 emissions may also increase as subsidence progresses and may remain elevated after the end of the eruption. These emissions can produce vog, which is carried to downwind communities.

3. **Explosions and high lava fountains**. Explosions at Kīlauea's summit during 2018 have produced only minor ashfall and limited ballistic deposits. As described above, based on our current understanding, explosive activity that is larger and more dangerous than what has already occurred in 2018 is not considered likely at this time. However, it is impossible to rule out such activity, so here we detail some of the associated hazards as currently understood. These hazards can currently be grouped into four types which occur in distinct geographical zones: A) ballistic projectiles, B) ashfall, C) fallout from high lava fountains, and D) pyroclastic surges. Hazards associated with (A) and (B) were detailed in a previous document (https://volcanoes.usgs.gov/vsc/file_mngr/file-180/PreliminaryAnalysisOfCurrentExplosionHazardsSummit_May8_2018.pdf) so are

reviewed only very briefly here. Pyroclastic surge and high lava fountain hazards were not previously described due to their very low probability of occurrence.

A. *Ballistic projectiles*. Near the vent, large projectile-like rocks travel on cannonball-like paths outwards in all directions. This is a zone of extreme hazard. Ballistics were produced during earlier CE events but are not currently being ejected from the vent.

B. *Ashfall.* Small ash particles are carried primarily downwind from the vent, where they can impact transportation, infrastructure and utilities. Ashfall is unlikely to directly threaten human life. Very little ash is currently produced during CE events, but emissions are possible at any time. Graphical forecasts of where ash would fall during a significant emission can be found here: https://volcanoes.usgs.gov/observatories/hvo/ash_information.html

C. *Fallout from high lava fountains*. The fallout from large lava fountains several hundred meters high can impact neighboring communities. The fall of reticulite from several contemporaneous fountains about 500 years ago fell throughout the golf course and Volcano Village areas, burning vegetation and accumulating a thickness of 10 cm (4 inches) or more. Numerous fires could result today from such an event, particularly during a dry period. The fountains about 500 years ago erupted from steeply inclined circumferential fissures within Kīlauea Caldera. Wholesale downdropping of the present caldera floor could produce a situation similar to that 500 years ago.

D. *Pyroclastic surges*. Pyroclastic surges and density currents are highly destructive, generally fast-moving clouds of volcanic gases and fragments of magma and older rocks. They are generally hot and form when eruption columns become unstable and collapse back around the vent. Surges typically travel tens of meters per second, but certain types can move as rapidly as 100 - 300 meters per second (200 - 700 mph). Surges usually extend radially from the vent in all directions, but can be influenced by topography, thickening in valleys and thinning over topographic highs. Due to their great heat and high speed, pyroclastic surges are among the most dangerous and destructive of volcanic hazards. There are very few survivors among those caught in the path of a hot surge, and property damage is severe.

   In the past, surges have been produced at Kīlauea by sustained eruption columns. For example, pyroclastic surges were produced at Kīlauea between the middle 1500s and A.D. 1790. Surges in and just before 1790 extended 3 - 5 km (1.8 - 3 miles) west and south of the caldera and form the basis for a surge-hazard map shown in Figure 5. The direction that surges may travel is difficult to predict, and the entire summit area of Kīlauea out to roughly 5 km (3 miles) from center of the caldera is susceptible to surges <u>if they were to occur</u> (Figure 5). At present, Kīlauea is not producing any sustained eruption columns even during the largest CE events.

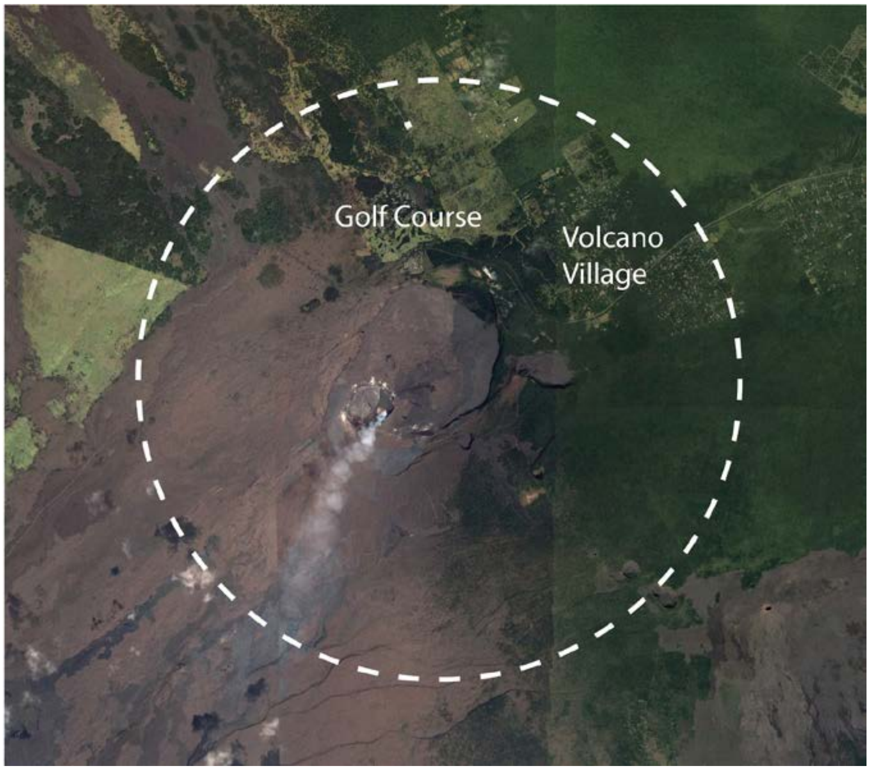

Figure 5: The dashed white circle indicates the approximate boundary of the pyroclastic surge zone at the summit of Kīlauea, assuming for simplicity a source near the center of the caldera. The white line shows only the maximum reasonable distance a surge would travel from the caldera as inferred from past eruptions; it does not indicate that such behavior is likely at this time (it is not), nor that surges would fill the entire area within the circle (surge deposits would likely travel within narrow regions). Background imagery from Google Earth.

Time frames of activity: how long might this last?

Deflation of Kīlauea's summit storage system is occurring in response to the removal of magma at a higher rate than the reservoir is being resupplied from its deep mantle source. If summit magma is predominantly feeding eruptive activity in the LERZ rather than filling storage space (independently of the LERZ eruption), then summit activity should cease soon after the LERZ eruption ends. The duration of the ongoing LERZ eruption cannot be predicted and at this time output appears steady. Historical eruptions in Kīlauea's LERZ in 1955 and 1960 lasted 88 and 38 days, respectively.

It is also possible that magma will continue to fill storage space in the rift zone, so that summit subsidence will continue even after the LERZ eruption ends. Alternatively, summit subsidence may greatly slow or even stop if the LERZ eruption decreases in vigor, or a new pressure equilibrium is obtained between the summit and LERZ. For these reasons it is not possible to forecast the duration of summit subsidence. It is most likely that it will continue for weeks to months, and it is possible although less likely that it will continue longer.

How will we know when the hazard has passed?

Hazards may remain present at the summit for months or longer even after subsidence and related strong seismicity stops. Earthquakes will likely occur at elevated but decaying rates, ground cracks may worsen, and rockfalls continue. Also, based on historical patterns, the summit will eventually re-inflate; this process will be associated with its own set of hazards, not specifically addressed here.

Conclusions

At present, the most likely course of activity for the immediate future at the summit of Kīlauea Volcano is continued subsidence of the caldera floor, episodic slumping into Halema`uma`u, felt moderate-sized earthquakes, and small ash plumes. The duration of this activity may be related to the duration of the LERZ eruption but cannot be confidently predicted. More hazardous explosive eruptions related to the ongoing subsidence are unlikely but possible. It is important not to underestimate the ability of volcanoes to evolve rapidly in unanticipated ways. More hazardous behavior is therefore possible at any time, and large-scale hazardous caldera collapse is a possible future outcome, although it is considered to be very unlikely and should be preceded by detectable warning signals. HVO should recognize these warning signs by direct observation and instrumental monitoring and, should they be detected, will alert authorities and the public.

Message from Hawaii County Civil Defense Agency

Hawaii County Civil Defense Agency (HCCDA) has committed to the preparation, response and recovery of the unfolding events with Kilauea. HCCDA is supported by law and proclamation by all the departments within the County, State of Hawaii and Federal Government to help the people cope with impacts caused by the volcano. USGS-Hawaiian Volcano Observatory (HVO) is the lead scientific agency in this disaster and provides the bulk of information used to identify hazards. The HVO is monitoring the situation 24 hours a day and maintains constant contact with your HCCDA to provide timely accurate information for your safety.