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Preliminary Analyses of Volcanic Hazards at Kīlauea Volcano, Hawai‘i, 2017–2018

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U.S. Department of the Interior
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Cover. Photograph of the upper part of the fissure 8 channel during the 2018 eruption of the lower East Rift Zone of Kīlauea Volcano. The view is to the northeast. Lava is flowing from lower right to upper center of the image. U.S. Geological Survey photograph taken on June 22, 2018.

Preliminary Analyses of Volcanic Hazards at Kīlauea Volcano, Hawai‘i, 2017–2018

By Christina A. Neal and Kyle R. Anderson

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Preliminary Analysis of Hazards at the Kamokuna Ocean Entry

By the Hawaiian Volcano Observatory

Chapter B

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By Kyle R. Anderson, Donald A. Swanson, Larry Mastin, Christina A. Neal, and Bruce F. Houghton

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By the Hawaiian Volcano Observatory

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Contents

Abbreviations

cm	centimeters
ERZ	East Rift Zone
ft	feet
GPS	Global Positioning System
HCCDA	Hawai‘i County Civil Defense Agency
HVO	Hawaiian Volcano Observatory
in.	inches
km	kilometers
LERZ	lower East Rift Zone
m	meters
m^3	cubic meters
m^3/s	cubic meters per second
m/h	meters per hour
mi	miles
NPS	National Park Service
ppm	parts per million
UAS	Unoccupied Aircraft Systems
USGS	U.S. Geological Survey

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By Christina A. Neal and Kyle R. Anderson

Introduction

From 2017 to 2018, the U.S. Geological Survey (USGS) Hawaiian Volcano Observatory (HVO) responded to ongoing and changing eruptions at Kīlauea Volcano as part of its mission to monitor volcanic processes, issue warnings of dangerous activity, and assess volcanic hazards. To formalize short-term hazards assessments—and, in some cases, issue prognoses for future activity—and make results discoverable to both the public and the authorities, HVO released reports online. These reports were published rapidly, received peer review under the USGS's Fundamental Science Practice guidelines, and were intended to address a focused question posed by one or more cooperating agencies—for this reason, they were called "cooperator reports." This Open-File Report concatenates four such products issued in 2017 and 2018 into a single publication. These reports have been reformatted and lightly edited for clarity, but the content has not otherwise been changed from the versions first publicly released.

Report Issued During the Pu‘u ‘Ō‘ō Eruption, Middle East Rift Zone

Kīlauea Ocean-Entry Hazards Analysis for the U.S. Coast Guard (March 2017)

Lava intermittently flowing into the ocean on the south coast of Kīlauea since 1986 posed a variety of hazards that have been described in both formal and informal publications (for example, Mattox and Mangan, 1997; Poland and Orr, 2014; Johnson, 2000; and status reports issued daily by HVO). Most of the land at the ocean-entry sites was managed by Hawai‘i Volcanoes National Park, which communicated warning information to visitors. In 2017, during a period of activity at the Kamokuna Ocean Entry inside Hawai‘i Volcanoes National Park, HVO was asked by the U.S. Coast Guard Honolulu Sector to inform management decisions about tour boat access to the ocean entries. To assist the Coast Guard in its rule-making process, HVO assembled the best available information to describe what was known about the extent of ocean-entry hazards. This report (chapter A) was delivered to the Coast Guard on March 29, 2017, and posted on the Coast Guard's public website related to the rule-making process. It was also later posted to HVO's website on June 27, 2018, during the 2018 activity.

Reports Issued During the 2018 Lower East Rift Zone Eruption and Summit Collapse

Kīlauea Volcano began a dramatic change in activity in late April 2018, culminating in a historically unprecedented eruption in the lower East Rift Zone and simultaneous episodic summit collapse that closed Hawai‘i Volcanoes National Park and forced the evacuation of thousands of people from lower Puna, a district in eastern Hawai‘i (Neal and others, 2019). During the eruption, which lasted more than three months, local authorities with responsibility for public safety and access management were in need of constant updates on the status of the activity, extent of the hazards, and prognosis for its progression. HVO provided this information during day-to-day interactions with officials and in writing in the form of three separate cooperator reports.

Kīlauea Summit Hazards Analysis for the National Park Service (May 2018)

As magma drained from Kīlauea's summit into the East Rift Zone, HVO recognized that the receding lava lake within Halema‘uma‘u Crater might lead to explosive activity—analogous to events believed to have occurred in 1924. This possibility became a key concern of Hawai‘i Volcanoes National Park management and Hawai‘i County Civil Defense Agency. To evaluate the potential for increasingly hazardous activity, K.R. Anderson and others prepared a report during the first week of May, only days after the onset of activity. Owing to the rapidly evolving situation, this report was constructed by a small group in 2–3 days and necessarily relied heavily on analogy with previous explosive activity at Kīlauea's summit. This report (chapter B) was delivered to Hawai‘i Volcanoes National Park on May 8, 2018, and formed the basis of a public meeting inside Hawai‘i Volcanoes National Park on May 9 at which USGS scientists described volcanic activity, the current assessment of hazards, and likely outcomes.

Updated Kīlauea Summit Hazards Analysis for the National Park Service (June 2018)

As the 2018 eruption and summit collapse activity continued, HVO re-evaluated future outcomes and the possibility of a transition to more hazardous behavior at Kīlauea's summit. This work formed the basis for a hazards analysis delivered to Hawai‘i Volcanoes National Park on June 29, 2018, in response to the park's request for input into their ongoing management decisions regarding park closure and the safety of employees and assets. The report (chapter C) addressed the possibility of larger and more dangerous activity that would involve response by the Hawai‘i County Civil Defense Agency.

This second summit report was constructed during a period of semi-steady eruptive activity. This allowed more time for HVO to solicit input from a broad group of experts within the USGS as well as colleagues in Iceland, Japan, and U.S. academic institutions. Expert opinion was evaluated, in part, in the context of an event-tree analysis (for example, Hoblitt and Newhall, 2002) led by colleagues from the Volcano Disaster Assistance Program of the U.S. Geological Survey and the U.S. Agency of International Development. The final report was shared with Hawai‘i Volcanoes National Park, discussed with the public at community meetings, and posted on the HVO website on July 5.

Kīlauea East Rift Zone Hazards Analysis for Hawai‘i County Civil Defense Agency (July 2018)

As the eruption continued and thousands were displaced from their homes, responding agencies grappled with planning for a severely impactful event of unknown duration. A recurring question for USGS scientists from both the public and responsible officials was how long would the effusion of lava likely continue? To address this concern and review ongoing hazards relevant to local, State, and Federal authorities, HVO scientists prepared a report (chapter D) for the Hawai‘i County Civil Defense Agency that was delivered on July 15, 2018. The product was developed by scientists most familiar with lower East Rift Zone geologic history and volcanic processes active at that time. In addition to being shared directly with the Civil Defense Agency, the report was posted on HVO's website.

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Chapter A. Preliminary Analysis of Hazards at the Kamokuna Ocean Entry

By the Hawaiian Volcano Observatory

Background

Since the onset of the Puʻu ʻŌʻō eruption in January 1983, lava has entered the Pacific Ocean for about half the time (as of March 2017), constructing dozens of lava deltas and adding about 440 acres of new land to the Island of Hawaiʻi. Above water, these deltas have ranged in size from tiny surfaces measured in tens or hundreds of square meters (similar dimensions in square yards) up to massive shelves tens of acres in size. The largest delta documented was 64 acres.

The lava deltas have usually begun to form as soon as a lava flow reaches the water (fig. 1). The size of the subsequent delta is likely determined, in part, by the length of time that the lava flow feeding it remains active, and presumably also by the size and (or) angle of the near-shore coastal slope upon which the delta forms. Most of the delta is composed of lava rubble that accumulates on this slope, fragmented during the interaction between the active lava flow and the cold sea water. When this fan of material builds up to sea level, lava that no longer interacts with sea water, and is therefore not fragmented, is emplaced on top, producing the relatively smooth flow surface that characterizes the visible lava delta. Thus, the lava deltas that we see are built upon a naturally unstable base.

Over time, most (if not all) deltas experience collapses where portions of the deltas fall into the water, probably in response to submarine landslides or slumps caused by (1) compaction of the rubble underlying the delta surface, (2) oversteepening of the underlying fan of rubble at the front of the delta, (3) erosion of the submarine delta by strong ocean currents or surf, (4) shaking caused by strong surf or earthquakes, or (5) perhaps by some other process not yet identified. These causes are in addition to normal erosion from ocean wave action. Most collapses are small and go unreported, and even those as large as several acres in size might be missed or only identified days later during aerial reconnaissance missions. Typically, the continued influx of lava causes the collapsed part of the delta to rebuild, or at least begin to rebuild, within a few days, often obscuring evidence that a collapse took place.

Observations have shown that at least some larger delta collapses—those ranging in size from several to tens of acres—occurred in piecemeal fashion, as the collapse of a series of smaller slices from the front of the delta. We infer that these scenarios are caused by considerably larger submarine landslides that develop progressively, often lasting several hours.

On rare occasions, delta collapses trigger small explosions—steam blasts—that can hurl both molten and solid fragments of the delta hundreds of meters (similar distances in yards) away, both inland and out to sea. Even collapses of about 1 acre have triggered explosions. Delta collapses can also cause local tsunami capable of flooding the adjacent delta, or even the land above the adjacent sea cliff. Hot, acidic steam can also engulf the immediate area, posing yet another hazard.

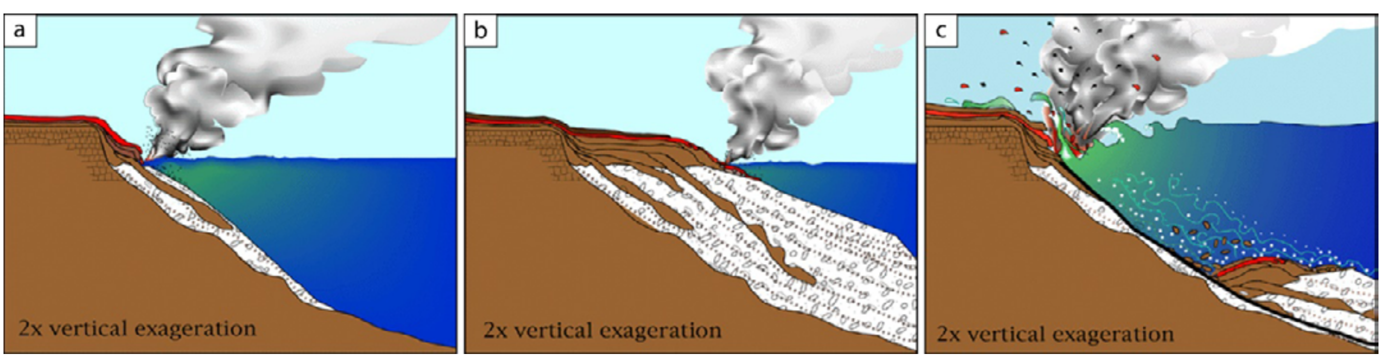

Figure 1. Schematic drawing that shows (*a*) development, (*b*) growth, and (*c*) collapse of a lava delta. Images also available at https://hvo.wr.usgs.gov/hazards/oceanentry/deltacollapse.

Summary of Current Conditions

The episode 61g lava flow reached the ocean along the south coast of Hawai‘i in late July 2016, at a location known as Kamokuna, and quickly began to build a lava delta. Many small collapses were reported by National Park Service (NPS) personnel over the following months, as the delta grew, but by the end of the year it had a surface area of about 23 acres. Starting mid-afternoon on December 31, 2016, the lava delta abruptly began to collapse piecemeal into the ocean (fig. 2). Most of the delta slid into the water over the next several hours, leaving behind narrow remnant ledges at the base of the sea cliff that totaled about 2.5 acres (fig. 3).

As the collapse progressed, it began to eat into the older sea cliff behind and adjacent to the east end of the delta, sequentially removing another 4 acres of land, possibly caused by undercutting promoted by the delta collapse. This portion of the older sea cliff included part of the Hawai‘i Volcanoes National Park viewing area. The collapse of the older sea cliff, in some instances, produced large waves that splashed back onto the sea cliff. The total area that collapsed, including the Kamokuna delta and the older sea cliff, was approximately 25 acres.

Lava continued to enter the ocean following the delta collapse, but did so as a large firehose-like stream of lava that emerged from a lava tube exposed at a height of approximately 21 meters (m; ~70 feet [ft]) above the ocean in the face of a sea cliff that is 28 m (~90 ft) high. This entry point is located at: 19.32056° N., 155.04015° W.

Unlike previously documented collapses at this delta and others, the delta did not immediately begin to re-form after the New Year’s Eve collapse in 2016. We suspect that the collapse formed an extremely steep slope descending underwater from the base of the sea cliff. Until the offshore region shallows enough (or the debris fan likely forming below water becomes less steep) to allow net accumulation of lava above sea level, construction of a new delta will not occur. Note that, at the time of this writing, observations at the coastline indicate that a small delta may have begun to form starting around March 20, 2017.

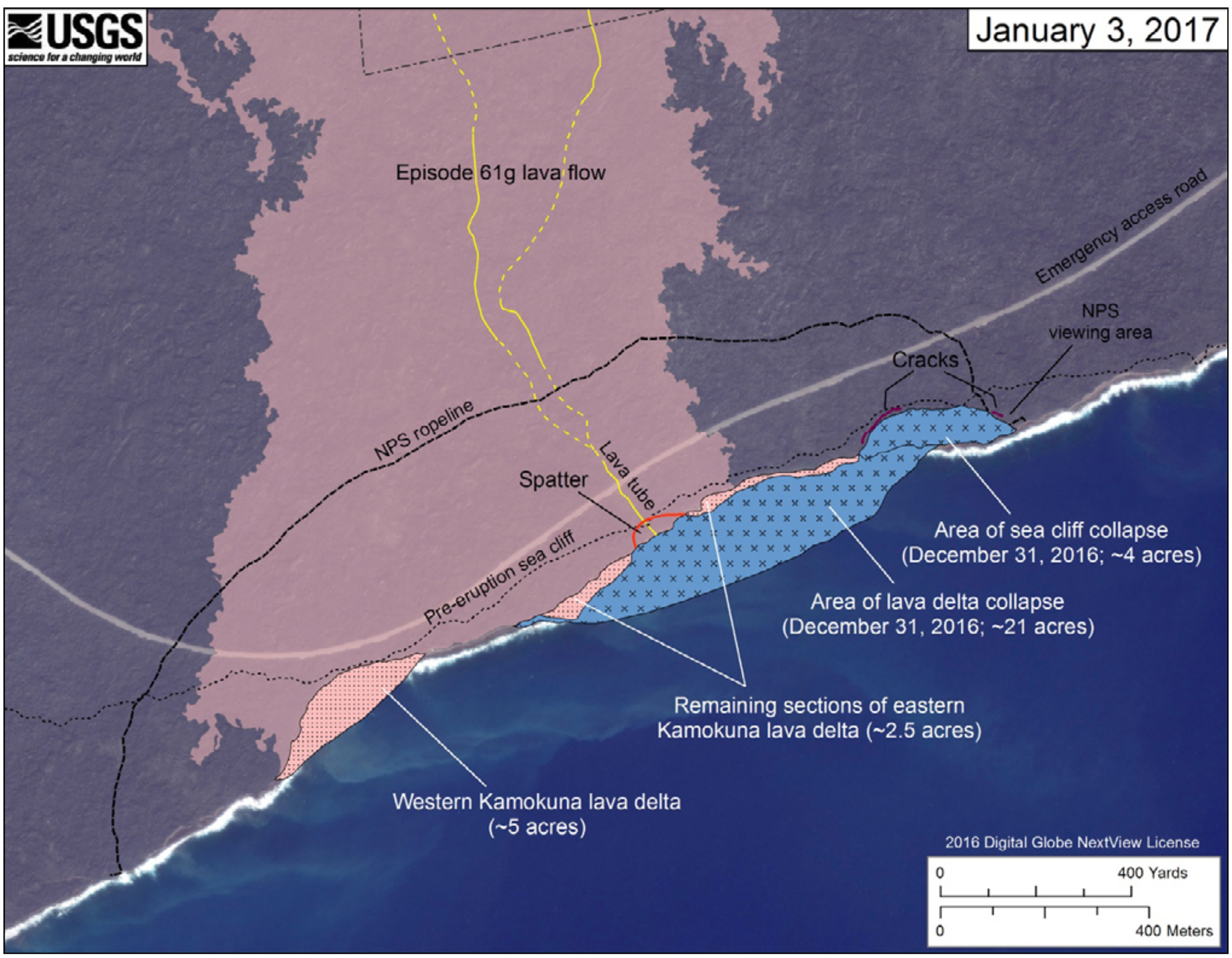

Figure 2. Map of the southeast shore of Kīlauea showing the area of the episode 61g lava flow near the coast and the Kamokuna lava delta on January 3, 2017.

Figure 3. Photographs of the Kamokuna lava delta before and after the December 31, 2016, collapse. *Left*, View of the delta on October 14, 2016, when its size was ~15 acres. U.S. Geological Survey photograph by L. DeSmither. *Right*, View on January 1, 2017, after the delta collapse, showing two remnants of the delta. U.S. Geological Survey photograph by M. Patrick.

Ongoing Hazards

Sea Cliff Collapse

Vertical sea cliffs in the vicinity of the lava entry point have proven to be unstable, producing collapses of various sizes. These collapses were preceded by the development of shore-parallel cracks inland of the cliff edge. For instance, on January 25, Hawaiian Volcano Observatory (HVO) geologists noted an arcuate crack running parallel to the 28-m-high (~90-ft-high) sea cliff about 15 m (~50 ft) inland of the stream of lava at the Kamokuna ocean entry. Ground inspection of this crack on Saturday January 28 showed 30 centimeters (cm; or ~12 inches [in.]) of separation across the crack. On Wednesday February 1, four days later, this crack had widened to about 70 cm (~28 in.), and the seaward block was visibly oscillating by as much as ~2 cm (~1 in.), possibly in response to explosions below as hot lava mixed with cool ocean water (fig. 4). In addition, the ground in the immediate vicinity was shaking.

Part of the block, estimated to be about 80 m long (~260 ft), collapsed into the ocean on February 2. HVO geologists in the field at the time observed a wave propagating outward from the sea cliff but noted the wave was no larger than a typical ocean swell. Photographs of the collapse by visitors at the national park viewing area show a large rebound splash that also threw dense blocks from the collapsed sea cliff roughly 100 m (~330 ft) out to sea.

The collapse of small parts of this cliff continued for some days after, some observed and filmed by tourists aboard tour boats. The few collapses for which good observations exist showed that the cliff crumbled to pieces as it fell. Whereas the collapses that were observed occurred as single events, it is difficult to know if other events might progress inland in piecemeal fashion, taking off additional slices of the sea cliff. It is also not known if all sea cliff collapses include only that part of the sea cliff above water, or if, during larger collapses, part of the submarine cliff also fails.

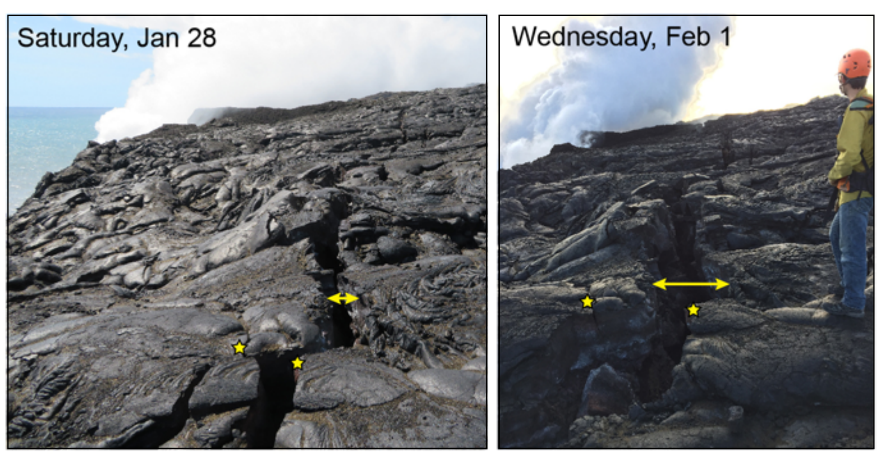

Figure 4. Photographs of the sea cliff crack inland from the Kamokuna ocean entry on January 28, 2017, when the crack was ~30 centimeters (cm) wide (*left*), and on February 1, 2017, when the crack was ~70 cm wide (*right*). U.S. Geological Survey photographs; also available at https://hvo.wr.usgs.gov/multimedia/uploads/multimediaFile-1627.jpg.

Tephra Jets

The stream of lava entering the ocean produces intermittent explosions of spatter and fine fragments, including Pele's hair (fig. 5). Based on HVO's limited observations of the current entry, large fragments of molten lava are being thrown vertically at least 30–40 m (about 100–130 ft), with some landing on the adjacent 28-m-high (~90-ft-high) sea cliff and building a small tephra cone. Most fragments, however, are raining offshore. Without a continuous record of activity, we cannot state precisely how far this hot spatter can be thrown, but past experience suggests that small pieces of material can be lofted as high and as far as 100 m (~330 ft). Large explosions with even greater throw distance are possible. Visit https://pubs.usgs.gov/fs/2000/fs152-00 for more information.

Figure 5. Photograph showing a typical tephra jet at the Kamokuna ocean entry. U.S. Geological Survey photograph taken on January 30, 2017.

Delta and Submarine Slope Collapse

As long as lava enters the ocean, further delta construction and collapse events could occur at some point. These collapses can be small or large and occur with little or no warning. Whereas submarine slope failures are probably closely associated with delta collapses, some might occur in the absence of delta collapses. We have no way of presently detecting or monitoring this phenomenon, nor do we know if it presents any perceivable hazard. However, the failure of the steep fan of rubble that develops offshore probably will displace water, potentially creating surface waves, though we have no information on how large the resulting waves (if any) might be.

For a schematic diagram illustrating the delta collapse process, see the fact sheet at https://pubs.usgs.gov/fs/2000/fs152-00.

Ballistics

Large, dense fragments ejected during some delta collapses can be thrown in all directions from the point of collapse, including out to sea, in response to the explosive interaction of the hot delta with cold sea water (fig. 6). Based on a review of nearly 30 years of delta collapse and ejecta distance observations mined from the HVO records (discussed in next section), we consider a radius of 300 m, or about 1,000 ft, to be a reasonable minimum high-hazard zone around a lava delta, where one is present (for example, see event of January 30, 1996, below).

Explosions are less likely for collapses of older, cooler material. However, observations of recent sea cliff collapses have shown that ballistics can be thrown as far as 100 m (~330 ft) out to sea owing to the dynamics of the rebounding splash following the impact of the sea cliff in the water.

There is no obvious relation between the size of the delta and the extent of ballistic hazard. Both large and small lava deltas (or large and small parts of deltas) have collapsed and triggered explosions. Why some collapses lead to explosions and some do not is not known, but likely depends on how hot the collapsing rock is, and possibly the size, style, and abruptness of the collapse, as well as the nature of the submarine slope.

Figure 6. Photograph of a ballistic block thrown inland during an explosion triggered by a lava delta collapse. U.S. Geological Survey photograph.

Waves and Surges

During collapse events, water is displaced impulsively and one or more waves can be produced that travel radially away from the point of collapse or explosion. During the December 31, 2016, collapse event, NPS eyewitnesses noted waves or splashes, probably related to the collapse of the older sea cliff, crashing atop the ~15-m-high (~50-ft-high) sea cliff near the public viewing area. Additionally, a visitor's video clip shows a small fishing boat taking on water when a small collapse event occurred nearby (unrelated to the December 31 collapse), which sent a wave out to sea.

An analysis by National Oceanic and Atmospheric Administration scientists that evaluates wave heights generated by sea cliff collapses indicates that, for a reasonable range of collapse sizes from the current sea cliff, waves of between about 1.5 and 5 m (5 and 16 ft) in height could travel as far as 100 m (~330 ft) from shore. With the exception of the splash in the immediate impact zone, these waves are not steep and breaking. Rather, they are more like those of typical ocean swells and will diminish rapidly in size with distance from the impact zone.

Scalding Water

Lava entry into the ocean produces a plume of hot, acidic water that travels offshore or along shore, depending on ocean currents. Recent HVO thermal imaging documented surface water temperatures of 60 °C (142 °F) as far as about 50 m offshore, and temperatures as high as 44 °C (111 °F) extending more than 300 m seaward (fig. 7). Past evaluation of this plume of hot water suggests it may be limited to the upper 1–2 m (3–7 ft) of the water column.

Laze

The interaction of hot lava and seawater produces "laze", a cloud of steam, hydrochloric acid droplets, and volcanic glass particles that can be harmful to breathe (fig. 8). Laze drifts downwind, making this hazard strongly dependent on wind conditions, which can change throughout the day. The plume is typically visible in an HVO webcam accessible at https://hvo.wr.usgs.gov/cams/panorama.php?cam=HPcam. Altitudes of the laze plume have not been rigorously tracked, but anecdotal evidence suggests that near the ocean entry, it remains typically below about 300 m (~1,000 ft) above ground level. No data exist on how often the laze plume drifts offshore into areas that could impact boat traffic.

The size of the laze plume can increase significantly during delta collapses. This hot, acidic plume can envelop nearby areas, causing scalding and potentially pulmonary edema and death, if inhaled.

Figure 8. Photograph of a laze plume as it drifts offshore from the ocean entry at Kamokuna on January 3, 2017. The edge of the lava "firehose" is visible as red incandescence. U.S. Geological Survey photograph; also available at https://hvo.wr.usgs.gov/multimedia/uploads/multimediaFile-1588.jpg.

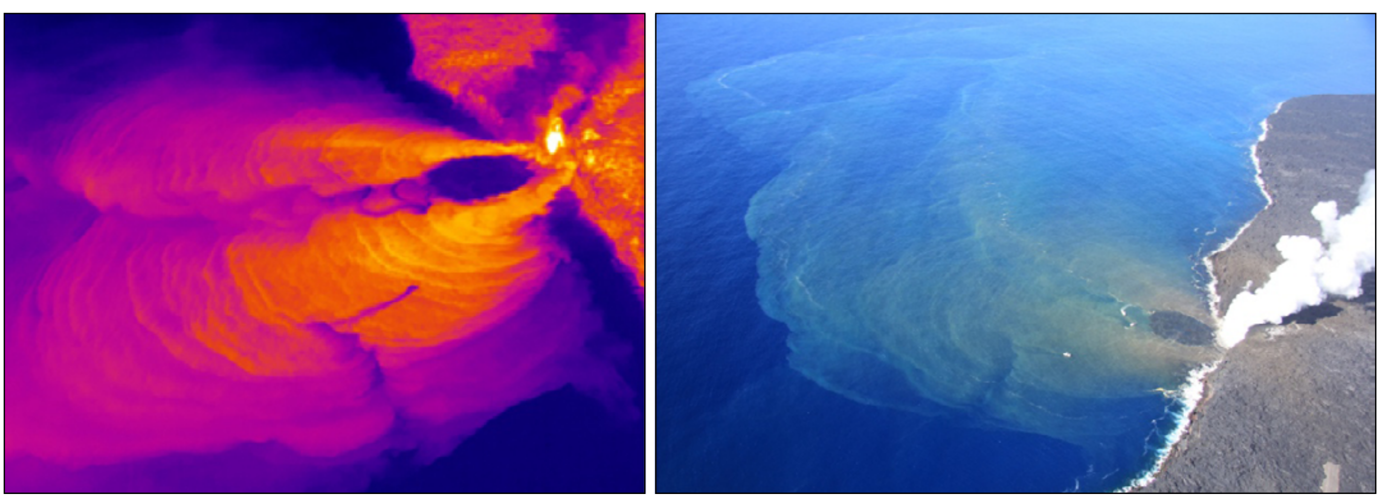

Figure 7. Thermal infrared image (*left*) and oblique aerial photograph (*right*) of the plume of hot water at the Kamokuna ocean entry that extends several hundred meters offshore. Boats for scale. U.S. Geological Survey photographs taken on March 16, 2017.

Summary of Hazardous Delta Collapses During the Puʻu ʻŌʻō Eruption

Not all delta collapse events from 1988 to present are included. This list includes collapse events that did one or more of the following: (1) triggered explosions that threw molten spatter or dense rocks onto the adjacent sea cliff; (2) caused localized tsunami; (3) caused the collapse of slices of the adjacent, older sea cliff; or (4) prompted incidents where people nearby had to run for safety. Information presented here was gleaned from HVO internal reports, with some additions from HVO field logbook entries.

March 26, 1988

Lava delta location/name: Kupapaʻu

Collapse size: No apparent collapse

Summary: NPS personnel living at the Wahaʻula Visitor Center, 1 km (~0.6 mi) west of the entry were awakened at 1:25 a.m. by a roar "like a jet engine" and reported large hydromagmatic explosions that lasted for about an hour, ejecting material as high as ~100 m (~330 ft) vertically and 100–150 m (~330–490 ft) laterally from two tephra cones at the front of the delta. Observations the next day found that both cones were heavily mantled with spatter, but the eastern tephra cone had a conspicuous deposit of dense spatter bombs, as large as footballs, that littered the area as far as 60 m (~195 ft) inland of the cone. Blocks of dense rock were also abundant in the deposit around the eastern cone. The event was inferred to be the result of a large underwater landslide or slumping event that opened cracks in the delta, which channeled water to the lava tube; no actual delta collapse was identified. The size of the delta was not reported, so it could not be determined if blocks and debris reached the adjacent sea cliff.

May 30, 1988

Lava delta location/name: Kupapaʻu

Collapse size: Not reported

Summary: Catastrophic slumping of the underlying submarine debris fan left the Kupapaʻu lava delta unsupported, causing a large delta collapse at 7:59 p.m. that resulted in large explosions. The blasts tossed blocks of dense pāhoehoe more than 100 m (~330 ft) inland, but it was not reported if this reflects the distance inland from the edge of the collapse scar or the sea cliff.

July 12, 1988

Lava delta location/name: Kupapaʻu

Collapse size: ~1 acre

Summary: The entire delta broke off into the ocean without warning at 8:42 a.m. Two large explosions occurred 10–20 seconds apart, throwing spatter about 100 m vertically and sending spectators running. Spatter was deposited within a radius of 50 m inland from the sea cliff, but most of the deposit fell 30 m (~100 ft) inland from the cliff where it covered 10–20 percent of the ground surface. Fallout included 10- to 30-cm-long (4- to 12-inch-long) ribbons and cow-dung bombs. This was the first collapse witnessed by an HVO scientist, who stated that "The collapses…permit no possible means of escape for anyone on the delta at the time of collapse."

August 15, 1988

Lava delta location/name: Kupapaʻu

Collapse size: ~4 acres

Summary: Almost the entire delta collapsed at 6:14 a.m. and NPS employees living at Wahaʻula Visitor Center felt the shock. Later in the day, a small deposit of spatter was discovered that covered an area about 10 m (~33 ft) wide and 20 m (~66 ft) long. Because the entire delta collapsed, we infer the deposit to be on the sea cliff.

September 15, 1988

Lava delta location/name: Kupapaʻu

Collapse size: ~1 acre

Summary: A major collapse at 11:07 p.m. removed the entire delta, triggering explosions that produced a tephra cone and hurled dense, fist-sized fragments of the sea cliff onshore.

January 23, 1989

Lava delta location/name: Kupapaʻu

Collapse size: Not reported

Summary: A major delta collapse occurred at 8:44 a.m., claiming 50 percent of the delta. Subsequent explosions threw dense blocks of lava 10–50 cm (~4–20 in.) in diameter as far as 40–50 m (~130–165 ft) inland from the edge of the collapse.

April 19, 1993

Lava delta location/name: Laeʻapuki

Collapse size: ~1 acre

Summary: A major collapse event that started at 9:43 p.m. was followed by an explosion containing incandescent rocks. These fragments were directed to the northwest and thrown as far as 200 m (~660 ft) inland from the source of the explosion (which was located ~120 m, or ~400 ft, inland from the sea cliff). Several meter-sized (yard-sized) blocks were found within 20 m (~65 ft) of the ocean and did not reach the sea cliff; beyond this area, fragments were generally <25 cm (<10 in.). One person disappeared into the ocean when the part of the delta they were standing on collapsed and 22 visitors were treated for injuries sustained from falls or from getting hit by rocks.

May 15, 1993

Lava delta location/name: Kamoamoa

Collapse size: Not reported

Summary: A deposit of mostly baseball- to football-sized rocks was discovered on May 17 scattered to the north and west as far as 100 m (~330 ft) inland from the ocean entry, with smaller debris extending 150 m (~490 ft) inland. The date of the event that produced this deposit is inferred from seismic data to be May 15.

November 26, 1993

Lava delta location/name: Kamoamoa

Collapse size: ~5 acres

Summary: Cracks formed on the delta in mid-November. On the afternoon of November 26, vigorous tephra jets started. In the evening, a large surface flow emerged from a crack on the delta, as the delta appeared to tilt seaward, sending spectators running. This was followed by a major delta collapse and large explosion at 9:28 p.m. A localized tsunami washed onshore right afterward.

February 22, 1994

Lava delta location/name: Kamoamoa

Collapse size: ~2.5 acres

Summary: Part of the delta collapsed on February 22, depositing a carpet of ribbon spatter and cow-dung bombs as far as 80 m (~260 ft) inland from the resulting scarp. Finer grained tephra and lava fragments were found hundreds of meters from the entry.

July 8, 1994

Lava delta location/name: Kamoamoa

Collapse size: ~2 acres

Summary: An inactive part of the delta collapsed at 12:36 a.m. Dense blocks as large as 0.5 m (20 in.) in diameter were deposited 30–40 m (~100–130 ft) inland on the surface of the remaining delta by the resulting localized tsunami.

January 30, 1996

Lava delta location/name: Kamokuna

Collapse size: ~4 acres

Summary: Part of the Kamokuna delta collapsed progressively, in piecemeal fashion, over a period of about 6 hours. Multiple explosions occurred, throwing blocks as large as 75 cm (~30 in.) across as far as 250 m (~820 ft) inland from the original coastline. A separate report stated than dense rocks were ejected to a height of nearly 100 m (~330 ft) and thrown more than 300 m (~985 ft) inland but does not specify if this is from the point of the explosion or the sea cliff. The final collapse in the sequence created a small, hot local tsunami that deposited 50-cm-diameter (20-inch-diameter) blocks as far as 30 m (~100 ft) inland from edge of the collapse scar on the delta.

July 12, 1996

Lava delta location/name: Lae‘apuki

Collapse size: ~3 acres

Summary: A collapse on July 12 cut back into older sea cliff and triggered explosions that deposited spatter and small blocks 5–30 cm (2–12 in.) in diameter as far as 30 m (~100 ft) inland of the sea cliff.

December 2, 1996

Lava delta location/name: Lae‘apuki

Collapse size: ~34 acres

Summary: The delta began to collapse in piecemeal fashion starting at 7:50 a.m. and continued over the next 2.5 hours, until the entire 26-acre delta was gone. In addition, another 8 acres of older sea cliff collapsed as well, bringing the total collapse area to 34 acres. Dense rock fragments were thrown 100 m (~330 ft) inland, and finer debris as far as 320 m (1,050 ft) inland, from the sea cliff. Blocks more than 30 cm (12 in.) across were thrown 50 m (~165 ft) inland.

December 10 or 11, 1998

Lava delta location/name: Kamokuna

Collapse size: ~14 acres

Summary: A large delta collapse, sometime on December 10 or 11, removed about 14 acres, including 6 acres of the older adjacent sea cliff.

March 8, 1999

Lava delta location/name: Kamokuna

Collapse size: ~20 acres

Summary: Nearly the entire Kamokuna delta collapsed on March 8. The collapse was preceded by an explosion that rocked the ground and threw spatter 60–75 m (~195–245 ft) into the air. Seven people on the delta, who had walked past warning signs, ran and made a narrow escape. The delta collapsed shortly afterward.

April 13, 1999

Lava delta location/name: Kamokuna

Collapse size: Not reported

Summary: The outer margin of the delta apparently collapsed, which triggered spattering that ejected ribbon spatter as long as 1 m (~1 yard) and flattened bombs the size of dinner plates, as well as dense rocks as large as 20 cm (~8 in.) in diameter. The deposit formed a continuous ground cover 30–35 m (~100–115 ft) inland from the sea cliff.

August 18, 1999

Lava delta location/name: Kamokuna

Collapse size: ~15 acres

Summary: A collapse in the morning removed about 15 acres of land, including 11.5 acres of the active delta and ~3.5 acres of older sea cliff.

August 27, 2005

Lava delta location/name: East Lae‘apuki

Collapse size: ~11 acres

Summary: A localized tsunami, triggered when part of the delta collapsed, swept blocks as large as 1 m (~1 yard) onto adjacent parts of the delta.

November 28, 2005

Lava delta location/name: East Lae‘apuki

Collapse size: ~44 acres

Summary: Starting at 11:10 a.m., and lasting for about 5 hours, the East Lae‘apuki delta collapsed in piecemeal fashion. Almost the entire 34-acre delta collapsed as well as an additional 10 acres of the older sea cliff behind the delta, bringing the total size of the collapse to 44 acres. Lithic blocks as large as 15 cm (~6 in.) across were thrown 150 m (~490 ft) inland from the pre-collapse cliff. Spatter was thrown 100 m (~330 ft) inland, and finer debris was deposited as far as 550 m (~1,800 ft) inland, with almost total ground coverage as far as 230 m (~755 ft) inland.

May 10, 2007

Lava delta location/name: East Lae‘apuki

Collapse size: ~23 acres

Summary: The East Lae‘apuki lava delta began to collapse in piecemeal fashion starting around 2:25 p.m. and continued for at least the next 4 hours, removing part of the delta and adjacent older sea cliff. Fist-sized dense rocks were thrown as far as 140 m (~460 ft) inland from the resulting collapse scar in the delta. The largest dense block, found 40 m (~130 ft) inland, was ~90 cm (~35 in.) across. A 35-cm-diameter (~14-inch-diameter) rock was thrown 120 m (~400 ft) inland. Surprisingly, the collapse occurred 2 months after the ocean entry stopped.

July 30, 2008

Lava delta location/name: Waikupanaha

Collapse size: ~2 acres

Summary: A small delta collapse occurred between 5:00 and 6:00 a.m., based on anomalous seismicity. Blocks of dense lava as large as 80 cm (~32 in.) across, but on average about 10 cm (~4 in.) across, were thrown as far as 110 m (~360 ft) inland.

August 27, 2008

Lava delta location/name: Waikupanaha

Collapse size: 1–2 acres

Summary: A small delta collapse occurred between 10:00 and 11:00 p.m., based on seismicity. Dense rocks were thrown as far as 180 m (~590 ft) inland from the sea cliff. The average block size was 5–10 cm (~2–4 in.), but many blocks were 25 cm (~10 in.) across.

December 7, 2008

Lava delta location/name: Waikupanaha

Collapse size: 3–4 acres

Summary: A delta collapse occurred on the morning of December 7, possibly between 2:40 and 5:23 a.m., based on seismicity. Fist-sized rocks and smaller fragments fell as far as 215 m (~705 ft) inland. Several dense rocks were found 375 m (1,230 ft) inland, but we cannot unequivocally say that they were deposited by this explosion.

January 18, 2009

Lava delta location/name: Waikupanaha

Collapse size: Not reported

Summary: Dense blocks of lava, thought to be recent, were found impacted into the tephra cone on top of the sea cliff on January 22, 2009. We infer that these are from a collapse that reportedly occurred on January 18.

February 17, 2009

Lava delta location/name: Waikupanaha

Collapse size: Not reported

Summary: A crack across the delta was observed on February 16 and was observed to be wider the next day. At about 1:30 p.m., the delta collapsed, throwing dense, angular fragments as far as 275 m (~900 ft) inland from edge of the collapse scar, or 240 m (~785 ft) inland from the older sea cliff. The deposit included pebble- to football-sized rocks as well as cow-dung bombs.

December 31, 2016

Lava delta location/name: Kamokuna

Collapse size: ~25 acres

Summary: A piecemeal collapse of the delta began in the mid-afternoon and continued into the evening. In addition to the collapse of about 21 acres of the delta, about 4 acres of the older sea cliff behind and to the east of the delta also collapsed, taking with it part of the NPS public viewing area. Little explosive debris was produced.

Chapter B. Preliminary Analysis of Current Explosion Hazards at the Summit of Kīlauea Volcano

By Kyle R. Anderson,[1] Donald A. Swanson,[1] Larry Mastin,[1] Christina A. Neal,[1] and Bruce F. Houghton[2]

Introduction

We examine here the possibility and potential impacts of future explosive events from within Halemaʻumaʻu. In particular, the potential for the summit lava lake surface to drop to or below the elevation of the groundwater table, estimated to be 460 meters (m; 1,500 feet, ft) below the caldera floor, raises the strong possibility of explosions caused by interactions of groundwater and hot rock which would impact the summit area. This document reviews current activity, describes a credible set of circumstances that could produce such explosions, examines hazards and their extent, and discusses uncertainties. It is meant as a guide for managing risk in the Kīlauea summit region.

Background

Kīlauea Volcano's summit lava lake is directly connected to its summit magma reservoir. As pressure in the reservoir decreases, the surface height of the lava lake also decreases, and vice versa. The elevation of the lava lake surface is measured by laser rangefinder, thermal camera, and other methods.

Current Activity

After repeatedly overflowing onto the floor of Halemaʻumaʻu in late April, the surface of Kīlauea's lava lake began to drop on May 2, 2018. Around the same time, deflation of Kīlauea's magma reservoir was detected by the summit tiltmeter network. The rate of lava lake subsidence increased slowly but over the last three days of available data has remained relatively constant at about 2 meters per hour (m/h; ~7 feet per hour). From its height at 1,025 m above sea level on May 2 to the most recent estimate at 9:00 p.m. on May 6, the lava lake surface dropped more than 200 m (660 ft). Measurements have become more difficult to make as the surface has dropped farther from monitoring instruments, but thermal camera imagery indicates continued lowering of the lake surface since that time, and tiltmeters at Kīlauea's summit also indicate a steady depressurization of the summit magma reservoir.

Outcome of Concern

Assuming the lake surface continues to drop at its current rate, we can extrapolate forward in time. Such an extrapolation is associated with very large uncertainty, as the system may change in unexpected ways, but it guides our thinking about potential outcomes. At the current rate of decline, the lava lake may drop below the water table near the end of this week (fig. 1).

Such a condition has been associated with explosive activity at the summit of Kīlauea Volcano in the past. In February 1924, for example, lava drained from Halemaʻumaʻu Crater and, by early May 1924, dropped below the water table. Collapse of the crater walls, and influx of groundwater into the conduit to Halemaʻumaʻu, caused repeated explosions between May 11 and 27, 1924. These explosions threw rocks larger than 25 centimeters (cm; 10 inches [in.]) in diameter—maximum size about 2 m (~7 ft)—as far as 1 kilometer (km; 0.6 miles [mi]) or more from the vent. Ash from the explosions fell from North Hilo to beyond Pāhala, pea-size rocks were reported to have fallen at the Volcano House, and gravel-size rocks were deposited 3 km (2 mi) southwest of Halemaʻumaʻu.

Potential Hazards

For management purposes, we can define two types of hazard zones for future Halemaʻumaʻu explosions:

1. *Ballistic projectile zone.*—This is a zone of extreme risk, in which large projectile-like rocks travel on cannonball-like paths outwards from the vent in all directions. The chance of fatality and severe injury within this zone is high. For practical purposes, a projectile size limit of 10 cm (4 in.) can be taken as the outer edge of this zone.

2. *Ashfall zone.*—This zone is located primarily downwind from the vent where smaller particles (ash to centimeter in size) fall. Debris falling in this

[1]U.S. Geological Survey.

[2]University of Hawaiʻi at Mānoa.

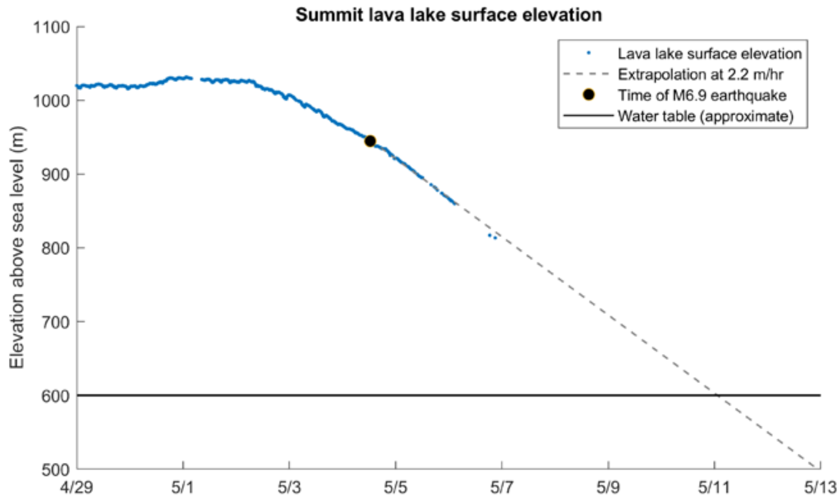

Figure 1. Plot of the elevation of Kīlauea's lava lake surface (in meters, m) versus time, with extrapolation into the future at a subsidence rate of 2.2 meters per hour (m/h). This subsidence rate is approximately its rate from the time following the magnitude 6.9 earthquake that occurred on May 4, 2018, to the present (May 8, 2018). The water table at roughly 600 m above sea level is indicated by the black horizontal line. At 2.2 m/h, the lava lake surface could reach the water table within the next several days, although such an outcome is far from certain. The water table around the lava lake is also likely complex, and its elevation there is only approximately known.

region is unlikely to threaten human life, but it can heavily impact transportation, infrastructure, and utilities. Visibility can be low, cars can lose traction on roadways, water supplies can be contaminated, machinery can be damaged by abrasion and corrosion, power transformers can short out, and prolonged exposure can result in respiratory problems. Some of these problems can persist for days or longer after an eruption stops, as wind re-suspends ash. A more complete discussion of ash impacts can be found at https://volcanoes.usgs.gov/volcanic_ash.

In the ballistic projectile zone, risk depends on the size of the projectiles, so we typically plot contours of rock size to make hazard projections (fig. 2). In the ashfall zone, the risk increases with ash thickness and with meteorological conditions. For example, wind affects visibility and ash infiltration into mechanical and electronic components, and wetness affects road traction and weight of ashfall on structures. Therefore, we typically plot ash thickness for scenarios or past events on a map (fig. 3).

Two eruptions—the March 19, 2008, and the 1924 explosions—provide information about the scale of hazards for (1) small and (2) moderate Halema‘uma‘u explosions.

1. *Small event.*—March 19, 2008. This small event began the current 2008–2018 summit eruption. The ballistic projectile zone extended radially outwards for a distance of 300 m (1,000 ft). The ashfall zone extended at least 1.5 km (1 mi) downwind (to the southwest).

2. *Moderate event.*—1924 explosions. The ballistic projectile zone extended 1 km (0.6 mi) to the north and south of the Halema‘uma‘u Crater rim, and less to the east and west. The ashfall zone extended at least 30 km (20 mi) from Halema'uma'u, in a variable pattern indicating complex winds over an extended period of time. Dispersal toward the southwest would be expected during normal trade winds, but winds can vary with daily meteorology. The U.S. Geological Survey is running twice-daily simulations of ashfall dispersal under current conditions for hazard planning (fig. 4).[3]

Less likely but more hazardous scenarios do exist. If the pressure in Kīlauea's shallow magma reservoir greatly decreases, it is possible that the ground surface in a broader area above the reservoir would begin to collapse along faults into the evacuated space. This process is distinct from the reduction in lava lake surface height described above and would require a greater degree of depressurization. This scenario does not seem likely at the present. In 1924, the ground above the reservoir subsided several meters without inducing a collapse—far more subsidence than has been recorded during the current activity. Larger eruptions are also known to have occurred in the late 18th century. However, there is no evidence at present that would suggest an eruption as large as those in the late 18th century is likely in the short term.

[3]Simulations are done using the Ash3D volcanic ash dispersion model at https://vsc-ash.wr.usgs.gov/ashgui/#/publicresults/MNL-1025775/DEP. [Editor's note: This link was actively updated during the eruption event.]

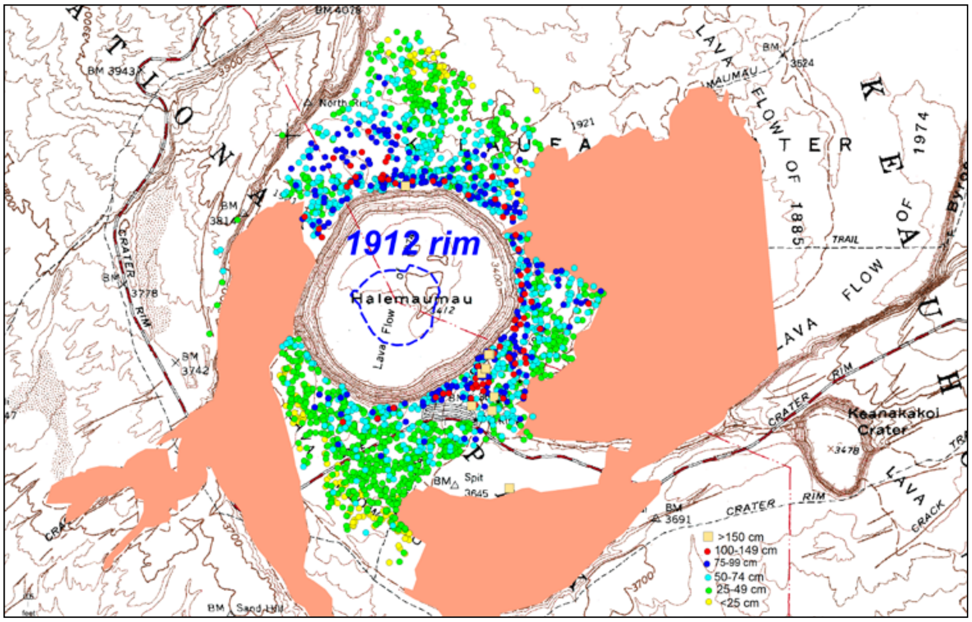

Figure 2. Map of the ballistic projectile zone for the 1924 eruption at Kīlauea's summit. Colored dots show individual projectiles from <25 to >150 centimeters in diameter. Collectively, they define a hazard zone of extreme risk with a radius of approximately 1 kilometer (0.6 miles). The orange color maps post-1924 lava flows, which buried any older ballistic rocks. Ballistic rocks fell in the white area just southeast of the crater but cannot be distinguished today from older rocks owing to human activity after 1924.

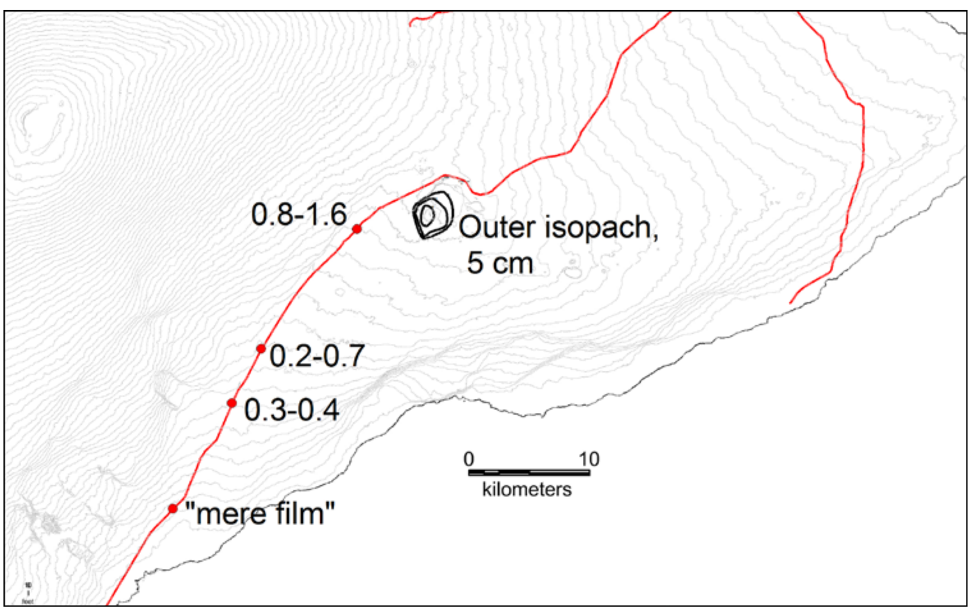

Figure 3. Map of the ashfall zone for the 1924 eruption of Kīlauea. The red line encloses the large and complex region of ashfall. Numbers show ash thicknesses (in centimeters, cm) measured by Thomas Jaggar soon after the 1924 eruption. We know that, in fact, the ashfall zone was much larger than shown here as reports indicate that ash was dispersed northward as far as North Hilo. An isopach is a line of equal ash thickness.

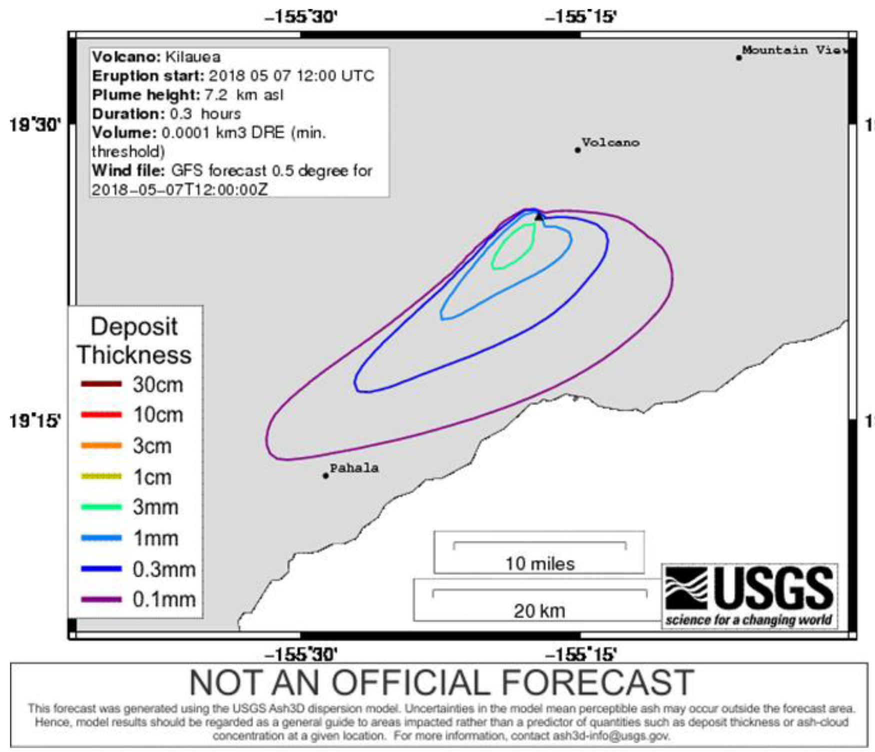

Figure 4. Map showing the model output of possible ash extent and thickness for a plausible explosive event from the Kīlauea summit should phreatic explosions commence. Contours show expected ash deposit thickness (in centimeters, cm) under the wind conditions of May 7, 2018, at 12:00 p.m. Coordinated Universal Time. The assumed plume height (in kilometers, km), duration, and erupted volume (in cubic kilometers of dense rock equivalent) used in the simulation are listed in the upper left. In this scenario, the maximum thickness is predicted to be less than 1 cm (<0.5 inches) at a distance of less than 5 km (3 miles) from the vent.

Uncertainties

Many aspects of this analysis have a high degree of uncertainty, which are discussed here.

1. *Time when the lava column reaches the water table.*—The current rate of lava subsidence (~2 m/h) is derived from only five days of observations. We do not fully understand why the magma reservoir is steadily draining, or how long it will continue to drain. The subsidence rate will likely change in coming days, but when, how much, and whether the rate will increase or decrease are all unknown. The rate may or may not be directly impacted by changes in the ongoing lower East Rift Zone eruption. The depth of the water table is also known only from observations in a research well located 1.5 km (0.9 mi) south of the lava lake. Details of the water table in the immediate vicinity of the lava lake are not well known.

2. *How long until water begins to interact with hot rock.*—As rock around the conduit cools, water will migrate towards the conduit; the duration of this process is not known.

3. *Whether or not conditions will produce explosions.*—Explosions are believed to require pressurization as water is heated to steam by magma. Crater walls may collapse and block the conduit, causing pressurization of steam. Alternatively, rapid mixing could produce steam and increase pressure even when confinement is poor. These processes are not well understood globally, and the timing of their occurrence (if they do occur) may be impossible to predict.

4. *How large explosions will be.*—Above we have outlined the two most credible scales for future explosions, that is, small and moderate events.

5. *How long such explosions will continue.*—Individual explosions may last minutes to tens of minutes. Episodes of historical explosive activity have lasted days (in 2008) to weeks (in 1924). Repeated episodes have persisted for longer only when the caldera floor was below the water table.

Conclusions

Interaction of magma, hot rock, and groundwater as the Halema‘uma‘u lava lake recedes deeper into the volcano is likely and has the potential to produce sudden and largely unpredictable explosions. Individual explosions may be brief (minutes) but may occur in sequences or clusters lasting weeks or longer. This process could begin as early as mid-May 2018 and may result in intermittently hazardous conditions in and around the summit of Kīlauea Volcano.

The onset of such activity will likely be abrupt and follow quickly after some triggering event; for example, collapse and blockage of the deepening crater. It is not certain that the Hawaiian Volcano Observatory will receive signals in monitoring data (earthquakes or tremor) that suggest the onset of this activity. Once the lava level reaches the groundwater elevation, the onset of continuous ashy plumes or a sequence of violent steam-driven blasts may be the first sign that activity of concern has commenced.

Chapter C. Volcanic Hazard at the Summit of Kīlauea; June 29, 2018, Update

By the Hawaiian Volcano Observatory

Introduction

This document is a guide for understanding current activity and hazards at and around the summit of Kīlauea Volcano. Here, we summarize activity from late April through the present (June 29, 2018), 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, owing to rift opening associated with the magnitude 6.9 earthquake on May 4, 2018). Reservoir deflation caused the floor of the caldera to subside at a rate of 6–8 centimeters per day (2–3 inches per day) near the overlook vent within Halemaʻumaʻu, and the lava lake to drop out of sight around May 10—more than 320 meters (m; 1,000 feet [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 Halemaʻumaʻu Overlook vent, causing rockfalls that 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 events.

Early collapse/explosion 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 (fig. 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

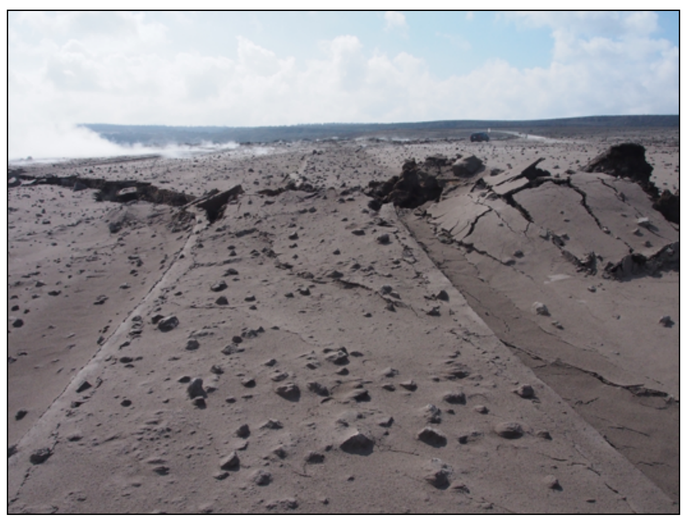

Figure 1. Photograph of the parking lot of the former Halemaʻumaʻu Overlook (closed since 2008) taken on June 8, 2018, showing disturbances caused by 2018 explosive eruptions. The rocks were ejected from the vent as ballistic projectiles—those in the median (center) were ejected in either 1924 or 2018, and those in the parking bays (left and right) were ejected in 2018. The gray color reflects that of 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 form by stresses and slumping associated with widening of Halemaʻumaʻu crater.

exsolution, expansion, and release of gases that were dissolved in the magma. Collapse/explosion events have occurred semiregularly with repose periods (time between events) of about 0.5 to 2 days. Seismicity increases in the hours preceding explosions, leading to cycles of earthquakes that are felt in the summit area (fig. 2).

The mechanism producing collapse/explosion 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 the surrounding Kīlauea Caldera[4] slump down into the shallow magma reservoir in a collapse/explosion event. The rock that 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 section on historical analogs).

In this way, magma evacuation is accompanied by relatively nonhazardous 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 (figs. 1 and 3), and, since May 29, a Global Positioning System (GPS) station near the north rim of Halema‘uma‘u crater dropped more than 100 m (330 ft) during collapse/explosion events.

At the end of May, collapse of rock from surrounding crater walls blocked the Halema‘uma‘u 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, collapse/explosion events generally have produced only weak ash plumes that do not rise higher than 6,000 ft 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; deformation has become more localized around Halema‘uma‘u crater and occurs at a higher rate. At the current time, subsidence of the caldera continues at a high rate owing to magma withdrawal from the Halema‘uma‘u magma reservoir.

Possible Outcomes

Ground subsidence will continue for as long as magma is withdrawn from the summit reservoir(s) at a rate that exceeds 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 for, see the section on time frames.

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 ft above sea level. As the reservoir deflates, cracking and slumping is gradually engulfing a broader extent of Kīlauea Caldera (as observed

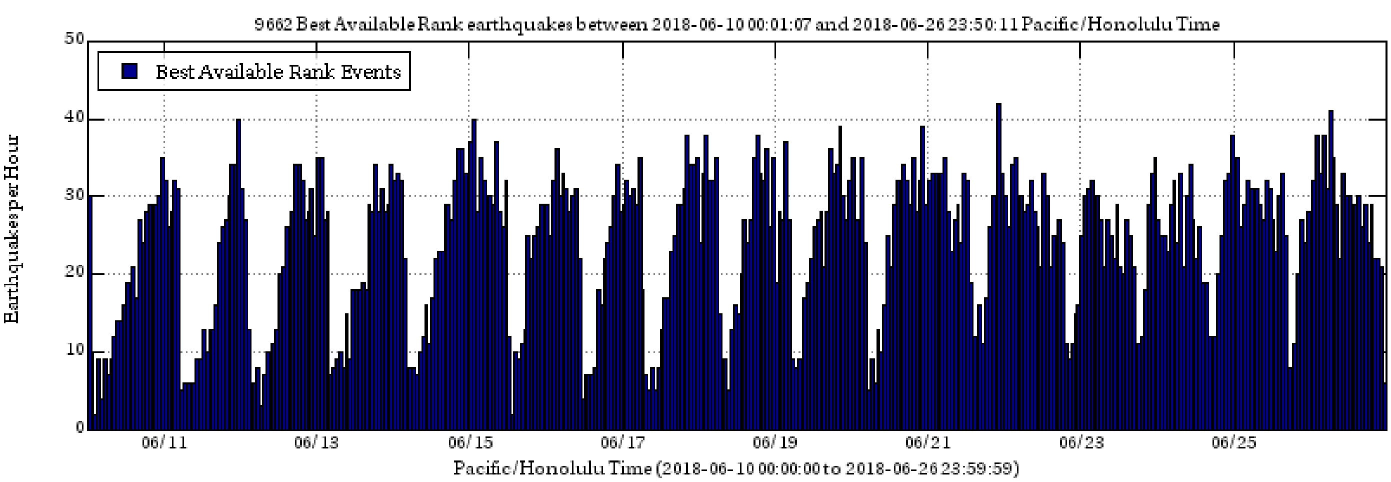

Figure 2. Plot of the number of earthquakes recorded per hour at the summit of Kīlauea from June 10 to June 26, 2018. A clear pattern of high and low seismicity rates is evident. Most of these earthquakes are far too small to be felt by nearby residents.

[4]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 Kīlauea 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.

in high rates of ground deformation and propagating cracks around Halemaʻumaʻu); this process will likely continue to enlarge Halemaʻumaʻu 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 Halemaʻumaʻu wall could abruptly collapse into the crater. Because a broad region east and northeast of Halemaʻumaʻu is currently deforming, it is difficult to predict how large such a collapse might be or its impact on explosion hazards. Most likely, such an event would generate strong seismic shaking and a robust ash plume.

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

- Damaging earthquakes—potentially exceeding magnitude 5 (hazards discussed more fully in the section on potential hazards),
- Ash plumes and ashfall (associated with collapse/explosion events and large rockfalls),
- Large and sudden collapses into the expanding Halemaʻumaʻu crater,
- Ground cracking and continued rockfall activity along steep caldera walls, and
- Vog (although sulfur dioxide output is approaching low pre-2008 levels).

Less Likely Outcomes for the Immediate Future (up to Two Months)

Several mechanisms could change the nature of activity and associated hazards. These are considered less likely but cannot be ruled out. 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 during ongoing subsidence and enlargement of Halemaʻumaʻu, and (2) sudden collapse of the larger caldera system. This list may not include all possible future outcomes and hazards.

1. *Larger explosions during ongoing subsidence.*—Activity in and around Halemaʻumaʻu 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 collapse/explosion 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).

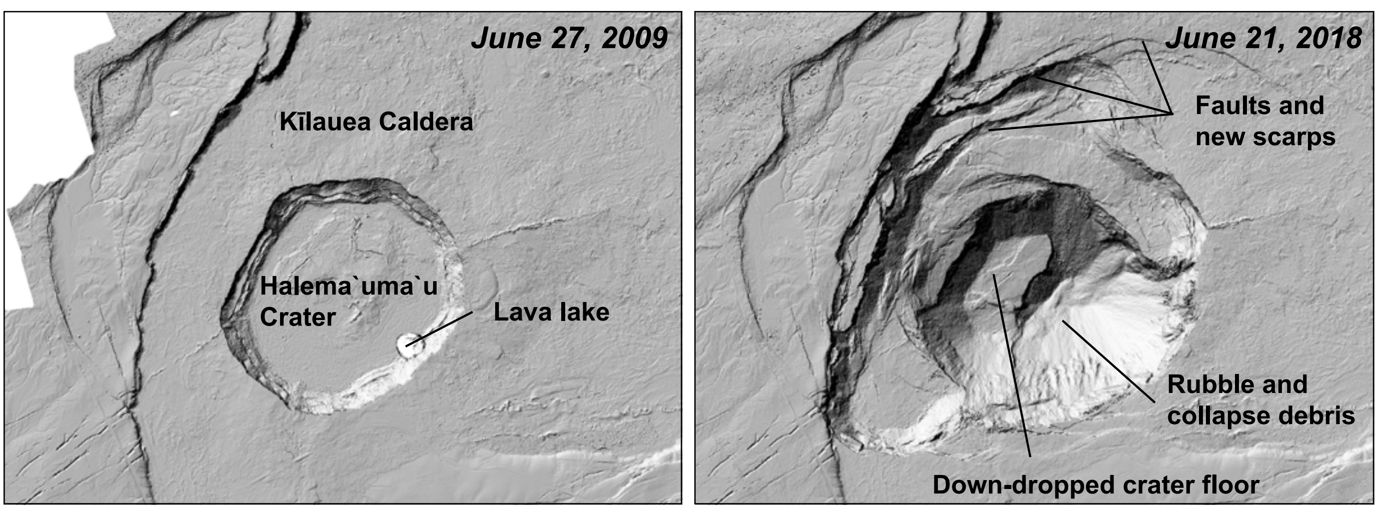

Figure 3. Comparison of the topography of Halemaʻumaʻu Crater in 2009 (*left*) and on June 21, 2018 (*right*). The 2018 data are from a photogrammetric survey of Kīlauea's summit by the U.S. Department of Interior Unoccupied Aircraft Systems' (UAS) Kīlauea response team. Since April, extensive cracking and faulting has occurred around the crater, which has enlarged through collapses of wallrock. The depth of the crater floor has increased by more than 350 meters (1,100 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.

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 owing 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 about 600–900 m (similar distance in 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 formed from ground shaking. Additional hazards associated with rapid, broad-scale caldera collapse could include high lava fountains and larger and more dangerous explosions that produce 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. Though every eruption is unique, these events can help inform our thinking about the current activity at Kīlauea. Collapses of summit calderas—caused by 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 Islands, 1968), Plosky 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 and (or) intrusions similar to what is occurring in the lower ERZ at Kīlauea. Moderate to large summit explosions at Miyakejima and Fernandina produced widespread ashfall and ballistics as far as 2 kilometers (km; 1.2 miles [mi]) 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 repeated 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 cubic kilometers (0.02–0.5 cubic miles), compared to a collapse volume of approximately 0.3 cubic kilometers (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 caused by earthquakes and explosions. These hazards are closely related but here we address them separately.

Earthquakes and Ground Cracking

During recent weeks, earthquakes at Kīlauea's summit have occurred in swarms associated with collapse/explosion events.

- *Earthquake swarms.*—As many as 40 earthquakes per hour have been recorded during earthquake swarms preceding collapse/explosion events (fig. 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 (fig. 4). Overall, more than 500 earthquakes per day have been recorded in the Kīlauea summit region during recent weeks. Felt earthquake event rates have exceeded 30 earthquakes per day at and around the summit.
- *Collapse/explosion events*.—Energy released during collapse/explosion 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 magnitude-5 earthquakes. Regardless, shaking can be strong and possibly damaging near the summit.
- *Other tectonic earthquakes*.—Strong earthquakes can occur at any time, and the risk of these events is larger now owing to ongoing stress changes in and around the caldera. These earthquakes will not necessarily occur during swarm seismicity or in association with collapse/explosion 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 and culminate in a collapse/explosion 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, Hawai‘i.

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/ for more information). During earthquakes, it is wise to drop, cover, and hold on. With more than six weeks of heightened seismic activity, structures are, in some cases, already weakened from strong shaking. Ongoing earthquake activity can damage these further, especially close to the summit in Hawai‘i Volcanoes National Park and the Volcano Golf Course areas. Ground cracks, rockfalls, and damage to roads, trails, rock walls, buildings, utilities, and water pipes may also occur.

Gas Emissions

Emissions of sulfur dioxide (SO_2) from Kīlauea’s summit are currently relatively low. This may possibly be 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 lower ERZ 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 volcanic air pollution (or vog), which is carried to downwind communities.

Explosions and High Lava Fountains

Explosions at Kīlauea’s summit during 2018 have produced only minor ashfall and limited ballistic deposits. As previously described, 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 that occur in distinct geographical zones: (1) ballistic projectiles, (2) ashfall, (3) fallout from high lava fountains,

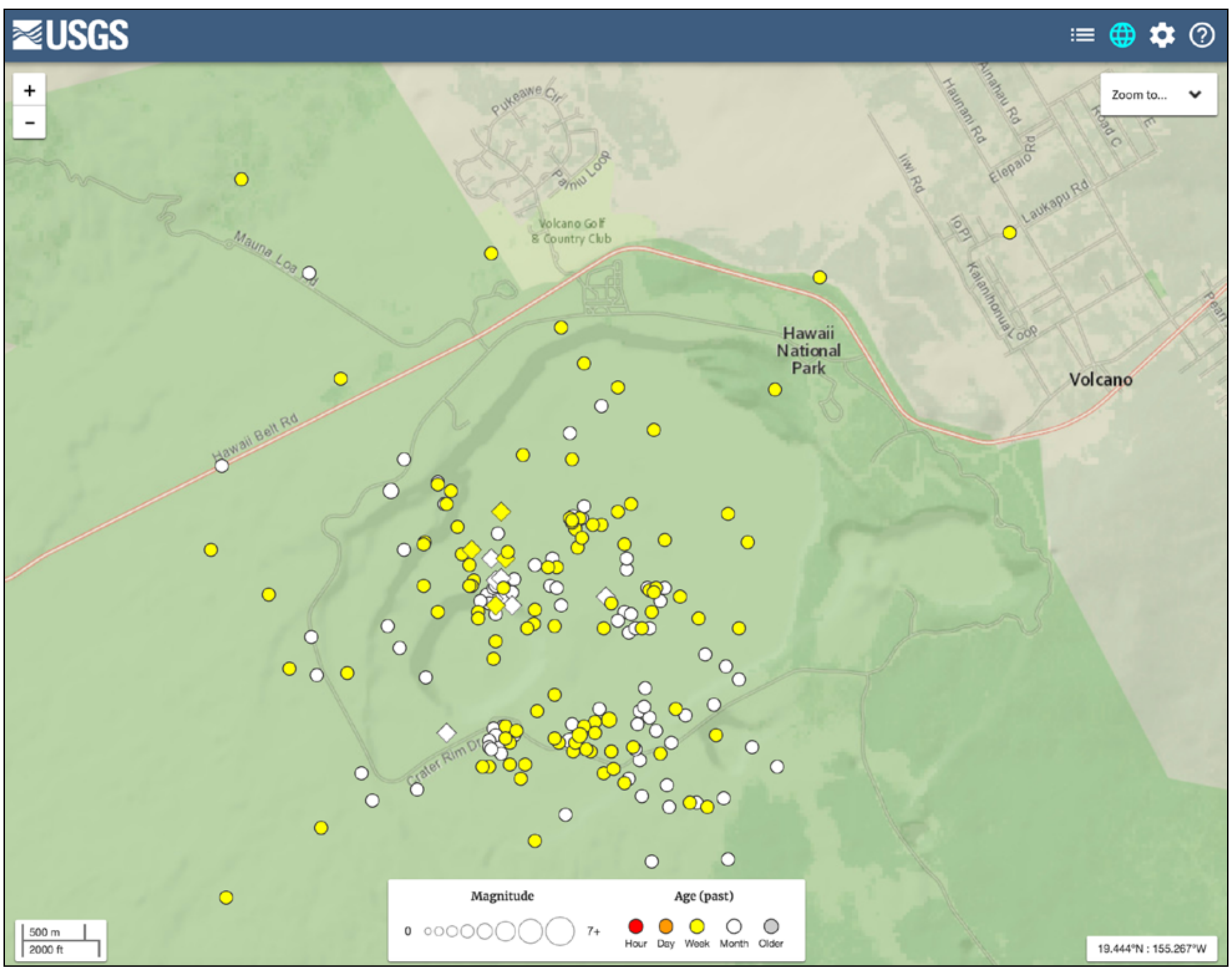

Figure 4. Map of the location of earthquakes that are magnitude 3 and greater at the Kīlauea summit region from June 1 to June 15, 2018.

and (4) pyroclastic surges. Hazards associated with ballistic projectiles and ashfall were detailed in a previous document[5] so are reviewed only briefly here. Pyroclastic surge and high lava fountain hazards were not previously described because of their very low probability of occurrence.

1. *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 collapse/explosion events but are not currently being ejected from the vent.

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

3. *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 centimeters (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.

4. *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 miles per hour). Surges usually extend radially from the vent in all directions, but can be influenced by topography, thickening in valleys and thinning over topographic highs. Owing to their high heat and 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 mid-1500s and 1790 A.D. Surges in and just before 1790 extended 3–5 km (1.8–3 mi) 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 about 5 km (3 mi) from the center of the caldera is susceptible to surges if they were to occur (fig. 5). At present, Kīlauea is not producing any sustained eruption columns even during the largest collapse/explosion events.

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 lower East Rift Zone (LERZ) rather than filling storage space (independent 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

[5]Chapter B of this report by K. Anderson and others.

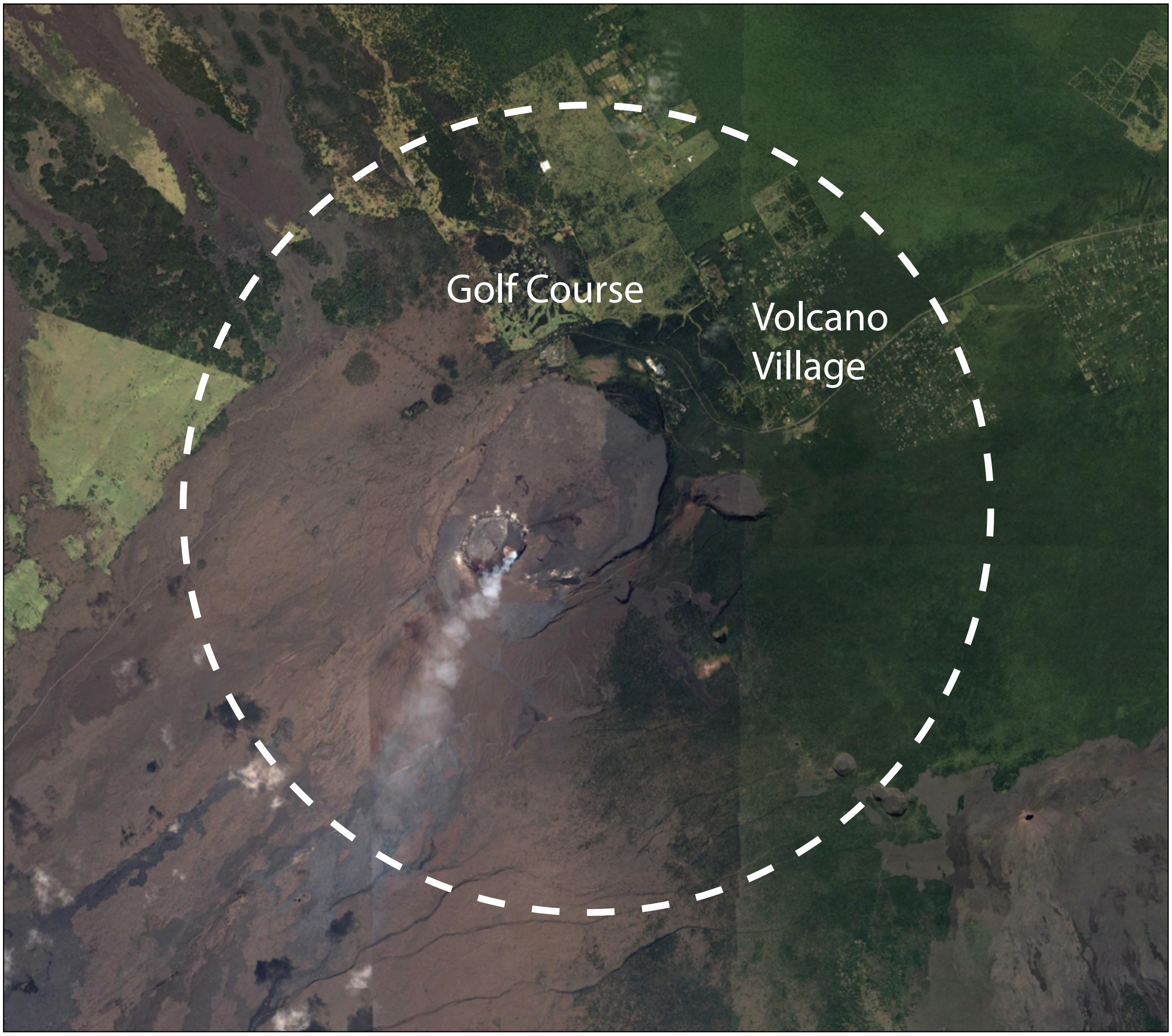

Figure 5. Map of the approximate boundary of the pyroclastic surge zone at the summit of Kīlauea (white dashed line). For simplicity, we assume a source near the center of the caldera. The boundary shows only the maximum reasonable distance a surge would travel from the caldera as inferred from past 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). Base map image from Google Earth © 2018.

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 lower East Rift Zone 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. The Hawaiian Volcano Observatory should recognize these warning signs by direct observation and instrumental monitoring and, should they be detected, will alert authorities and the public.

Message from Hawai‘i 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.

Chapter D. Preliminary Analysis of the Ongoing Lower East Rift Zone Eruption of Kīlauea Volcano—Fissure 8 Prognosis and Ongoing Hazards

By the Hawaiian Volcano Observatory

Introduction

In late April 2018, the long-lived Puʻu ʻŌʻō vent collapsed, setting off a chain of events that would result in a vigorous eruption in the lower East Rift Zone (LERZ) of Kīlauea Volcano, as well as the draining of the summit lava lake and magmatic system and the subsequent collapse of much of the Kīlauea caldera floor. Both events originated in Lava Flow Hazard Zone 1 (Wright and others, 1992), which encompasses the part of the volcano that is most frequently affected by volcanic activity.

We examine here the possible and potential impacts of the ongoing eruptive activity in the LERZ of Kīlauea Volcano, and specifically activity at fissure 8 (fig. 1). Fissure 8 has been the dominant lava producer during the 2018 LERZ eruption, which began on May 3, 2018, in Leilani Estates, following intrusion of magma from the middle and upper East Rift Zone, as well as the volcano's summit, into the LERZ. The onset of downrift intrusion was accompanied by collapse of the Puʻu ʻŌʻō vent, which started on April 30 and lasted several days. Kīlauea Volcano's shallow summit magma reservoir began deflating on about May 2, illustrating the magmatic connection between the LERZ and the summit. Early LERZ fissures erupted cooler lava that had likely been stored within the East Rift Zone, but was pushed out in front of hotter magma arriving from farther uprift. This hotter magma, similar in composition to lava that had been erupting at Puʻu ʻŌʻō, arrived in mid-May, coincident with an increase in discharge from the fissures.

The volume of lava erupted during the current activity exceeds that of many past eruptions. Given this volume and the sustained withdrawal of magma from the summit reservoir without appreciable deformation in the LERZ, it is most likely that the LERZ eruption may continue for months to years. Whereas additional fissures may form either uprift or downrift of the current activity at fissure 8, the continued focus of activity within the current fissure system after 10 weeks of activity (as of July 15, 2018) makes this scenario increasingly unlikely. This document reviews current activity, focusing on the fissure 8 vent, channel, and ocean entry. It describes a credible set of future scenarios for fissure 8 and discusses uncertainties. This document is meant as a guide for managing hazards and risks in Kīlauea's East Rift Zone.

Summary of Activity for April 30–July 15, 2018

In early 2018, the lava lake in a small pit crater within Halemaʻumaʻu crater rose to high levels, overflowing a few times. On April 30, the Puʻu ʻŌʻō vent in the middle East Rift Zone began to collapse, and seismicity and deformation migrated downrift, signifying an intrusion of magma into the LERZ beneath the Leilani Estates subdivision. Cracks began to form within the subdivision during the next few days.

An eruption started on May 3 with brief spattering from a fissure in the southeastern portion of the subdivision. Additional short-lived fissures opened along a 6.7-kilometer (4.2-mile) stretch of the LERZ and erupted sporadically, both uprift and downrift, over the following week, and produced only small, viscous flows.

There was a marked increase in the vigor of the eruption starting on May 18, coincident with the production of more fluid lava. Activity became longer lived, and large, fast-moving channelized flows were produced that first reached the ocean along Kīlauea's southeast coast on May 20, but remained active for only a few days. Activity eventually coalesced at fissure 8 and the other fissures became inactive or sporadically weakly active through June.

Fissure 8 was first active May 5 but reactivated during the third week of May with episodic spattering and began to erupt with a vigorous fountain late in the day on May 27, producing a relatively fast-moving channelized flow that travelled northeast. The fountain abruptly stopped the following morning (May 28), and the flow it fed stalled after crossing Pohoiki Road. The fissure 8 fountain restarted later the same day, however, and began feeding a new fast-moving, channelized flow northeast and depositing tephra downwind. This new flow crossed Pohoiki Road early the next morning (May 29) and Highway 132 in the afternoon, isolating Puna Geothermal Venture.

The fissure 8 channelized flow continued to advance rapidly downslope over the following days, reaching the ocean at Kapoho Bay late in the day on June 3. The flow filled the bay and spread along the coast quickly, destroying hundreds of homes and the tide pools south of Kapoho Bay.

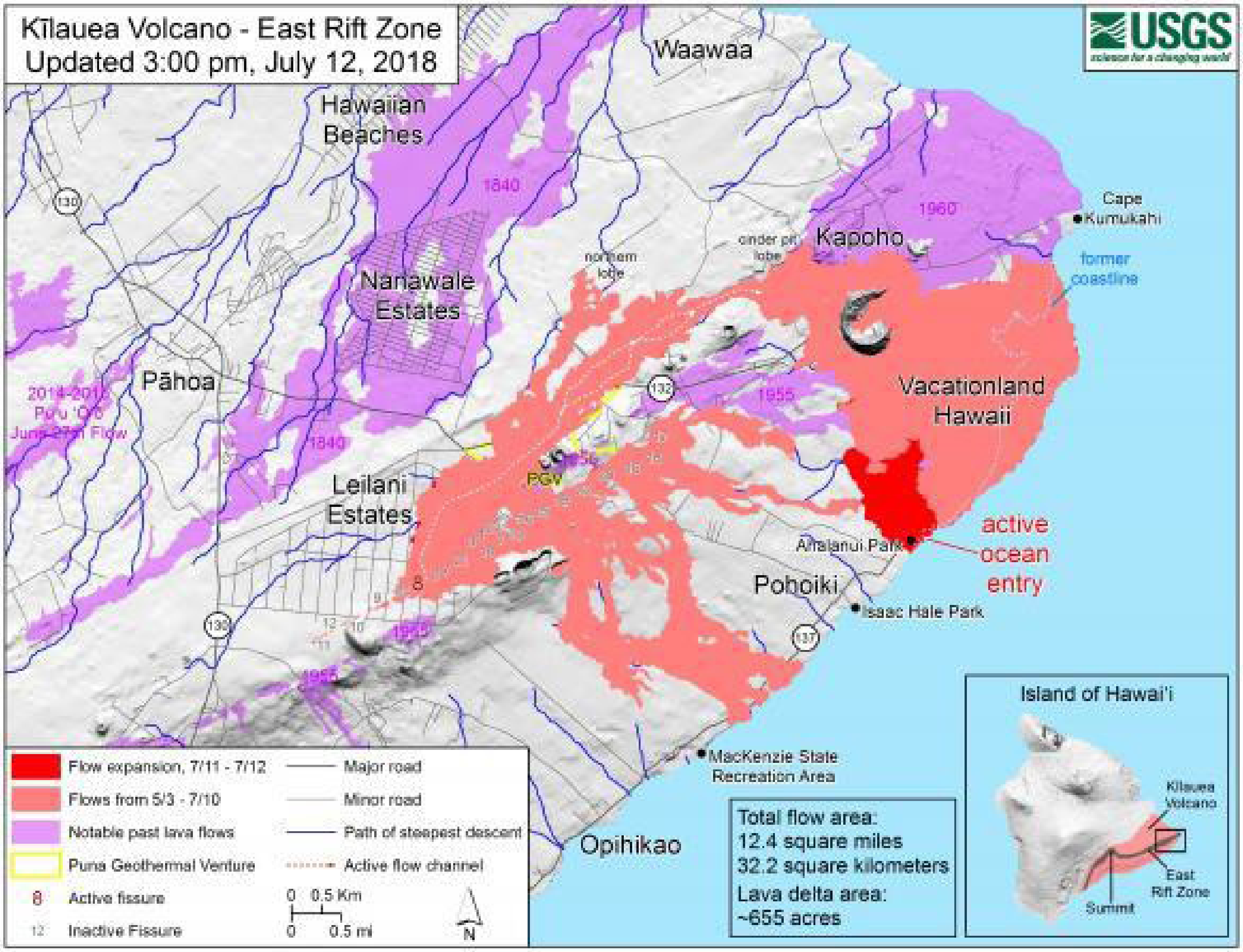

Figure 1. Example map of the 2018 eruption of Kīlauea's lower East Rift Zone updated on July 12, 2018. Lava flows from the current eruption are shown in pink (flows from May 3–July 10) and red (July 11–12) and lava flows from the 1840, 1955, 1960, and 2014–2015 eruptions are in purple.

Fountaining and spattering from fissure 8 began constructing a spatter cone (fig. 2), which by the end of June was about 55 meters (m; or 180 feet, ft) high and open to the northeast. Discharge from the vent continues to feed directly into the relatively stable channel, which carries lava 13 kilometers (km) to the ocean. Although difficult to measure, the most plausible estimates of the eruption rate from fissure 8 range from 50 to 150 cubic meters per second.

After several blockages and subsequent clearing or channel rerouting around the blockage to keep the channel flowing to the north and east of Kapoho Crater, the channel overflowed just northwest of Kapoho Crater and a new lobe advanced southward along the west margin of the previous flow and entered the ocean on July 12. This diversion of the channel flow was the first major change in the fissure 8 channel. Even though the channel no longer directly fed the massive lava delta to the southeast of Kapoho Crater, lava continues to ooze out of the flow front into the ocean in many locations.

Ongoing Fissure 8 Hazards

The upper 4 km of the channel (fig. 3) stand 16–22 m above ground level and are as much as 400 m wide. The middle section of the channel is braided and fairly narrow, whereas the lower section merges again into a single channel feeding a gradually thickening and spreading ʻaʻā flow at the coast. The main hazard from the source cone and the channel system is failure of the cone or channel walls or blockage of the channel where it divides into narrower braids. Either could divert most, if not all, of the lava to a new course depending on where the breach occurs.

Areas Potentially Threatened by Fissure 8 Channel Blockages or Failures

Estimates of future potential flow paths are made here for three areas along the north edge of the fissure 8 channel system

Figure 2. Photograph of fissure 8 lava fountains within the cinder and spatter cone feeding a wide channelized flow. U.S. Geological Survey photograph taken on June 22, 2018.

using drainage areas and the steepest descent lines calculated from a 10-m resolution digital elevation model. The drainage areas, here called lavasheds (fig. 4; Kauahikaua and others, 2003), define the areas in which fluids flow toward a steepest descent line (fig. 4; Kauahikaua and others, 2016).

Only flows to the north of the existing channel system will be considered because, as of the writing of this report, residents to the south have been evacuated whereas residents to the north have not.

Upper Channel

Any major flow caused by a breach of the west wall of the channel between the vent (location A in fig. 4) and the intersection of Pohoiki Road and Highway 132 (location B in fig. 4) is likely to advance northeast into lavashed 1, hugging the northeast edge of the existing flow. Beyond Highway 132, the flow may enter lavashed 2 and become captured by steepest descent lines that pass along the eastern boundary of the Nānāwale Estates subdivision (along Road A and possibly Seaview Road). If the flow continues to advance, it will ultimately cross Railroad Avenue and Government Beach Road, enter lavashed 3, and reach the ocean between 1.3 and 2.3 km southeast of Kahakai Boulevard (Hawaiian Beaches). If the flow enters lavashed 2 and stalls, subsequent lava flows advancing along the west side of the stalled

Figure 3. Photograph of the upper part of the fissure 8 channel. The view is to the northeast. Lava is flowing from lower right to upper center of the image. U.S. Geological Survey photograph taken on June 22, 2018.

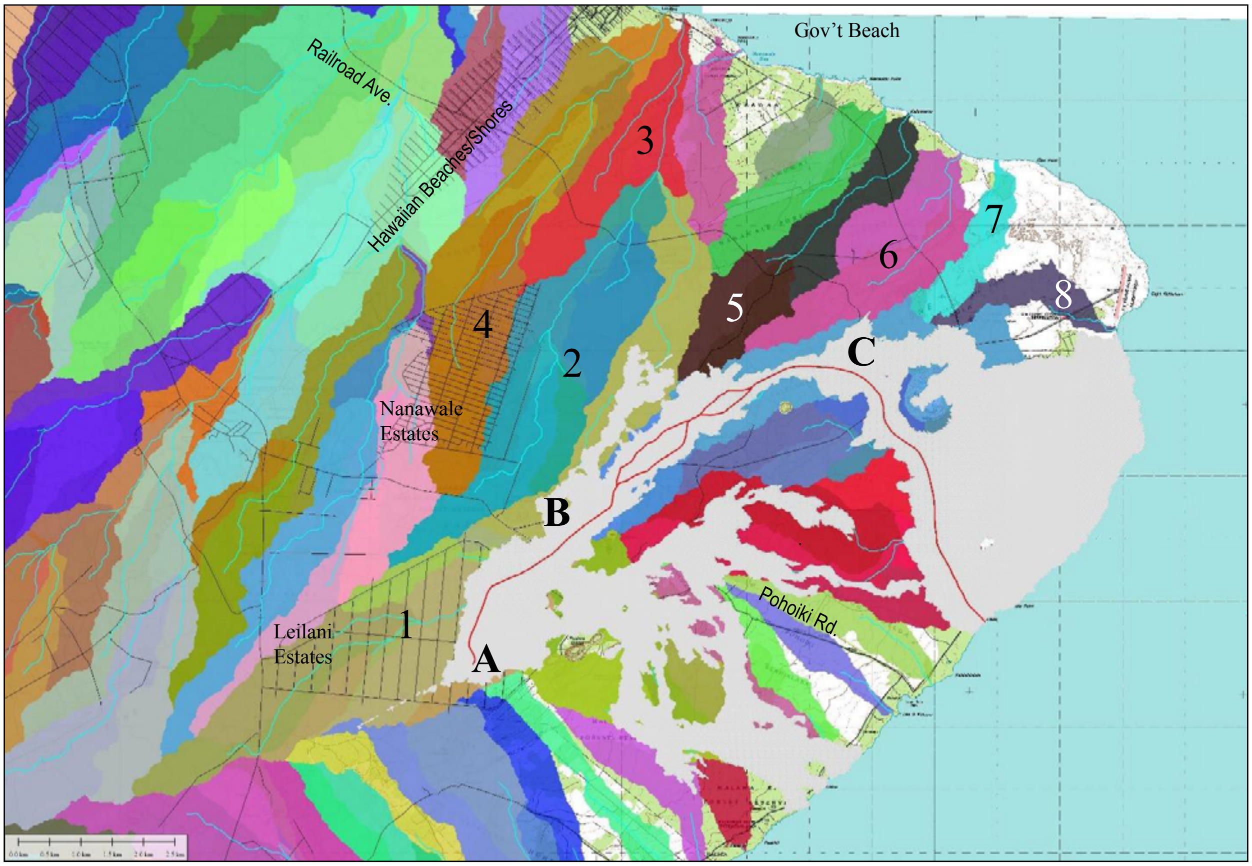

Figure 4. Map of lavasheds—lava drainage areas—that drain through steepest descent lines (light blue lines). The numbered lavasheds are described in the text. The gray area shows the erupted lava from all fissures of the 2018 eruption as of July 12, 2018, and the red line within represents the fissure 8 channel system on that same date.

flow could enter lavashed 4 in Nānāwale Estates subdivision and ultimately reach the coast slightly closer to the Hawaiian Beaches and Hawaiian Shores subdivisions.

Middle Channel

The fissure 8 channel becomes braided northeast of location B (in fig. 4), with narrower sections that could form choke points. If one of the narrower sections becomes blocked by large collapse fragments from the channel wall or spatter cone, lava could be diverted out of the channel. If, in this scenario, part of the channel is redirected to the north, lava could feed into lavasheds 5 or 6 and threaten homes and infrastructure in the Noni Farms area, as well as cross Railroad Avenue, Papaya Farms Road, and Government Beach Road before entering the ocean between Kalamanu and the northern edge of the 1960 lava flow.

Lower Channel

The ʻaʻā channel has been unstable in the area of Kapoho Crater (location C in fig. 4) and beyond to the ocean. Most recently, on July 9–10, a channel overflow in the area northwest of Kapoho Crater created a new lobe that advanced south along the west margin of the existing flow and entered the ocean on July 12, destroying a school and a beach park; however, the previous flow to the northeast continued to ooze lava into the ocean along its entire front. Although not fed by any surface flow, the earlier flow north and east of Kapoho Crater to the ocean is still oozing lava into the ocean from its front and could potentially thicken and widen beyond the current flow margins—as it has in the past several weeks. Flows advancing from a breach in the northeast side of the channel near Kapoho Crater may enter lavasheds 7 or 8 and again threaten the handful of remaining structures in the Kapoho Agricultural and Beach Lots, structures built on the eastern section of the 1960 lava flow, and the Cape Kumukahi Lighthouse.

Gas and Tephra Hazards

Vog

Volcanic gas emissions (or vog) from the fissure 8 vent (fig. 5) have continued to be unusually high since mid-May (over 30,000 metric tons per day—more than 4 times the average daily amount from Kīlauea's summit lava lake prior to

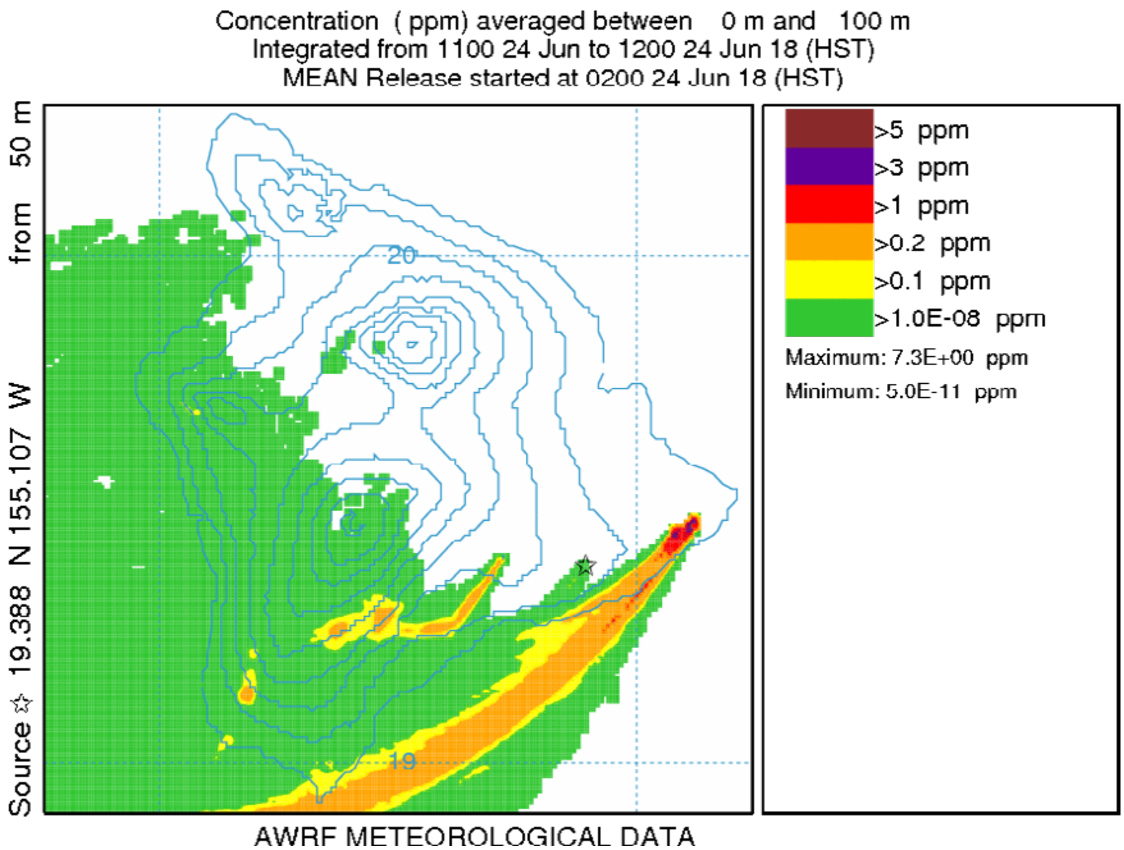

Figure 5. Example map of the SO_2 forecast for the Island of Hawai‘i on June 24, 2018, posted at http://weather.hawaii.edu/vmap/hysplit/. The warm colors show elevated SO_2 levels (in parts per million, ppm) and the blue lines show topographic relief.

May 3, 2018), coincident with the increase in eruptive vigor. This has caused a significant increase of vog in downwind areas, including the Kailua Kona coast. When trade winds slacken, easterly and southeasterly winds can blow gases into areas on the east side of the Island of Hawai‘i. Fissure 8 is now the dominant producer of volcanic gas on the Island of Hawai‘i and will remain so as long as current rates of eruption continue.

Increased Distribution of Tephra Fall

At the moment, lava from fissure 8 erupts from a 60- to 80-m-long fissure segment. Discharge from the fissure was initially characterized by relatively steady low fountaining but has evolved into more chaotic Strombolian activity (large bubble bursts). If the eruption begins to coalesce into a single point along the fissure, higher fountains (100–300 m) could be produced, which would result in more widespread deposition of Pele’s hair and cinder. Pele’s hair has already been reported several times in Pāhoa (about 5 km [3 miles, mi] northwest of fissure 8 lava fountains) during slack or southerly winds. Both the 1955 and 1960 eruptions in the same general area produced lava fountains much higher than what has yet occurred during the current eruption.

Tephra fall from 100- to 300-m-tall fountains could produce a 30-centimeter (1-ft) deposit several hundred meters (similar distance in yards) downwind. This deposit may be thinner if the wind is variable and spreads the tephra laterally. Previous eruptions produced a 30-centimeter (1-ft) thick deposit as far as 625 m (2,000 ft) downwind from the vent at Kīlauea Iki Crater, 1.6 km (1 mi) downwind from the vent at Mauna Ulu, and 900 m (3,000 ft) from the vent at Pu‘u ‘Ō‘ō.

Ocean Entry Hazards

See chapter A of this report on the Kamokuna ocean entry for more detailed information.

Delta Collapse

The entry of lava into the ocean at Kapoho Bay (fig. 6) has built a 6-km-wide lava delta that now extends as far as 800 m (0.5 mi) from the pre-eruption coastline of Kapoho Bay. As with any lava delta, there is the potential for collapse without warning, which could lead to explosions caused by the interaction of seawater with hot rock exposed by the collapse.

Figure 6. Photograph of the lava delta at Kapoho Bay (looking south) built by lavas traveling 8 miles from fissure 8, which can be seen erupting in the distance (orange spot in upper right). U.S. Geological Survey photograph taken on June 18, 2018.

Hydrovolcanic Explosions

Boat tours, as well as observers in the air, have reported hydrovolcanic explosions occurring without warning as far as 100 m offshore. These events, which last 10–15 seconds, have been observed rarely, but may occur several times per day. They burst through the water, sending fragments of lava and hot water 25 to 100s of meters high. It is likely they are caused by the underwater emplacement of ‘a‘ā lava, where large amounts of molten lava suddenly come in contact with seawater during collapse of a lava conduit.

Both delta collapse and hydrovolcanic explosions are primarily hazardous only to boats and other watercraft because this area is currently closed to foot traffic. Based on an extensive study of these coastal hazards during the 35-year eruption of the Pu‘u ‘Ō‘ō vent, a zone with a radius of 300 m is considered a minimum high-hazard area around pāhoehoe lava deltas (Mattox and Mangan, 1997; chapter A of this report). The 2018 Kapoho Bay lava delta is composed of ‘a‘ā lava and more study will be required to determine whether this high-hazard margin should be modified.

Laze Plume

The large lava haze (or laze) plume (fig. 7) produced at the ocean entry poses a health risk to those exposed to it. It will continue as long as lava enters the ocean. The composition of the plume is the result of the interaction between molten basaltic lava and sea water and includes hydrochloric acid, hydrofluoric acid, and halide precipitate. It is not known how far downwind harmful constituents drift in a laze plume of this size. At times, onshore winds carry the laze plume an unknown distance inland.

Figure 7. Photograph of the laze (lava haze) plume from the fissure 8 ocean entry (leftmost incandescence) lit by the source fountain (rightmost incandescence) and lava channel. White lights to the far right are from Pāhoa. Photograph taken on the evening of June 20, 2018, by Klaus Hodapp (University of Hawai‘i at Mānoa).

How Long Will This Eruption Last?

The current eruption started with 23 days of sporadic eruption from 24 different fissures that covered a distance of 6.7 km (4.2 mi), some composed of multiple segments, before focusing at fissure 8, which has been erupting continuously since May 27. More than 430×10^6 cubic meters (m^3) of lava has erupted so far (as of July 15). Most of this volume has come from fissure 8, which is discharging lava at an estimated rate of about 100 cubic meters per second (m^3/s). This exceeds the duration (38 days), erupted volume (122×10^6 m^3 of lava), and peak time-averaged eruption rate (38 m^3/s for the first 2 weeks) of the 1960 eruption. Whereas the current eruption has not yet lasted as long as the 1955 eruption (88 days, including pauses), it has erupted far more lava at a higher rate; the 1955 eruption produced 81×10^6 m^3 of lava at a peak time-averaged discharge rate of 31 m^3/s (for the first phase of the 1955 eruption). In this regard, the current eruption may be more similar to the 1840 eruption, which, though only lasting for 26 days, erupted 210×10^6 m^3 of lava at a time-averaged discharge rate (for the entire eruption) of 94 m^3/s. See appendix for brief overviews of the 1840, 1955, and 1960 eruptions, as well as the 1924 intrusion event.

A glance around the LERZ reveals numerous large pyroclastic cones, indicating repeated volcanic activity in this area. Pu‘u Kali‘u, which borders the southern edge of Leilani Estates, and a younger vent complex that overlies it, are both very close to the location of the current fissures. Both of these older eruptions are thought to have produced about 200×10^6 m^3 of lava (Moore, 1992). Other eruptions in the area, including flows erupted in the late 1700s, may have produced similar volumes. Perhaps eruptions in the LERZ only continue until pressure in the magmatic system, partly controlled by vent elevation, becomes too low to sustain the eruption. The volume of the current eruption has exceeded that of these older nearby eruptions. The steady discharge from fissure 8 shows no sign of waning supply, suggesting relatively constant magma pressure; the lack of significant ground deformation in this area shows that there is neither storage nor withdrawal from the May intrusion since its initial emplacement.

If the ongoing eruption maintains its current style of activity at a high eruption rate, then it may take months to a year or two to wind down. Whereas this seems to be the most likely outcome, a pause in the eruption, followed by additional activity, cannot be ruled out, nor can an abrupt cessation or a transition to steady, longer lived activity at a lower effusion rate.

The shield complex of Heiheiahulu, located 9.5 km (6 mi) upslope of fissure 8, represents a more voluminous eruption that could have lasted several years (Moore, 1992), similar to the 35-year-long eruption of Pu‘u ‘Ō‘ō. Both of these eruptions started with several short ‘a‘ā flows erupted along a 3.5 km (2.2 mi) and 7 km (4.3 mi) long fissure system, respectively, before centralizing to a single vent (Moore, 1992; Wolfe and others, 1988) and eventually erupting tube-fed pāhoehoe flows. The 2018 LERZ eruption has erupted only ‘a‘ā flows so far but the eruption rate is high, and a stable channel system is being elevated by frequent spillovers of pāhoehoe flows above Kapoho Crater. The flow maintains its ‘a‘ā character below that point to the ocean, where a pastier lava oozes from its interior along its edges. A change in the character of the channel toward pāhoehoe, if it occurs, could signal a gradual change of eruption style and a potentially longer eruption with more destruction of infrastructure.

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Appendix. Comparisons to Other Eruptions Along the Lower East Rift Zone

The ongoing 2018 lower East Rift Zone (LERZ) eruption is occurring in a similar location to the 1840, 1955, and 1960 LERZ eruptions, as well as the location of intrusive activity in 1924. Discharge or effusion rates during the peak phases of the 1955 and 1960 eruptions are very similar to that occurring now. The onset of the current activity, with fissures opening both uprift and downrift from the initial outbreak, shifting back and forth amongst these fissures, and starting and stopping erratically, was similar to the 1955 and the 1960 eruptions, although the 1960 fissure system was considerably shorter, so the effects of the eruption were more focused. The start of the current eruption prior to the continuous eruption of fissure 8 that started on May 27, resembles the beginning of the 1955 eruption, but ramped up more slowly and was more chaotic. The current eruption has not yet produced high (>50 meter) fountains similar to those of the 1955 and 1960 eruptions, and instead has evolved into a relatively steady eruption at fissure 8 characterized by low fountaining and Strombolian activity that feeds a large-volume channelized flow.

1840 Eruption, May 30–June 24

Observations of the 1840 lower East Rift Zone eruption are described by Coan (1841) and are repeated here. The 1840 eruption started in the upper East Rift Zone and quickly migrated to a fissure just west of present-day Pāhoa. T. Coan writes, “On Monday, June 1st, the stream began to flow off in a northeasterly direction and on the following Wednesday, June 3d, at evening, the burning river reached the sea having averaged about half a mile an hour in its progress...Sometimes it is supposed to have moved five miles an hour, and at other times...make no apparent progress...For three weeks this terrific river disgorged itself into the sea with little abatement.”

The fissure sources extended about 6.1 kilometers (km) (3.8 miles, mi) along a northeast-southwest trend parallel to, and 2.6 km (1.6 mi) northwest of, the 2018 fissure system. The volume of the 1840 flow was more recently estimated to be 210×10^6 cubic meters (m^3) at an average rate of 94 cubic meters per second (m^3/s) over 26 days of the eruption. The distance from fissure vent to coast is about 11 km (7 mi) for an average initial advance rate of 150–230 meters per hour (170–250 yards per hour).

Also of interest were the changes at Kīlauea summit just before the 1840 eruption started. Coan describes it vividly,

> For several years past the great crater of Kilauea has been rapidly filling up, by the rising of the superincumbent crust, and by the frequent gushing forth of the molten sea below. In this manner the great basin below the black ledge, which has been computed from three to five hundred feet deep, was long since filled up by the ejection and cooling of successive masses of the fiery fluid. These silent eruptions continued to occur at intervals, until the black ledge was repeatedly overflowed, each cooling, and forming a new layer from two feet thick and upwards, until the whole area of the crater was filled up, at least fifty feet above the original black ledge, and thus reducing the whole depth of the crater to less than nine hundred feet. This process of filling up continued till the latter part of May, 1840, when...the whole area of the crater became one entire sea of ignifluous matter, raging like old ocean when lashed into fury by a tempest. For several days the fires raged with fearful intensity, exhibiting a scene awfully terrific. For several days... The infuriated waves sent up infernal sounds, and dashed with such maddening energy against the sides of the awful caldron, as to shake the solid earth above, and to detach huge masses of overhanging rocks, which, leaving their ancient beds, plunged into the fiery gulf below. So terrific was the scene that no one dared to approach near it, and travellers [sic] on the main road, which lay along the verge of the crater, feeling the ground tremble beneath their feet, fled and passed by at a distance...Every thing [sic] within the caldron is new. Not a particle of lava remains as it was when I last visited it. All has been melted down and re-cast. All is new.

Although the summit and rift zone activities bear some similarities to 2018 events, the chronological order is reversed. The summit’s apparent collapse preceded the LERZ eruption in 1840 whereas the 2018 summit collapse started after the LERZ eruption began.

1924 Intrusion

Observations of the 1924 intrusion event are described on the Hawaiian Volcano Observatory website (https://volcanoes.usgs.gov/volcanoes/kilauea/geo_hist_1924_halemaumau.html) and repeated here. After years of rising lava levels within, and overflows from, Halema‘uma‘u Crater, the lava lake dropped out of sight in February 1924. It was followed by an earthquake swarm that began in early April, reaching a peak on April 23 with ground cracking, faulting, at least 3.6 meters (m) (12 feet, ft) of coastal subsidence, and hundreds of felt earthquakes indicating the intrusion of magma from the summit into the LERZ. Ultimately, no lava was erupted.

The Hawaiian Volcano Observatory website states, "Halema‘uma‘u Crater was 115 m (377 ft) deep following the draining of the lake. As seismicity waned in lower Puna, the crater floor began to collapse on April 29, deepening to more than 150 m (490 ft) on May 1 and nearly 210 m (690 ft) on May 7. Frequent dust clouds indicated continuing collapse in the following days."

The website describes observations of "...more than 50 explosive events during a 2.5-week period in May 1924. The explosions were then, and remain today, the most powerful at Kīlauea since the early 19th century, throwing blocks weighing as much as 14 tons from the crater. Halema‘uma‘u doubled in diameter, deepened to about 400 m (1300 ft), and drastically changed in behavior—for the next 85 [sic; 84] years it no longer hosted a long-lived lava lake, until one returned in 2008."

Although there was no LERZ eruption during this activity, the subsidence and plentiful earthquakes suggested an intrusion similar to the 2018 intrusion and it was followed by summit collapse and explosive events. No evidence of an offshore eruption has been found after several submarine expeditions in the area.

1955 Eruption, February 28–May 26

The 1955 LERZ eruption lasted for a total of 88 days but consisted of three eruptive periods separated by pauses in activity. Descriptions of the 1955 eruption here are primarily from Macdonald and Eaton (1964).

The first period of the eruption lasted from February 28 to March 7 (8 days) and consisted of fissures that extended 5.7 km (3.5 mi) from Pu‘uhonua‘ula to Kapoho Crater, along a trend overlapping the eastern part of the 2018 fissure system, but north of it. The 1955 fissures generally propagated to the northeast, but chaotically, with activity starting and stopping and shifting back and forth along the rift zone. This behavior was similar to that displayed during the early part of the current 2018 activity, but ramped up more quickly, with longer lived fissures, higher fountains and spattering, and more voluminous lava flows. There was also considerable steam and ash venting, which has only been a very minor part of the current activity so far. The lavas erupted in 1955 were among the most differentiated lavas on Kīlauea.

The first eruptive period in 1955 ended abruptly on March 7, but seismicity continued southwest of the initial breakout point near the current site of the Puna Geothermal Venture facility. The second period of the eruption began March 12 in the area where the continued seismicity was occurring. This area is south of Pu‘u Kali‘u, which is on the southern edge of Leilani Estates. The second set of 1955 fissures overlaps with the western part of the current fissure system, but is south of it. This lava was less evolved (fresher) than the magma erupted during the first eruptive period that had been stored underground for at least decades.

Activity associated with the second period of the eruption (34 days) along a 7 km (4.3 mi) long fissure system to the southwest of the first eruption period fissure system, also ramped up quickly, producing fountains within a few days that were higher than any that have occurred during the current activity, and sending lava to the ocean. Outbreaks continued to occur progressively farther southwest, with some exceptions, producing fast-moving flows. Fountaining exceeded 250 m (820 ft) by the end of the first week. Most of the fissures were short-lived (hours to a few days), and a few vents started and stopped repeatedly. The activity stopped on April 7.

After a pause of 16 days, during which seismicity continued, the third period of the eruption started unexpectedly on April 24 with a resumption of activity at the western fissures. The eruption was episodic and relatively weak initially, but its vigor gradually increased through mid-May. On May 16, there was a sudden increase in lava output near the west end of the western fissure system, with fountaining and new fast-moving flows. After 32 days of activity, fountaining ended abruptly on May 26, accompanied by a marked decrease of notable seismicity.

About 81×10^6 m^3 of lava erupted (dense rock equivalent with 25 percent void space). The time-averaged dense rock equivalent discharge rate is 14 m^3/s over the 66 days of actual eruption. Considered separately, the three eruptive periods equate to time-averaged dense rock equivalent discharge rates of 31, 18, and 7 m^3/s for periods 1–3, respectively.

1960 Eruption, January 13–February 19

The following descriptions of the 1960 eruption comes from Richter and others (1970). The 1960 eruption, which lasted about 5 weeks, opened along nearly the entire 1.4 km (0.9 mi) length of its fissure system at the onset of eruption. These fissures behaved erratically for the first few days, often starting and stopping, but coalesced around a few points and began feeding fountains more than 400 m high by the end of the first week of activity. Early activity often included phreatic steam and ash venting. The high fountaining was accompanied by heavy tephra fall, and a large tephra cone built up.

A few weeks later, after a substantial edifice, filled with ponded lava, had grown around the dominant vents, two new fissures opened to the east of, and along the same trend as, the initial line of fissures. This may have been caused by an increase in head pressure in the magmatic system in response to construction of the tephra cone complex and ponded lava.

The lava chemistry changed from more evolved (stored magma) to fresher (directly from the summit reservoir) about half way through the eruption. This did not seem to cause a change in eruptive behavior. The dying phase of the eruption lasted from February 7 to 20, with a marked reduction in discharge. Whereas slow deflation at the summit began about 4 days after the eruption started, summit collapse really began in earnest on about February 7, coincident with the start of the dying phase of the eruption.

About 122×10^6 m^3 of lava erupted in total. The time-averaged discharge rate was about 38 m^3/s during the first two weeks of the eruption.

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