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The First Five Years of Kīlauea's Summit Eruption in Halema'uma'u Crater, 2008–2013

The eruption in Halema'uma'u Crater that began in March 2008 is the longest summit eruption of Kīlauea Volcano, on the Island of Hawai'i, since 1924. From the time the eruption began, the new "Overlook crater" inside Halema'uma'u has exhibited fluctuating lava lake activity, occasional small explosive events, and a persistent gas plume. The beautiful nighttime glow impresses and thrills visitors in Hawai'i Volcanoes National Park, but the continuous emission of sulfur dioxide gas produces "vog" (volcanic smog) that can severely affect communities and local agriculture downwind. U.S. Geological Survey scientists continue to closely monitor the eruption and assess ongoing hazards.

An active lava lake fills the "Overlook crater," about 525 feet (160 m) across, contained within Halema'uma'u Crater in the larger depression of Kīlauea Caldera at the summit of Kīlauea Volcano. The walls of Halema'uma'u show white in the middle distance, while the Hawaiian Volcano Observatory (HVO) and Jaggar Museum, perched on the edge of the caldera wall, are visible as a small bump on the horizon. USGS photo by David Dow.

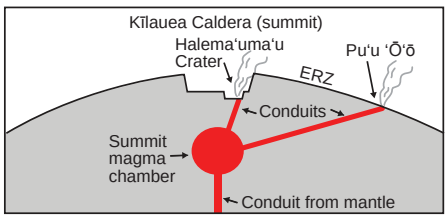
On the afternoon of December 21, 2011, U.S. Geological Survey (USGS) scientists at the Hawaiian Volcano Observatory (HVO) detected a small but distinctive earthquake in the summit area of Kīlauea Volcano. Real-time webcam images revealed that a large portion of the rim of "Overlook crater," nested within Halema'uma'u Crater, had collapsed into its lava lake, triggering a violent explosive eruption of gas and hot lava fragments. Donning helmets and gas masks, the scientists drove the five minutes from the observatory to Halema'uma'u and set out to sample and map the new deposit. This episode was yet another explosive event in the ongoing eruption at Kīlauea's summit that had begun more than 3 years earlier.

Kīlauea forms the southeast portion of the Island of Hawai'i, and most eruptions occur from its summit or down the flanks along its two "rift zones." Since 1983, an ongoing eruption on the East Rift Zone, around Pu'u 'Ō'ō cone, has covered 48 square miles (124 square kilometers) with lava flows and destroyed more than 200 structures, including scores of homes. With the summit eruption ongoing since March 2008, it is the longest time in at least two centuries that eruptions of Kīlauea have occurred simultaneously at the summit and along a rift zone.

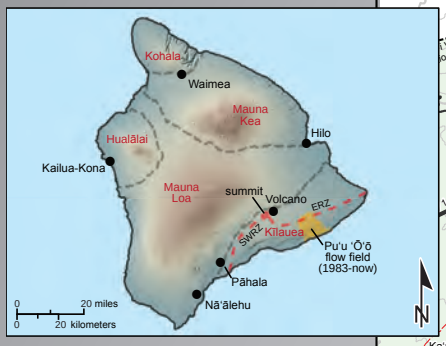
Eruption Chronology

Signs of unusual activity at Kīlauea's summit began in late 2007. In November, ground vibrations known as seismic tremor that suggest underground movement of molten rock (magma) increased well above normal "background" levels, and by late December, sulfur dioxide (SO_2) gas emission rates had also started increasing. At the same time, however, the summit of Kīlauea was deflating, which often means a reduction of magma supply to the summit magma chamber. Thus, initial signs were conflicting, and renewed eruptive activity at the summit was far from certain. Increased gas emissions led the National Park Service to close visitor access to much of the Kīlauea Caldera floor, including the western portion of Crater Rim Drive, on February 20, 2008. By early March, both seismic tremor and SO_2 emissions were several times higher than normal levels. On March 12, a vigorous high-temperature fuming area appeared on the south wall of Halema'uma'u Crater, immediately below the closed visitor overlook. This fuming area glowed at night and was compelling evidence that magma was near the surface and might erupt soon.

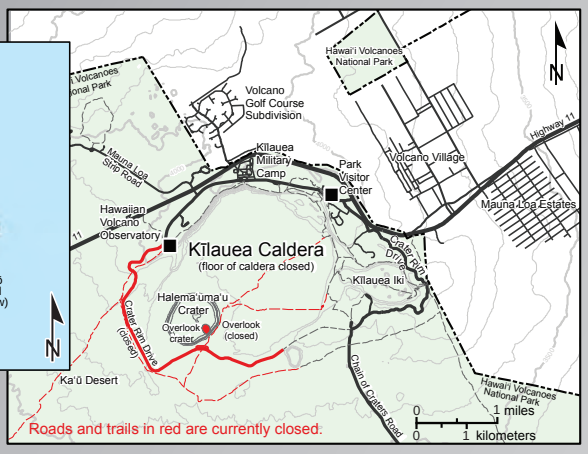
At 2:58 a.m. on March 19, 2008, a glowing, gaping crater, about 115 feet (35 m) wide, opened below the fuming area, and an explosive eruption threw hot fragments of rock onto the rim of Halema'uma'u, breaking and burning the visitor overlook fencing. These initial ejecta were all solid and "lithic" (pieces of old, solidified lava from the floor and



Simplified cartoon of Kīlauea Volcano's magmatic "plumbing" system that brings magma from depth to surface vents, showing the connection between the summit and East Rift Zone (ERZ).



The Island of Hawai'i, known as the Big Island, is the southernmost Hawaiian island. It is formed from five overlapping volcanoes, delineated by the dashed gray lines, with Mauna Loa and Kīlauea being the most active in recent times. Kīlauea's summit area is shown by the red dot, and the East Rift Zone (ERZ) and Southwest Rift Zone (SWRZ) are shown by dashed red lines. The area covered by lava during the ongoing eruption on the East Rift Zone is shown in orange. Selected towns are shown with black dots.



The large depression of Kīlauea Caldera, within Hawai'i Volcanoes National Park, dominates the summit region of Kīlauea Volcano. Embedded within the caldera is Halema'uma'u Crater, in a corner of which is the currently active vent called the Overlook crater (red dot). Several residential subdivisions form the village of Volcano (pop. 2,575). Trails and roads in red have been closed by the Park because of volcanic hazards.

wall of Halema'uma'u). Several days later, however, "juvenile" liquid particles were ejected, originating from fresh, gas-rich lava deep in the new pit, now informally called the "Overlook crater."

Over the next few months, several more weak explosive events hurled lava fragments around the Halema'uma'u Overlook. But the lava was still not visible in the fume-filled crater. Finally, during a helicopter overflight on September 5, 2008, HVO staff glimpsed a roiling, spattering lava lake deep in the Overlook crater—the first direct view of molten lava at Kīlauea's summit since 1982.

For the next year and a half, the lava remained deep in the crater and was only occasionally seen. During day-long periods of summit inflation, lava would rise into view as a small lava lake but then quickly drain and disappear once the summit deflated. Two large collapses of the crater wall, in December 2008 and June 2009, choked the vent with rubble for several weeks, but each time lava eventually crept back into the bottom of the Overlook crater.

But in mid-February 2010, a permanent lava lake appeared within the Overlook crater as the summit began to inflate. This lake has persisted into late 2013, with only one brief interruption—in March 2011, the Kamoamoa eruptive event on the East Rift Zone depressurized the summit-east rift magmatic system, causing the lava lake to drain out of view for about a week.

Normally the lava lake in the Overlook crater circulates placidly. Fresh lava wells up at the north lake margin and slowly migrates across the lake, cooling at the surface to form plates of thin black crust separated by jagged, red, incandescent cracks. The lava sinks back down at the south margin, where a persistent spattering source emits a plume of gas and often throws spatter about 15–35 feet (5–10 m) in the air.

How Far Down Is the Lava?

The level of the lava lake fluctuates constantly. From hour to hour, the lava can undergo rise and fall cycles (sometimes called "gas pistoning") driven by gas buildup within the lava that pushes the surface up as much as 65 feet (about 20 m), before the gas rapidly escapes and the lava drops down again. From day to day, cycles of deflation and inflation of the summit magma reservoir can cause the level to rise and fall over a range of as much as 165 feet (50 m). Finally, over weeks and months, broad changes in pressure in the summit magma reservoir can cause the lava level to change gradually. The level of the lava lake has been as high as 72 feet (22 m) below the Overlook crater rim (that is, below the floor of Halema'uma'u Crater) and, at its lowest, has dropped more than 720 feet (220 m) below the rim. During 2013, the lava level was generally 100–165 feet (30–50 m) below the rim.

Will the lava ever rise and flood the floor of Halema'uma'u Crater—or even fill Halema'uma'u and flow onto the caldera floor, as lava did in the early

FLUCTUATING LAVA LEVELS

The lava level in the active vent ("Overlook crater") in Halema'uma'u Crater fluctuates constantly. On January 10, 2010 (left), the lava is at one of its lowest stands, about 720 feet, or 220 m, below the floor of Halema'uma'u. On March 3, 2011 (right), the lava is at a relatively high level, only about 200 feet (60 m) below the Overlook crater rim. Both photos look northwest from the (now closed) Halema'uma'u Overlook. USGS photos by Tim Orr.

A plume of volcanic gases, tiny particles, and droplets rises from the active vent in Halemaʻumaʻu Crater and drifts southwest in the tradewinds. This volcanic smog ("vog") plume can be harmful to humans, agricultural crops, and machinery. The Hawaiian Volcano Observatory (HVO) is about 1.2 miles (1.9 km) from the vent. USGS photo by Mike Poland. Upper right: Both native plants and introduced species can be chemically burned by this acidic volcanic pollution. Photo by Scot Nelson, University of Hawaiʻi at Mānoa. Lower right: Farm and ranch infrastructure, such as fences and gates, have shown increased corrosion due to vog. USGS photo by Tamar Elias.

1900s? The lava level today is lower than it was in the early 1900s, likely because the ongoing eruption at Puʻu ʻŌʻō, on Kīlauea's East Rift Zone is also tapping the summit magma reservoir. If the magma supply to this East Rift Zone eruption were to end, the lava in Halemaʻumaʻu would likely rise to higher levels than we see today.

Collapses, Explosions, and Ejecta

The Overlook crater has grown considerably over the years as a result of collapses of its rim and walls. When this vent opened on March 19, 2008, the crater was about 115 feet (35 m) wide. As of late 2013, the crater had grown to about 525 feet (160 m) wide by 700 feet (215 m) long. Heat from the molten lava cracks and weakens the walls, causing pieces to fall into the lake, widening the crater. The rumble and sharp cracks of rockfalls and rock breaking can sometimes be heard from the Jaggar Museum overlook, adjacent to HVO. It is not known how large the Overlook crater could eventually grow, but it will almost certainly continue enlarging for some time.

Explosive events at Overlook crater are triggered by collapses of the crater walls—massive blocks dropping into the lava lake cause violent gas release and splashing of the liquid lava. Of the hundreds of small explosive events since March 2008, about two dozen have hurled lava fragments and rock material (collectively called ejecta) outside of the Overlook crater. These explosive events also produce a brown plume of volcanic ash (ejecta less than 2 mm [0.08 in] in diameter), and the largest have thrown blocks (lithic ejecta larger than 6.4 cm [2.5 in]) and bombs (juvenile ejecta larger than 6.4 cm) as far as 1,000 feet (300 m) from the vent.

Although very small compared to explosive eruptions at other volcanoes, such as Mount St. Helens in Washington, several of these explosive events could have injured or killed anyone standing nearby on the Halemaʻumaʻu Crater rim. The area around the vent has been closed to the public, so that the explosive events now pose no threat to visitors.

Even between explosive events, the continuous eruption plume carries up countless liquid lava droplets, mostly smaller than 2 mm (0.08 in), wafted upwards in thermal updrafts. These quickly chill to form glassy threads ("Pele's hair"), teardrop-shaped blebs ("Pele's tears"), and tiny hollow spherules. The plume also carries small rock particles from frequent collapses of the Overlook crater walls. Small amounts of fine ash and Pele's hair can sometimes be blown into nearby residential areas, particularly when the wind is from the south.

How the Eruption Affects People and Agriculture

In addition to the juvenile lava and rock particles, the eruptive plume is made up of water vapor, carbon dioxide, sulfur dioxide, and smaller amounts of other gases, including hydrogen chloride and hydrogen fluoride, along with entrained air. The 500–5,000 metric tons (1.1–11 million pounds) of sulfur dioxide emitted from the Overlook crater each day react in the atmosphere and, with the other gases and particles, form "vog" (volcanic smog) downwind. Vog is a respiratory irritant that can affect residents in downwind communities, such as Pāhala, Nāʻālehu, and towns on the west side of the Island of Hawaiʻi. With less common wind conditions, vog can spread across the island and affect other areas such as Hilo, and even drift north and reach the other Hawaiian Islands.

Common reactions to vog include sore throat, eye irritation, headaches, coughing, and breathing difficulties. Symptoms are especially pronounced for those with preexisting respiratory conditions such as asthma or chronic obstructive pulmonary disease (COPD). In addition, the tiny droplets of sulfuric acid in vog cause acid rain, which can leach lead and other metals from roofing and plumbing materials. Leached lead can pose a health hazard if it contaminates drinking water, such as in rooftop rainwater-catchment systems.

The impact of vog on agriculture has been severe on the Island of Hawaiʻi, and particularly in the Kaʻū district, which most of the time is directly downwind of Kīlauea's summit. Farmers report major economic losses due to vog damage to

SUMMIT ERUPTION STATISTICS 2008 TO 2013

Overlook crater size

- Initial, March 2008: 115 feet (35 m) diameter; late 2013: 525 feet (160 m) wide; 700 feet (215 m) long

Lava lake

- Dimensions: variable, as large as 525 feet (160 m) wide; 740 feet (225 m) long
- Distance below rim: highly variable, between 72 feet (22 m) and 720 feet (220 m) below Overlook crater rim (floor of Halemaʻumaʻu Crater)

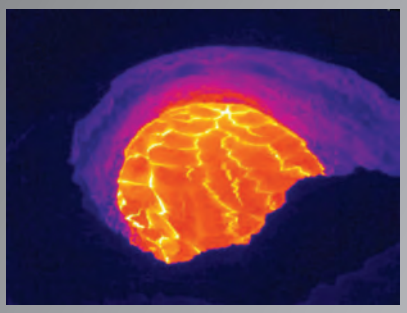
Explosions

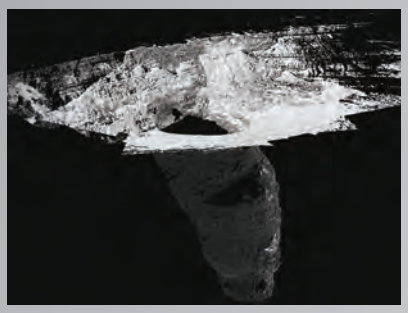
- Number of explosive events throwing blocks or bombs out of Overlook crater: about two dozen
- Maximum distance blocks or bombs thrown from vent: 1,000 feet (300 m)

Gas emission

- Typical SO_2 emission rate: 500–5,000 metric tons (1.1–11 million pounds) per day

INNOVATIONS IN VOLCANO MONITORING





Scientists at HVO use advanced technology to monitor the vent and its hazards. Left: A thermal camera keeps constant watch on the lava lake and can "see" through thick volcanic fume. Center: Periodic laser scans of the crater and lava lake help track the evolving crater geometry. Image by Todd Erickson, University of Hawai'i at Mānoa. Right: A Fourier transform infrared (FTIR) spectrometer measures the composition of gas emissions. These tools are part of a robust monitoring network maintained by HVO that includes seismometers, tiltmeters, Global Positioning System (GPS) sensors, gas monitoring sensors, and webcams. Some of the real-time data can be seen on the HVO Web site (http://hvo.wr.usgs.gov).

vegetable and orchard crops, flowers, and foliage. Ranchers also report detrimental effects to range grasses and livestock and increased corrosion of metal fencing and other infrastructure. As a result of these impacts, the U.S. Department of Agriculture provided Federal disaster assistance to farmers and ranchers on the Island of Hawai'i from 2008 through 2011. The impacts of vog on the agricultural industry and on human health remain areas of ongoing concern and study.

Past, Present, and Future

Halema'uma'u Crater has long hosted lava lake activity and, according to native Hawaiian tradition, is the current home of the volcano deity Pele. A lava lake was nearly continuous in Halema'uma'u from the time of the first written record in 1823 until 1924. Mark Twain remarked in 1866 that the view was like "gazing at the sun at noon-day" and the sight "fascinated the eye with its unapproachable splendor." Other early visitors mention the smell of volcanic gas far downwind, suggesting that vog has been a common product of eruptions on Kīlauea. The near-constant summit eruption during the early 1900s, allowing continuous observation of volcanic activity, was the impetus for founding the Hawaiian Volcano Observatory on the caldera rim in 1912. A collapse of Halema'uma'u Crater with violent steam explosions that killed one person ended that long-lived lava lake in 1924. For the remainder of the 1900s, Kīlauea's summit eruptions were only occasional and usually short, lasting days or weeks—in one case, 9 months.

Now in its sixth year, the current summit eruption harks back to the persistent lava lake in Halema'uma'u during the 1800s and early 1900s, suggesting that it has the potential to last for many years. Thus far, there are no signs that the eruption is either slowing down or ramping up. It could end tomorrow or go on for decades. In the meantime, the eruption provides beautiful sights and opportunities for scientific study, but also a chronic impact on air quality in downwind communities. USGS scientists with the Hawaiian Volcano Observatory will continue to monitor the eruption closely and alert the public and emergency managers to volcanic hazards. This work is only part of the USGS Volcano Hazards Program's ongoing efforts to protect people's lives and property in all of the volcanic regions of the United States.

Visitors pose in front of a circular and overflowing lava lake in Halema'uma'u Crater in 1893. This "perched" lava lake was elevated by walls (levees) built from solidified overflows. Lava lake activity was usually present in Halema'uma'u Crater until explosions and crater collapse in 1924 ended that continuous phase of activity. Photo by unknown photographer, reproduced courtesy of Hawai'i State Archives.

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See also *The ongoing Pu'u'O'o eruption of Kilauea Volcano, Hawai'i—30 years of eruptive activity* (USGS Fact Sheet 2012–3127) and other USGS volcano Fact Sheets http://volcanoes.usgs.gov/Products/sproducts.html

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