

COOPERATOR REPORT TO: US COAST GUARD

Preliminary Analysis of Hazards at the Kamokuna Ocean Entry

Prepared by the U.S. Geological Survey Hawaiian Volcano Observatory

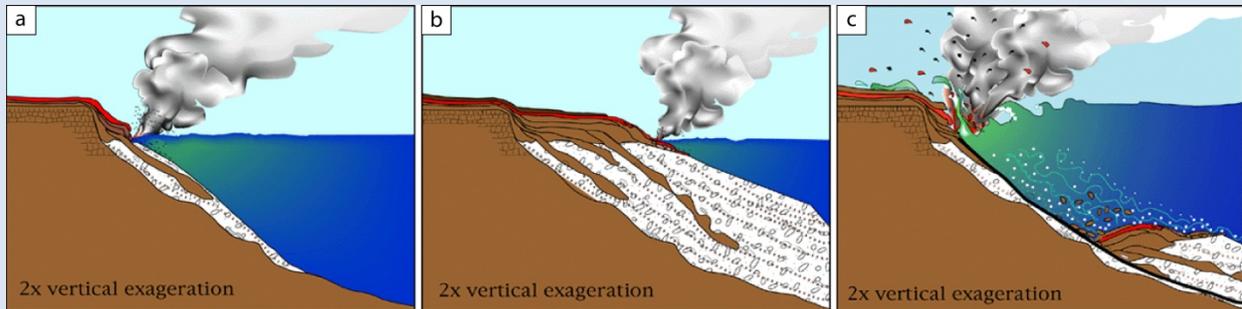
March 29, 2017

Background

Since the onset of the Pu‘u ‘Ō‘ō 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 Hawai‘i. Above water, these deltas have ranged in size from tiny surfaces measured in 10s or 100s of square meters (square yards) up to massive shelves 10s of acres in size. The largest delta documented was 64 acres in size.

The lava deltas have usually begun to form as soon as a lava flow reaches the water. 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) slope 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 are in addition to normal erosion from wave action. Most collapses are small and go unreported, and even those up to 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 had taken place.



Sketch showing (a–b) development and structure, as well as (c) collapse of a lava delta (<https://hvo.wr.usgs.gov/hazards/oceanentry/deltacollapse>).

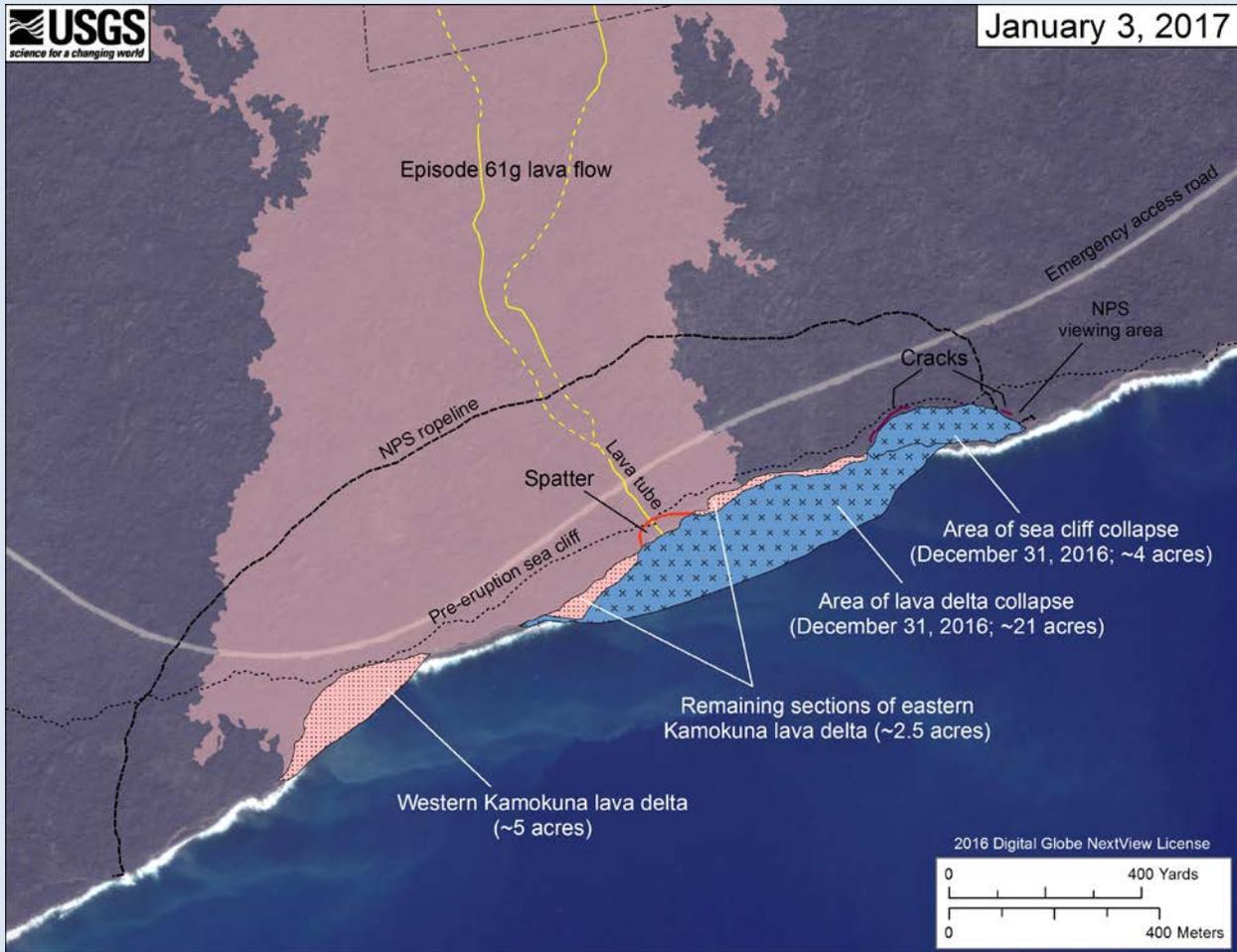
Observations have shown that at least some larger delta collapses—those ranging in size from several acres to 10s of acres—occurred in piecemeal fashion, as the collapse of a series of smaller slices from the front of the delta. We infer that these scenarios are caused by considerably larger submarine 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 up to hundreds of meters (yards), 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.

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 at mid-afternoon on December 31, 2016, the lava delta abruptly began to collapse piecemeal into the ocean. 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.

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 due to 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.



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

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 approximately 21 m (~70 ft) above the water in the face of a sea cliff that is 28 m (~90 ft) high. This entry point is located at: 19.32056N, 155.04015W (see map <https://hvo.wr.usgs.gov/maps/uploads/image-364.jpg>).

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. We suspect that the collapse resulted in 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: Observations at the coastline indicate that a small delta may have begun to form, starting about March 20.]*

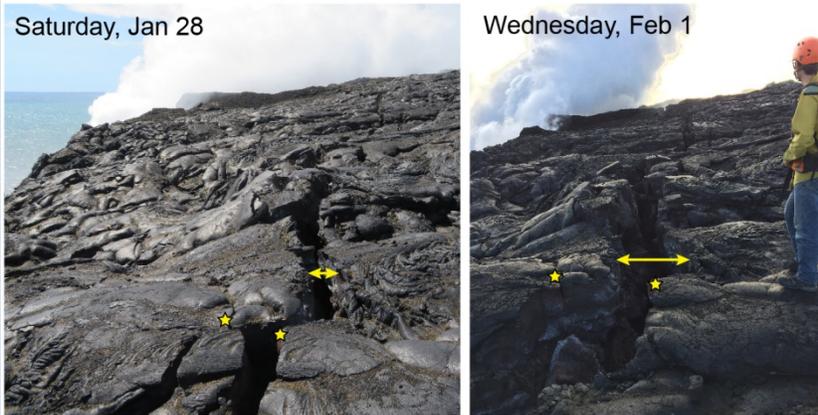


Kamokuna lava delta before and after the December 31, 2016, collapse. (left) View of the delta on October 14, 2016, when ~15 acres (USGS photo by L. DeSmither). (right) After the December 31 delta collapse, showing remnants of the delta (USGS photo by M. Patrick, January 1, 2017).

Ongoing hazards

Sea cliff collapse – Vertical sea cliffs in the vicinity of the lava entry 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, 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 cm (~12 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 up to about 2 cm (~1 in), possibly in response to explosions below as hot lava mixed with the cool ocean water. In addition, the ground in the immediate vicinity was shaking.

A portion 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 which also threw dense blocks from the collapsed sea cliff roughly 100 m (~330 ft) out to sea.



(left) Sea cliff crack inland from Kamokuna ocean entry on January 28, 2017, when ~30 cm wide, and (right) on February 1, 2017, when ~ 70 cm wide. (USGS photos, <https://hvo.wr.usgs.gov/multimedia/uploads/multimediaFile-1627.jpg>).

The collapse of small portions 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. While 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 might also fail.

Tephra jets – The stream of lava entering the ocean produces intermittent explosions of spatter and fine fragments, including Pele’s hair. 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) 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. [<https://pubs.usgs.gov/fs/2000/fs152-00/>]



Photo showing a typical tephra jet at the Kamokuna ocean entry (USGS photo, 30 January 2017).

Delta collapse 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. While 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 developing 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 this fact sheet:

<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. Based on a review of nearly 30 years of delta collapse and ejecta distance observations mined from the HVO records (next section), we consider a radius of 300 m, or about 1000 ft, as a reasonable minimum high hazard zone around a lava delta, when one is present (e.g., see event of January 30, 1996, below).

Explosions are less likely for collapses of older, cooler material, though observations of the recent sea cliff collapses have shown that ballistics can also be thrown perhaps as much as 100 m (~330 ft) out to sea due to the dynamics of the rebounding splash following the impact of the sea cliff into the water, as noted above.



Ballistic block thrown inland during explosion triggered by a lava delta collapse (USGS photo; https://hvo.wr.usgs.gov/hazards/oceanentry/deltaexplosions/4303053_L.jpg).

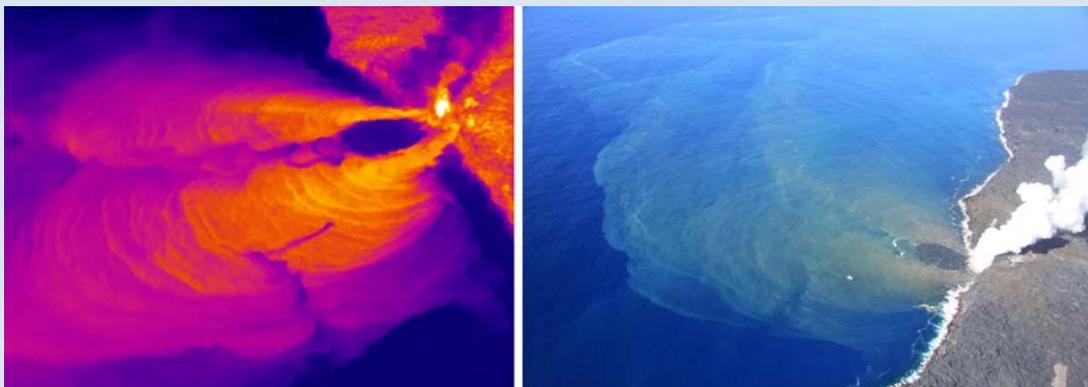
There is no obvious relationship between the size of the delta and the extent of ballistic hazard. Both large and small lava deltas (or large and small portions of deltas) have collapsed and triggered explosions. Why some collapses lead to explosions and some do not is not known but likely depends on 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.

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 roughly 15-m-high (~50-ft-high) sea cliff near the public viewing area. HVO has seen one video clip of a small fishing boat taking on water when a small collapse event occurred nearby (unrelated to the December 31 collapse), sending a wave out to sea.

An analysis by NOAA scientists evaluating wave heights that could be generated by sea cliff collapses indicate 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 up to 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 in a typical ocean swell 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) up to about 50 m off shore, and temperatures as high as 44 °C (111 °F) extending more than 300 m seaward. 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.



(left) FLIR image and (right) oblique aerial photograph of the plume of hot water at the Kamokuna ocean entry extending several hundred meters off shore. Boats for scale. (USGS photos, 16 March 2017; <https://hvo.wr.usgs.gov/multimedia/uploads/multimediaFile-1653.jpg>).

“Laze” – Interaction of hot lava and seawater produces a cloud of steam, hydrochloric acid droplets, and volcanic glass particles that can be harmful to breathe. This laze will drift downwind, so the hazard is strongly dependent on wind conditions, which can change throughout the day; the plume is typically visible in an HVO webcam: <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 (~1000 ft) above ground level. We have no data 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, if inhaled, pulmonary edema and death.



Laze plume drifts offshore from the ocean entry on 3 January 2017; edge of firehose visible (USGS photo; <https://hvo.wr.usgs.gov/multimedia/uploads/multimediaFile-1588.jpg>).

Summary of hazardous delta collapses during Pu‘u ‘Ō‘ō 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 tsunamis; (3) also caused the collapse of slices of the adjacent, older sea cliff; and (4) prompted incidents where people nearby had to run for safety. Information was gleaned from HVO internal reports, with some additions from HVO field logbook entries.

1) March 26, 1988

Lava delta location/name: Kupapa‘u

Collapse size: No apparent collapse

Summary: NPS personnel living at Waha‘ula, 1 km (~0.6 mi) west of the entry were awakened at 1:25 AM by a roar “like a jet engine” and reported large hydromagmatic explosions that lasted for about an hour, ejecting material up to about 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, up to football-size, that littered the area up to 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 landslide or slumping event that opened cracks in the delta, which channeled water to the lava tube, and no actual 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.

2) May 30, 1988

Lava delta location/name: Kupapa‘u

Collapse size: Not reported

Summary: Catastrophic slumping of the underlying submarine debris fan left the Kupapa‘u lava delta unsupported, causing a large delta collapse at 19:59 PM, resulting 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.

3) July 12, 1988

Lava delta location/name: Kupapa‘u

Collapse size: ~1 acre

Summary: The entire delta broke off into the ocean without warning at 8:42 AM. 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 cliff where it covered 10-20% of ground surface. Fallout included 10–30-cm-long (4–12-in-long) ribbon 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.”

4) August 15, 1988

Lava delta location/name: Kupapa‘u

Collapse size: ~4 acres

Summary: Almost the entire delta collapsed at 6:14 AM, and NPS employees living at Waha‘ula 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. Since the entire delta collapsed, we infer the deposit to be on the sea cliff.

5) September 15, 1988

Lava delta location/name: Kupapa‘u

Collapse size: ~1 acre

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

6) January 23, 1989

Lava delta location/name: Kupapa‘u

Collapse size: Not reported

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

7) April 19, 1993

Lava delta location/name: Lae‘apuki

Collapse size: ~1 acre

Summary: A major collapse event starting at 9:43 PM was followed by an explosion containing incandescent rocks. These fragments were directed to the northwest and thrown up to 200 m (~655 ft) inland from the source of the explosion (roughly 120 m, or about 395 ft, inland from the sea cliff). Several meter-sized (yard-sized) blocks were found within 20 m (~65 ft) of 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; 22 visitors were treated for injuries sustained from falls or from getting hit by rocks.

8) May 15, 1993

Lava delta location/name: Kamoamo

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 up to 100 m (~330 ft) inland from the ocean entry, with smaller debris extending 150 m (~490 ft) inland. The date of May 15 is inferred from seismic data.

9) November 26, 1993

Lava delta location/name: Kamoamo

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 came out of 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 PM. A localized tsunami washed onshore right afterward.

10) February 22, 1994

Lava delta location/name: Kamoamo

Collapse size: ~2.5 acres

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

11) July 8, 1994

Lava delta location/name: Kamoamo

Collapse size: ~2 acres

Summary: An inactive part of the delta collapsed at 12:36 AM. Dense blocks up to 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.

12) 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 up to 75 cm (~30 in) across up to 250 m (~820 ft) inland from the original coastline. A separate report stated that 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-in-diameter) blocks up to 30 m (~100 ft) inland from edge of the collapse scar on the delta.

13) 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 up to 30 m (~100 ft) inland of the sea cliff.

14) 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 AM 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 much 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.

15) 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.

16) 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 for it and made a narrow escape. The delta collapsed shortly afterward.

17) April 13, 1999

Lava delta location/name: Kamokuna

Collapse size: Not reported

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

18) 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.

19) 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 yd) onto adjacent parts of the delta.

20) November 28, 2005

Lava delta location/name: East Lae‘apuki

Collapse size: ~44 acres

Summary: Starting at 11:10 AM, and lasting for about 5 hours, the East Lae‘apuki delta collapsed in piecemeal fashion. Almost the entire 34-acres delta collapsed, and an additional 10 acres of the older sea cliff behind the delta fell in as well, bringing the total size of the collapse to 44 acres. Lithic blocks up to 15 cm (~6 inches) 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 up to 550 m (~1,800 ft) inland, with almost total ground coverage up to 230 m (~755 ft) inland.

21) 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 at around 2:25 PM 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 up to 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-in-diameter) rock was thrown 120 m (~395 ft) inland. Surprisingly, the collapse occurred 2 months after the ocean entry stopped.

22) July 30, 2008

Lava delta location/name: Waikupanaha

Collapse size: ~2 acres

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

23) 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 PM, 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.

24) 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 AM, 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.

25) 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.

26) 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 seen to be wider the next day. At about 1:30 PM, the delta collapsed, throwing dense, angular fragments up to 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.

27) December 31, 2016

Lava delta location/name: Kamokuna

Collapse size: ~25 acres

Summary: A piecemeal collapse of the delta began in 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 a portion of the NPS public viewing area. Little explosive debris was produced.