

Identifying hazards associated with lava deltas

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Abstract Lava deltas, formed where lava enters the ocean and builds a shelf of new land extending from the coastline, represent a significant local hazard, especially on populated ocean island volcanoes. Such structures are unstable and prone to collapse—events that are often accompanied by small explosions that can deposit boulders and cobbles hundreds of meters inland. Explosions that coincide with collapses of the East Lae ‘Apuki lava delta at Kīlauea Volcano, Hawai‘i, during 2005–2007 followed an evolutionary progression mirroring that of the delta itself. A collapse that occurred when the lava–ocean entry was active was associated with a blast of lithic blocks and dispersal of spatter and fine, glassy tephra. Shortly after delta growth ceased, a collapse exposed hot rock to cold ocean water, resulting in an explosion composed entirely of lithic blocks and lapilli. Further collapse of the delta after several months of inactivity, by which time it had cooled significantly, resulted in no recognizable explosion deposit. Seaward displacement and subsidence of the coastline immediately inland of the delta was measured by both satellite and ground-based sensors and occurred at rates of several centimeters per month even after the lava–ocean entry had ceased. The anomalous deformation ended only after complete collapse of the delta. Monitoring of ground deformation may therefore provide an indication of the potential for delta collapse, while the hazard associated with collapse can be inferred from the level of activity, or the time since the last activity, on the delta.

Keywords Lava delta · Kīlauea Volcano · Volcanic hazards · Lava–ocean interaction · Volcano deformation · Hydrovolcanic explosions

Introduction

Lava deltas, formed where lava enters the ocean and builds a shelf of new and often unstable land, are a common feature at oceanic volcanoes (e.g., Mattox and Mangan 1997; Skilling 2002; Ramalho et al. 2013; Bosman et al. 2014) and represent a significant localized hazard, even after they have ceased active growth. On the Island of Hawai‘i, numerous lava deltas have formed and been destroyed since 1800 as a consequence of lava flows from Hualālai, Mauna Loa, and Kīlauea volcanoes. Interactions between lava and the ocean have been best described at Kīlauea, where East Rift Zone eruptions in 1955, 1960, 1969–1974, and 1983–present have resulted in well-documented lava deltas of various sizes and durations (Fig. 1). Indeed, the first direct documentation of pillow lava formation was made, and models of lava delta evolution were developed, during multiple lava–ocean entries that were part of the Mauna Ulu eruption in 1969–1971 (Moore et al. 1973). Subsequent observations of lava entering the sea during the 1983–present Pu‘u ‘Ō‘ō eruption have further elucidated the features associated with shallow water lava flows (Tribble 1991; Umino et al. 2006) and the means by which lava deltas grow and collapse (Mattox and Mangan 1997). Additional information on delta growth in the deeper submarine environment has been collected at Stromboli, Italy, where it was found that the submarine delta is several times larger in volume than the subaerial delta (Bosman et al. 2014), and where collapse of an unstable subaerial and submarine slope in 2002 caused a tsunami with a run-up of up to 10 m and inland inundation of up to 130 m (Chiocci et al. 2008).

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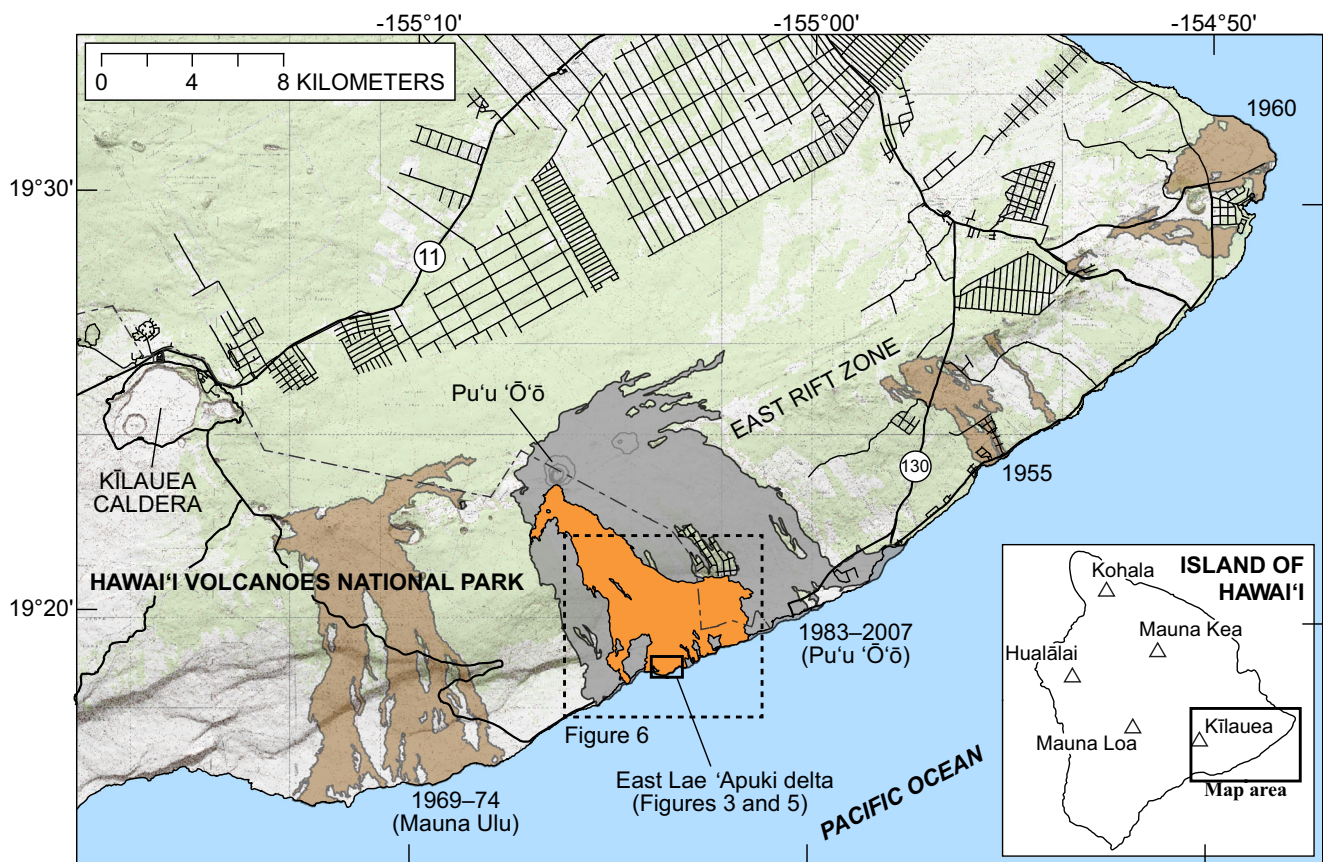


Fig. 1 Map of the eastern half of Kīlauea Volcano, Hawai'i, showing lava fields that formed deltas. *Brown* 1955, 1960, and 1969–1974 Mauna Ulu lava fields. *Gray* 1983–2007 Pu'u 'Ō'ō lava field. *Orange* Prince Kūhiō Kalaniana'ole (PKK) lava flow which produced East Lae 'Apuki

delta. *Solid box* area covered by maps in Figs. 3 and 5. *Dashed box* area covered by interferograms in Fig. 6. *Inset* Island of Hawai'i and its five volcanoes showing area covered by map

Although the hazard associated with lava–ocean entries is usually restricted to their immediate surroundings (with the exception of large tsunami-generating collapses, like that of Stromboli in 2002) and is less obvious than the lava effusion, explosive eruptions, and earthquakes that generally accompany volcanic activity, the danger from delta growth and collapse should not be overlooked. Among the hazards that accompany lava–ocean interaction, that from the ocean entry plume is the most pervasive. Ocean water is boiled completely dry when it interacts with lava, resulting in a hot, toxic plume that contains not only water vapor, but also hydrochloric acid and fine particles of volcanic glass (Edmonds and Gerlach 2006). The point where lava enters the ocean is also the site of weak tephra jets, which can occur suddenly and are capable of throwing pyroclasts to heights and distances of several tens of meters (Mattox and Mangan 1997). Because they are composed of a lens of layered flows overlying water-saturated rubble and debris (Moore et al. 1973; Mattox and Mangan 1997; Bosman et al. 2014), deltas are prone to catastrophic collapse from their unstable fronts (often referred to as “benches” based on their geomorphic expression), which can cause explosions that hurl rocks and fine ash hundreds

of meters inland (Mattox and Mangan 1997) and even result in tsunamis (Chiocci et al. 2008; Bosman et al. 2014). In addition, delta instability, even without collapse, can result in bubble bursts and littoral lava fountains that have the potential to bombard areas tens of meters or more inland with spatter and tephra.

The threefold hazard of hot vapor emissions, unpredictable collapses, and small hydrovolcanic explosions can be catastrophic to anyone in the vicinity (Fig. 2). The three recorded fatalities that have been directly attributed to volcanic activity during the course of Kīlauea's Pu'u 'Ō'ō eruption to date have all occurred at the lava–ocean entry. In 1993, one person was swept out to sea during a delta collapse, and many more individuals nearby were injured by lithic debris thrown up to 200 m inland as lava and hot rock were suddenly exposed to cold seawater (Mattox and Mangan 1997). Two other people were killed in 2000 after inhaling an unusually hot ocean entry plume, possibly associated with a delta collapse.

While the plume is fairly obvious and easy to avoid, the location and extent of a delta and its propensity for collapse are more difficult to assess. Often, the original sea cliff is obscured due to lava accumulation on the delta (Moore et al.



Fig. 2 Hazards associated with lava–ocean entries include a toxic and scalding plume, small explosions, and sudden collapse. The person in this photo is exposed to all three of these effects (this is a bad place for a “selfie”)

1973; Mattox and Mangan 1997), blurring the distinction between stable and unstable land. The temporal evolution of the hazards associated with delta collapse is also unclear, as is the point in time at which an inactive delta can be considered stable and safe.

We address these issues by observing the deformation and subaerial geologic deposits associated with Kīlauea’s East Lae ‘Apuki lava delta, which was an active ocean entry point for tube-fed lava on the volcano’s south flank during 2005–2007 (Fig. 1). The delta collapsed and reformed repeatedly during that time period, but the character of the associated explosions varied according to the activity level of the delta. In addition, anomalous seaward displacement of the “stable” coastal land a few hundred meters inland of the delta occurred even after the delta ceased its growth, and the motion only ended once the delta collapsed completely and did not reform. These results suggest a progression of collapse-related hazards over time, as well as a means of recognizing unstable deltas that may be prone to future collapse—conclusions of obvious importance

for identifying hazards near current and former lava–ocean entries at volcanoes around the world.

Growth and collapse of Kīlauea’s East Lae ‘Apuki lava delta

The Lae ‘Apuki area has been the site of numerous ocean entries and overlapping lava deltas since flows from Pu‘u ‘Ō‘ō first entered the ocean there in March 1993. The initial delta, in fact, was the site of the first fatality associated with the Pu‘u ‘Ō‘ō eruption (mentioned above). Lava entered the ocean sporadically, usually for periods of weeks, until mid-1995, and collapses were common throughout the more than 2 years of discontinuous lava–ocean interaction.

After a period of quiescence, lava entered the ocean almost continuously at Lae ‘Apuki from April 1996 through January 1997. During the summer of 1996, the delta collapsed every 15–18 days, removing most of the area of new land each time. The delta became more stable thereafter, and it grew to dimensions of 750-m long by more than 200-m wide. In early December 1996, the entire delta collapsed as a series of at least 20 events over a 2.5-h period. The collapse removed 1.4×10^5 m² of land and scattered lithic (defined as previously formed and solidified rock) blocks and lapilli and juvenile (defined as fluid at the time of collapse or explosion) spatter up to 100 m inland from the new coastline—the largest delta failure during the Pu‘u ‘Ō‘ō eruption to that time. The delta quickly regrew to roughly its previous size before activity abruptly ceased at the end of January 1997.

Lava occasionally reached the ocean at Lae ‘Apuki over the several years that followed, each time resulting in ocean entries that lasted from hours to a few months. In early May 2005, lava from the Prince Kūhiō Kalaniana‘ole (PKK) flow reached the ocean, establishing an entry and building a lava delta that persisted until March 2007. Active for nearly 23 months, this entry remains the longest lived of the Pu‘u ‘Ō‘ō eruption to date and was the site of the East Lae ‘Apuki delta, which is the focus of our analysis.

The 2005–2007 East Lae ‘Apuki delta formed within an embayment between different generations of older Lae ‘Apuki deltas. Helicopter overflights, conducted on a semi-weekly basis, allowed personnel from the Hawaiian Volcano Observatory to map the areal extent of the delta over time. The delta grew rapidly, suffering frequent small collapses from its seaward edge. In response, the National Park Service, in whose land the activity was occurring, erected a rope-line barricade with warning signs several hundred meters inland from the delta to notify visitors of the hazards. Despite this, people were frequently (almost daily) observed crossing the delta to get close views of lava entering the ocean. By August 2005, the delta’s surface area exceeded that of the large Lae ‘Apuki delta that collapsed in December 1996, and

the potential for another large collapse was indicated by the numerous discontinuous cracks which cut the delta parallel to the coastline, at least some of which opened as a result of small-scale collapses. This potential was realized on August 27, when a collapse removed $5.2 \times 10^4 \text{ m}^2$ from the front of the delta. The collapse caused a localized tsunami which deposited blocks up to a meter in diameter on the eastern side of the delta.

The delta immediately began to regrow, filling the scar from the August collapse and widening to the west over the following months. By late November 2005, the delta had grown to an area of $1.3 \times 10^5 \text{ m}^2$. Starting at 1110 HST (UTC-10 h) on November 28, the delta began a piecemeal collapse that occurred in three distinct phases and lasted approximately 4.5 h; the complete sequence was captured by a time-lapse camera system deployed on the east side of the delta (Supplementary Movie). Nearly the entire delta was removed by the collapse (only a single piece of $\sim 180 \text{ m}^2$ near the delta's eastern edge remained), as was $3.4 \times 10^4 \text{ m}^2$ of older Lae 'Apuki deltas and $8.7 \times 10^3 \text{ m}^2$ of the preexisting ~ 500 -year-old sea cliff beneath the Pu'u 'Ö'ö flows and against which the Lae 'Apuki deltas were built (Fig. 3). The active lava tube feeding the ocean entry at the distal end of the delta was truncated by the collapse, resulting in a "fire hose" of lava from the side of the sea cliff for several days until a new tube and delta formed (Fig. 4a). The deposit associated with the collapse consisted of spatter bombs within about 50 m inland from the new sea cliff, angular lithic blocks as large as 15 cm in diameter up to 95 m inland, and a more aerially extensive fall of fine ash and glass particles, including Pele's hair and

Limu o Pele (Pele's seaweed—thin, delicate sheets of volcanic glass formed from bubble walls), with nearly complete coverage up to 360 m inland and dispersed coverage up to 500 m inland (Figs. 3d and 4b). These accumulations and the imagery from the time-lapse camera are consistent with the tephra jet and lithic blast categorizations of Mattox and Mangan (1997) that are indicative, respectively, of interactions between the lava tube and the ocean and between the hot rock of the delta and the ocean.

The East Lae 'Apuki delta began to reform following the November 2005 collapse, rapidly reaching, and then exceeding, its pre-collapse area by March 2006. The rest of that year was characterized by continued growth punctuated by small collapses and attendant minor explosions, with cracks across the delta surface, parallel to the coastline, providing a reminder of the unstable nature of the surface. In some instances, these cracks were filled with water. Small delta-sloughing events further opened these cracks and allowed the water to interact with the lava tube just beneath the surface, leading to small spattering events and bubble bursts of lava within the area of the delta (Mattox and Mangan 1997). Visual observations confirmed that the rate of lava delivery and delta growth waned in early 2007, and the ocean entry terminated in March of that year, with the delta having reached a size of approximately $2.6 \times 10^5 \text{ m}^2$ —the largest delta of the Pu'u 'Ö'ö eruption to date. The delta was ~ 1.78 -km long and extended $\sim 390 \text{ m}$ seaward from the sea cliff at its widest point.

The next major collapse of the East Lae 'Apuki delta took place over the course of about 4 h on May 11, 2007, when $9.3 \times 10^4 \text{ m}^2$ of the delta was lost to the sea, forming a deep

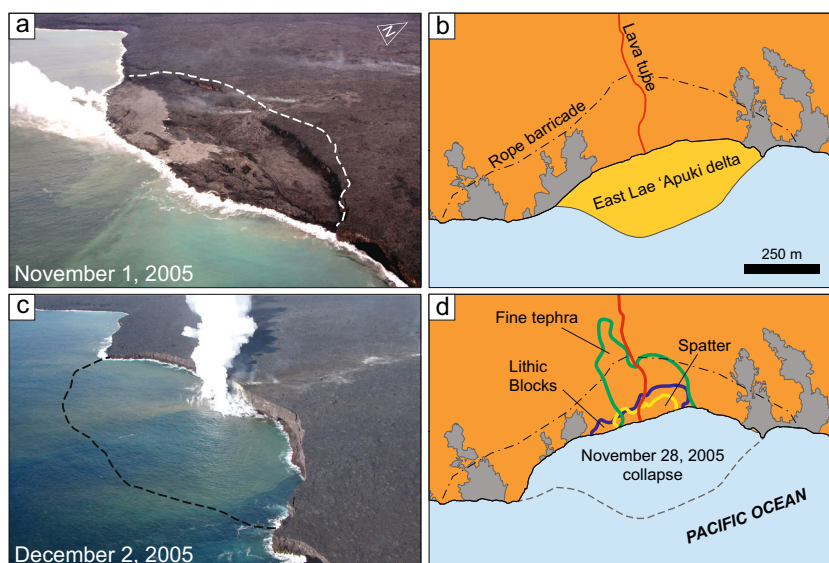


Fig. 3 **a** Oblique aerial photo showing East Lae 'Apuki delta on November 1, 2005. *Dashed white line* marks the location of sea cliff after November 28 collapse. **b** Map showing East Lae 'Apuki delta before the November 28 collapse. *Heavy black line* along the coast marks pre-delta sea cliff. *Yellow color* gives area of delta, and *orange* shows lava coverage due to the Pu'u 'Ö'ö eruption. **c** Oblique aerial photo with similar

geometry as panel **a** and showing East Lae 'Apuki delta on December 2, 2005 after the November 28 collapse. *Dashed black line* marks the position of the front of the delta before collapse. **d** Map showing area of the November 28 collapse. *Blue line* marks limit of lithic deposit. *Yellow line* marks limit of spatter deposit. *Green line* marks limit of nearly continuous carpet of fine tephra

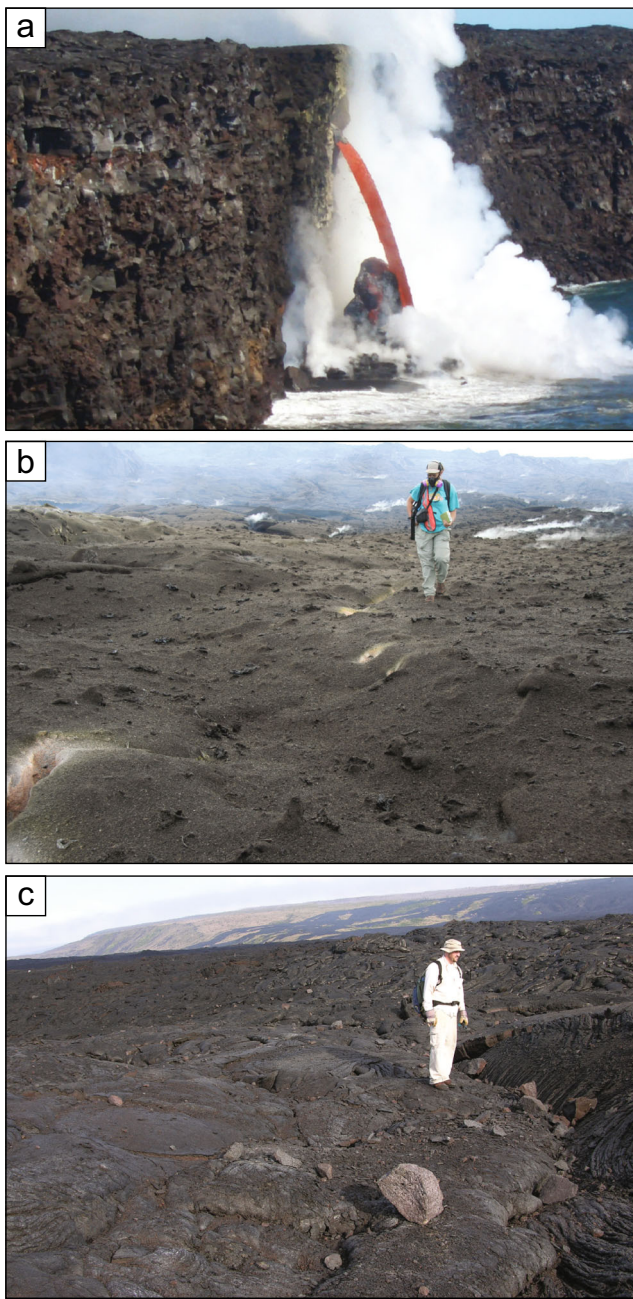


Fig. 4 **a** “Firehose” from truncated lava tube on November 29, 2005 after the November 28 collapse of East Lae ‘Apuki delta. Collapse scarp is ~30-m high. Photo courtesy of Greg Santos, National Park Service. **b** Deposit of lithics, spatter, and fine tephra blanketing lava surface inland from November 28 collapse scarp. **c** Lithic blocks and lapilli inland from May 11, 2007 collapse scarp

scallop in the coastline (Fig. 5a–d). Although it had been inactive for several weeks, the rocks making up the delta were still hot, and energetic explosions ensued as that rock was exposed to cold seawater over the course of the collapse—eyewitness accounts described bright incandescence in the exposed face of the scarp as pieces of the delta sloughed away. The deposit was characterized almost entirely of angular lithic

blocks with very few fines and no juvenile spatter or glass (Figs. 4c and 5d), consistent with a lithic blast (Mattox and Mangan 1997), and it was spread over an area of about $1.3 \times 10^4 \text{ m}^2$ and reached about 120 m inland of the new coastline.

No further activity occurred at East Lae ‘Apuki until August 13, 2007, when almost the entirety of the remaining portion of the delta and some of the preexisting sea cliff—approximately $1.7 \times 10^5 \text{ m}^2$ in total area—collapsed into the sea (Fig. 5e, f). The exact timing and evolution of the collapse is uncertain, but it coincided with high surf due to passage of a major hurricane (Hurricane Flossie) immediately south of the Island of Hawai‘i, as well as a M5.4 earthquake beneath Kīlauea’s south flank, either or both of which might have undermined the delicate stability of the delta. There was no deposit associated with this failure, suggesting that the rock making up the delta had cooled sufficiently since the end of the lava–ocean entry 5 months previously so that no major explosions occurred.

Deformation measurements

That lava deltas are unstable and deform continuously is obvious from their structure, which usually includes multiple large, ocean-parallel cracks (Kauahikaua et al. 1993; Mattox and Mangan 1997). Geodetic measurements of lava delta surfaces indicate subsidence rates of several centimeters per month, attributed to thermal contraction of cooling lava and compaction of the fragmental debris that makes up the delta below sea level (Kauahikaua et al. 1993; Marie et al. 2003). Although deformation monitoring may provide an indication of whether or not a delta is prone to future collapse—lack of subsidence may indicate that the shelf has become stable (Marie et al. 2003)—ground-based surveys are not advisable owing to the hazard from unanticipated collapses.

Interferometric synthetic aperture radar (InSAR) provides a space-based means of measuring volcano surface displacements with high spatial resolution, although temporal resolution is limited by satellite repeat times that commonly range from several days to more than a month (e.g., Massonnet and Sigmundsson 2000; Zebker et al. 2000). The challenge with respect to monitoring lava-delta deformation with InSAR is coherence. Areas of the surface that change significantly between the times of satellite over passes—due, for example, to resurfacing by lava or especially rapid deformation—will not be coherent in deformation interferograms, meaning that surface displacements cannot be recovered (e.g., Zebker et al. 1996). Active deltas are almost never coherent owing to their rapid growth; the preexisting coastline, however, is usually coherent as long as it is not covered by lava during the time spanned by an interferogram. InSAR data that were acquired by the ENVISAT satellite and that imaged the East Lae ‘Apuki lava delta are frequently characterized by a crescent-shaped

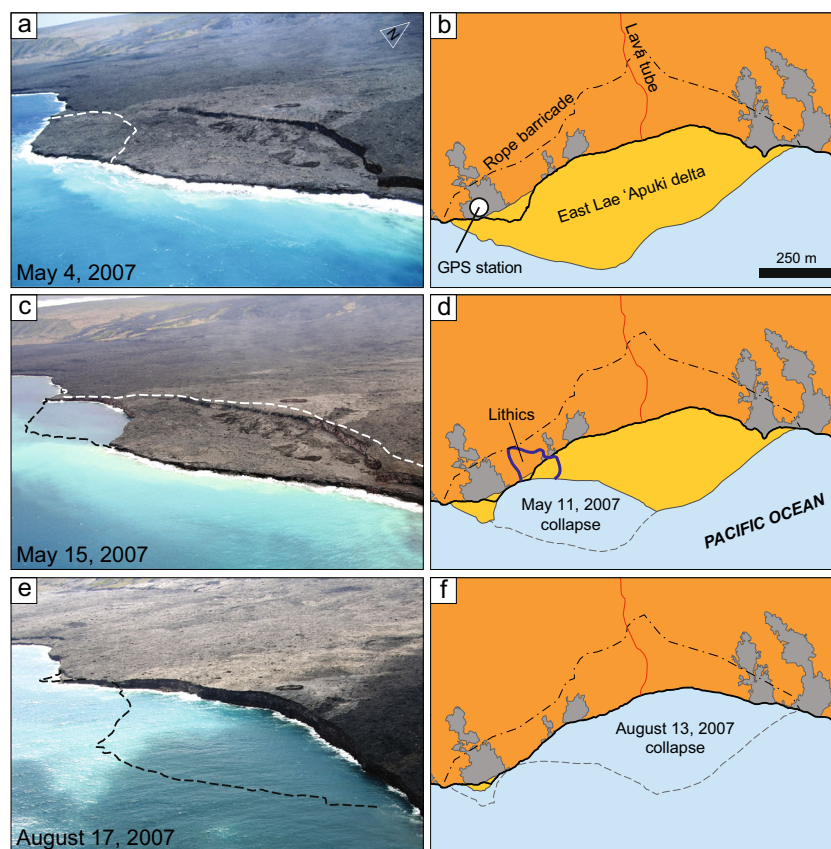


Fig. 5 **a** Oblique aerial photo showing East Lae 'Apuki delta on May 4, 2007. *Dashed white line* marks the location of the sea cliff after the May 11 collapse. **b** Map showing East Lae 'Apuki delta before the May 11 collapse. Western edge of delta overlaps older delta. *Heavy black line* marks pre-delta sea cliff. **c** Oblique aerial photo with similar viewing geometry as panel **a** and showing East Lae 'Apuki delta on May 15, 2007 after the May 11 collapse. *Dashed black line* marks the position of the

front of the delta before collapse. *Dashed white line* marks the location of sea cliff after the August 13 collapse. **d** Map showing area of the May 11 collapse. *Blue line* marks the limit of lithic deposit. **e** Oblique aerial photo with similar viewing geometry as panel **a** and showing East Lae 'Apuki delta on August 17, 2007 after the August 13 collapse. *Dashed black line* marks the position of the front of the delta before collapse. **f** Map showing the area of August 13 collapse

patch of fringes that extends ~600 m inland of the delta (Fig. 6), indicating deformation of the coastline. The fringes are first apparent in InSAR data starting about February 2006. Lava activity just inland of the delta disrupts the coherence of the region in early 2007, obscuring any potential deformation, but there is no sign of the fringes from late 2007 onward despite excellent coherence.

The crescent-shaped fringes inland of the East Lae 'Apuki delta may indicate line-of-sight subsidence of the coastline by a maximum of several centimeters per month, but could also be related to atmospheric or topographic artifacts. We rule out atmospheric artifacts because the patch of phase change has the same geometry in multiple independent interferograms, with no significant variation over time (Fig. 6). Topographic artifacts in interferograms are a result of differences in the elevation of the surface with respect to the digital elevation model (DEM) that is used to remove the topographic contributions to the interferometric phase (e.g., Ebmeier et al. 2012). Such artifacts are common on volcanoes, especially Kīlauea,

where changes in topography are frequent and extreme (up to hundreds of meters) due to persistent lava effusion and even the formation of cinder cones (e.g., Poland 2014). We used a DEM derived from the 2000 Shuttle Radar Topography Mission (Farr et al. 2007); therefore, it is possible that lava emplacement between 2000 and the acquisition of the ENVISAT imagery several years later created topographic differences sufficient to introduce artifacts in the interferograms. Because the magnitude of a topographic artifact is directly proportional to the InSAR perpendicular baseline (i.e., the distance between the satellite position at the time the images are acquired), topographic artifacts should be greater in interferograms with large baselines and vice versa. In other words, if the crescent pattern of fringes is a topographic artifact, interferograms with large baselines should show more fringes near the East Lae 'Apuki delta than interferograms with short baselines. Further, the fringes should persist regardless of the time spanned because the topographic difference with respect to the 2000 DEM would not diminish

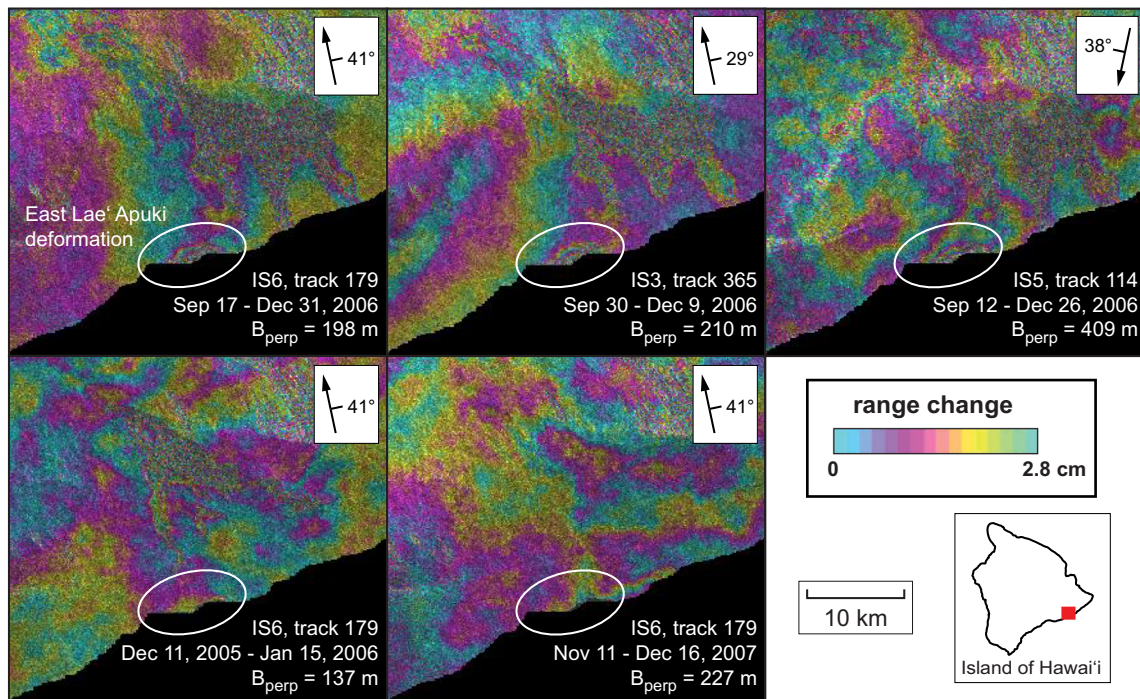


Fig. 6 Interferograms showing line-of-sight range change in the vicinity of the East Lae 'Apuki lava delta during 2006–2007. Area covered by each interferogram is the same and is indicated on Fig. 1. White ellipses cover the same area in each image. Upper row are interferograms from three independent look angles and timespans with differing perpendicular baselines (B_{perp}), all of which show line-of-sight displacements with

similar magnitudes along the coast near the lava delta (circled in white). Lower row gives interferograms spanning time periods before the onset of major seaward motion in early 2006 (left) and after the August 13, 2007 collapse (middle), neither of which displays any indication of the coastal deformation apparent in the upper row of interferograms. Arrows indicate satellite flight direction and look angle in degrees from vertical

over time. As is apparent from the interferograms shown in Fig. 6, the crescent-shaped pattern of fringes is not dependent on baseline length and is also not present during all time periods, suggesting it is not a topographic artifact. We therefore conclude that the fringes indicate real surface deformation of the coastline adjacent to the East Lae 'Apuki lava delta.

Unfortunately, the coastal deformation pattern is only apparent in interferograms that span 1–2 months—longer time span images are incoherent in that region, probably because the deformation rate over that small area is too rapid to retain coherence. For this reason, multi-temporal InSAR techniques (e.g., Hooper 2008) are not appropriate for deriving deformation time series. For better temporal resolution on the development of the deformation, we therefore employed ground-based methods.

A semi-permanent GPS station was installed in late November 2006—shortly after the deformation pattern was noticed in InSAR data—on the coastline adjacent to the western end of the delta, near the point of maximum deformation in interferograms (Fig. 5b). The equipment was in place episodically throughout the subsequent year, with gaps in the time series resulting when the instrumentation was removed for use in other places on Kīlauea. After October 2007 (following complete collapse of the lava delta), the site was only occupied for a few days each year during GPS

campaigns. During late 2006 to early April 2007, the GPS station moved to the south–southeast and downward at steady rates of ~12 and 10 cm/month, respectively (Fig. 7). The station was not in place at the time of the May 11, 2007 collapse, but was deployed shortly thereafter and for the next month recorded south–southeast and downward motion, both at rates of about 2 cm/month. The station was again absent when the remainder of the delta collapsed in August 2007. Reestablishment later that month revealed that both horizontal and vertical deformation rates had dropped dramatically and were steady from that time onward, with velocities that reflected overall motion of Kīlauea's south flank (e.g., Owen et al. 2000).

The coastal deformation adjacent to the delta may have several mechanisms, including cooling of hot rock, loading due to emplacement of lava and formation of the delta, and gravity sliding due to the unstable nature of the delta. While cooling is probably important on the delta itself (Kauahikaua et al. 1993; Marie et al. 2003), it is not likely to be a significant factor inland of the delta, since the preexisting coastline had long since cooled. Loading is also not likely, given that the rate of deformation did not scale with the size of the delta—indeed, deformation was not occurring prior to early 2006 (Fig. 6), despite the presence of a significant delta at that time. Gravity sliding is the most probable cause of the coastal

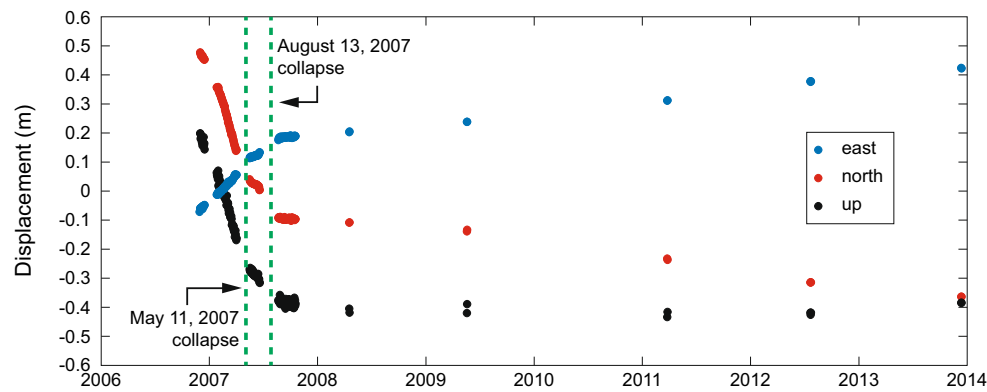


Fig. 7 Time series of east (*blue*), north (*red*), and up (*black*) components of motion at a GPS station located just inland of the East Lae ‘Apuki lava delta (see Fig. 5b for station location). *Green dashed lines* give the times of the May 11 and August 13, 2007 collapses. Seaward displacement

deformation given the strong association of the deformation with the presence of the delta, as well as the character of the deformation itself. The deformation was not present until after the large collapse of November 2005, which removed some preexisting coastline. This event may have also destabilized the coastline, resulting in a coupling between the coastline and the subsequent delta, such that seaward instability of the delta was able to pull the adjacent sea cliff towards the ocean. Partial delta collapse in May 2007 slowed the rate of gravity-sliding displacement, but that deformation did not cease until the delta collapsed completely in August 2007 and the source of the pull was removed.

Characterizing hazards associated with lava deltas

Experience derived from numerous episodes of lava delta growth and collapse over the course of Kīlauea’s Pu‘u ‘Ō‘ō eruption—highlighted by the East Lae ‘Apuki delta during 2005–2007—coupled with insights from geodetic data support a model for the hazards that attend lava delta evolution over time as well as a means of recognizing when some deltas may be prone to future collapse. With respect to hazards, the style and impact of small explosions associated with delta evolution varies according to the activity level of the ocean entry. Actively growing lava deltas can experience a range of locally hazardous explosion types, from spattering caused by interaction between water and lava, to collapse-related tephra jets and lithic blasts that can scatter hot rock and lava bombs several hundred meters inland. Even after ocean entry activity has ceased, a hazard exists due to the hot nature of the solidified lava making up the delta—collapse soon after the end of delta growth can still generate powerful lithic blasts, as exemplified by the May 11, 2007 collapse at East Lae ‘Apuki. Only after a delta has been inactive for long enough to cool to ambient levels—perhaps several months, depending on delta size—does the danger of explosion pass, although sudden

rates are highest prior to May 11, 2007; are reduced somewhat between May 11 and August 13, 2007; and resemble background deformation of Kīlauea’s south flank after August 13, 2007

collapse is still possible and will pose a danger to anyone on the delta surface or nearby, where a small tsunami may have a significant impact.

While the style of potential explosions can be related to the activity level of delta, the delta age gives no information about its propensity for collapse—that information may, however, be indicated by deformation of the preexisting coastline just inland of the delta. Displacements associated with the East Lae ‘Apuki delta were first apparent in InSAR data in early 2006, after the delta had largely reformed following its complete collapse a few months earlier. The development of the instability may indicate that the November 2005 collapse destabilized the preexisting coastline. The instability, however, was clearly tied to the existence of the delta—rapid seaward displacements continued even after the May 11, 2007 partial collapse (although they were reduced with respect to pre-collapse rates), indicating that the delta was still unstable and there was still potential for failure even months after it ceased growing. It was only after the delta collapsed completely in August 2007 that the anomalous coastal deformation disappeared. It is possible that small displacements of the preexisting sea cliff were occurring prior to early 2006 but were not measurable by InSAR, or that the extreme size reached by the East Lae ‘Apuki delta starting in early 2006—the largest to exist during the course of the Pu‘u ‘Ō‘ō eruption to date—coupled with the loss of some preexisting coastline in November 2005 was necessary to trigger the extreme coastal deformation. Both factors probably played a role in the magnitude of the deformation, given that similar patches of coastal displacements have not been observed by InSAR associated with other ocean entries at Kīlauea since the onset of frequent InSAR acquisitions in the 2000s. Regardless, centimeter-scale deformation over distances of tens to hundreds of meters can be clearly imaged by InSAR, especially given the increased spatial resolution available from many SAR satellites (e.g., Richter et al. 2013). Smaller-scale deformation (in terms of both magnitude and

spatial extent) would be best monitored using continuous GPS, which, if telemetered, could also be used to track coastal deformation in near-real time.

Conclusions

Lava deltas represent an important, if localized, hazard, especially on populated ocean island volcanoes. Fortunately, the progression of hazard types due to explosive interaction between the delta and seawater is predictable and evolves in concert with the delta itself. Active deltas, at points where lava is entering the ocean, will be characterized by minor lava fountains and spattering. When these deltas collapse, they can generate powerful tephra jets and lithic blasts that can deposit debris several hundred meters inland. Collapse of inactive, but still hot, deltas is associated with lithic blasts, while failure of cool deltas will not generate an explosion (although they may be associated with local tsunami). The potential for future collapse could be indicated by deformation of the preexisting shoreline. Large deltas might generate deformation of sufficient magnitude and spatial extent to be visible in InSAR data, but a continuous GPS station will provide finer resolution on deformation rates and also offers the potential for near real-time monitoring of coastal displacements in support of hazards assessment.

While these insights provide a starting point for identifying the hazards associated with lava–ocean entries, there are still a variety of questions that have yet to be answered about the style of interaction between water and lava. For example, what controls the areal extent that a lava delta can reach? The East Lae ‘Apuki region of Kīlauea has traditionally been the location of the largest deltas during the course of the Pu‘u ‘Ō‘ō eruption, but the factors that control such behavior are not clear—is delta size related to submarine morphology and lava effusion rate, as suggested by investigations at Stromboli (Bosman et al. 2014)? To what extent do local ocean currents, wave action, and the geometry of the coastline play a role? Similarly, do collapses occur without warning, or do seaward displacement rates accelerate immediately prior to a collapse (which would be valuable information for hazards mitigation)? If so, over what temporal and spatial scales does the acceleration in motion occur? Additional research into the formation and destruction of lava deltas should focus on these issues to better understand the mechanisms controlling delta evolution, in addition to the consequences we have addressed here. In this context, the development of integrated physical models to evaluate the temporal evolution of delta stability could furnish new insights into the volumes that may be affected by gravitational collapse or sliding and the likely impacts of that sliding on nearby populations and infrastructure.

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