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Depositional processes of alluvial fans along the Hilina Pali fault scarp, Island of Hawaii

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ABSTRACT

A series of previously unstudied alluvial fans are actively forming along the Hilina Pali escarpment on the south flank of Kīlauea volcano on the Island of Hawaii. These fans are characterized by their steep slopes, coarse grain sizes, and lobate surface morphology. Fans are fed by bedrock channels that drain from the Ka'ū Desert, but sediment is mostly sourced from deeply eroded alcoves carved into the Hilina Pali. Examination of recent deposits indicates that the fans are dominantly constructed from gravel and larger sized sediment. Flow discharges calculated using field measurements of channel geometries and the Manning equation indicate that events inducing sediment transport are of high magnitude and occur during high intensity precipitation events, including Kona storms. The fans along the Hilina Pali appear to be a rare example of fans formed predominately from sieve lobe deposition owing to the area's high slopes, high discharge, coarse bedload, and limited supply of fine-grained sediment. Given such conditions, sieve lobe deposition can form large lobes consisting of boulder-sized material, which may have implications for the identification of depositional processes when interpreting the stratigraphic record.

1. Introduction

Alluvial fans are depositional landforms that form where a sediment laden channel exits mountainous terrain onto a lower gradient surface. The reduction of carrying capacity and lateral spreading of the channel forces the deposition of sediment into a semi-conical shape. Alluvial fans form in environments with steep topography and sufficient sediment production and fluid discharge (Blair and McPherson, 2009). They occur in all environmental settings with fluid-driven sediment flow and sharp topographic relief, occurring not only on Earth, but also Mars (Moore and Howard, 2005) and Titan (Birch et al., 2016), the two other planetary bodies known to have had surface fluid flow.

Processes that provide sediment to alluvial fans are broadly defined as either sediment-gravity processes such as debris flows, or fluid-gravity processes, which include sheetfloods and incised channel flows (Blair and McPherson, 2009). When sediment-laden flow debouches onto a permeable, coarse-grained fan surface, water may infiltrate into the fan and the coarsest material in the flow acts as a sieve, permitting water and fines to transport through while coarser grains are deposited. Hooke (1967) described this process as sieve lobe deposition, and it was once widely used in alluvial fan literature to describe such processes and their subsequent deposits (Hooke, 1967, 1968; Bull, 1972; French, 1987; Nemec and Postma, 1993). This style of deposition is particularly prevalent in settings with a scarcity of fine-grained sediment, significant bedload, and permeable ground (Nemec and Postma, 1993). Later researchers argued that such conditions do not occur in nature and that the sieve lobe model is based on the erroneous interpretation of weathered, fine-winnowed debris flow deposits (Blair and McPherson, 1992, 1993, 2009). Following Blair and McPherson's (1992, 1993, 1994, 1995, 2009) rejection of the sieve lobe model, the term fell out of usage, but has recently been revived as a fundamental process in describing alluvial fan formation and architecture (Milana, 2010; Chen et al., 2017).

In this report, we describe a series of alluvial fans along the south flank of Kīlauea volcano on the Island of Hawaii. These landforms were included in the Wolfe and Morris (1996) geologic map as Holocene and Pleistocene alluvial and colluvial fill and have been noted in previous studies (Tunison et al., 1994; Craddock et al., 2006; Craddock and Golombek, 2016), but to date have not been studied in detail. We present results from a remote sensing study and field investigation of the fans, and describe our interpretation of the fan deposits as having formed dominantly from sieve deposition associated with the region's the limited availability of fine-grained sediment and steep slopes that assist bedload transport.

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2. Geologic and climatic setting

Hawaii is the largest and most volcanically active island in the Hawaiian island chain. It is comprised of five volcanoes, the youngest of which is Kīlauea at an elevation of 1200 m. Eruptions occur both from the summit caldera and the two rift zones that radiate from the summit to the southwest and east (Fig. 1). The north flank of Kīlauea is stabilized against the much larger Mauna Loa volcano, but the south flank is unstable and is moving seaward at a rate of ~6–10 cm/yr (Owen et al., 1995, 2000), though it may move catastrophically, such as the 3 m of displacement that took place during the 7.2 M 1975 Kalapana earthquake (Lipman et al., 1985). At the surface, this slippage is manifested as two normal fault systems, the Koa'e Fault Zone and the much larger Hilina Fault System along the coast. The 42 km long, up to 5 km wide, and ~9 km deep Hilina Fault System's subaerial component is dominated by the 500 m high Hilina Pali escarpment.

Twelve distinct fan landforms exist along the base of the Hilina Pali (Fig. 2 and Table 1). The fans are fed by channels that have carved deep alcoves into the Hilina Pali (Figs. 2 and 3) and drain the Ka'ū Desert, on the leeward flank of the Kīlauea volcano. The Ka'ū Desert receives ~1300 mm of rainfall annually (Giambelluca and Sanderson, 1993), so it is not a true desert but rather a chemical desert because of sulfuric aerosol fallout from the summit caldera that inhibits vegetation growth (Schiffman et al., 2000). No weather stations record precipitation in the Ka'ū Desert, but several NOAA weather stations exist in the surrounding area (Table 2). Volcanic eruptions along the Southwest Rift Zone occur frequently, and the Ka'ū Lava Ramp is regularly resurfaced. Geologic mapping and radiometric-derived ages indicate that the oldest surfaces in the Ka'ū Desert are <750 yr old (Wolfe and Morris, 1996) and consist of lavas, splatter cones, and tephra. The Ka'ū Desert is bisected by the 10–20 m high, 12 km long, and 2 km wide Koa'e Fault Zone that connects the rift zones south of the Kīlauea summit caldera ~4 km upslope from Hilina Pali and is the smaller subaerial expression of the south flank slip. The Koa'e system as a whole is likely a long-lived feature (Podolsky and Roberts, 2008), but from lava flow stratigraphy, current rates of seaward displacement, and oral records of native Hawaiians, Duffield (1975) estimated that most of the observable displacement has occurred in the past 500 yr. The water table depth at Kīlauea summit is 490 m (Zablocki et al., 1974), and groundwater in the Ka'ū Desert is essentially nonexistent except immediately following precipitation.

The main bedrock formation exposed along the Hilina Pali escarpment is a 300 m thick portion of the Hilina Basalt, consisting of pāhoehoe and 'a'ā lava flows (95% of exposure) with interspersed ash layers (5% of exposure) (Easton, 1987). Layers of pāhoehoe and 'a'ā both show evidence for surface weathering, with the pāhoehoe lava layers having lost ~1–10 cm of material and the 'a'ā clinker zones having been partially to totally weathered to a reddish-brown clay (Easton, 1987). The Hilina Pali is overlain by the ~15 m thick, 31 ± 0.9 ka Pahala ash and the ~50 m thick, <23 ka Puna Basalt formations, which is capped by the 5–12 m thick, ~500 yr old Keanakāko'i ash (McPhie et al., 1990). The total thickness and age of the Hilina Basalt is uncertain, but ash layers near the base of the exposed lavas date from ~100 ka (Easton, 1987).

3. Methods and data

The primary remote sensing datasets we used in our analyses are a digital elevation model (DEM) with a 10 m horizontal resolution and ~5 m vertical accuracy (Sugarbaker et al., 2017) and public domain aerial orthoimagery with resolution of ~0.25 m (USGS, 2010). We define the fan apex as the location where contours shifted direction from concave (convergent flow) to convex (divergent flow), lateral fan boundaries by an abrupt end of convex form, and fan toes by the sharp change in slope and an end to convex contour orientation. We measured a number of morphometric properties, including fan size, gradient, feeder channel geometry and relief, and watershed area.

We generated longitudinal profiles using 13 points along each transect: the fan toe, five equally spaced points along the fan, fan apex, seven equally spaced points along the alcove, and the upper edge of each alcove where it met the feeder channel. We took the average elevation within a 15 m radius around each point to compensate for the roughness of the fan and alcove surface.

Feeder channels were mapped both visually using the orthoimagery and by using a D8 algorithm within ArcHydro to derive flow accumulations, extract watersheds, and discern flow paths from the DEM. The terrain is difficult to traverse, consisting of a number of overlapping, undulating older lava flows, and the area is also extensive (~30 km^2), so we did not bring heavier surveying tools such as differential GPS, which would have required establishing several

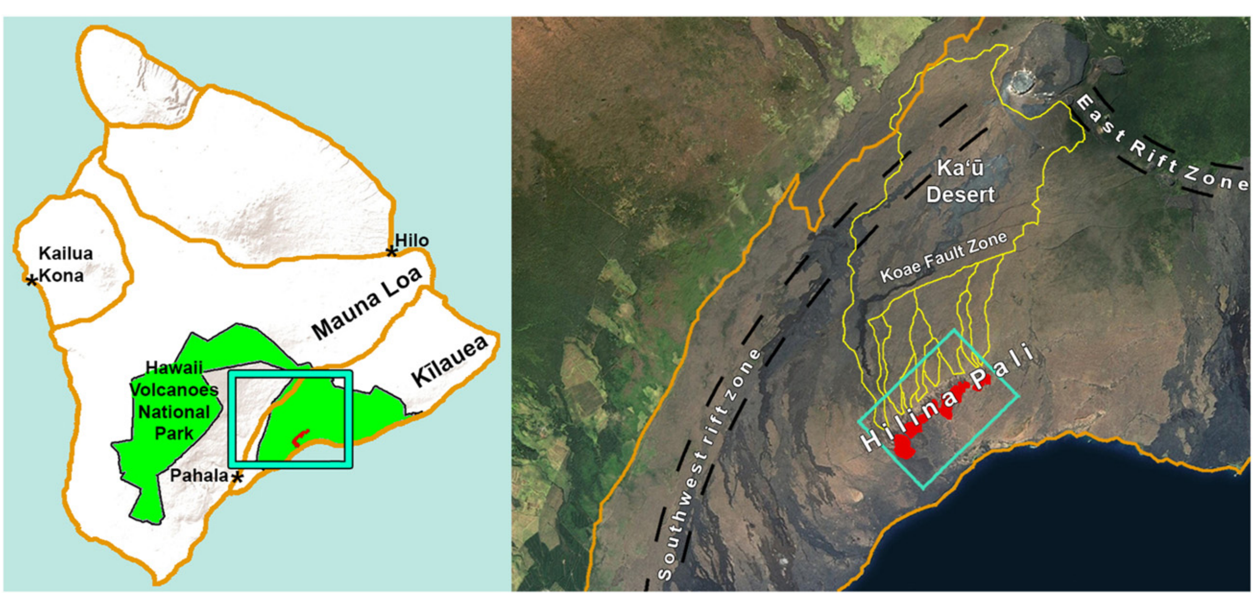

Fig. 1. Overview of study region. Left: map of the Island of Hawaii centered on 19.6°N, 155.4°W. Box indicates location of image on right. Right: Global Land Survey 2010 imagery of southeastern Island of Hawaii with features mentioned in text. Alluvial fans along the base of the Hilina Pali escarpment are outlined in red. ArcHydro-derived watersheds (see Section 3 for discussion) are outlined in yellow. The Koa'e Fault Zone directs all surface runoff from the northern Ka'ū Desert to fan F1. Box indicates the location of Fig. 2a.