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CORRESPONDENCE: kimmbishop57@yahoo.com

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Landslide hypothesis for the origin of Haleakala volcano's crater and great valleys, Hawaii

Kim M. Bishop*

Department of Environment and Geosciences, California State University, Los Angeles, 5151 State University Drive, Los Angeles, California 90032, USA

ABSTRACT

Active Haleakala volcano on the island of Maui is the second largest volcano in the Hawaiian Island chain. Prominently incised in Haleakala's slopes are four large (great) valleys. Haleakala Crater, a prominent summit depression, formed by coalescence of two of the great valleys. The great valleys and summit crater have long been attributed solely to fluvial erosion, but two significant enigmas exist in the theory. First, the great valleys of upper Keanae/Koolau Gap, Haleakala Crater, and Kaupo Gap are located in areas of relatively low annual rainfall. Second, the axes of some valley segments are oblique for long distances across the volcanic slopes. This study tested the prevailing erosional theory by reconstructing the volcano's topography just prior to valley incision. The reconstruction produces a belt along the volcano's east rift zone with a morphology that is inconsistent with volcanic aggradation alone, but it is readily explained if it is assumed the surface was displaced along scarps formed by a giant landslide on Haleakala's northeastern flank. Although the landslide head location is well defined, topographic evidence is lacking for the toe and lateral margins. Consequently, the slope failure is interpreted as a sackung-style landslide with a zone of deep-seated distributed shear and broad surface warping downslope of the failure head. Maximum downslope displacement was likely in the range of 400–800 m. Capture of runoff at the headscarps formed atypically large streams that carved Haleakala's great valleys and explains their existence in low-rainfall areas and their slope-oblique orientations. Sackung-style landslides may be more prevalent on Hawaiian volcanoes than previously recognized.

INTRODUCTION

The Hawaiian Islands, formed at the Hawaiian hotspot, one of Earth's most geologically active locations, experience volcanism, volcano spreading, earthquakes, and megascale landsliding. With its varied and prolific geologic activity, the Hawaiian Island chain has been the focus of intense geologic study. Despite the attention, discoveries continue to be made and prevailing viewpoints can be challenged. In this vein, this study proposes that a previously unrecognized giant, inactive landslide on Haleakala volcano's northeastern flank has been a primary influence on the morphology of the summit crater and the great valleys, challenging the view that fluvial erosion has been the only process.

Haleakala volcano, also known as East Maui volcano, comprises the eastern three quarters of Maui island (Fig. 1). With a summit elevation of 3000 m and subaerial dimensions of 52 km east-west and 42 km north-south, the shield volcano is the Hawaiian Islands' second most voluminous volcano (Robinson and Eakins, 2006). Three rift zones form broad ridges that radiate north, southwest, and east from the summit and descend to the coast along a horizontal distance of ~30 km and from the coast extend many kilometers offshore. Volcano slope gradients typically average 7°–10° near sea level and 20°–25° around the summit.

As described by Sherrod et al. (2007), Haleakala volcano, having erupted frequently during the Holocene, is classified as active. Manifest by the presence of abundant well-defined cinder cones, fresh-appearing lava flows, and rift trenches, recent activity has been concentrated on the southwest and east rift zones. The north rift zone, lacking in youthful volcanic features, has been inactive for several thousand years.

A striking geomorphic aspect of the volcano is the presence of four relatively large valleys, which, following the usage of Stearns (1942), are referred to herein as "great valleys." Consisting of Keanae/Koolau Gap, Kipahulu, Kaupo Gap, and Waihoi (Fig. 1), the great valleys generally range from 3 to 5 km wide and 200 to 600 m deep. Each valley is partially filled by at least a few hundred meters of lava, giving each a flat-floored cross-profile.

Another significant feature, Haleakala Crater, is an east-trending depression 11 km long, 3.5 km wide, and 300 m deep at the volcano's summit (Fig. 1). Similar to the great valleys, the crater has a flat-floored cross-profile owing to partial infilling by younger volcanic deposits. At its northwest corner, the depression is open and drains into Koolau Gap, which in turn drains into Keanae Valley. Koolau Gap and Keanae Valley are the north and south segments of a single great valley informally referred to as Keanae/Koolau Gap valley in this study. Haleakala Crater is also open at its southeast corner where it merges with and drains into Kaupo Gap great valley. The crater, then, serves as the headwater for two of the great valleys, with the drainage divide formed by a line of youthful rift zone vents trending obliquely across the crater floor.

The geologic map of Haleakala (Fig. 1) shows that the volcano's slopes are underlain by the Kula Volcanics, which erupted between ca. 930 and 145 ka. Locally mantling the Kula lavas, primarily along the southwest and east rift zones, the Hana Volcanics erupted from ca. 120 ka to the present (Sherrod and Kauahikaua, 2003; Sherrod et al., 2007). Early Kula Volcanics consist of hawaiite,

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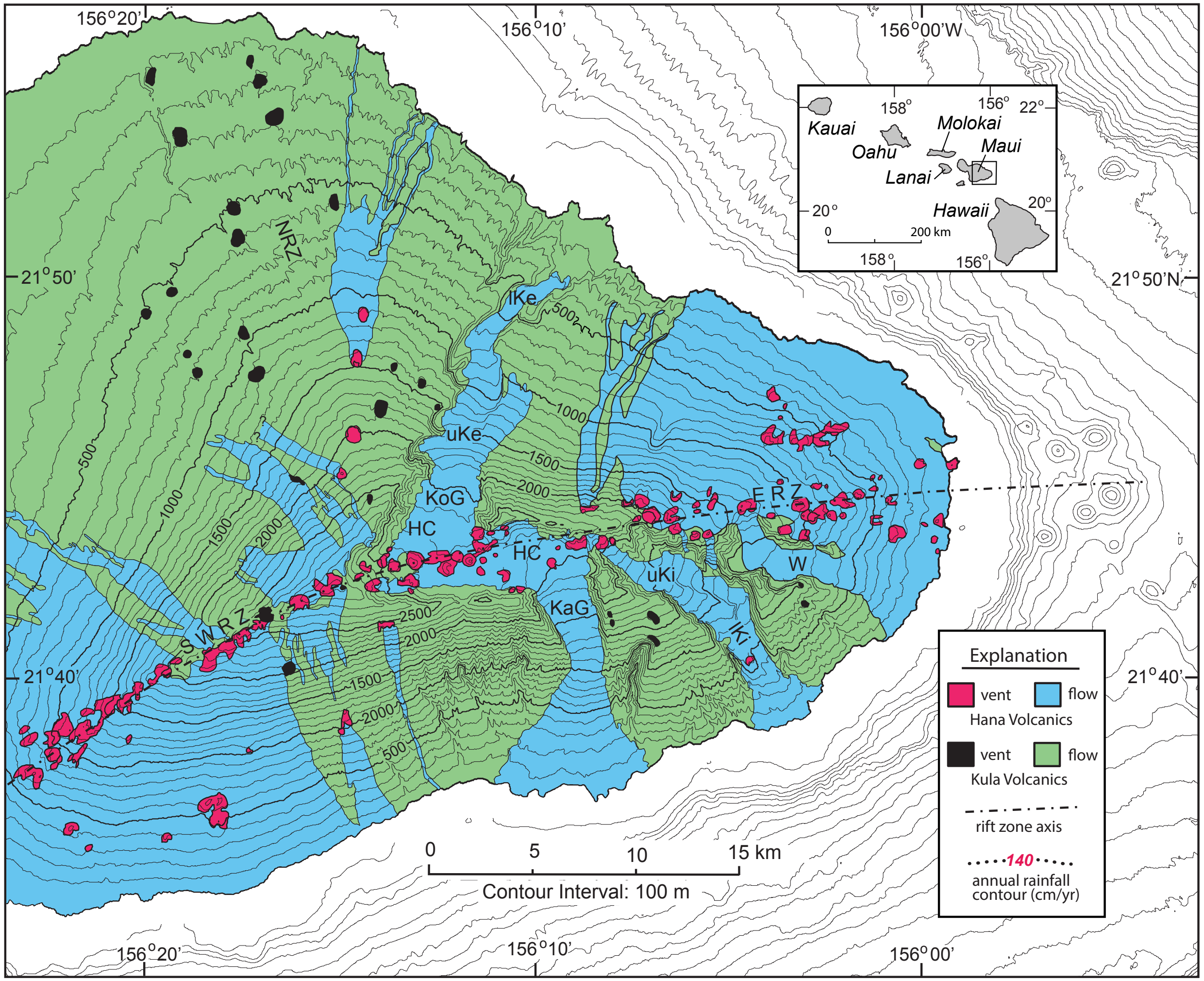
*Present address: P.O. Box 4941, Sunriver, Oregon 97707, USA

Figure 1 is interactive. Use the buttons directly below the map to view the different layers. Layers may be viewed separately or in combination using the capabilities of the Acrobat (PDF) layering function (click "Layers" icon along vertical bar on left side of window for display of available layers; turn layers on or off by clicking the box to the left of the layer name). If the interactive buttons do not work in the version of the paper you are reading, please visit https://doi.org/10.1130/GEOS.S.15173700.



Geology Map | Annual Rainfall Contours | Drainage Directions and Valley Axes | Areas of Figures 2–4 | Figure 1 - ALL layers

Figure 1. Haleakala volcano location, geology, and rainfall map. SWRZ—southwest rift zone, ERZ—east rift zone, NRZ—north rift zone, HC—Haleakala Crater, lKe—lower Keanae Valley, lKi—lower Kipahulu Valley, KaG—Kaupo Gap, KoG—Koolau Gap, uKe—upper Keanae Valley, uKi—upper Kipahulu Valley, W—Waihoi Valley. Purple boxes delineate the areas of Figures 2, 3, and 4. Boundaries of the great valleys at the level of their Hana Volcanics infill are shown as red-dashed lines, and the red solid lines delineate the great valley axes. Arrows indicate the direct downhill direction of the volcanic slopes. Note that the axes of upper Keanae/Koolau Gap, Haleakala Crater, Waihoi, and upper Kipahulu valleys trend oblique to the arrows. Also note the thin black lines in shallow valleys on Haleakala's north and south slopes showing the trajectory of selected streams. Black dots at or near the rim of Haleakala Crater indicate the location of dated surface lava flows with their ages labeled in thousands of years (from Sherrod et al., 2007). Purple squares on the east and west valley walls at Koolau Gap and south rim of Haleakala Crater mark the locations of accumulation rate determinations by Sherrod et al. (2007). Annual rainfall contours are from Frazier et al. (2016). Geology was modified from Sherrod et al. (2007). Figure 1 is interactive. Use the buttons directly below the map to view the different layers. Layers may be viewed separately or in combination using the capabilities of the Acrobat (PDF) layering function (click "Layers" icon along vertical bar on left side of window for display of available layers; turn layers on or off by clicking the box to the left of the layer name). To interact with Figure 1 if reading the full-text version of this paper, please visit https://doi.org/10.1130/GEOS.S.15173700.

whereas late Kula and all of the Hana Volcanics are chiefly basanite (Sherrod et al., 2007). Given the significant compositional overlap of the late Kula Volcanics and the Hana Volcanics, the two lava series are divided on the basis of geomorphic rather than chemical differences. Specifically, the Kula Volcanics are recognized as having erupted prior to maximum development of Haleakala's great valleys, and the Hana Volcanics erupted after their maximum development (Stearns and Macdonald, 1942). Consequently, the erosional walls of the great valleys and Haleakala Crater expose Kula Volcanics, whereas Hana Volcanics form the valley infill.

Radiometric ages of the Kula and Hana volcanics provide timing constraints regarding development of the great valleys and Haleakala Crater. Rim-capping Kula basalts surrounding Haleakala Crater range between 230 and ca. 150 ka, interpreted by Sherrod et al. (2003) to indicate that the crater reached its present size after 230 ka and perhaps as recently as 160–150 ka. Similar ages likely apply to the development of Keanae/Koolau Gap and Kaupo Gap great valleys that drain the crater. Concerning Kipahulu Valley, an intracanyon Hana lava flow dated at 120 ka shows the valley to have been well developed by that time (Macdonald et al., 1983; Sherrod et al., 2003). From a geomorphic standpoint, the similar lengths and widths of the great valleys are consistent with the interpretation that they are all of similar age.

During the late nineteenth and first half of the twentieth centuries, several geologists speculated that Haleakala Crater and several of the great valleys mainly had structural origins. Dutton (1884, p. 206–207) hypothesized that the crater formed as a fault-bounded caldera analogous to the modern calderas at Kilauea and Mauna Loa volcanoes on the island of Hawaii. Dana (1890, p. 278) postulated that Kaupo Gap and Keanae/Koolau Gap valleys formed by graben subsidence. Powers (1917) and Hinds (1931) agreed with Dana's graben theory for the two valleys and with Dutton's caldera hypothesis for the summit depression. Powers (1917) believed that Kipahulu presents clear evidence of being a rift valley.

Stearns (1942), noting the lack of evidence supporting a structural origin for any of the great valleys and Haleakala Crater, reasoned that all these features formed exclusively by erosion. Observing that the amphitheater heads at Waihoi and Kipahulu Valleys are typical of large erosional valleys throughout the Hawaiian island chain, he proposed that Haleakala Crater is simply the coalesced erosional heads of Kaupo Gap and Keanae/Koolau Gap valleys. Stearns (1942) envisioned that the two valleys at one time had abutting amphitheater-shaped heads separated by a sharp, narrow ridge near the middle of the present-day crater and that these features are now buried by young lava flows forming the relatively flat floor of the depression. For the past 75 yr, Stearns' (1942) hypothesis of an erosional origin without structural deformation for any of the great valleys and Haleakala Crater has been widely accepted (e.g., Macdonald et al., 1983; Hackett, 1987; Hazlett and Hyndman, 1996; U.S. Geological Survey, 2001).

An enigma regarding Stearns' (1942) hypothesis is the location of Haleakala Crater and some of the great valleys relative to annual rainfall (Fig. 1). Haleakala Crater, Kaupo Gap, and upper Keanae/Koolau Gap valleys are formed in the relatively low-rainfall summit area, where annual rainfall rates range between 75 and 290 cm/yr. In contrast, extensive slope areas on the northeast side of the mountain, where annual rainfall is greater than 480 cm/yr and locally over 840 cm/yr, are relatively unincised. Although it is possible the erosional development of Haleakala Crater and the great valleys in low-rainfall areas was affected by factors such as higher annual rainfall during a different past climate regime or differences in storm and runoff intensity patterns across the mountain that differ from annual rainfall patterns, it is puzzling that the deeply etched Haleakala Crater, Kaupo Gap, and upper Keanae/Koolau Gap valleys are in areas of comparatively low annual precipitation, whereas there is an absence of great valleys across a large swath of slope on Haleakala's northeast flank that receives substantially greater annual rainfall.

A second enigma is that the axes of Haleakala Crater and upper Keanae/Koolau Gap, upper Kipahulu, and Waihoi Valleys trend obliquely across the volcanic slopes for significant distances rather than directly downslope, as would be expected if their paths were determined solely by gravity on an even slope (Fig. 1). For example, upper Keanae/Koolau Gap valley trends 11° west of the direct downhill direction for a distance of 7 km. Similarly, upper Waihoi Valley trends at least 16° east of the direct downhill direction across a distance of 4 km. The most extreme example is Haleakala Crater, where for 5 km, its axis on the volcano's southern slope trends roughly 75° east of that slope's direct downhill direction. Finally, the trend of Kipahulu Valley's upper 6 km section is east of the downhill direction, although the degree of obliquity is difficult to determine because the valley's north side is along the east rift zone ridge, where prevalley contour lines would have been relatively sharply curved. Assuming the east rift zone ridge was symmetric before valley erosion, the degree of obliquity is ~45° eastward.

It is to be expected that some segments of valleys will have slope-oblique trends owing to their origin along the margins of lava flows that do not everywhere trend directly downhill. This effect is apparent in the paths of a number of youthful valleys on the mountain (Fig. 1). However, such an explanation for the obliquity of the great valleys seems unlikely as demonstrated by the fact that nowhere on the volcano are the slope-oblique segments of youthful streams as long as those of the great valleys.

Past tilting due to differential isostatic subsidence is potentially a factor in creating the anomalous great valley trends. Faichney et al. (2010) determined from a series of drowned coastal reefs that eastern Maui has tilted a net average of 1.53° toward S81E in the past 920 ± 20 k.y. Quantitative analysis to determine how much the tilting may have affected the valley orientations is not feasible, mainly because of uncertainty in the age of valley initiation relative to the timing of tilting. However, the fact that the slope-oblique axes for Keanae/Koolau Gap and Kipahulu valleys change from trending obliquely to directly downhill in their lower reaches suggests tilting is not a significant factor; otherwise, their lower valley segments would also be slope-oblique. This same argument pertains to slope-oblique Haleakala Crater in that it drains into Kaupo Gap valley, which has an axis trending directly downhill.

An additional problem in Stearns' (1942) erosion hypothesis is the absence of a long period of eruptive quiescence between the Kula and Hana volcanics episodes, whereas Stearns (1942) proposed a significant interval of quiescence that provided the time for the valleys to form. Age dating by Sherrod et al. (2003) has shown the time gap separating the two volcanic sequences may have been as short as 30 k.y., essentially the same amount of time as between most eruptions throughout Kula and Hana volcanics time. The question arises: What caused the valleys to form when they did, if a long period of volcanic quiescence was not involved?

The purpose of this study was to investigate the possibility that a process in addition to erosion was involved in the development of the great valleys and Haleakala Crater. A premise of the study is that the great valleys and Haleakala Crater became significant geomorphic features along their entire lengths, whether by erosion involving simultaneous deepening and widening along their entire lengths, or by knickpoint retreat, within the relatively short geological time of a few tens of thousands of years near or at the end of Kula volcanism. The outcome of the study is that a previously unrecognized giant landslide occupies Haleakala volcano's northeastern flank that provided the critical control on the development and morphology of the great valleys and Haleakala Crater.

METHODS

For the study, contour maps were used to reconstruct Haleakala's topography in the great valley areas for the time just prior to valley inception. To produce the reconstructions, contour lines on the volcanic surfaces bordering the valleys were extrapolated across the valleys. In this paper, the term "volcanic surface" refers to constructional surfaces formed of the surfaces of lava flows and excludes erosion-created surfaces.

For complete accuracy in the reconstructions, the contour maps would need to depict the volcanic surfaces that border each side of the great valleys as they were when valley incision began. Because the maps were drawn based on today's volcanic surfaces, error may exist, depending on the valley. Most of the volcanic surfaces bordering the valleys consist of Kula Volcanics, but in some areas, one side or the other consists of Hana Volcanics. Where this happens, the condition needed for complete accuracy is clearly violated, given that, by definition, the Hana Volcanics postdate initial valley development. Volcanic surfaces consisting of the Kula Volcanics potentially present a similar problem. Although the Kula volcanic surfaces of today predate maximum valley development, there is no certainty that each of these surfaces predated valley initiation. Compounding this problem, there is uncertainty in the age of valley inception. Although the reconstructions may, and in some cases do, have inaccuracies because of these surface-age issues, sufficient age data exist to assess the potential magnitude of inaccuracy and from the result evaluate the validity of the conclusions drawn from the reconstructions. This is addressed later in the paper.

The principal contour map used for topographic reconstruction is presented in Figure 1. Because only the contour lines on volcanic surfaces are relevant to the reconstruction procedure, intravalley contour lines, starting at the tops of valley walls, are omitted. For the purposes of describing and analyzing the topographic reconstruction, three areas are first considered separately (Fig. 1).

Unless otherwise stated in the figure caption, the base contour maps presented in the various figures were created using ARCGIS with data input from http://www.soest.hawaii.edu/HMRG/multibeam/bathymetry.php, presented by the School of Ocean and Science Technology, University of Hawaii at Manoa. Missing bathymetric contour line segments are artifacts in the data.

The initial step for reconstructing topography at each great valley was to delineate the valley edges at the level of their Hana lava infill. In drawing the edge lines, reentrants formed by subsidiary stream valleys splaying from the main valley were ignored. Based on the edge locations, each valley's centerline was drawn.

To create the reconstructions for a valley, the valley's centerline was assumed to be the location of the stream that initiated incision. If the stream incised vertically, and there were no complicating processes involved, such as infilling by lava followed by renewed incision at a location away from the centerline, and if the opposing valley walls have equal gradients, then the assumed centerline position of the initial stream should be correct.

The assumption that opposing valley walls have equal gradients can be tested. Although the great valley walls are mostly buried under Hana Volcanics and therefore unavailable for full measurement, the upper exposed parts of the walls are available for study. From the contour maps, several (5–13) gradient measurements were determined for opposing walls where the walls were at least 150 m high. From these, the average gradient of each wall was calculated. For Haleakala Crater, Kaupo Gap, Kipahulu Valley, and Waihoi Valley, the deviations between the average opposing wall gradients were found to fall between 0 and 6°. Drawing lateral cross sections for each valley and extrapolating the location of the buried wall sections using the average wall gradients resulted in thalweg locations deviating from valley midpoint locations by at most 130 m, which is less than 5% of each valley's width.

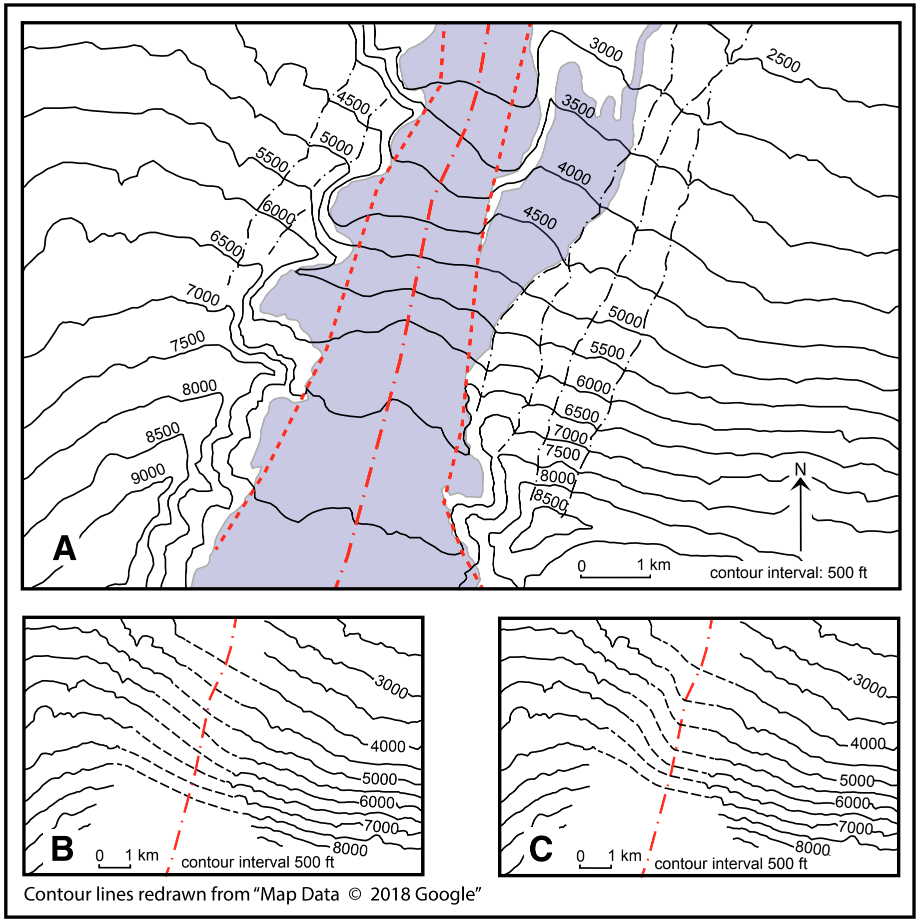
The possibility that a lava flow partially filled a developing great valley and that renewed incision began at a location not at the valley's centerline, thereby negating the assumption of a centerline position for the valley-initiating stream, cannot be discounted. Indeed, this process appears to have happened at Kipahulu Valley. The process could have affected other great valleys, with the evidence now buried under Hana Volcanics infill. Fortunately, for reconstruction purposes, the most important aspect of a valley-initiating stream's position is not its map location, but its trend, which should be parallel to the valley centerline in any case. As will be seen, the reconstructions indicate that a break in slope was present adjacent to several of the valley-initiating stream segments. If the assumed map location of the valley-initiating stream is inaccurate, then the reconstructed location of the break in slope may be laterally mispositioned on the slope by a few hundred meters, but the break nonetheless must have existed, and the conclusions drawn from the reconstruction remain the same.

RESULTS

Upper Keanae/Koolau Gap Valley

Topographic reconstruction of upper Keanae/Koolau Gap valley is presented in Figure 2. An initial simple reconstruction presented in Figure 2B cannot be valid because the reconstructed contour lines between the elevations of 3000 and 7500 m do not intersect the valley-initiating stream perpendicularly. This problem is overcome in Figure 2C, where reconstructed contours on the east side of the valley intersect the stream perpendicularly such that the stream trends directly downslope. With this reconstruction, the semiplanar western Kula volcanic surface is higher than the eastern Kula surface when viewed in contour-parallel profile.

As an optional reconstruction, the contour lines extrapolated to intersect the stream perpendicularly could have been drawn from the valley's west side and then curved to connect with the east side contours. However, that would place the stream that initiated valley incision directly along the upper edge of the higher surface, which seems an unlikely location. The reconstruction shown in Figure 2C is therefore preferred, but either option presents the same important result that a break in slope separates the west side Kula surface from the lower east side Kula surface.



Contour lines redrawn from "Map Data © 2018 Google"

Figure 2. Upper Keanae/Koolau Gap area topographic reconstruction maps. See Figure 1 for map location. (A) Contour map showing present-day topography. Areas exposing Hana Volcanics is shaded light purple, and Kula Volcanics are unshaded. Valley edges at the level of the Hana Volcanics infill are shown with red dashed lines. The inferred location of the stream that initiated valley incision is shown by a red dash-dot line. (B) Reconstruction of prevalley topography using black dashed contour lines extrapolated as straight as possible across the valley. Red dot-dash line shows inferred stream location from diagram A. Note that the stream crosses the contour lines obliquely. (C) Reconstruction of prevalley topography with the contour lines from the east side of the valley intersecting the valley-initiating stream (red dash-dot line) perpendicularly. Topographic contour maps redrawn from Google Maps (images from 2018, https://www.google.com/maps/). Contour interval: 500 ft = 152 m.

Waihoi Valley

Contour reconstruction of Waihoi Valley is presented in Figure 3. The reconstruction results are quite similar to those for upper Keanae/Koolau Gap valley. The initial simple reconstruction (Fig. 3B) cannot be correct because the reconstructed contour lines are not perpendicular to the stream.

The problem is corrected in Figure 3C, where contour lines on the northern volcanic surface were projected across the valley to intersect the stream perpendicularly and then curved to connect with their counterparts on the volcanic surface bordering the valley's south side. Similar to upper Keanae/Koolau Gap valley, the result indicates that one Kula surface is higher than the other. In this case, the south surface rests roughly 250 m (600 ft) higher than the north side surface.

In reality, the relief of the two prevalley volcanic surfaces would have been greater than that presented in Figure 3C because the south side surface is formed of Kula Volcanics and the north side has a veneer of Hana Volcanics. The buried prevalley Kula Volcanics surface on the valley's north side is likely several meters and possibly several tens of meters lower than the present topographic

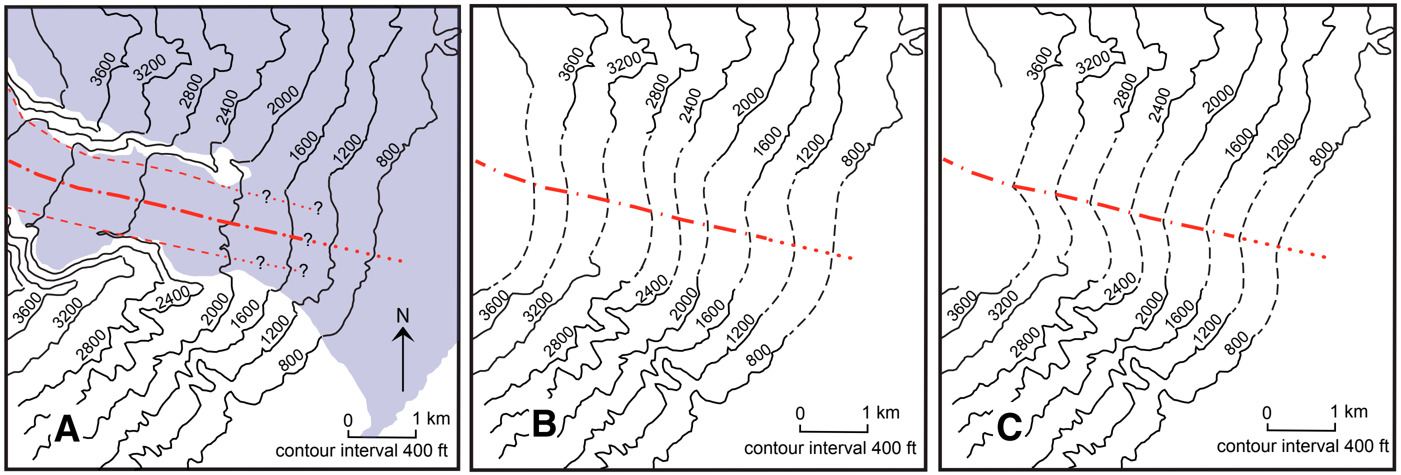


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Figure 3. Waihoi Valley area topographic reconstruction maps. See Figure 1 for map location. (A) Contour map showing present-day topography. Areas exposing Hana Volcanics is shaded light purple, and Kula Volcanics are unshaded. Waihoi Valley edges at the level of the Hana Volcanics infill are shown with red dashed lines, and the inferred location of the valley-initiating stream is shown by red dash-dot line. (B) Hypothetical contour map reconstruction of prevalley topography extrapolated using evenly curved contour lines (dashed). Note that the valley-initiating stream crosses the contour lines at oblique angles. (C) Reconstruction of prevalley topography with contour lines (dashed) from the north side of the valley projected such that they intersect the stream perpendicularly. Topographic contour maps redrawn from Google Maps (images from 2018, https://www.google.com/maps/). Contour interval: 400 ft = 122 m.

surface. Thus, the 250 m relief between the surfaces is a minimum.

Haleakala Crater, Upper Kipahulu Valley, and Kaupo Gap

Reconstructed prevalley contour lines for the Haleakala Crater and the upper parts of Kipahulu and Kaupo Gap valleys are presented in Figure 4. In creating the reconstruction for the area north of the stream (Figs. 4B and 4C), contour lines from the northern volcanic slopes were extrapolated in a manner that recreated a symmetric rift zone ridge. The logic for a symmetric ridge is recognition that all of Haleakala’s intact rift zones, including the entire southwest and north rift zones and the eastern end of the east rift zone, are, for the practical purposes of this study, symmetric.

South of the valley-initiating stream, the contour lines were extrapolated from the southern volcanic slope nearly to the stream in a manner that maintained their trend as they are on the volcanic slopes, but slightly adjusted to provide realistic spacing relative to adjacent contour lines. Next, the ends of the contour lines extrapolated from the north and south volcanic slopes were connected by a line drawn parallel to and just south of the stream. Placing this intervening segment on the south side of the stream rather than the north side was dictated by the necessity of reconstructing a channel for the stream.

DISCUSSION

Analysis of the Reconstructed Topography—Lava Aggradation Cannot Account for the Topography

The reconstructed topography (Fig. 5) reveals unusual morphology consisting of breaks in slope facing north to northeastwards in upper Keanae/Koolau Gap valley, through Haleakala Crater and upper Kipahulu valley, and into Waihoi Valley. In contrast, the reconstructed topography at lower Keanae, Kaupo Gap, and lower Kipahulu valleys displays no such unusual morphology.

Keanae/Koolau Gap and Waihoi Valleys

The breaks in slope at upper Keanae/Koolau Gap and Waihoi valleys could potentially have been created by differential volcanic aggradation. An added complexity is that the timing of the differential buildup could have been either before or after valley incision began.

In the first scenario (prevalley incision), differential aggradation would have formed by the building of a lava flow field originating from an isolated vent or cluster of vents. The great valley would have then formed adjacent to one of the flow field’s

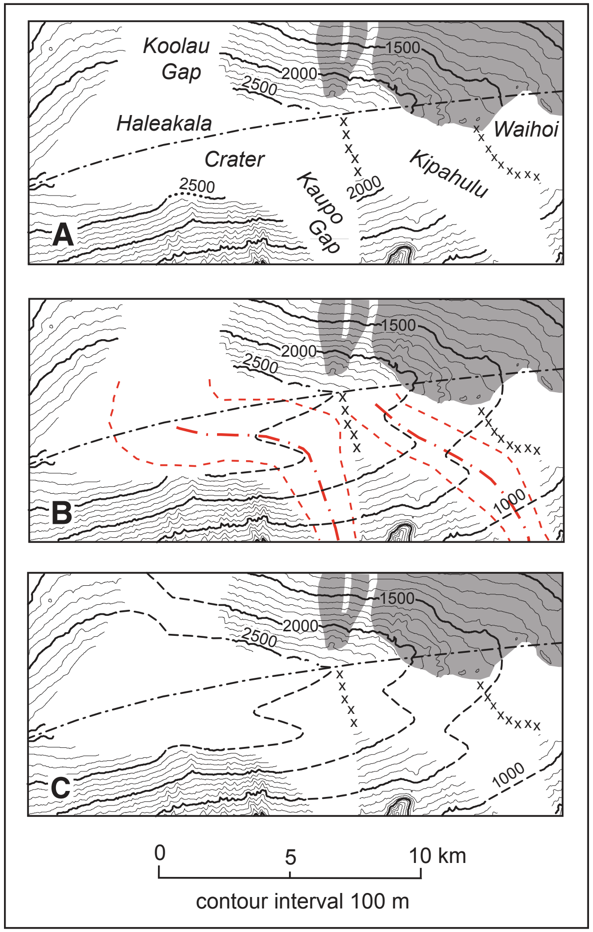

Figure 4. Haleakala Crater and upper Kipahulu Valley area topographic contour maps. See Figure 1 for map location. Black dot-dash line represents the rift zone axis. X's mark the locations of the ridge lines separating Haleakala Crater from upper Kipahulu Valley and upper Kipahulu Valley from Waihoi Valley. Gray shaded volcanic slopes expose Hana Volcanics, and unshaded slopes expose Kula Volcanics. (A) Valley location map. (B) Hypothetical prevalley topographic reconstruction using 500 m interval contour lines (black dashed). Valley edges at the level of the Hana Volcanics infill are shown with red dashed lines. Inferred location of the valley-initiating stream is shown by the red dash-dot line. (C) Reconstructed contour lines (black dashed) with stream and valley edge lines omitted.

edges. Several examples of recent, high-standing flow field surfaces exist on Haleakala (Fig. 5). It is useful to compare their morphology to that of the reconstructions in Figures 2C, 3C, and 5. The recent flow fields are fan-shaped with apexes at the vent. They are bounded by two relatively steep marginal slopes that descend to the volcanic surface upon which the field is built. The maximum relief at the flow field margins occurs at the vent and is generally a few tens of meters. Of the eight flow fields identified in Figure 5, the largest relief at 100 m occurs at the margin of the field above Manawainui Valley. Downslope from their vent, the relief of each flow field gradually decreases. The elevated surface of each field gradually widens and thins downslope until its surface essentially blends in with the older adjacent slopes. Contour lines defining the flow field surface are generally convex downhill.

Comparison of the upper Keanae/Koolau Gap and Waihoi Valley topographic reconstructions with the recent flow fields reveals important differences. First, the relief of the reconstructed breaks in slope is twice the 100 m relief of the highest recent flow field margin. Second, in contrast to the recent flow field surfaces, the potential flow fields in the reconstructions are essentially constant thickness in the downslope direction. Third, the high-standing surfaces at upper Keanae/Koolau Gap and Waihoi Valley have only the single break in slope in the reconstruction rather than the two breaks in slope formed at the margins of the flow fields. At upper Keanae/Koolau Gap valley, if the missing second break in slope were to exist, it would be west of the valley, and at Waihoi Valley, the missing break in slope would be to the southwest. Given the 200 m relief at upper Keanae/Koolau Gap valley and 250 m at Waihoi Valley, at least some topographic evidence of these opposing margins should exist, but it does not. Taken in total, comparison of the topographic reconstructions for upper Keanae/Koolau Gap and Waihoi Valley with recent flow field margins on Haleakala indicates that these are not correlative features.

In the second timing scenario (postvalley incision), differential aggradation would have occurred after the valleys were cut. In this case, the valleys acted as barriers that prevented lava flows accumulating on one side of the valley from crossing over and building up the other side. With respect to upper Keanae/Koolau Gap valley, lava accumulation rates determined by Sherrod et al. (2003) from lavas exposed on the east and west walls of Koolau Gap (Fig. 1) provide evidence for evaluating the scenario's veracity. On the east side, lava aggradation rates were 200 m/100 k.y. from 620 to 450 ka and 59–80 m/100 k.y. from 450 to 181 ka. No lava younger than 181 ka is present. On the west side, aggradation rates were 100 m/100 k.y. from 600 to 500 ka and ~27 m/100 k.y. from 500 to ca. 200 ka. Also pertinent, on the west side of upper Keanae/Koolau Gap valley, there is a 234 ka surficial lava flow located 1.5 km north and 1 km west of the traverse location (Fig. 1), which indicates little to no lava accumulation occurred on the valley's west side since roughly 230 ka.

These accumulation rates are opposite to those that would be expected if different amounts of stratigraphic aggradation are called upon to explain upper Keanae/Koolau Gap valley's west side being higher than its east side. The west side should have the higher accumulation rate and expose

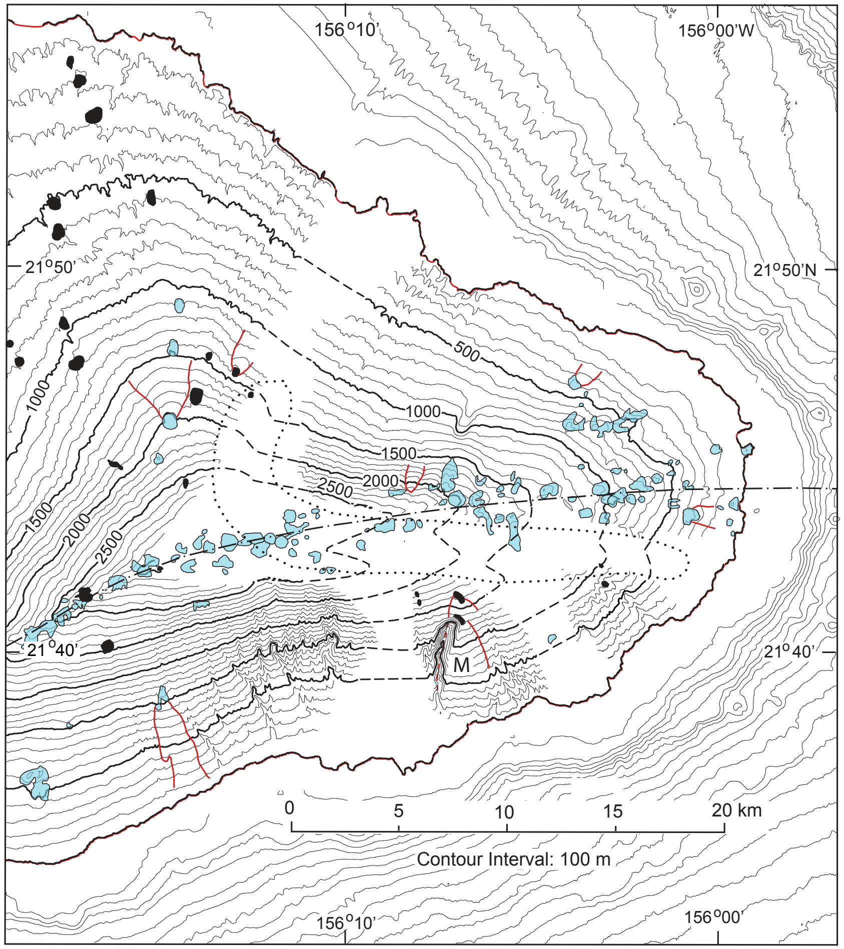

Figure 5. Summary topographic reconstruction map using 500-m-interval contour lines (dashed and labeled) and locations of prominent lava flow fields. Dash-dot lines designate the location of the southwest/east rift zone axis. Light blue blebs represent Hana pyroclastic vent deposits, and black blebs represent Kula pyroclastic vent deposits. In addition to reconstructed contour lines from Figures 2C, 3C, and 4C, the figure shows the reconstructed contour lines for lower Keanae, lower Kipahulu, and Kaupo Gap valleys. The dotted line encircles the belt of reconstructed topography containing breaks in slope. The red lines mark the margins of eight lava flow fields. M—Manawainui Valley. Note that reconstructed contour lines across Kaupo Gap, lower Kipahulu, and lower Keanae valleys do not display breaks in slope, in contrast to Haleakala Crater and upper Kipahulu, Waihoi, and upper Keanae/Kaupo Gap valleys.

the youngest flows. Admittedly, uncertainty exists because explanations exist that are consistent with the available age data and yet allow for the west side of upper Keanae/Koolau Gap valley to have a higher surface. For example, the north rift zone could have contributed lava to the west side of the valley, helping to build the volcanic surface without contributing lava at the traverse site, which would mean the accumulation rates do not apply to a large part of the western slope. Nonetheless, the key point is that the available age and accumulation rate evidence contradicts the post-valley-initiation model to explain differential accumulation at upper Keanae/Koolau Gap valley.

For Waihoi Valley, lava aggradation rate and age information are lacking, but geomorphic considerations contradict the model for this area, too. The higher volcanic surface bordering the valley is on the southwest, which is the side of the valley away from the rift zone. Assuming Waihoi Valley acted as a barrier to lava flows, it is improbable that the southwest slope could have grown significantly higher than the northeast slope. Indeed, the presence of the valley should have completely starved the south volcanic surface from lava accumulation during a time when the north side surface, essentially on the rift zone, was free to grow. As with upper Keanae/Koolau Gap valley, because the relief of the two volcanic slopes bordering the valley is opposite to that which is expected from lava accumulation alone, the model seems unlikely to apply.

Haleakala Crater and Upper Kipahulu Valley

Interpretations based on the reconstructed Haleakala and upper Kipahulu Valley areas requires consideration of potential error in the reconstruction caused by using volcanic surfaces of known different ages. In Figure 4, the present-day 1500 m and 2000 m contour lines north of Kipahulu Valley are on slopes mantled by Hana lava flows and vents (shaded areas), while their counterparts south of the valley are on slopes consisting of Kula lava flows. Similar to the situation described for Waihoi Valley, contour lines drawn on the surfaces mantled by Hana lavas cannot accurately reflect prevalley topography.

Consequently, the contour map reconstruction shown in Figures 4B and 4C somewhat incorrectly depicts the positions of the 1500 and 2000 m lines. To correct the depiction, the contour lines on the north side of the valley would need to be drawn on the buried Kula surface. Because the thickness of the overlying Hana Volcanics is uncertain, no attempt at contour line adjustment has been made. However, the distance of contour shift expected if an adjustment were to be made can be roughly calculated. The rate of stratigraphic aggradation around the summit area averaged ~20–30 m per 100 k.y. for the last several hundred thousand years (Sherrod et al., 2003). Using this rate and assuming the age of the basal Hana Volcanics is 150 ka (Sherrod et al., 2003), Hana lava aggradation may have raised the volcanic surface 35–45 m above the Kula surface. Based on the 20° to 25° slope gradients in the area, the contour lines would shift eastward and/or southward ~75–125 m if the Hana Volcanics were removed—a negligible distance at the scale of the map.

A larger potential problem involves the different ages of the Kula volcanic surfaces used in the reconstruction. Figure 1 shows the locations and ages of five rim-capping lavas at the perimeter of Haleakala Crater. The oldest is 228 ka, and the youngest is 145 ka. The important question is whether or not these surfaces were the ones present when valley incision began. For all five surfaces to predate the valley, stream incision would have to have begun after 145 ka, a proposition that seems unlikely given that the oldest Hana infill is 120 ka, and this would require that the valleys developed entirely within 25 k.y. Because a longer interval seems probable, it is likely that some, if not all, of the five locations experienced aggradation after valley initiation began, which in turn indicates inaccuracy in the reconstruction.

Enough information exists to crudely estimate the potential magnitude of the inaccuracy. In addition to the five rim-capping lava ages, lava aggradation rates for the time of valley development are available from three locations around the perimeter of Haleakala Crater (Fig. 1). Two of these locations are the aforementioned east and west walls of Koolau Gap. The third is at the crater's south rim, where an aggradation rate of 39 m/100 k.y. from 480 to 150 ka has been determined (Sherrod et al., 2003).

The accuracy analysis presented here will roughly estimate the horizontal distance that points on contour lines could have shifted owing to lava aggradation after valley initiation. For the analysis, where there is a choice of parameter values, the chosen value will be the one that maximizes contour line shifts in order to help determine a worst-case scenario. Two simplifying assumptions used for the analysis are: (1) surface accumulation resulted from continuous lava aggradation, and (2) the accumulation rate was the same everywhere around the summit.

The age of 228 ka, which is the age of the oldest of the five dated rim-capping lavas, was selected for the time of valley initiation. Regarding the time that the valleys reached their maximum extent, 120 ka was chosen because it is the oldest known age of Hana infill. Using these two ages, Haleakala Crater, Kaupo Gap, and Kipahulu Valley would have fully developed in ~110 k.y., an amount of time that could be too short. To lengthen the interval would require choosing an older time for valley initiation. However, this not required for the error analysis because the conclusions from the reconstruction depend on the shape of the volcano, not its elevation or size. Given that the error analysis assumes the accumulation rate on the volcanic surfaces was the same everywhere, for any time period during which all of the volcanic surfaces were accumulating lava, there only would be changes in the mountain's elevation and size, not in its shape. Given that the available data indicate the volcanic surfaces are 228 ka or younger, any time interval before 228 ka is not important to the analysis.

The greatest source of reconstruction error would result from elevation changes of the surface that accumulated lava for the longest period of time after valley initiation, which in this case is the 145 ka surface. The question becomes how much horizontal change in the contour positions would have occurred from accumulation on this surface after 228 ka? The answer depends in part on the assumed accumulation rate. From the three locations where rates of accumulation are available, the fastest rate of 80 m/100 k.y. was chosen. Using this value, the increase in elevation of the 145 ka surface was calculated to be 66 m.

To determine the horizontal shift in contour positions caused by the elevation change, the slope gradient was assumed to have been 20°. Utilizing that and the elevation gain of 66 m, the contours were calculated to shift 180 m. At the scale of the map in Figures 4C and 5, shifting the contour line locations for the 145 ka volcanic surface by 180 m would have an insignificant effect on the reconstruction and, more importantly, no effect on the conclusions drawn from the reconstruction. Any shift in the contour lines for the older volcanic surfaces around Haleakala Crater would also have no significant effect, given that their shifts would be smaller. Although this error analysis is highly simplified in that (1) lava accumulation is episodic rather than continuous, (2) the lava accumulation rates would not have been the same everywhere, and (3) the slope gradients vary somewhat from assumed value of 20°, as well as (4) the fact that the age data are sparse, considering that worst case parameters were used, the results suggest that any potential reconstruction error for the Haleakala summit area caused by accumulation of lava that may have occurred after valley initiation is negligible in the analysis.

Regarding the breaks in slope reconstructed in the Haleakala Crater and upper Kipahulu Valley area (Fig. 4), just as with the other two reconstruction areas, the margins of lava flow fields appear to be the only potential lava aggradation analogues, but the evidence suggests they are not. First, the relief of the breaks in slope in the Haleakala Crater and upper Kipahulu Valley is ~300–400 m, i.e., significantly greater than the maximum relief of 100 m at recent lava flow fields. Second, there is no opposing break in slope in the reconstructed area as compared to the two-sided nature of flow fields. Finally, the break in slope in Haleakala Crater makes an angle with the direct downhill direction that is approximately twice the largest angle of the flow field margins.

Gravitational Instability

A notable aspect of the breaks in slopes displayed in Figure 5 is that they form a belt that corresponds spatially with the locations where great valley axes trend obliquely across the volcanic slopes. This is consistent with a model that invokes surface deformation as an additional factor to lava aggradation in prevalley landscape development. Present knowledge of Hawaiian volcano dynamics provides a potential mechanism for such deformation, namely, slope displacement associated with gravitational instability.

General Hawaiian Island Instability

Evidence for ubiquitous gravitational instability and slope failures on Hawaiian volcanoes has become well established over the past few decades (Fig. 6; Moore, 1964; Moore et al., 1989, 1994; Denlinger and Morgan, 2014; Clague and Sherrod, 2014). Approximately 20 giant landslides with surface areas of tens of square kilometers mantle the ocean floor surrounding the various Hawaiian islands (Moore et al., 1989). In addition, normal faults, graben, and closed depressions caused by pull-apart deformation at the heads of gravitationally displaced slopes have been identified or proposed at volcano summit areas on the islands of Kauai (Hazlett and Hyndman, 1996; Sherrod et al., 2015), Lanai (Hazlett and Hyndman, 1996; Flinders et al., 2010), Maui (Sherrod and Kauahikaua, 2003), Hawaii (Moore et al., 1989; Bishop, 2017), and Molokai (Clague and Moore, 2002; Moore et al., 1989, 1994; Fig. 6). These subaerial features, along with the submarine landslides littering the seafloor, indicate that gravitational instability affects Hawaiian volcanoes from base to summit.

With respect to Haleakala volcano, two large ancient flank landslides have been proposed. The Hana Slump, a giant submarine landslide at the base of the volcano's northeast flank (Fig. 6), has a crown 15–20 km offshore and 1–1.5 km below sea level (Eakins and Robinson, 2006). The poorly understood Pahihi landslide affects Haleakala's subaerial south flank (Fig. 6; Sherrod and Kauahikaua, 2003). Existence of the feature is postulated mainly on the basis of a down-to-the-south normal fault exposed in the southern wall of Haleakala Crater. As currently understood, neither of these landslides could be responsible for the deformational belt proposed in this study because the crown of the Hana Slump is too low on Haleakala's flank and the Pahihi landslide involves the southern slope.

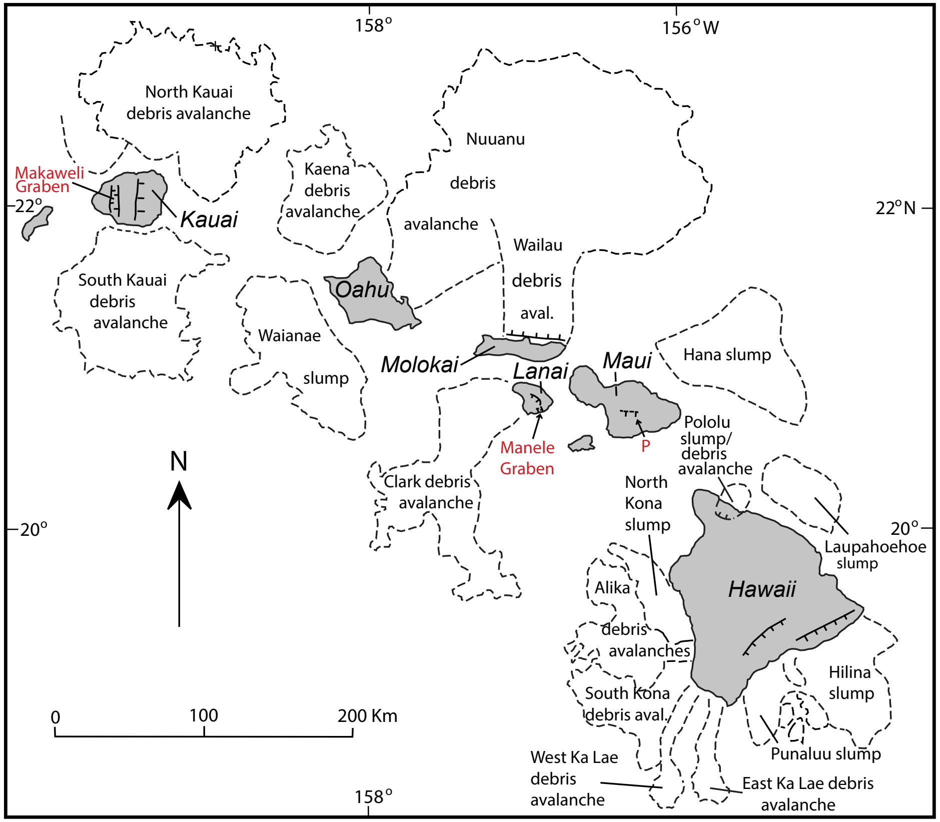

Figure 6. Location map of Hawaiian Island landslides and landslide scarps. The dashed lines outline giant landslides. Hachured lines designate known and proposed headscarps, with the hachures on the downthrown side. P—Pahihi landslide. Debris avalanches are defined as catastrophic landslides emplaced in minutes, and slumps are slow-moving landslides active over many years. Landslide locations were slightly modified from Moore et al. (1989). Scarp locations were compiled from Hazlett and Hyndman (1996), Sherrod et al. (2003, 2007, 2015), and Bishop (2017).

Haleakala Northeast Flank Landslide

This study proposes that a giant, inactive, landslide mantles Haleakala's northeast slope from the east rift zone ridge to an area low on the submarine flank. Northward displacement of the landslide is postulated to have resulted in a northerly facing headscarp zone (Figs. 7 and 8), represented by the breaks in slope displayed in Figure 5. The scarp zone contains three distinct subzones separated by ridges exposing Kula Volcanics that are, as best as known, not cut by landslide faults. One of the ridges separates Haleakala Crater from upper Kipahulu Valley, and the other separates Kipahulu Valley from Waihoi Valley (Fig. 7). Whether the scarp structure within each subzone consisted of a single, large, north-facing scarp, a system of numerous

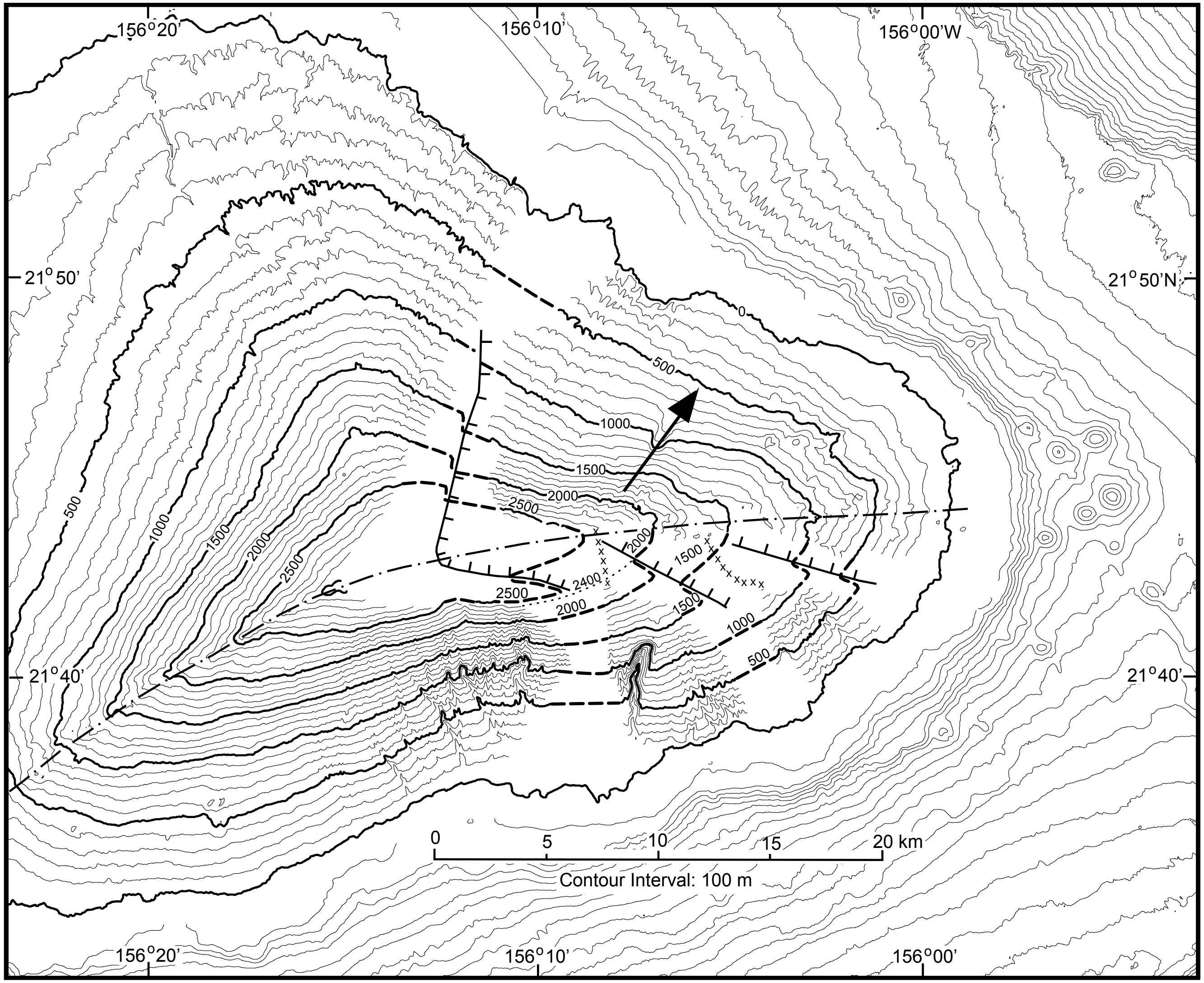

Figure 7. Location map for hypothesized landslide scarps shown with hachured lines. Arrow indicates assumed direction of landslide movement. Dashed lines show reconstructed contour lines across the great valley areas. X's denote the locations of ridges exposing Kula Volcanics that do not appear to be cut by landslide faults and thereby divide the overall scarp zone into subzones. The scarp locations are not well constrained and should be considered approximate only. Note that the dotted-line projection of the 2400 m contour line south of Haleakala Crater approximately aligns with the 2000 m contour on the opposite side of the scarp, indicating ~400 m vertical displacement across the scarp.

smaller scarps, possibly with antithetic scarps, or some combination of these in different locations is unknown because of obliteration by erosion.

Other than the head zone determined from the topographic reconstruction, no other landslide boundaries are evident in the contour map. Two possible explanations are: (1) the displacement was too small to have created discernible topographic distortion downslope of the landslide head, or (2) the slide displacement was relatively large, but the toe and lateral boundary deformation occurred by distributed shear that resulted in broad zones of undetectable topographic deformation.

The maximum amount of vertical drop at the head of the landslide would have been ~400 m based on contour misalignment near the volcano's summit (Fig. 7). Because the dip of the slide plane at the scarp is unknown, a range of permissible slide plane displacements exists to create 400 m of vertical displacement. Using simple geometry and assuming a single scarp, if the scarp formed vertically, the displacement along the slide plane would have been 400 m. If the scarp formed with a primary 30° dip, displacement would have been 800 m. If the displacement along the slide plane or zone was nearly constant from head to toe, the landslide's maximum surface displacement was between ~400 and 800 m.

Qualitatively, with 400 m or greater displacement along a discrete slide plane, it seems likely that evidence of surface deformation downslope of the head would be topographically recognizable, especially at the landslide's toe. Because no such evidence has been found, it is proposed that a single, discrete slide plane does not exist downslope of the proximal region.

Instead, surface deformation in the distal parts is envisioned to consist of an indiscernible outward bulge created by slide movement involving a thick zone of distributed shear. This style of landslide kinematics has been recognized on tall, steep mountain slopes throughout the world and is commonly referred to as "sackung" (Pánek et al., 2015) or, less commonly, "mountain slope deformation" (Hungr et al., 2014). Sackungen (plural for sackung) involve large-scale sagging of mountain slopes above a zone of deep-seated shear (Pánek et al., 2015). Surficial pull-apart structures observed at known sackung sites vary, but they usually consist of features such as uphill- and/or downhill-facing scarps, ridge troughs (graben), and closed depressions (Pánek et al., 2015), all of which commonly occur at or near ridge tops. Although mostly recognized on subaerial slopes, sackungen have also been recognized in the submarine environment (Conway and Barrie, 2018). In the few instances where pull-apart rates at the head have been determined, the rates range from a few meters to less than a centimeter per year (Varnes et al., 2000; Hungr et al., 2014).

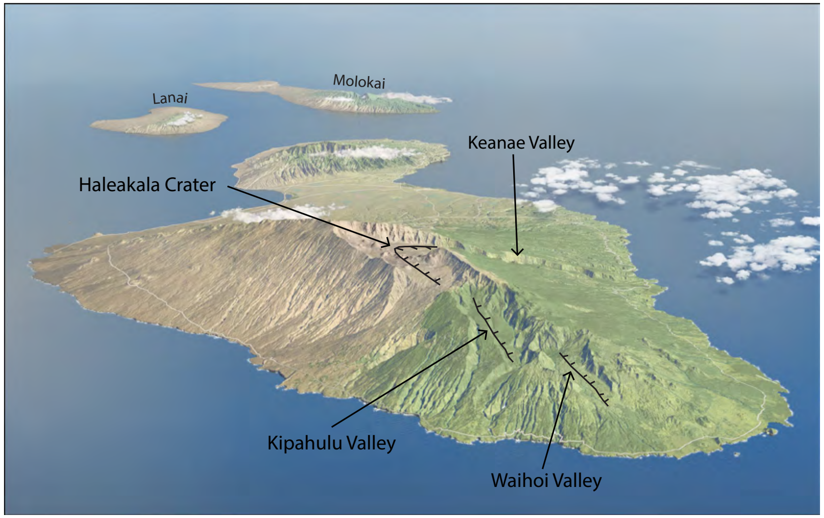

Figure 8. Relief map of Haleakala volcano showing approximate scarp locations (hachured lines). View is toward the northwest. Relief image is from U.S. National Park Service. The widest part of Maui is 42 km and the summit elevation is 3055 m.

No instance of sackung on a volcano was found during the course of this research, but the lithologic structure of Hawaiian volcanoes seems favorable for such behavior. Above sea level, the bulk of a Hawaiian volcano consists of subaerially crystallized lava flows, whereas below sea level, away from a pillow basalt core, the volcano's bulk consists extensively, if not predominantly, of volcanic debris formed at the coast by interaction of lava with water that is gravitationally swept down the volcano's submarine flank (Moore et al., 1973; Moore and Chadwick, 1995; Schiffman et al., 2006). The boundary separating the subaerial lava from the underlying submarine-formed debris-rich zone dips gently toward the volcano's center and is below sea level, owing to isostatic subsidence caused by the weight of the volcano. With consideration of these lithologic characteristics, Figure 9 presents a speculative geometry for the landslide's basal shear zone, consisting of a discrete slide plane under the slope failure's upper part, where basal shear cuts through subaerial lava flows, and a zone of distributed shear in its lower part, where it cuts through debris-rich lithology. The distributed shear could have occurred in a thick zone of continuous shear (cataclastic flow) or in stacked zones of concentrated shear.

Origin of the Great Valleys and Haleakala Crater

The pull-apart deformation proposed in this study provides an explanation for the development

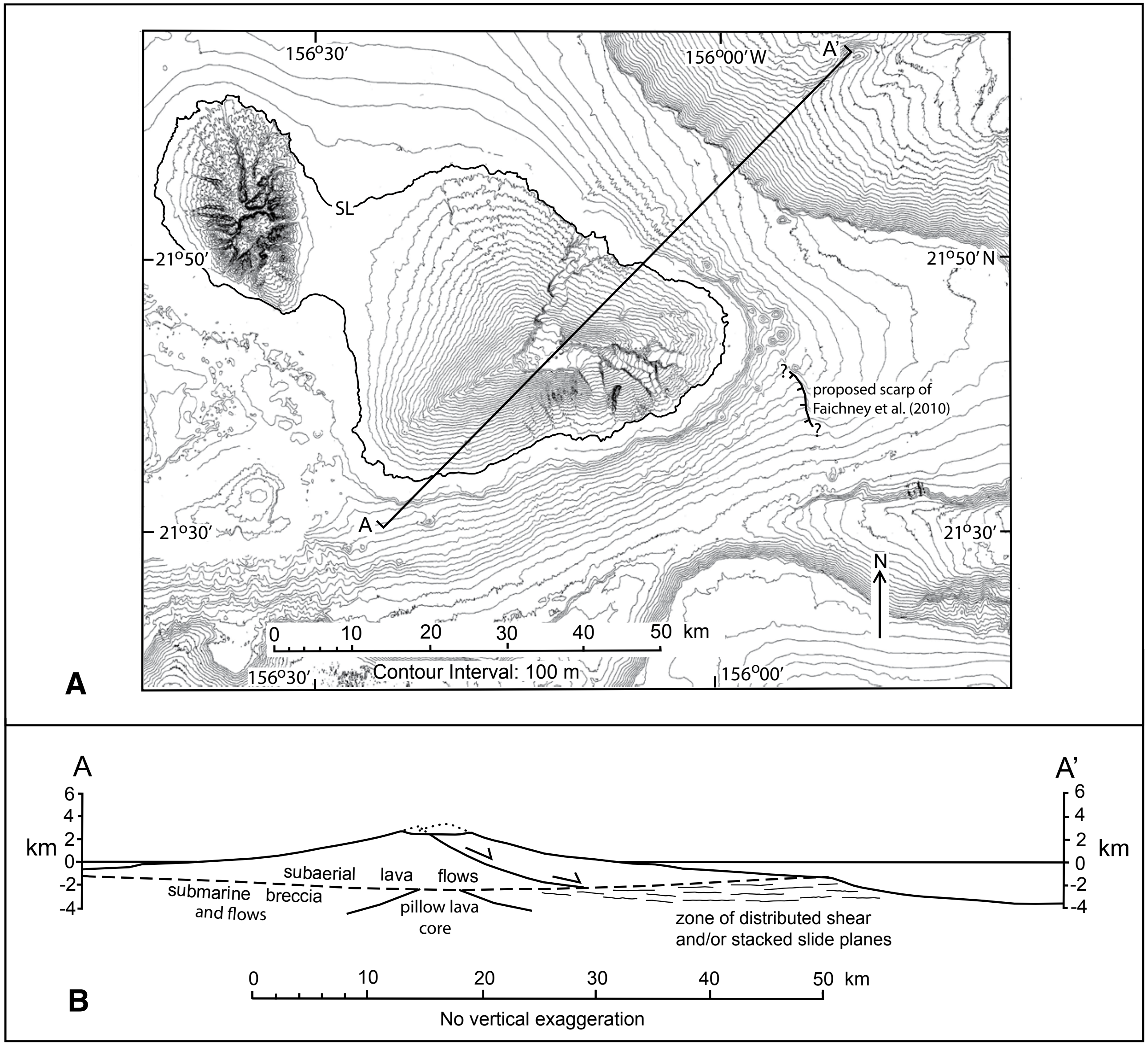

Figure 9. Cross section of proposed sackungen. (A) Profile line location. Heavy contour line marks sea level (SL). (B) Cross section showing the proposed location of the sackungen shear zone. Note that the shear zone is hypothesized to be a discrete surface where it cuts through subaerial lava flows and a zone of distributed shear where it cuts through submarine breccia and lava flows. The hachured line southeast of Maui in A is the location of the submarine scarp identified by Faichney et al. (2010) that cuts three ancient shorelines.

and orientation of Haleakala's great valleys and summit crater. Trending obliquely across volcanic slopes, the landslide faults responsible for the scarps would have been zones of readily erodible crushed rock. Additionally, the various north-facing scarps on southerly descending slopes would have captured upslope surface runoff and deflected it to flow along the scarp bases. Accelerated erosion owing to these larger-than-typical streams (for Haleakala) along the weak fault zones could then have resulted in the formation of Haleakala Crater, and upper Kipahulu, and Waihoi great valleys. At upper Keanae/Koolau Gap valley, because runoff interception would have occurred at the top of the scarp, the presence of a graben or fracture at the base of the scarp or scarps seems likely in order for runoff to have been channelized along the base to form the great valley. Meanwhile, lower Keanae, Kaupo Gap, and lower Kipahulu valleys would have been created by the various streams below the point where they spilled off the lower ends of the scarps. Figure 10 presents a re-creation of Haleakala's topography just prior to slope movement along with the locations where the scarps and streams originated. Gray shading indicates the drainage area captured at each scarp's base.

The size of the runoff capture areas ranges from 2.5 km^2 at Haleakala Crater to 6.0 km^2 at upper Keanae/Koolau Gap valley. After development of these initial capture areas, increasingly large scarp faces would have added to their size. Assuming that scarps attained a 35° gradient, either directly at the time of displacement or subsequently owing to weathering and erosion, and assuming 400 m of displacement, the total captured drainage area would have enlarged to 6.0 km^2 at Haleakala Crater and 8.0 km^2 at upper Keanae/Koolau Gap valley. Two modern-day examples of larger-than-normal valleys forming as the result of captured drainage area by landslide fault scarps are Waipio and Honokane Nui valleys on Kohala volcano at the north end of the island of Hawaii (Stearns and Macdonald, 1942; Moore et al., 1989; Lamb et al., 2007; Bishop, 2017).

The landslide model explains the two enigmatic aspects of the great valleys described earlier. First, Haleakala Crater and significant portions of the great valleys trend obliquely across the volcanic slopes because they follow the trend of the landslide scarps. Second, upper Keanae/Koolau Gap, Kaupo Gap, and Haleakala Crater valleys were able to form in areas of relatively low rainfall because of their enhanced drainage areas caused by runoff capture at the scarps, along with the faults being readily erodible. Additionally, the existence of the lower Keanae, Kaupo Gap, and lower Kipahulu great valley segments and their directly downhill axial trends fit well with the landslide model. Because these great valley segments were created by the larger than normal streams, but away from the scarps, there were no structures to cause them to form oblique to the slopes.

Two possible alternatives to the landslide hypothesis are that: (1) the reconstruction landscape represents normal variation in irregular volcanic topography formed by lava aggradation, or (2) the topographic complexity resulted from contemporaneous volcanism and erosion. With regard to the first alternative, the reconstructed topography forms a 25-km-long belt containing 200–400-m-high breaks in slope that are consistently lower on the north to northwest sides. Such morphology is unlike irregular topography formed by lava aggradation anywhere else on Hawaiian volcanoes. As for the second alternative, an important effect of valley erosion with contemporaneous volcanism on Haleakala would be lava starvation on volcanic slopes where the trajectory of an uphill valley intercepted and diverted lava flows emanating from the southeast and west rift zones. However, the reconstructions across slope-oblique–trending Haleakala Crater, upper Kipahulu Valley, and Waihoi Valley show that the volcanic slopes on the downhill sides of the valleys are higher than expected, rather than lower as anticipated by lava starvation.

Evidence for the proposed landslide comes primarily from topographic reconstructions: No direct evidence from geologic structures such as landslide faults has been identified. However, the problems with the alternative hypotheses discussed above leave the landslide hypothesis as the more plausible one to explain the reconstructed morphology. In combination, the observations that giant landslides on Hawaiian volcanoes are common, that the reconstructed irregular topography forms a continuous 25-km-long belt, and that the hypothetical scarps at the heads of the landslide provide the most coherent explanation for the existence and trajectories of the great valleys support the landslide hypothesis.

Other sackung-style landslides may exist in the Hawaiian Islands. On the submarine southern flank of Haleakala, just south of Maui's east end, Faichney et al. (2010) identified a southwest-facing scarp that cuts three ancient submerged shorelines by up to 200 m (Fig. 9). The authors attributed the scarp to slumping but provided no detail. If it is a slump scarp, its orientation and relatively short length suggest it may be the remnant of a much larger scarp mostly buried on the north by younger lava. The scarp is a strong candidate to be an analogue to the scarps postulated in this study. As another possibility, Sherrod et al. (2015) concluded that a buried landslide scarp bounds the east side of Lihue basin on Kauai, but the researchers could find no evidence for the location of the toe and suggested that the slide plane might transition downward into a zone of distributed shear. Finally, on the island of Hawaii, a bulge exists on Kohala volcano's northeast slope between Waipio and Honokane Nui valleys. Landslide headscarps at the volcano's summit provide evidence that the slope is a giant landslide (Moore et al., 1989; Bishop, 2017). The bulge could be the result of slope sagging that occurred early in the landslide evolution.

CONCLUSIONS

Contour map reconstruction of Haleakala volcano's pre–great valley topography leads to the proposal that a large, inactive, northerly displaced landslide mass mantles the northeast flank of the volcano. The head of the landslide, located mainly along the volcano's east rift zone in areas occupied today by great valleys, was marked by a scarp zone that accommodated up to 400 m of down-to-the-north vertical movement. Lack of topographic evidence for the existence of distinct lateral edges and a compressional toe suggests the feature is a sackung. With this classification, shear

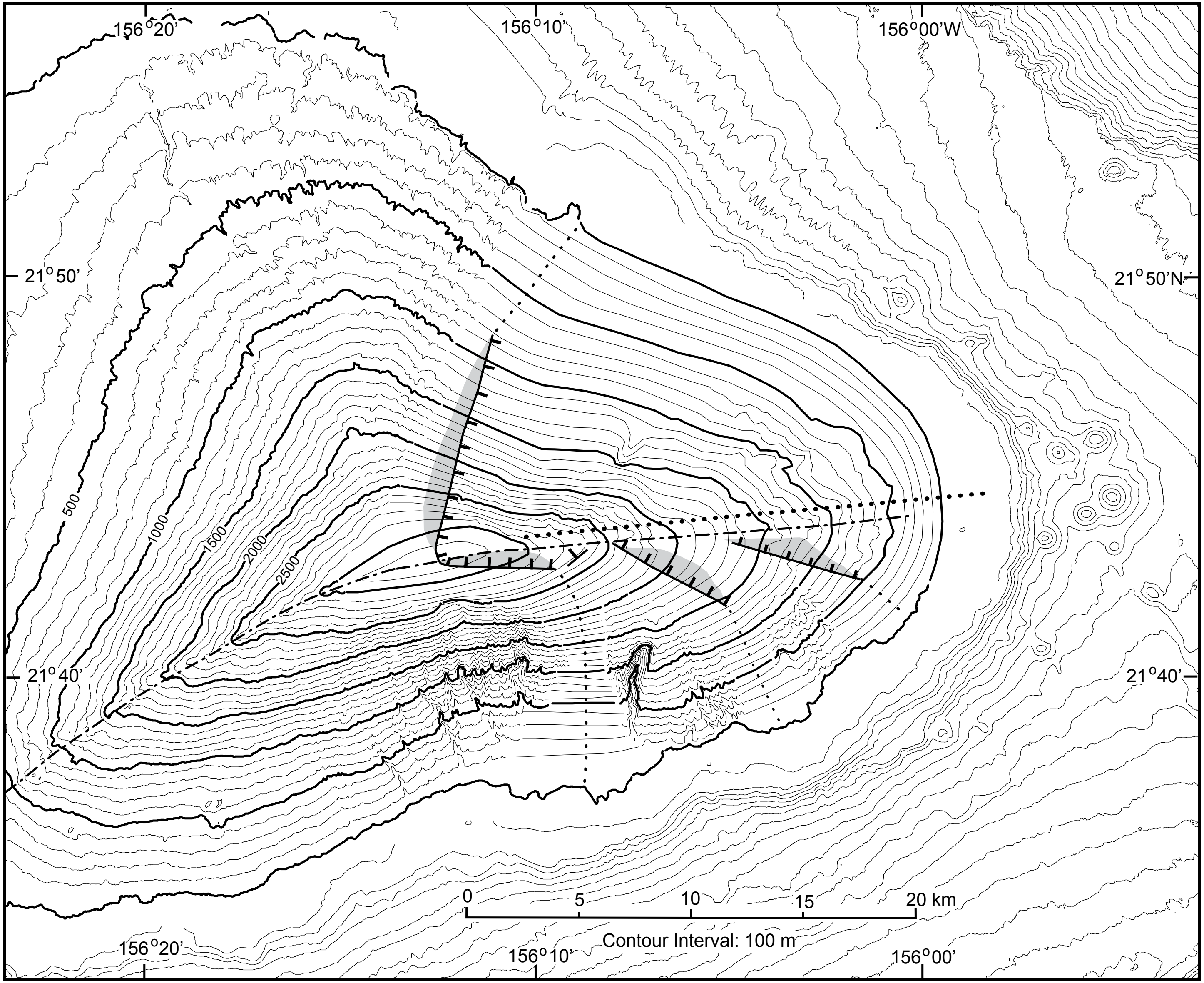

Figure 10. Hypothetical reconstruction showing Haleakala volcano just prior to landslide movement. To construct the diagram, the northeast slope contours were relocated as best as possible to positions that reconstruct a symmetric rift zone and that align the contour lines on the volcanic slopes bounding upper Keanae/Koolau Gap and Waihoi valleys. The reconstructed (pre-landslide) position of the rift axis ridge is shown by the dot-dash line, and its present position (post-landslide) is indicated by the large-dot line. Gray shading shows the drainage areas that would have been captured at the nascent scarps (hachured lines). The pathways of the great valley streams downhill of the scarps are shown with small-dot lines.

displacement is envisioned as having been accommodated by a slide plane below the landslide's proximal region and by a thick zone of distributed shear below the distal region.

The landslide hypothesis provides a more consistent explanation for the existence, location, and orientation of Haleakala's great valleys and summit crater than the prevailing fluvial erosion hypothesis. The landslide's headscarps are modeled as having formed oblique to the volcanic slopes. Faults at the base of the scarps would have been relatively erodible. Also, the uphill-facing scarps would have captured upslope surface runoff and deflected it to flow along the scarp bases. Being unusually large compared to most streams on the mountain because of their enhanced drainage areas, the streams carved atypically large valleys. Upper Keanae/Koolau Gap, Haleakala Crater, upper Kipahulu, and Waihoi are valleys that originated at the bases of scarps, which explains their slope-oblique trajectories. Lower Keanae, Kaupo Gap, and lower Kipahulu valleys developed downslope of the locations where the streams flowed around the ends of scarps. Because their downhill trajectories were not controlled by faults and their scarps, the axes of these valleys trend directly downhill.

Features suggestive of sackung-style landslides are present on other Hawaiian volcanoes, indicating they may be more prevalent on the Hawaiian Islands than previously known. Future investigations of gravitational slope failure on the islands may benefit from this realization.

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