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Morphology of the Island of Hawaii

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ABSTRACT

Digital elevation data for the island of Hawaii from the U.S. Geological Survey gridded at 30 m spacing was used to generate a slope map, a shaded relief map, and plots that compare slope and elevation for each of the five volcanoes that compose the island. These computer-generated products are useful in analyzing the morphology of the island. The volcanoes become steeper with increasing age. The five volcanoes, in order of increasing age, are Kilauea, Mauna Loa, Hualalai, Mauna Kea, and Kohala; their average slopes are 3.3°, 5.4°, 6.6°, 7.0°, and 11.3°, respectively. This relation apparently results from growth of the late, steeper alkalic cap on the older volcanoes that includes more viscous, thicker flows, flows that are smaller and hence tend to pile up more near the summit vents, and volatile-rich lavas that commonly produce steep-sided cinder cones at summit vents. The causes of the gentler slopes of younger volcanoes include the high proportion of exposed fluid lava flows from the shield-building stage, the ponding of lava against earlier volcanoes, and the grading of lava to sea level; subsidence of the older volcanoes has caused these gently dipping near–sea-level lava flows to subside below the sea. Finally, steep erosional canyons have developed in large areas of the older volcanoes (notably Kohala).

Virtually all of the major fault systems on the island appear to be related to the upper parts of giant landslides, most of which are hidden below sea level on the submarine flanks of the volcanoes. These are generally normal faults in the tensional regime at the heads and upper parts of the landslides. Subtle changes in slope hint at buried landslide-related fault scarps that have been covered by subsequent lava flows.

Major erosional canyons are present in only two places, each presumed to be in the amphitheaters of major landslides. They probably formed in this setting because stream erosion is favored by the steep slopes generated at the heads of landslides. The slope map clearly displays two bands of steep slope on Mauna Kea that mark the terminal moraines at the edges of the last two advances of the Pleistocene ice cap.

INTRODUCTION

We are on the threshold of a new era of map making and map interpretation as a result of ready access to computer technology to process the body of digital cartographic data that is rapidly increasing in coverage and detail. Recent work has focused on relatively coarse digital data of large areas such as the entire planet (Moore and Mark, 1986) or major parts of continental masses (Pike, 1991; Simpson and Anders, 1992). Here we examine how digital topographic data of a relatively small island (Fig. 1), about 100 km in diameter, can provide new insights into the volcanic and degradational processes that have shaped its surface.

The five volcanoes that compose the island of Hawaii (Fig. 2) are particularly amenable to slope analysis because they are young, they are in a relatively simple oceanic, intraplate geologic environment, and the compositional range of the lavas, as well as the mode of eruption, is limited. Recently available digital elevation data for the island from the U.S. Geological Survey are the most detailed yet available and provide a basis for the computer manipulation of topographic information.

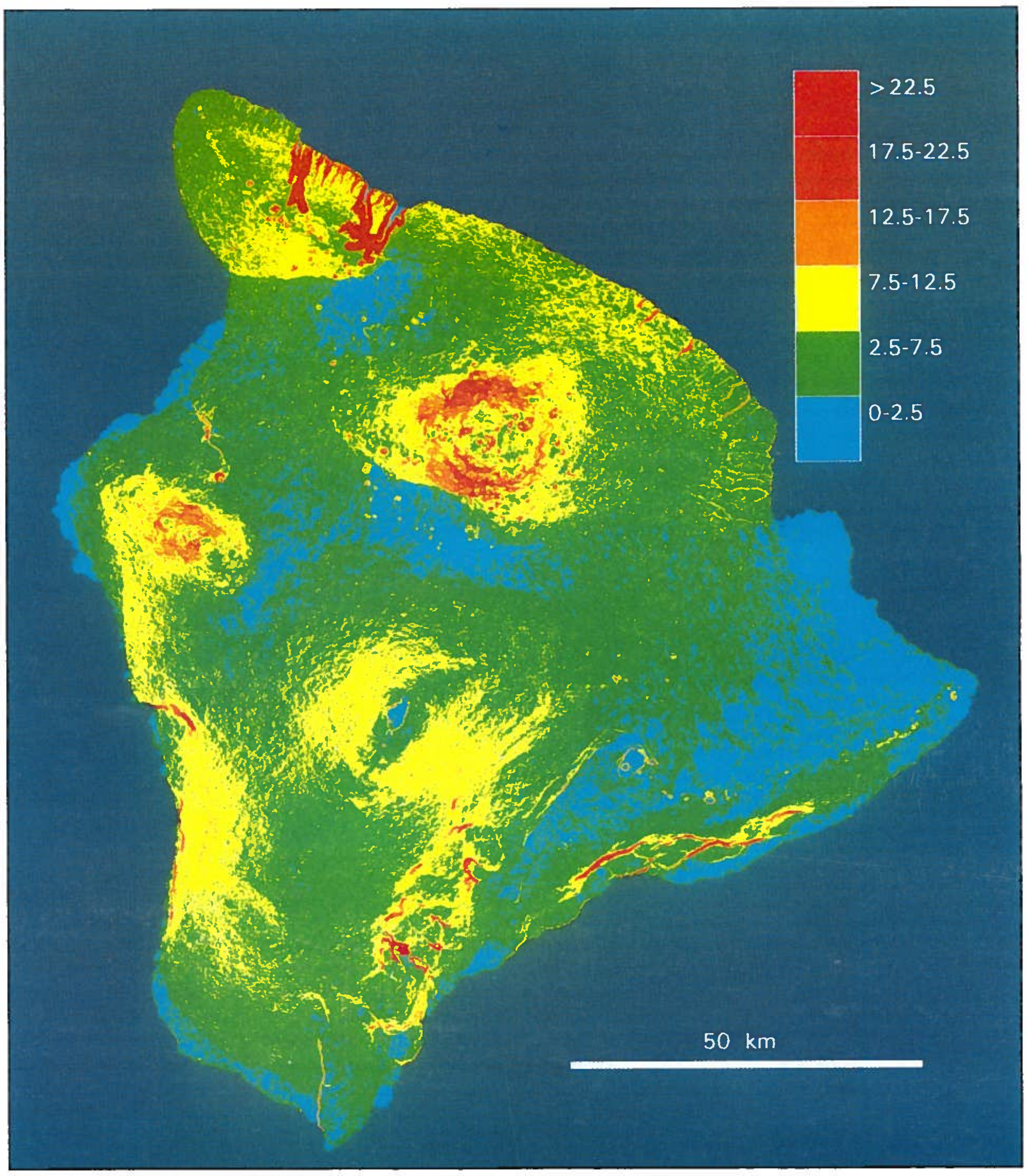

Figure 1. Slope map of the island of Hawaii. Colors indicate six 5° categories of topographic slope; warmer colors indicate steeper slopes.

Terrain slopes are a sensitive indicator both of the processes that built a particular landform and of those that have subsequently degraded it. On Hawaii, the process of construction is largely volcanic. The individual volcanoes were built mostly from lava flows that issued from near the summit and from flanking rift zones. In addition, intrusions of various sizes and depths have played a role in volcanic construction. The shield-building stage of Kohala, the oldest volcano on the island, ended about 465 ka. Shield building on both Mauna Kea and Hualalai ended at about 130 ka, whereas Mauna Loa and Kilauea are still in the active shield-building stage.

Processes that have modified the original volcanic morphology include collapse into magma bodies, producing summit calderas and rift-zone pit craters and grabens, as well as erosion and landsliding. Erosion is minor except on Kohala, which is carved by giant canyons, and Mauna Kea, which was man-

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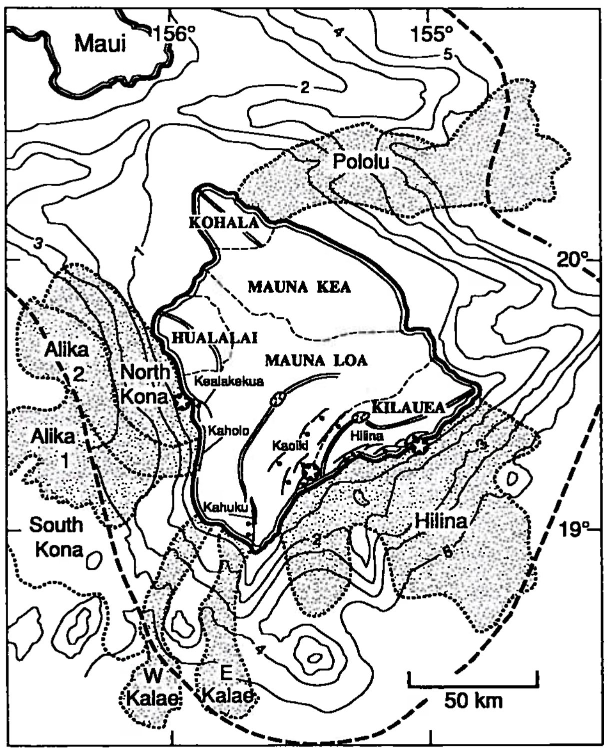

Figure 2. Island of Hawaii and offshore bathymetry; depth contours in kilometres. Dashed lines outline the five volcanoes that compose the island; the dot pattern shows major submarine landslides. Fine lines with ball on downthrown side show major fault systems; double lines show volcanic rift zones. Stars mark largest Hawaiian earthquakes—from west to east, 1951, 1868, 1975.

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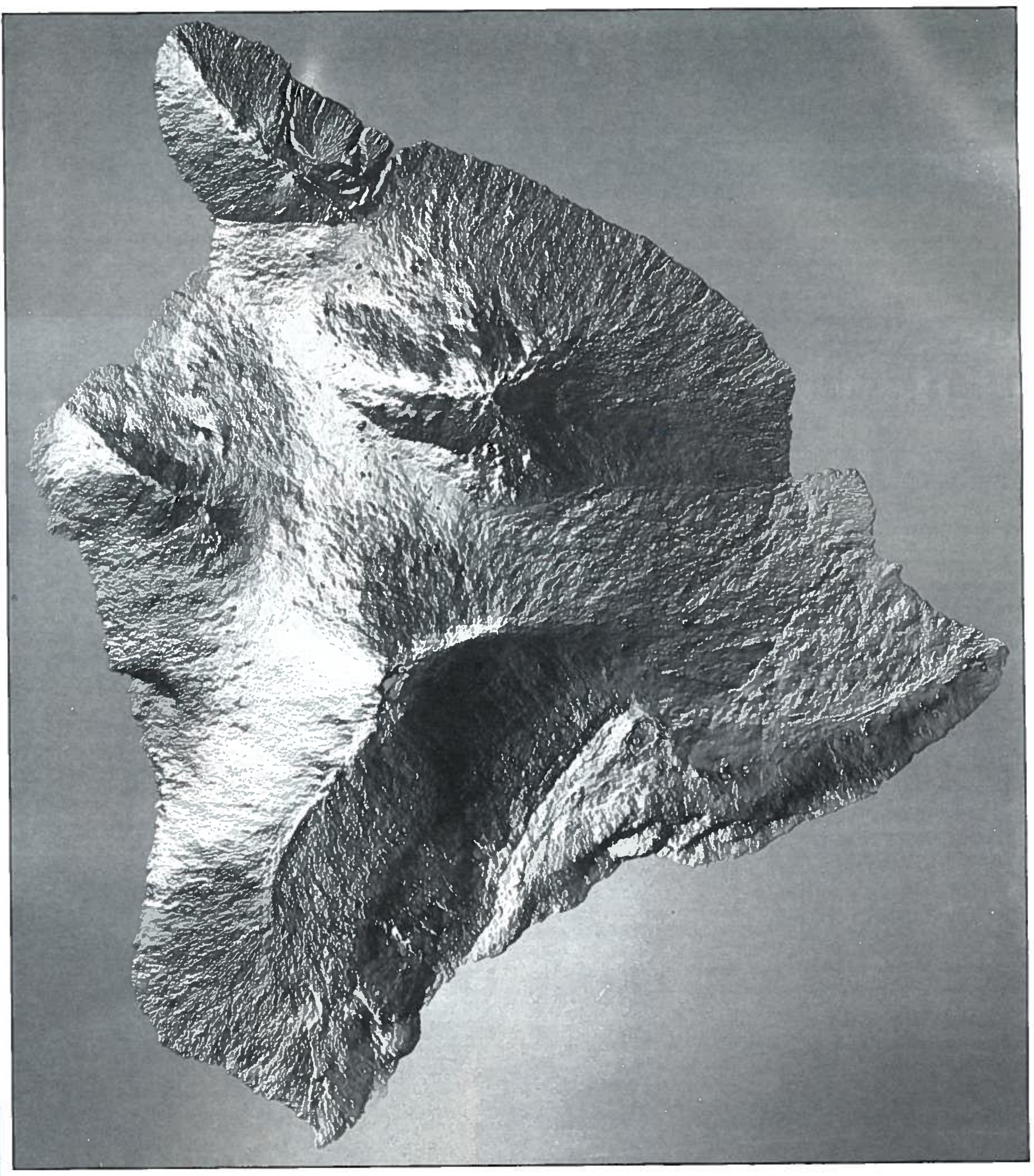

Figure 3. Shaded relief of the island of Hawaii with illumination from north, northwest, west, and southwest combined so as to enhance oblique illumination (see text).

tled by a series of Pleistocene ice caps. Giant slumps and debris avalanches have produced anomalous topography and debris aprons on the submarine slopes of the volcanoes (Moore et al., 1989), but they also are related to most of the fault systems exposed above sea level.

METHODS

Maps and plots were based on recent digital elevation data from the 84 7.5-minute quadrangles that cover the island. These U.S. Geological Survey data were generated by running parallel scan lines at a land spacing of 50–150 m across stereoscopic models projected from aerial photographs. The data were gridded at 30 m horizontal spacing and include 11.6 million grid points with a vertical precision of a few metres. Slopes were computed by ARC/INFO GRID slope function (Environmental Systems Research Institute, Inc., 1991), and the slope map of the island was made by assigning separate colors to each of six ranges of topographic slope (Fig. 1). The general features of this map can be compared with a coarser (750 m grid spacing) slope map of the island, and the surrounding submarine slopes (Mark and Moore, 1987).

Elevation data were acquired by scanning aerial-photograph stereoscopic images along either a north-south or east-west direction. Errors in maintaining the elevation indicator precisely on the ground surface while scanning have introduced a faint north-south or east-west stripe pattern in the map that cannot be readily corrected.

A newly developed technique (Mark, 1992) was used to produce the multidirectional, oblique-weighted, shaded-relief image (Fig. 3). This image, which emphasizes oblique illumination on all surfaces, was produced by combining four computer-generated shaded-relief images illuminated from 225°, 270°, 315°, and 360° azimuth; each from 30° above the horizon. Weights were calculated for each image, on a cell-by-cell basis, using a generalized aspect map (smoothed 1000 m cells), such that

$$W\,(225^\circ) = \sin^2\,(\text{aspect angle} - 225^\circ)$$
$$W\,(270^\circ) = \sin^2\,(\text{aspect angle} - 270^\circ)$$
$$W\,(315^\circ) = \sin^2\,(\text{aspect angle} - 315^\circ)$$
$$W\,(360^\circ) = \sin^2\,(\text{aspect angle} - 360^\circ)$$

$$\text{Weighted image} = [W\,(225^\circ) \times \text{image}\,(225^\circ) + W\,(270^\circ) \times \text{image}\,(270^\circ) + W\,(315^\circ) \times \text{image}\,(315^\circ) + W\,(360^\circ) \times \text{image}\,(360)]/2.$$

The aspect angle is the azimuth of the downslope direction of a given slope element.

This technique produces more detail in those parts of an image that would otherwise be washed out by direct light or left in darkness by a single-source illumination, and can produce detail in a single image that otherwise would require several images with different directions of illumination (Simpson and Anders, 1992, their Fig. 2).

Plots of elevation vs. average slope (Fig. 4) are useful for evaluating the origin of slope anomalies. They were produced by averaging the slope data points within elevation increments of

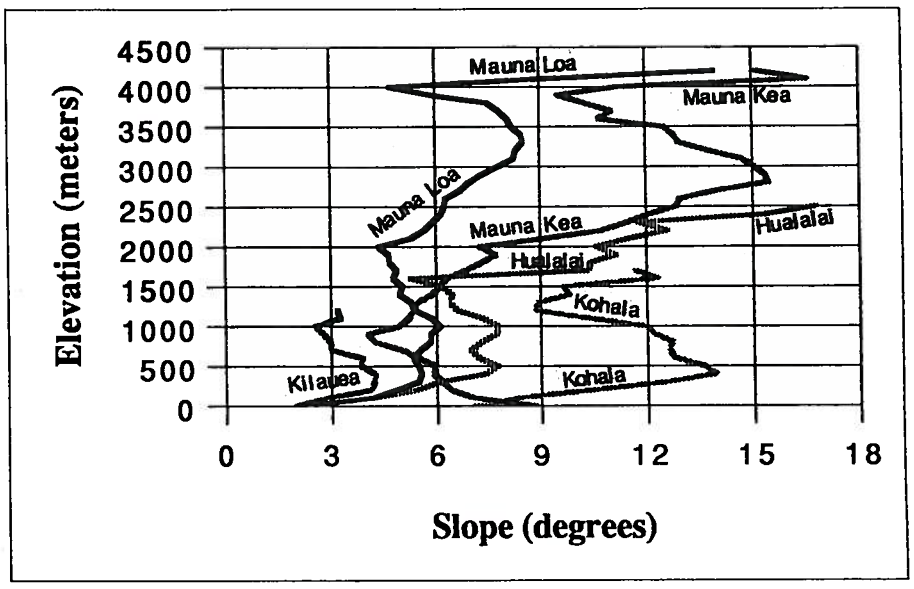

Figure 4. Average slope within 100 m elevation increments for each of the five volcanoes on the island of Hawaii.

100 m and comparing these averages with elevation separately for each of the five volcanoes as delimited by the geologic boundaries described by Stearns and Macdonald (1946). Note that the extreme variations in slope within 300 m of the summit of a volcano result from the steep slopes of summit cinder cones or the steep walls of a summit caldera; these slope averages may be amplified by the small number of points in the uppermost elevation category.

Histograms of slope distribution for each of the five volcanoes (Fig. 5) compare the areal proportion of each edifice that falls within 3° slope categories.

SLOPE FEATURES

Volcanism

The general contrast in morphology of the five volcanoes that make up the island results from many processes, but perhaps the most important is the composition and hence viscosity and eruptive mode of the younger lavas that compose the upper parts of the volcanoes. Mauna Kea, Hualalai, and to a lesser extent Kohala, have steep slopes near their upper parts (Figs. 1 and 4). They have sizable subsummit regions steeper than 17.5°, and Mauna Kea has a considerable area steeper than 22.5° (Fig. 1). The average maximum slope (excluding the slopes within 300 m of the summit) is 15.5° for Mauna Kea at 2800 m elevation, 14° for Kohala at 400 m, and 12.5° for Hualalai at 2200 m (Fig. 4).

The steeper upper-central region of Mauna Kea and to a lesser extent Kohala and Hualalai probably results from their cap of alkalic lava flows, some of which are richer in SiO_2 and more viscous than tholeiitic lavas. These three older volcanoes have undergone the transition from eruption of tholeiitic to alkalic basalt, a transition that occurs near the time when waning of eruptive activity spells the end of shield-building. Consequently, the flows are thicker and pile up closer to the vent. Also, many of the alkalic flows are of small volume, flowed a short distance from their vent, and increased the volume of material deposited near the summit. Finally, the alkalic lavas are richer in gas than the tholeiitic lavas of the shield-building stage and consequently have built numerous cinder cones at vents. These steep pyroclastic cones, concentrated on the upper parts of the volcano, tend to increase subsummit slopes.

In contrast, the slopes of the tholeiitic volcanoes Kilauea and Mauna Loa are gentler. The average maximum slope of Mauna Loa is 8.5° at 3300 m elevation and of Kilauea 4.5° at 400 m. The summit of Mauna Loa is dominated by steep slopes on the caldera walls, whereas the broad, gentle-slope summit region of Kilauea offsets the steep slopes of its caldera walls (Fig. 4).

Several conspicuous regions of gentle slope on the island result from grading of lava flows to sea level or to the flanks of an older adjacent volcano. The still-active volcanoes Kilauea, Mauna Loa, and Hualalai have broad areas of low slope (avg. <2°) near sea level (Fig. 4). The higher average slope at sea level of about 8° for Mauna Kea and Kohala results because they have subsided about 400 m and 1000 m, respectively, since the end of shield building and are graded to previous shorelines now below sea level (Moore, 1987). Mauna Kea has a pronounced average slope minimum at 900 m elevation caused by ponding of lavas in the saddle with Kohala (elev. 880 m); Mauna Loa has a slope minimum at 2000 m caused by ponding of lavas in the saddle with Mauna Kea (2005 m); and Hualalai has a slope minimum at 1600 m caused by ponding of lavas in the saddle with Mauna Loa (elev. 1590 m).

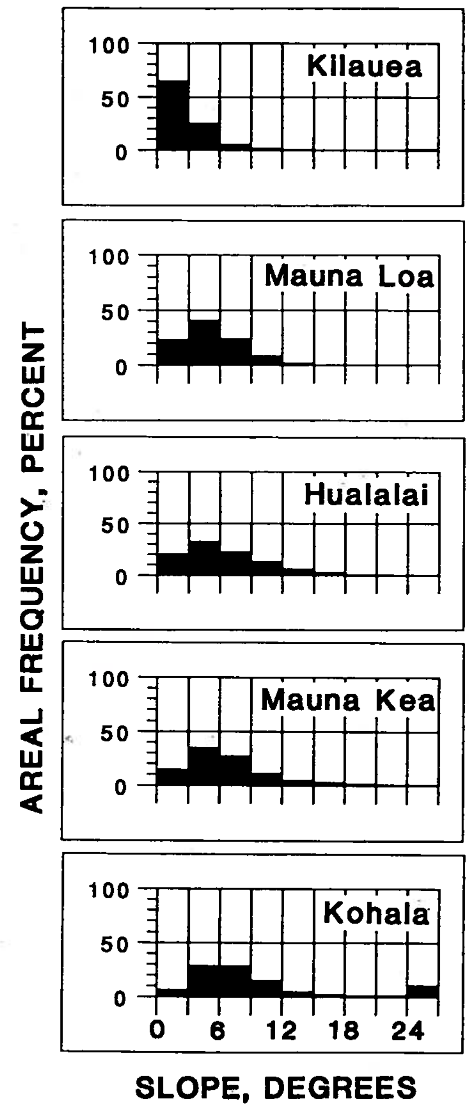

Figure 5. Histograms of slope distribution in 3° categories for each of the five Hawaii volcanoes arranged in order of increasing age.

Histograms of slope distribution show a systematic increase in the steepness of overall volcano slope from Kilauea through Mauna Loa, Hualalai, and Mauna Kea, to Kohala (Fig. 5). In this same order, which is the order of increasing age of the volcanoes, the average slope of each volcano is 3.3°, 5.4°, 6.6°, 7.0°, and 11.3°, and the percentage of area where the slope is less than 3° is 64%, 23%, 20%, 14%, and 7%, respectively. This increase of slope with age results not only from the late, steeper alkalic cap on the older volcanoes, but also because lava from younger volcanoes ponds against earlier volcanoes and forms low slopes. Moreover, lava from the younger volcanoes is graded to sea level, whereas the low-slope coastal lavas have subsided below sea level in the older volcanoes. Finally, large areas of steep erosional canyons have developed on the older volcanoes (notably Kohala).

The tholeiitic volcanoes Kilauea and Mauna Loa, still in the shield-building stage, both are indented in their summit regions by young calderas a few kilometres in diameter bounded by well-defined marginal subsidence faults. Calderas do not currently exist on Hualalai, Mauna Kea, or Kohala, and the slope map does not show evidence that they ever existed, though a former caldera could be buried beneath an alkalic cap.

A conspicuous zone of steep slope on the north side of Hualalai volcano (Fig. 1) is caused by the trachyte lava flow that issued from Puu Waawaa, the largest pyroclastic cone on the island. This viscous lava (62–63 wt% SiO_2) flowed 9 km northwest and produced flow units 75–150 m thick whose steep marginal slopes contrast sharply with those of the surrounding thin and fluid basaltic lavas.

The individual basaltic lava flows on Mauna Loa and Kilauea are virtually invisible on the slope map (Fig. 1), but some are discernible on the shaded relief map (Fig. 3) because of the enhancement achieved by oblique illumination. The more massive aa lava flows are visible on the southwest flank of Mauna Loa, where they are young and virtually untouched by erosion. In contrast, lavas on the older Mauna Kea volcano are emphasized in relief by flanking stream valleys that have produced a prominent downslope-trending pattern on the windward (northeast) slope of the volcano.

The rift zones of Mauna Loa and Kilauea that radiate from the summit calderas are inconspicuous on the slope map (Fig. 1), but they have a variety of small-scale features that are well shown on the shaded relief map (Fig. 3). The east rift of Kilauea is marked on its upper (western) part by pit craters, on the central part by grabens and cracks, and on the lower (eastern) part by cinder cones. In contrast, the southwest rift zone of Mauna Loa shows few such embellishments on the scale of the shaded relief map, but it does display a subtle ridgelike construction along the crest which may be produced by aligned spatter ramparts flanking rift-centered eruptive vents.

High on Mauna Loa are relatively steep (7.5°–12.5°, Fig. 1) regions about 15 km wide on the northwest and southeast sides. This zone appears in Figure 4 as the zone of high average slope (7°–8.5°) between 2800 and 3800 m elevation. This broad swell across the top of the shield possibly results from intrusion of dikes and sills out from the high-level subsummit magma reservoir which caused a bulging and steepening of the upper part of the edifice. Alternatively, the swell may result from accumulation of short-traveled lava flows related to repeated overflow of the summit caldera.

Erosion and Deposition

The most obvious stream-cut valleys on the island are the giant flat-floored canyons of northeast Kohala. These canyons were mostly cut when the volcano stood much higher, but their flat floors developed during subsidence. They can be traced 5 km offshore and were apparently cut subaerially before island subsidence drowned the present offshore parts and caused alluviation of the canyon floors above sea level (Moore, 1987). The restriction of the canyons to the amphitheater of the giant Pololu landslide (defined by the 3-km-wide, 18-km-long indentation of the shoreline shown in Figs. 1–3) suggests that canyon cutting was fostered by the landsliding processes. Apparently, canyon cutting was enhanced by slope steepening and removal of vegetation within the landslide amphitheater (Moore et al., 1989). The canyons (and associated giant sea cliffs) so dominate the topography that they have imposed a distinct bimodal slope distribution on the volcano (Fig. 5).

Belts of steep slopes aligned downslope on the southeast flank of Mauna Loa volcano resemble those of the Kohala canyons (Figs. 1 and 3). Lipman et al. (1990) suggested that these belts are the remnants of canyons, mostly buried by lava, that were originally about the same size as the Kohala canyons. Likewise, these canyons were cut in the oversteepened amphitheater of a giant landslide, directed southeast, that moved prior to the growth of Kilauea.

Other erosional canyons large enough to show on the slope map (Fig. 1) are not common. About six appear on the northeast flank of Mauna Kea, and one on the southwest flank of Kohala. Virtually no erosional features are evident on Hualalai, Kilauea, and Mauna Loa (except for the mostly covered southeast slope canyons mentioned), and surface running water is rare except during and immediately after torrential rainfall.

Sea cliffs are most prominent on the northeast Kohala coast where they have developed in the same region as the deep canyons, apparently because the steep landslide-generated offshore slopes permit aggressive marine erosion on this, the windward side of the island.

Two concentric arcuate belts of steep slope on the south side of Mauna Kea at elevations of 3360–3600 m and 2800–3050 m are conspicuous on the slope map (Fig. 1). These belts are close to the margins of the Pleistocene ice caps that occupied the summit of the mountain and correspond to the lower limits of the Makanaka drift (3400 m) and the Waihu drift (3000 m) as mapped and defined by Porter (1979).

Landsliding

The major fault systems on the island, except for those bounding the summit calderas, were apparently generated in the upper, tensional regime of giant landslides that extend far below sea level on the submarine flanks of the volcanoes and out on the surrounding abyssal plain (Fig. 2). The systematic mapping of these landslides below sea level was accomplished with the GLORIA side-scan sonar system, and the assignment of subaerial structural features to the largely submarine landslides was based on this mapping (Moore et al., 1989). The epicenters of the three largest historic earthquakes in Hawaii (magnitude 7 and above; each of which produced tsunamis), are all near apparent landslide-induced fault systems (Fig. 2).

Perhaps the best example of faults related to landslides is the Hilina fault system on the south side of Kilauea volcano where there is a series of steep concave-seaward normal fault scarps near the upper part of a complex system of landslides that extend far offshore, collectively referred to as the Hilina landslide or slump (Moore et al., 1989). These faults were reactivated at the time of the November 1975 magnitude 7.2 earthquake (Fig. 2), when a 50-km-long section of the south coast of the island subsided as much as 3.5 m (Tilling et al., 1976).

A series of scarps and subtle slope changes are present on the southeast slope of Mauna Loa. At the southeast base of this slope and at the boundary between Mauna Loa and Kilauea volcanoes are the principal Kaoiki fault scarps marked by two southeast-facing scarps clearly visible on both the slope map and the shaded relief map. Above them, and extending almost all the way to the northeast rift zone of Mauna Loa, is a series of four or five subtle scarps best seen on the shaded relief map (Fig. 3). Hawaii's largest historic earthquake, the great Kau earthquake of April 2, 1868, estimated at magnitude 8, occurred in the southwestern part of the Kaoiki fault system (Wyss, 1988; see Fig. 2).

Several belts of steep terrain, commonly about 4 km apart, are directed downslope on the lower slopes of Mauna Loa, south of the summit caldera (Figs. 1 and 3). As previously discussed, they are interpreted as partly lava-filled erosional valleys of Kohala type that formed within the amphi-

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theater of a major landslide (termed the Punaluu landslide, Lipman et al., 1990). This notion is supported by belts of steep slopes parallel to regional contours upslope from the canyons, belts that appear on both the slope map and shaded relief image. These scarps, which resemble in a subdued fashion the fault-line scarps of the Hilina fault system, may mark the lava-buried headwall scarps of the landslide system, which perhaps was reactivated after canyon cutting.

A series of faults and zones of steep slope on the subaerial west flank of Mauna Loa (Figs. 1 and 2) is believed to be the upslope expression of three of the four major slumps and debris avalanches directly offshore on the submarine flank (Lipman et al., 1988). The Kealakekua fault, curving southeast from the shoreline and downthrown on the southwest, was the site of a magnitude 7 earthquake (as determined at Berkeley, California) on August 21, 1951 (Macdonald and Wentworth, 1954; see Fig. 2). This fault apparently marks the upper, north boundary of a part of the North Kona slump. The principal movement that created this scarp occurred prior to 13 ka, because an offshore coral reef of that age shows no offset in the region of the offshore projections of the fault.

An anomalously steep zone extends north of the Kealakekua fault for 20 km to the steeper part of Hualalai (Fig. 1). This oversteepened region is directly upslope from the northern North Kona slump, and it may represent the upper part of a lava-buried amphitheater of a landslide involving a sector encompassing south Hualalai and part of west Mauna Loa.

The north-trending Kaholo fault, south of the Kealakekua fault, follows the coast for 25 km. It and the broad belt of steep slope that extends inland connect with the Kealakekua fault and seemingly mark a broad landslide amphitheater now entirely covered by younger lavas. This is the region from whence repeated downslope movement apparently fed the Alika debris avalanches and North and South Kona slumps that drape the submarine west flank and extend out into the Hawaiian Deep (Fig. 2).

The north-trending Kahuku fault produces a 20 km slope anomaly near the south cape of the island (Fig. 1). This apparent normal fault, downthrown on the west and mantled by lava on the north, is believed to be related to the landsliding of the south and west flank of Mauna Loa evident in the submarine topography. The East Kalae landslide, which moved south from a zone immediately west of the south cape of the island (Fig. 2), is one of the latest expressions of these widespread gravity failures. The head of this landslide is directly offshore from the terrain bounded on the east by the Kahuku fault, and the fault is regarded as the partly buried east wall of the amphitheater of this landslide.

CONCLUSIONS

The morphology of the five volcanoes that compose the island of Hawaii can be compared by using digital elevation data gridded at 30 m that includes nearly 12 million points. The resulting slope map, shaded relief map, and slope and elevation plots have led to the following general conclusions.

The volcanoes become steeper with increasing age. Their average slope from youngest to oldest is: Kilauea—3.3°, Mauna Loa—5.4°, Hualalai—6.6°, Mauna Kea—7.0°, and Kohala—11.3°. This increase probably results primarily from the late, steeper alkalic cap on the older volcanoes, a cap that includes viscous and thicker flows, lava flows that are smaller and hence pile up more near the summit vents, and volatile-rich lavas that more commonly produce sizable cinder cones near summit vents. The gentler slopes of younger volcanoes result from the predominance of more fluid tholeiitic lavas, the ponding of lava against earlier volcanoes, and the grading of lava to sea level; subsidence of the older volcanoes has caused these gently sloping near-sea-level lavas to subside below the sea. Finally, the oldest volcano (Kohala) has large areas of steep erosional canyons.

Virtually all of the major fault systems on the island except for those ringing the summit calderas seem to be related to the upper parts of giant landslides, most of which are hidden below sea level on the submarine flanks of the volcanoes. These arcuate normal-fault systems occur in the upper, tensional regime of the landslides. Subtle changes in slope hint that more such landslide-related fault scarps have been covered by subsequent lava flows.

There are major erosional canyons in only two places, each presumed to be in the amphitheaters of major landslides. They are probably present in this setting because stream erosion is favored by the landslide-induced increase in slope. The slope map displays two bands of steep slope high on Mauna Kea that mark the morainal edges of the last two advances of the Pleistocene ice cap.

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This award honors high school, college, or university teachers who have played a significant role in the education and support of women students both within and outside the classroom. Support for women students may take a variety of forms, including encouraging them to enter and continue in a geoscience career and providing opportunities for field and laboratory experience. In addition, awardees are selected on the basis of their own contribution as professionals, including activities such as active research and publication (in the case of university faculty members), involvement in professional societies or groups, and contributions as educators in areas that extend beyond the classroom.

Deadline for nominations is January 15, 1993. All nominations should include a supporting letter, vita for the nominee, and names of at least six individuals who know the candidate well and who can provide letters in support of the candidate. In general, letters of support should come from students as well as professional colleagues of the nominee. Send nominations to the chair of the selection committee: Maria Luisa Crawford, Department of Geology, Bryn Mawr College, Bryn Mawr, PA 19010.

The award is given at the Annual Meeting of the GSA and its associated societies.