SLOPES OF THE HAWAIIAN RIDGE

By Robert K. Mark *and* James G. Moore

ABSTRACT

Slopes of the southeastern Hawaiian Ridge have been computed from elevation and bathymetric data digitized at 750-m spacing. Maps derived from these data show that most of the subaerial slopes of Mauna Loa shield volcano, built of tholeiitic basalt, are 3° to 6° and the steepest average slope is 8° at 3,300-m elevation. The lower slopes of much of Mauna Kea, capped by alkalic basalt, are also 3° to 6°, but they steepen to 6° to 9° on the east side, and the steepest average slope is 13° at 3,000-m elevation.

Submarine slopes are generally steeper than subaerial slopes on an active marine volcano, but both submarine and subaerial slopes become gentler downward. Consequently, submarine slopes are steepest slightly below sea level and merge upslope with the gentlest subaerial slopes. On Kilauea and Mauna Loa the average subaerial slope below 2,000-m elevation is 4°, but 500 m below sea level the slope increases to 13°. This sharp downward-slope increase at the subaerial-subaqueous transition results from several processes, but perhaps the most important depends on the buoyant effect of water on propagation of a lava flow. A flow cannot move downhill as readily underwater because gravity exerts less force on it, and so the flow will thicken, spread laterally, and build up the slope. Depression of this slope change in older volcanoes is a measure of subsidence of the volcano that has occurred since termination of the major period of shield growth.

Major submarine landslides commonly head in regions with regional slopes of 14° to 17°, but are flanked by slopes as great as 19°, the landslide having reduced the slope at its head. Arcs of anomalously steeper slopes at intermediate depths apparently mark gravitationally induced creep zones that bulge the volcano flank seaward.

INTRODUCTION

The present slope of landforms results from the equilibrium attained between the processes that built up the landform and those gravitationally induced processes that operate to reduce it to a flat plane. Volcanic activity, first on the sea floor and eventually on island peaks, is the chief process that built up the Hawaiian Ridge. Concurrently the ridge has undergone reduction by erosion, mass wasting, landsliding, and isostatic subsidence. An insight into all of these processes can be attained by analysis of slope.

Digitized topographic and bathymetric data (fig. 3.1) were employed to generate slope maps and plots of the southeast Hawaiian Ridge (figs. 3.2, 3.3). This proprietary data set, which includes over 42,000 scattered elevation values, was provided by Dynamic Graphics, Inc. Using the Surface Gridding Library (Dynamic Graphics, Inc., 1978), we computed a grid of 751 rows and 931 columns, with 750-m spacing, from the scattered data. Slopes were computed by fitting a quadratic surface to the three-by-three array around each grid point. Color separation negatives for publication were produced on the Scitex Response 280 System laser drum plotter.

The computer slope calculations determine the tangent of the angle of slope as measured from the horizontal. The color boundaries on the slope maps (figs. 3.2, 3.3) are in even increments of slope-angle tangent, which multiplied by 100 is equal to the percent grade. The equivalent angle in degrees is shown in table 3.1. Degrees are used in discussing slopes in the text because this is probably more meaningful to the average map user.

Rapid computer techniques were employed to determine the area-averaged slope for each 100-m interval of depth and elevation for the six segments of the age-progressive Hawaiian Ridge shown in figure 3.1. These average slopes were smoothed using RSMOOTH (Velleman and Hoagun, 1981) and plotted against depth (fig. 3.4). The slope-depth plots of the six segments, which are systematically older to the northwest, permit analysis of the changes in slope that occur through time.

ACKNOWLEDGMENTS

The digitized version of the topographic and bathymetric data used to generate the slope map and plots was provided by Dynamic Graphics, Inc. Careful reviews of the manuscript were made by D.A. Clague and M.A. Clynne. We are grateful for this help.

SUBAERIAL SLOPES

The unmodified subaerial slopes of Mauna Loa shield volcano are mostly very gentle (fig. 3.2). Substantial parts of the the lower slopes are between 3° and 6°, and slopes near the summit are rarely steeper than 11°. The steepest average slope is 8° and occurs at 3,300-m elevation (fig. 3.4). Flatter surfaces occur in saddles between Mauna Loa and the neighboring volcanoes Mauna Kea and Hualalai, where lavas are ponded. The smaller tholeiitic shield of Kilauea, which is built on the south side of Mauna Loa, shows gentle slopes generally less than 3°. In part this gentle slope is probably caused by ponding of both Mauna Loa and Kilauea lavas between the southeast flank of Mauna Loa and the summit and east rift zone of Kilauea. The flat area that covers much of the southeast part of the island (Puna) results from such lava flows ponded north of the east-rift-zone ridge of Kilauea. This area generally slopes less than 3° and is the largest such gently sloping area on the Hawaiian Islands.

The southern coastal part of Kilauea shows anomalously steep slopes exceeding 9° and locally exceeding 17°. These steep areas are clearly related to the Hilina fault system, in which steep fault scarps are common. A similar coastal region of steep terrain occurs on the west side of Mauna Loa and probably represents lava-mantled fault scarps (Normark and others, 1979).

In contrast to Mauna Loa and Kilauea, the central part of Mauna Kea Volcano is capped by alkalic lava that produces steeper slopes. Though much of the lower parts of this volcano has slopes between 3° and 6°, they steepen to 6° to 9° on the east side. The upper central part, however, commonly reaches a maximum slope of 14°. The steepest average slope is 13° and occurs at an elevation of 3,000 m (fig. 3.4).

This steeper central region of Mauna Kea is a result of several factors. Firstly, the alkalic lava flows, particularly hawaiite that erupted from vents on the upper slopes, are generally somewhat richer in SiO_2 and hence more viscous than the alkali basalt flows of the lower slopes or the tholeiitic basalt flows of Mauna Loa. Consequently the flows are thicker and pile up closer to the vent. Secondly, many of the alkalic flows are of smaller volume than tholeiitic flows and hence flow a shorter distance, thereby piling up near the summit. Thirdly, the younger lava flows of Mauna Kea were not erupted from long rift zones as on Mauna Loa, but from vents clustered near the summit. Finally, the alkalic lava of Mauna Kea is apparently rich in gas and has built dozens of rather large cinder cones on the upper parts of the volcano. These steep pyroclastic cones are concentrated on the upper part of the volcano and, with the lava flows that pond between them and cover them, tend to produce a steep cap to the volcano.

Haleakala Volcano on East Maui (fig. 3.3) is steep like Mauna Kea, also in part because of its cap of alkalic lava. The volcano is asymmetric, being steeper on the south side, both above and below sea level. This steep south side may result from faulting or landsliding. Slopes on the upper part of the volcano commonly exceed 17° and parts of the south slope exceed 19°. The steepest average slope is 14° and occurs at 1,700-m elevation (fig. 3.4).

Some of the localized areas of steep subaerial slope result from erosion of deep canyons. The young volcanoes of the Island of Hawaii are little eroded except for Kohala. Steep slopes on northeast Kohala result from several major stream-cut canyons. The canyons of north Kauai and east Molokai also generate moderate areas of steep slope (fig. 3.3).

SUBMARINE SLOPES

On average, submarine slopes on the Hawaiian volcanoes are steeper than subaerial slopes but, like their subaerial counterparts, generally flatten downward. Consequently the submarine slopes are steepest slightly below sea level on a young volcano, and near sea level this steep subaqueous slope meets the more gentle subaerial slope. The average subaerial slope from the shoreline of Kilauea and Mauna Loa up to about 2,000-m elevation is about 4°. Below sea level this slope steepens abruptly to an average of 13° at 500-m depth (fig. 3.4).

Not only does the slope angle increase when a lava flow passes from land to sea, but a similar phenomenon occurs where a rift zone crosses the shoreline. Even though individual lava flows issue at many points along the rift zone, both above and below sea level, the axial crest of the rift-zone ridge plunges more steeply below sea level. The crest of the east rift zone of Kilauea plunges an average of 1.5° for 50 km from the summit caldera to the east cape of the island. Below sea level the rift zone extends another 80 km to its end at 5,500 m depth, and over this distance the crest plunges at an average angle of about 4°.

This marked slope change at the subaerial-subaqueous transition zone is the result of several processes, primarily volcanic. Regional slopes are modified at sea level by erosion and by growth of coral reefs. However, development of the steepening just below sea level on the young, active volcanoes Mauna Loa and Kilauea, where erosion and reef growth are minimal, indicates that volcanic processes must be the dominant cause. One process is the chilling effect of water on flowing lava. This tends to increase the flow's effective viscosity and cause it to thicken or divide into pillowed flow lobes and hence flow a shorter distance, thus steepening the general slope angle. A second process is the disturbance of a lava flow crossing the shoreline by vigorous surf action, which disrupts flow channels and lava tubes and causes the flow to divide, spread, and flow a shorter distance over a broader front. Both of these processes can cause a flow to break up into solid fragmental material, producing a flow-foot breccia (Moore and Fiske, 1969). A third, and perhaps the most important, process depends on the buoyant effect of water on the propagation of a lava flow. When a flow crosses the shoreline and enters the sea, its effective density drops by 1 g/cm^3. The flow cannot move downhill on the same slope as readily, because gravity exerts less force on it, and so the flow will thicken and spread laterally.

The net effect of these processes that inhibit flow of lava under water is to cause the shoreline to be extended seaward with a gentle subaerial slope and to pile lava up below sea level at shallow depth, thus creating a steep slope below sea level. This marked slope change caused by the subaerial-subaqueous lava transition can be identified on older volcanoes, where it occurs at considerable depth (fig. 3.4). The depth of the slope change is a measure of the subsidence that the volcano has undergone since the slope change was created. One of the more striking feaures of the slope map of the Hawaiian Ridge is the presence of a zone of steep slope surrounding all of the islands. The steep slope surrounding the islands of Maui, Kahoolawe, Lanai, Molokai, and Oahu marks the former shoreline of a giant island more than twice the size of the present Island of Hawaii (fig. 3.3).

LANDSLIDES

Because of its youth, great height, and steep slopes, the Hawaiian Ridge is the site of numerous landslides that occur at widely different scales. Many landslides head in the exceptionally steep zone originally formed just below sea level. Because lava flows apparently do not propagate readily underwater, mass movement

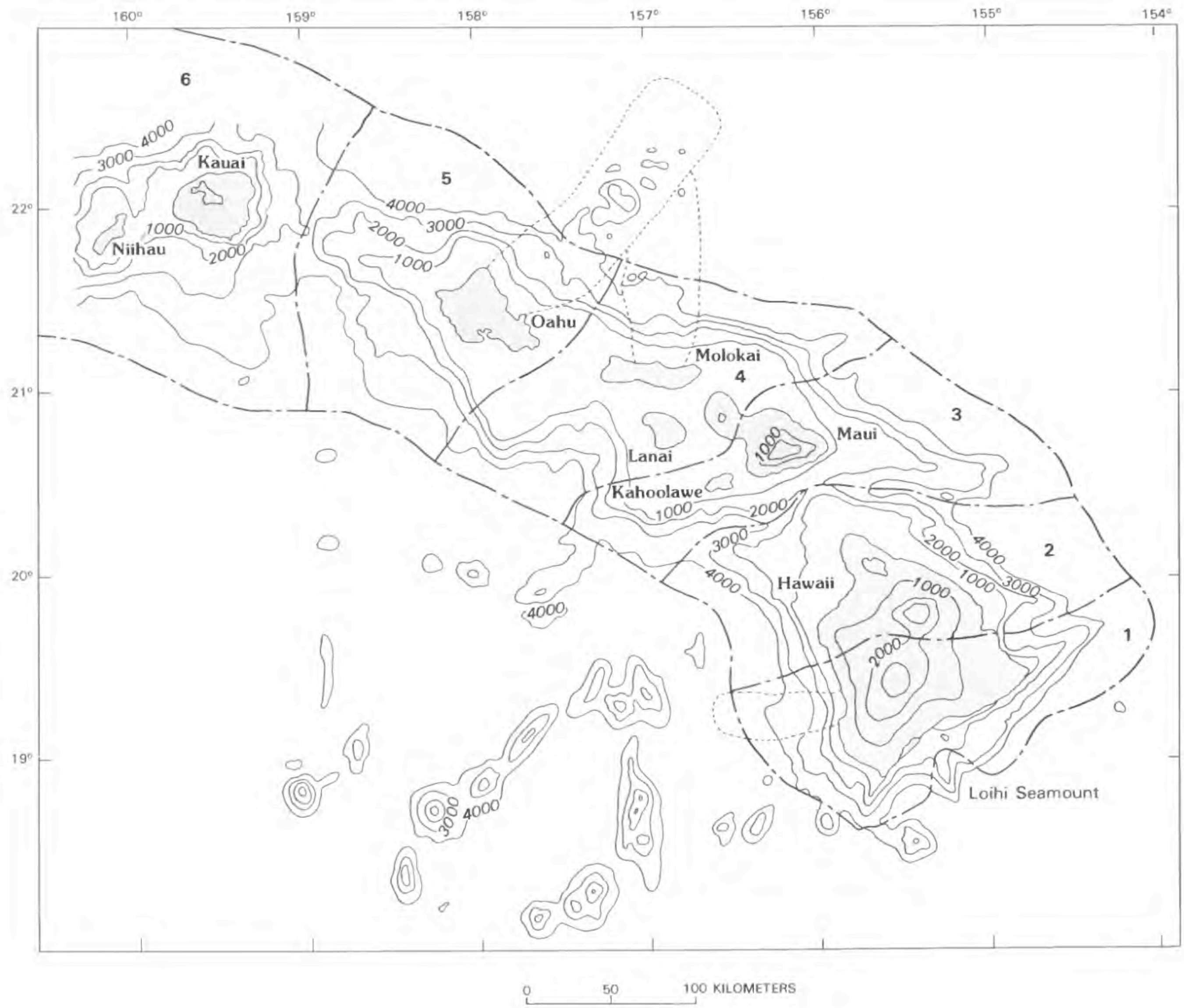

FIGURE 3.1.—Generalized topography and bathymetry of southeastern part of the Hawaiian Ridge. Contours in meters. Dotted lines bound major landslides; dash-dot lines bound age-progressive segments of ridge, numbered 1–6 (1 is youngest).

must be an important process in carrying volcanic material from near the shoreline to depth in order to maintain a slope in equilibrium.

Major landslides are suggested by two features of the slope map: They generally head on a particularly steep segment of the subaerial-subaqueous transition zone, but they are flanked by even steeper zones, the landslide having reduced the slope at its head. These relations are evident for the proposed landslides off the north coasts of Molokai and Oahu (fig. 3.1; Moore, 1964), and for the Alika landslide off the west coast of Hawaii. The landslide north of Molokai heads in a region where the maximum regional slope is about 17°, but it is flanked by steeper slopes exceeding 19°. The landslide northeast of Oahu likewise heads in a region with maximum slopes generally less than 14° but is flanked by slopes as steep as 19°. The Alika landslide off west Hawaii heads in a region with average slopes somewhat exceeding 14°, but it is flanked by slopes exceeding 19°. Additional steep offshore regions of Hawaii, prone to massive submarine landslides such as these three, are the east coast of Kilauea Volcano north of the the east cape of the island, and the south coast of Mauna Loa Volcano northeast of the south cape of the island (fig. 3.3).

Aside from these major landslides, other curious features of the slope map are probably related to downslope movement. These are arcs of steep slope at moderate depths that are separated from the main steep subaerial-subaqueous transition zone by a region of

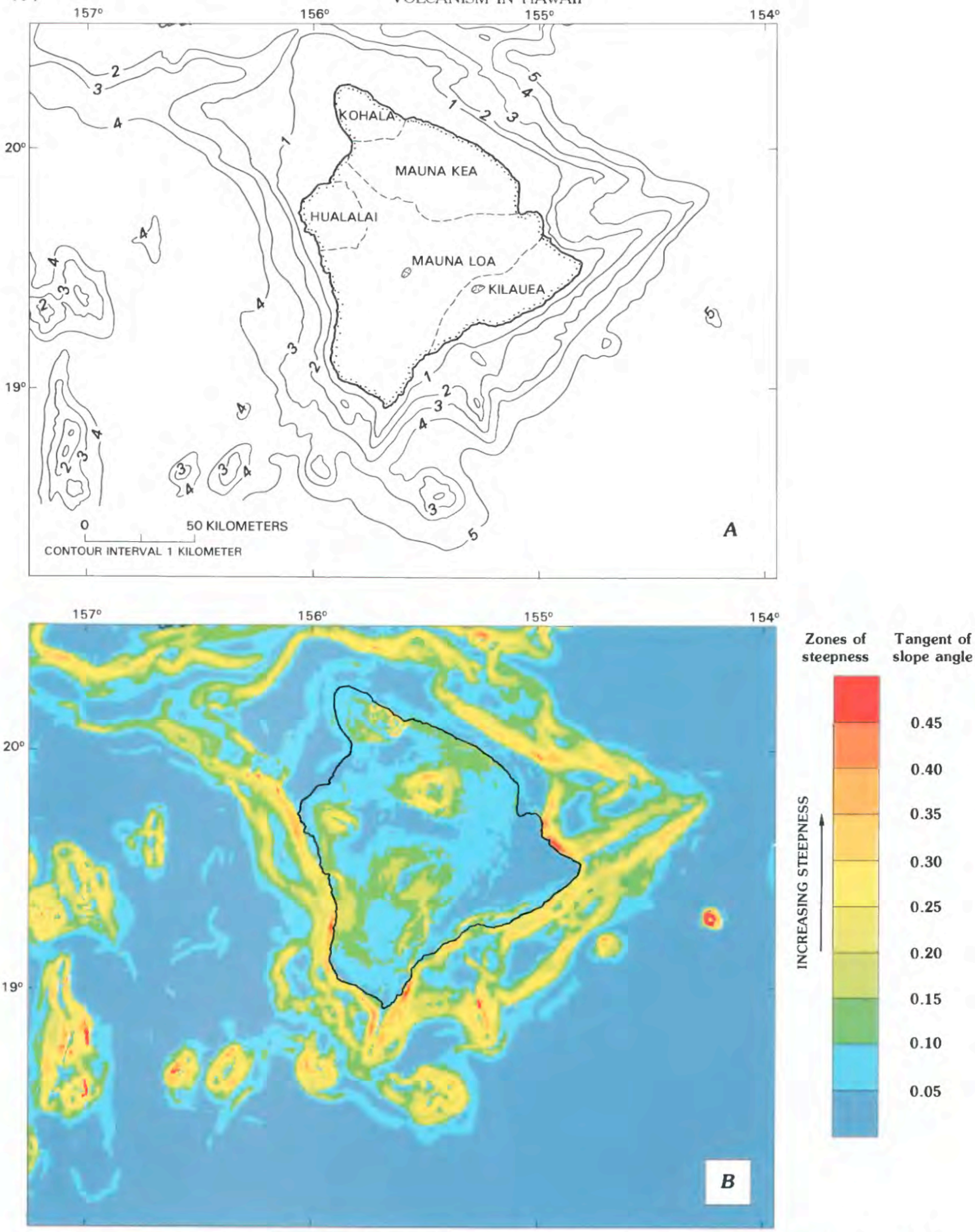

FIGURE 3.2.—Bathymetry and slopes around the Island of Hawaii. ***A***, Generalized bathymetric map. Dashed lines on the island are boundaries between the five volcanoes. ***B***, Computer-generated slope map of same region (including land areas). Slope steepness represented by color-coded intervals defined by tangents of slope angle measured from horizontal. Each color represents a slope-angle range of about 2.5° (see also table 3.1).

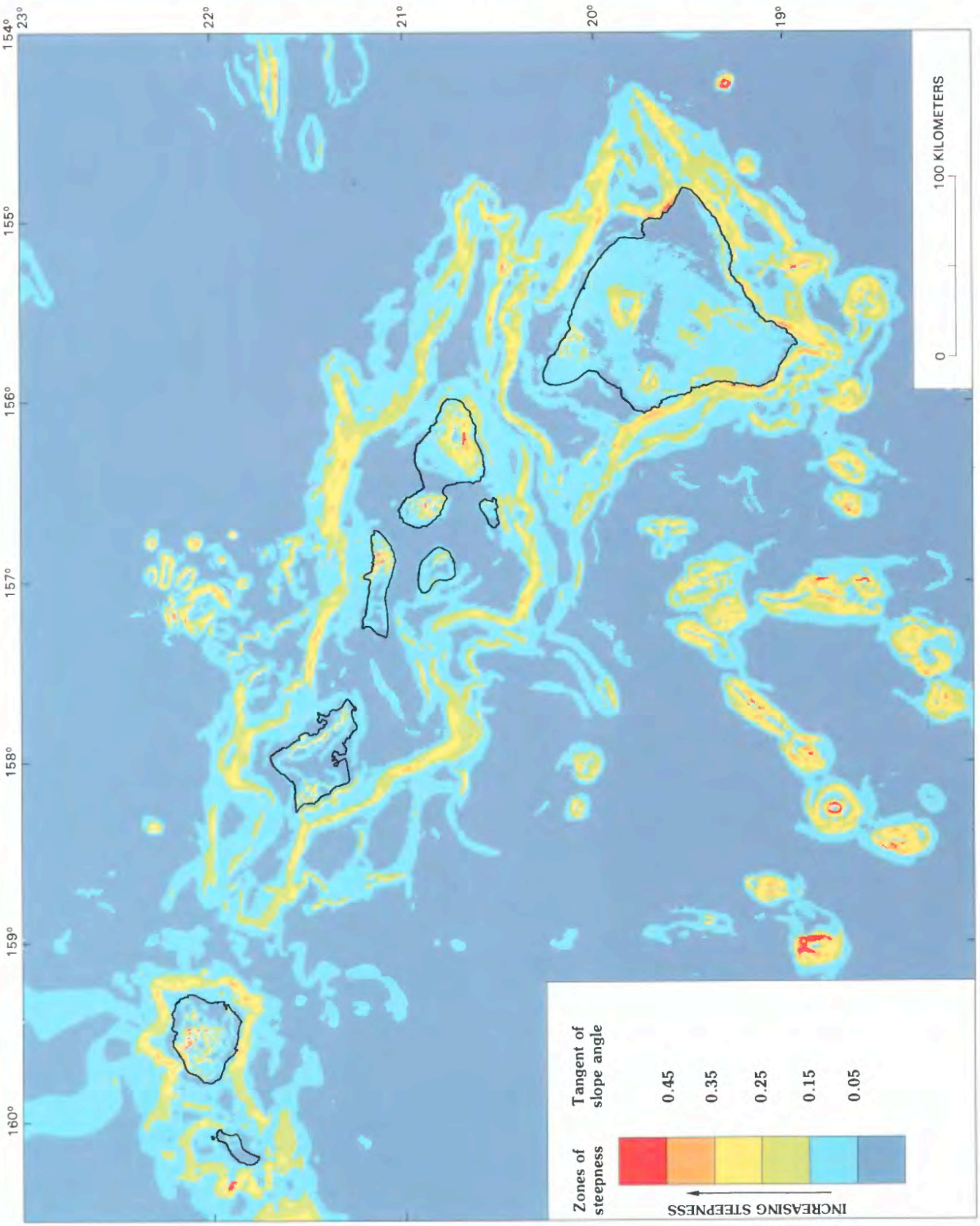

FIGURE 3.3.—Computer-generated slope map of southeastern part of the Hawaiian Ridge. Slope steepness represented by color-coded intervals defined by tangents of angle of slope. Each color represents a slope-angle range of about 5° (see also table 3.1).

TABLE 3.1.—*Angles of slope equivalent to values of tangent used as interval boundaries*

Tangent	Slope angle (degrees)
0.55	28.8
.50	26.6
.45	24.2
.40	21.8
.35	19.3
.30	16.7
.25	14.0
.20	11.3
.15	8.5
.10	5.7
.05	2.9

gentler slope. A prime example is the steep band at about 3,000-m depth that extends from Loihi Seamount off the south coast of the Island of Hawaii to near the east cape of the island (fig. 3.2). Others appear both north and south of the Alika landslide off west Hawaii. These arcs of anomalously steep terrane seem to mark gravitationally induced creep zones where the volcano flank is markedly bulged seaward. The probability of such bulges failing and producing major submarine landslides is not known.

SLOPE CHANGES WITH AGE

The bathymetric data have been compartmentalized into six segments (fig. 3.1) representing a volcanic age sequence becoming progressively older toward the northwest. The southeasternmost segment (number 1) includes Kilauea and Mauna Loa Volcanoes on the southern part of the Island of Hawaii. This segment is considered typical of youthful marine volcanoes because it includes the youngest, and currently most active, volcanic systems. The remaining segments with their included islands and general age of completion of major volcanic growth are, from southeast to northwest: (2) north Hawaii, 0.4 Ma; (3) east Maui and Kahoolawe, 0.8 Ma; (4) Molokai, Lanai, and west Maui, 1 Ma; (5) Oahu, 2.5 Ma and (6) Kauai and Niihau, 5 Ma. The slope-depth plot of each of these segments is compared to that of segment 1 so that departures from the assumed original volcanic condition can be evaluated (fig. 3.4). These departures apparently result from subsidence of the volcanoes and from erosional degradation.

The most extreme slope change of all the segments occurs in segment 1 near sea level and results from the subaerial-subaqueous lava transition. The average slope changes from about 4° at 200 m above sea level to 13° at 500 m below sea level. A similar abrupt change can be recognized in the other segments, although it is generally deeper and less distinct. The center of the slope change in segment 2 is 1.3 km below sea level; in 3, 2.1 km; in 4, 1.3 km; in 5, 1.3 km; and in 6, 1.0 km. These variations of the depth of the slope change from that in segment 1 are believed to be a measure of volcano subsidence since extension of the shoreline during a major period of volcano growth. Many of the areas of slope change are less distinct than that of segment 1. This results from the fact that the averaging technique includes different shorelines of different ages and

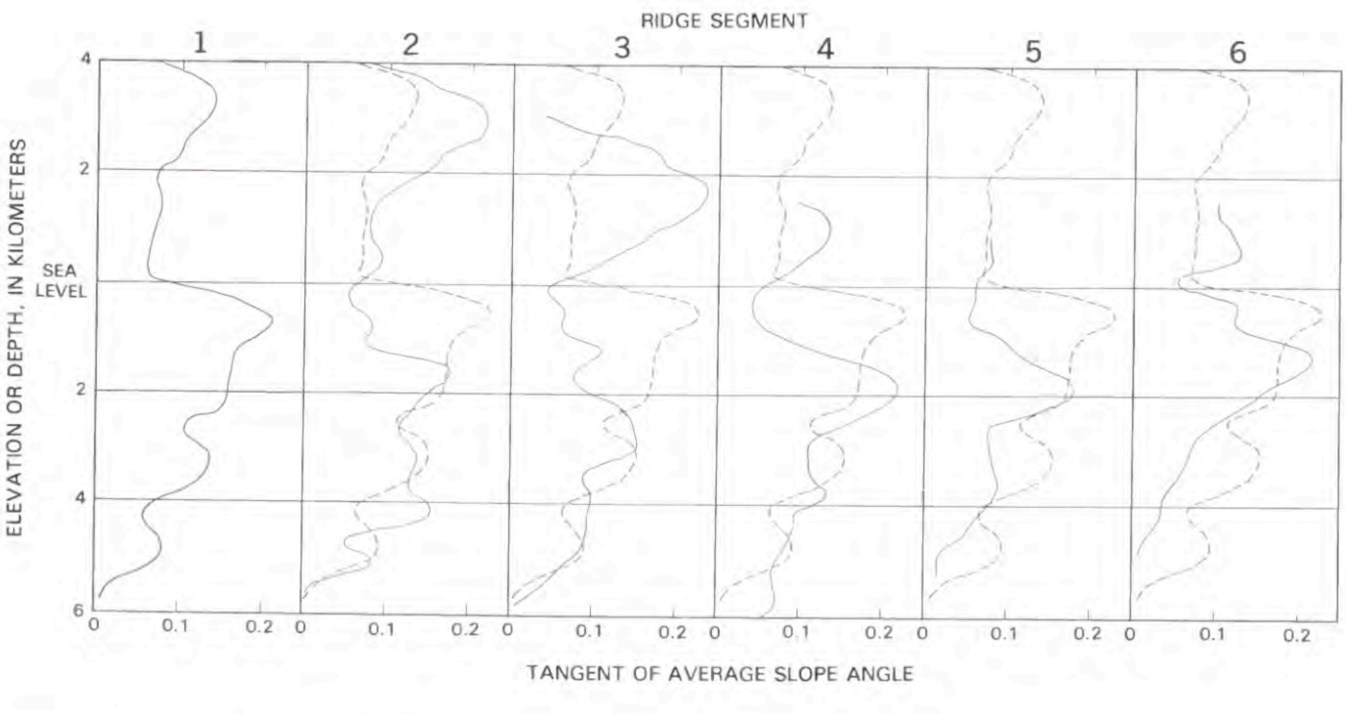

FIGURE 3.4.—Smoothed profiles of area-averaged slope against elevation for six segments of the Hawaiian Ridge (see figure 3.1). The trend of segment 1 (south Hawaii) is repeated as dashed line on the other five plots.

the same shoreline which has been warped and has subsided different amounts (Moore, chapter 2).

A marked smoothing of the lower submarine flanks of the volcanoes appears to proceed with age. On segment 1 the slope below the subaerial-subaqueous transition undergoes a general decrease with depth, which is interrupted twice by changes toward steeper slopes which are the bulges previously described. The first slope change increases the average slope 2.3° and the second about 1.7°. On segment 2 the slope decrease is interrupted 3 times by slope increases of 1.3°, 1.7°, and 2°. Segment 4 shows three zones of slope increase of 1.3°, 0.2°, and 0.4°. Segment 5 has only one, of 0.6°, and segment 6 has no zones of increase in slope below the transition zone.

Smoothing of the lower flanks is, moreover, accompanied by a general reduction of slope, so that all the zones of steep slope seem to have been removed (see segment 6 area on figures 3.3 and 3.4). The arcuate zones of steep slopes on the mid-depth submarine slopes of the younger volcanoes are missing on the older ones. Some form of mass wasting, requiring several million years to be effective, seems to smooth and flatten the lower slopes of these giant volcanoes.

REFERENCES CITED

Dynamic Graphics, Inc., 1978, User manual for the surface gridding library: 129 p.

Moore, J.G., 1964, Giant submarine landslides on the Hawaiian Ridge: U.S. Geological Survey Professional Paper 501–D, p. D95–D98.

Moore, J.G., and Fiske, R.S., 1969, Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii: Geological Society of America Bulletin, v. 80, p. 1191–1202.

Normark, W.R., Lipman, P.W., and Moore, J.G., 1979, Regional slump structures on the west flank of Mauna Loa Volcano, Hawaii: [abs.]: Hawaii Symposium on Intraplate Volcanism and Submarine Volcanism, Hilo, Hawaii, July 16–22, 1979, Abstracts with Program, p. 72.

Velleman, P.G., and Hoagun, D.C., 1981, Applications, basics, and computing of exploratory data analysis: Boston, Mass., Duxbury Press, 354 p.