SUBMARINE TOPOGRAPHY AROUND THE HAWAIIAN ISLANDS

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ABSTRACT

The submarine topography around the Hawaiian Islands reflects the time-integrated effects of volcanism, Pacific-plate tectonic fabric, island subsidence, sedimentation, gravitational collapse of unbuttressed volcano sides, and low-relief debris flows that transport shallow-water carbonate and volcanogenic sediment to greater depths on the submarine slope. First-order topographic relief around the islands is created by the submarine extensions of volcanic rift zones. The height above the surrounding abyssal sea floor and the topographic roughness of these rifts are inversely proportional to the age of the adjacent volcano. Second-order sea-floor relief around Hawaii is typified by Cretaceous seamounts that lie west of Hawaii and a few young volcanoes, including Loihi Seamount, direcly south of Hawaii. In addition to these obvious volcanic seamounts, a group of flat-topped mounts and small cones (Oahu Seamounts) extends to the northeast from the Island of Oahu. More subtle relief on the slumping of large sections of unbuttressed volcano flanks. These slumps form prominent steps on the otherwise regular, steep submarine slopes. Relief created by localized debris flows of surficial sediment and carbonate/volcanic rubble is usually less than 50 m; however, this process appears to be active on all Hawaiian submarine slopes investigated with Sea MARC II side-scan sonar and may be the principal agent for downslope sediment transport. Finally, reef development on the shallow parts of older, subsided volcanic foundations forms wide, low-gradient platforms that have karst-like microtopography.

INTRODUCTION

The strategic location of the Hawaiian Islands for oceanic exploration and the commerce that followed has resulted in the study of their natural history and geologic evolution since the 1700's. They have been a focus of marine research for the past 50 years, and much literature has been devoted to various aspects of Hawaiian marine geology and geophysics. The principal aim of this paper is to summarize the major topographic elements of the sea floor around Hawaii and to present new graphical and remote-sensing images of the sea floor around several of the islands. Only brief background information is offered, because much of the detailed information has already been discussed in the references we cite. In addition, other papers in this volume discuss specific topics that bear upon the development of the sea floor topography around the Hawaiian Islands. In particular, questions relating to island subsidence, carbonate-platform development, and submarine canyons are discussed in papers by Mark and Moore (chapter 3) and Moore (chapter 2). Data on Loihi Seamount is discussed by Malahoff (chapter 6), and the evolution of Hawaiian submarine rift zones is presented by Fornari (chapter 5).

ACKNOWLEDGMENTS

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REGIONAL BATHYMETRY

The regional bathymetry around the Hawaiian Islands (fig. 4.1) has been mapped by numerous oceanographic institutions, the U.S. National Ocean Survey, and the U.S. Navy (see, for example, Chase and and others, 1971; Chase and others, 1980; Wilde and others, 1980, and references therein). The principal regional bathymetric features are the Hawaiian Deep and the Hawaiian Arch (fig. 4.2), which are topographic manifestations of lithospheric flexure, superimposed on the regional swell of the Hawaiian Ridge, that result from the load of the volcanic islands on the oceanic lithosphere (Betz and Hess, 1942; Dietz and Menard, 1953; Hamilton, 1957; Menard, 1964; Watts, 1976; Watts and others, 1985). The Molokai Fracture Zone (fig. 4.2) represents a diffuse zone of elongate troughs that reach depths below 5,000 m to

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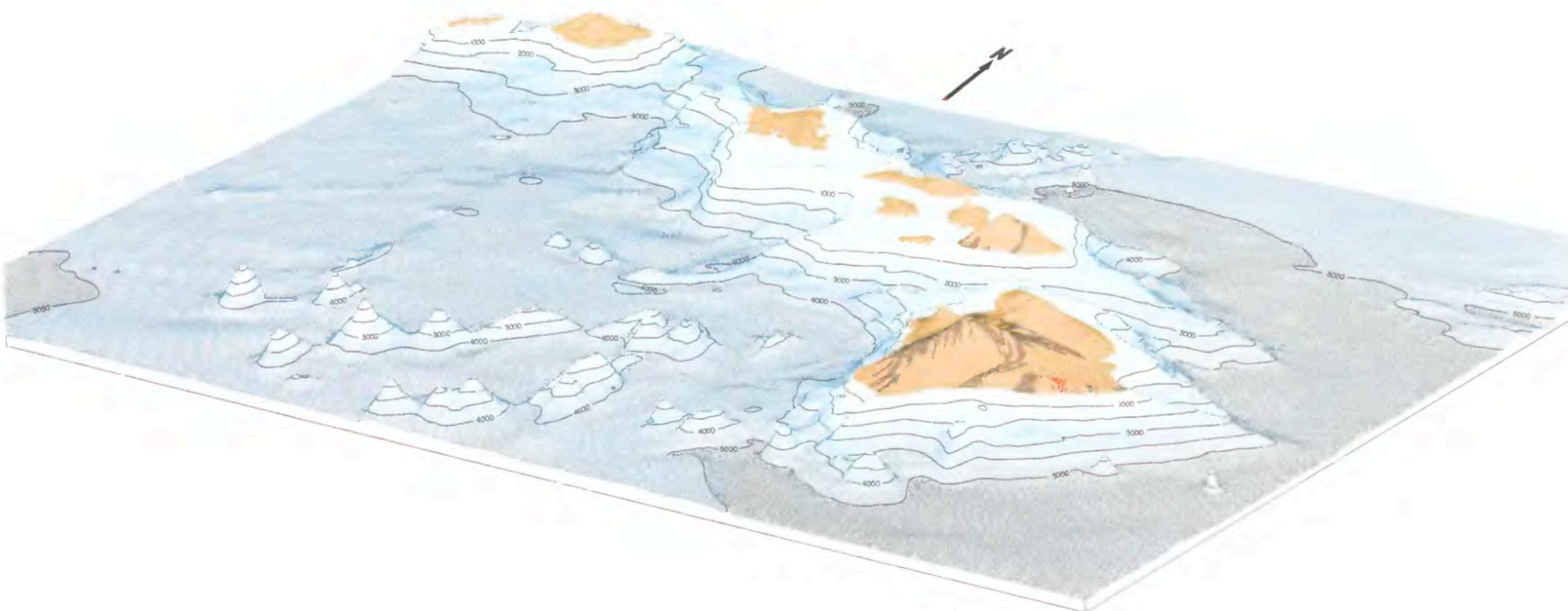

FIGURE 4.1.—Computer-drawn perspective model of the ocean floor around the Hawaiian Islands. Data base from Chase and others (1980) and Wilde and others (1980) and bathymetric charts of the U.S. National Ocean Survey (Nautical Chart Catalog No. 2, Panels, B, C, E). Bathymetric contour interval 1,000 m; grid spacings between nodal points (E.-W.) 1,667.18 m, and (N.-S.) 1,674.87 m. Subaerial contours from U.S. Geological Survey topographic map series. Black areas on land, historical lava flows (drawn from U.S. Geological Survey 1:100,000 series maps and Scientific Event Alert Network Bulletin, Smithsonian Institution, June 30, 1983). Red areas on land, 1983 lava flows from the east rift zone of Kilauea. Green areas, older slopes of inactive volcanoes. See figure 4.2 for geographic names. Vertical exaggeration ×5. Provided by Dynamic Graphics Inc., Berkeley, Calif.

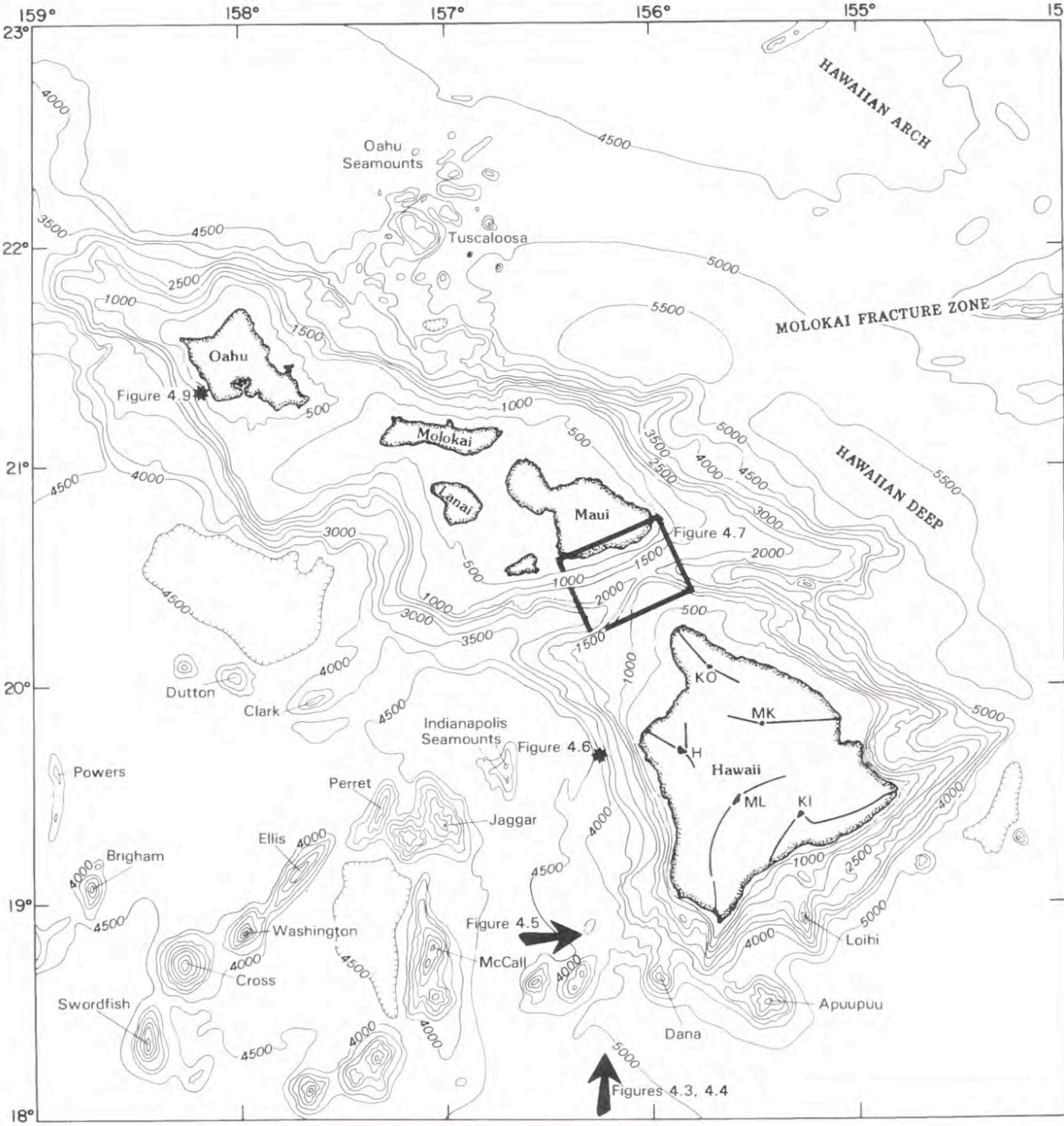

FIGURE 4.2.—Bathymetry around the principal Hawaiian Islands. Contour interval 500 m, simplified from Wilde and others (1980). Sites, viewing directions, and areas covered in some other figures are also indicated. Volcanoes on the Island of Hawaii: KO, Kohala; MK, Mauna Kea; H, Hualalai; ML, Mauna Loa; KI, Kilauea.

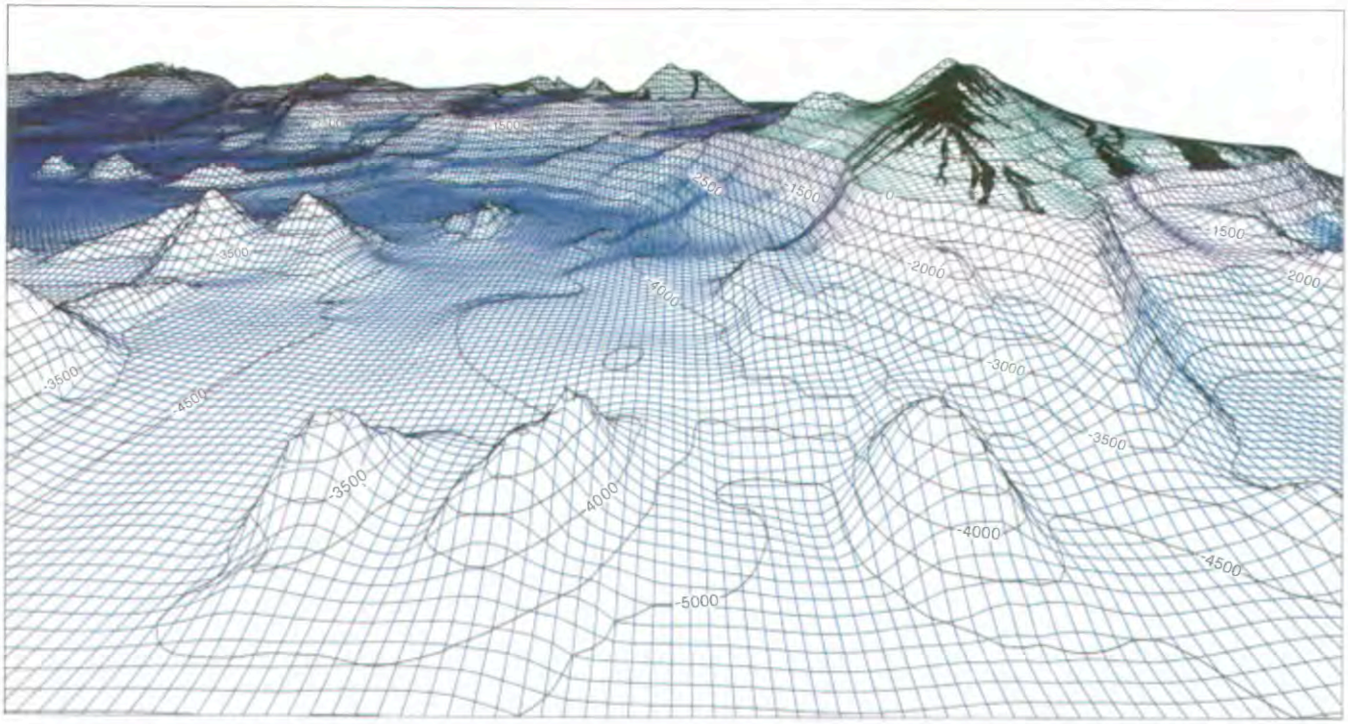

FIGURE 4.3.—Computer-drawn perspective model of the sea floor on western flank of Hawaiian Ridge from Hawaii to Oahu, looking approximately north. Contour interval 500 m. View point and direction marked on figure 4.2. Elevation of view point is 5,285 m above sea level. Data base is same as for figure 4.1. Vertical exaggeration ×5. Provided by Dynamic Graphics Inc., Berkeley, Calif.

the east of the Hawaiian Arch. The fracture zone topography narrows considerably within the arch and is likely to be responsible for the lineated contour pattern, trending west-northwest, found on the carbonate platform east of Molokai. Indeed, the principal trends of the subaerial and submarine rift zones of the East and West Molokai Volcanoes are subparallel to the fracture-zone trend and are likely to have been partly controlled by it (Furumoto and Woollard, 1965; Strange and others, 1965; Moberly and McCoy, 1966; Malahoff and Woollard, 1968).

DETAILED SEA-FLOOR TOPOGRAPHY, HAWAII TO OAHU

A computer-drawn perspective model of the sea floor around the southern Hawaiian Islands (produced by Dynamic Graphics Inc., of Berkeley, California) is shown in figure 4.1. The data base used to generate this figure is from Chase and others (1980), Wilde and others (1980), and bathymetric charts of the U.S. National Ocean Survey. The bathymetric data were gridded, digitized as a set of 43,000 x, y, and z coordinates, and then used to calculate a surface model of least tension in the form of a rectangular grid. The grid model contains 480,000 grid points (800×600) and was calculated by the Surface Gridding Library program of DGI. The bathymetric map in figure 4.2 shows the plan-view contours of most of the area of figure 4.1 and serves to locate the islands and seamounts, the starting points and azimuths of the perspective views shown in figures 4.3–4.5, and the location of other figure areas.

Three principal topographic elements are present on the sea floor shown in figure 4.1. They are (1) the submarine extensions of subaerial volcanic rift zones; (2) old and young seamounts; and (3) carbonate platforms. In addition to these major topographic features, there are several subtle steps in the western submarine slope of Hawaii (see figs. 4.3-4.5) that we interpret to be large-scale gravitational slumps of parts of Mauna Loa and Hualalai Volcanoes. One of these features is the already recognized Alika slide of Normark and others (1979).

SUBMARINE RIFT ZONES

Each principal island within the Hawaiian chain is composed of several volcanoes; consequently, the submarine flanks of each island are dominated by rift-zone ridges that may have as much as 3,000 m of relief above the surrounding abyssal sea floor. These submarine ridges are oriented in three principal directions: east to northeast, south-southwest, and northwest. A detailed discussion of the submarine topography and structure of the submarine rifts of Hawaii is presented in Fornari (chapter 5). In general, however, the total relief and topographic roughness of Hawaiian submarine rifts is

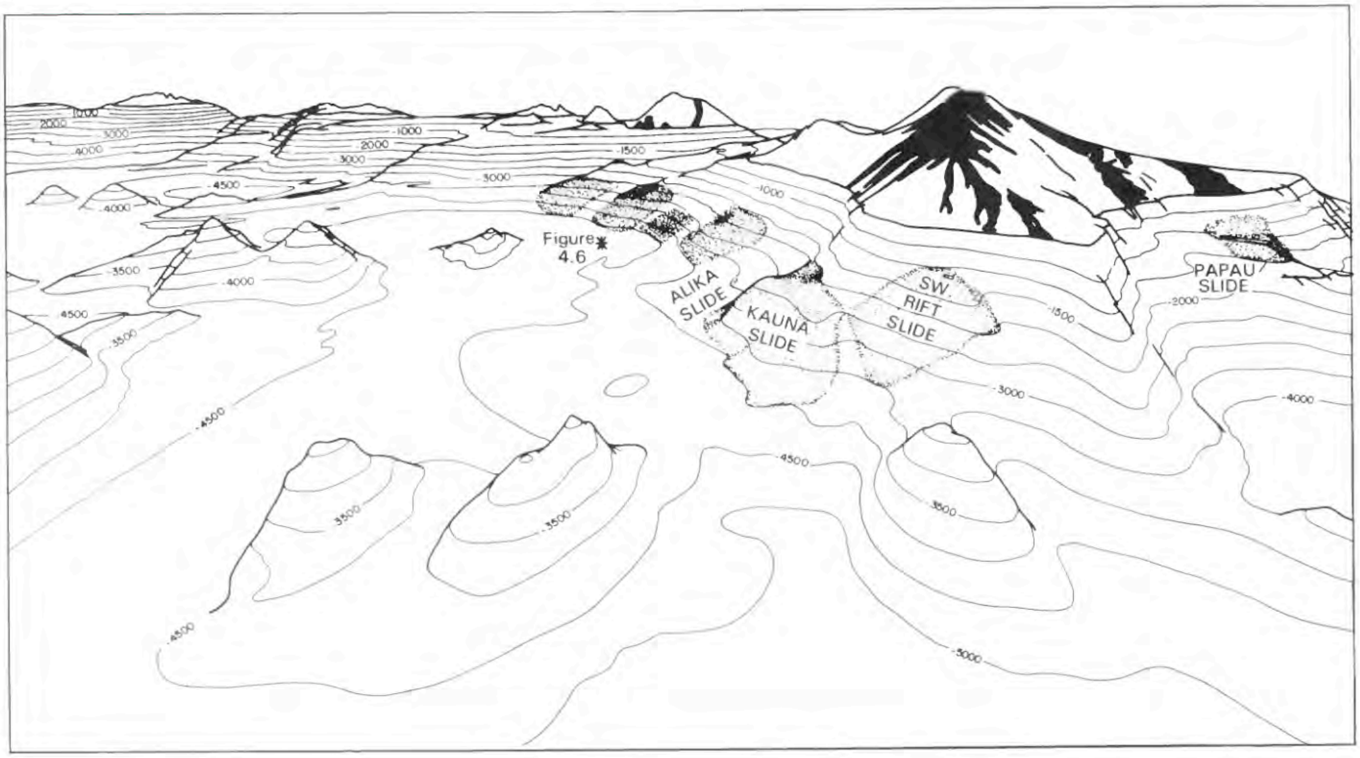

FIGURE 4.4.—Interpretative sketch of view seen in figure 4.3 showing positions of large gravitational slide blocks on the west flank of Island of Hawaii. Contour interval 500 m.

greatest next to the most active volcanic centers. The prominent asymmetry in the across-strike profiles of some of these submarine ridges can be directly attributed to the mobility of ridge flanks that are not buttressed by an adjacent volcano (Fornari, chapter 5; Stearns and Macdonald, 1946; Fiske and Kinoshita, 1969; Fiske and Jackson, 1972; Koyanagi and others, 1972; Swanson and others, 1976; Lockwood, 1979; Lipman, 1980).

The nearshore morphology of the submarine rifts changes as the islands subside (figs. 4.1, 4.2; Moore, chapter 2; Moore, 1970; Moore and Fornari, 1984). The shape and development of the carbonate platform that surrounds and lies between the Islands of Maui and Oahu have been largely controlled by the rift topography of East and West Molokai Volcanoes, as well as that of Waianae, Koolau and Penguin Banks(?) Volcanoes, parts of which now lie buried beneath a carbonate and sediment cover (Gregory and Kroenke, 1982). Off northwestern Hawaii, the northwest rift zone of Hualalai forms the southern boundary of the Kohala terrace, the wide platform that extends northwestward between Hualalai and Kohala Volcanoes. Flows ponded between Hualalai's rift and Kohala's northern rift zone created a broad, buttressed volcanic foundation that gradually subsided but was not subject to large-scale gravitational slumping; hence this was an ideal environment for reef buildup and platform development (Campbell and Erlandson, 1979, 1981; Campbell, 1984). For a further discussion of the subsidence history of the Hawaiian Islands and the development of carbonate platforms and reef terraces the reader is referred to Moore (chapter 2).

SEAMOUNTS

Important second-order topography around the Hawaiian Islands that is created by seamounts is also depicted in figures 4.1 and 4.2. Most of the seamounts that lie west of Hawaii are older features (see, for example, Moore, 1965; Francheteau and others, 1970), generally considered to be approximately Cretaceous in age, that were probably created at or near a ridge axis. The alignment of the main cluster of seamounts is generally northeast-southwest; however, two separate lineaments appear to meet at Perret and Jagger Seamounts to form a V shape pointing northeast. This V shape and the curious butterfly-like shape of Perret-Jagger Seamounts (fig. 4.2) imply a possible tectonic control on volcanism (the lineation is oblique to the trend of the Molokai Fracture Zone). These seamounts have not been studied in great detail, however, and their precise origin and volcanic history are unknown.

A few seamounts south of Hawaii (Dana and Apuupuu) may be genetically related to Hawaiian volcanism. Loihi Seamount, located 35 km south of Kilauea's south flank, is clearly a Hawaiian volcano and has been the subject of several deep-sea camera, dredging, and bathymetric surveys, and earthquake studies (Malahoff, chapter 6; Moore and others, 1979; Malahoff and others,

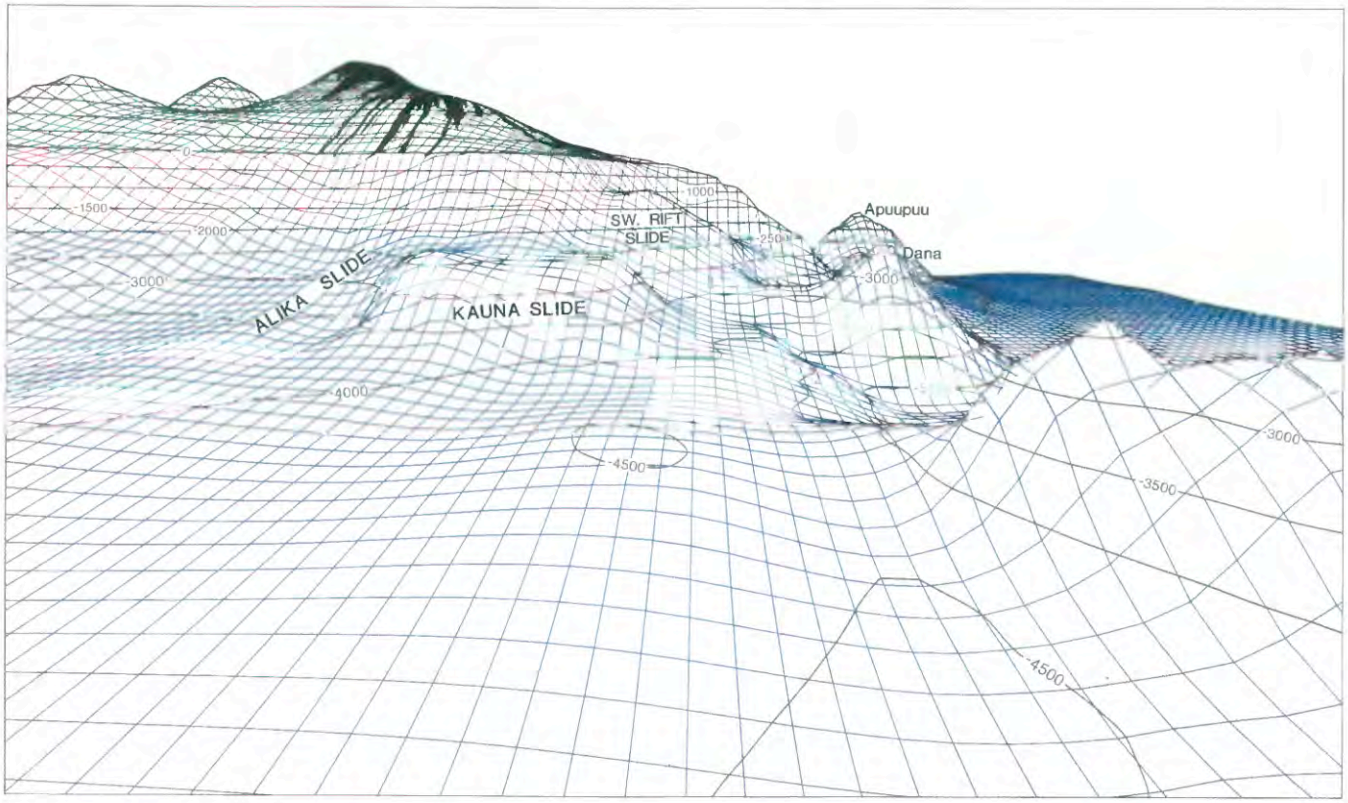

FIGURE 4.5.—Computer-drawn model of sea floor off southwestern part of Island of Hawaii, showing prominent step and bulge in the slope created by the Kauna slide. Alika slide of Normark and others (1979) is low, broad bulge to north of Kauna block. Contour interval 500 m. View point of perspective located 1,162 m below sea level; it and direction of view marked on figure 4.2. Apuupuu Seamount in background. Loihi Seamount hidden behind ridge created by submarine continuation of Mauna Loa's southwest rift zone. Vertical exaggeration ×5. Provided by Dynamic Graphics Inc., Berkeley, Calif.

1982; Moore and others, 1982; Klein, 1982). This submarine volcano rises 4,000 m above the surrounding abyssal floor and its topography is dominated by an elongate rift-zone ridge that extends to the south from summit pit craters. The diverse suite of alkalic to tholeiitic pillow basalts recovered from Loihi has led to new perspectives on the classical so-called thoeliitic shield-building stage of Hawaiian volcanism, and the chemistry of mafic inclusions recovered in the dredge hauls promises to further refine models of Hawaiian petrogenesis and volcanic history (Moore and others, 1982; Staudigel and others, 1984). Detailed U.S. Navy SASS multibeam bathymetry and ANGUS camera tows over Loihi (Malahoff, chapter 6; Malahoff and others, 1982) reveal that most constructional volcanism is restricted to the summit pit craters and shallower parts of the southern and northern rift zones, whereas most of the flanks are covered by clastic volcanic rocks and hemipelagic sediment. These data suggest that Hawaiian volcanoes develop submarine rift zones and shallow-level magma reservoirs early in their development. Additionally, the north-south elongation of Loihi appears to be partially controlled by the presence of Mauna Loa's southwest rift zone to the west. This physiography agrees with the predictions made by Fiske and Jackson (1972) regarding volcano shape and rift zone orientation and the genetic dependence of these two parameters on the locations of preexisting edifices.

A group of flat-topped seamounts of more problematic origin is located northeast of Oahu (Oahu seamounts, see figs. 4.1, 4.2). After analyzing bathymetric charts of this area, Moore (1964) suggested that these topographic highs are landslide blocks created by large slumps that affected the northeastern slope of Oahu and, to a lesser extent, the northern slope of Molokai. A close inspection of the sea-floor topography in figure 4.1 and the contours in figure 4.2 shows two prominent tongue-like features at the base of the northeast slopes of Oahu and Molokai. One feature extends northeast from Oahu at depths between 2,000 m and 4,000 m, and the other extends north from Molokai at depths between 3,000 m and 4,000 m. At the head of each tongue is an amphitheater-like reentrant in the regional slope contours (fig. 4.2). These bathymetric features could represent large gravitational slides that have affected the unbuttressed parts of volcanoes on each island. This area has been resurveyed using sparker and air-gun reflection profiling equipment (Andrews and Bainbridge, 1972) and more recently with multichannel seismic reflection methods (A.B. Watts, oral commun., 1985). Andrews and Bainbridge (1972) concluded that the lobate structures at the base of Oahu's northeast slope resulted from transport of detrital sediment by turbidity currents that were channelled down submarine canyons and deposited their load over preexisting basement highs.

We agree with Moore (1964) that these basement highs could be large slump blocks. The prominent disruption of bathymetric contour trends along the northeast coast of Oahu and north coast of Molokai indicates that these island flanks have probably been subjected to gravitational mass-wasting processes and that surficial sediment has been transported downslope by rubble slides and turbidity currents (Mathewson, 1970; Andrews and Bainbridge, 1972).

The origin of the seamounts that extend seaward from the edges of these probable slump blocks is, however, quite different. Available bathymetric data indicate that several of the smaller topographic highs form well-developed closed-contour peaks similar to many small volcanic seamounts that dot the Pacific Basin. The larger features seem to have been formed by two volcanoes coalescing together to form a crude figure 8 or bow-tie shape. The prominent flat top of Tuscaloosa Seamount, the principal topographic high in the group, is rather large but not unusually so in the context of Pacific guyots (see, for example, Menard, 1984; Vogt and Smoot, 1984). In addition, Andrews and Bainbridge (1972) determined that the topographic highs in the Oahu Seamount group have controlled sediment deposition around the seamounts and that the sedimentary layers seen on seismic reflection records are not distorted or chaotic, as would be expected if they had been emplaced by slumping or sliding. Unpublished multichannel seismic records from north and east of Oahu (A.B. Watts, oral commun., 1985) do not show any evidence of lystric or other faults between the seamounts or of distortion of sedimentary layers. In addition, the large distance between Tuscaloosa Seamount and the Oahu shelf (approx. 85 km) decreases, in our opinion, the probability that such large volumes of material could be transported across the slope.

Whereas the topography at the southwest end of the Oahu seamounts is likely to have been created by large landslides, we suggest (along with Andrews and Bainbridge, 1972) that the isolated topographic highs in the central and northeastern part of the group are older (Cretaceous?), partially buried volcanic edifices and that some may be guyots. These seamounts are not aligned along any known rift zone that extends from Oahu. In fact, the trend of the group is perpendicular to the strike of the Koolau volcanic range. The Oahu seamounts have summit depths and shapes that are similar to those of seamounts in the Musicians Seamount group, located north of Oahu (Rea and Naugler, 1970).

GRAVITATIONAL SLUMP BLOCKS

A model produced by DGI of the west flank of the Hawaiian Ridge is shown in figure 4.3. The starting viewpoint and azimuth of the perspective shown in figure 4.3 are marked on figure 4.2. The most interesting features displayed by this bathymetric compilation are the pronounced steps in the morphology of the basal slope of the ridge. These prominent steps in the otherwise steep slopes of the Hawaiian Ridge are likely to reflect large-scale gravitational slumping of parts of the volcanoes that have not been buttressed during their growth and development. A line drawing of the model shown in figure 4.3 appears as figure 4.4 on which the most obvious slump blocks have been shaded. It is apparent from these graphical representations of bathymetry that the tops of most slide blocks lie at depths of 2,000–2,500 m. The exception is the southwest-rift slide (fig. 4.3), which is much shallower (1,000–1,500 m) and is probably the youngest feature of this kind on the western flank of Hawaii. The shallower depth of the southwest-rift slide is likely to result from its position near the submarine extension of Mauna Loa's southwest rift zone and the short time over which it could have subsided since its formation. The coincidence in top depths of most of the slide blocks shown in figure 4.4 may be a function of the integrated effects of volcano growth, island subsidence, and oversteepening of the flanks to a critical point after which they are gravitationally unstable.

The Alika slide (Normark and others, 1979) is the best studied slump in this area; it shows up on figures 4.3–4.5 as a broad, low bulge in the lower southwest flank of Hawaii. This feature covers a depth range between 2,000 m and the base of the island slope at 4,000 m. Normark and others (1979) have mapped the entire area of the slide using airgun, 3.5-kHz echo-sounder, and gravity measurements and found that it is approximately 200 m thick at the toe and covers an area 20–25 km wide and nearly 80 km long.

The Kauna slide is a more prominent bulge to the south of the Alika slide and has nearly 2,000 m of relief from the top of the step to the foot of the block (figs. 4.3–4.5). Emplacement of the Kauna block most likely predated the movement of the Alika slide, because it appears to have channelled the Alika flow along its northern margin.

A similar but much less prominent step is present on the central south flank of Hawaii, between 2,500-m and 3,000-m depth (figs. 4.1, 4.2; see also, Moore, chapter 2), southeast of the Papau slide (Fornari and others, 1979b). On the southwest side of Oahu (figs. 4.1, 4.2), a prominent break in the slope at 2,500-m depth is likely to represent the top of a major slump block or group of blocks that developed on the unbuttressed southwest flank of the Waianae Range. Alternatively this feature may be the top of an older volcano that is now partially buried by the Waianae Range.

The development of these large slump-block features on the flanks of Hawaiian volcanoes suggests that gravitational failure of the slopes is an important process that alters the original constructional slopes of volcanoes during the early and mature shield-building stages. This process restabilizes the edifice, widening its base, and creates prominent steps in the steep submarine slopes. It is not known if the gravitational failures take place principally subaqueously or subaerially, nor whether the relief created by these features represents the aggregate of many episodes of slumping and mass-wasting or only a few events of enormous proportions.

A possible answer to these questions may be found through the study of the Hilina fault system, a series of subparallel and echelon faults that trend northeast on the south flank of Kilauea Volcano. Swanson and others (1976) and Tilling and others (1976) have demonstrated that the Hilina faults result from gravitational slumping

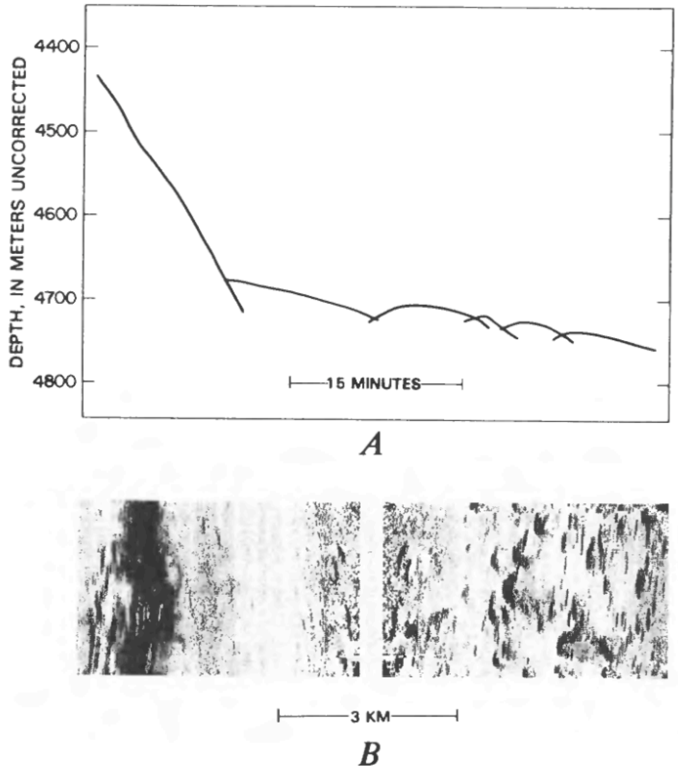

FIGURE 4.6.—Character of sea bottom off west coast of Island of Hawaii. ***A***, Tracing of 3.5-kHz echo-sounding profile (see figures 4.2 and 4.4 for location). Steep slope at left is base of Hualalai Volcano. Just seaward of slope is smooth sediment pond that appears to cover large blocks, represented by hyperbolic echos, that appear farther offshore. Horizontal scale is time; ship was moving at approximately 10 knots. ***B***, Sea MARC II side-scan sonar record of approximate area shown in *A*. Steep slope is represented by strong reflection at left of image, the large blocks as discrete reflections to right.

of the south flank of Kilauea. The slumping is induced by injection of magma into the east rift zone, thereby dilating the rift and forcing it to expand southward, in the direction it is not buttressed. These faults are a part of the initial stage of synconstructional edifice modification; they are known to continue out onto the submarine slope and have probably localized subsequent gravitational failures along their fault planes. The total relief created by the Hilina fault system is approximately 600 m, and the relief on a few individual scarps is as high as 300–450 m (Macdonald and others, 1983). The faults of the Hilina system may be viewed as modern-day analogs of faults (and fault systems) that now lie buried on the west flank of the Island of Hawaii whose cumulative activity and relief have created the large-scale gravitational slumps mapped on figures 4.3–4.5. Smaller scale features such as the Alika slide and Papau slide are likely to represent individual slide events in an area prone to gravitational collapse.

The development of prominent steps on the basal flanks of many of the Hawaiian Islands (and probably other volcanic oceanic islands) is controlled by the distribution of buttressing rift zones and gravitational mass-wasting of unbuttressed volcano sides. Clearly, large-scale gravitational mass-wasting of volcano flanks is responsible for the development of subtle but nonetheless important bathymetric features around Hawaii and probably around other oceanic volcanic islands as well (for example, Reunion Island, Duffield and others, 1982; Dallas Jackson, written commun., 1985).

LOW-RELIEF SUBMARINE RUBBLE AND DEBRIS FLOWS

The large-scale topographic features of the sea floor around Hawaii that are discussed above are easily resolved with standard bathymetric sonar tools. The investigation of smaller relief features and the microtopography of the sea floor has necessitated the development and use of sophisticated side-looking sonar systems that measure the acoustic reflectivity of the sea floor. The most successful system of this kind is the Sea MARC system, developed by International Submarine Technology of Redmond, Washington.

The Sea MARC II system, operated by the Hawaii Institute of Geophysics of the University of Hawaii, has been used in several surveys of the submarine flanks of Hawaiian volcanoes (Blackinton and others, 1983; Campbell, 1983; Campbell and Hussong, 1983; Fornari, 1984; Niedoroda and others, 1985). The technical details of the system have been described by Kosalos and others (1982) and Blackinton and others (1983). This system operates at 12 kHz, can insonify a swath of sea floor as large as 10 km wide, and can resolve linear sea floor topopgraphic features as small as 5–10 m high and several tens of meters long at survey speeds as great as 8 knots. Lateral changes in sea-floor reflectivity can be mapped and correlated to possible structural, morphologic, and sedimentologic facies.

An example of the use of the Sea MARC II system is presented in figure 4.6, which shows a 5-km-wide swath of sea floor in the Hawaiian Deep, west of Keahole Point on the Island of Hawaii. The Sea MARC II data show blocks as large as one kilometer in length and several tens of meters high that appear to be randomly scattered on the bottom. A dive made near this location by the Navy submersible *Trieste* found blocks reported to be the size of houses scattered on the bottom. These blocks are likely to be the deposits that were generated by one of the large gravitational slides located along this unbuttressed part of Hualalai Volcano.

Another principal result of the Sea MARC II surveys around the Hawaiian Islands has been the recognition of extensive rubble and debris flows and their deposits on the steep submarine flanks of the volcanoes. A mosaic of Sea MARC II side-scan sonar images (fig. 4.7) shows part of the Alenuihaha Channel and the deep channel that separates the Island of Maui from Hawaii, and an interpretative geologic sketch map of the principal features of this sonar mosaic is shown in figure 4.8.

Three major bathymetric features are present in the area shown in figure 4.8. These are the Kohala terrace, the northern slope of Kohala Volcano, and the southern slope of Haleakala Volcano on Maui. As can be seen on figure 4.7, nearly the entire submarine slope of Haleakala is covered by sinuous and branching patterns of high reflectivity, separated by linear acoustic shadows, which we have interpreted as being debris flow-lobes and channels. In several

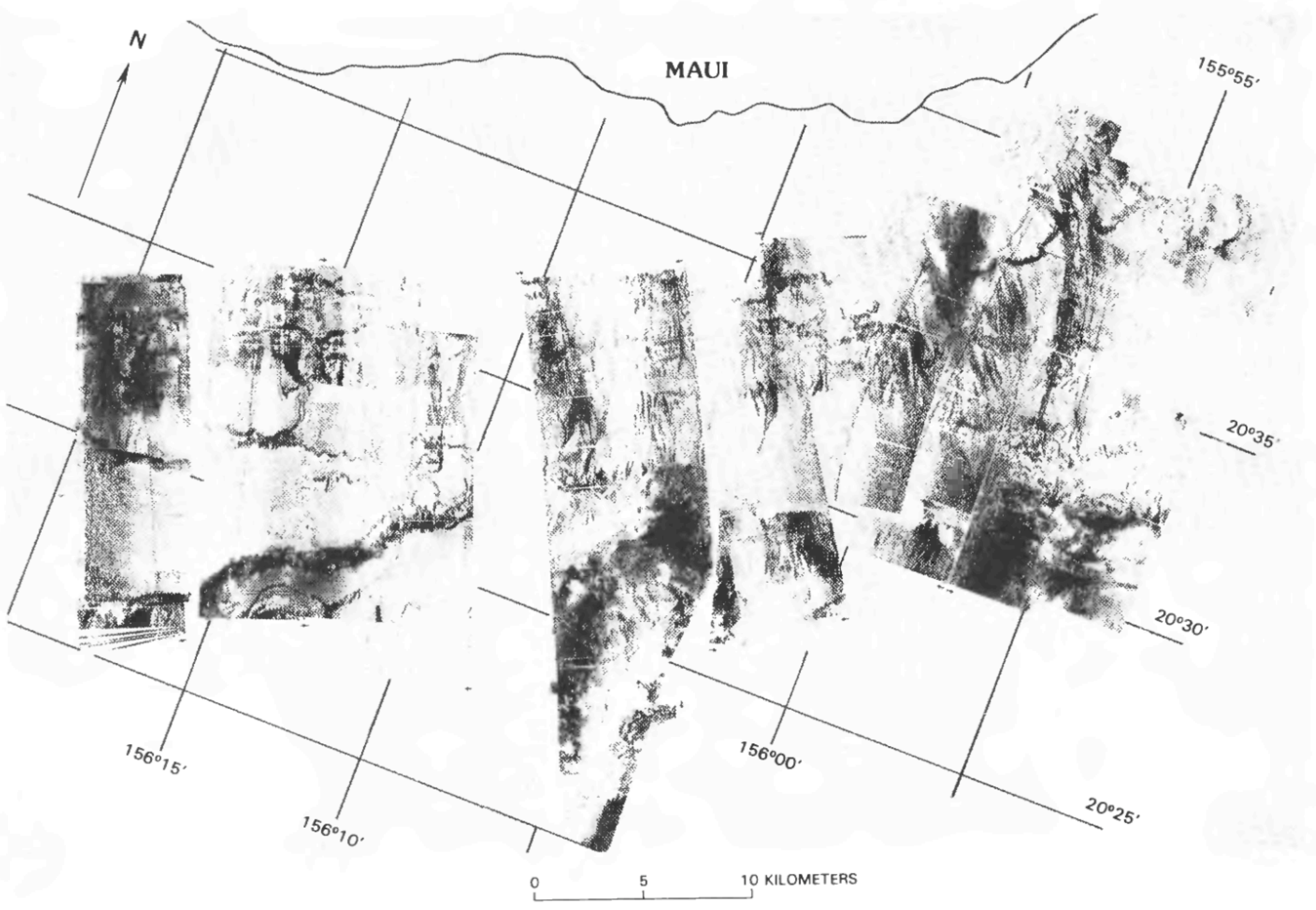

FIGURE 4.7.—Sea MARC II side-scan sonar image of the Alenuihaha Channel to south of Island of Maui. Dark areas on records are reflections from either hard, reverberant sea floor (such as volcanic rock or pavements with little sediment cover), or from linear relief that rises above surrounding sea floor. Light areas are acoustically less reflective and represent sediment-covered bottom or sea floor in complete or partial acoustic shadow (varied shades of gray). See figure 4.8 for interpretative map and Campbell (1983) for detailed description of this sea-floor area.

cases one can see that debris flows have been channelled by cuts and reentrants in flow fronts or scarps that trend across the slope. These flow fronts or scarps create strong reflections on the sonar images, implying that they have vertical or near-vertical faces. The total relief of these features may be as much as 100–200 m; the relief on individual flow fronts or scarps, however, is likely to be on the order of a few tens of meters, given the width of the returned signal and the difficulty in resolving these narrow features by conventional echo sounding. In comparison, the Sea MARC II image of the northern submarine flank of Kohala consists principally of strong returns suggestive of volcanic sea floor (Campbell, 1983), with very little dendritic fabric that could represent reflections from debris slides or channels. The northwestern edge of the Kohala terrace (Campbell and Erlandson, 1981; Campbell, 1984) has low reflectivity similar to the Alenuihaha Channel axis and other areas with gentle slopes that are covered with sediment. It is likely that the axis of the Alenuihaha Channel is largely filled with volcanic and coralline debris shed from Haleakala's southern slope. These sediments have been transported in fluvial erosional channels on land, in shallow submarine canyons on the upper slopes, and by debris flows and turbidity currents down the middle and lower submarine slopes (Campbell, 1983).

A Sea MARC II side-scan sonar mosaic of the sea floor off southwestern Oahu is shown in figure 4.9. There are several prominent morphological features in this area, including (1) the shelf-terrace area that lies between the shoreline and the top edge of the carbonate escarpment; (2) the continuous steep carbonate escarpment, which marks the western edge of a relict carbonate platform; (3) reflective ridge-and-gully terrain that lies seaward of the base of the escarpment; (4) highly reflective swaths of terrain that trend up and down the slope and are located seaward of the base of the escarpment; and (5) digitate lobes of alternating high- and low-reflectivity sea floor, located near the break in the slope between 1,500 m and 2,250 m at the downslope ends of the highly reflective

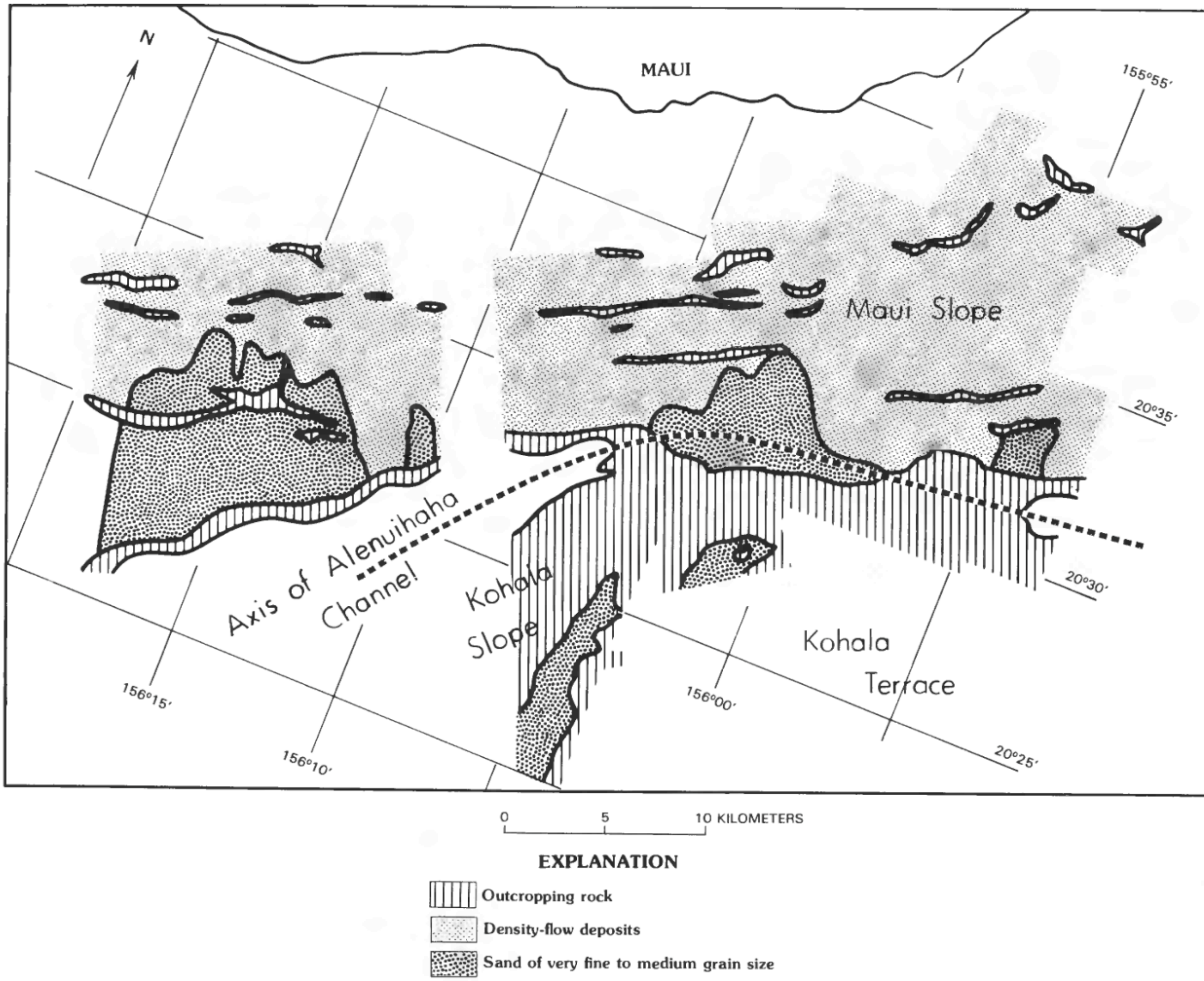

FIGURE 4.8.—Interpretative map of area of Sea MARC II images shown in figure 4.7. Note extensive linear, branching reflections and intervening acoustic shadows on south flank of Maui that we interpret as debris flows. Northern flank of Kohala Volcano forms a distinctly separate acoustic province. Samples, deep-sea photography, and Sea MARC II survey indicate that this submarine slope consists largely of outcropping volcanic flows and flow fronts with some volcanogenic and carbonate sediment on small terraces.

swaths, that are likely to represent localized landslide lobes (Fornari, 1983, 1984). The details of the sea-floor geology in this area have been studied with marine geophysical methods (Normark and others, 1982; Niedoroda and others, 1985) and with submersibles (Coles, 1982; Fornari, 1982, 1983, 1984).

The mosaic image in figure 4.9 and the interpretative maps in figures 4.10 and 4.11 provide an insight into the contemporary processes that act to shape the submarine shelf and slope areas on an older Hawaiian island such as Oahu. Also indicated on figure 4.10 are the telephone cable breaks that occurred during a hurricane on November 23, 1982. The reader is referred to Noda (1983), Fornari (1983), and Hollister (1984) for a detailed treatment of the cable-break data and the relation between cable breaks, sea-floor topography, and ocean-floor sediment dynamics.

Seaward of the base of the carbonate escarpment shown in figures 4.9 and 4.10 there are numerous zones of slightly higher reflectivity (fig. 4.10, unit C) that form crudely fan-shaped swaths of terrain interpreted to be more cobbly sea floor within the ridge-and-gully terrain identified on DSV *Turtle* dives (Fornari, 1982; 1983). These swaths of sea floor are characterized by linear patterns on the side-scan sonar records, and some swaths trend into the axes of the bathymetric reentrants typical along this southwestern coast of Oahu (Niedoroda and others, 1985). Seaward of these unit C acoustic reflectivity zones, swaths of terrain with much higher reflectivity (fig.

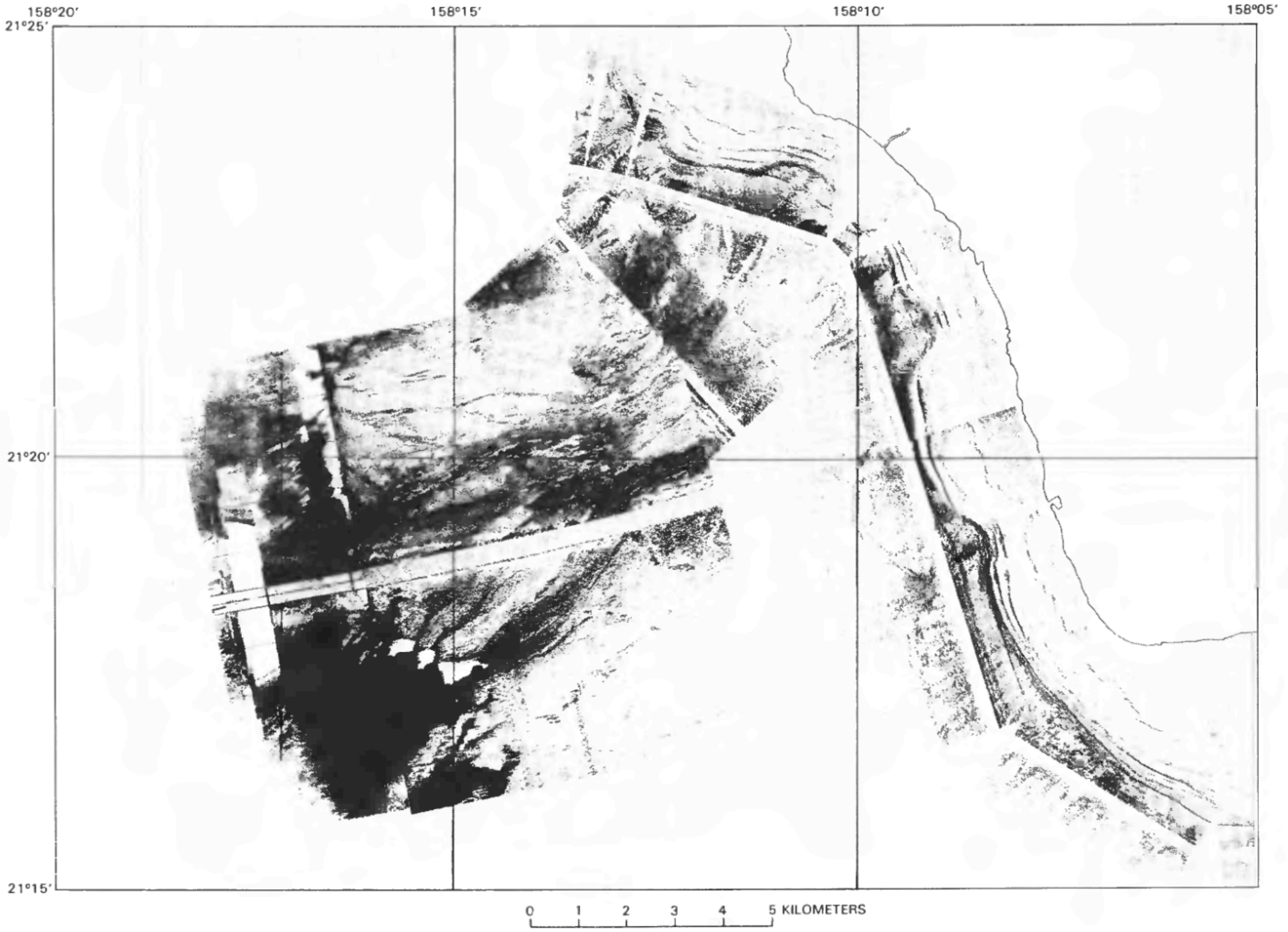

FIGURE 4.9.—Sea MARC II side-scan sonar image of the sea floor off Kahe Point, Oahu. See figure 4.10 for interpretation and Fornari (1984) for complete discussion of these data.

4.10, unit R) are likely to be areas of sea floor consisting of either gravelly or hard sediment (possibly indurated, cemented carbonate or manganese pavement). The acoustic contrast between the R and C zones is easily seen on figure 4.9, as is the higher reflectivity of these areas compared to the N zones (nonreflective). Near the southwestern edge of the sonar image in figure 4.9 there are several finger-like zones of sea floor characterized by narrow, alternating swaths of high and low reflectivity that create prominent acoustic shadows (figs. 4.9 and 4.10). These zones have been mapped by the symbol L on figure 4.10, and they appear to lie directly downslope from the R acoustic-facies zones.

A comparison between the Sea MARC II image in figure 4.7 and that in figure 4.9 points to the similarity in acoustic character of the sea-floor areas affected by low-relief rubble and debris flows. The importance of downslope transport of sediment by these processes on the flanks of Hawaiian volcanoes (Fornari and others, 1979b; Campbell, 1983; Campbell and Hussong, 1983) is suggested by the sinuous outline of the flow lobes and the delicate branching reflectors separated by intervening areas of low reflectivity that are likely to represent dendritic flow lobes and channels. Relief created by the debris flows is not great, usually on the order of a few tens of meters or less above the surrounding sea floor (Niedoroda and others, 1985). In most cases these features cannot be resolved with standard bathymetric echo sounding from the sea surface.

Thick wedges of clastic sediment, transported by debris flows and deposited on the submarine flanks of volcanoes, are important components of the gross stratigraphy of oceanic volcanoes and result from gravitational mass-wasting of large sections of unbuttressed volcano flanks and downslope movement of sediment in rubble and debris flows.

CARBONATE ESCARPMENTS

An interpretative sketch is shown in figure 4.12 of the stratigraphy viewed from the submersible *Makali'i* during several dives on

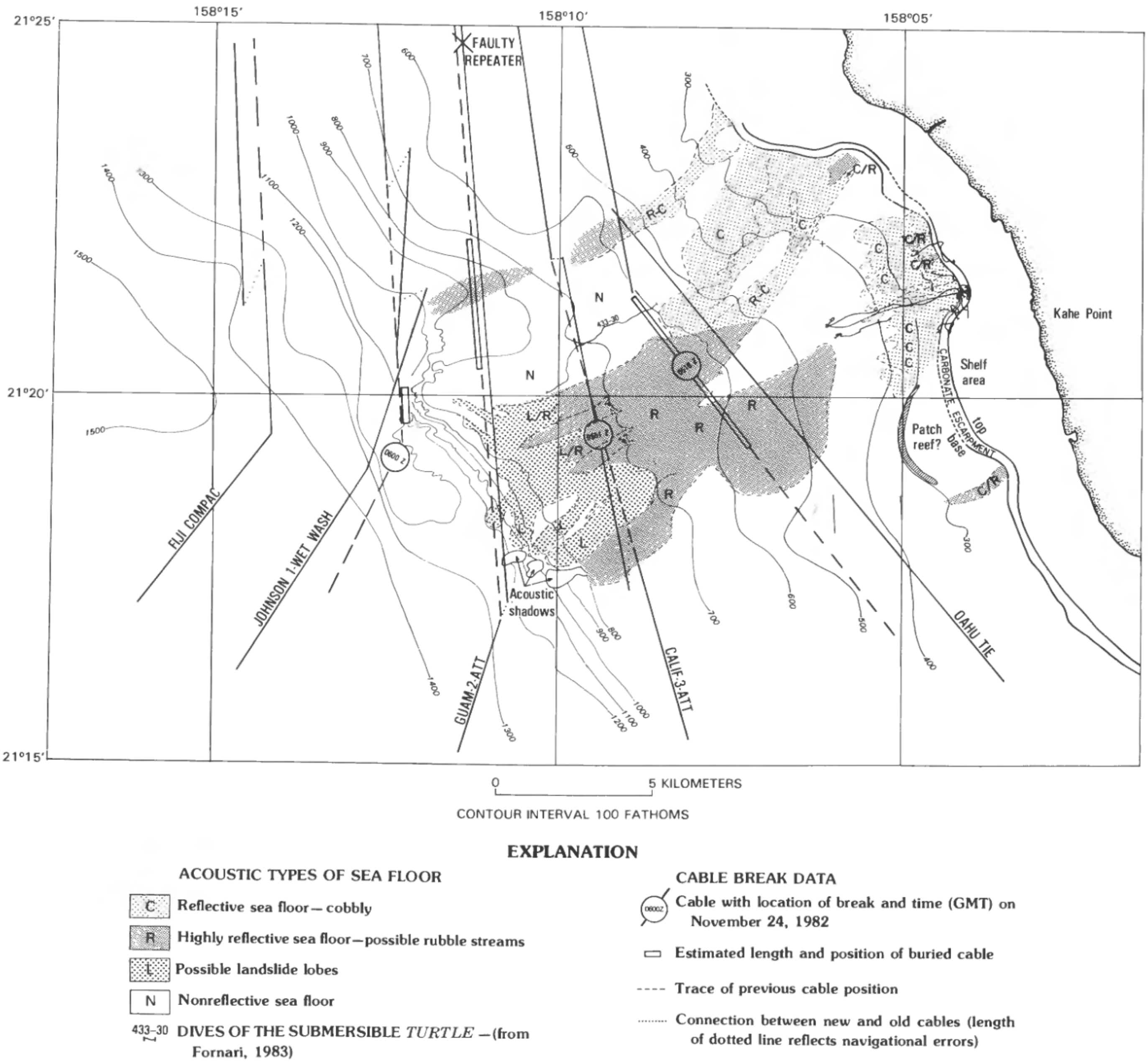

FIGURE 4.10.—Interpretative map of area of Sea MARC II image shown in figure 4.9. Major changes in acoustic reflectance relate to changes in surface sediment and depositional process. Prominent landslide lobes show analogous acoustic character to similar features on the south flank of Maui (see fig. 4.7). Reflective cobbly zones coincide with probable areas of active downslope transport of coarse volcanic and coralline rubble in traction carpets or rubble streams. See Fornari (1983, 1984) for further details and discussion of cable-break data.

the carbonate escarpment that is located just seaward of Kealakekua Bay, Hawaii (Moore and Fornari, 1984). During the traverse of *Makali'i* dive 164 (Moore and Fornari, 1984) a prominent cliff 3–10 m high was found in depths between 350 and 360 m. This cliff is continuous in a northwest direction along a contour-parallel trend, is subparallel to the escarpment, and exposes a volcanic conglomerate (fig. 4.12). The conglomerate consists of angular to subangular volcanic clasts that range in size from 0.5 cm to 0.5 m, with the median size being 0.5–2 cm, in a matrix of finer volcanic and biogenic carbonate silt and sand. Few bedding planes or graded beds were observed in the exposures; however, abundant fractures parallel to the original depositional surface indicate that crude bedding is probably present in the deposit and that it was laid down in successive episodes. Outcrops of the reef carbonate on the

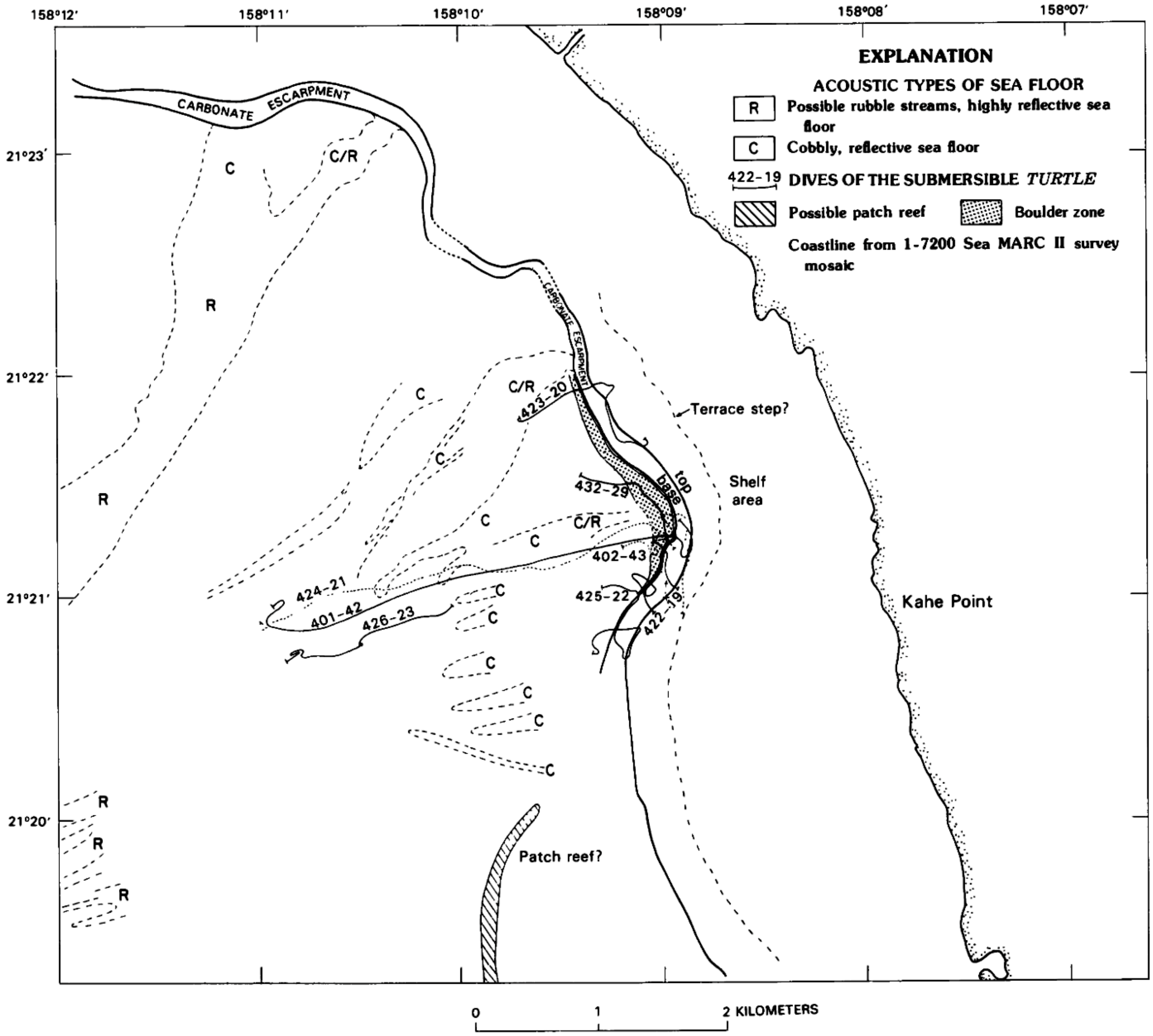

FIGURE 4.11.—Schematic map of nearshore part of area covered by Sea MARC II image off Kahe Point, Oahu, shown in figure 4.10. Submersible dive tracks and details of the sonar image have been mapped. See Fornari (1983, 1984) for further details.

escarpment above this cliff indicate that the conglomeratic deposit underlies and is the foundation for the massive limestone terrace (fig. 4.12). The instability of the volcaniclastic deposit in Kealakekua Bay is suggested by the common occurrence of large tabular blocks of the conglomerate on the sea floor immediately west of the cliff that were probably spalled off the vertical face. In some cases the base of the cliff was observed to have been undercut by as much as several meters, a process that certainly must accelerate the shedding of blocks from the escarpment.

This volcaniclastic deposit and exposures of other similar sedimentary sequences along the shallow submarine slope of Hawaii (Fornari and Perfit, unpub. data) indicate that erosion of the volcanic foundation takes place at a rapid rate. Deposition of clastic volcanogenic sediment by debris flows down the slopes leads to seaward-thinning wedges of mechanically weak clastic deposits that, when covered by successive sequences of lava, may provide an ideal surface on which seismically induced gravitational slumping can occur. This notion is supported by earthquake studies (Crosson and

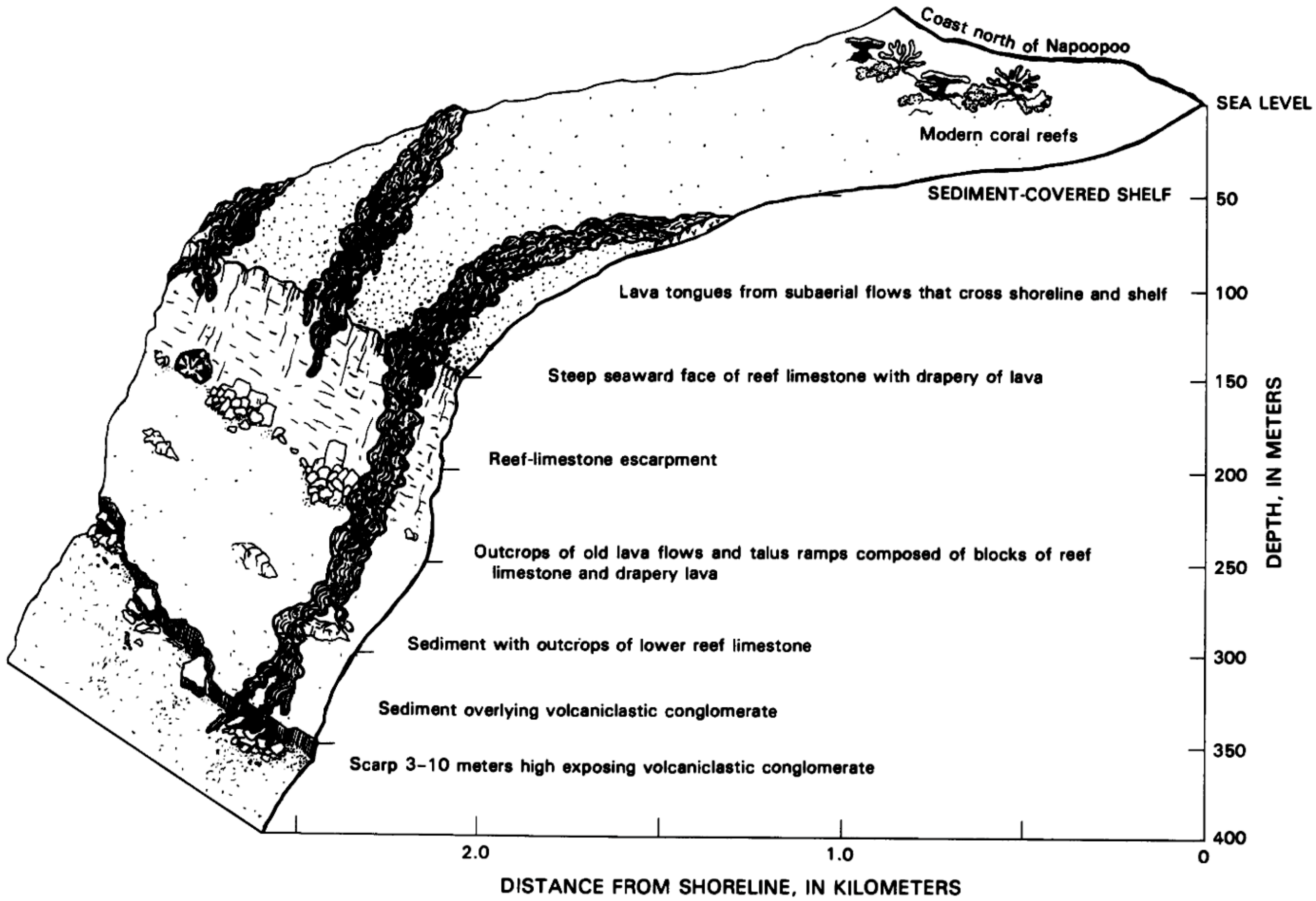

FIGURE 4.12.—Interpretative drawing of sea floor to 400-m depth off Kealakekua Bay, Hawaii, based on *Makali'i* dives (Moore and Fornari, 1984). Lava at base of carbonate escarpment is surrounded by reef limestone. This type of intercalation results from flows crossing an actively growing reef and being covered by later reef growth as subsidence occurs. Note volcaniclastic conglomerate bed 3–10 m thick that forms a continuous scarp along the base of the subsided reef terrace. This deposit was created by erosion of volcanic and carbonate outcrops on the slope and shore and deposited by rubble flows. Drawn by C.L. Fornari.

Endo, 1982) that indicate that focal mechanisms associated with nonvolcanic earthquakes on Kilauea's south flank occur within a slip plane that is coincident with a weak layer above old oceanic crust.

CONCLUSIONS

The sea floor around the Hawaiian Islands comprises several major classes of topography that are intimately related to (1) constructional volcanism that built the islands; (2) the preexisting fabric of the oceanic crust upon which the islands are built; (3) island subsidence; (4) gravitational collapse of unbuttressed volcano sides; and (5) low-relief debris flows that transport clastic sediment down the submarine slopes. The submarine continuations of subaerial rift zones create the most prominent relief around the islands. The topographic roughness and regional slope of each submarine rift is directly proportional to the age of the adjacent volcano. Seamounts around the Hawaiian Islands are largely older (Cretaceous) volcanoes that have been been partially buried by sediment. Some of these features may be drowned guyots. Several young seamounts that are genetically related to Hawaiian volcanism lie south of the Island of Hawaii. More subtle topographic features are present on the basal flanks of the Hawaiian Ridge and form steps and bulges in the lower slopes. These features were created by large-scale gravitational mass wasting of volcano flanks not buttressed by adjacent edifices. Low-relief debris flows appear to be the principal mechanism whereby clastic sediment is transported down the submarine flanks of oceanic volcanoes.

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