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Volcanic structure of the crest of the Puna Ridge, Hawaii: Geophysical implications of submarine volcanic terrain

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ABSTRACT

The morphology of submarine volcanic terrain on the crest of the Puna Ridge, Hawaii, was observed during two manned submersible dives in water depths of as much as 2,000 m. Steep-walled linear ridges 30 m high, trending 060°, and composed of lava pillows and narrow fissures with the same strike were the principal volcanic features observed on the ridge crest. Lava tunnels, tubes, and pillows frequently were observed to be partially broken through, thereby exposing water-filled voids, which are inferred to be interconnected to great depths within the extrusive submarine volcanic pile. Low compressional wave velocities reported by other authors for the crustal layer composed of submarine volcanic extrusives and the low effective density of this layer, as determined from published surface gravity observations, are attributed to the large intraflow and interflow porosity of submarine volcanic terrain. Areal variations in heat flow through the crust of submarine volcanic features are also attributed to the high porosity and consequent permeability of submarine volcanic terrain which is likely to persist to the bottom of the submarine extrusive pile.

INTRODUCTION

Submarine volcanism is known to be a principal constructional mechanism whereby oceanic crust is formed, and it is the process by which the vast number of islands that rise from the depths of the world ocean have been built. This has been substantiated by several decades of oceanographic research, and the details of this process have been recently investigated by studies employing manned submersibles that made in situ observations of the morphology and structure of submarine volcanic terrain in the central rift valley of the Mid-Atlantic Ridge (Ballard, and others, 1975; ARCYANA, 1975; Ballard and van Andel, 1977).

The objective of this study was to investigate recent island-ridge, mid-ocean basin submarine volcanic activity to determine the processes that form the volcanic micro-

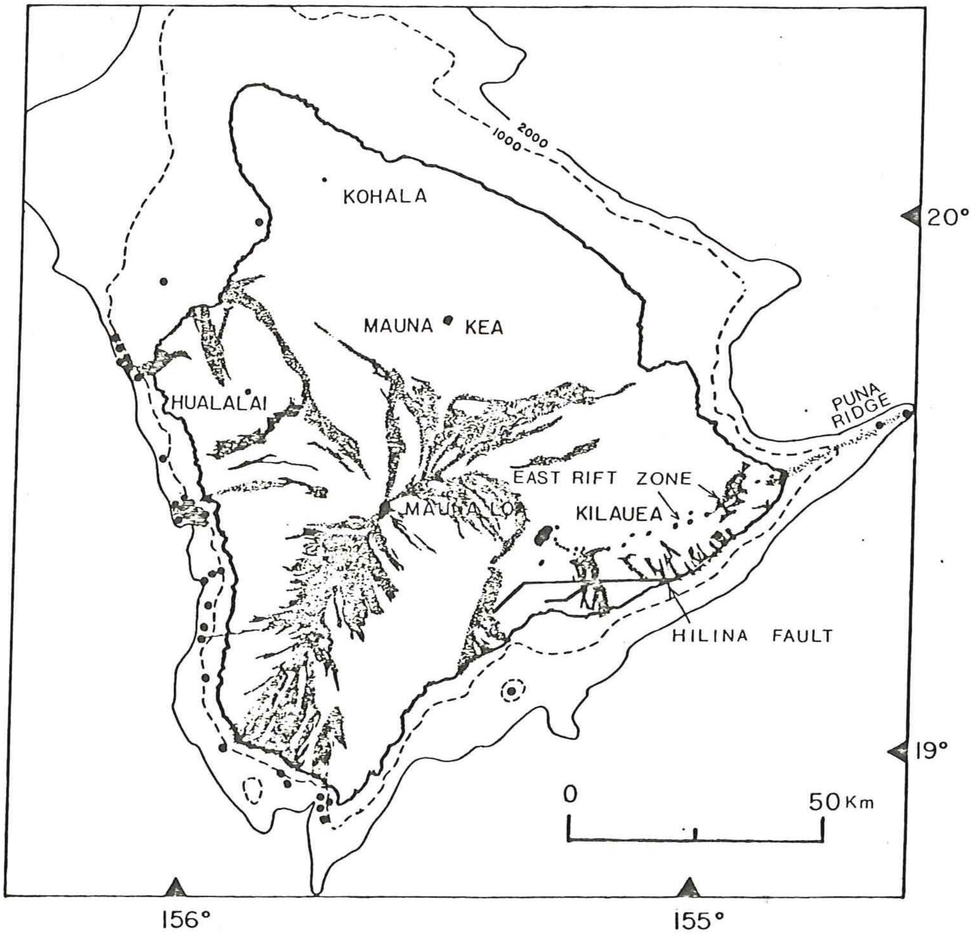

Figure 1. General base map of Island of Hawaii. Shaded areas represent areal extent of most historically recent subaerial lava flows. Black dots show locations of DSV *Sea Cliff* dives during July and August 1974 and September and October 1975.

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morphology of a submarine rift zone in close proximity to a "hotspot" located under Hawaii.

The Island of Hawaii has been subjected to extensive stratigraphic, petrologic, structural, and geophysical investigations for the past 50 years (Macdonald and Abbott, 1970). This extensive geological and geophysical coverage of the region around Hawaii, coupled with the recent volcanic activity along the southeastern sector of the island, focused our studies on the Puna Ridge, the submarine continuation of the East Rift Zone of Kilauea volcano (see Fig. 1). Kilauea is presumed to be currently located over the active hotspot or mantle plume that created the Hawaiian Ridge (Shaw and Jackson, 1973).

The two submersible dives to the crest of the Puna Ridge were made in July 1974 with the U.S. Navy Deep Submergence Vehicle *Sea Cliff. Sea Cliff* is a small three-man submersible capable of descending to depths of 2,000 m and traversing the bottom for periods as much as six hours. It is equipped with three 14-cm-diameter viewports, forward-looking sonar, echo sounder, external deep-sea strobe, and a 70-mm camera system, and two remotely operated manipulators. The submersible is launched and retrived by a crane mounted on the sterm of the truck boat *Maxine-D*.

GEOLOGIC SETTING

The Puna Ridge is a northeast-trending volcanic ridge that extends approximately 70 km out to sea from Cape Kumukahi, Hawaii, and represents the submarine continuation of the subaerial East Rift Zone of Kilauea volcano. Surface-ship remote-sensing studies, including deep-sea camera stations, dredging, and geophysical measurements have been conducted over the Puna Ridge (Moore and Reed, 1963; Moore, 1965; Malahoff and McCoy, 1967). These studies confirmed the extrusive volcanic nature of the Puna Ridge and its direct structural relationship to the subaerial volcanic features of Kilauea.

The deep-sea bottom photographs published by Moore and Reed (1963) clearly show (1) the presence of fresh pillow basalt forms on the crest of and ocean floor surrounding the Puna Ridge, (2) an absence of benthic organisms, both sessile and mobile, from the surface of the pillows and tubes, and (3) a lack of interstitial sediments. All of these observations suggest that historically recent episodes of submarine extrusion have taken place along the length of this ridge. Petrographic studies of samples dredged from various depths along the Puna Ridge (Moore, 1965; Moore and Fiske, 1969) indicate that all of the samples are olivine tholeiite basalts, compositionally similar to the subaerially extruded basalts of Kilauea. These analyses also show that there is a systematic decrease in vesicularity and increase in weight percentage of olivine in the samples with increasing depth down the ridge crest. Geophysical studies over the Puna Ridge (Malahoff and McCoy, 1967) suggest that the internal structure of the ridge is analogous to the composite plug and dike complexes that form the volcanic cores of the islands in the Hawaiian chain.

PUNA RIDGE MORPHOLOGY

A detailed echo-sounding survey employing land-based Hi-Fix navigation was carried out over the Puna Ridge by the U.S. Coast and Geodetic Survey in 1967 (see Moore, 1971). Profiles of the original 12-kHz records and the location of the ship tracks relative to Hawaii are shown in Figure 2. The profiles in Figure 2 have been aligned relative to the ridge crest to show the summit morphology and the changing echogram character of the ridge crest as a function of water depth and distance from Cape Kumukahi. Figure 3 shows profiles of these 12-kHz records at a larger scale for the areas around dives 108 and 115.

A detailed analysis of the echo-sounder records suggests the presence of a nearly continuous medial rift zone along the ridge crest. The rift zone is best developed along the central parts of the ridge. The echo reflection character of the ridge crest appears to be marked by indistinct, often barely visible, steep-sided hyperbolae which indicate bare-rock outcrops and steep-walled, narrow summit elevations that follow the general northeast strike of the ridge. The flanks of the ridge have a mean slope of 10° and comprise a morphological province based on echogram character which is recorded as distinct, broader hyperbolae sucessively overlapping downslope. The shallower southwestern end of the ridge appears to have a much broader crestal zone, and the southern flank exhibits what is interpreted to be normal faulting, with the downthrown block to the south, a geologic setting similar to that associated with the Hilina fault system on Hawaii (see Fig. 1). This feature has been interpreted as being a structural continuation of the Hilina fault system along the southern flank of the shallower parts of the Puna Ridge (Malahoff and McCoy, 1967).

Figure 4 is a photograph of a 12-kHz echogram recorded onboard the *Maxine-D* over the crest of the Puna Ridge near the site of dive 108. The previously mentioned echogram character of indistinct, steep-sided hyperbolae is clearly shown in this recording. As will be shown in this paper, the bottom morphology observed visually during dive 108 agrees with the geological interpretation of this type of reflected return.

IN SITU OBSERVATIONS FROM *SEA CLIFF*

Two dives were made along the crestal zone of the ridge at the locations shown in the inset of Figure 3. During each dive the submersible traversed the crestal zone of the ridge. The central ridge-and-fissure area was traversed from flank to flank, and the break in slope from the crest to the upper flank was easily observed. The submersible tracks for dives 108 and 115 are shown in Figures 5 and 6, respectively, with the bottom character and extrusive forms along the track depicted by a series of symbols.

During dive 108 an area observed to be frequently cut by long linear fissures was investigated. These long fissures, of which a central segment is depicted in Figure 7, were observed to pinch out and re-form as subparallel fissures that continued beyond the field of view (Fig. 8, top left). The width and depth of these fissures varied, but on the average they attained widths of 10 m or more and depths of the same order. The lengths are inferred to be about 0.5 to 1 km on the basis of multiple crossing of the same fissure and postdive navigation plots.

The bottom character visually observed during dive 108 correlated well with the surface-ship echo-sounder display over this dive site. The broader, distinct hyperbolae recorded by the surface ship over the ridge's upper flank were interpreted as reflections off lava pillow and tube terrain that was seen to contain small accumulations of black glassy sand and buff-colored ooze in the interstices between the extrusive forms. The upper flank and crestal zones of the ridge were delineated on the basis of a marked absence of sediment over the crestal zone. The transition between the two zones was observed to be very narrow. On the crest, the fissured areas were always seen to be marked by broken pillows and collapsed lava tubes. A particularly striking aspect of the fissures was that the extrusive forms on both sides of the scarps, although broken, appeared to match across the chasm.

During dive 115, *Sea Cliff* traversed a somewhat shallower segment of the Puna Ridge crest located to the southwest of the area observed during dive 108. The dive 115 bottom traverse began on the upper south flank of the ridge, where fresh, unfractured pillow lavas were observed to coalesce into roughly linear mounds, from several metres to 20 m in height, with the

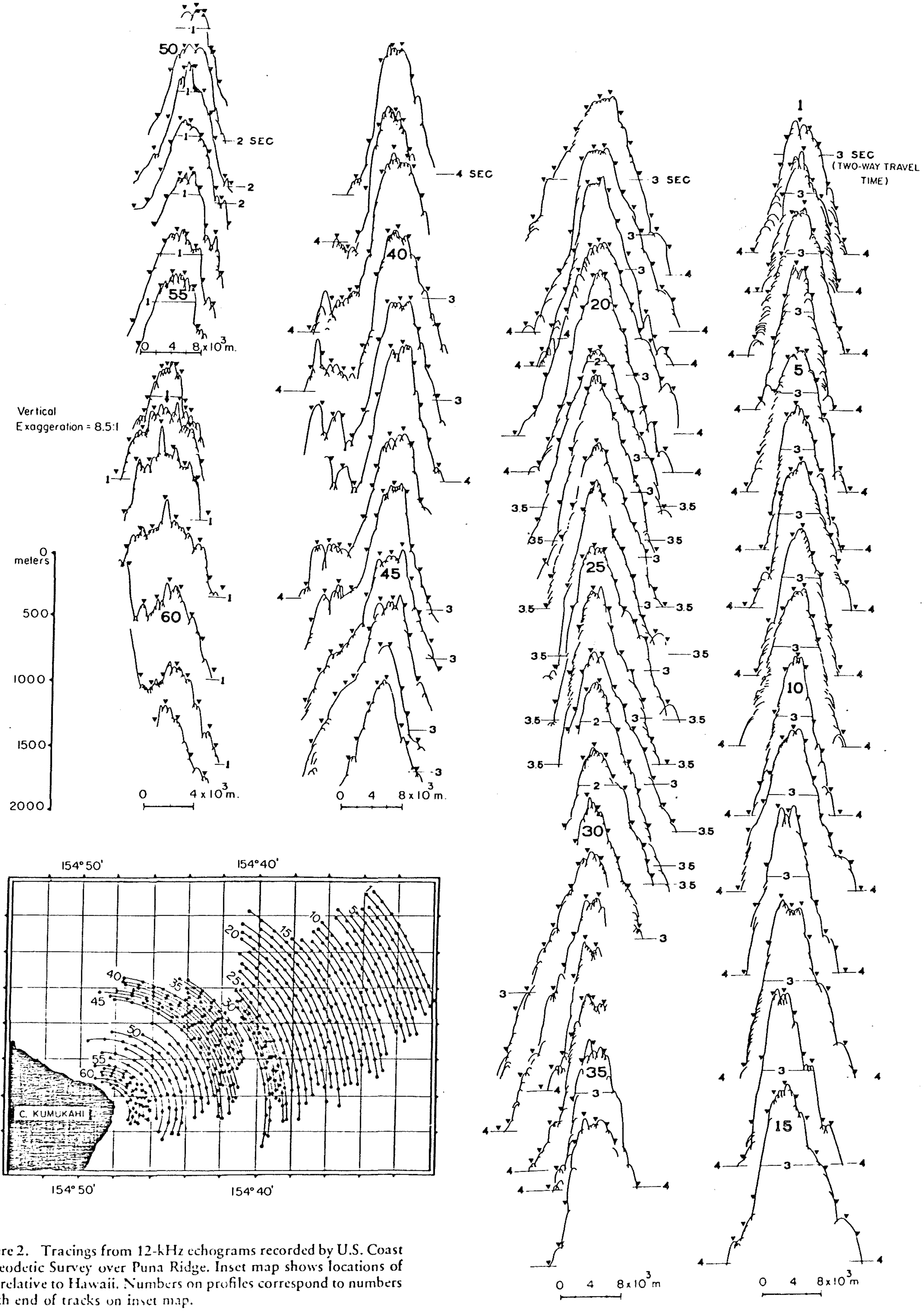
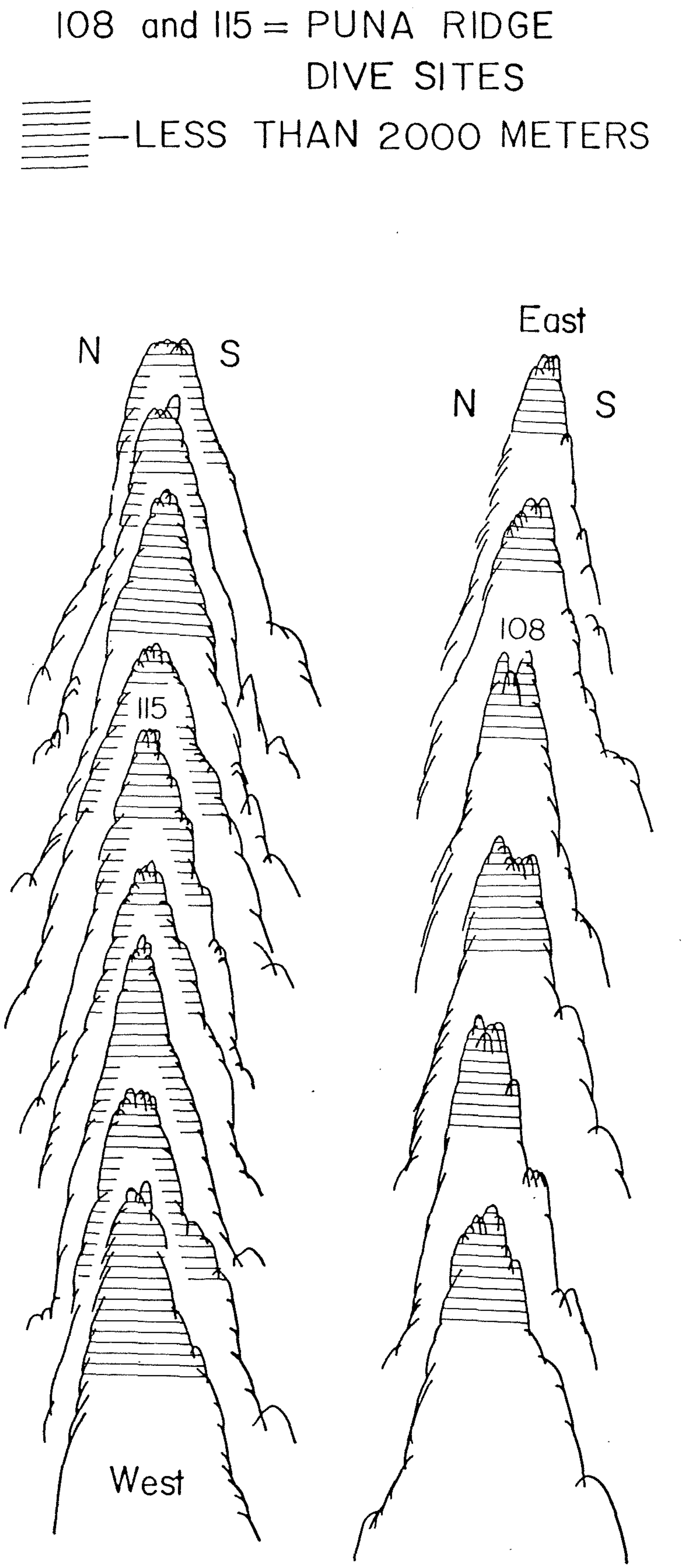


Figure 2. Tracings from 12-kHz echograms recorded by U.S. Coast and Geodetic Survey over Puna Ridge. Inset map shows locations of tracks relative to Hawaii. Numbers on profiles correspond to numbers at north end of tracks on inset map.



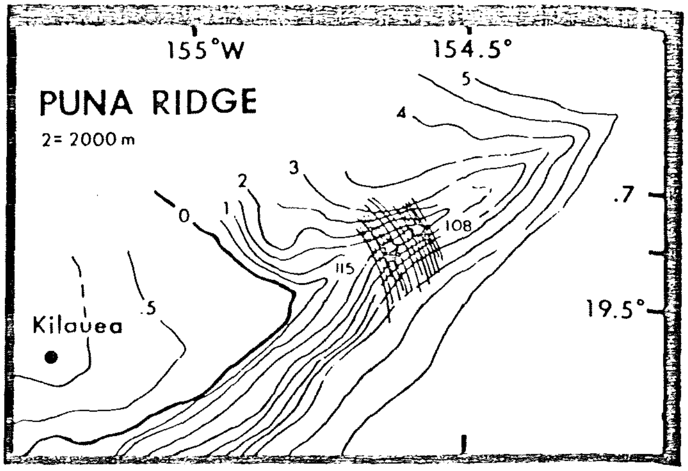


Figure 3. Enlarged tracings of 12-kHz echograms (see Fig. 2) near areas of dives 108 and 115 on crest of Puna Ridge. Note difference in bottom morphology, as revealed by echogram character, between profile that corresponds to dive 115 and one recorded near dive 108. Steep-sided narrow hyperbolae recorded over crest of Puna Ridge near dive site 115 are thought to be reflections from pillow-wall terrain.

horizontal distance between the mounds being of the order of 20 m. No broken or fractured volcanic forms were observed on the upper flank. A minimum of interstitial sediment was observed between the pillows, most of which appeared to have a characteristic "elephant-hide" surface texture (the "spreading cracks and corrugations" of Moore, 1975), probably caused by contraction during cooling of the outer rind (Fig. 8, top right).

During this dive an abrupt change was observed from the rough upper-flank topography, characterized by the presence of elongate pillow mounds, to the ridge-crest terrain. The crest terrain is characterized by narrow, subparallel linear ridges that trend 060°. These ridges were observed to be from 3 to 8 m wide on top, roughly 40 m wide at their bases, and as much as 30 m high, and they range from 0.5 to 2 km in length. The sides of the ridges are consistently near vertical and composed exclusively of unfractured lava pillows that have the appearance of having been piled up one

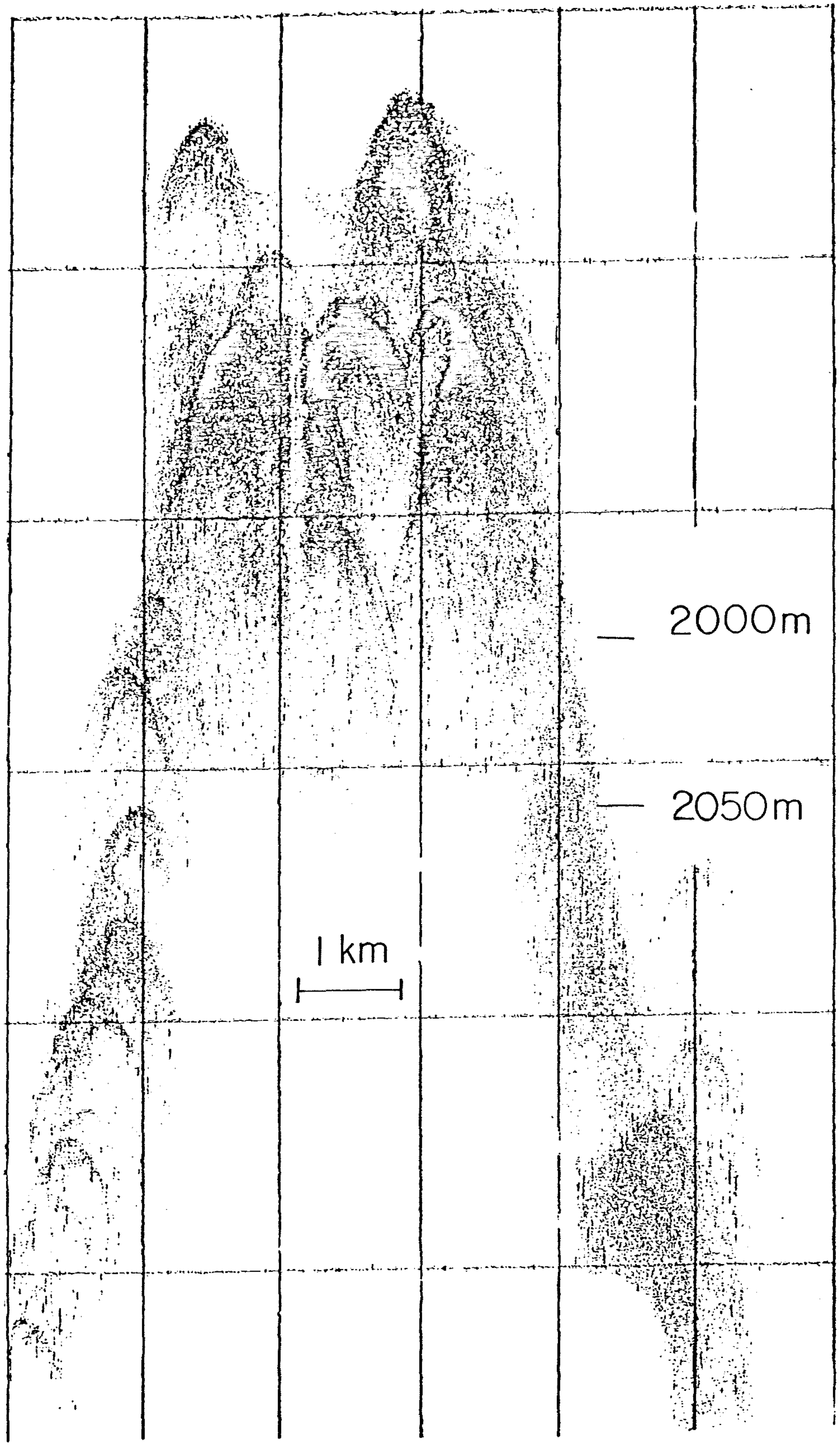


Figure 4. Echogram (12 kHz) recorded on board *Maxine-D* near site of dive 108.

on top of the other. At the foot of most of the ridges an accumulation of nearly whole pillows and lava pillow fragments were observed (Fig. 8, middle left and bottom left). Presumably these fragments had spalled off the vertical sides as a result of cooling stresses. These ridges, hereafter called "pillow walls," are inferred to have formed by the accumulation of lava pillows and tubes erupted from long linear vents on the sea floor. These vents are presumed to be hidden from view beneath the pillow walls. The crests of these pillow walls were sometimes observed to be rifted by small vents (Fig. 8, middle right). An artist's composite drawing of a pillow wall, drawn directly from an assemblage of *Sea Cliff* 70-mm bottom photographs, such as those in Figures 8 and 9, is shown in Figure 10.

The center of the ridge crest area is marked by narrow fissures with walls of unfractured lava pillows which trend northeast, parallel to the strike of the pillow walls and Puna Ridge itself. These median rifts were also observed to taper out and re-form as other subparallel fissures in a manner similar to that observed on dive 108 (see Fig. 7). In some cases the extrusive forms had the appearance of having been fractured as a result of the fissures' opening (Fig. 8, middle right). The bulbous unfractured lava pillows encountered at the beginning of the dive were replaced at the ridge crest by lava tubes and tunnels as much as 10 m in diameter. Several of the tubes and tunnels were observed to be collapsed, thereby exposing their water-filled interiors (Fig. 8, bottom right). These features had the general appearance of subaerially erupted pahoehoe lava forms.

DISCUSSION

Formation of Pillow Walls

The fissures and pillow-wall ridges observed during the two dives to the crest of the Puna Ridge are the major morphological features of the crest of this submarine volcanic ridge. The three basic components of these pillow walls are (1) an inferred dense dike plug under the crest of the pillow wall, (2) the central fissure of the pillow wall located at the crest that represents the fossil trace of the vent which gave rise to the stack of pillows and tubes, and (3) the pillow wall itself, composed of coalesced lava pillows and tubes stacked on top of one

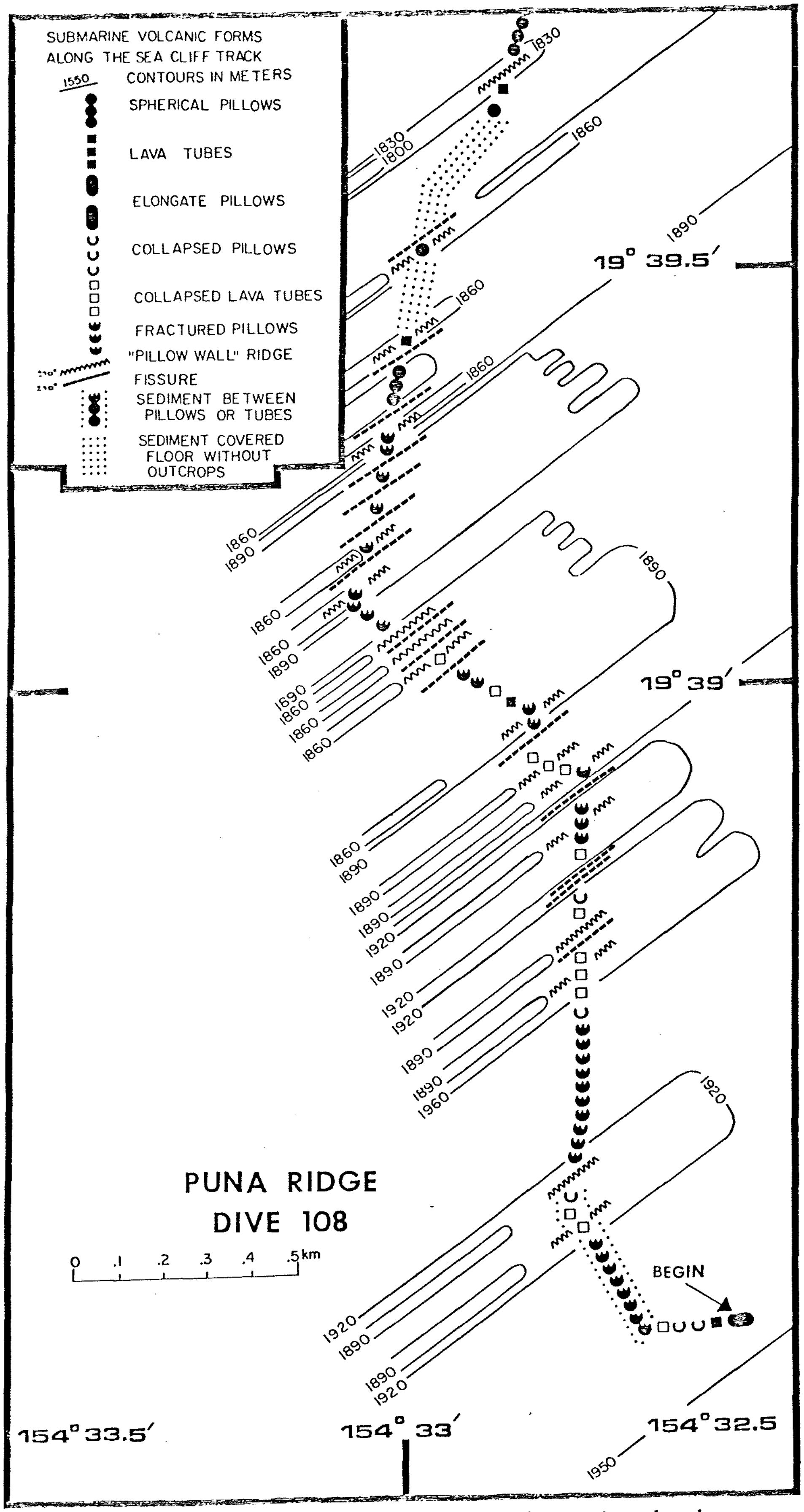


Figure 5. Dive 108 *Sea Cliff* track. Geological interpretation of observations taken along traverse of dive 108 is shown schematically.

another. Because of the similarities in water depth, general basaltic composition, and flow characteristics, the similarities in echogram character between the crest of the Puna Ridge and segments of the Central Rift Valley of the mid-oceanic ridge system suggest that the processes of pillow-wall formation are a common feature of mid-ocean volcanism.

Solid, Fractured, and Hollow Submarine Volcanic Forms

The bottom character observed along the upper flank and crest of the Puna Ridge consists predominantly of fresh, unbroken lava pillows and tubes, with the percentage of broken pillows and fractured lava tubes increasing toward the ridge crest. The percentage of broken and evacuated volcanic forms on the ridge crest is estimated visually to be approximately 75% in the area of dive 108 and 25% in the area of dive 115, with the remaining forms in both cases being spherical pillows and unfractured lava tubes. Because dive 108 was located on a site consisting of predominantly fissured terrain, the greater percentage of broken extrusive forms encountered on this particular dive is a reflection of the local tectonic regime. Dive 115, on the other hand, was located in the pillow-wall area, and the greater percentage of unfractured forms estimated to be present here reflects the constructional volcanic processes that appear to be active along this segment of the ridge.

These percentages of whole and fractured volcanic forms are in general agreement with those determined by Moore and Fiske (1969) that were calculated from shipboard bottom photographs. Their four camera stations located along the crest of the Puna Ridge gave a mean percentage of 75% pillows, the rest being pillow fragments; two stations on the south flank of the ridge gave a mean percentage of 46% pillows. The bottom categories of Moore and Fiske do not implictly distinguish between (1) unfractured spherical pillows and tubes and (2) those forms that do show some degree of fracturing but have not been reduced to rubble. It is inferred that their "pillow" category includes only unfractured spherical or elongate forms, while their "pillow fragment" category includes broken forms, both in place and transported.

A significant observation that is important in distinguishing between submarine volcanic areas of solid-rock bottom and those that are broken up, either tectonically, thermally, or both, is the difference between smooth-surfaced pillows and tubes and those with elephant-hide or rough surface textures produced during cooling of the volcanic form. From the numerous observations made during the two submersible dives on the Puna Ridge and from other dives in submarine volcanic terrain elsewhere around Hawaii, it is believed that the smooth-surfaced forms (comparable to subaerial pahoehoe) actually have hollow interiors (water-filled), while those with rough and cracked rind textures are solid throughout. We postulate the following set of events that could account for the observed facts. Under initial conditions of an eruption of lava from a fissure on the sea floor at water depths of 2,000 m, the lava would chill instantaneously upon contact with the water, forming lava pillows that would eventually accumulate vertically, creating the pillow walls we observed. Once a slope is established, the lava issuing from the vent or vents on the pillow wall will migrate downslope either as a series of successive eruptions into the surrounding water or through a lava tube. This sequence of events continues as long as the supply of magma from the main feeder vent remains constant. As the volume and pressure of the magma begin to decrease, they give rise to a possible imbalance between the eruptive pressure forcing the magma out and the overlying hydrostatic pressure that constrains the flow of the lava. When the eruptive flow of magma wanes or ceases, sea water then breaks through the thin insulating outer crust and either diverts the lava to another conduit or, if the eruptive pressure is weak enough, stops the flow altogether. The lava that remains in the tube at the time the water breaks through will then drain downslope. The volcanic forms that result from this sequence of events are (1) an upslope part of a lava tube that is water filled and was a smooth surface texture because of the temperature equilibrium established over a short period of time on both sides of the outer crust and (2) a downslope terminus of the lava tube that is filled with the lava that drained there from farther upslope. In this lower part of the lava tube, there would be a large temperature difference between the interior of the tube and the exterior. This would cause the outer crust of the tube to crack and pull apart as it cooled, giving rise to the characteristic elephant-hide or "breadcrust" surface texture of subaqueously extruded lavas.

Although the details of this process are unquestionably more complicated than the few steps outlined above, the hollow submarine volcanic forms often observed during the *Sea Cliff* dives attest to the frequency of this sequence of events during extrusions of lava onto the deep sea floor.

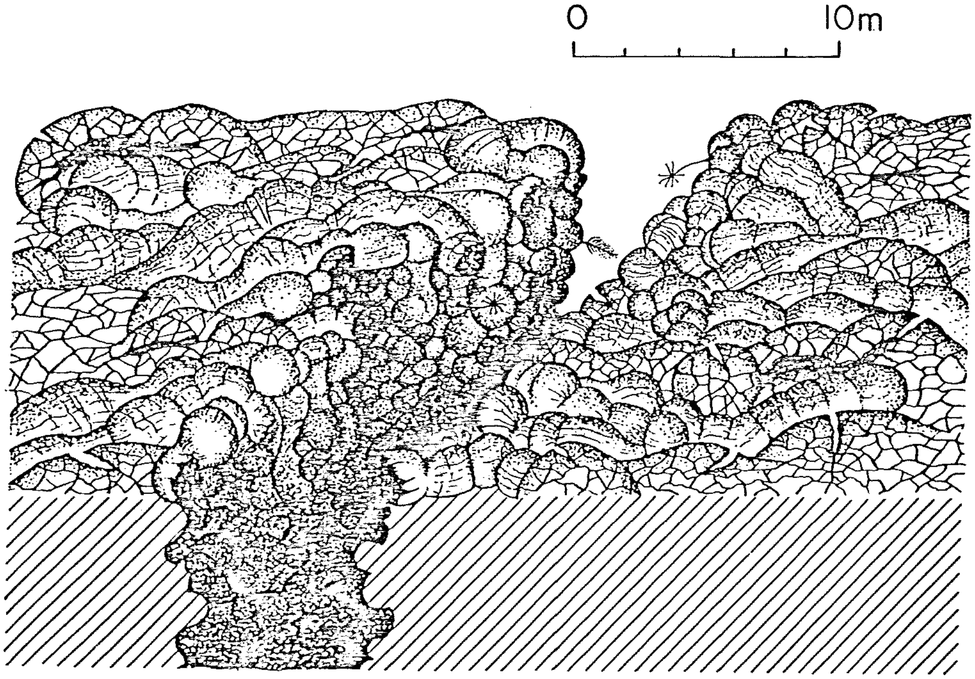


Figure 7. Composite drawing of central part of fissure similar to those observed on dive 108; rendered from assemblage of *Sea Cliff* 70-mm bottom photographs (artist: Suzanne MacDonald).

Geophysical Implications of Submarine Volcanic Terrain

Geophysical studies of the Hawaiian Ridge have been continuously carried out over the past few decades (Woollard, 1954: Raitt, 1956; Shor, 1960; Eaton, 1962; Shor and Pollard, 1964; Furumoto and Woollard, 1965). As a result of these studies, the general physical properties of the crust and mantle in this area are reasonably well known. The compressional wave velocity structure of the Hawaiian Ridge can be described in the form of four layers. Layer 1 (2 to 3 km thick) has compressional velocities between 2.9 and 4.0 km/s and principally represents volcaniclastic debris. Layer 2 (6 to 8 km thick) has a V_p that varies from 4.5 to 5.2 km/s; it makes up the bulk of the Hawaiian Islands and is assumed to be basaltic lavas extruded subaqueously in intermediate to deep water depths. Layer 3 (4 to 7 km thick) has compressional velocities that vary from 6.4 to 7.2 km/s and is inferred to be dense volcanic plug and dike material. Layer 4 is mantle material that occurs at depths of 14 to 16 km and has a compressional velocity of 8.1 km/s.

Using the Nafe-Drake curve (Nafe and Drake, 1963), the compressional velocities of layer 2 have been found to be too low, by approximately five-tenths of a second, to correspond to the measured average bulk density of 2.8 g/cm^3 (as determined from rock specimens) for the submarine extrusive lavas that compose this layer. To a small degree this discrepancy can be explained by the presence of large quantities of glass within this layer created by the quenching

Figure 8. *Sea Cliff* 70-mm bottom photographs. Top left: Central segment of deep, narrow fissure on crest of Puna Ridge. Note lava tubes that droop over edge of scarp. Depth, 2,000 m; foreground width, 2 m. Top right: Lava tubes and "squeeze-ups." Note matching corrugations across spreading crack at axis of symmetry of tube at lower left-hand corner. Depth, 1,920 m; foreground width, 3 m. Middle left: Side view of nearly vertical pillow wall at crest of Puna Ridge. Outer end of pillow in center has broken off and fallen to base of wall. (see Fig. 9 for perspective). Depth, 1,860 m; foreground width, 1 m. Middle right: Newly rifted lava surface similar to those observed on dive 108. Depth, 1,890 m; foreground width, 2 m. Bottom left: Talus consisting of pillow-lava fragments located at base of pillow wall. Depth, 1,890 m; foreground width, 3 m. Bottom right: Collapsed surface of lava tunnel. Note lava shelf within hollow tunnel at far right center, which indicates temporary fossil stillstand of lava within lava tunnel network. Depth, 1,990 m; foreground width, 3 m.

Figure 9. *Sea Cliff* 70-mm bottom photographs. Top left: Lava tubes and pillows on crest of Puna Ridge. Note lack of interstitial sediment and absence of benthic organisms. Depth, 2,000 m; foreground width, 3 m. Top right: Lava pillows and tubes near crest of Puna Ridge. Note that middle right photograph shows close-up view of background in this photograph. Depth, 1,830 m; foreground width, 4 m. Middle left: Lava tubes on crest of Puna Ridge. Depth, 2,000 m; foreground width, 2 m. Middle right: Lava pillows and tubes and "squeeze-up" at crest of Puna Ridge. Depth, 1,830 m, foreground width, 3 m. Bottom left: Laza tube terrain near crest of Puna Ridge. Depth, 2,000 m; foreground width, 3 m. Bottom right: Recent submarine flow over pre-existing submarine volcanic terrain off Kona coast of Hawaii. Sinuous lava tube and digital pillows at terminus end of tube are resting on top of pahoehoe sheet flow with typical ropy structure formed by wrinkling of thin, once-plastic crust. Wrinkling of pahoehoe sheet (ropy structure) is totally different from corrugations on lava tubes in top right photo of Figure 8 and is not common in most submarine flows. Physical characteristics of ropy structure seem to indicate extremely rapid subaqueous extrusion rates (J. G. Moore, 1977, personal commun.; Lonsdale, 1977). Depth, 1,200 m; foreground width, 5 m.

of molten lava by the bottom waters (Strange and others, 1965). Furthermore, gravity traverses across the Marcus-Necker Ridge and Jasper Seamount, southwest of Hawaii, can best be interpreted with densities of 2.3 g/cm^3 for these features (Wollard, 1951; Worzel and Harrison, 1963; Malahoff and Woollard, 1971). This gravimetrically interpreted low density is in sharp contrast to the laboratory-determined densities of 2.8 g/cm^3 for rocks dredged from these areas.

Similarly, the gravity measurements over Hawaii are incompatible with the laboratory measurements of samples of the tholeiitic basalts that compose the bulk of the islands. In order to reach an agreement between the observed gravity field over Hawaii, which suggests that the island mass is isostatically compensated, regionally, and the calculated densities of the rocks that make up the island, the density of layer 2 as a whole must be lower (approximately 2.6 g/cm^3) than the observed average density of 2.8 g/cm^3 for the submarine volcanic extrusives.

CONCLUSIONS

Our in situ observations lead us to believe that these discrepancies between the geophysical and geological data are caused primarily by the presence of bulk voids in the volcanic mass. These voids could result from (1) the very irregular bottom morphology in submarine volcanic terrain which creates large interconnected water-filled networks between interflow surfaces and (2) by the presence of intraflow, water-filled spaces located inside smooth-surfaced lava tubes and tunnels. The in situ observations made during dives 108 and 115 confirm the presence of voids in the volcanic mass of the Puna Ridge.

The question of heat-flow variations and hydrothermal circulation over known loci of submarine volcanic activity has been the topic of several recent studies (Lister, 1972; Williams, and others, 1974; Sclater and others, 1974; Anderson and others, 1976). The principal problem that appears to exist is in calculating the effective permeability of submarine volcanic terrain, which in turn has a limiting effect on the volume of sea water that may be circulated hydrothermally. This hydrothermal circulation through submarine volcanic terrain would have the effect of reducing the apparent conductive heat flux through the crust. It is important to note that the instruments used to record temperature gradients in the ocean floor measure only conducted heat and not any heat transfer from convective processes that are 10 to 100 times more efficient (R. N. Anderson, 1977, personal commun.).

The implication of our observations to this problem is significant. The volumetrically large water-filled voids within and surrounding the volcanic forms are likely to give rise to a network of interconnecting channels that probably extend deep into the sea floor composed of submarine volcanic extrusious.

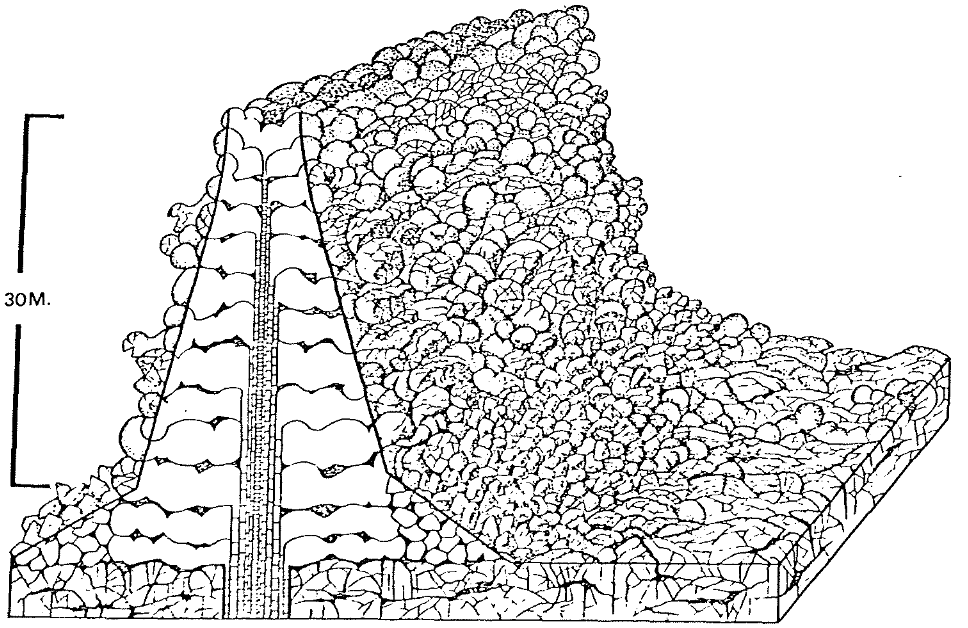


Figure 10. Composite drawing of a pillow wall rendered from assemblage of *Sea Cliff* 70-mm bottom photographs. Inferred internal structure of pillow wall has been shown in cross section, and it is assumed that pillow wall has been built over pre-existing submarine volcanic extrusive terrain (artist: Suzanne MacDonald).

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