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MORPHOLOGY AND STRUCTURE OF LOIHI SEAMOUNT BASED ON SEABEAM SONAR MAPPING

Daniel J. Fornari,¹ Michael O. Garcia,² Robert C. Tyce,³ and David G. Gallo⁴

Abstract. Loihi seamount has been mapped using Seabeam multibeam sonar, and the resulting data have been processed to produce bathymetric maps with a 10-m contour interval and shaded-relief perspective images. Analysis of morphological and structural data recorded in the maps and images indicates that constructional volcanism on Loihi has been localized predominantly along its southern and northern rift zones and that these rifts have been active since early in the seamount's history. The distinct asymmetry between Loihi's eastern and western slopes (the eastern slopes are steeper) is attributed to mass wasting of large sections of the volcano's west flank. Two large amphitheater valleys on the seamount's west flank are believed to have resulted from repeated mass-wasting events triggered by earthquakes associated with an early rift zone whose core now lies buried beneath the block feature present on Loihi's southwest flank. The prominent kink in the present south rift zone of Loihi may represent a fundamental readjustment of along-rift magma conduits that was caused by gravitational slumping on the southwest flank of the volcano. Lava cones and constructional volcanic ridges are present along the rims of summit pit craters and form a continuous chain of volcanic constructs around the periphery of the summit platform. The concentric arrangement of young eruptive vents on Loihi's summit may be caused by ring dikes. The morphology and structural interrelationships of pit craters on Loihi's summit suggest that the southeastern pit is the youngest. The formation of a summit platform on Loihi may have been caused by repeated collapse of pit craters and the southward migration of primary magma conduits that underlie the pits. This model predicts a north-to-

south age progression for volcanism on Loihi's summit.

Introduction

The Hawaiian-Emperor volcanic chain is a prominent physiographic feature of the North Pacific basin and comprises, from north to south, a linear chain of large seamounts, banks, and islands (Figure 1). The volcanoes which comprise the chain have grown in response to Pacific plate motion over a melting anomaly (hotspot) in the mantle whose position in the asthenosphere has remained nearly fixed [e.g., Morgan, 1971; McDougall, 1971; Jackson et al., 1980; Clague and Dalrymple, 1987]. The southeastern edge of the hotspot now lies to the south of the island of Hawaii, the southernmost island in the chain. Recent studies have suggested that Loihi seamount represents the most recent volcanic manifestation of the hotspot and the submarine core of the next island in the chain [Moore et al., 1982; Klein, 1982; Malahoff et al., 1982]. The seamount is positioned in the region where the submarine slopes of Mauna Loa and Kilauea merge, although the bulk of the volcano is probably built largely upon a Kilauean surface (Figure 1).

Recent interest in Loihi seamount is primarily the result of early seismic events monitored by the Hawaiian Volcano Observatory [Klein and Koyanagi, 1979; Klein, 1982] that resulted in the identification of Loihi as a seismically active undersea volcano having both shallow and deep focus earthquakes. Swarms of shallow (2-5 km) focus earthquakes were observed to be generally located near the summit of the volcano; however, activity was also recorded on its southern and southwestern flank. This pattern is similar to the sequential character of seismic activity between Kilauea volcano's summit and its east rift zone. Klein [1982] suggested that the fan-shaped distribution of shallow focus earthquakes on Loihi's southwest flank corresponds to extensive mass wasting and submarine-sliding events which are triggered by intrusion and rifting near the summit. Deep (20-62 km) focus events are fewer in number but clearly indicate that Loihi has its own magmatic plumbing system and is not a satellite vent of Kilauea. Furthermore, geochemical studies have shown that Loihi's lavas are chemically distinct from those of Kilauea and Mauna Loa [Staudigel et al., 1984].

Loihi was first mapped using conven-

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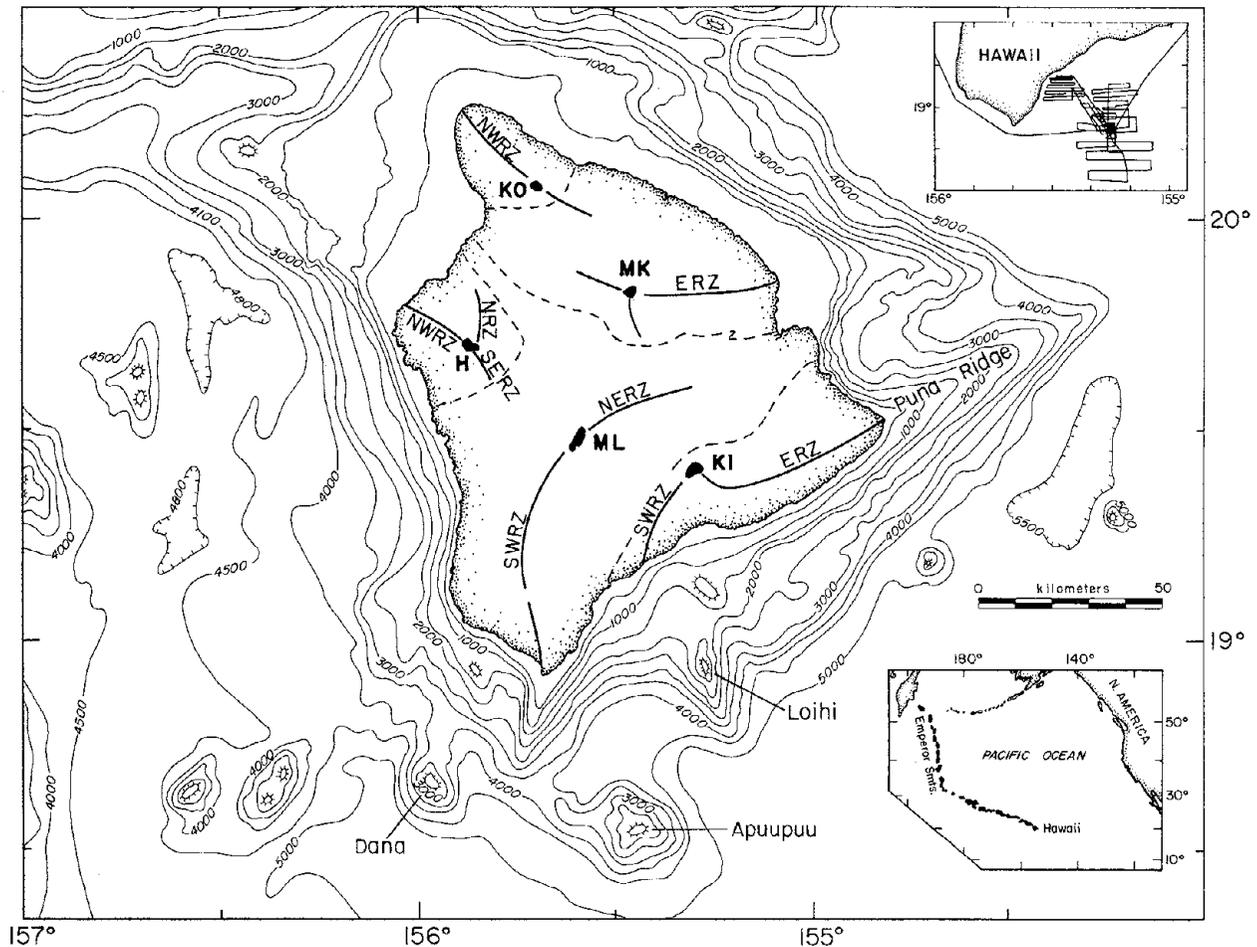


Fig. 1. Island of Hawaii and regional bathymetric contours in meters. Rift zones of subaerial volcanoes are shown by heavy lines, and boundaries between volcanoes shown as dashed lines. Summits and calderas of volcanoes shown by dark areas. Volcano symbols are: KI, Kilauea; ML, Mauna Loa; MK, Mauna Kea; H, Hualalai; KO, Kohala. Upper inset shows distribution of track lines for Seabeam survey of Loihi and SWRZ of Kilauea. Lower inset shows location of island of Hawaii at southern end of the Hawaiian-Emperor chain [from Clague and Dalrymple, 1987]. Note that seamounts south and west of Loihi are Cretaceous in age [e.g., Clague and Dalrymple, 1987].

tional echo sounding by Emery [1955] and has subsequently been remapped in more detail using conventional and Sonar Array Sounding System (SASS) multibeam echo sounding [Moore et al., 1982; Malahoff et al., 1982; Pryor et al., 1987] and more recently by Sea MARC II side-looking sonar [Fryer et al., 1987]. Sampling of Loihi by dredging and submersible [Moore et al., 1982; Garcia and Frey, 1987] has resulted in the recovery of a suite of alkalic rocks whose chemistry and presence have profoundly influenced current models of Hawaiian volcano petrologic evolution [e.g., Frey and Clague, 1983; Lanphere, 1983; Clague and Dalrymple, 1987; Garcia and Frey, 1987]. Further dredging, and deep sea camera tows on the summit and flanks of Loihi [Malahoff et al., 1982; Malahoff, 1987] revealed the presence of low temperature hydrothermal

deposits and vast fields of volcanic breccia on the upper flanks of the seamount. Recent *Alvin* and *Pisces V* submersible diving [Craig et al., 1987; McMurtry et al., 1987; Edmond et al., 1987; Karl et al., 1988] has allowed direct sampling of hydrothermal vents on Loihi's summit and resulted in the discovery of low-temperature (<30° C) fluids extremely enriched in CO₂, He, Fe and particulate adenine triphosphate (ATP).

The purpose of this study is to present the results of a detailed bathymetric survey of Loihi. The new maps (Figures 2 and 3) and perspective images of Loihi are used to define the major structural and physiographic features of the volcano. In our discussion of these data we have developed working hypotheses to explain the geomorphic evolution of this young volcano and the possible tem-

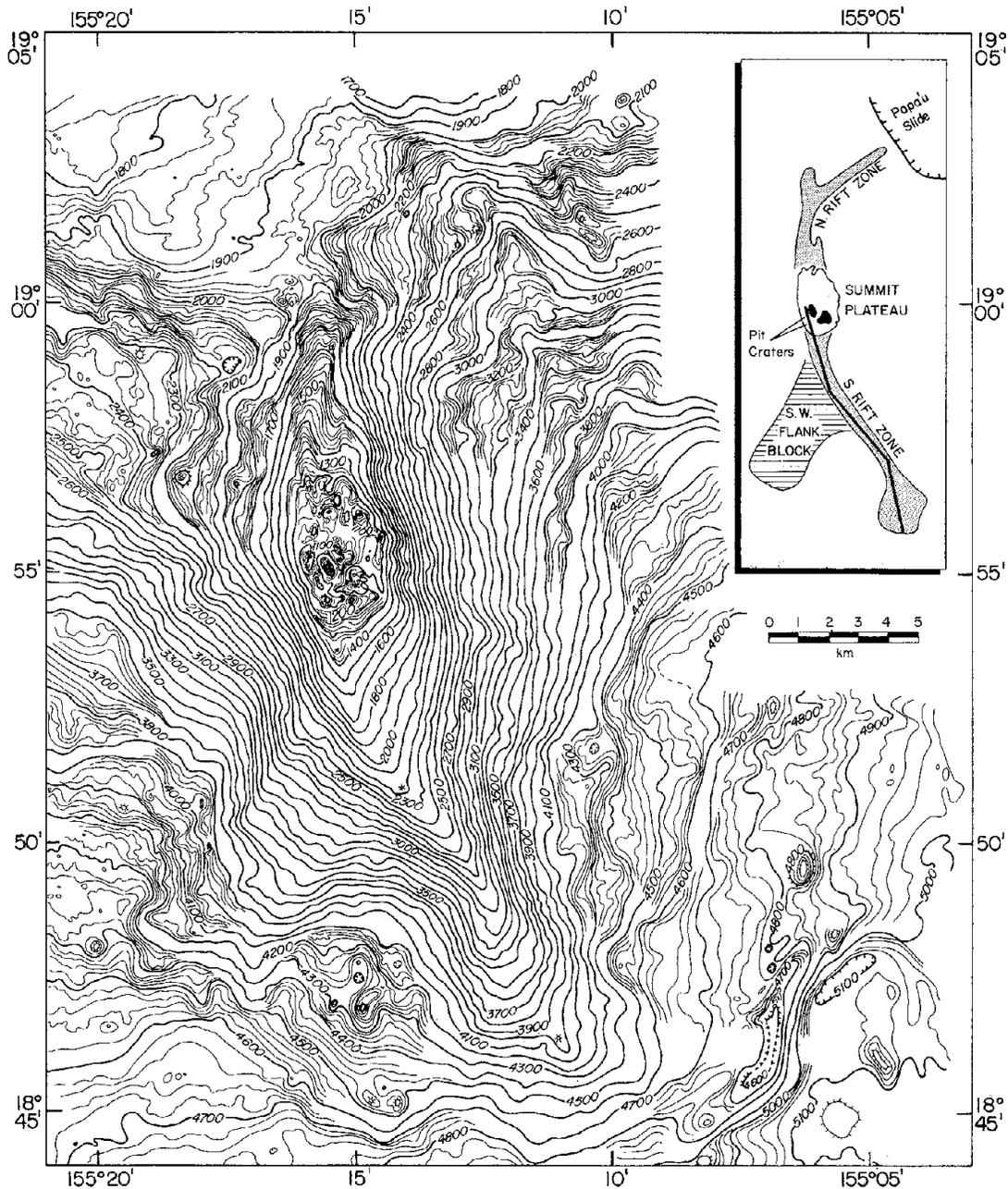


Fig. 2. Seabeam map of Loihi seamount. Heavy lines are corrected 100-m contours with 20-m contours shown where possible. Inset shows major morphologic features of the volcano that are discussed in the text.

poral and spatial relationships between magmatism, volcanism, and tectonism. The new data presented here are essential as a baseline for evaluating the nature of future volcanic and land-slide events on the volcano and for planning future Ocean Drilling Program investigations of Loihi.

Seabeam Survey

Navigation and Gridding Technique

The Seabeam [Renard and Allenou, 1979] multibeam sonar survey discussed here was

carried out as an ancillary study of an Alvin diving program that investigated Loihi's summit. Survey lines were mainly oriented east-west except for one line that followed the crest of the south rift zone from the summit to the base of the volcano (see Figure 1, upper inset).

Navigation for the survey utilized Global Positioning System (GPS) satellite positioning when available (approximately 8 h/d) and dead reckoning between transit satellite fixes otherwise. Navigational errors were corrected by comparing Seabeam topography at track crossings, using

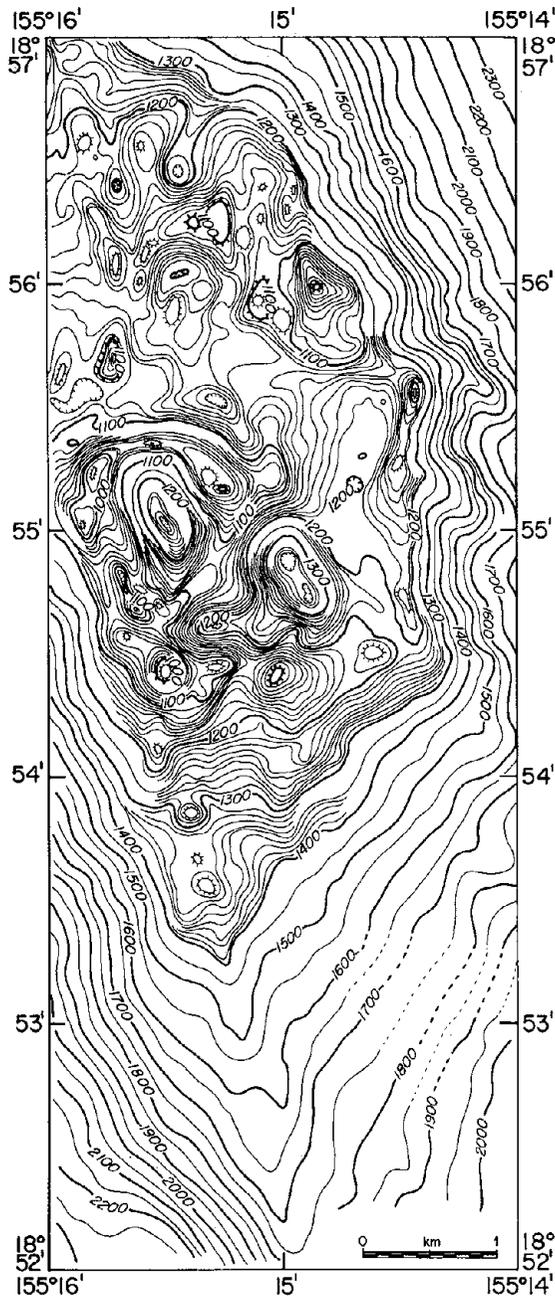


Fig. 3. Seabeam map of the summit of Loihi seamount. Heavy lines are corrected 100-m contours with 10-m contours shown on the summit platform. Thin contour lines below 1400 m depth are 50-m intervals. Note abundance of small to large volcanic cones around pit craters and along edge of summit platform. Note also the sharp truncation of contours at the southeastern end of the western pit.

the best east-west lines controlled by GPS, and a long line down the south rift zone for reference. Required corrections from original navigation did not exceed 200 m.

Seabeam coverage is 80-90% complete

over the survey area, with Seabeam returning topography for a swath that is 80% of the water depth. Since the data include both overlaps and gaps in coverage, gridding of the data into a regular latitude-longitude grid was required before perspective images and continuous contour maps could be generated. The gridding process in use at the University of Rhode Island utilizes techniques developed by T. Davis and W. E. Rankin of the Naval Oceanographic Office. The process first averages redundant data in a grid cell, then computes a regional grid spanning gaps using the minimum curvature approach of Swain [1976], and finally integrates actual data with the regional surface in the resulting data grid. This produces detailed texture where survey data exist, and a smooth surface where gaps occur in the data. The difference in textural detail can be seen in the color shaded-relief perspective images (Plates 1-3), which use the full 1-m depth resolution of Seabeam. (Plates 1-3 are shown here in black and white. The color versions can be found in the separate color section in this issue). These images were produced for arbitrary points of view on a Raster Technologies model 1/380 graphics system.

Seabeam Data

A new bathymetric map of Loihi has been made using Seabeam data and is shown at a 20-m contour interval in Figure 2. It shows that Loihi is elongate (33 km x 22 km) in a north-south direction and has a minimum depth of about 975 m (found on the arcuate constructional ridge that delimits the southwestern edge of the summit) (Figure 3). The maximum basal depth of approximately 5000 m occurs where the south rift zone merges with the abyssal Pacific basin floor. The eastern flank of the seamount is steeper than the western flank. There appears to be an inflection point in the flank slope profile at about 2700 m depth that separates the much steeper upper slopes (18° - 36°) from the lower flank slopes (13° - 16°) of the seamount.

Rift Zones

The seamount's shape is dominated by the two ridges that extend north and south from the summit area and which comprise the principal active rift zones of the volcano. The north rift is shorter, extends 11 km from the summit plateau, and plunges at an angle of 6° . Near the summit platform the north rift consists of two segments separated by a small trough that is about 0.5 km wide and 50 m deep (Figure 2). The eastern segment is shorter (2.6 km) and steeper (10°) than the western segment, and it merges into the seamount's north slope at a depth of 1600 m. Some of the larger lava cones on

the summit platform lie along sinuous north trending lineaments that connect with the eastern and western segments of the north rift. There is a distinct asymmetry between the east and west slopes of the north rift. The western slope is consistently between 14° and 15° while the eastern slope is steeper, varying between $>24^{\circ}$ near the summit and 18° midway down the rift.

The western segment of the north rift bifurcates 5 km north of the summit platform at about the 1700-m depth level (Plate 1). One section of the western segment continues north for 2.5 km, while the other section curves northeastward, possibly extending to the west side of the submarine canyon that forms the western margin of the Papa'u submarine slide [Fornari et al., 1979] (Plate 1).

The southern rift zone of Loihi is 19 km long and extends as a sharp-crested, southeast trending feature from the edge of the summit platform at 1100 m depth to 3200 m depth. At 3200 m depth the south rift zone crest becomes much broader, and it continues as such until 4800 m depth where it finally loses morphologic definition (Figure 2 and Plate 2). The crest of the south rift plunges 10° over its length, and the rift flanks have asymmetrical profiles. From the south edge of the summit plateau at 1200 m depth down to approximately 2000 m depth the west slopes of the south rift are steeper. However, along the middle and lower sections of the south rift the eastern slopes are consistently steeper (15° - 26°) than the western ones (11° - 20°). Near the summit, the crest of the south rift consists of a nearly linear chain of small (<200 m diameter) lava cones 10-60 m high. Below 1400 m depth, the Seabeam contours indicate only two 50-m-high closed-contour peaks, with summits at 2140 m and 3930 m, along the rift.

There are some flank or basal cones around the volcano (Figure 2). On the northwest flank of Loihi, three small cones 60-80 m high between 1700 and 2400 m depth form a crude northwest lineament. We are, however, uncertain whether this small lineament represents the surficial expression of a secondary northwest rift or if the cones represent isolated flank eruptions. We favor the latter explanation as there is very little suggestion in the 1200- to 1700-m depth contours (from the edge of the summit platform to the first cone) of a topographic rift zone. The 1800- to 2100-m depth contours, in the area between the cones, also do not show a continuous ridgelike structure that would be present if eruptions were repeatedly localized along a linear rift. There are also some small (<100 m relief) cones and lobe-shaped highs on the south flank of the volcano; no well-defined rift or ridge connects them, and some of these features may be toes of debris flows.

The lack of abundant (>2) rift zones on Loihi is typical of Hawaiian shield volcanoes. In contrast, guyots and seamounts in the western Pacific that are similar in size to Loihi commonly have three or more poorly developed flank rift zones that give each volcano a "starfish" shape in plan view [Vogt and Smoot, 1984]. The predominance of two rifts on Hawaiian volcanoes is probably related to their well-developed magmatic reservoir system and high supply rate [e.g., Ryan et al., 1981].

Summit Platform

The summit of the seamount has a surface area of approximately 12 km² above the 1200-m depth contour. The summit area consists of a platform that contains a variety of constructional volcanic features, principally around the perimeter, and several closed-contour depressions the most prominent of which are two well-defined pit craters (Figure 3). The western edge of the summit is formed by an arcuate chain of small cones 10-40 m high that extends north and south of the pit craters and merges with the crests of the north and south rift zones. The central portion of the chain consists of a 100-m to 120-m-high horseshoe-shaped ridge that nearly encircles the western pit crater. The summit of that arcuate ridge is dotted with small, 10-m to 20-m-high conical peaks which probably represent the most recently active volcanic vents that constructed the ridge. A traverse along this ridge was made using Alvin and the lavas observed all have fresh, sediment-free glassy surfaces and appear young.

The shallowest portion of the ridge is marked by a cone in the northwest corner of the summit plateau whose peak reaches just above 980 m depth. Another shallow cone on the southern margin of the plateau peaks at just above 990 m depth. It is the site of extensive, low-temperature hydrothermal activity (Pele's Vent) and was investigated by recent Alvin diving programs [e.g., Karl et al., 1988]. The eastern margin of the summit is also defined by the presence of an arcuate lineament of volcanic cones and ridges. The relief of these constructional features varies between 10 and 100 m; the largest one being a 100-m-high, 0.5-km², roughly elliptical cone on the northeast edge of the summit (Figure 3).

Loihi's pit craters are steep-walled and have slopes of 25° - 42° . They lie along a NW-SE trend with the eastern pit being the most southerly collapse feature on Loihi's summit platform. The western pit is 300 m deep; the eastern pit has up to 370 m of relief on its northwest side. The western pit is roughly elliptical in plan view and trends NNW, while the eastern one is slightly larger, also trends NNW, but has an E-W trending embayment on

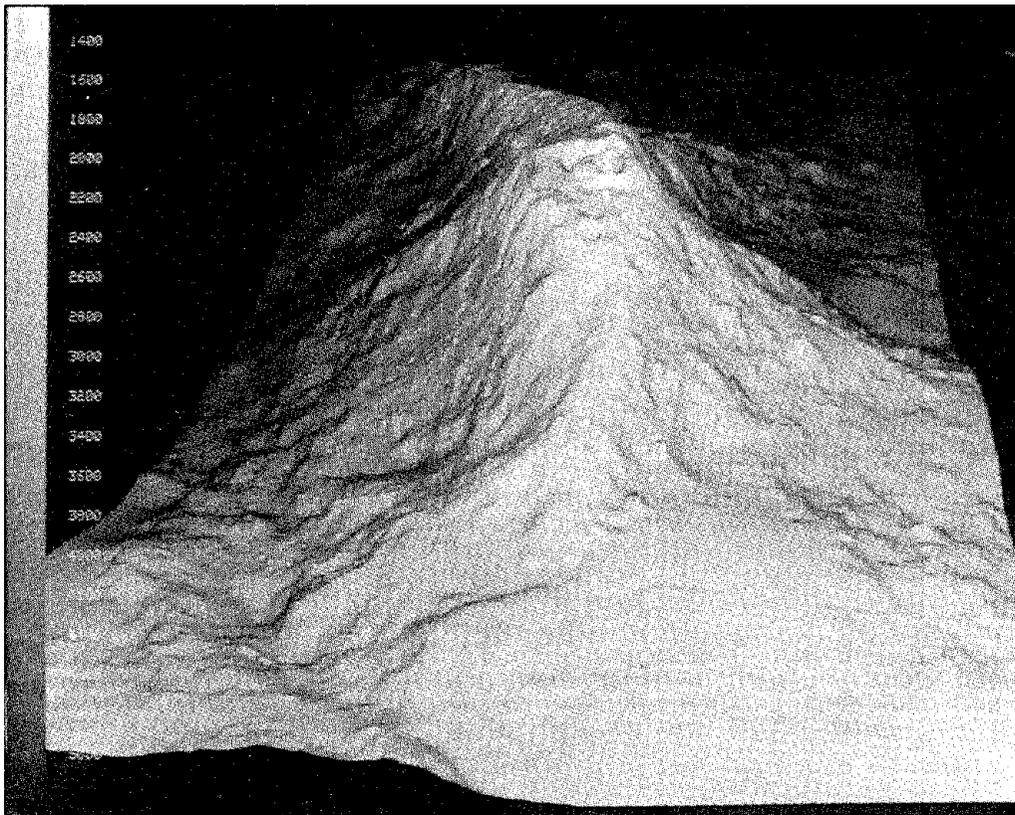


Plate 1. Three-dimensional perspective image of the summit and north rift zone of Loihi Seamount as viewed from the north looking south. (The color version and a complete description of this figure can be found in the separate color section in this issue.)

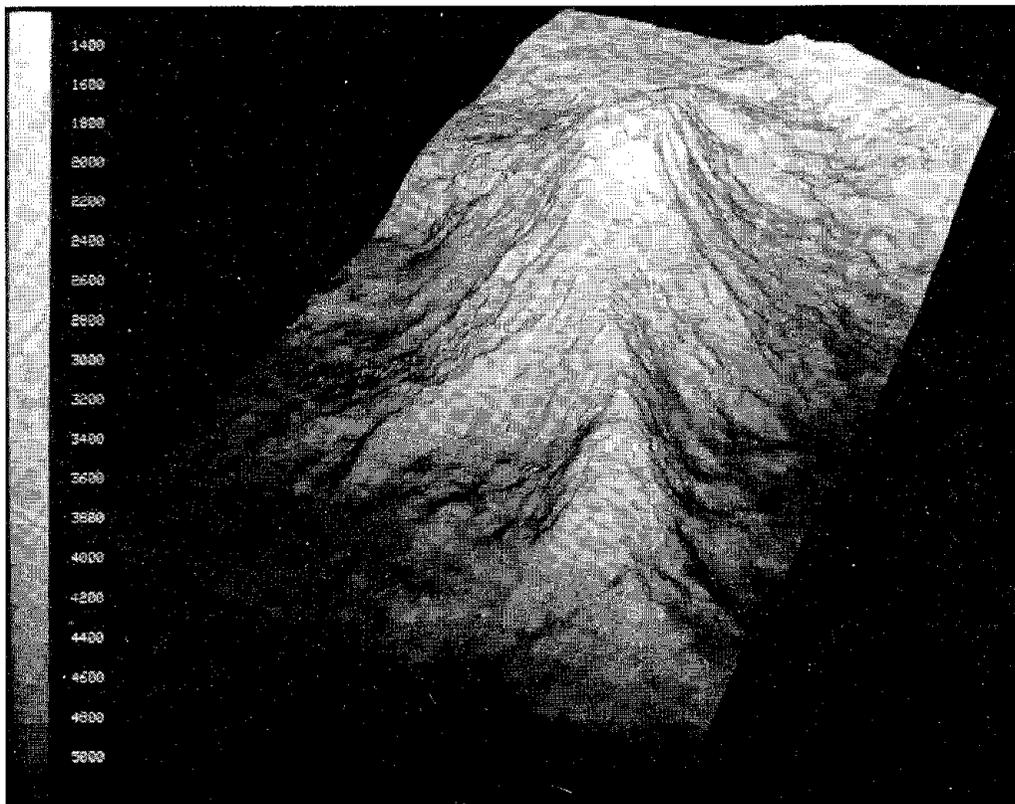


Plate 2. Three-dimensional perspective image of Loihi as viewed from high above the volcano from the southeast looking northwest. (The color version and a complete description of this figure can be found in the separate color section in this issue.)

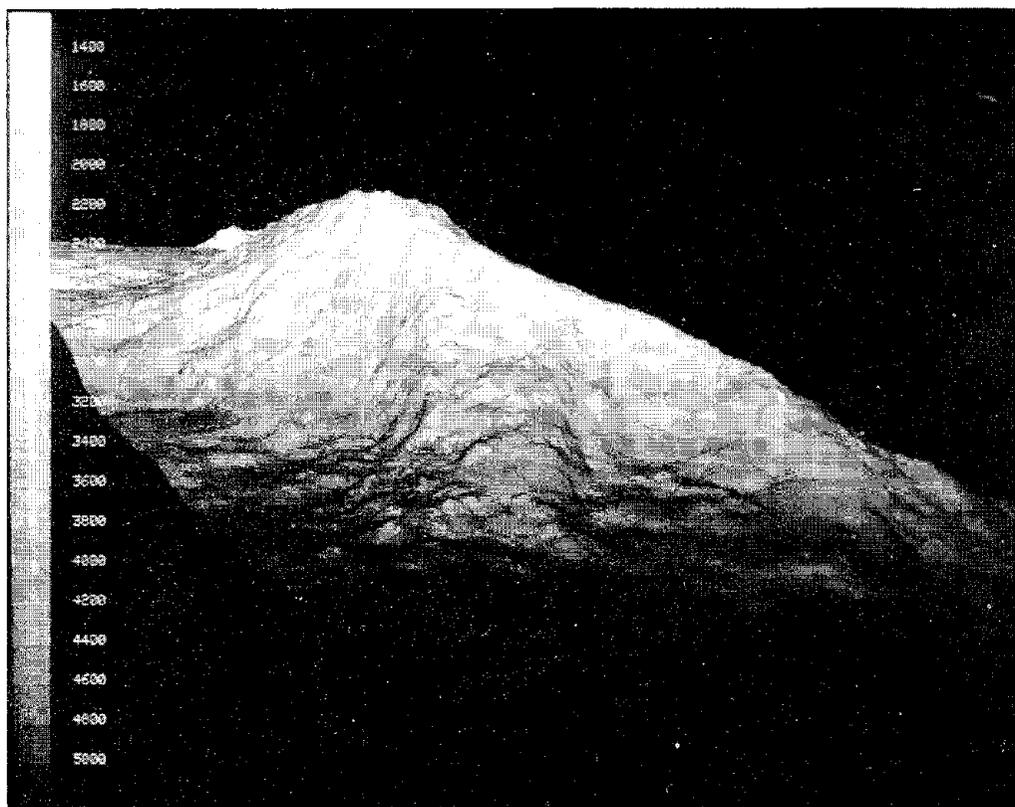


Plate 3. Three-dimensional perspective image of the western flank of Loihi looking directly northeast (from about the 3000-m-depth level) at the block feature on the volcano's southwest flank. (The color version and a complete description of this figure can be found in the separate color section in this issue.)

its west side that gives it a "nested" morphology (Figure 3).

It is important to note the rather sharp truncation of the southeastern end of the western pit. The trend of those contours defines a northeast lineament that includes the wall of the pit and the southern end of the arcuate ridge that borders the east side of the pit (Figure 3). This morphology suggests that the western pit may be older because collapse associated with the formation of the eastern pit appears to have modified the southern end of the western pit. This interpretation is supported by visual observations on *Alvin* dives which indicate a much greater extent of talus within the western pit than in the eastern pit.

West Flank

The western flank of Loihi is dominated by a large southwest trending block-shaped ridge that covers over 50 km² and extends from the 2200-m depth contour down to about 4400 m depth (Figure 2 and Plate 3). The block separates two large amphitheater-shaped valleys that incise Loihi's west flank and are believed to have formed by repeated mass wasting. The block has a crest that is 3 km wide and rather featureless

across slope. The crest plunges at an angle of 15° to the southwest over the length of the feature, while the northwestern and southeastern facing flanks have slopes of 24° and 20°, respectively. The overall morphology of this feature (Plate 3) is similar to that of gravitational slump blocks that occur on the unbuttressed flanks of other Hawaiian volcanoes [e.g., Lipman et al., 1988; Fornari and Campbell, 1987; Normark et al., 1979].

While the surficial morphology of the block suggests that its face and upper sections have been modified by gravitational slumping, the northwest flank of the block is steep and linear and may be structurally controlled. In contrast, the SW flank of the block is less steep, merges more gradually with the adjacent slope, and has a rounded morphology. The strong inferred structural control on the block can be seen in the sharp bending of depth contours along the NW flank of the block from 4300 to 2300 m depth. The points at which each of the contours in that depth range curves north to NNE form a NE trending lineament (Figure 2). The fact that the block stands out between two prominent valleys on Loihi's west flank also suggests that the internal structure of the block may have been more

resistant to large-scale erosion events. The block may be underlain by a dike complex that has made it more resistant to mass wasting.

The irregular, bumpy topography at the foot of the block and the prominent steplike features present on its face from the 3500-m depth contour to the base (Plate 3) are suggestive of seafloor morphology created by submarine sliding and gravitational slumping. We see little evidence in the Seabeam data of recent constructional volcanism on or surrounding the block. In fact, the only large, apparently constructional lineament near Loihi that trends NNE is the 6-km-long, 300- to 400-m-high ridge (crest just above 4600 m depth) that lies east of the foot of the south rift (Figure 2).

Discussion

On the basis of the morphology and structure of Loihi as portrayed by the Seabeam data it is apparent that constructional volcanism on the seamount has been dominated by eruptions along the rift zones and that the rifts have been active since very early in Loihi's volcanic history. We contend that if Loihi had been built by centrally focused magmatic conduits, with rift zones developing only recently, the volcano would be much more circular and the rift zones would appear as "starfish"-like appendages on the main edifice [see Vogt and Smoot, 1984]. The analogy may be drawn with seamounts that develop along or near the mid-ocean ridge (MOR) crest which usually do not have well-defined rift zones and whose shapes often resemble near-perfect cones or frustums. The roundness (in plan view) and lack of rift zones in seamounts near MORs has been attributed to summit-controlled eruptive history throughout the life of the volcano [e.g., Fornari et al., 1984]. Consequently, we conclude that Loihi's pronounced N-S elongation indicates long-term magmatic and volcanic activity along its rift zones. Using Loihi as a model of a very young Hawaiian volcano, we suggest that rift zones develop very early in Hawaiian shield evolution.

The different lengths, morphology, and structural character of Loihi's rifts suggest important differences in their evolution. The double ridge character of the north rift zone may be a structural response to either (1) the lateral migration of magmatic feeders during Loihi's recent volcanic history, or (2) the graben collapse of the axial region of the upper north rift.

The short length of the north rift's eastern segment could be due to the younger age of this feature or may result from the curving of the western segment across the rift tip creating a structural barrier to further propagation. It is not possible at present to distinguish

between these two hypotheses. Further investigation by submersible of Loihi's north rift, in situ sampling of rocks and comparison of lava freshness and sediment cover between the eastern and western segments of the north rift should provide data to resolve the origin of this unusual feature.

The curvature of the western segment of Loihi's north rift is generally parallel to the trends of the northern portions of Kilauea and Mauna Loa's southwest rift zones (SWRZ) (Figure 1). Interestingly, the distances separating these rifts is 30-35 km, which is also the distance between Kilauea's SWRZ and the curve in Loihi's north rift, and the approximate spacing between adjacent rift zones of many Hawaiian volcanoes. The spacing between the summits of adjacent volcanoes in Hawaii is 40-50 km.

The dike complex of Loihi's north rift is clearly within the shallow internal structure of Kilauea's south flank. The internal structure of Kilauea's south flank is likely to be a sequence of interfingering submarine and subaerial flows separated by volcaniclastic wedges, the whole of which is cut by generally E-W trending normal faults (downthrown to the south) of the Hilina fault system [e.g., Moore and Fiske, 1969; Peterson and Moore, 1987]. A rift may propagate through the distal portions of this volcanic pile relatively easily, as seen by the straight segment of Loihi's north rift. However, the deeper the rift cuts into Kilauea's flank the greater the internal forces (e.g., overburden pressure and gravitational stresses) acting against rift propagation.

We therefore suggest that the 30-35 km distance between Loihi's curving north rift and the bend in Kilauea's SWRZ may reflect an approximate threshold at which a juvenile rift growing next to a large shield volcano starts to structurally respond to the increasing difficulty in propagating through the flank of an adjacent edifice. One response to this structural setting could be a change in rift orientation. We also note that because Loihi's north rift curves eastward, this implies the presence of a structural barrier north and west of the seamount. We suggest that the presence of Mauna Loa and Kilauea's southern flanks, and Kilauea's SWRZ north and west of Loihi has had a controlling effect on the eastern curvature of the north rift. This structural response confirms the predictions of Fiske and Jackson [1972] regarding orientation and growth of Hawaiian rift zones.

The perspective images shown in Plates 2 and 3 suggest that there may be an interactive relationship between Loihi's south rift zone and the southwest flank block. While the overall trend of Loihi's south rift is generally southeast, the rift is sinuous and can be mapped as

three linear segments each about 6 km long and trending 165°, 140°, and 168°, from north to south along the rift (Figure 2, inset). The central segment starts at about 1900 m depth (slightly shallower than the top of the block feature) and ends at 3000 m depth. The prominent southern bend in the south rift zone at a latitude of about 18° 48.5'N marks the start of the third segment of the rift. This latitude is nearly coincident with the base of the block and is the point at which the spacing of depth contours at the foot of the block widens. South of this latitude the width of the crest of the south rift zone widens from <0.5 km to 2.0 km (Figure 5). The widening of the crest of Loihi's south rift may be a structural response to the decreased buttressing effect that the block feature has on the lower portion of the south rift zone.

The southwest flank block lies between two prominent embayments in Loihi's western flank. The most probable explanation for the presence of these large, amphitheaterlike valleys is that they have been created by large-scale mass wasting. Large-scale mass wasting of unbuttressed volcanic slopes has been found to be common on the submarine flanks of many Hawaiian volcanoes [e.g., Fornari and Campbell, 1987; Lipman et al., 1988]. While it is difficult to unequivocally attribute these features to mass wasting solely based on the Seabeam data we do note the presence of hummocky terrain and lobate features at the base of each valley that may represent lobes of volcanic debris deposited by slides. The most recent evidence of this process is reflected in small mounds between the 4100-m and 4500-m contour range that could represent debris lobe ridges with relief of <100 m (Figure 2 and Plate 2). In addition, photographs of the seafloor terrain on the upper flanks of the volcano show large areas of talus with virtually no intact extrusive forms or outcropping constructional features [Malahoff et al., 1982; Malahoff, 1987]. Side-looking sonar data and sediment cores from Loihi's western flank are required to confirm the origin of these large valleys.

Curiously, there is no evidence for large slump-related valleys on Loihi's eastern flank which, given its relative orientation with respect to Kilauea and Mauna Loa, is Loihi's least buttressed flank and should be most prone to mass wasting. We suggest that this may be related to a fundamental difference in the structure of Loihi's eastern and western flanks. The resistance of the southwest flank block to mass wasting suggests that the block may be underlain by a poorly developed rift that was active during the early stages of Loihi's growth. The rift zone core could have provided a buttress that delimited a zone of resistance to mass-wasting, while

earthquakes generated by magmatic activity along the rift could have provided the impetus for mass-wasting events on either side of the block. The steepness of Loihi's eastern slope and its lack of large-scale erosional features, despite its unbuttressed nature, suggest that seismic events on that flank were not of sufficient magnitude, or did not occur frequently enough to severely disrupt the slope.

A detailed shipboard magnetometer survey, that includes closely spaced lines oriented NW-SE, over Loihi's southwest flank would certainly be able to resolve the anomaly (probably >200-300 nT) caused by a rift zone core, if one exists within the southwest flank block of Loihi.

Despite the predominance of volcanic construction along Loihi's rift zones we still see abundant evidence for extensive volcanic activity on the summit platform. This recent activity is exemplified by the arcuate constructional ridges along the southwestern and northeastern margins of the summit (Figure 3 and Plate 1) and Alvin dive observations and photographic evidence which show fresh lava surfaces [Malahoff, 1987; M. Garcia, unpublished data, 1987]. If one connects all the young volcanic cones along the margin of the summit plateau, the line would form an oval that encircles the pit craters. The circumferential arrangement of recent volcanic vents may indicate the formation of ring dikes at the summit of Loihi (e.g., Deception Island, [Walker, 1984]). This is especially true of the vent ridge that nearly encircles the western pit.

The two pit craters and several other closed-contour depressions on Loihi's summit (Figure 3) are similar in diameter and shape to the larger pit craters along Kilauea's east rift zone (ERZ) [Macdonald et al., 1983]. Loihi's pits are, however, notably deeper (≥ 300 m) than even the deepest pit along the ERZ (Makaeopuhi crater, 130-150 m deep). The northernmost closed-contour depression on the summit lies along latitude 18°56'N and is bordered to the north by an arcuate chain of small cones and flanked to the east by a large 100-m-high cone. This feature may be an old pit crater; it is now partly filled by sediment and talus (A. Malahoff, unpublished data, 1988). The presence of the possibly older pit to the north, inferred younger age of the eastern pit (which is also the southernmost collapse feature on the summit), and the greater relief and hydrothermal activity on volcanic cones and ridges in the southern portion of the summit suggest a possible southerly shift in the locus of primary volcanic activity on Loihi's summit through time.

The summit of Loihi appears to be truncated above the 1200-m contour level, however, this 12-km² plateau is unlikely to have been created by erosion. Rather,

repeated collapse of Loihi's summit and possible subsidence caused by high-density cumulates in the summit reservoir [Walker, 1988] may have contributed to the formation of a summit platform. Evidence of recent collapse can be seen in the modern platform which has two large pit craters and one smaller crater. The summit platform of Loihi has most likely been an area of repeated collapse as magma is withdrawn from the summit reservoir to feed the rift zones. A 15-m-thick section of columnar jointed lavas, observed from Alvin in the west wall of the western pit crater, was probably formed in an earlier pit crater whose internal structure is now exposed in the wall of the modern pit. Thus the summit of Loihi and the summits of Kilauea and Mauna Loa volcanoes are sites of repeated collapse and subsidence as well as areas of volcanic construction [Walker, 1988].

Conclusions

The present size and shape of Loihi seamount are principally controlled by eruptions from its rift zones. At present, the most active hydrothermal venting and some of the shallowest volcanic constructional features are present along the upper south rift zone. Loihi's pit craters are not centrally located but are displaced to the southern half of the summit platform. A possibly older pit lies north of them and crosscutting relationships between the two most recently formed pits suggest that the southeastern one is the youngest. These structural and morphological observations lead us to suggest that primary magma conduits may have moved southward during Loihi's growth.

The two large valleys on Loihi's west flank are interpreted to have resulted from repeated mass wasting. The large block feature on the southwest flank of the volcano that separates the valleys has resisted mass wasting, and we suggest that its internal structure may contain a dike complex associated with an early rift zone. Seismic activity associated with magmatism along the rift could have initiated the mass-wasting events that formed the flanking valleys. This suggests a fundamental structural difference between Loihi's eastern and western slopes and may explain why no large slump features are present on Loihi's east flank despite its steep slopes and unbuttressed character.

The pronounced kink in the trend of Loihi's south rift and the coincidence of this change in rift orientation with the adjacent block feature lead us to suggest that the lower portion of the seamount's south rift has migrated east through time. The increase in crestal width of the lower section of the south rift suggests that the block on Loihi's southwest flank may have acted as a buttress,

confining dike emplacement along the south rift to a very narrow zone beneath the crest from 1100 m down to 3200 m depth.

The proposed installation of an array of seafloor sensors on the summit and upper flanks of Loihi (F. Dunnibier, personal communication, 1987) and the drilling of Ocean Drilling Program boreholes into Loihi's summit will permit long-term monitoring of seismic, volcanic, and hydrothermal activity on the seamount. This should lead to a better understanding of the relationships between seismicity beneath Loihi and that associated with Kilauea and Mauna Loa. The new data will also aid in the development of magmatic and hydrothermal models that describe volcanic cyclicality on a young Hawaiian submarine volcano. These and other field studies of Loihi, which focus their efforts on some of the enigmatic features discussed here, will undoubtedly test and refine our models for the geomorphic evolution of Loihi.

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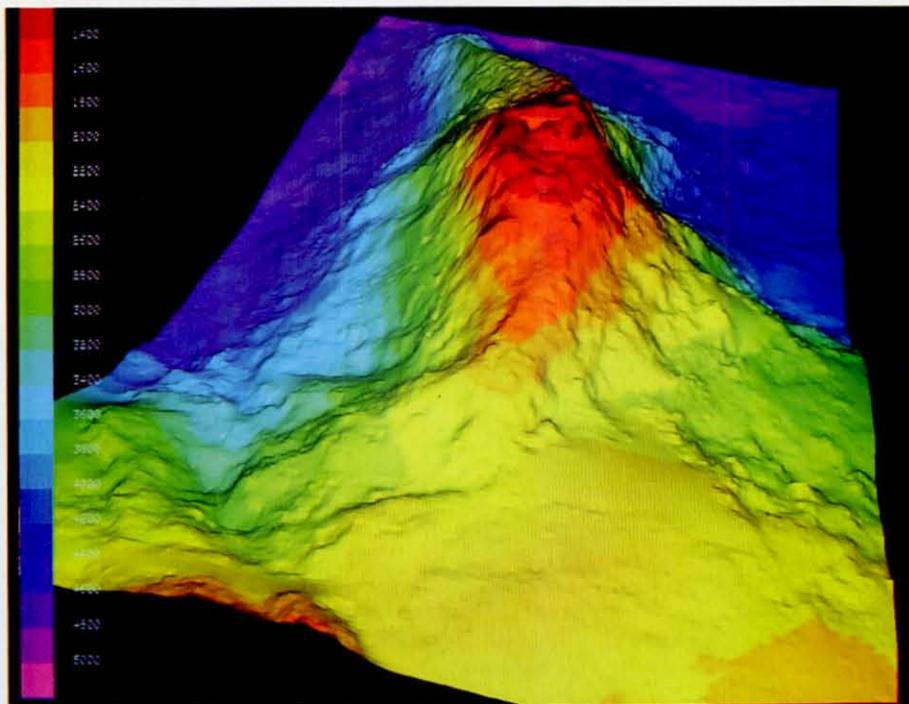


Plate 1 [Fornari et al.]. Three-dimensional perspective image of the summit and north rift zone of Loihi seamount as viewed from the north, looking south. Note the double character of the north rift and the sweeping curve of the western prong of the north rift that continues to the canyon that separates Loihi's northeast flank from the Papa'U slide lobe. Grid spacing is 150 m; viewpoint is from a level above the volcano's summit, and the grid surface has been tilted toward the viewer. Vertical exaggeration 2.5x. North is to lower left, along the edge of the image. Color scale on each image shown in Plates 1-3 shows depths in corrected meters.

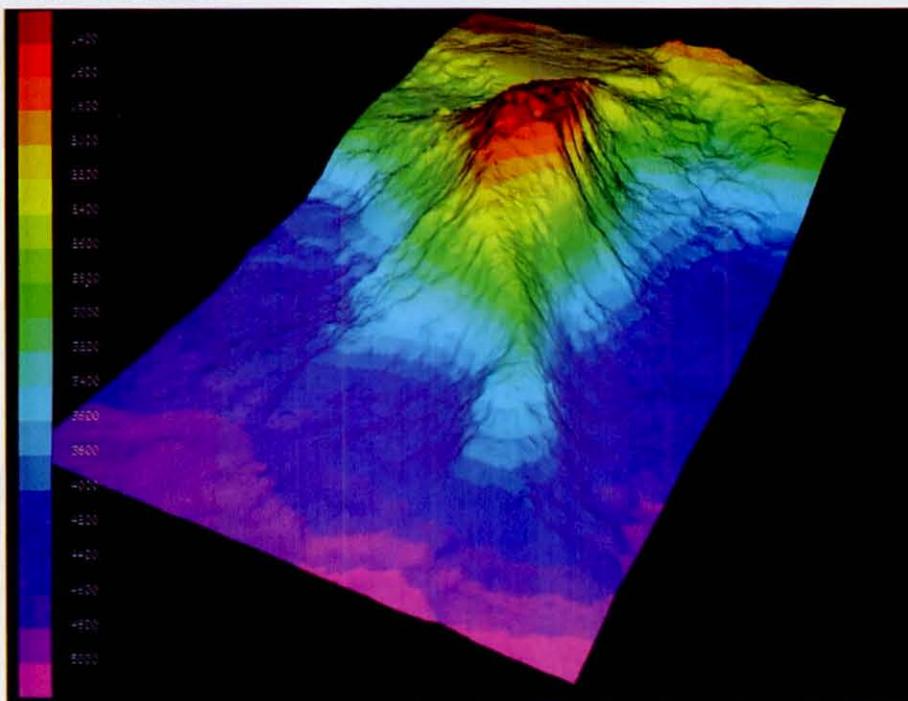


Plate 2 [Fornari et al.]. Three-dimensional perspective image of Loihi as viewed from high above the volcano from the southeast, looking northwest. Note prominent kink in the crest of the south rift zone in the area adjacent to the block feature on the southwest flank of the volcano. Note also the widening of the crest of the south rift zone and the coincidence of this change in morphology with the base of the adjacent SW flank block. See text for discussion. Grid spacing is 150 m; vertical exaggeration 2.5x. North is to upper right, along the edge of the image.

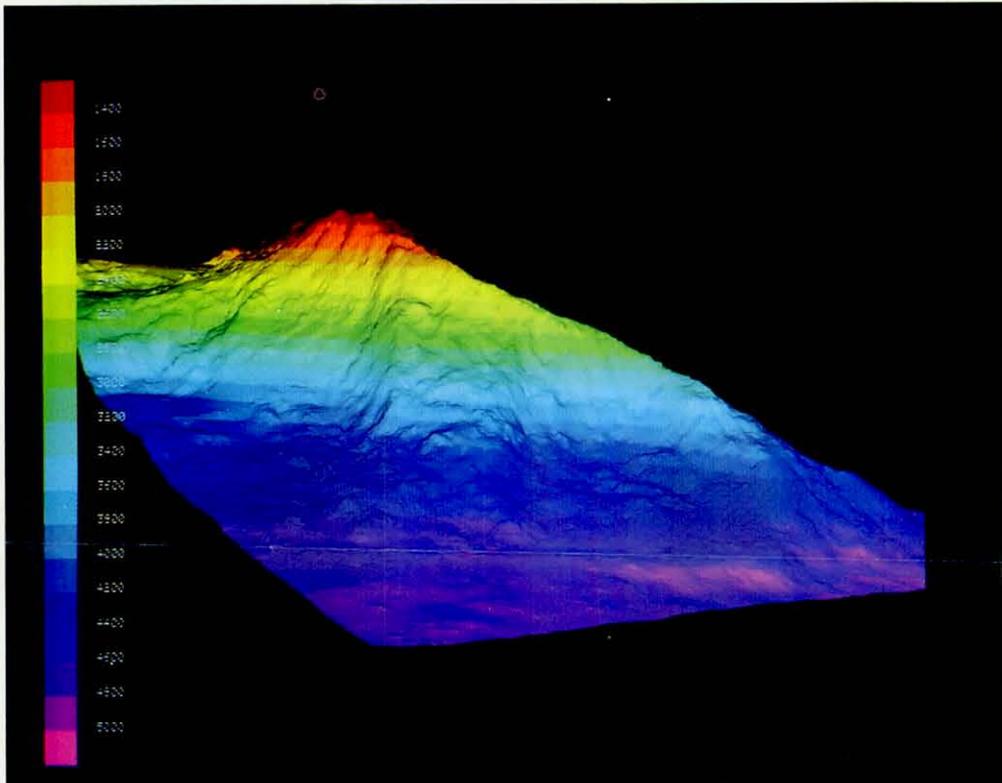


Plate 3 [Fornari et al.]. Three-dimensional perspective image of the western flank of Loihi looking directly northeast (from about the 3000-m depth level) at the block feature on the volcano's southwest flank. Hummocky topography and low-relief hills at the foot of the block feature and at the base of the valley between the block and the south rift are probably toes of sediment slides caused by mass wasting of Loihi southwest flank. Note the uneven, stair-step character of the face of the block that suggests repeated gravitational slumping. Grid spacing is 150 m; and vertical exaggeration 2.5x. North is to upper left, along the edge of the image.



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