THE GEOMORPHIC AND STRUCTURAL DEVELOPMENT OF HAWAIIAN SUBMARINE RIFT ZONES

By Daniel J. Fornari[1]

ABSTRACT

The structure and morphology of Hawaiian submarine rift zones reflect the time-integrated effects of constructional volcanic processes, island subsidence, destructive gravitational slumping of unbuttressed volcano sides, and reef buildup and sedimentation. Structural modification of submarine rift flanks begins during initial stages of eruptive history and reaches a maximum during the shield-building stage. This process is exemplified by faults on the south submarine flank of Kilauea's east rift zone, debris slides like the Papau slide on the south flank of Hawaii, and large gravitational slump features, like the Kauna and Alika slides, on the southwest flank of Mauna Loa. The submarine northwest rift of Hualalai and Mauna Kea's submarine east rift have morphological characteristics indicating that their structural evolution is largely complete. Further changes to these evolved submarine rift zones and to older Hawaiian submarine slopes will be caused principally by subsidence, burial beneath carbonate platforms and sediments, and erosion and redeposition of hemipelagic and volcanogenic sediments by rubble flows and debris slides that transport sediments down steep submarine slopes.

INTRODUCTION

The submarine slopes of three shield volcanoes on the Island of Hawaii have been investigated since 1974 using the U.S. Navy submersibles DSV *Turtle* and DSV *Sea Cliff* (Fornari and others, 1979a). The resulting data have increased our understanding of volcanic and morphologic features on the submarine slopes of Kilauea, Mauna Loa, and Hualalai Volcanoes, and have led to the development of basic models of oceanic-island structure using submarine flank terrains as modern analogs of past volcanic episodes and processes (Fornari and others, 1979a).

The east rift of Kilauea (known offshore as the Puna Ridge) (Fornari and others, 1978) and the southwest rift of Mauna Loa (figs. 5.1, 5.2; Fornari and others, 1979b) were studied previously using U.S. Navy submersibles. With the analysis of data from seven dives on the south flank of the northwest rift of Hualalai Volcano (Schwartz and Fornari, 1982) and additional dredge and surface-ship (remote sensing) studies (Campbell and Erlandson, 1981; Clague, 1982), it has been possible to compare the morphological and structural evolution of these submarine features. That comparison forms the focus of this paper; it is especially interesting because of the age difference among the three Hawaiian submarine rifts, Hualalai's being the oldest and Kilauea's the youngest.

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HAWAIIAN RIFT ZONES

SUBAERIAL PORTIONS

Hawaiian rift zones form swaths of tectonically disrupted terrain with rugged topography that consists of eruptive fissures, spatter ramparts and cones, and open cracks and collapse features (Stearns and Macdonald, 1946; Macdonald and Abbott, 1970; Lipman, 1980). The surficial expression of rift zone volcanism is usually a zone 3–4 km wide showing constructional and extensional features and normally coincident with a topographic ridge.

Geophysical anomalies (principally Bouguer gravity and magnetic anomalies) are useful in delineating the width of the intrusion zone, a steeply dipping plexus of dikes through which magma rises to the surface from shallow reservoirs located 2–6 km beneath the summit area (Swanson and others 1976; Ryan and others, 1981). Gravity and magnetic studies indicate that the intrusive dike complex beneath the narrow zone of surface rifting may be as wide as 12–17 km at depths of 3–4 km (Malahoff and Woollard, 1968; Broyles and others, 1979).

The positions of individual rift zones with respect to their volcanic centers and to neighboring volcanoes were investigated by Fiske and Jackson (1972) and in later field studies by Broyles and others (1979) and Lipman (1980a, b). Their conclusions are that

[1]Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

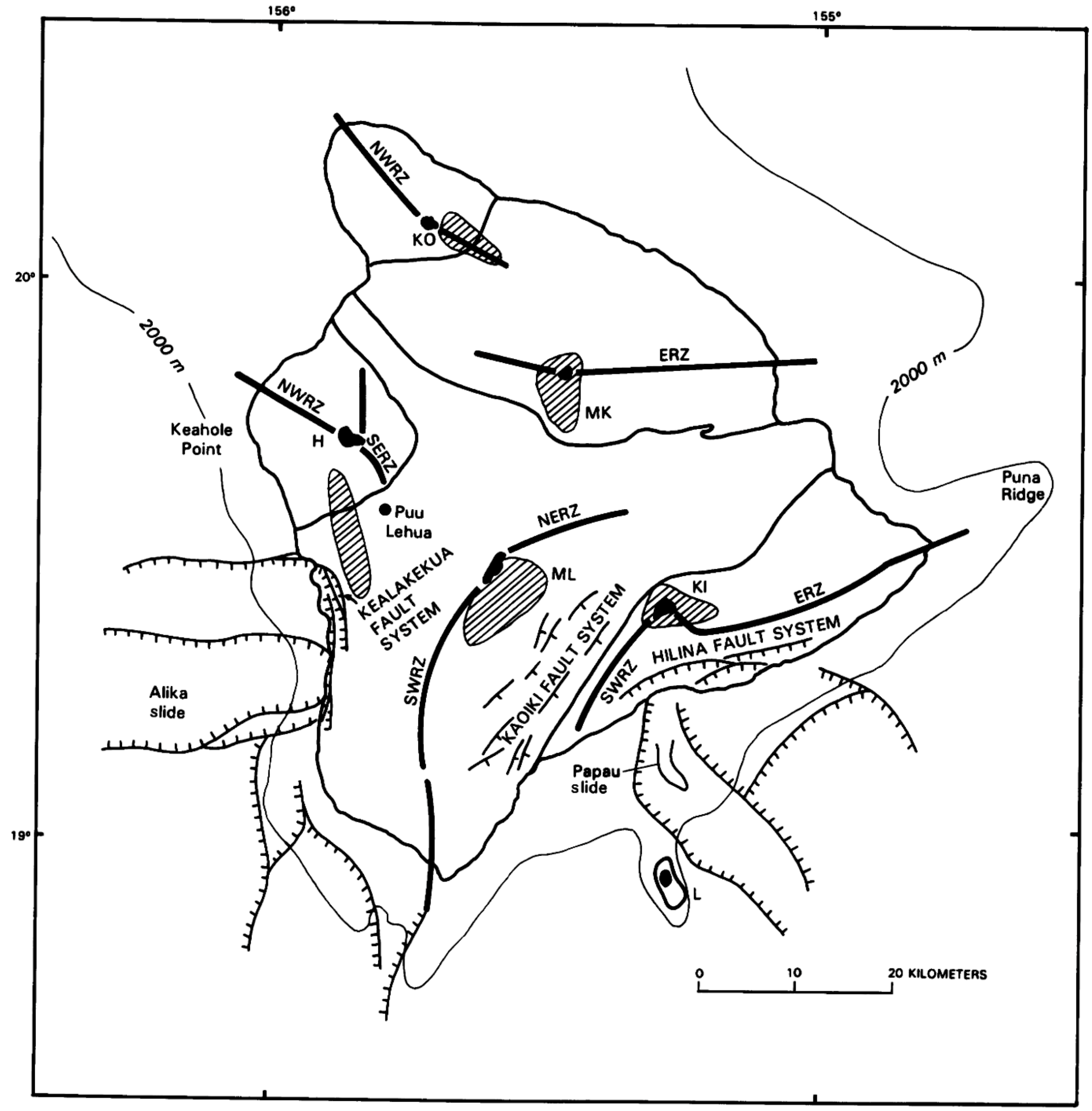

FIGURE 5.1.—Island of Hawaii showing boundaries between volcanoes, traces of rift zones, some fault systems,and areas of closed-contour Bouguer gravity highs (lined) from Kinoshita and others (1963). Volcanoes: KI, Kilauea; ML, Mauna Loa; H, Hualalai; MK, Mauna Kea; KO, Kohala; L, Loihi Seamount. Boundaries of submarine slump structures (ticks on downthrown side) are from Normark and others (1979). NWRZ, northwest rift zone; SWRZ, southwest rift zone; SERZ, southeast rift zone; ERZ, east rift zone; NERZ, northeast rift zone.

Hawaiian rift zones are shallow-level features whose locations are principally dictated by gravitational stresses within an edifice, but also indirectly by the shapes and positions of preexisting shields whose flanks have served as foundations for nascent volcanoes. As a result, the rifts vary in length; Kilauea's east rift zone and Mauna Loa's southwest rift zone are more than 100 km long including their submarine portions. Variation in rift-zone length may be attributed to the distribution of surrounding edifices that are large enough to inhibit or attenuate the development of a young rift zone. For example, Kilauea's southwest rift zone is sandwiched between Loihi

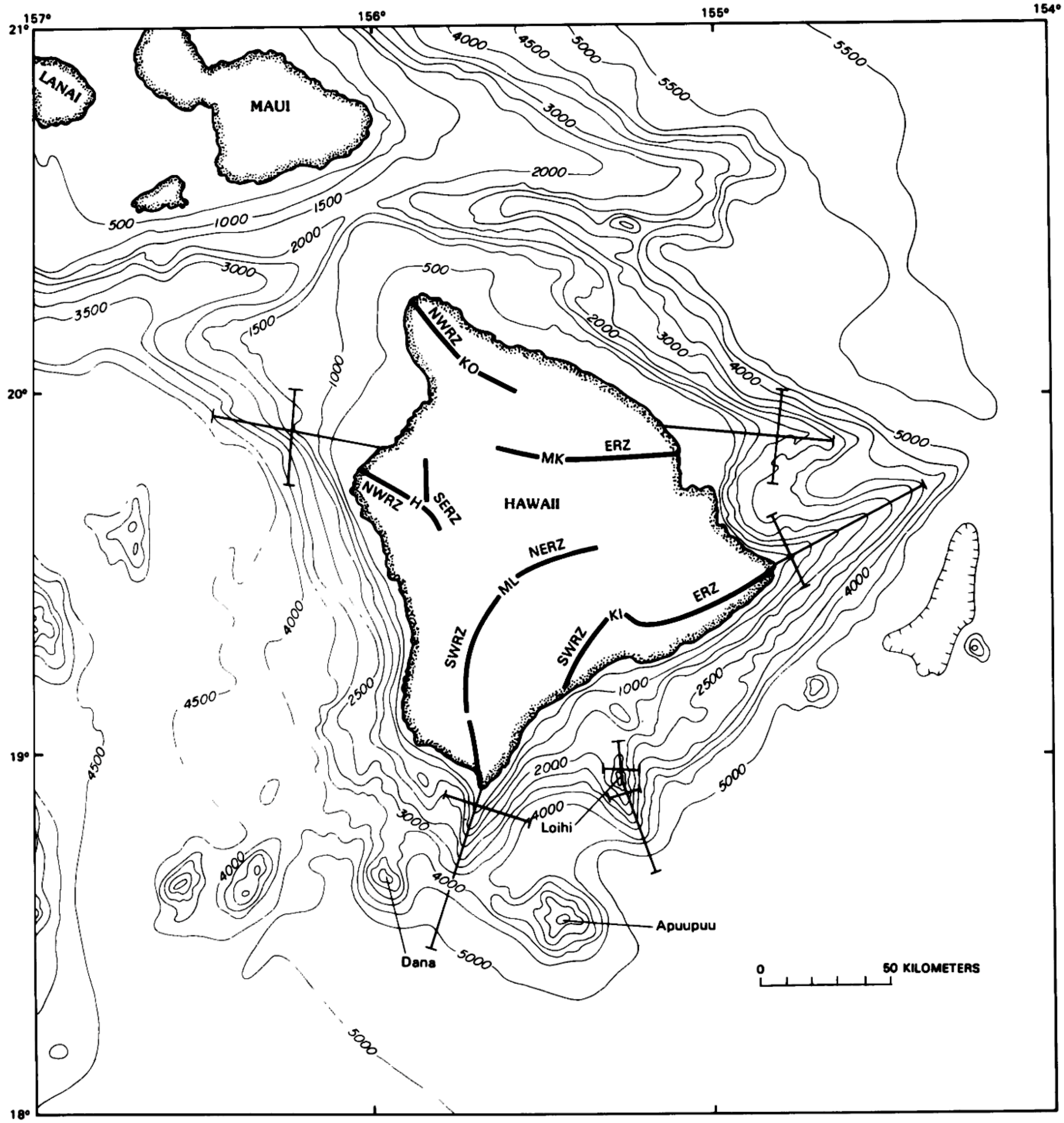

FIGURE 5.2.—Island of Hawaii showing 500-m submarine contours (from Wilde and others, 1980), traces of principal subaerial rift zones from each volcano, and locations of profiles shown in figures 5.3 and 5.4. Volcanoes: KI, Kilauea; ML, Mauna Loa; H, Hualalai; MK, Mauna Kea; KO, Kohala. NWRZ, northwest rift zone; SWRZ, southwest rift zone; SERZ, southeast rift zone; ERZ, east rift zone; NERZ, northeast rift zone.

Seamount to the south and Mauna Loa's southwest rift zone to the north and west, and its evolution and growth have thus been hindered. As a result, the southwest rift zone of Kilauea is rather short (~25 km, on land) and has no substantive morphologic expression on the sea floor south of Hawaii (see Fornari and Campbell, Chapter 4). Fiske and Jackson (1972) have pointed out that a basic understanding of the temporal and spatial growth of individual volcanoes within a composite shield can be achieved by studying the lengths and relative positions of each volcano's rift zones.

SUBMARINE PORTIONS

PUNA RIDGE

Surface ship studies (Malahoff and McCoy, 1967; Moore and Fiske, 1969) and submersible investigations (Fornari and others, 1978) have shown that Puna Ridge (the submarine continuation of Kilauea's east rift zone; figures 5.1, 5.2) consists of purely constructional volcanic terrain on its crest and upper flanks. This terrain is characterized by steep flow-front escarpments separated by constructional benches on the upper flanks and narrow, linear volcanic ridges (pillow walls) and subparallel tensional and eruptive fissures on the ridge crest. All these features strike N. 45° E., parallel to the trend of the ridge (Fornari and others, 1978). The flank and ridge-crest terrains differ significantly. At the ridge crest there is an almost total absence of sediment and a dominance of constructional volcanic features. The flank areas, in contrast, have progressively more sediment with increasing depth, extrusive features that appear slightly more weathered and older (glassy crusts on extrusive forms that are starting to devitrify and spall off), and more common evidence of contemporary faulting and disruption of the volcanic sea floor. On the southern flank of Puna Ridge, at depths shallower than about 500 m, there are southeast-dipping normal faults that appear to be continuations of fault-line scarps of the Hilina fault system (fig. 5.1; Malahoff and McCoy, 1967). The subaerial Hilina scarps represent headwalls of major landslide blocks (Swanson and others, 1976), and the shallow submarine scarps probably also reflect lateral, slump-block readjustment of the unbuttressed flank of Kilauea caused by magma injection and dilation.

The slumping and mass-wasting that affects Hawaii's south flank leads to a fault-block-like submarine topography having alternating linear highs and lows that generally trend in a northeast direction. One major result of the tectonic and erosional processes is the redeposition of large quantities of sediment on the lower south flank of Puna Ridge and on the island's submarine south flank. This sediment is augmented by coarse basaltic debris derived through wave erosion of lava flows along the south coast and by the downslope transport of this material by tidal currents and debris flows and slides such as the Papau slide (Moore and Fiske, 1969; Fornari and others, 1979c).

MAUNA LOA'S SOUTHWEST RIFT ZONE

The southwest rift zone of Mauna Loa (figs. 5.1, 5.2) has also been investigated by submersibles and by remote-sensing from surface ships. Geophysical data show the gross structure of the rift as a series of scarps with steep west-facing walls that have vertical relief of 100 m to nearly 2,000 m (Fornari and others, 1979b). The principal linear scarp continues out to sea for about 50 km, and its asymmetric and faulted morphology has been interpreted to be a result of gravitational slumping of the unbuttressed west flank of Mauna Loa (Fornari and Campbell, chapter 4; Fornari and others, 1979b; Normark and others, 1979; Lipman, 1980a). The face of this scarp was acsended on three submersible dives and found to be composed of pillow-lava sequences, exposed in steeply (60°–70°) sloping outcrops and surrounded by volcaniclastic sediment. Less steep benches (10°–30° slopes) separate the outcrops. The tops of the outcrops are often capped by vertical walls, 1–3 m wide and 10–60 m high, formed by exposed dikes that have been stripped of their surrounding volcanic cover (Fornari and others, 1979b, fig. 6). Mass wasting of scarps must be very active because the steeply sloping outcrops and vertical dikes are highly unstable and prone to collapse. During the dives, extensive evidence of undercutting and erosion was seen in the form of toppled dike walls and faceted blocks of diabase dike rock strewn around the sea floor at the base of the walls and on the sediment (Fornari and others, 1979b).

Geophysical records of the sea floor to the west of the main scarp (Fornari and others, 1979b, fig. 4) suggest that thick deposits of clastic sediment lie in structural fault-bounded basins created by gravitational slump tectonics. Farther offshore, along the southern part of Hawaii's west coast, similar large slump-block features (for example, the Kauna and Alika slides) have been recognized on bathymetric compilations and geophysical records (Fornari and Campbell, chapter 4; Normark and others, 1979).

HUALALAI'S NORTHWEST RIFT ZONE

The submarine extension of Hualalai's northwest rift zone (figs. 5.1, 5.2) has been previously studied using conventional echo sounding (Campbell and Erlandson, 1981), dredging (Clague, 1982), and submersible diving (Schwartz and Fornari, 1982). These studies revealed the gross bathymetric character of the rift, the morphology and structure of parts of the submarine slope, and also determined that the exposed volcanic rocks are largely tholeiite and picritic, tholeiitic pillow basalt. The geochemistry of these rocks indicate that they have probably been derived from mantle sources separate from those feeding the other volcanoes on Hawaii (Clague, 1982).

The northern submarine flank of the rift zone has a regional slope of 3°–7° (the Puna Ridge has an average slope of 10°; Moore, 1971) and rugged topography created by constructional volcanism operating principally on the crest and north flank of the rift (Campbell and Erlandson, 1981). The data of Campbell and Erlandson (1981) clearly show that volcanic flows coming from the north flank are ponded against the preexisting terrace topography of the Kohala shelf.

The south flank of the rift zone, as seen in profile C of Campbell and Erlandson (1981, fig. 4) and in unpublished profiles recorded by the Hawaii Institute of Geophysics, differs from the north flank in having a steeper regional slope (16°–26°) and smoother acoustic reflectivity with fewer hyperbolae.

The southeastern part of the rift zone's south flank forms the submarine slope west of Keahole Point (figs. 5.1, 5.2) and has been observed during three previously reported DSV *Turtle* dives (Fornari, 1982). This area has microtopographic relief of 1–3 m; however, at shallower depths (less than 300 m) the outcrops have relief of as much as 7 m. Much of this relief is created by the downslope ends or edges of subaerially derived lava flows. Average slope

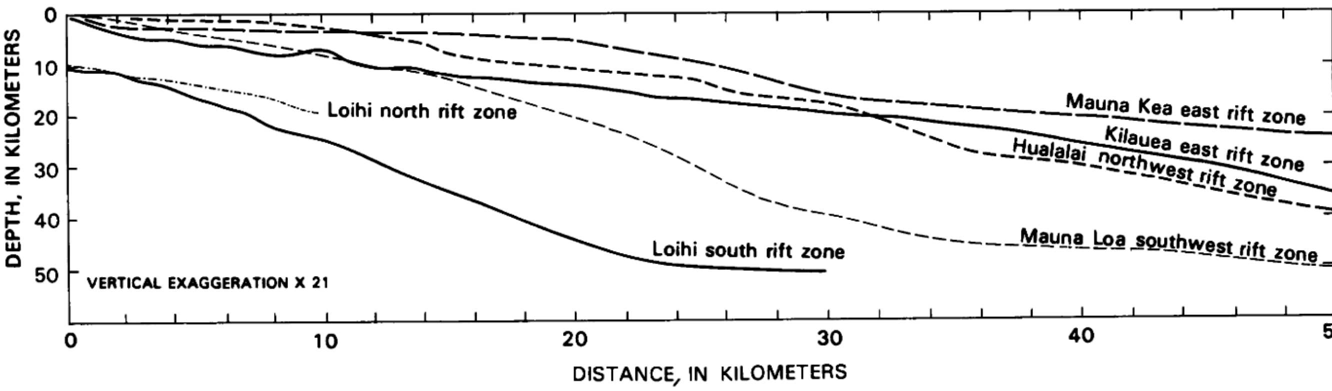

FIGURE 5.3.—Profiles of Hawaiian submarine rift zones taken along their strike. Drawn from published bathymetric maps (see references in text) and plotted following the axis of minimum depth of each rift. Data points were taken every 100 m of depth change. Horizontal distance is from the shoreline except for Loihi's rifts. Profile locations shown on figure 5.2.

angles for various segments of each dive traverse show that an abrupt increase in slope from approximately 15° to 27° occurs at about 750 m depth. This depth roughly conforms to the upslope onset of a ridge-and-gully terrain that is the principal sea-floor morphology in this area and apparently also occurs in similar depth ranges on other Hawaiian submarine slopes investigated with submersibles. The ridges and gullies are oriented parallel to the slope and usually have relief of 1–5 m (amplitude) and varied wavelengths. These features are likely to represent consequent topography developed over buried flow lobes (probably subaerial ones that have since subsided, although some may have originated from shallow submarine vents), which have subsequently served to channel tidal scouring in between the highs, thereby maintaining the troughs while sediment continued to accumulate on the low ridges.

This slope transition may be the result of basement faults, now largely buried, associated with earlier episodes of gravitational slumping of the west flank of Hualalai and its northwest rift zone. Only small fault scarps were observed during the submersible dives in this area, however, and those scarps are largely confined to depths below 1,000 m and have relief of 3–6 m. The scarp faces are smooth, in contrast to the rough, jagged flow fronts, and expose massive lava with occasional intercalations of carbonate, either as blocks or lenses several tens of centimeters thick (Fornari, 1982; Schwartz and Fornari, 1982). Alternatively, this slope change may reflect the general paleodepth to which subaerial flows were able to move. Historical subaerial flows (ranging in date from 1801 to 1950) that have flowed into the sea on the west flank of Hawaii have been mapped using a submersible, and they are known to have only reached depths of approximately 250 m (D.J. Fornari and M.R. Perfit, unpublished data).

Wide expanses of the sea floor in this area are covered by volcanic and carbonate clastic debris and sediment. These deposits bury most evidence of flow fronts and fault scarps; however, several southwest-facing ramps with 5–10 m of relief were traversed and are thought to have been formed by depositional draping over a preexisting basement structure. Much of the area examined during the dives between depths of 350 m and 1,000 m is covered by these clastic deposits. South of latitude 19° 48′ N. and below 1,500 m depth, the spacing between isobaths increases and the regional slope decreases to about 10° (fig. 5.2).

Extrapolation of dive observations, echo sounding, and bathymetric data indicate that the lower south flank of Hualalai's northwest rift zone is largely covered by volcanic and carbonate erosional debris and hemipelagic sediment. The net geomorphic effect has been to smooth and obscure nearly all of the constructional volcanic morphology through mass-wasting of flow fronts and scarp faces, resulting in deposition of talus and in downslope transport of erosional products. While indications of downslope movement of talus are present, no slump scars or discrete slump deposits were observed during the *Turtle* dives. The north flank of Hualalai's northwest rift zone, on the other hand, consists primarily of pillow lava and constructional volcanic topography that is variably covered by hemipelagic sediment.

DISCUSSION

Profiles drawn along the strike and across strike of several Hawaiian submarine rift zones are shown in figures 5.3 and 5.4, respectively. These profiles were constructed from 100-m bathymetric contour data (Chase and others, 1971; Moore, 1971; Wilde and others, 1980; Campbell and Erlandson, 1981; Malahoff and others, 1982; Moore and others, 1982). The differences between rift-zone profiles can largely be explained by age differences and differences in structural evolution. The profiles shown in figure 5.3 clearly show the differences in plunge angle as well as the localized effects of constructional volcanism along the crests of the youngest rifts (Puna Ridge and Loihi Seamount's north and south rifts).

The profile of Mauna Kea's east rift zone shows the effects of the carbonate reef buildup that has constructed a 20-km-wide shelf

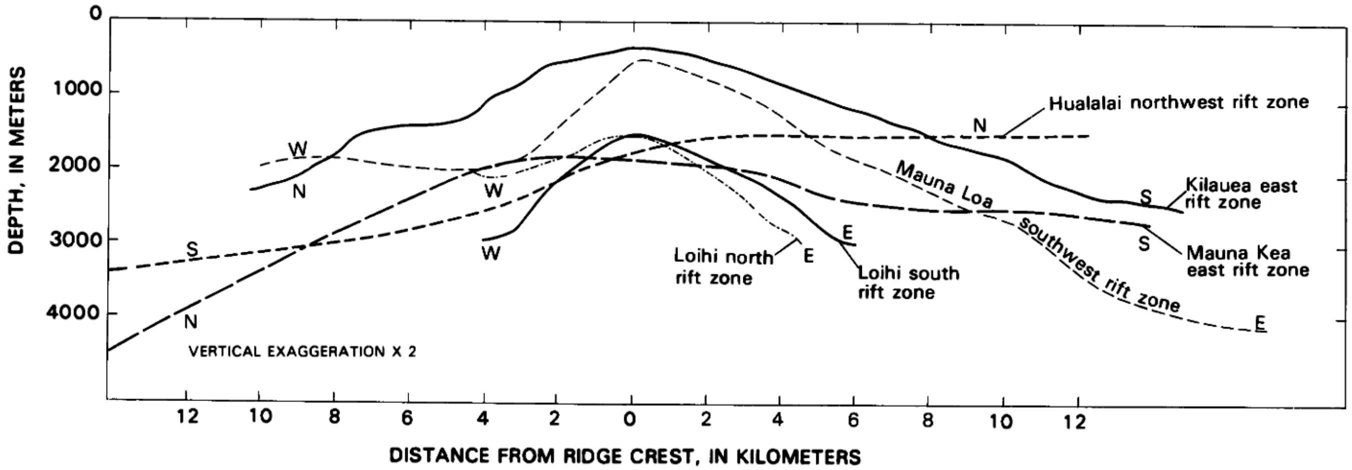

FIGURE 5.4.—Profiles of Hawaiian submarine rift zones taken across their strike. Drawn from same data set used in figure 5.3. Horizontal distance is centered on the topographic crest of each rift. Profile locations shown in figure 5.2. Approximate compass orientations of profiles indicated by labels on ends (N, north; E, east; S, south; W, west).

over the nearshore segment of this rift. Because volcanic activity has been absent along this rift for tens of thousands of years, the rough constructional topography of the rift has been buried by clastic and hemipelagic sediment and a coralline mantle. Mauna Kea's east rift zone shows two prominent slope transitions. The shallower one reflects the change from carbonate platform to a steeper slope that probably more closely reflects the original constructional rift slope. Farther seaward, the slope of the rift axis decreases abruptly about 30 km from the shoreline and then continues at this lower value past the end of the profile shown in figure 5.3. If the profile were extended (see fig. 5.2 for contours), one would see that Mauna Kea's profile consists of several steeper sections separated by wide, lower gradient benches that eventually merge onto the abyssal sea floor at approximately 5 km depth. This characteristic old-rift topography is similar to that of Hualalai's northwest rift zone, although the steeper ramp sections are smaller on Hualalai, possibly reflecting the smaller size of Hualalai Volcano compared to Mauna Kea.

Hualalai's northwest rift zone has a slightly steeper profile than Mauna Kea's east rift zone, but it also shows the effects of reef growth and carbonate terrace development. Along Hualalai's rift the terrace extends about 8 km from the shoreline; however, the Kohala terrace to the north is a much broader feature, whose morphology and development reflect the extended period of volcanic quiescence along the northwest coast of Hawaii and the older age of this portion of the island (Campbell and Erlandson, 1981). Hualalai's rift profile also appears rather smooth; but this is most likely a result of the use of wide-beam echo sounders to survey this area. A detailed inspection of echo-sounder records from the crest of Hualalai's northwest rift zone shows an abundance of overlapping hyperbolae suggestive of constructional volcanic sea floor (Campbell and Erlandson, 1981).

Mauna Loa's southwest rift zone also has a smooth profile, but its regional slope is greater than that of all other rifts except Loihi's (fig. 5.2). The smoothness of this profile does reflect a general absence of recent constructional volcanism on the rift-zone crest; however, young-looking volcanic flow fronts and outcrops are present on the west flank of the rift (Fornari and others, 1979b). The absence of a carbonate shelf on Mauna Loa's southwest rift zone indicates that this part of the island is still too young (volcanically active) and gravitationally unstable to allow carbonate reef terraces to grow and develop.

Kilauea's east rift zone (Puna Ridge) shows much more local irregularity than do the rifts of Mauna Kea, Hualalai, and Mauna Loa (fig. 5.3), undoubtedly because it is linked to the most active volcano and subaerial rift zone on Hawaii. Because of its young age, Puna Ridge does not possess a carbonate terrace (fig. 5.3). The rather constant gradient of this rift zone out to 50 km from shore and its greater elevation above the surrounding sea floor (for corresponding distances from shore) compared to Mauna Loa's southwest rift zone, probably result from the buoyant effects of magma intrusion and lack of subsidence, similar to the manner in which the crest of the East Pacific Rise is supported and elevated by accretionary magmatism (see Macdonald and others, 1984, and references therein).

Loihi Seamount's north and south rift zones are excellent examples of juvenile Hawaiian submarine rift zones. Both have steep plunge angles and local topographic roughness created by constructional volcanism on the rift crests. The north rift is not as steep as the south rift because of the constraining effects of Kilauea's south flank and southwest rift on its development. The crests of Loihi's rifts are known from deep-sea photography (Malahoff and others, 1982) to consist of pillow-lava flows, while the flanks of the rift zones and much of the volcano sides are covered with coarse pillow-lava talus.

Profiles across the strikes of these Hawaiian rifts are shown in figure 5.4. The most important feature of these profiles is the consistently asymmetric character of the rifts. In all cases the rift flank that is not buttressed is steeper, indicating that gravitational slumping of rift flanks fundamentally alters the geometry of a rift zone. As exemplified by Loihi Seamount's rifts, this process is initiated at a very early stage in a rift zone's growth and continues through the volcano's early-mature stage of development.

Hence, Hawaiian rift zones initially develop and grow purely through constructional volcanism; however, early in the rift zone's active life the influence of adjacent volcanoes on its growth becomes important. The following model illustrates the importance of gravitational slumping and preexisting volcano location to the development of rift zones and volcano flank morphology and structure. In addition, this model offers an explanation for the absence of large-scale gravitational slumps on the west flank of Mauna Loa north of approximately latitude 19° 30′ N.

Fiske and Jackson (1972), who used the gravity data of Kinoshita and others (1963) to support their thesis, suggested that Hualalai's southeast rift zone has played a dominant role in the construction of the original Hualalai edifice, much of which is now buried beneath the flank of Mauna Loa (fig. 5.1, 5.2). The Bouguer gravity map of Hawaii (Kinoshita and others, 1963) shows an elongate north-south gravity high (265 mGal closed contour) that continues south of the surficial boundary between Hualalai and Mauna Loa and reaches latitude 19° 25′ N (fig. 5.1). South of the summit of Hualalai, the gravity high is west of the surface position of the rift zone, and the gravity maximum is the lowest of the five gravity highs on the island. This may be in part because the dense dike rocks are buried under 1–2 km of Mauna Loa lava and clastic deposits. The location of the gravity high, offset to the west with respect to the present surface rift, is still within the 12- to 17-km width of the dike complex proposed by Broyles and others (1979). However, the buttressing of Mauna Loa's west flank (see Lipman, 1980a, b) would lead one to expect the surface rift to lie west of the gravity high, in the direction that can most easily accommodate extensional tectonics because it is not buttressed.

I suggest that the dike complex under Hualalai's gravity high is a foundation that buttresses the northern part of the west flank of Mauna Loa. Deep-seated gravitational slumping on the west flank of Mauna Loa is, therefore, restricted to the area south of the end of the gravity high (approximate latitude 19° 25′ N. fig. 5.1). The extension of the Kealakekua fault north of latitude 19° 25′ N. may represent gravitational slump-block failure (Normark and others, 1979; Lipman, 1980a) of just the upper few kilometers of Mauna Loa's west flank that are unbuttressed by Hualalai's southern rift dike complex. In addition, the abrupt development of a carbonate terrace north of latitude 19° 30′ N. (fig. 5.2) probably results partially from the relative stability and low rate of volcanic activity along Hualalai's west flank as compared to Mauna Loa's gravitationally unstable west flank south of Kealakekua Bay.

CONCLUSION

There are several morphologic similarities between the youthful Puna Ridge and Hualalai's older northwest rift zone. Echo reflection characteristics and data from dives and dredges in the summit areas of both rifts reveal a predominance of fresh pillow lava and constructional morphology on the ridge crests. The unbuttressed south flanks of both rifts are mantled by volcaniclastic deposits resulting from mass wasting of constructional topography and from gravitational slumping. The latter process has disrupted the constructional slopes and widened the bases of the topographic ridges.

Because these two rifts are near opposite ends of the age spectrum for the Island of Hawaii, it is apparent that the processes of constructional volcanism (centered on a line source along the rift axis) and mass wasting of the unbuttressed rift flank are fundamental to the evolution of submarine rift-zone morphology and structure. The principal difference between Hualalai's northwest rift zone and Puna Ridge is the nearly complete burial of the headwalls of slump blocks on Hualalai's rift by subsequent volcaniclastic deposits that cover nearly all of the original constructional relief and fault scarps.

The morphology and structure of the submarine continuation of Mauna Loa's southwest rift zone are quite different from those of Puna Ridge and of Hualalai's northwest rift zone. The unbuttressed west flank of the southwest rift is very unstable at this stage in Mauna Loa's shield-building history, and gravitational slumping has created a prominent asymmetric scarp topography rather than a more symmetric constructional rift topography (fig. 5.4). The large vertical offsets and horizontal extent of the slumping indicate that this reconfiguration of the cross-sectional and plan-view structure and morphology of the rift zone is deep seated and extends well down into the volcanic pile. The abundance of these large-scale gravitational slump features (for example, Kauna and southwest rift slides) on the west flank of Mauna Loa attests to the predominance of this process during the mature phase of shield building (Fornari and Campbell, chapter 4). The size of gravitational slumps on volcano flanks is probably controlled by edifice size and by the constraining influence of adjacent volcanoes, which act to buttress parts of the volcanic pile.

The structure and morphology of Hawaiian submarine rift zones are primarily the result of a time-integrated sequence of volcanic constructional processes and gravitational tectonics. Initially constructional volcanism dominates, although parts of a rift may begin to be modified by gravitational slumping even during the juvenile stage. Early in a volcano's mature shield-building stage, however, the instability of the subaerial shield (whose foundation is the clastic volcanic sequences laid down during the volcano's emergence) results in the dominance of destructional gravitational slumping over constructional processes and the drastic reshaping of the submarine rift. At a still later date the combined effects of repeated slumping, minor renewed volcanism, the possible growth of a new volcano nearby, subsidence of the island, and development of a carbonate reef terrace result in a mature submarine rift like that of Mauna Kea's east rift zone or Hualalai's northwest rift zone.

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