

The Giant Submarine Alika Debris Slide, Mauna Loa, Hawaii

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A 4000-km² area of submarine slump and slide deposits along the west flank of Mauna Loa volcano has been mapped with GLORIA side-scan sonar images, seismic reflection profiles, and new bathymetry. The youngest deposits are two debris avalanche lobes that travelled from their breakaway area near the present shoreline as much as 100 km into the Hawaiian Deep at water depths of 4800 m. The two lobes partly overlap and together are designated the Alika slide. They were derived from the same source area and probably formed in rapid succession. Distinctive hummocky topography, marginal levees, and other features on lower slopes (0.3°–0.6°) of these deposits resemble subaerial volcanic debris avalanche deposits such as 1980 Mount St. Helens and suggest high emplacement velocities. The breakaway area for the Alika slide (10°–15° slopes) is characterized by large block slumps, bounded by normal faults, that probably represent multiple subsidence events before, during, and after the debris avalanches. Lower slopes of the slide contain distinctive lobate-terraced deposits that are interpreted as having been emplaced more slowly, prior to the debris avalanches. Estimated thicknesses of 50–200 m suggest volumes of 200–600 km³ for the two lobes. The combined volume of the entire slide and slump terrane is probably 1500–2000 km³. The slide deposits predate a 13-ka coral reef and probably postdate the block-faulted Ninole Basalt, roughly dated as a few hundred thousand years old. The Alika slide, or a similar deposit recognized on GLORIA images further north along the Hawaiian Ridge, probably triggered a giant wave that washed 325 m high on Lanai at about 100 ka. Slumping on Mauna Loa has been most intense adjacent to the large arcuate bend in its southwest rift zone, as the rift zone migrated westward away from the growing Kilauea volcano. Slumping events were probably triggered by seismic activity accompanying dike injection along the rift zone. Such massive slumps, landslides, and distal submarine turbidity flows appear to be widespread on the flanks of Hawaiian volcanoes.

INTRODUCTION

The submarine flanks of young volcanoes along the Hawaiian Ridge are among the steepest underwater slopes in the world [Mark and Moore, 1987]. From sea level to the axis of the Hawaiian Deep at a depth of nearly 5 km, offshore slopes are commonly as steep as 15°–20° (Figure 1). In contrast, subaerial slopes of the volcanoes are much gentler, typically 3°–8°, especially those formed during rapid growth in the tholeiitic shield-building stage. Massive seaward gravitational failure of the submarine slopes has long been inferred from on-land observations of seaward facing normal faults (Figure 2), such as the Hilina system on Kilauea [Stearns and Clark, 1930; Swanson *et al.*, 1976] and seemingly analogous but less active faults of the Kaoiki system on the southeast flank of Mauna Loa [Lipman, 1980]. A gravitational failure event, associated with the magnitude 7.2 Kalapana earthquake on the south flank of Kilauea, caused as much as 8 m of horizontal seaward displacement and 3.5 m of subsidence along the south coast in 1975. This event generated a major local tsunami, caused by uplift low on the submarine volcanic slope in the toe region of the gravitational slump [Tilling *et al.*, 1976; Lipman *et al.*, 1985].

Massive underwater landsliding from the Hawaiian Ridge has also been inferred from chaotically hilly submarine morphology on the north flanks of Oahu and Molokai islands [Moore, 1964]. A large region of submarine slumping on the southwest flank of Mauna Loa was inferred during mapping

of the atypically steep on-land slopes (as steep as 12°), even though all on-land slump structures are now covered by younger lavas [Lipman, 1980]. The entire region bounded by the on-land Kealakekua and Kahuku faults (Figure 2) seemingly was involved, owing to oversteepening adjacent to the conspicuous bulge in the southwest rift zone of Mauna Loa.

This inferred region of gravitational failure was studied during 1976 and 1978 cruises of the R/V *S.P. Lee*, operated by the U.S. Geological Survey; slump and slide features were detected as far as 80 km west from the shoreline by echo sounding and seismic reflection profiling (Figure 3). These submarine slides are prominent features of the island flanks and constitute some of the largest known submarine landslides. An especially striking large debris slide, its source centered on the Alika land section, was named the Alika slide [Normark *et al.*, 1979], and bathymetric expression of the broader slump features was also discussed by Fornari and Campbell [1987]. These studies could not resolve details of the morphology and distribution of the slide deposits because of the limited resolution of existing bathymetry, geometric aspects of the two-dimensional profiling, and navigational uncertainties.

Additional surveys were conducted in 1986 from the research ship M/V *Farnella*, using the side-scanning sonar system Geologic Long-Range Inclined Asdic (GLORIA), echo sounding, 3.5-kHz profiling, and airgun seismic reflection profiling (Figure 3). GLORIA is a dual-channel long-range system which gives a swath width of up to 22.5 km to each side of the survey ship track [Somers *et al.*, 1978]. The smallest features readily detectable are a few hundred meters across (individual pixels are about 50 × 50 m). Although lower in resolution than some other currently available sonar-imaging systems such as SeaMARC II, the GLORIA system is capable of viewing much larger areas, typically of the order of 8500 km² per day. This large-scale synoptic capability is essentially suited for the study of features that extend over many tens to hundreds of kilometers, such as the submarine slides adjacent

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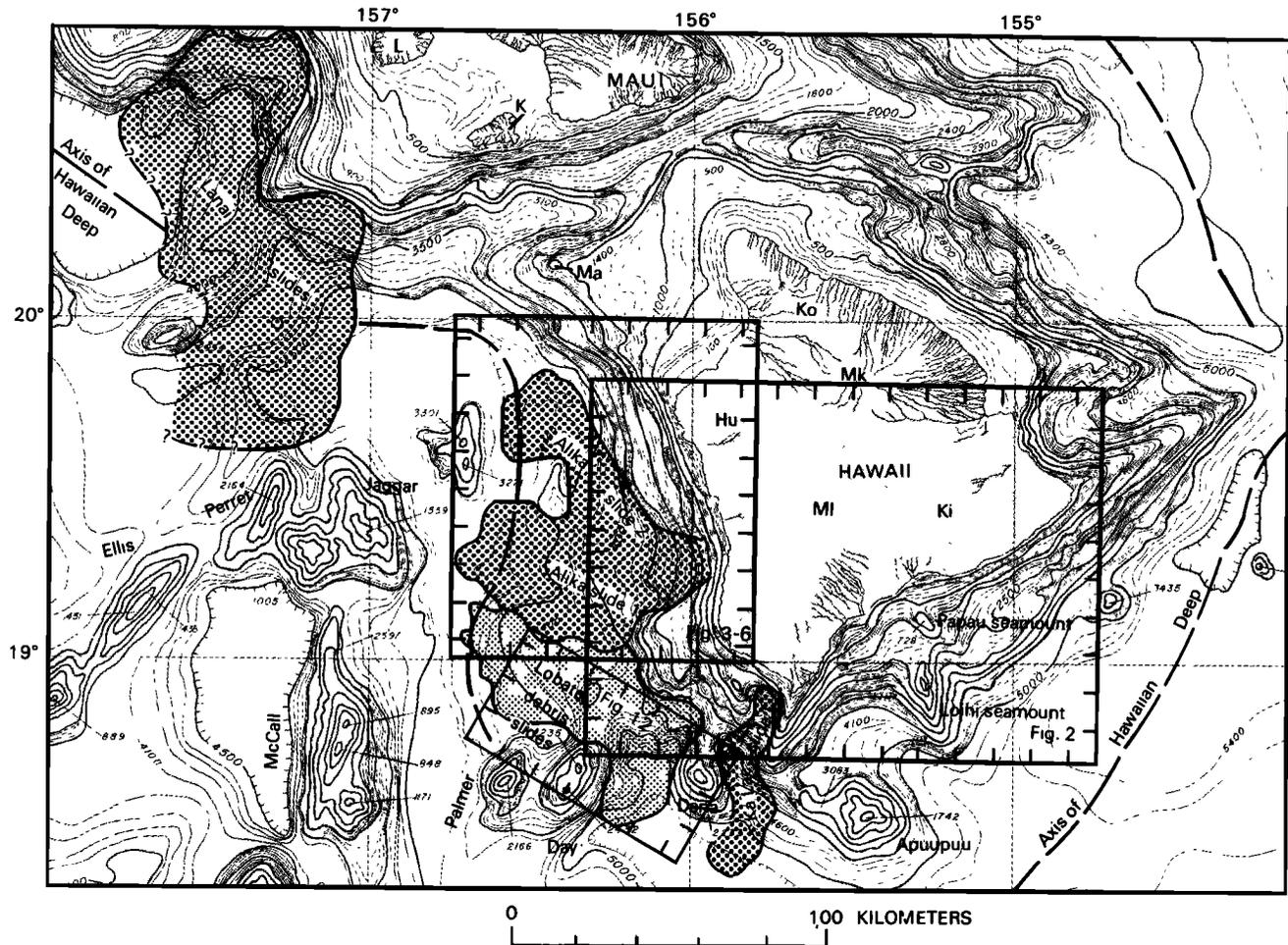


Fig. 1. Index map of Hawaii Island and offshore bathymetry [after Wilde *et al.*, 1980]. Contour interval, 100 m. Locations of Figures 2, 3–6, and 12 shown by hachured boxes; major slide deposits along southwest flank of Hawaiian Ridge and island areas shown by stipple patterns. Islands: K, Kahoolawe; L, Lanai. Volcanoes of Hawaii Island: Hu, Hualalai; Ki, Kilauea; Ko, Kohala; Ma, Mahukona submarine volcano; Mk, Mauna Kea; MI, Mauna Loa.

to the Hawaiian Ridge. The GLORIA surveys are part of a study of the U.S. Exclusive Economic Zone (EEZ), extending 200 nautical miles (370 km) beyond the coastline, and are a cooperative project between the U.S. Geological Survey and the British Institute of Oceanographic Sciences. This report integrates the 1986 data with our earlier observations from the *S.P. Lee* in order to document the areal extent, morphology, depositional units, and emplacement mechanisms of the slide and slump deposits. Survey techniques and limitations in interpretations are summarized in a cruise report [Normark *et al.*, 1987].

GEOLOGIC SETTING

The west side of Hawaii Island (Figures 1 and 2) consists of the overlapping edifices of Kohala, Hualalai, and Mauna Loa volcanoes. Volumes of Holocene lava generally have increased southward, and the resulting variations in slope steepness appear to have influenced timing and size of the associated submarine slides. Kohala last erupted at about 60 ka; Hualalai has erupted about 200 times since 10 ka but only once (1801) in the last 200 years (historic record); Mauna Loa is largely covered by lavas younger than 4 ka and has erupted on average every 5–10 years during the past 150 years [Moore

et al., 1987; Lockwood and Lipman, 1987]. The volcanic history of the west side of the island is more complex than a simple southeastward migration of activity, as indicated by the presence of lavas (Ninole Basalt) a few hundred thousand years old on the south flank of Mauna Loa. These likely are an early part of Mauna Loa [Lipman, 1980], or they could be remnants of a separate older volcano [Stearns and Macdonald, 1946; Macdonald and Abbott, 1970].

The combined volcanism has constructed a relatively simple submarine slope about 4.5 km high, 200 km long, and broadly concave to the southwest (Figures 4 and 5), that almost merges with the composite volcanic platform of Kahoolawe, Lanai, and Maui, across the Alenuihaha Channel to the north. This channel and other major submarine canyons between offshore extensions of subaerial rift zones of Hawaiian volcanoes (Figure 1) result from construction of the adjacent rift zones, rather than from erosion. The rift zones grow by venting from dikes injected laterally from shallow magma reservoirs (3–5 km) below the volcanic summits. Rift orientations are influenced by gravitational stresses from adjacent volcanic edifices and may migrate as the volcanoes grow at varying rates [Fiske and Jackson, 1972; Swanson *et al.*, 1976].

The westward bulge in the southwest rift zone of Mauna

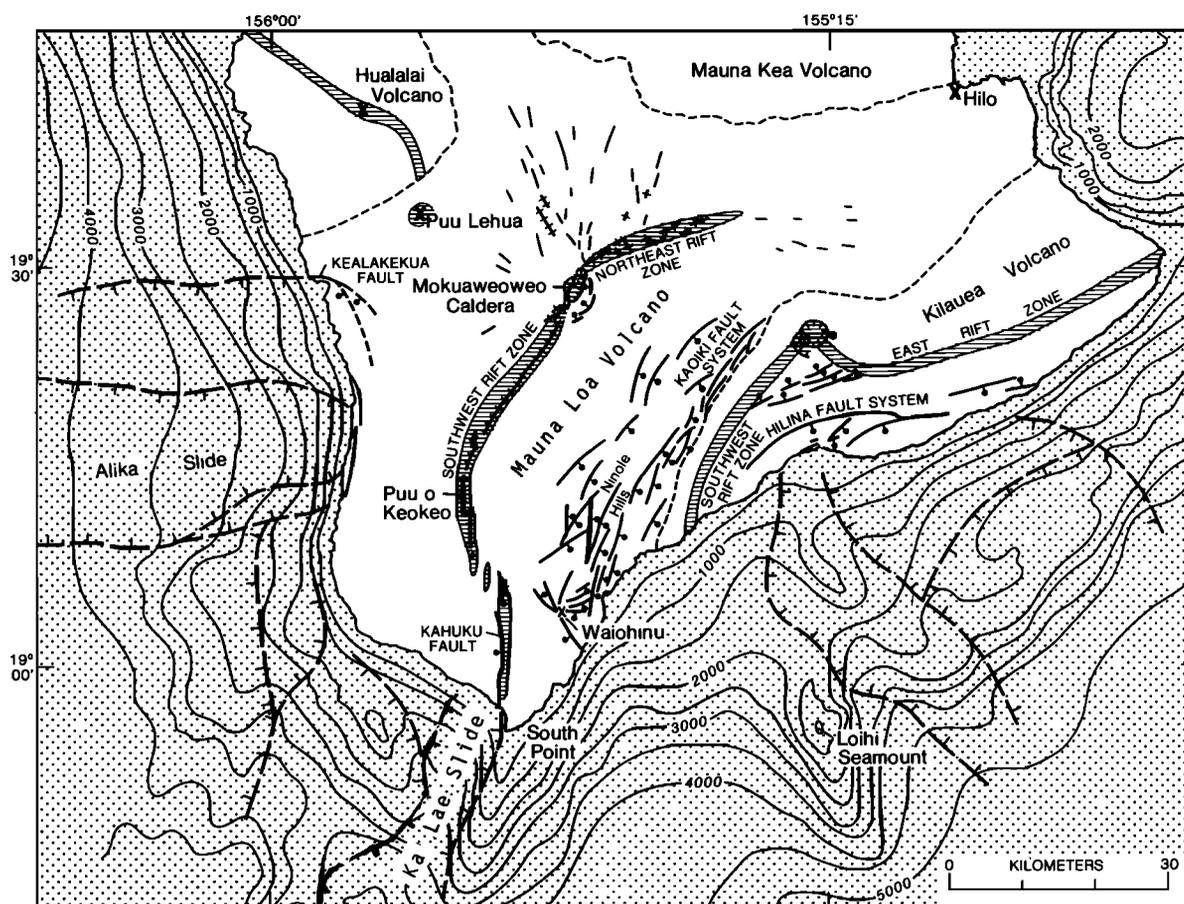


Fig. 2. Generalized structural map of south part of island of Hawaii and offshore bathymetry [after U.S. Naval Oceanographic Office, 1973]. Bathymetric contour interval, 500 m. Geometry of submarine slide and slump features (hachure lines) shown as understood from 1978 S.P. Lee studies [Normark et al., 1979]. Bar-and-ball symbol indicates downthrown side of fault. Horizontal line pattern, crests of rift zones; railway-track lines, historic Mauna Loa eruptive vents; solid lines, selected prehistoric vents. Dashed lines on land are boundaries between volcanoes. Modified from Lipman [1980].

Loa (Figure 2) is thought to result from westward migration of dike intrusion along this rift zone in response to the growth of Kilauea [Lipman, 1980]. Eruptions have been infrequent along southern parts of the subaerial southwest rift zone, at least during the past few thousand years; in contrast, the axis of the bulge at Puu o Keokeo and the segment to the north have been particularly active [Lipman and Swenson, 1984]. This concentrated eruptive activity along the northern part of the rift zone, accompanying dike injection, and the resulting lateral stressing of the upslope edifice may be directly related to the adjacent downslope location of the largest gravitational slump features along the west flank of the island. Intersection of slump structures with dikes from the summit of Mauna Loa also may have influenced the locations of infrequent lower flank eruptions, such as the submarine activity in Kealakekua Bay in 1877. [Fornari et al., 1980; Moore et al., 1985].

The shallow submarine platform, adjacent to the west coast of Hawaii Island, broadens and deepens to the north, reflecting progressive submergence of the older volcanoes along the Hawaiian Ridge [Moore, 1987]. The inflection in slope, from 2°–3° on the platform to more than 5° at greater depth, is interpreted as the boundary between submarine and subaerial volcanism during the tholeiitic shield-building phase. The

composite platform between Hualalai and Kohala contains drowned coral reefs, dated at 13 and 120 ka [Szabo and Moore, 1986], that truncate the submarine extension of the Hualalai northwest rift zone. Younger lavas from Hualalai and Mauna Loa have accumulated in shallow water on the platform, but few have extended across the 13-ka reef, indicating relatively low rates of Holocene lava accumulation in this sector.

Where not greatly complicated by gravitational failure, the submarine slopes of the Hawaiian platform descend relatively uniformly at gradients of 5°–15° to the Hawaiian Deep, e.g., the southwest slopes of Hualalai and Mahukona volcanoes. The Hawaiian Deep is a depression in the Cretaceous age seafloor of the region, resulting from late Cenozoic loading by the massive volcanoes of the Hawaiian Ridge [Moore, 1987]. The seafloor west of Hawaii Island is also studded with hundreds of seamounts, representing volcanoes largely of Cretaceous age. These range in size from small volcanoes less than a kilometer across and a few hundred meters high, first observed on the GLORIA images [Normark et al., 1987], to previously known and named seamounts tens of kilometers across and several kilometers high (Figure 1). The axis of the Hawaiian Deep is locally obscured west of Hawaii Island by

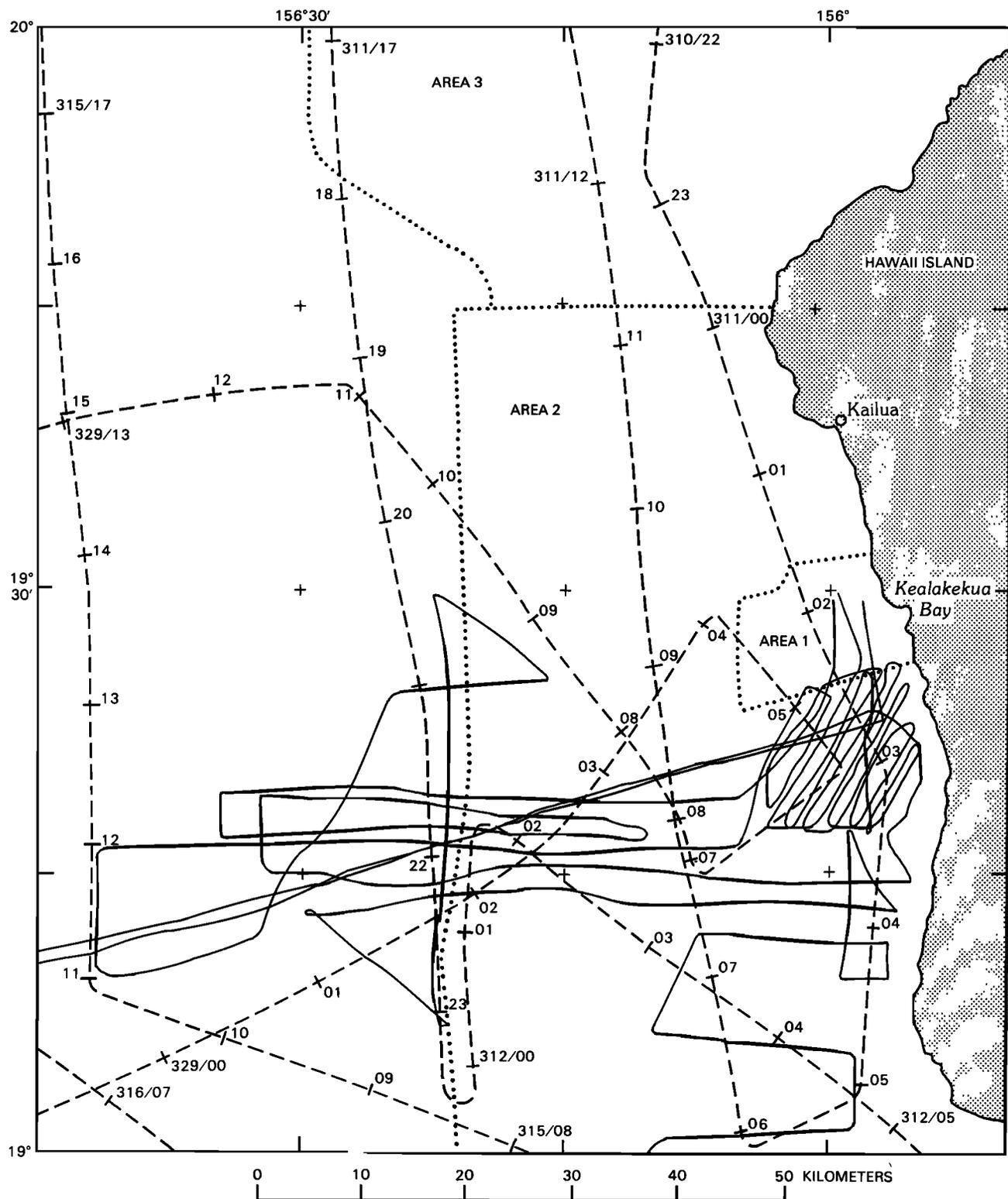


Fig. 3. Ship tracks for new depth data used in refining bathymetry of Alika slide area (Figure 4; see Figure 1 for location). Solid lines, tracks for *S.P. Lee* in 1978; dashed lines, tracks for *Farnella* in 1986 (hour and Julian day shown at tick marks). Dotted lines enclose areas for which additional data were available: (1) a detailed 1976 survey of the Kealakekua Bay area [Normark *et al.*, 1978], (2) uncontoured soundings from the *National Ocean Survey* [1972], (3) contours generalized from *Campbell* [1987]. The generalized bathymetric map of the Hawaiian Islands [Chase *et al.*, 1981] was also used for guidance in areas where detailed data are sparse.

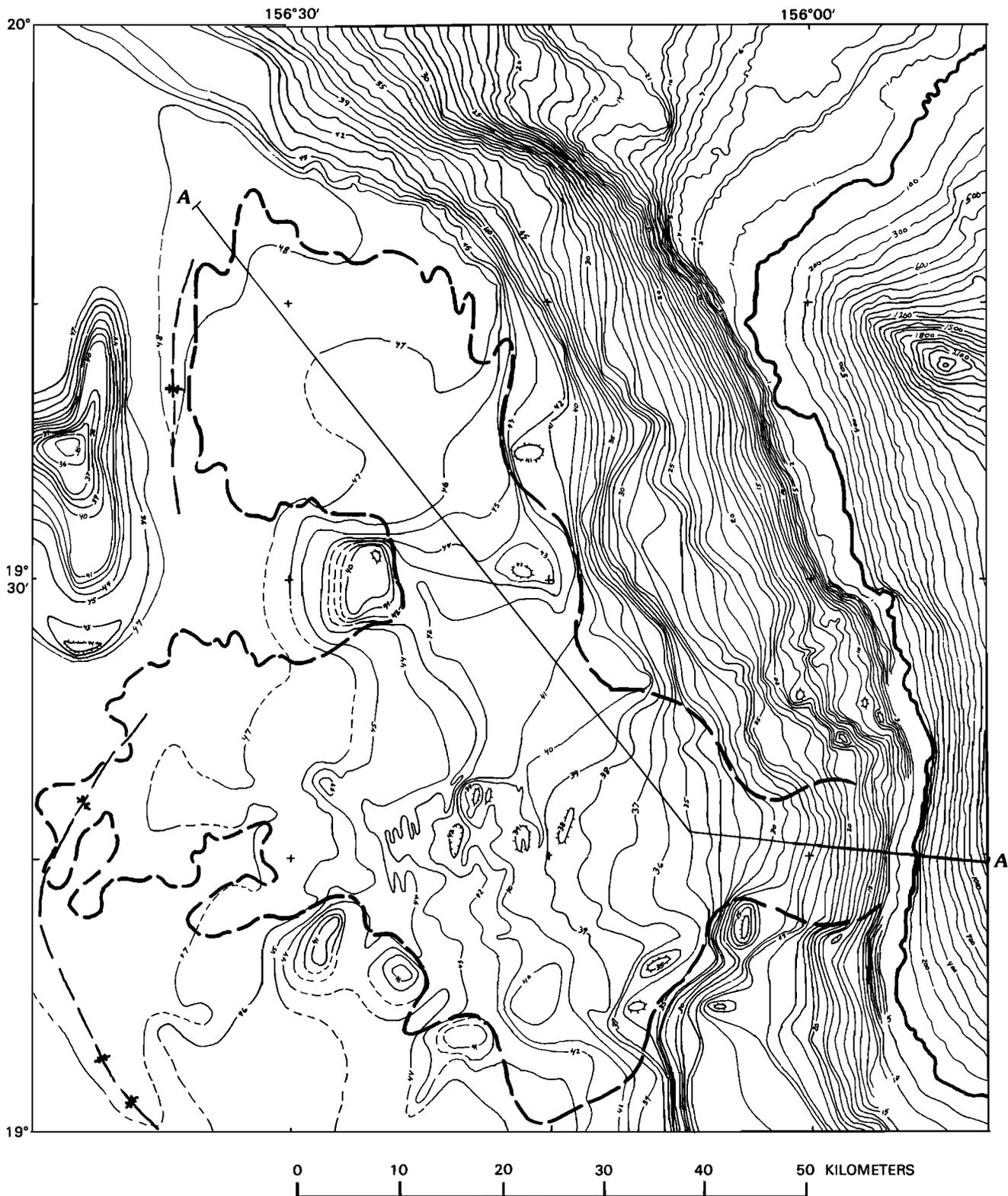


Fig. 4. Bathymetry of the Alikā slide area. Constructed from the data sources summarized in Figures 3 and 5. Contour interval, 100 m; submarine contours labeled in hundreds of meters below sea level; subaerial contours, in meters above sea level. Scale same as Figure 3. Heavy line, outline of Alikā slide from Figure 6. Profile A-A' shown in Figure 7.

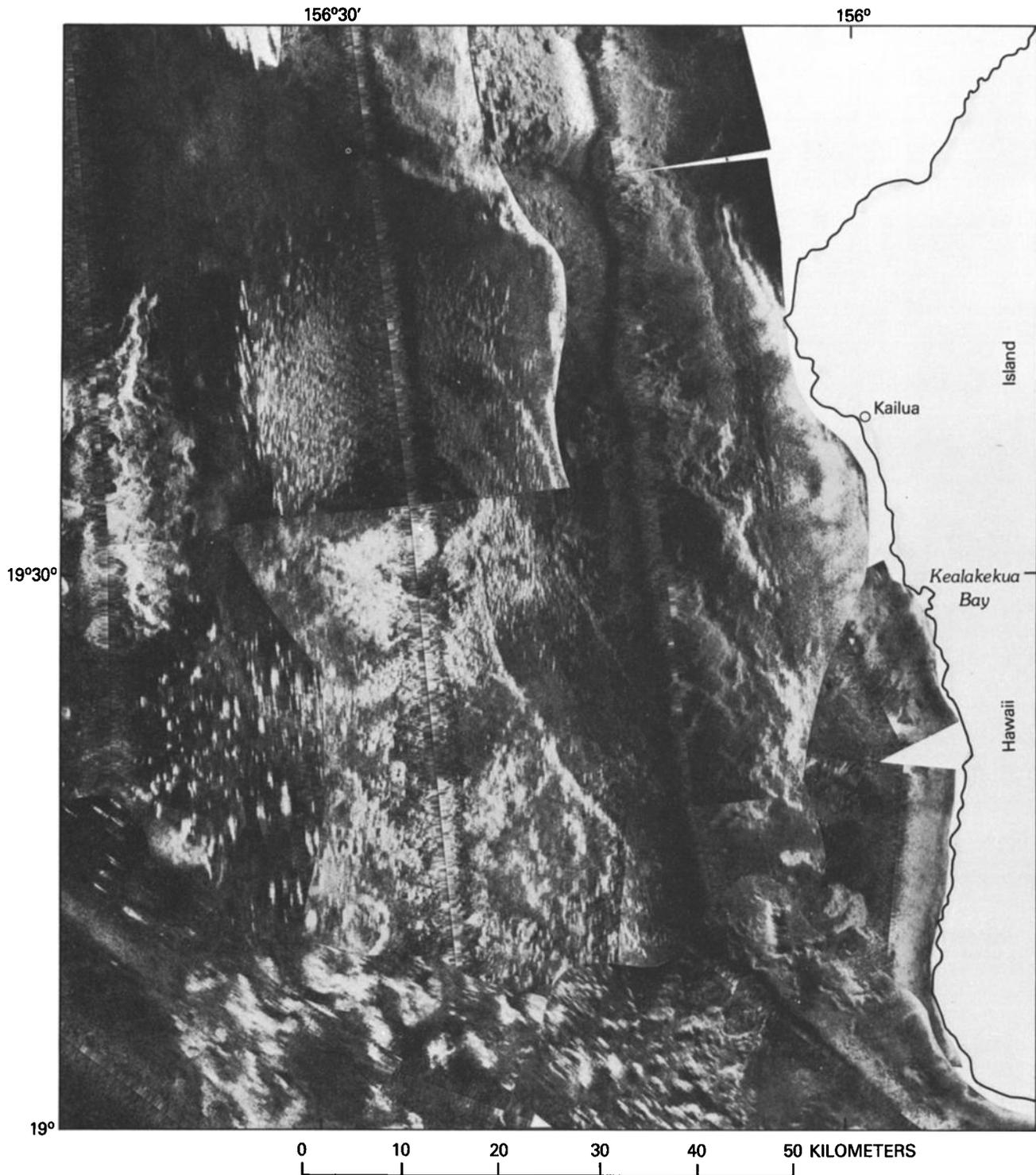


Fig. 5. Mosaic of GLORIA images for the Alikā slide area. Scale same as Figures 3 and 4. The images are made so that areas of high and low sonar backscatter are shown by light and dark tones, respectively. Backscatter is a function of viewing geometry and local relief, texture, and composition of varying seafloor materials; lava surfaces typically appear lighter than sediments because they provide greater acoustic backscatter. The smallest features imaged are commonly a few hundred meters wide except in a narrow swath of lower resolution directly beneath the survey ship. Some discontinuities in the mosaic result from changed direction of insonification between adjacent ship tracks, especially over steep submarine slopes. These images represent an intermediate stage in processing, and the mosaic was produced by splicing individually processed segments as an interim step to digitally merged images.

these seamounts, and it is also displaced by the large gravitational slides from the island.

ALIKA SLIDE

The GLORIA sonar images (Figure 4), integrated with improved bathymetric data (Figure 5) and seismic reflection profiling, indicate that the slide area adjacent to the southwest coast of Hawaii Island is larger and more morphologically complex than previously recognized. The images show that the Alika slide represents several geologically rapid events involving mass flowage, rather than a prolonged or repetitive sequence of slump or creep events. The debris avalanche deposits are associated with, and largely overlie, less rapidly emplaced gravitational slump and slide features that occupy most of the entire west slope of Hawaii Island from Ka Lae (South Point) north to the submarine terminus of the northwest rift zone of Hualalai volcano (Figure 6).

Nomenclature used in this paper for submarine slides generally follows that reviewed by Moore [1977] and includes (in order from the most coherent to most fluidized downslope movement) fault-bounded block slumps, morphologically complex debris avalanche deposits, and lobate debris slide and flow deposits. The GLORIA images define two partly overlapping debris avalanche lobes of the Alika slide that are associated with a partly older assemblage of block slumps and debris flows; these slides, slumps, and flows collectively are loosely designated the Alika slide complex. The debris avalanche deposits are especially large and provide striking GLORIA images. They are characterized by large-scale hummocky surfaces similar to those of catastrophically emplaced subaerial debris avalanches.

Morphology

The Alika slide covers a region roughly 55×80 km and has a total area of about 4000 km². At least two major lobes can be distinguished on the sonar images. Initial failure led to westward directed transport, here designated as phase 1; these are the features detected during the 1978 study with the *S.P. Lee*. Later, the upper part of the slump mass, or additional debris from higher on the Mauna Loa slope, moved laterally northward to form a large second lobe. The phase 2 deposit is characterized by a lower part (phase 2A), separated from a more proximal upper part (phase 2B) by an abrupt steepening in slope at a water depth of about 4600 m (Figures 4, 6). For each phase of the debris avalanche, five major deposit types can be distinguished: (1) upper breakaway slumps, (2) middle smooth debris flow deposits, (3) lower hummocky debris slide deposits, (4) fringing zones of isolated slide blocks, and (5) outer turbidite apron.

These two lobes overlie at least two earlier gravitational failure deposits, represented by isolated slide blocks as much as 5 km in diameter and several hundred meters high which obstructed later movement of the Alika slide and by lobate-terraced slide deposits that extend beyond the isolated hills and the debris avalanche deposits, especially south of the Alika phase 1 deposits (Figure 6, bottom). It is presently unclear how much time is represented by emplacement of these diverse deposits.

Some small slump features with high backscatter signals on the GLORIA records are streaked and elongated, especially in the far-field ranges. This problem is especially evident for

hummocky lower reaches of the Alika slide (Figure 5). The invariable parallelism of such streaks to the ship course on oblique crossings of the same area demonstrates that their elongation is spurious. This artifact gives equant hills the visually misleading appearance of ridges. The streaking apparently results from beam spreading in the far field, especially for areas with a high contrast in backscatter between rock surfaces and sediment-smoothed seafloor. The rock surfaces are thus imaged multiple times, compared with more subdued and smoother seafloor.

Breakaway slumps. The Alika slide heads in an area of steep subaerial and submarine slopes (8° – 20°) on the west flank of Mauna Loa that are characterized by normal fault scarps, generally concave to the west in plan view. Some scarps show at least several hundred meters' minimum displacement down toward the west. One such scarp is the seaward extension of the Kealakekua fault that had historic ground cracking during the 1951 Kona earthquake [Macdonald and Wentworth, 1952], that was mapped in detail by Normark et al. [1978]. Submersible studies show no detectable offset of the submarine Kealakekua fault since formation of a coral reef at 13 ka [Fornari et al., 1980; Moore and Fornari, 1984]. A series of submarine volcanic vents were active in 1877 parallel to the Kealakekua fault down to depths of greater than 1000 m [Fornari et al., 1980; Moore et al., 1985]. Hence tensional features associated with such slumps appear locally to have intersected the magmatic plumbing system of Mauna Loa volcano. Many small fault scarps were recognized along the upper 2 km of the underwater slope in the Kealakekua Bay area during submersible studies [Fornari et al., 1980], and steps in the bathymetry (Figure 4) define a major fault system at depths of 1500–2000 m. Many scarps are also evident on GLORIA images as zones of high backscatter or shadows, depending on the illumination direction of the sonar source.

These features define a block slump terrain, similar to but smaller and presently less active than the subaerial and submarine Hilina system on the south flank of Kilauea volcano. Much of the steep subaerial southwest flank of Mauna Loa is believed to represent prehistoric oversteepening by such block slumps that subsequently have been largely covered by historic and late prehistoric lavas erupted from the southwest rift zone of Mauna Loa [Lipman, 1980]. Anomalously steep subaerial slopes extend to about 2000-m elevation above sea level on the southwest slopes of Mauna Loa. Submarine block slump structures appear to continue northward along the west flank of Hualalai volcano, without apparent change in style at the boundary between volcanoes (Figure 6). These block slumps are thought to result from loading of the unbuttressed seaward flanks of Mauna Loa and Hualalai by rift zone volcanism and by dike injection along the rift zones [Lipman, 1980]. Many of the block slumps along the coast appear to predate the Alika slide and to channel it, but some slumps, especially in the bathymetrically complex area offshore from Kealakekua Bay, may constitute parts of the breakaway zone of the Alika slide. Discontinuous gradations downslope between block slumps, chaotic landslide material, and more fluidized debris flow deposits are also well established for individual subaerial slides [Varnes, 1978; Voight, 1978].

Middle smooth debris flow deposits. The upper 25 km of the mapped slide area, to a water depth of about 3700 m, is characterized by a smooth, relatively featureless surface on the

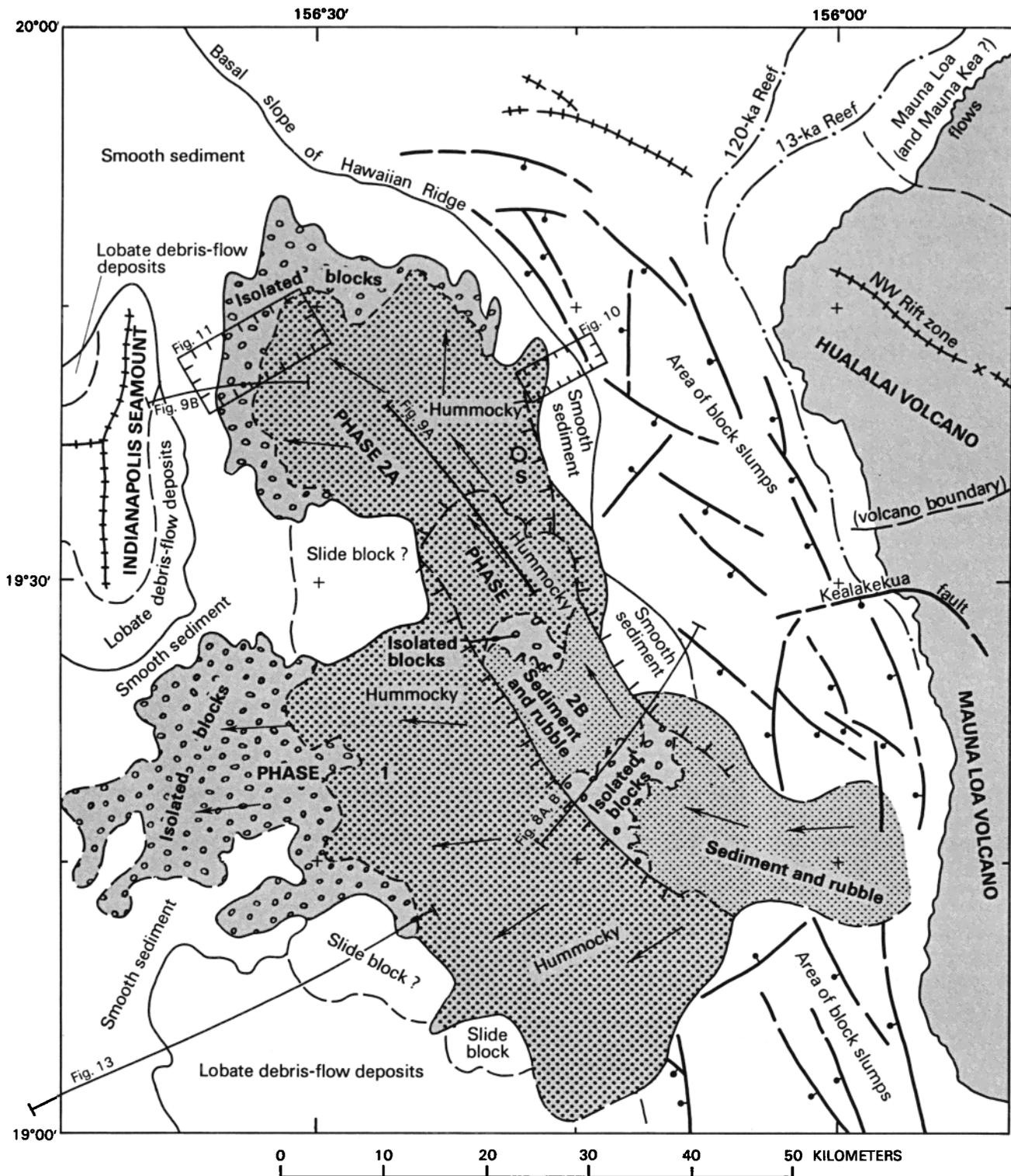


Fig. 6. Interpreted generalized geology of the Aliko slide and adjacent flanks of Hawaii Island. Scale same as Figures 3-5. Arrows indicate movement during successive phases of the slide. Long-dashed lines, gradational or approximate contacts; short-dashed lines, gradational contacts between depositional facies of Aliko slide; hachured lines, levees and depositional fronts between phases of slide; heavy lines, inferred fault scarps of block slump areas, with bar and ball on down-dropped side; railway track lines, rift zones on Hualalai volcano and Indianapolis Seamount. Locations of seismic reflection profiles (Figures 8, 9, 13) and SeaMARC II images (Figures 10 and 11) also shown. S, location of deep-tow images obtained by Scripps Institution of Oceanography [Spiess, 1981].

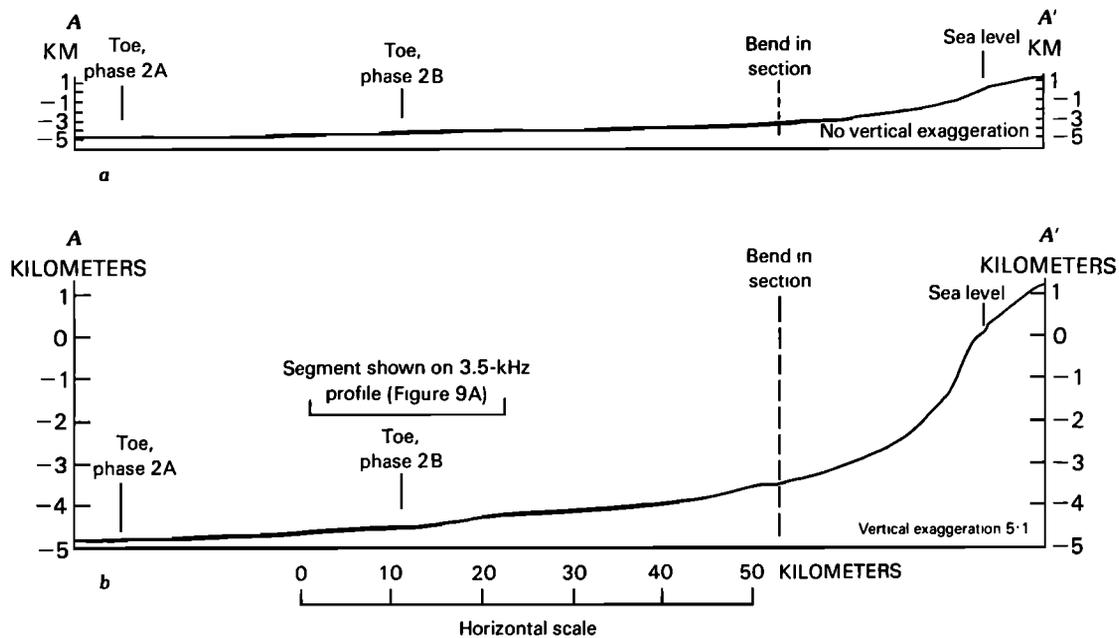


Fig. 7. Longitudinal topographic profile of the Alika slide. Location of profile shown in Figure 4. (a) No vertical exaggeration. (b) Vertical exaggeration is 5:1.

GLORIA images; on the 3.5-kHz profiles, surfaces are sharply defined, without side echos or penetration to subbottom reflectors. From just offshore to a depth of about 2500 m, slopes are steep (15° – 25°), and submersible observations [Fornari *et al.*, 1980] indicate that these slopes constitute the breakaway trough of the Alika slide, partly filled by near angle-of-repose *a'a* rubble from relatively young Mauna Loa flows, most recently those of 1950.

Between 2500 and 3500 m the slopes flatten to about 5° , and the downslope convexity of bathymetric contours starting at about 3200 m indicates a zone of deposition (Figure 7). The 3.5-kHz records show continuous smooth strongly reflecting surfaces, suggesting that the redeposited material is sand-rich slide rubble in which fine-grained material was thick enough to bury any large coherent masses of the type that make the conspicuously hummocky terrain lower in the slide.

Lower hummocky debris slide deposits. The most widespread and distinctive facies of the slide is the lower region of closely spaced hummocky mounds (Figures 5–6). Most mounds are probably subequant in shape; the apparent elongation of many on the GLORIA images is an artifact of the sonar imaging system, as noted above.

Many individual mounds are as much as a few hundred meters across and 25–75 m high, as measured from the 3.5-kHz profiles (Figure 8a), but some hills are as much as several kilometers across and sufficiently large to define by bathymetric contours (Figure 4). Over much of the hummocky terrain, especially within the phase 2 lobe, individual hummocks are closely spaced and similar in size and height, but their presence is shown on the 3.5-kHz profiles by irregular hyperbolic reflections (Figure 8a). Deep-tow profiles and photographs made by Scripps Institution of Oceanography in 1980 for an area near the upper east margin of the phase 2A hummocky deposits (Figure 6, location S) detected discrete mounds from as much as 200 m in diameter and 40–60 m high to blocks less than 1 m across recognizable only from deep-tow photography [Spiess, 1981]. Rocky surfaces of the mounds are thinly mantled by light-colored sediment.

The surface of the hummocky zone of phase 1 is rough, and margins are poorly defined because of the presence of numerous blocky mounds as much as 100–150 m high. In contrast, phase 2 (especially 2B) forms a well-defined lobe about 10 km wide and marked by steep marginal levees, which show prominently on the GLORIA images (Figure 5), and are as much as 100 m high as determined from the 3.5-kHz records (Figure 8a). In places the levees themselves appear hummocky; they may constitute linear clusters of mounds. The lower reaches of phase 2 (2A) spread into the axis of the Hawaiian Deep over a remarkably gentle surface (5–10 m/km, or 0.3° – 0.6° , for 30-km length), and the mounds appear relatively small and uniform in height, in comparison with those in phase 1 or even phase 2B (Figure 9a). Along the margins of phase 1 as mapped, several hilly areas, as much as 10 km across and standing several hundred meters above the adjacent slide deposits, may represent larger slide blocks carried downslope along with the more mobile slide material now forming the hummocky terrain. Alternatively, these may represent preexisting hills, either earlier slide deposits or Cretaceous volcanoes, that have been surrounded by deposits of the Alida slide.

The hummocky zone is morphologically similar to many subaerial debris avalanches, thus providing suggestive evidence of sudden failure and rapid emplacement of the two main phases of the Alika slide. By analogy with the subaerial deposits, hummocks in the Alika slide are considered to represent far-travelled masses of shattered but semicoherent lava derived from the upper submarine and subaerial flanks of Mauna Loa. This morphology and emplacement mechanism contrasts with the block slump failure along large normal faults of the Hilina system on Kilauea volcano, or with the slow creep indicated by the morphology of the adjacent Papa'u Seamount slide [Fornari *et al.*, 1979].

Fringing zone of isolated blocks. Downslope, the zone of closely spaced hummocks grades into a peripheral zone of scattered large mounds beyond the margins of massive slide material. Some of these blocks, especially those associated with phase 1 of the slide complex, are as much as several

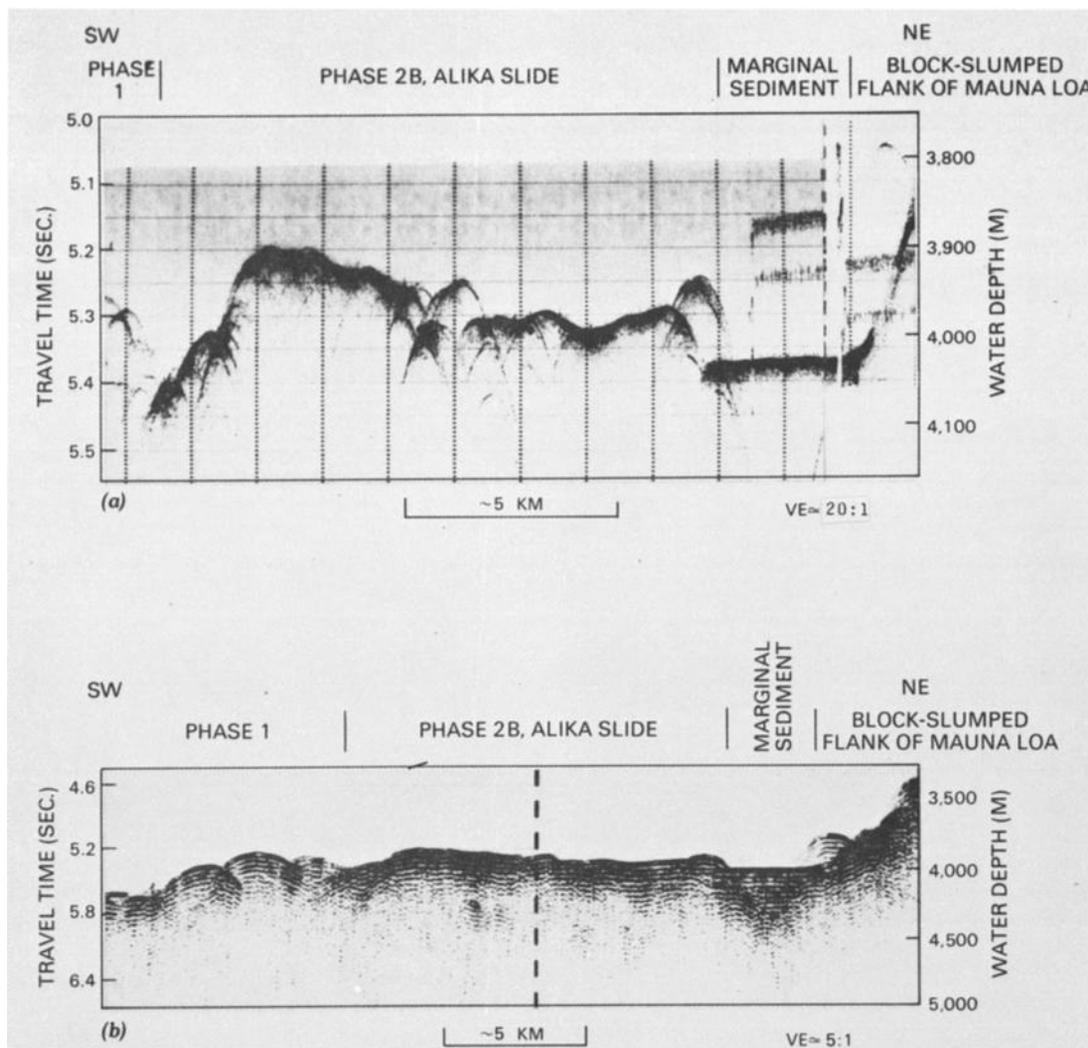


Fig. 8. Transverse seismic reflection profiles across phase 2B of the Alika slide. Locations of profiles shown in Figure 6; note that Figure 8b extends slightly further than Figure 8a. Depth is from sea surface at assumed sound velocity in water of 1500 m/s. (a) Profile at 3.5 kHz; vertical exaggeration about 20:1. (b) Two-channel seismic reflection profile with airgun sound source; same section as Figure 8a; vertical exaggeration about 5:1.

kilometers across and 100–200 m high on the 3.5-kHz profiles. Reflection profiles across the fringing zone are especially distinctive where the slide entered the flat sedimented axial terrane of the Hawaiian Deep; scattered hyperbolic echos are generated by isolated blocks that lie predominantly to the sides of the ship track. In outer parts of this zone, individual blocks may be separated by as much as 3–4 km of seemingly undisturbed sediment on the floor of the Hawaiian Deep, and some echo sounder profiles across this zone failed to encounter any of the scattered blocks evident on the GLORIA records. In other places, clusters of several large blocks define an abrupt termination of the debris avalanche deposit (Figure 9b). The axis of the Hawaiian Deep as previously mapped is crossed by distal lobes of the Alika slide, thus initially suggesting some upslope movement (Figure 1). Our data show, however, that toes of the slide lobes entered axial areas of the deep but that the deepest seafloor now lies beyond the slide termini (Figures 4 and 5).

Higher-resolution SeaMARC II sonar images are available for two parts of the fringing zone. One image (Figure 10) was obtained on a 3-km-long traverse along the basal southwest slope of Hualalai, during an equipment test by the Hawaii

Institute of Geophysics [Fornari and Campbell, 1987, Figure 4.6]. This image covers part of the northeast margin of phase 2A (Figure 6). Detailed examination of the image (Figures 10b, 10c) indicates the presence of at least 40 discrete blocks within the 10-km² area of best resolution. Diameters of individual blocks (dimensions measured perpendicular to the vehicle track) range from a maximum of about 400 m to 50 m (the smallest features resolvable on the published image).

Additional unpublished SeaMARC II images, provided by J. F. Campbell and A. N. Shor, cross the north margin of phase 2A in three places (Figure 11c). These images show especially clearly the transition (a few kilometers wide) from discrete isolated blocks into the zone of closely spaced hummocks. Shapes of hummocks are readily discernible only in the fringing zone, where individual mounds 300–400 m across are common, and an exceptional mound is about a kilometer in diameter. The smallest resolvable mounds are about 50 m in diameter for these images, also. The number of identified mounds of all sizes decreases from more than 60 per 10-km² area in the interior of phase 2A to only a single block in some marginal 10-km² areas. In contrast to the abrupt termination of the debris avalanche deposits seen in the nearby *Farnella*

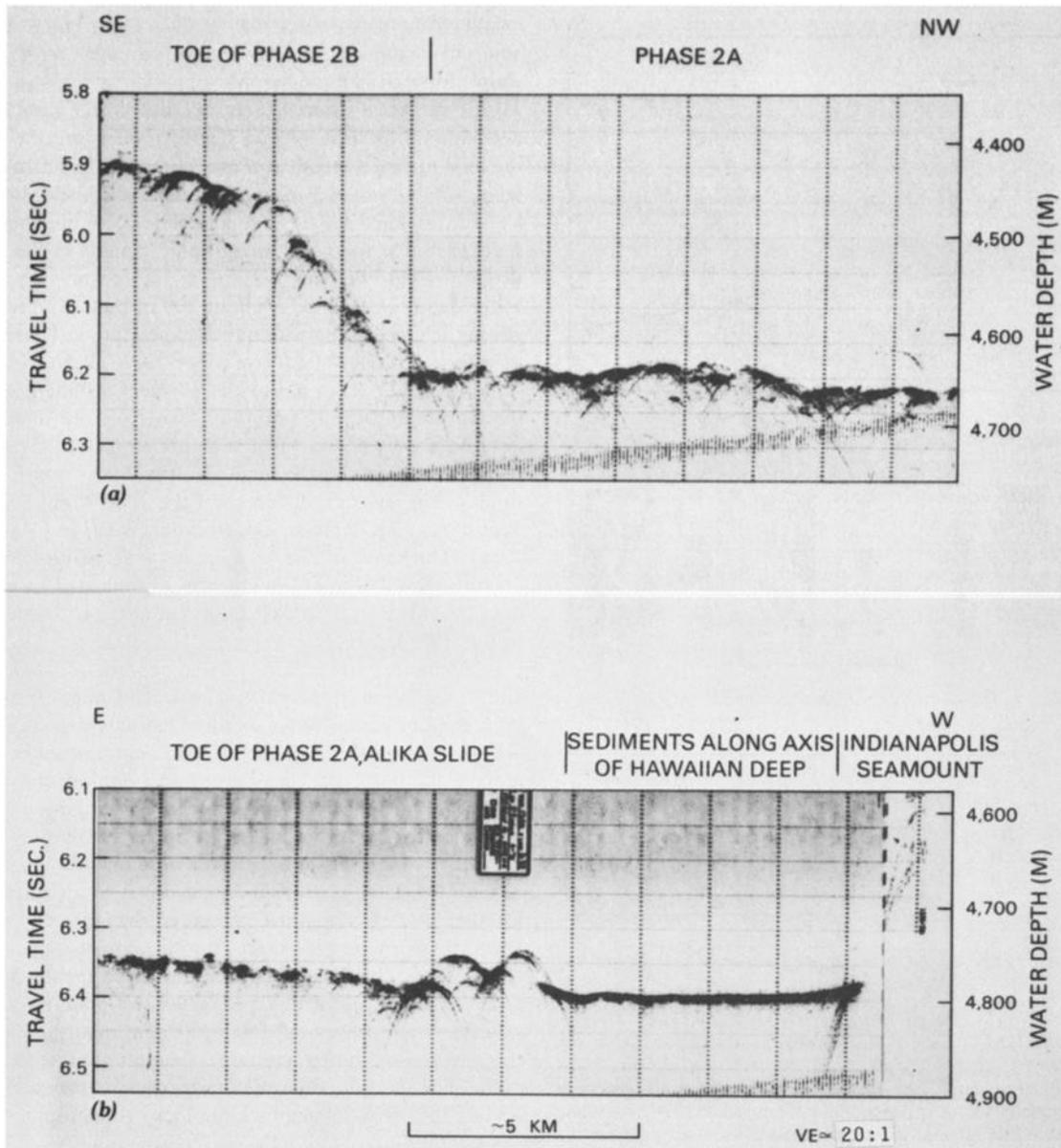


Fig. 9. Profiles at 3.5 kHz along axis of phase 2A of the Alika slide. Location of profiles shown in Figure 6. Depth is from sea surface, at assumed sound velocity in water of 1500 m/s. Vertical exaggeration about 20:1. (a) Profile from steep front of phase 2B of slide down onto gently sloping upper part of phase 2A; this profile coincides with part of the longitudinal topographic profile of Figure 7. (b) Profile across toe of phase 2A of Alika slide, across sediment-subdued axis of Hawaiian Deep, and onto steep northeast flank of Indianapolis Seamount (compare with Figure 11).

3.5-kHz profile (Figure 9b), these profiles show gradational decreases on both the side-looking sonar and the echo sounder images.

Although diameters of the isolated blocks in distal parts of phase 1 appear larger than those of phase 2, the GLORIA data are inadequate to evaluate whether median size of blocks varies with distance from source, comparable to the decreases that have been documented for subaerial debris avalanches [Siebert, 1984]. The changes represented by the fringing zones of isolated blocks at margins of the Alika slide do seem closely comparable to the increases in mound separation and proportion of matrix facies mapped in terminal areas of large subaerial debris avalanche deposits such as prehistoric Mount Shasta [Crandell et al., 1984].

Outer turbidite apron. Much of the smoothly sedimented

axis of the Hawaiian Deep adjacent to the Alika slide is characterized by sediment that yields weak backscatter on the GLORIA images and is relatively acoustically opaque on the 3.5-kHz profiles (Figure 9b). Similar sediments fill areas between the isolated mounds of the fringing zones of the slide complex, pockets within the hummocky zone, and the shallow trough between the basal slope of Hawaii Island and the phase 2 slide (Figure 8a). The airgun seismic reflection data (Figure 8b) show reflections on sediments with delays of as much as 0.2 s, indicating a thickness of at least 150 m in this area. Some sediment may have accumulated by continued slow deposition since emplacement of the slide complex, but much of it is interpreted as the deposits of turbidity flows generated during rapid emplacement of the slide masses. The increased relief on the hummocky mounds with distance from

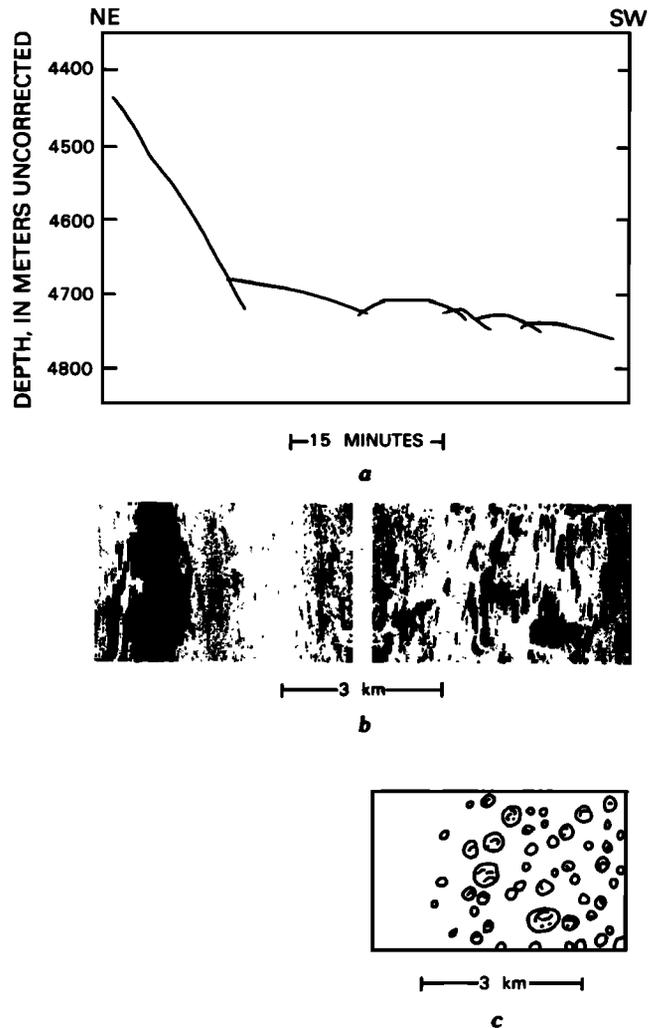


Fig. 10. Northeast margin of phase 2A, Aliko slide [from Fornari and Campbell, 1987, Figure 4.6]. Approximate location of survey shown in Figure 6. (a) Tracing of 3.5-kHz profile. Steep slope at left is base of Hualalai volcano. Just seaward of slope is smooth sediment pond that appears to onlap large blocks, represented by hyperbolic echos. (b) SeaMARC II side-scan sonar record that encompasses the profile in Figure 10a. Note that image brightness is the reverse of that on the GLORIA images; i.e., dark regions are high backscatter. Steep slope is represented by strong backscatter (dark) at left of image, the large mounds as discrete reflections to right. (c) Tracing sketch of all mounds recognizable on right side of sonar record (Figure 10b), represented as subequant to correct for distortion in sonar image. The smallest mounds identified are about 50 m across.

the breakaway source region for the slides suggests that coherent masses were segregated effectively from their matrix during downslope travel. The missing matrix material was probably dispersed in turbidity currents that flowed beyond the debris avalanche deposit. Even the gently sloping surface of the phase 2B deposit lacks sediment cover sufficiently thick or fine grained to be readily detected on the airgun or 3.5-kHz profiles.

Volume

Volumes of the slide material are only approximate because of uncertainties about thickness. Penetration of the slide material by seismic energy was poor, and seismic data do not define the base of the slide mass.

Minimum thicknesses for the late phases can be estimated

locally from bathymetry where slide lobes stand above the adjacent seafloor, but only a few transects cross relatively simple lobes at high angles. Marginal levees of phase 2B stand 75–150 m above adjacent deposits in a profile near the upper depositional limit at 3900-m depth (Figure 8a); the height of the lobe in this traverse averages about 75 m. These are minimum values because an indeterminate thickness of sediment has accumulated adjacent to the slide lobe, and because the slide probably followed topographic trough rather than flat seafloor. The inflection in slope at the toe of phase 2B, at a water depth of 4600 m, is about 200 m high (Figure 9a), suggesting a greater depositional thickness along lower parts of the phase 2B lobe. The toe of phase 2A is marked by mounds standing about 50 m above the adjacent sedimented plain of the Hawaiian Deep (Figure 9b). These inferred thicknesses of discrete phases of the Aliko slide are similar to those of sub-aerial debris avalanche deposits that are morphologically similar. The average thickness of the 1980 Mount St. Helens deposit is 45 m; its maximum thickness is 195 m [Voight *et al.*, 1981]. Thickness of the large prehistoric Mount Shasta deposit exceeds 120 m at least locally, as indicated by water well data [Crandell *et al.*, 1984]; D. R. Crandell, written communication, 1987].

A minimum total volume for the deposits of Aliko phases 1 and 2, assuming an average thickness of only 50 m (smaller than the horizontal dimensions of features detectable on the GLORIA images), would be 200 km³; more probable volumes may be about 400 km³ for phase 1 and 200 km³ for phase 2. If the entire slide complex, including the earlier large slide blocks and lobate debris flows, is considered together, the total volume is much greater. By reconstruction the preslide slope of the west flank of Hawaii Island down to a depth of about 4500 m and inferring the extent of the adjacent Hawaiian Deep, we estimate that more than a kilometer of fill has accumulated at the base of the island slope in the Aliko slide area. A simple wedge-shaped cross-sectional interpretation yields a total volume of 1500–2000 km³ for the entire slide complex. An unknown additional amount of material involved in the slides is probably widely dispersed as turbidite sediment beyond the areas defined by hummocky topography.

Age

The Aliko slide complex, although poorly dated, appears to be the youngest major gravitational slump on the west side of Hawaii Island. An unbroken 13-ka submerged reef indicates that the Kealakekua fault and subordinate breakaway scarps of the Aliko slide have been inactive since that time, despite minor historic ground cracking [Moore and Fornari, 1984]. A radiocarbon age of 31.4 ka on soil beneath a lava flow low in the exposed Kealakekua fault scarp [Kelley *et al.*, 1979] suggests a possible maximum age for the last major movement along this structure, though the carbon content of the sample is so low that radiogenically “dead” material (>40 ka) may have been contaminated by young organic matter. A maximum age for preserved subaerial gravitational slumping of Mauna Loa is provided by the Ninole Basalt, roughly dated radiometrically as a few hundred thousand years old [Lipman, 1980; G. B. Dalrymple, written communication, 1978].

Deep-tow photographs of slide blocks near the toe of the Aliko slide (F. N. Spiess, written communication, 1987) appear to show only 5–10 cm of sediment accumulation on gentle surfaces. Sedimentation rates in deep water of the Hawaiian Deep and Rise may be as low as 1 mm/ka [Winterer *et al.*,

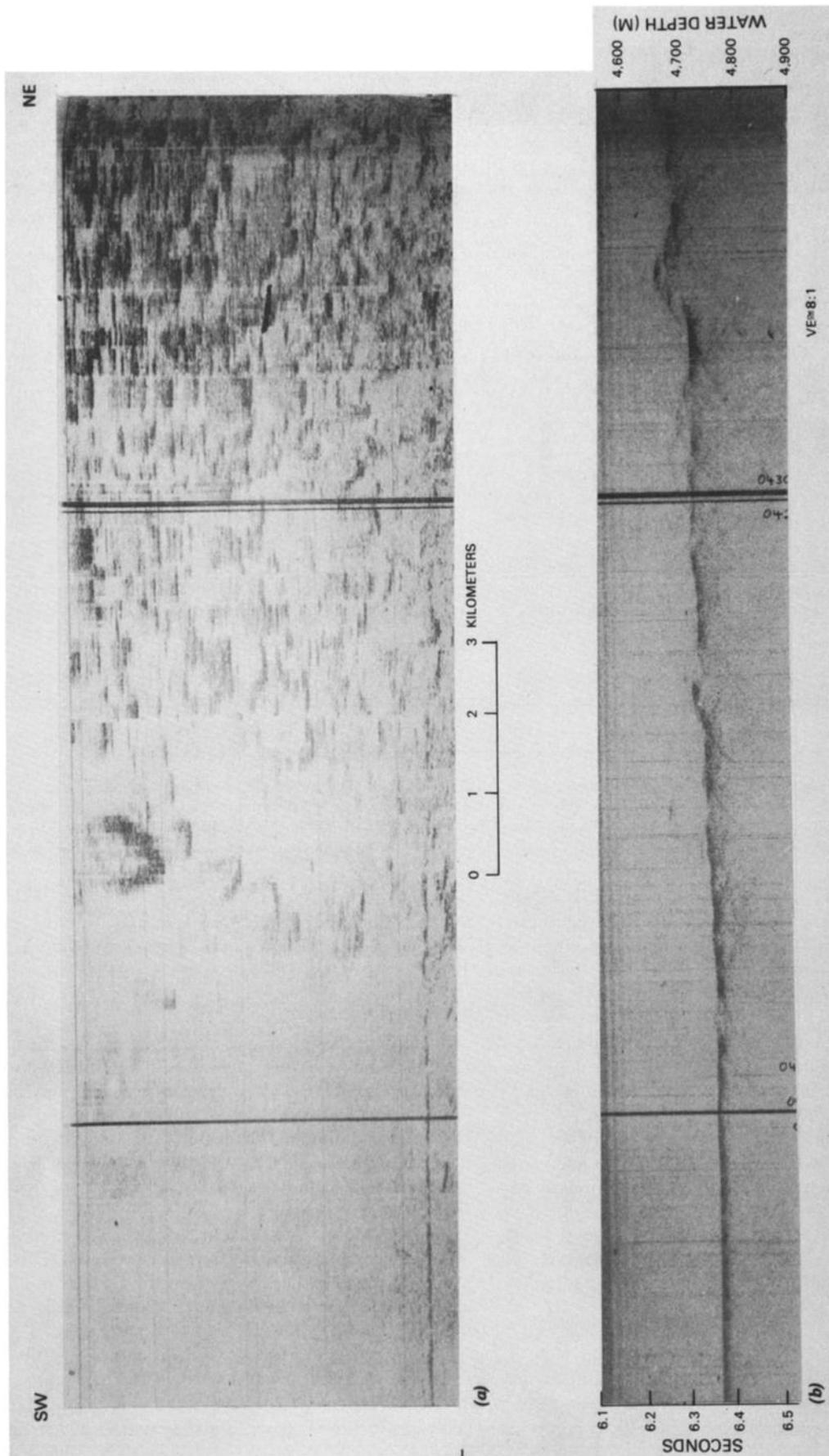


Fig. 11a, b. North margin of phase 2A, Alika slide (unpublished data provided by J. F. Campbell and A. N. Shor (written communication, 1987)). Location of survey area shown in Figure 6. (a) SeaMARC II side-scan sonar record of area approximately 8 by 13 km; only area northwest of ship track was imaged. Note that image brightness is the reverse of that on the GLORIA images; i.e., dark regions are high backscatter. The number of large mounds gradually increases toward interior of the slide. (b) Profile at 3.5 kHz. Number of mounds yielding hyperbolic reflections gradually decreases toward slide margin; compare with Figure 9(b).

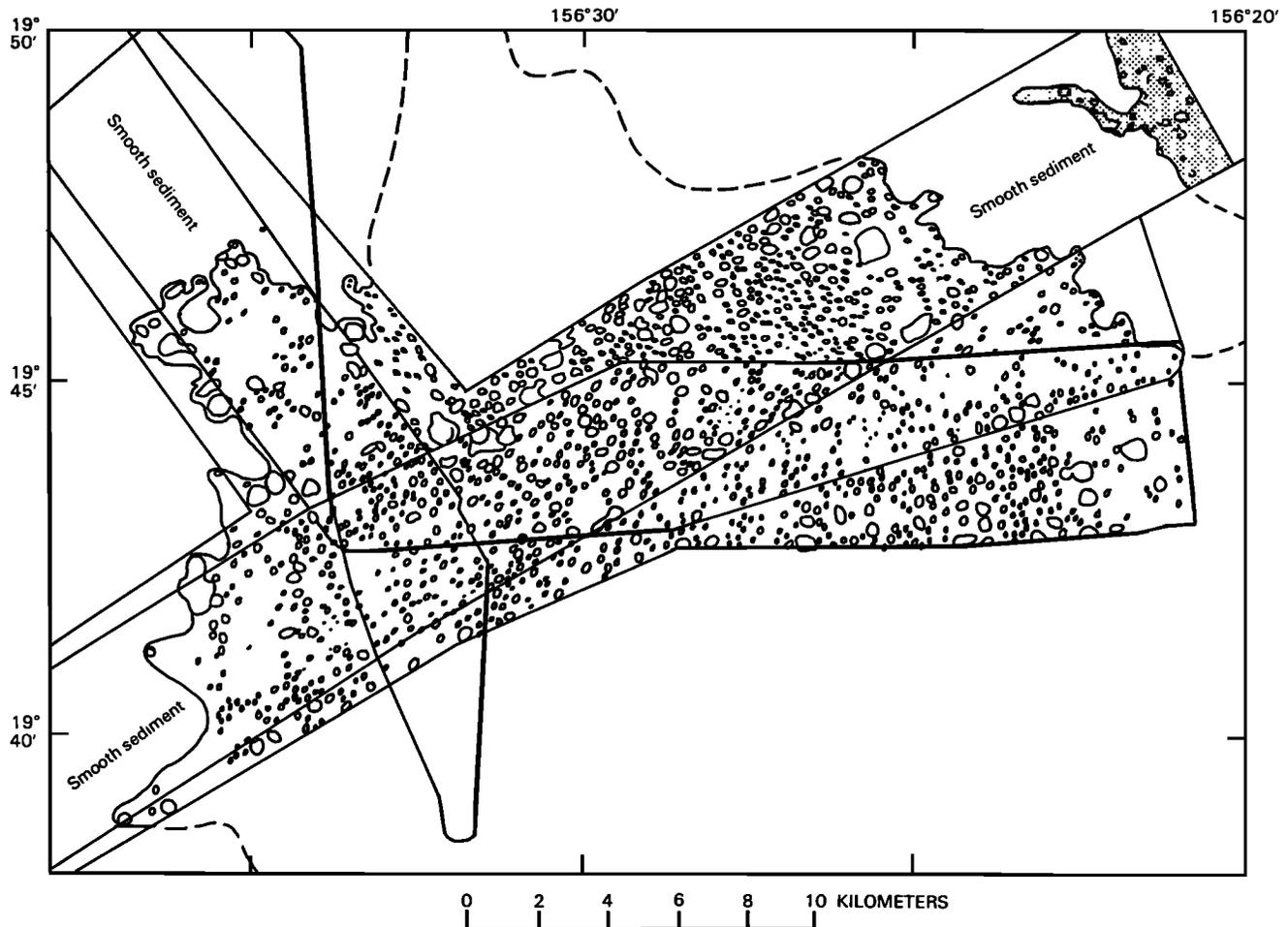


Fig. 11c. Sketch of all mounds recognizable on the SeaMARC II records. The smallest mounds identified are about 50 m across; mounds are so close together in interior of slide that individual ones are difficult to distinguish and the total number is underestimated. Extent of the toe of the Alika slide beyond the area covered by SeaMARC II is indicated by heavy dashed line, from Figure 6. Lower submarine flank of Hualalai volcano (stippled) at upper right.

1971], suggesting that the slide blocks were emplaced as early as 50–100 ka. Such an interpretation remains uncertain because of possible substantial turbidite deposition during the slide as well as subsequent bottom current erosion.

The two main phases of the Alika slide have been discussed as successive events in a single composite mass failure, based on their morphologic similarity and overlapping source regions. The alternative, that phases 1 and 2 differ in age by many years, cannot be excluded by available data; study of the amounts and types of subsequent surface sedimentation using core samples could be informative. Relations among the block slumps on the upper submarine slopes are similarly ambiguous; we interpret these as multiple gravitational slump features, related to repeated intrusion of dikes along the adjacent volcanic rift zones. Especially severe block faulting, associated with major seismic events, probably triggered the more catastrophic Alika slide.

OTHER GRAVITATIONAL SLIDES

In addition to the Alika slide complex, gravitational slide features were imaged widely elsewhere along the west coast of Hawaii Island. These include (1) large areas of lobate-terraced debris slide material along the lower southwest slope of Mauna Loa, (2) debris avalanche deposits off the west side of

Ka Lae (South Point) of Mauna Loa, and (3) similar deposits along the southwest flank of the Maui-Lanai platform (Figure 1).

Lobate Debris Slides

A distinctive submarine terrane along the lower southwest flank of Mauna Loa is characterized by an intricately lobate-terraced morphology. These deposits are tentatively interpreted as an older assemblage of gravitational debris slide deposits, emplaced as fluidized material that moved more slowly than the debris avalanches of Alika slide. Less likely, they could constitute unusually viscous lava flows related to the Cretaceous seamounts.

The main mass of this material occupies a northwest trending elliptical low area along the basal southwest flank of the Mauna Loa shield, largely south of the area covered in Figures 3–6. The area is 90–120 km long and about 25 km wide, mostly at water depths of 3500–4700 m (Figure 1). Overall slopes are gentle on surfaces of these deposits, without steep scarps or evidence of constructional volcanic centers other than the nearby large Cretaceous seamounts. This material is immediately downslope from and seemingly merges with the largest block slump features on the southwest side of Mauna Loa, between the Alika and Ka Lae slides; movement appears

to have been partly blocked to the south by Dana and Day seamounts.

Individual lobate masses are mostly 1–5 km across. They vary from subequant to highly irregular in plan (Figure 12). Many are marked by steep margins that are characterized by high backscatter on GLORIA images, and they are as much as 100–200 m high on 3.5-kHz profiles (Figure 13). Interiors of the lobes are commonly shadowed on the sonar images; they appear flat to slightly depressed in comparison with the margins, resulting in a terraced appearance. The movement style appears to have been that of a viscous liquid, characterized by a minimum yield threshold as modeled by a Bingham fluid. Such morphology in subaerial environments characterizes fluidized debris slides and viscous mudflows that are emplaced relatively slowly. Similar lobate-terraced deposits flank most of the large Cretaceous seamounts south and west of the Alika slide (Figures 1 and 6), as well as along the lower submarine slopes on the northeast side of Hawaii Island where debris avalanche deposits are absent.

These deposits are interpreted as debris slides downslope from the major block fault slump features on Mauna Loa's seaward flank. They probably moved slowly for sustained periods, in contrast with the sudden rapid movement of the Alika slide. Similar morphologies also characterize relatively viscous, slowly moving intermediate-composition to silicic lava flows. No unambiguous submarine basaltic flows related to the Hawaiian volcanoes have such viscous flow features, though; an instructive contrast is with the well-defined lava field around the west base of Loihi volcano [Normark *et al.*, 1987].

Accordingly, this terrain seems unlikely to represent unusually viscous Cretaceous lava flows predating the Hawaiian volcanism. No vent edifices seen associated with the lobate-terraced terrane, which is characterized by low relief, and no comparably large areas of such terrain are directly associated with the Cretaceous seamounts away from the Hawaiian Ridge. A large terrane (15 × 45 km across) of similar lobate terraced deposits, south of Jagger Seamount [Normark *et al.*, 1987], may mainly constitute distal debris flows from the flank of Hawaii Island.

Ka Lae Slide

This slide mass follows a channel from the upper submarine flank of Mauna Loa immediately west of Ka Lae and the major Kahuku fault on its west side (Figures 1 and 2). It is morphologically broadly similar to the Alika slide, but it is shorter, narrower, and less clearly imaged by the GLORIA system. The slide is about 65 km long and extends to a water depth of about 5200 m. It is only 8–15 km wide, reflecting confinement within a broad channel bounded by Dana Seamount to the west and the submarine continuation of the southwest rift zone of Mauna Loa to the east. The toe of the slide consists of hummocky ground characterized by a streaky sonar signature; similar but less clearly imaged material appears to extend up the channel to depths as shallow as 3000 m. Several faultlike steps are indicated by reflective zones in the detachment area at about 2000-m depth, but the main breakaway structure appears to be a larger steep slope at 500- to 1000-m depth. Some material may have slid from the flanking Kahuku fault scarp as well. Detailed configuration of the breakaway is obscured by the voluminous historic (1868, 1887) and late prehistoric Mauna Loa flows funnelled into this area by the subaerial Kahuku fault scarp.

Lanai Slides

Hummocky seafloor, imaged over an area of several hundred kilometers in the Kahoolawe Deep at the margin of the GLORIA survey, represents the terminus of several major slides derived from steep embayments (18° slope) at 1000- to 3000-m water depth on the southwest flank of the Lanai platform (Figure 1). Only part of this slide area was imaged; southwest bulging bathymetric contours at the base of the steep slopes probably mark the upper depositional limit of the slide masses. Total north-south length of the slide area is more than 100 km, and more slide terrane probably lies west of the imaged area.

An area of scattered mounds, also at the margin of the 1986 survey, wraps around the north flank of Perret Seamount (Figure 1). These mounds may constitute a fringing zone of isolated blocks near margins of the Lanai slide, in which case an intervening zone containing few blocks must have been heavily sedimented. Perhaps these thick sediments are turbidite deposits associated with emplacement of the Alika slide. Alternatively, the blocks may have slid north from Indianapolis Seamount, but no breakaway source is readily apparent.

The Lanai slides may have caused the giant tsunami that washed as high as 325 m on adjacent islands at about 100 ka [Moore and Moore, 1984], but this hypothesis cannot be evaluated further until the full extent of the slide is mapped and some independent method is developed to date the deposits.

DISCUSSION

The Alika slide complex is the largest submarine slide that has been documented in its entirety by side-scan sonar techniques. Other slides inferred to extend 120–170 km to the northeast from Oahu and Molokai [Moore, 1964] are likely candidates for features larger than the Alika slide, but sonar images and detailed bathymetry are lacking.

Comparisons With Other Submarine Landslides

The area occupied by the Alika slide, approximately 4000 km², is in the middle range of slide deposits described from continental margin settings [Moore, 1977]. Many large areas of slope failure have been recognized on or adjacent to deep-water submarine fans off major river deltas [Walker and Massingill, 1970; Droz and Bellaiche, 1985]. The Amazon Fan, for example, has several major slide deposits, the largest covering 32,000 km² [Damuth and Embley, 1981]. Even larger areas of slope failure are known from passive continental margins [Jacobi, 1976; Dingle, 1980], but the volume of the Alika slide complex (1500–2000 km³) makes it one of the largest deposits yet described.

Many of the large continental margin slides involve a few tens to a few hundreds of meters of the uppermost sediment section and occur along slope-parallel bedding surfaces on relatively gentle slopes, in contrast to the thicker rotational slump features in the volcano flank source area for the initial proximal Alika failure. All the large continental margin deposits involve unconsolidated or weakly consolidated sediment, in contrast to the lava flow parent material for the Alika slide complex. As a result, thickness, volume, and morphologic relief all tend to be lower for the continental margin deposits than for Hawaiian Ridge slides of comparable area (Figure 14). Despite these differences in scale, types of depositional units tend to be similar in both environments.

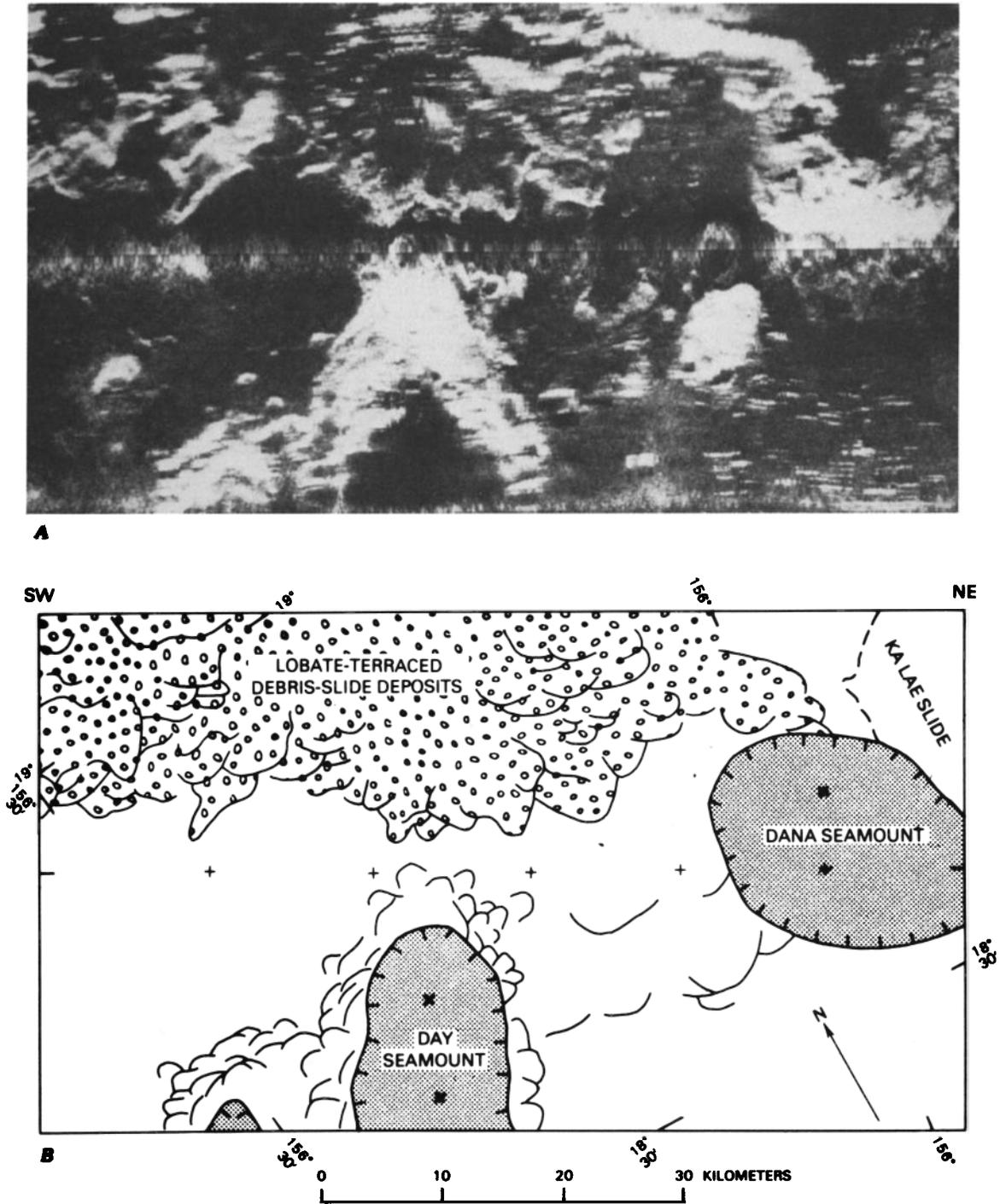


Fig. 12. Lobate-terraced debris slide deposits on lower flank of Mauna Loa south of Alika slide and similar but smaller lobate deposits surrounding bases of Cretaceous seamounts. Location of image shown in Figure 1. (a) GLORIA image of area, processed as in Figure 5. (b) Interpretive sketch of image shown in Figure 12a. Lobate-terraced deposits in upper left are southern margin of large terrane of this type between Alika and Ka Lae slides (Figure 1). Steep frontal margins of lobate terraces are indicated by arcuate lines. Approximate base of steep slopes of Cretaceous seamounts, as determined from regional bathymetry [Chase *et al.*, 1981], are shown by hachured lines; seamount summit indicated by x. Lobate terrace deposits widely flank bases of large Cretaceous seamounts southwest of Hawaii Island [Normark *et al.*, 1987]. Featureless areas in lower left and right are sedimented smooth seafloor. Crosses indicate hour marks along nadir of ship track.

From 3.5-kHz profiles of the submarine slides off Africa, Jacobi [1976] distinguishes four depositional units that are generally similar to those of the Alika slide: (1) hummocky slide deposits, (2) blocky slide deposits, (3) debris flows, and (4) deposits from turbidity currents that were generated during

the slide movement. Hummocky and blocky deposits are both zones of hyperbolic reflections, distinguished from each other by the smaller size of clasts and lack of internal structure within the blocky deposits. The blocky deposits are thought to consist of clasts that are intermediate in size between intact

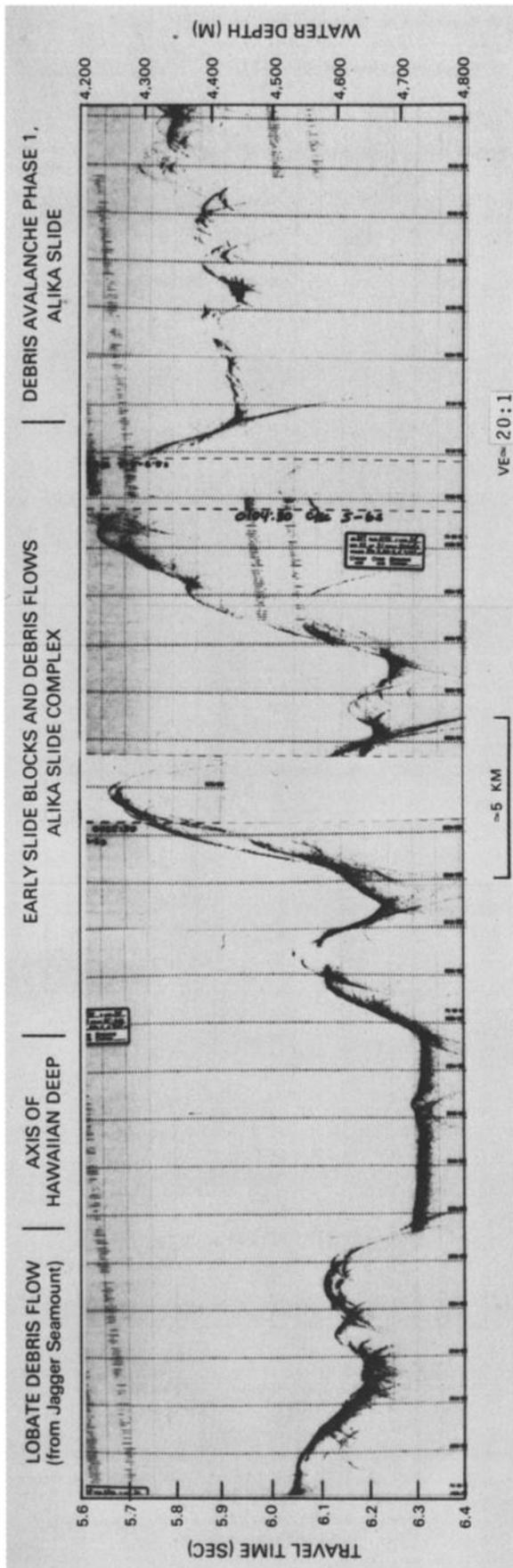


Fig. 13. Profile at 3.5 kHz across sedimented axis of Hawaiian Deep, extending from lobate debris flow deposits on flank of Jagger Seamount to terminus of large blocks from early phase of Alika slide complex. Location of profile shown in Figure 6. Depth is from sea surface at assumed sound velocities in water of 1500 m/s. Vertical exaggeration about 20:1.

glide blocks and clasts in debris flows. The hummocky areas are commonly separated from and elevated with respect to undisturbed slope deposits by scarps [Walker and Massingill, 1970; Jacobi, 1976; Damuth and Embley, 1981].

One submarine slide deposit that has been thoroughly characterized by side-scan sonar and 3.5-kHz reflection profiles is the small (6.8 km²) fjord-delta slide at Kitimat, British Columbia [Prior *et al.*, 1984]. The shallow water and small area of the Kitimat deposit allowed sonar resolution of features as small as a few meters across. The Kitimat slide involved as little as the top 4–5 m of slope deposits. Although the scale of this slide deposit is much smaller than many other continental margin deposits or the Alika slide, it includes two depositional units not described elsewhere: (1) a flanking zone of arcuate pressure ridges of folded sediment downslope from the hummocky lobes of the slide that generate weak diffuse echos on 3.5-kHz profiles and (2) outrunner glide blocks of partly indurated sediment resting on undisturbed preslide seafloor. The outrunner blocks are randomly distributed, show linear and curved glide trails, and are as large as 50 m in width, yet only 5 m or less thick. These blocks have moved across the fjord floor as much as several hundred meters.

No large submarine slides, comparable in scale to the Alika slide, are conspicuous on GLORIA images for the tectonically active west coast of the conterminous United States, where sonar coverage is complete [EEZ SCAN 84 Scientific Staff, 1986]. The 75-km-long Sur slide [Hess *et al.*, 1979; Normark and Gutmacher, 1988], involving downslope movement of unconsolidated sediments, is inconspicuous on GLORIA images in comparison with the high contrast in backscatter between volcanic rocks and sediments for the Alika slide.

Emplacement Mechanisms

Motion of the Alika slide, documented by distribution of the deposit types and by broad bathymetric features of the overall slide deposit, is shown by arrows in Figure 6. The initial phase of the slide moved 80–100 km west from a breakaway area on the steep flank of Mauna Loa, south of the Kealakekua fault. Much of the submarine and inferred sub-aerial breakaway region has been filled and subdued by younger lavas from the southwest rift zone, but anomalously steep underwater slopes, averaging 15°–20° and locally approaching vertical as viewed from a submersible in 1976 [Fornari *et al.*, 1980], extend to 3500-m depth. Below 3500 m, the contours bulge westward, indicating the upper limits of deposited slide material. Lower parts of the slide area consist of hummocky ground, with the possible exception of the relatively featureless equant low hill about 12 km across near the northern margin of the phase 1 slide. This may constitute a bedrock remnant, earlier slide material, or a large coherent mass rafted downslope within the phase 1 slide. The fringing zone of detached blocks is as much as 20 km wide and maximum block size is large, indicating sudden failure and rapid emplacement. Westward convexity of the bulge in bathymetric contours indicates that the bulk of the material was deposited during this phase.

The second slide phase was probably initiated by failure of a thick upper accumulation of the phase 1 deposit at a depth of about 4000 m. Additional material from the shallow block slump area may also have been involved. This second slide mass moved obliquely northward 55–60 km down the less steep lower slopes of Mauna Loa, also to about 4600-m depth.

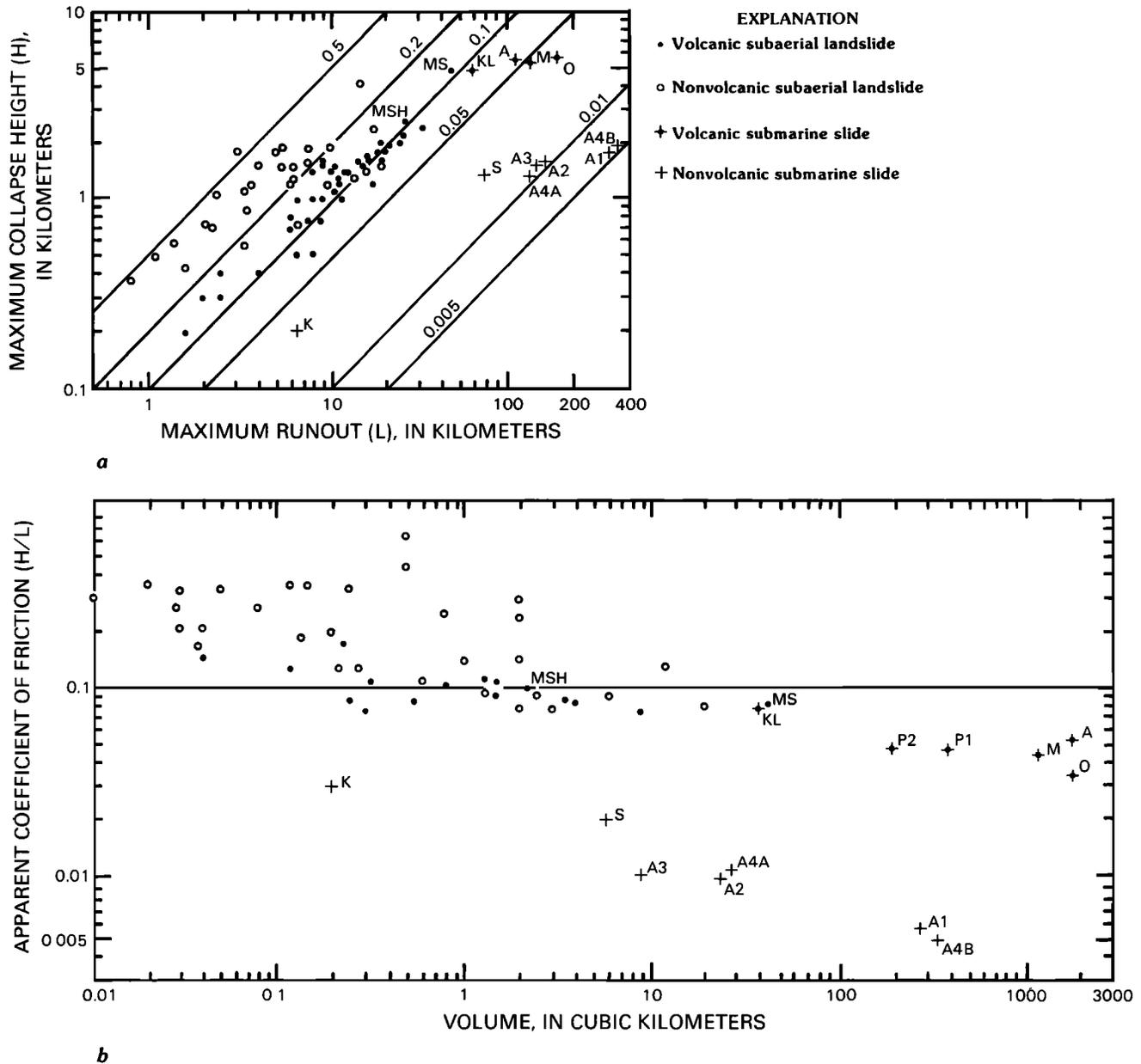


Fig. 14. Comparison of geometric relations between Alika slide, selected other submarine and subaerial slides, and subaerial debris avalanche deposits in Japan (modified from *Ui et al.* [1986a]). Alika slide values are for entire complex (A), and for the discrete late lobes of phases 1 (P1) and 2 (P2). Ka Lae slide (KL) data are also from this paper. Additional data symbols and sources for slides discussed in text: inferred Oahu and Molokai slides (O, M [Moore, 1964]), Mount St. Helens (MSH [Voigt et al., 1981]), Mount Shasta (MS [Crandell et al., 1984]), submarine Kitimat slide (K [Prior et al., 1984]), submarine Sur slide (S [Hess et al., 1979; Normark and Gutmacher, 1988]); five submarine debris slides on the African continental margin (A1, A2, A3, A4A, A4B [Jacobi, 1976]). *H* values for Hawaiian slides are based on inferred upper breakaway elevations at 1 km above present sea level, except that breakaway elevations near present sea level are inferred for the late lobe (phase 2) of Alika slide and for Ka Lae slide. Amounts of postsliding subsidence are broadly constrained by depths of -150 m for the 13-ka reef and -360 m for the 120-ka reef [Szabo and Moore, 1986]. (a) Relation between the maximum collapse height (*H*) and maximum runout distance (*L*). Diagonal lines indicate ratios of apparent coefficient of friction (*H/L*). A coefficient of friction of 0.1 is equivalent to a slope of 5.7° ; 0.01, to a slope of 0.6° . Uncertainties in approximating the coefficient of friction are discussed by Cruden [1980]. (b) Relation between apparent coefficient of friction (from Figure 14a) and deposit volume. Values for Alika slide are preferred estimated volumes for phases 1 (P1) and 2 (P2) and estimated volume of entire prism of slide debris down to level of Cretaceous seafloor (A); see text.

The direction of movement and failure area is defined by a prominent depositional lobe 40–50 km long and 10–12 km wide, bounded by scarplike lateral flow levees 20–50 m high that yield prominent linear sonar reflectors. The breakaway zone for phase 2 is probably indicated by a relatively feature-

less zone within the upper reach of the leveed trough, at a depth of 3000–3200 m, bounded on both sides by scattered mounds that are interpreted to represent attenuated remnants of the phase 1 hummocky material. Mounds of the phase 2 hummocky zone are smaller than in phase 1 deposits, and the

fringing zone of detached blocks is narrower, suggesting less energetic emplacement. Phase 2A most likely represents the fluidized runout during a single slide event, for which phase 2B was the more viscous later part. The concordant axes of flowage of phases 2A and 2B, anomalously oblique to the regional volcanic slope, suggest that they are closely related, rather than constituting discrete events.

The scale and morphology of the Alika slide is similar to some subaerial debris avalanche deposits, generated by gravitational failure of flanks of andesitic arc volcanoes. Examples include 1980 Mount St. Helens, prehistoric Mount Shasta, 1886 Bandai in Japan, and prehistoric Mount Egmont in New Zealand [Ui *et al.*, 1986a; Siebert, 1984]. Although larger in volume and horizontal extent than any known subaerial debris avalanche deposit, relations between collapse height and transport distance for the Alika slide merge with those of the largest subaerial deposits, indicating an only slightly lower apparent coefficient of friction (H/L ratio; Figure 14). Seemingly, the decreased gravitational acceleration for slide debris in water, as contrasted with that in air, is compensated by other effects such as fluidization in the aqueous medium. For subaerial debris avalanches, greater mobility of volcanic debris avalanches than nonvolcanic landslides has been analogously related to presence of abundant fluids [Ui, 1983], perhaps from melting of snow and ice derived from upper levels of the volcanic edifices. Nonvolcanic submarine landslides, such as the Kitimat, Sur, and African continental margin slides, have lower apparent coefficients of friction, presumably because of the near-mudflow behavior of the weakly consolidated sediments in water. Each group shows a trend of decreasing apparent coefficient of friction with increasing size of slides, as is typical for subaerial slides. Giant landslides in the equatorial troughs of Mars (10^2 – 10^4 km³), for which lubricating entrained fluids are inferred [Lucchitta, 1978, 1979], are similar in H/L ratios (0.03–0.10) to Hawaiian submarine volcanic slides of broadly comparable size, despite the contrasting emplacement environments and the lower gravity (40%) on Mars than on Earth.

Longitudinal profiles of the Alika slide (Figure 7) are also within ranges of those for many subaerial slides, implying rapid flowage velocities and emplacement times that may be analogous to those observed at subaerial debris avalanches such as Mount St. Helens in 1980 or calculated for representative deposits (Ui *et al.* [1986a] and Figure 7). Such velocities for subaerial slides have been observed or inferred to be as much as several hundred kilometers per hour (summarized by Siebert [1984]). Notably, the slopes of the Hawaiian Deep over which lower portions of the Alika slide traveled are no gentler than those for some large subaerial debris avalanches, such as the Mount Shasta slide that traveled at least 45 km beyond the base of the volcano on a slope of about 5 m/km [Crandell *et al.*, 1984]. The slope traversed by the lower 50 km of the Alika slide (phase 2), beyond the base of Hawaii Island, averaged more than 10 m/km and only approached 5 m/km over the lowermost 20 km of the slide area.

Velocities for the Alika slide are also likely to have been greater than those for submarine slides in unconsolidated sediments. Velocities for such slides of as much as 100 km/h and for associated turbidity currents of at least 65 km/h have been inferred for the 1929 Grand Banks slide [Heezen and Ewing, 1952; Menard, 1964, pp. 208–211; Shepard, 1963, pp. 339–343]. Menard and Shepard argue that the highest Grand

Banks velocities inferred by Heezen and Ewing are not appropriate for the observed turbidity current deposits; we infer that the higher velocities are those of the causative Grand Banks slide. The Alika slide, because of its dense lava constituents and hummocky character, would seem likely to have had even higher emplacement velocities.

Mechanisms for generating the characteristic hummocky topography by fragmentation and abrasion during flowage [Ui *et al.*, 1986b; Ui and Glicken, 1986] may also be applicable to the Alika slide. Progressive generation of a fine-grained matrix is considered particularly important during downslope movement. This fine-grained component would be relatively mobile during emplacement and would tend to flow away from larger blocks that dragged along the base of the slide, leaving them standing in relief. The hummocks would thus represent a large-scale lag deposit. Considerable fine-grained material may also have been present in the source region for the Alika slide, as rubble produced by coastal wave action. Sandy rubble is presently abundant along the upper submarine slopes of Mauna Loa.

The striking, broad marginal zones of detached blocks in the Alika slide and other submarine slides around the flanks of the Hawaiian Ridge appear qualitatively different from most subaerial debris slides, although they may result from the same basic fragmentation processes during movement. The concentration of mounds decreases toward the terminus of the Mount Shasta debris avalanche, the largest known subaerial volcanic slide; this decrease is attributed to lag deposition of blocks as the finer matrix drained downslope [Crandell *et al.*, 1984; D. R. Crandell, written communication, 1986]. In a subaqueous environment, such sorting may be more effective, and downslope segregation of the debris into block and matrix accordingly more efficient. Thus the fringing zones of isolated blocks seem reasonably interpreted as the distal portions of the debris slide, from which the muddy matrix segregated efficiently and generated turbidity flows that deposited fine-grained sediments on the seafloor beyond the toe of the main slide. Gliding of discrete isolated blocks in advance of the debris slide, as documented for some other submarine slide masses [Moore, 1977; Prior *et al.*, 1984], accordingly would not be required. Further insight into the origin of the marginal zone of detached blocks for the Alika slide might come from detailed deep-tow survey; blocks less than 50 m wide and 5 m high cannot be resolved from available data.

Unresolved Problems

The GLORIA images and related new data represent a significant advance in understanding the gravitational failure features present on the flanks of the Hawaiian Ridge, but many problems remain. Uncertainties about age of the features and timing between different phases have already been mentioned. Much also remains to be learned about the causes of failure, likelihood of recurrence, and implications for geologic hazards.

The confinement of large debris avalanche deposits, characterized by the distinctive hummocky terrain, to the southwest side of the surveyed part of the Hawaiian Ridge is perplexing. Not only is the Hawaiian Deep on average almost a kilometer shallower than on the northeast side of the islands, but it is locally obscured by the cluster of large seamounts that may partly buttress and stabilize this side of the Hawaiian Ridge. This contrast in water depth could be due to more intense volcanism, on average, and hence greater loading

along the northeast side of the Hawaiian Ridge (Kea trend) than on the southwest side (Loa trend), or to a different response of the seafloor on the southwest resulting from the clustered seamounts there.

Perhaps a significant factor in inhibiting debris avalanches on the northeast side is the generation of abundant clastic debris by wave erosion and formation of large seacliffs on the windward (northeast) sides of the islands, as well as by vigorous stream erosion on these rainy sides. Such clastic detritus may feed relatively abundant but small debris flows that have produced the characteristic lobate-terraced deposits of the windward underwater slopes. Such deposits may be efficient in cumulatively reducing the gravitational load on the subaerial and upper submarine slopes of the volcanic edifices, as well as providing a depositional buttress on the lower underwater volcanic flanks. In addition, vigorous subaerial erosion acting on the subsiding ridge could tend to stabilize the steep volcanic slopes.

These interpretations may not be valid for older segments of the Hawaiian Ridge, if the large inferred Oahu and Molokai slides are confirmed by subsequent GLORIA surveys. These slides appear to represent gravitational failure of entire half flanks of Hawaiian volcanoes, along their rift zones and extending back toward their summit calderas. These slides may result from effects of asymmetrical subsidence into the Hawaiian Deep, magmatic processes during the waning of volcanism, or other poorly understood controls. Because we have thus far sampled only a small segment of the ridge, much remains to be learned by future synoptic sonar surveys.

Finally, what are the potential hazard implications of such massive gravitational slides? What volcanic and seismic conditions trigger them, and what scale of tsunamis might be associated with such catastrophic events? Any tsunami run-up adjacent to the Alika slide area on Hawaii Island has long been covered by younger lavas. Generation of the giant wave that rode up as much as 325 m on the slopes of Lanai perhaps provides the best presently available analog of the potential for such tsunami hazards.

The likelihood of another major debris avalanche along the southwest coast of Hawaii Island is probably much lower than in the past. The rate of volcanic activity and seaward deformation along the southwest flank of Hualalai diminished with the transition from tholeiitic to alkalic volcanism about 120 ka. Rates of volcanism at Mauna Loa may also have been slowing during the past few tens of thousands of years [Lipman, 1980; Lockwood and Lipman, 1987].

The highest present potential for a debris avalanche appears to be along the south flank of Kilauea. This major region of block slumping, associated with a high rate of rift activity, is comparable to the older structures that developed along the upper submarine South Kona slopes prior to the Alika slide. Such block slumping may be a necessary prerequisite to disrupt and destabilize the seaward flank of a volcano, prior to catastrophic failure as a debris avalanche.

The submarine geologic record clearly shows that such catastrophic debris avalanches are relatively infrequent along slopes of the Hawaiian Ridge (one per 25,000–100,000 years?), but they should be considered in any "worst-possible-case" scenario for tsunami hazards in Hawaii. When the dynamics of such slides are better understood, especially their emplacement velocities, it may become possible to calculate the size of the tsunamis that could be generated.

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