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Submarine geology of Hana Ridge and Haleakala Volcano's northeast flank, Maui

Barry W. Eakins *, Joel E. Robinson

U.S. Geological Survey, 345 Middlefield Road MS 910, Menlo Park, CA 94025, USA

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Abstract

We present a morphostructural analysis of the submarine portions of Haleakala Volcano and environs, based upon a 4-year program of geophysical surveys and submersible explorations of the underwater flanks of Hawaiian volcanoes that was conducted by numerous academic and governmental research organizations in Japan and the U.S. and funded primarily by the Japan Agency for Marine–Earth Science and Technology. A resulting reconnaissance geologic map features the 135-km-long Hana Ridge, the 3000 km^2 Hana slump on the volcano's northeast flank, and island-surrounding terraces that are the submerged parts of volcanic shields. Hana Ridge below 2000 m water depth exhibits the lobate morphology typical of the subaqueously erupted parts of Hawaiian rift zones, with some important distinctions: namely, subparallel crestlines, which we propose result from the down-rift migration of offsets in the dike intrusion zone, and an amphitheater at its distal toe, where a submarine landslide has embayed the ridge tip. Deformation of Haleakala's northeast flank is limited to that part identified as the Hana slump, which lies downslope from the volcano's submerged shield, indicating that flank mobility is also limited in plan, inconsistent with hypothesized volcanic spreading driven by rift-zone dilation. The leading edge of the slump has transverse basins and ridges that resemble the thrust ramps of accretionary prisms, and we present a model to describe the slump's development that emphasizes the role of coastally generated fragmental basalt on gravitational instability of Haleakala's northeast flank and that may be broadly applicable to other ocean-island slumps.

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Keywords: Haleakala Volcano; Hana Ridge; Hana slump; geologic map; submarine morphology; landslides

1. Introduction

The subaerial geology of Haleakalā Volcano on the Island of Maui has been studied extensively since the pioneering field work of Harold Stearns in the 1940s (Stearns, 1942, 1946; Stearns and Macdonald, 1942). Three elongate rift zones radiate from its eroded summit, with the principal east rift zone extending far offshore as the Hāna Ridge (Fig. 1). Like other Hawaiian volcanoes, Haleakalā is thought to be evolving through the typical progression of early alkalic, shield, postshield alkalic, and rejuvenated stages found along the Hawaiian Chain (Clague and Dalrymple, 1987). It is currently nearing the end of the postshield stage (Sherrod et al., 2003) and its most recent eruption, Kalua o Lapa on the southwest rift zone, has a radiometric age corresponding to the interval A.D. 1425–1613 (U.S. Geological Survey, 1999). The three principal volcanic units of the subaerial edifice, as desig-

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* Corresponding author: Present address: Scripps Institution of Oceanography, 9500 Gilman Drive, Mail Code 0205, La Jolla, CA 92093-0205, USA. Tel.: +1 858 534 3355; fax: +1 858 534 6849.

E-mail address: beakins@ucsd.edu (B.W. Eakins).

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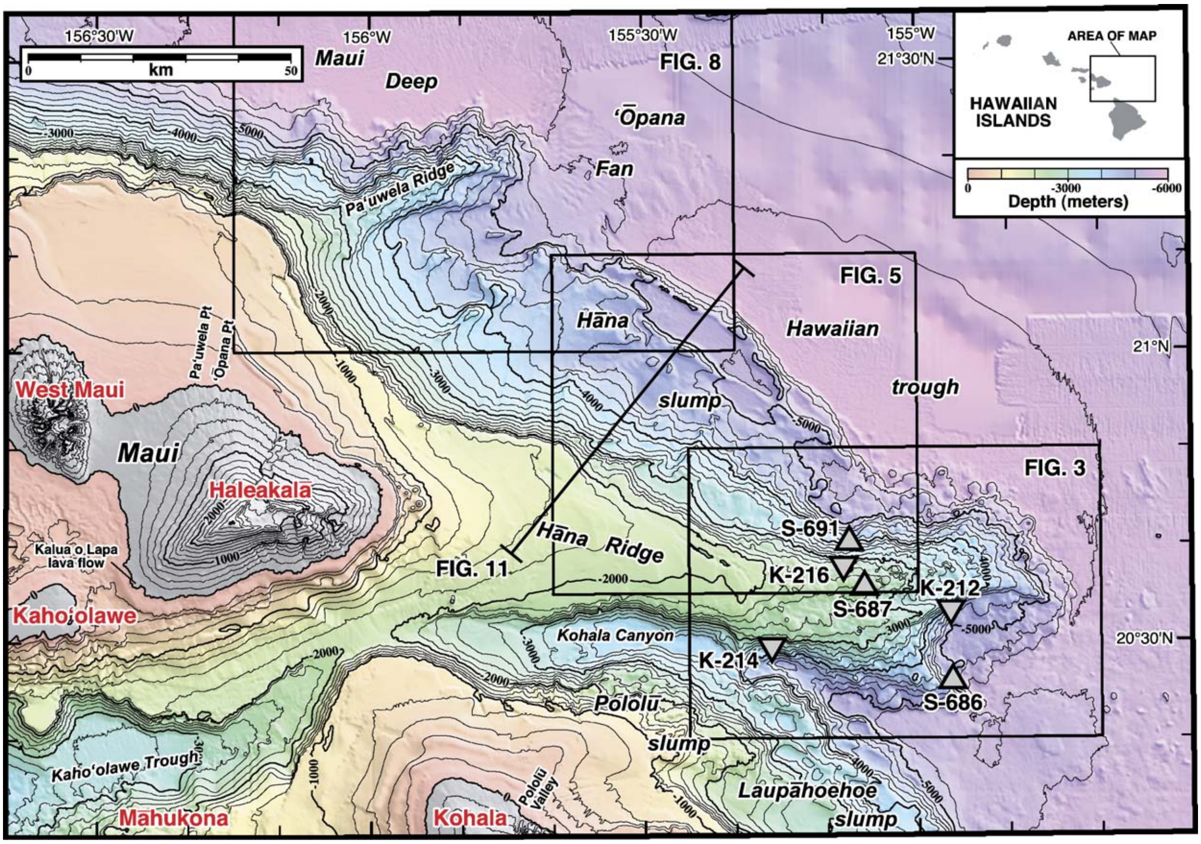

Fig. 1. Shaded-relief contour map of the subaerial (gray) and submarine (color) parts of Haleakalā Volcano and environs. The most prominent submarine features are the elongate Hāna Ridge (Haleakalā's East Rift Zone), the sediment-blanketed Hāna slump on that ridge's northern flank, and expansive, nearly horizontal terraces that represent formerly subaerial shields of Haleakalā and other, nearby Hawaiian volcanoes. Paʻuwela Ridge and ʻŌpana Fan are named after coastal headlands at the northern edge of East Maui. Triangles locate JAMSTEC submersible dives conducted on Hāna Ridge (upright—*Shinkai 6500*; inverted—*Kaiko*). Contour interval: 200 m, bold every 1000 m.

nated by Stearns and Macdonald (1942), are: (1) Honomanū Basalt—late shield-stage or early postshield-stage tholeiitic and alkalic basalts (1.1–0.97 Ma; Chen et al., 1991); (2) Kula Volcanics—postshield alkalic lavas (0.93–0.15 Ma; Chen et al., 1991; Sherrod et al., 2003); and (3) Hāna Volcanics—waning postshield, chiefly basanitic lavas (0.12 Ma–present; Sherrod et al., 2003). Postshield lava and tephra account for just 300 km^3 (Sherrod et al., 2003), about 0.4% of Haleakalā's total volume of 70×10^3 km^3 (Robinson and Eakins, 2006-this issue), but they blanket the subaerial edifice, except for limited exposures of Honomanū Basalt in deep canyons and coastal bluffs found along the northeastern coast of East Maui. Haleakalā's shield stage ended prior to 0.93 Ma, when the earliest dated lavas of the compositionally distinct, postshield Kula Volcanics erupted (Chen et al., 1991).

Haleakalā's submarine expanse is less well mapped, although the GLORIA sidescan sonar surveys of Hawaii's Exclusive Economic Zone during the 1980s (Groome et al., 1997) illuminated its major morphologic features: the 135-km-long Hāna Ridge and the Hāna slump, a large landslide on that ridge's north flank (Moore et al., 1989). A large, low-slope terrace that surrounds East Maui (Fig. 2) and caps much of Hāna Ridge is considered to be part of Haleakalā's subaerial shield, now submerged by loading-induced subsidence of the underlying Pacific plate (Moore et al., 1990). Holcomb and Robinson's (2004) geologic map of the Hawaiian Islands is based upon that GLORIA seafloor-reflectance imagery. Our interpretations presented here are augmented by more detailed, high-resolution multibeam bathymetry, seismic reflection profiles and deep-diving submersible video collected during a 4-year Japan–USA collaborative exploration of the deep underwater flanks of Hawaiian volcanoes that took place intermittently between 1998 and 2002. Smith et al. (2002b) present results from the first two years, which included mapping of Hāna Ridge's distal toe.

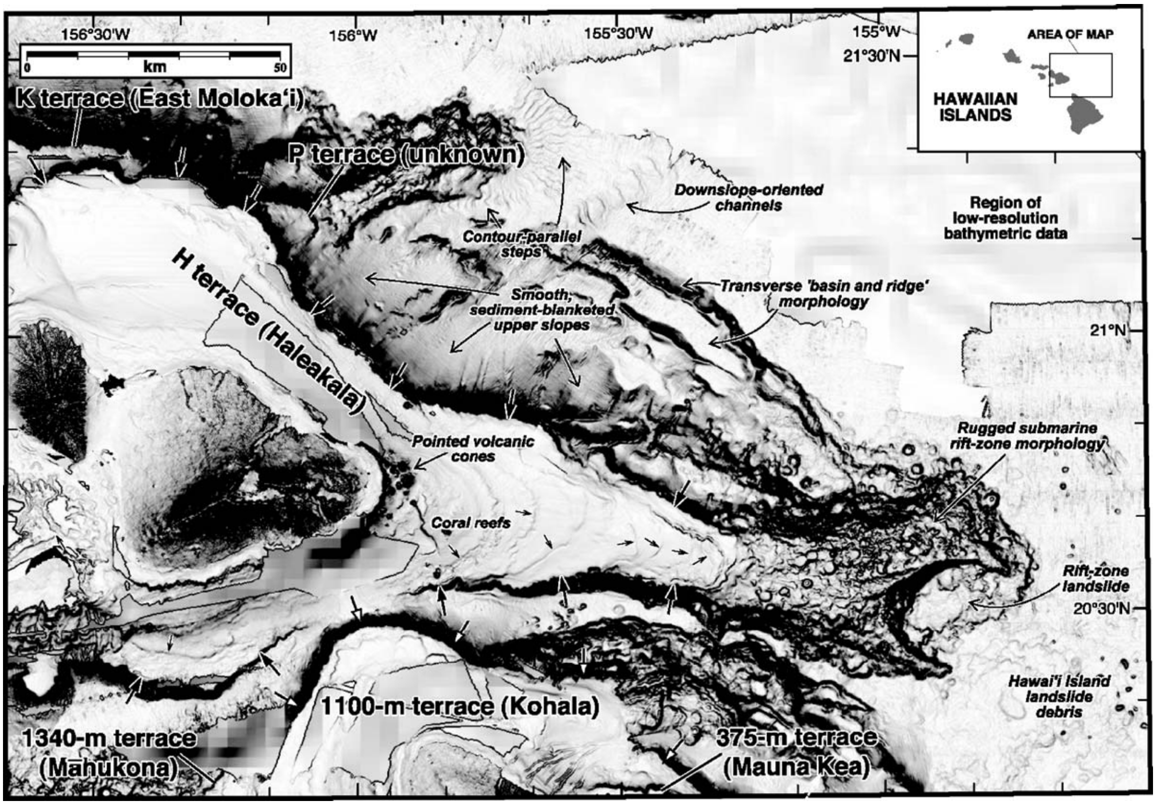

Fig. 2. Slope map of Haleakalā Volcano and environs; dark gray denotes steep slopes, light—flat-lying areas. The pronounced slope breaks at the edges of island-surrounding terraces represent the farthest extent of the subaerially built (now-submerged) volcanic shields: closed solid arrows denote edge of Haleakalā's H terrace, which overlaps the deeper K and P terraces to the north; open arrows denote edge of Kohala's terrace, Island of Hawai‘i; small arrows identify submerged coral reefs on Hāna Ridge. Other morphologic features discussed in text are also located.

Giant submarine landslides have been shown to be an integral part of the development of Hawaiian volcanoes (Moore et al., 1989, 1994). They are thought to occur predominantly during the period of active growth of the morphologic shield, when the massive volcanoes are most unstable due to vigorous lava production—oversteepening and overloading their flanks—and frequent seismic activity. They can be grouped into two general categories: debris avalanches and slumps. The avalanches are catastrophic, rapidly moving gravitational failures that deeply incise the parent volcanic edifice and typically produce arcuate headwall amphitheaters; their long-runout deposits exhibit hummocky or blocky terrain. Slower-moving, coherent slumps are wider rather than long, are relatively thick, and have transverse ridges and steep scarps at their toes; they presumably build through continual creep, punctuated by seismic events (e.g., the 1975 magnitude-7.2 Kalapana earthquake on Kīlauea's actively deforming south flank; Tilling et al., 1976; Lipman et al., 1985). The fragmental quenching of shoreline-crossing subaerial lava flows, and the production of massive volumes of volcaniclastic debris that subsequent subaerial flows build out upon, likely contribute to flank instability (Moore and Chadwick, 1995). Subaerial landslide failures, and submarine slides that retrogress to the coast, may also enhance the erosion of volcanic flanks (e.g., Pololū and Waipi‘o valleys on Kohala) and are one possible causative agent in the excavation of Haleakalā's summit crater (D.R. Sherrod, written communication).

In this paper we use multibeam sonar surveys and submersible observations of Haleakalā's underwater expanse to describe the submarine geology of the volcano and to make some inferences of its deeper structure, in particular of its mobile northeast flank, that may be applicable to other Hawaiian and ocean-island volcanoes. Two other prominent seafloor features, an elongate volcanic ridge of unknown origin and a large deep-sea fan (herein named Pa‘uwela Ridge and ‘Ōpana Fan, respectively), are also described, and we speculate on their significance.

2. Data and methods

The 4-year collaborative Japan–USA program was carried out onboard two Japan Agency for Marine–Earth Science and Technology (JAMSTEC) research vessels, R/Vs *Yokosuka* and *Kairei*. Both ships are equipped with SeaBeam 2112 hull-mounted, 151-beam sonars that record across-track bathymetry and seafloor backscatter (pseudo-sidescan) and have 'footprints' of ~140 m in 5000 m of water-depth, and are thus capable of resolving morphologic features down to a few hundred meters in size at that depth. A portable single-channel seismic (SCS) reflection system—utilized during each cruise—was towed intermittently behind ship for imaging subseafloor structures. During the 2002 survey, SCS reflection profiles were specifically oriented orthogonal to the Hāna slump's morphologic features as revealed in the multibeam bathymetry. The SCS system comprises a 350-cu. in. air gun towed 30 m aft at a depth of 3–12 m, and a 65-m-long, 48-hydrophone streamer towed 135 m aft at a depth of 8–10 m. The system was operated at a ship's speed of ~5 knots, with 'shot-points' occurring every 20 s (approximately every 50 m).

The principal use of R/Vs *Yokosuka* and *Kairei* is for deploying the manned submersible *Shinkai 6500* and unmanned towed vehicle *Kaiko*, respectively. Each submersible made three dives along Hāna Ridge's submarine-erupted volcanic zone, recording high-resolution digital video of the seafloor along the dive tracks and collecting seafloor rock samples for petrographic and geochemical analysis. Table 1 gives a brief description of the main morphologic observations and interpretations from each of these dives.

Fig. 1 shows the submarine bathymetry and subaerial topography of Haleakalā Volcano, named seafloor features, locations of submersible dives, and other figures mentioned in the text. We incorporate multibeam bathymetric data archived with: the World Data Center for Marine Geology and Geophysics, National Geophysical Data Center, Boulder, CO; Geologic Data Center,

Table 1
Summary of observations and interpretations from JAMSTEC submersible dives on Hāna Ridge (*Kaiko* in 2001; *Shinkai 6500* in 2002)

Dive no.	Site (chief observer)	Start depth (mbsl)	End depth (mbsl)	Dominant morphologies and lithologies (rock samples)	Interpretation
K-212	Inner, south-facing wall of distal arcuate amphitheater (K. Johnson)	4837	3614	Staircase of steep cliffs of truncated pillows, sediment-covered terraces, and extensive talus piles (picrites)	Northern arm of amphitheater is landslide headwall scarp
K-214	Lower slope of southern flank (T. Hanyu)	4439	3127	In situ sheet flow and pillows; talus covers steeper, shallower slopes (picrites and olivine basalt)	Entire slope is constructional (non-landslide)
K-216	Flatted-topped cones on upper slope of northern flank (Y. Orihashi)	3182	2350	In situ pillows and lobate flows on mid-slope; cones comprised of subrounded talus on ridge summit (vesicular olivine basalt)	Cones erupted in shallow submarine environment prior to significant subsidence
S-686	Southern edge of amphitheater: basal lobe on amphitheater floor and southern ridge (K. Johnson)	5241	4734	Intact and truncated pillows on basal lobe; intact pillows on southern ridge (olivine basalt). No landslide indicators.	Southern arm of amphitheater is constructional, as is basal lobe on southernmost amphitheater floor.
S-687	Flat-topped and steep-sided cones on northern ridge crest (S. Umino)	2618	2124	Flat-topped cone predominantly intact pillows and lobate sheet flows; steep-sided cone mostly broken-pillow talus. Both cones have summit pit craters with interior sheet flows.	Flat-topped cone inflational (lava pond), while steep-sided cone eruptional (magma pipe). Contrast dependent upon magma supply rate? Summit pit craters from magma withdrawal.
S-691	Lower slope of northern flank (E. Takahashi)	4347	3706	Upslope sequence of talus piles and intact pillows topped by lobate and sheet flows; sequences separated by small gulches	Flank eruptions build flat-topped terraces with steep sides of pillow lavas and pillow rubble at their bases. Northern flank comprised of numerous such stacked and overlapping flow mounds.

Scripps Institution of Oceanography, La Jolla, CA; and the University of Hawaii at Mānoa, Honolulu, HI, as well as high-resolution, shallow-water multibeam sonar surveys of the crest of Hāna Ridge (MBARI, 2000) and north of the Island of Maui (Dartnell and Gardner, 1999). We also take advantage of GLORIA sidescan imagery (Groome et al., 1997) and two-channel air gun (TCAG) seismic reflection and 3.5 kHz echo-sounder profiles archived by the U.S. Geological Survey's (USGS) Coastal and Marine Geology Program, Menlo Park, CA. Some of these profiles proved exceedingly useful in interpreting the structure of the Hāna slump and

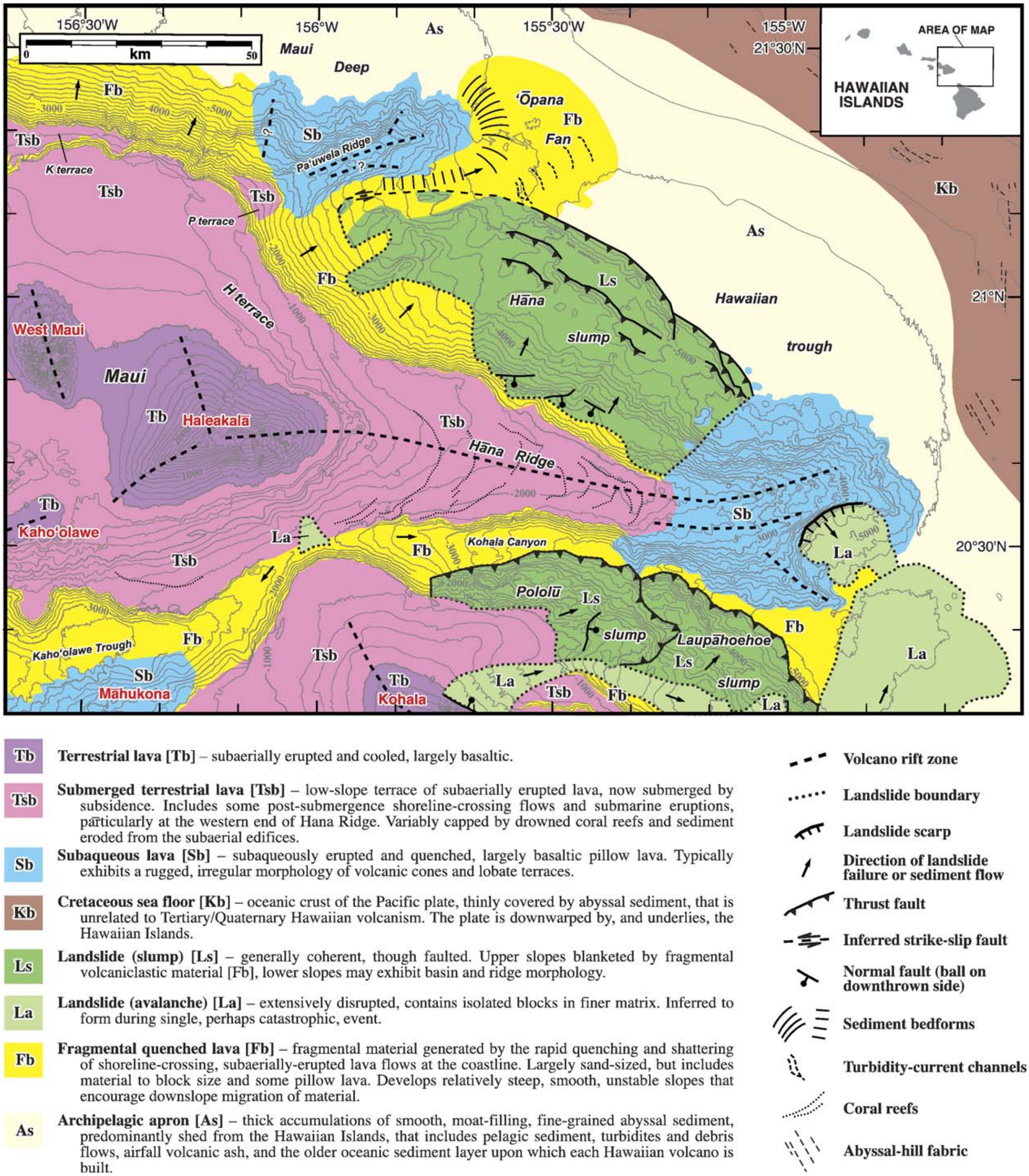

Plate 1. Reconnaissance geologic map of submarine Haelakalā Volcano and environs. Contour interval: 200 m, bold every 1000 m.

‘Ōpana Fan, a deep-sea fan infilling the Hawaiian trough. Subaerial topography is from the USGS National Elevation Dataset (1 arc second, ~30 m resolution; Data available from U.S. Geological Survey, EROS Data Center, Sioux Falls, SD).

The multibeam bathymetric data and seafloor backscatter imagery were processed, edited and displayed using the software packages MB-System (Caress and Chayes, 1995, 1996) and GMT (Wessel and Smith, 1998). ESRI’s ArcGIS software was used for generating slope and curvature grids (e.g., Fig. 2) from the compiled bathymetric and topographic data, which aided in identifying structural features and locating boundaries between geologic provinces. Plate 1 is a reconnaissance geologic map of submarine Haleakalā Volcano based upon the geophysical and submersible investigations discussed below. For this map we identify and describe geologic units consistent with previous mapping efforts around the Hawaiian Islands (e.g., Moore and Chadwick, 1995; Holcomb and Robinson, 2004).

3. Geomorphology and structure of submarine Haleakalā Volcano and environs

3.1. Hāna Ridge

The 135-km-long Hāna Ridge is the submarine extension of Haleakalā Volcano’s east rift zone, which at 160 km is the longest identified rift zone in the Hawaiian Chain (Moore et al., 1990). For much of its length it is capped by a low-slope terrace with numerous surmounting coral reefs (Fig. 2 and Plate 1) now drowned by subsidence of the ridge and tilted ~1° southward by the subsequent growth of the Island of Hawai‘i (Moore et al., 1990); the deepest reef now lies ~2000 m below sea level (mbsl). Hāna Ridge’s distal, deeper part, east of 155°15′ W (Fig. 3), exhibits the classic rugged morphology of volcanic cones and lobate terraces found on other submarine rift zones (e.g., Puna Ridge; Smith et al., 2002a). It is distinct from Puna Ridge, however, in that it has two subparallel volcanic ridge crests with an intervening 300-m-deep trough, and a third, smaller ridge deviating

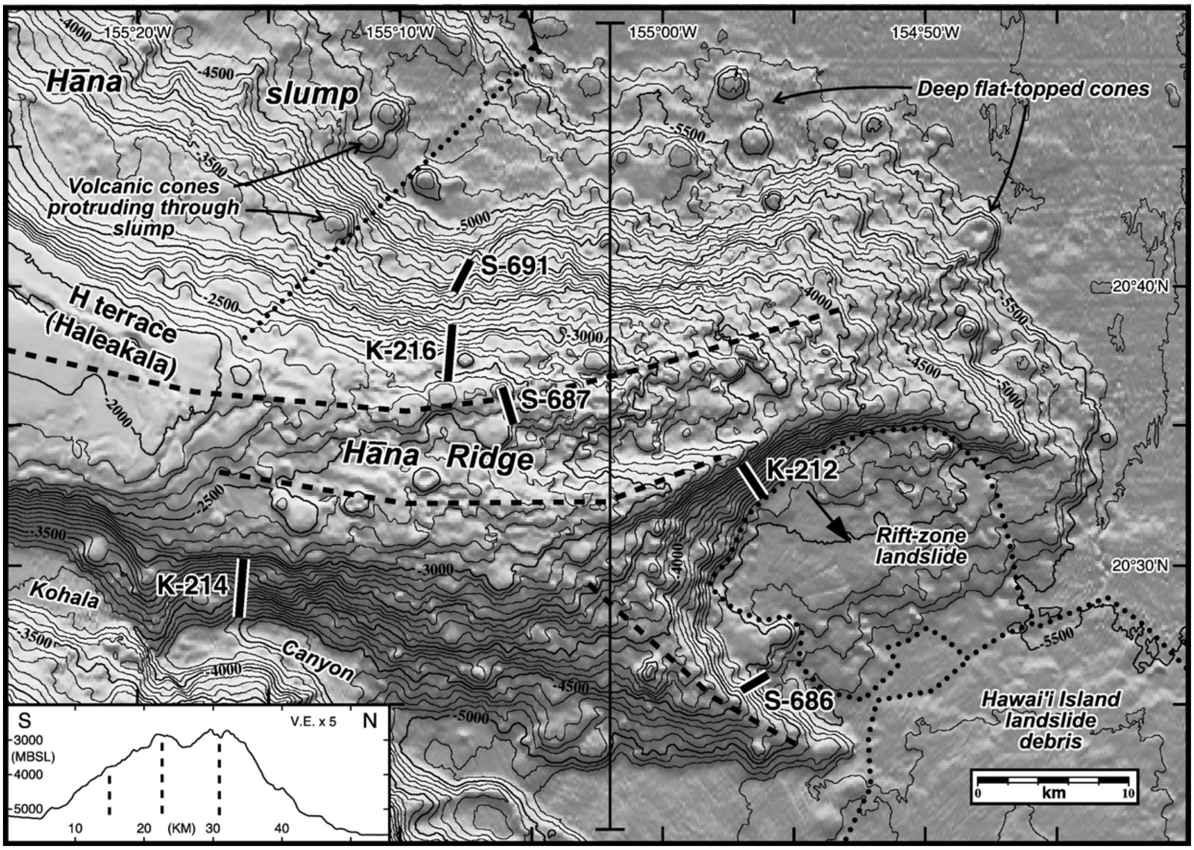

Fig. 3. Shaded-relief bathymetric map of the submarine-erupted part of Hāna Ridge. Bold lines approximate JAMSTEC submersible dive tracks; other line symbols as in Plate 1. Inset shows a north–south bathymetric profile at 155°02′ W illustrating the dual crestlines along this part of the ridge. Contour interval: 100 m, bold every 500 m. Map location shown in Fig. 1.

to the southeast (Fig. 3). Its 45-km-wide distal toe has a 22-km-wide, horseshoe-shaped amphitheater, with as much as 1600 m of relief, which Smith et al. (2002b) interpreted as a landslide scar.

Between 155°15′ W and 154°55′ W the summit of Hāna Ridge is defined by subparallel, volcanically constructed ridge crests that are separated by ~8 km (Fig. 3, inset), which Smith et al. (2002b) identified as separate volcanic axes. The northernmost crest rises 300–400 m above the intervening trough and near 155°10′ W is 200 m shallower than its southern cousin. The gentler gradient of the southern crest, however, leads to equivalent crestal depths at 155° W, where the southern crest meets the steep wall of the distal amphitheater and is diverted northeastward around that feature. The multibeam sonar data illustrated in Fig. 3 do not reveal any features (e.g., steep, inward-facing scarps) that would be consistent with the trough being a very large extensional graben—overlying a wide rift zone—with magma supplied concurrently to its faulted margins.

High-resolution shallow-water surveys along the shallow crest of Hāna Ridge (west of 155°W) and elsewhere around the Hawaiian Islands (MBARI, 2000) imaged numerous circular, flat-topped volcanic cones with horizontal summits. On Hāna Ridge the summits, like the reefs, dip southward 1.0–1.3° (Clague et al., 2000). Sampling of those flat-topped cones that are located on submarine rift zones indicates that they are composed of tholeiitic basalt and erupted underwater during their parent volcano's shield stage (Clague et al., 2000). Our multibeam survey of Hāna Ridge's deeper parts imaged several other flat-topped cones, the easternmost of which, at 154°48′ W and 5600 mbsl, is 380 m high and 3 km across at its base—its 0.13 aspect ratio is similar to those described by Clague et al. (2000) though at the high end of their size range. Its summit is tilted south-southwest 0.3° and has a 100-m deep, 800-m wide, circular, flat-floored collapse pit. Magma drainage is inferred to have collapsed the summit, as observed at other flat-topped cones (Clague et al., 2000), though we see no region of high backscatter in sidescan imagery of the moat (Groome et al., 1997) that would indicate a corresponding sheet flow was emplaced there.

3.1.1. Submersible observations of Hāna Ridge

Two JAMSTEC submersible dives, K-216 and S-687, were conducted along the northernmost of the subparallel volcanic crests of Hāna Ridge (Fig. 3). Dive K-216 investigated two east–west elongate volcanic cones just north and below the ridge crest (2410 and 2350 mbsl). The two cones consist of subrounded, highly vesicular (up to 30%) volcanic fragments (olivine basalt), indicating that the cones erupted in shallow water (Table 1 and Orihashi, 2001). The more easterly dive, S-687, visited two morphologically distinct volcanic cones at the crestline: one large flat-topped (summit at 2405 mbsl); and one steeper-sided, though also with a (smaller) flat summit (2114 mbsl). The flat-topped cone is constructed primarily of intact, in situ pillow basalt and lobate sheet flows (Table 1 and Umino, 2002). Clague et al. (2000) propose that such flat-topped cones develop through inflation of a submarine lava pond that grows upward and outward as solidification of lava spilling over the pond's marginal levees builds them ever higher. The second, steep-sided cone, which lies atop the crestline, is built mostly of rubbly pillow scree (7–15% vesicularity); few in situ broken pillow faces were observed (Umino, 2002). The morphologic contrast between the two cones may reflect differences in magma supply rate to the eruptive centers, with lower rates facilitating lava cooling and thus upward (steep-sided) growth. Both cones have summit collapse pits that reflect magma withdrawal at eruption end. As the two cones visited by dive K-216 presumably erupted in shallower water, some degree of ridge subsidence must have occurred before eruption of the shallowest, steep-sided cone on the ridge axis. Gaping fissures and collapse grabens were not observed during the dives, suggesting that extrusive, rather than intrusive, events predominated during the waning stages of volcanism. In contrast, such extensional features are observed along the crest of Puna Ridge and are thought to result from intrusive events dilating that active rift zone (Lonsdale, 1989).

Dive S-691 obliquely ascended the lower, northern volcanic slope of Hāna Ridge (Fig. 3), encountering an upslope-repeating sequence of basal pillow rubble, steep slopes of mostly intact pillow lava, and surmounting flat terrace; small gullies intervened between sequences (Table 1 and Takahashi, 2002). Rock samples collected were consistently of lower vesicularity, and higher olivine phenocryst content, than those from the summit of the ridge, consistent with a deeper eruption depth (Takahashi, 2002). Takahashi (2002) considered the slope to be a series of stacked and overlapping, single-eruption flow mounds, with each terrace representing an eruptive center. This notion supports a primarily growth model for the rift zone, where nearly the entire ridge flank is overlain by relatively young flows (i.e., the earliest rift zone eruptions would be deeply buried in the ridge interior), rather than a primarily dilation model where eruptions are confined to the ridge crest and magma intrusion displaces the flanks laterally (Borgia and Treves, 1992).

Dive K-212 traversed up the steep (26° average) slope of the arcuate, northwestern amphitheater wall at the distal end of the ridge (Fig. 3) in the hope of determining its structure and origin (Johnson, 2001). That dive found intact, downslope-oriented, elongate pillows and blocky talus on the lower slope (4837–4489 mbsl), all thickly mantled by sediment (Table 1 and Johnson, 2001). Above that lies a staircase of 20–40-m-high scarps (>50°) exposing pillow cross-sections (e.g., Fig. 4a) that are topped by gently sloping, sediment-covered terraces, typically 100–300 m wide; the scarps also have extensive talus ramps at their feet. The terraces extend (contour-parallel) for a kilometer or more and, with a length–width ratio of 5–10, are unlikely to have formed via individual flank eruptions, which typically build overlapping (stacked), quasi-circular lobate terraces. Although no clear evidence of a classical landslide scarp (i.e., fault-sheared vertical cliff) was observed on this or any other JAMSTEC submersible dives around the Hawaiian Islands, the steep, arcuate slope (one of the steepest on Hāna Ridge—see Fig. 2), elongate terraces, and the broken nature of pillow outcrops are consistent with a landslide headwall, thus the northwestern part of the amphitheater is identified as such in Plate 1 (see also Smith et al., 2002b). Rock samples collected during the dive have thick (up to 1 mm) manganese (Mn) coatings that, along with difficulties removing rocks from their abode (even talus), and the thickness of accumulated sediments (themselves semi-indurated and Mn-encrusted in spots), indicate significant time (1 m.y.?) since emplacement (Johnson, 2001).

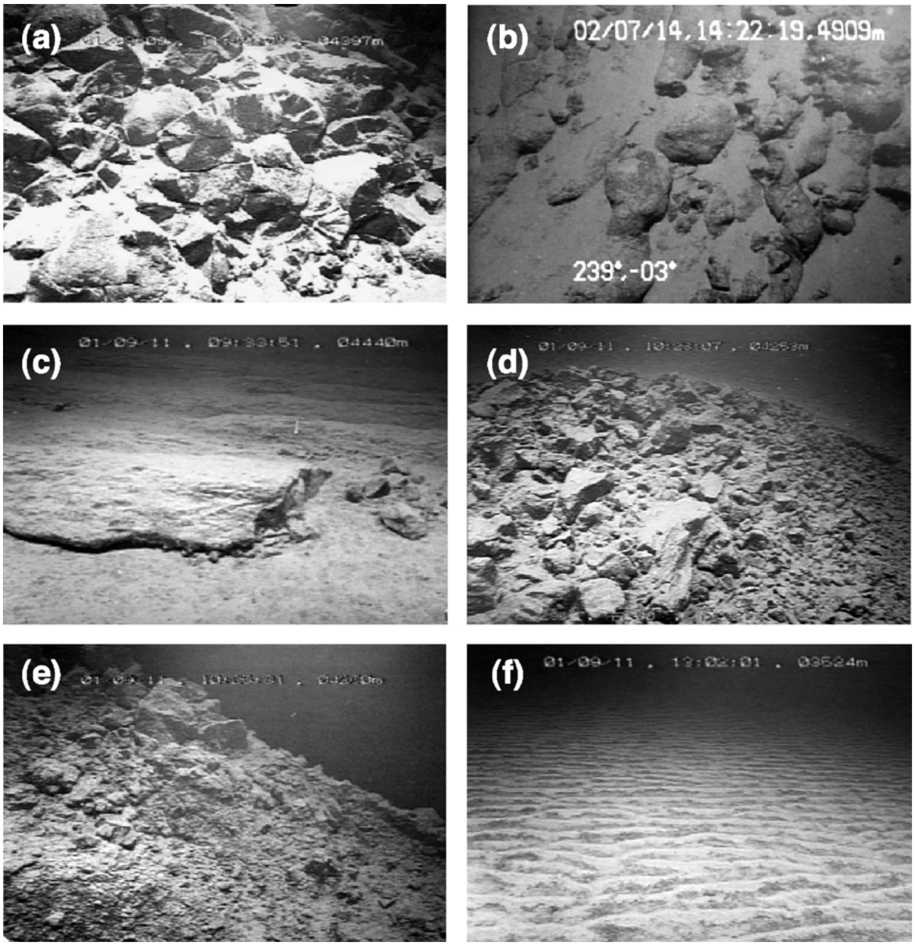

Fig. 4. Images captured from seafloor video taken during *Shinkai 6500* and *Kaiko* submersible dives on Hāna Ridge. (a) Broken pillow cross-sections exposed in a steep cliff found along northwestern amphitheater wall (K-212; 4397 mbsl). (b) Elongate, downslope-oriented pillow lava on distal, constructional southern arm (S-686; 4909 mbsl). (c) Wrinkled leading margin of sheet flow on northern edge of Kohala Canyon (K-214; 4400 mbsl). (d) Rubble mound of suspected phreatic-explosion debris found on south flank—note crater rim exposed on right-hand side of image (K-214; 4253 mbsl). (e) Ridge of autobrecciated picrite (spatter rampart?), also of suspected phreatic-explosion origin, lying a few hundred meters north of image ‘d’ (K-214; 4250 mbsl). (f) Extensive ripple field on summit of south flank vent (K-214; 3524 mbsl). Dive locations shown on Figs. 1 and 3.

The hummocky terrain of the amphitheater floor resembles other Hawaiian avalanche deposits (Moore et al., 1989), though this deposit lacks the long runout characteristic of its larger, catastrophic cousins (e.g., Nuʻuanu Slide). The southern arm of the amphitheater was explored during dive S-686 (Fig. 3), which chiefly encountered intact, downslope-oriented pillow flows (e.g., Fig. 4b), indicating that this part of the horseshoe is an in situ constructional ridge unaffiliated with the landslide (Table 1 and Johnson, 2002). The hummocky mound southeast of the horseshoe-shaped amphitheater (Figs. 2 and 3) is the long-runout deposit of a debris avalanche shed from the Island of Hawaiʻi, either Mauna Kea or Kohala (Smith et al., 2002b), that may have partially overridden the Hāna Ridge landslide deposit.

The scalloped nature of the southern margin of Hāna Ridge, downslope of the H terrace (Figs. 1 and 2), is suggestive of the (subaerial) headwall scarps of small debris avalanches. Deposits associated with such events, however, have been largely buried by growth of younger Kohala and its Pololū slump; one (young?) deposit is recognizable in the bathymetric and backscatter data in the shoalest part of the channel between Maui and Hawaiʻi islands (Plate 1). Submersible dive K-214, just east of these possible landslide amphitheaters, and beyond the H terrace (Fig. 3 and Table 1), encountered a thinly sedimented sheet flow on the canyon floor (Fig. 4c), upslope of which were in situ pillow lava and evidence of explosive events (rubble mound and autobrecciated ridge) apparent in the dive video (e.g., Fig. 4d and e). Higher still lies an extensive ripple field (Fig. 4f) that was interpreted as a sediment-covered flank vent (Hanyu, 2001). Above the terrace, the slope increases from an average of 18° to ~28° and is entirely debris covered, consisting of angular pillow scree and thin, mantling mud flows that were probably induced to migrate downslope by seismic shaking. No unambiguous landslide indicators were observed (e.g., steep headwall scarps), although the dive stopped short of the ridge crest.

3.2. Submarine terraces

Extensive low-slope terraces fringe most of the Hawaiian Islands, with the principal exceptions being Hawaiʻi's southern (Kīlauea) and western (Mauna Loa) flanks; both of these volcanoes have been vigorously active throughout the Holocene. The submarine terraces are inferred to be the submerged shields of volcanoes that have subsided under their own massive weight (Mark and Moore, 1987). Subsidence occurs throughout the shield stage, when the volcanoes grow most rapidly and load the underlying Pacific plate, and presumably continues into the postshield stage while neighboring volcanoes grow and isostatic equilibrium is approached (Moore, 1987).

Volcano growth above sea level builds the classic low-profile Hawaiian shield as effusive, low-viscosity lava flows are able to travel large distances over low gradients before significant cooling occurs. Flows that reach the coastline, however, are rapidly quenched by seawater, forming a steep, unstable near-shore slope of fragmental volcaniclastic sediment near the angle of repose (Mark and Moore, 1987; Moore and Chadwick, 1995). This pronounced coastal slope-break is continually reworked by shoreline-crossing flows as the volcano grows rapidly. Once volcanism wanes and subsidence predominates, the slope-break is submerged, forming a submarine terrace whose margin marks the paleocoastline at the end of major shield building (Moore, 1987). Coral reefs that surmount these terraces provide a means of dating submergence and the end of the parent volcano's morphologic shield stage (Moore and Campbell, 1987).

The H terrace that wraps around East Maui (Fig. 2) represents Haleakalā's submerged shield (Moore, 1987). It extends eastward along the south flank of Haleakalā, covers part of Hāna Ridge, and thence extends northwestward toward Paʻuwela Ridge, forming a broad shelf. Other terraces apparent in Fig. 2 include the East Molokaʻi Volcano's K terrace, and the terraces of Kohala, Mauna Kea, and Māhukona, which partially ring the Island of Hawaiʻi. On Plate 1 these terraces are mapped as 'submerged terrestrial lava,' although sampling of Haleakalā's H terrace has been limited to capping coral reefs and post-submergence 'pointed volcanic cones' (Moore et al., 1990; Clague et al., 2000). The H terrace overlaps and thus post-dates the K terrace and a 'P' terrace above Paʻuwela Ridge. Gentle eastward tipping of the K terrace is inferred to result from the subsequent construction of Haleakalā to the southeast (Clague and Moore, 2002). The significance of the P terrace will be discussed below.

Recovery of subaqueously erupted tholeiitic basalt samples during dredging of coral reefs on the H-terrace summit of Hāna Ridge indicates that tholeiitic basalts continued to erupt after the end of the morphologic shield stage, when the H terrace was already largely submerged (Moore et al., 1990); rocks dredged from the pointed volcanic cones at the western end of the ridge (Fig. 2) are highly vesicular hawaiite and likely erupted in shallow water during the postshield stage (Clague et al., 2000). There thus appears to be an offset between the end of the morphologic shield stage, when volcanic production wanes and the shield starts to submerge, and the end of the petrologic shield stage, when erupted lavas change from predominantly tholeiitic to predominantly alkalic compositions. It also seems likely that coastally derived volcaniclastic sediment and weathering products shed from East Maui are mostly accumulating on the wide H terrace and are no longer being fed in significant quantities to the Hāna slump, ‘Ōpana Fan, or into the Hawaiian trough.

3.3. Hāna slump

The submarine northeast flank of Haleakalā was mapped by Moore et al. (1989) as a large landslide that is downslope from the formerly subaerial part of Hāna Ridge and from Haleakalā's summit (Figs. 1 and 2, and Plate 1). Morphologically, the landslide fits their criteria for slumps, which are inferred to move incrementally and coherently over a significant period of time, rather than during a single (catastrophic) event, and we concur with that interpretation. The Hāna slump is 95 km wide by 40 km across, covering an estimated 3000 km^2, and has a series of transverse basins and ridges at its toe that are reminiscent of the leading edges of accretionary prisms (e.g., Huguen et al., 2001). The Cretaceous oceanic crust underneath the Hāna slump, and Haleakalā's entire edifice, tilts ~2° southwest towards the axis of the Hawaiian Ridge (Watts and ten Brink, 1989).

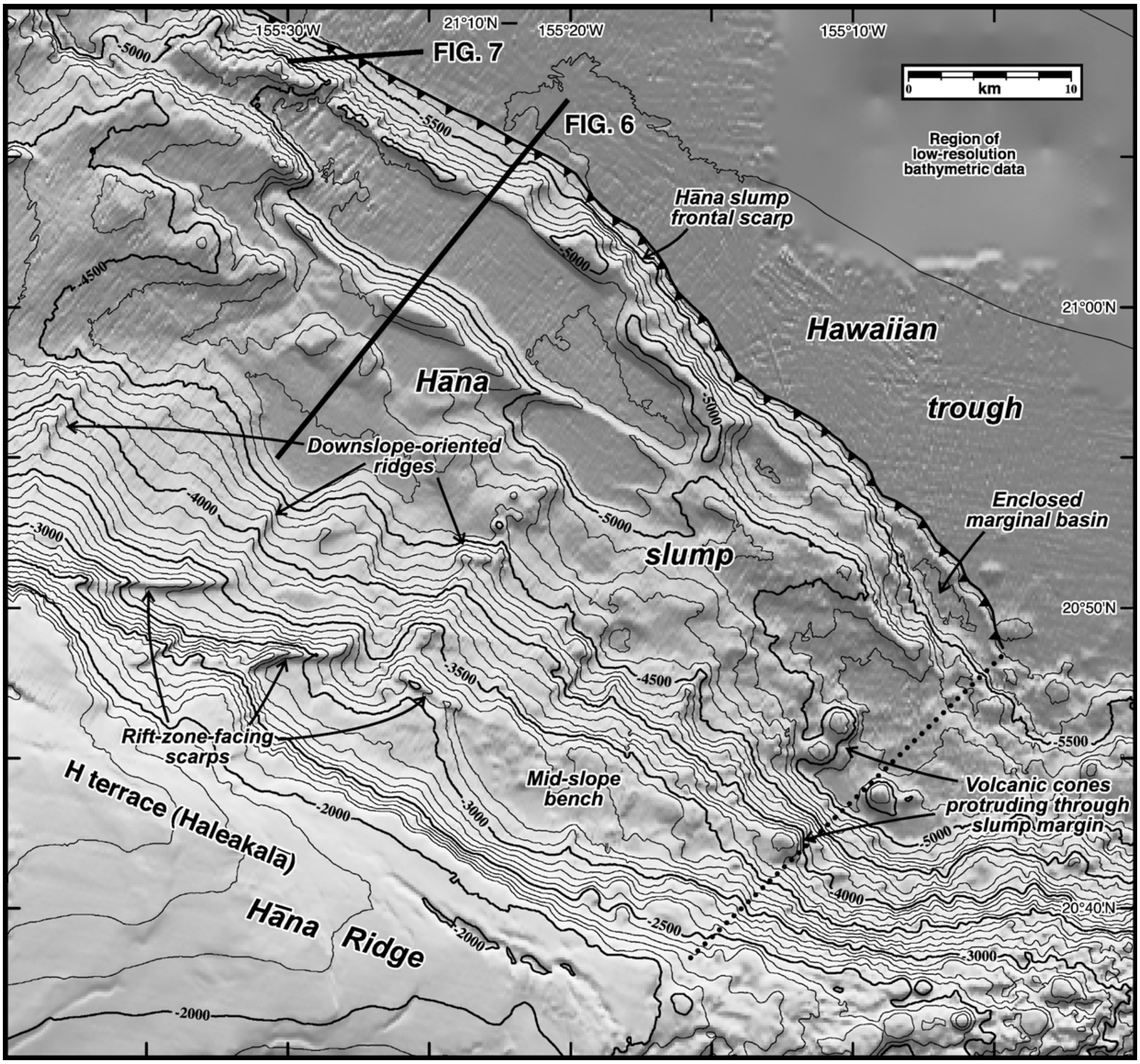

Fig. 5. Shaded-relief bathymetric map of the Hāna slump. Line symbols as in Plate 1. Contour interval: 100 m, bold every 500 m. Map location shown in Fig. 1.

3.3.1. Hāna slump's upper slope

The northwestern half of the Hāna slump's upper slope, below Haleakalā's summit, is morphologically smooth (Fig. 2) with relatively low sonar backscatter. A similarly smooth slope below subaerial Kīlauea has been identified as a sediment blanket (Moore and Chadwick, 1995). Multichannel seismic reflection profiling of Kīlauea's upper submarine flank (Hills et al., 2002; Morgan et al., 2003) supports that interpretation: it shows up to 1.5 km of young, largely undeformed, slope-parallel sedimentary bedding that unconformably overlies older, partly deformed, 1-km-thick volcaniclastic sediment. As we have no constraints on the thickness of the Hāna slump, we infer a similar thickness in its interior, thinning toward the margins.

Elongate ridges, with roughly 100 m of relief and high sonar backscatter, extend downslope from the edge of the H terrace, one of which lies within the smooth, presumably sediment-rich slope (Figs. 2 and 5). JAMSTEC submersible dives on similarly situated ridges on Kīlauea show that those are ribs of massive pillow lava, interpreted as primary volcanic edifice protruding through the thick sediment pile (Lipman et al., 2002). Such large ribs might also be constructed by flank vents or voluminous shoreline-crossing flows that develop underwater lava tubes and build pillows downslope upon the sediment pile.

The slump's southeastern upper slope is morphologically more complex. A mid-slope bench at 3300 mbsl may be a downdropped part of Haleakalā's shield (Fig. 5). Below the bench lie several downslope-oriented ridges that may also be pillow lava ribs. Linear, east-trending ridges, at 20°50′ N, 155°35′ W, and a small transverse ridge immediately to the southeast (Fig. 5) have the only rift-zone-facing scarps on the upper slopes. Landslides that are largely translational (i.e., basal failure surface is mostly planar; Varnes, 1978) may exhibit antithetic normal faults at the head of the slide (an extensional regime) and these landward-facing scarps are interpreted as such on Plate 1.

3.3.2. Hāna slump's distal toe

The distal part of the Hāna slump comprises several linear, transverse ridges behind which lie flat-floored basins (Figs. 2, 5 and 6). The main, distal ridge is up to 800 m high and 44 km long and is convex moatward in plan; its frontal scarp defines the central leading edge of the slump (Figs. 2 and 5, and Plate 1). Behind it lies a prominent, elongate (35 × 5 km) and enclosed basin that is deepest (5500 mbsl) at its southeastern end, which may indicate regional tilt or preferential sediment supply at its northwestern end. Seismic reflection profiles across this basin and others (e.g., Fig. 6) reveal sedimentary layers that are tilted increasingly landward with depth, indicating gradual back-tilting during basin development. Other, smaller ridges at the distal toe are also convex moatward; their basins are also typically flat-floored, though inclined slightly landward (Fig. 5).

The Hāna slump's frontal scarp shows a pair of flat benches at its leading edge (600 m and 2 km wide, and

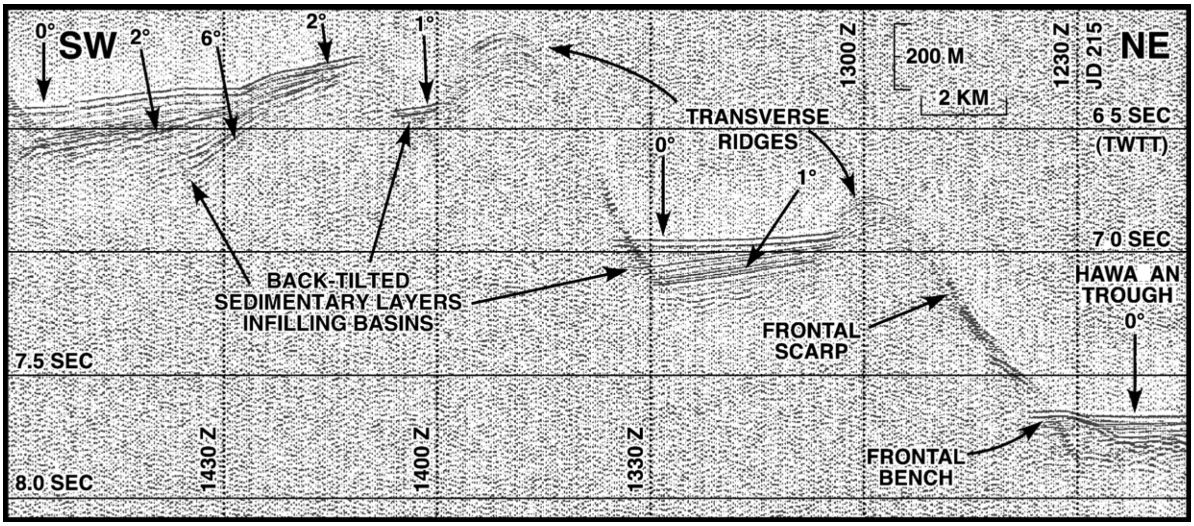

Fig. 6. SCS profile 10-3 across the Hāna slump's transverse basins and ridges, collected during JAMSTEC survey YK2002. Profile illustrates the increasing landward tilt with depth of sedimentary layers within the basins, indicating gradual rotation of strata (calculated tilt angles assume 2 km/s sediment velocity). Opacity of ridges is inferred to result from the low power output of the SCS gear. Vertical scale bar for panel assumes two-way travel time (TWTT) of 750 m/s. Profile location shown in Fig. 5.

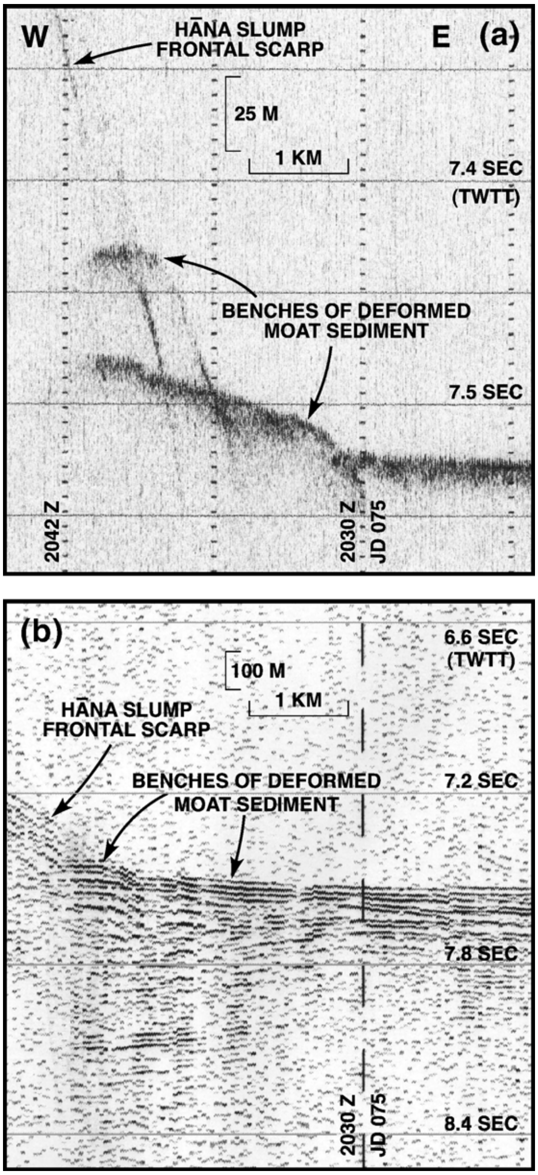

Fig. 7. Deformed moat sediments at toe of the Hāna slump. (a) 3.5 kHz profile. (b) TCAG profile. Uplifted, though still horizontal, sedimentary (moat) layers comprise the frontal benches, which are 600 m and 2 km in width, and uplifted 70 and 10 m above moat floor, respectively. Note exaggerated two-way travel time (TWTT) scale of panel (a) relative to (b); vertical scale bars assume a TWTT of 750 m/s. Profiles from GLORIA survey F-3-88-HW; location shown in Fig. 5.

70 m and 10 m above the Hawaiian trough) that are most obvious in the 3.5 kHz echo-sounder profile of Fig. 7a, but also apparent in the SCS and TCAG profiles of Figs. 6 and 7b. These frontal benches are composed of horizontal layers that appear to be moat sediments uplifted by advancement of the slump's toe.

3.3.3. Hāna slump's lateral margins

The Hāna slump's southeastern margin (Fig. 5) is a diffuse, 10-km-wide transition from the generally smooth, low sonar backscatter of the largely sediment-laden main slump to the rugged morphology and higher backscatter of Hāna Ridge's submarine-erupted volcanic zone. That transition zone exhibits increasing protuberance of volcanic cones (Figs. 2, 3 and 5) with inferred decreasing sediment thickness, similar to the striking textural contrast downslope from the easternmost cape of the Island of Hawai‘i, where Kīlaeua's east rift zone extends offshore (Moore and Chadwick, 1995). There is no evidence of strike-slip faulting along this margin of the slump, and we cannot determine whether the observed volcanic features erupted through (post-date) the sediment pile or were partly buried by it (pre-date).

There is a very narrow (10 × 2 km) enclosed marginal basin at the base of the transition zone, just 50 m shallower than the moat, that is fronted by an 80–100-m-high ridge (Fig. 5), which might also be considered evidence of sediment off-scraping. A point worth emphasizing here, however: the Hāna slump's frontal scarp does not extend past the downslope continuation of the H terrace's farthest extent. This correlation of Haleakalā's most distal paleocoastline with the edge of the slump implies a linkage between volcaniclastic sediment supply at the shoreline and the development of the slump, which we will discuss further below.

To the west of the Hāna slump's transverse ‘basin and ridge’ complex are several large knolls (up to 10 km across and 500 m high) of unknown composition and origin (Fig. 8). These blocks lie downslope from the steep summit region of Haleakalā, a solid edifice built mostly of thick sequences of subaerially cooled lava flows rather than fragmental hyaloclastite. We suspect that the knolls were calved from Haleakalā's paleoshoreline during slump development, perhaps as largely cohesive, individual landslide (avalanche?) events, and have included them within the slump's geographic outline (Plate 1). If this is true then they would be composed predominantly of thick stacks of intact, though probably brecciated, subaerial lava flows, similar to heavily fractured though still recognizable pāhoehoe flows encountered on a JAMSTEC submersible dive that visited landslide blocks at 3400 and 3100 mbsl on Mauna Loa's western flank (Eakins, 2002).

A seismic reflection profile (Fig. 9) across a linear, downslope-oriented ridge on the southern margin of the ‘Ōpana Fan's sediment chute (Fig. 8) shows that it contains folded sedimentary layers that onlap chute sedi-

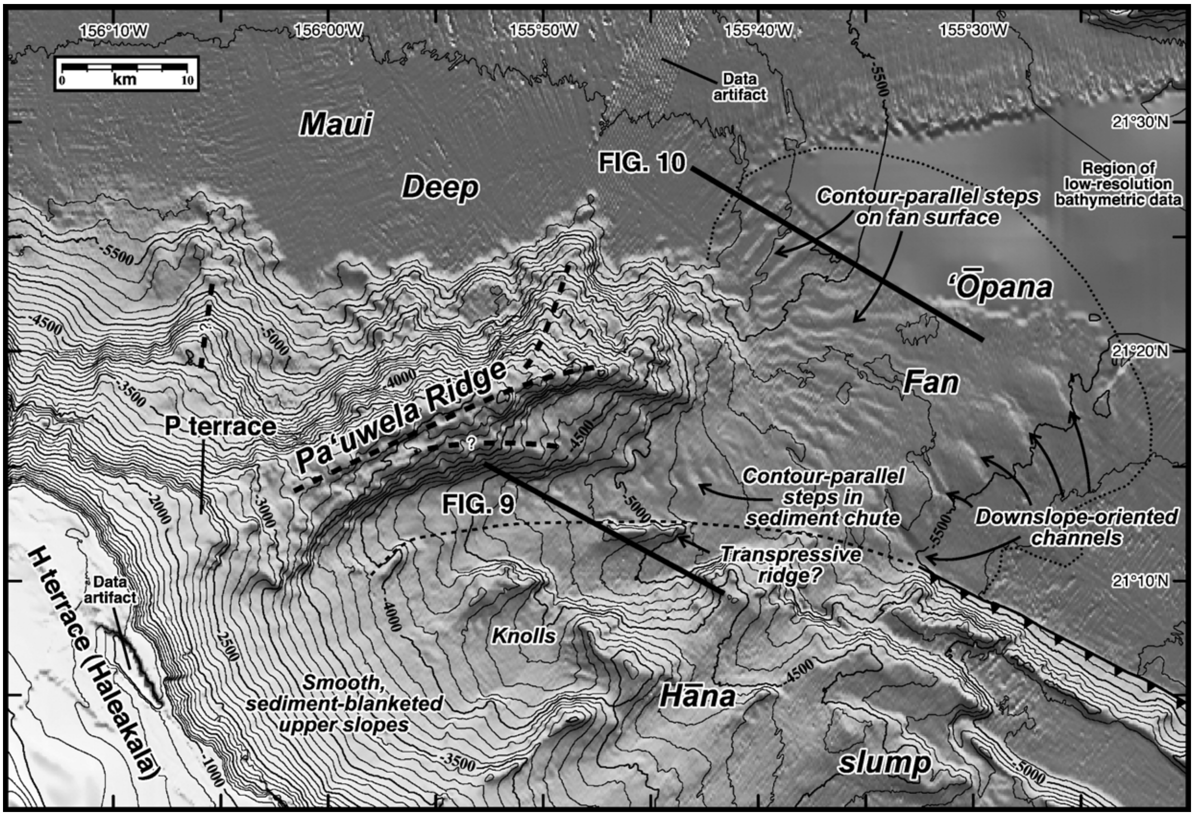

Fig. 8. Shaded-relief bathymetric map of Pa‘uwela Ridge and ‘Ōpana Fan. Line symbols as in Plate 1. Contour interval: 100 m, bold every 500 m. Map location shown in Fig. 1.

ments. High-resolution multibeam bathymetry and seismic reflection profiling of Papa‘u Seamount on Kīlauea’s and Mauna Loa’s shared flank, in a potentially similar tectonic environment, indicate that that ridge was uplifted due to oblique convergence (upthrusting and shearing) at the margin/toe of the Hilina slump (Morgan et al., 2003). We infer that the ‘chute ridge’ is similarly transpressive in origin and marks the northwestern lateral margin of the slump (Plate 1). The presence of ‘Ōpana Fan directly downslope (fed by the sediment chute) and the low sonar backscatter of the Hāna slump’s northwestern upper slope, as well as the upslope summit of Haleakalā, imply that sediment was supplied in significant quantities to this region of the slump. Shearing of the northwestern slump margin, which is not observed on the southeastern margin, suggests that the largest dis-

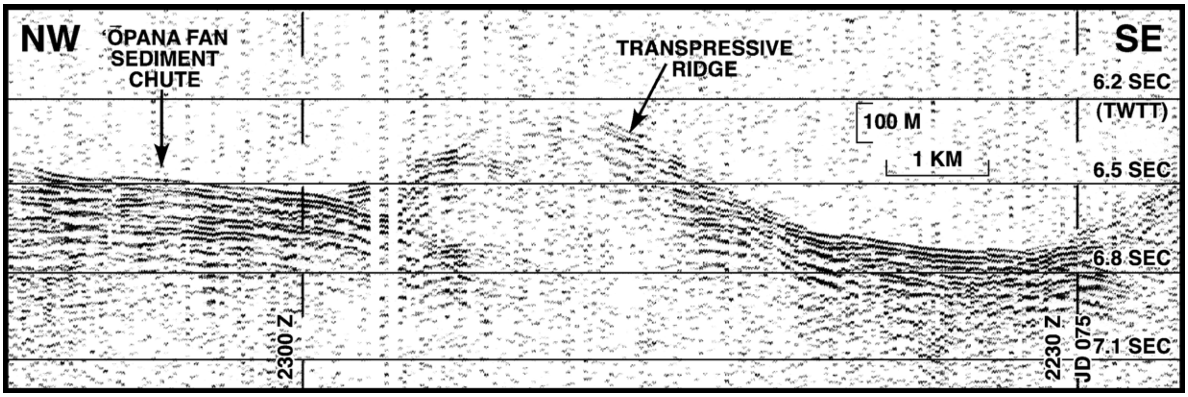

Fig. 9. TCAG seismic reflection profile across the Hāna slump’s northwestern lateral margin. Profile from GLORIA survey F-3-88-HW; location shown in Fig. 8.

placement occurred on the central and northwestern parts of the slump.

3.4. Hawaiian trough

The smooth, flat-floored trough lying in front of the Hāna slump (Figs. 2 and 5; max. depth 5750 mbsl) is tilted ~0.5° towards the Island of Hawai‘i such that its axis lies only a few km beyond the slump's leading edge. On the order of 100 m of abyssal (pelagic) sediment mantles the Cretaceous oceanic crust away from the Hawaiian Islands (Winterer, 1989), incompletely obscuring the underlying abyssal-hill fabric (Plate 1 and Holcomb and Robinson, 2004). That material thickens towards the Hawaiian trough into a smooth archipelagic apron that is largely derived from mass wasting of Hawaii's volcanoes (Plate 1 and Holcomb and Robinson, 2004). The apron likely consists of fine-grained turbidite sequences, debris flows, volcanic ash and pelagic sediment.

3.5. Pa‘uwela Ridge

Pa‘uwela Ridge is a 50-km-long, 20-km-wide ridge lying north of East Maui that rises 2600 m above Maui Deep (Figs. 2 and 8); Moore et al. (1989) speculated that it may be a Hawaiian rift-zone ridge. It is characterized by an irregular, rugged morphology, high sonar backscatter, and a bifurcated distal toe, similar to the tips of other submarine rift zones (e.g. Puna Ridge; Lonsdale, 1989) where the rift-zone plumbing system is thought to end short of the ridge tip and eruptive flows build outward in several directions. The ridge is capped at its western end by the small, low-slope P terrace at 2300 mbsl (Figs. 2 and 8) that, like the similar K and H terraces, we infer to be the submerged part of a formerly subaerial volcanic shield, and we follow Moore et al. (1989) and Holcomb and Robinson (2004) in interpreting it as a Hawaiian rift-zone ridge constructed primarily of subaqueously erupted pillow lava (Plate 1).

It is tempting to affiliate Pa‘uwela Ridge with East Moloka‘i Volcano as it roughly aligns with that volcano, and East Moloka‘i's K terrace extends eastward to 156°20′ W, where it is overlapped and buried by younger Haleakalā (Figs. 1 and 2, and Plate 1); the ridge is not aligned with Haleakalā or West Maui volcanoes. Pa‘uwela Ridge's capping P terrace, however, is 600 m deeper than the K terrace (deeper even than the projection of the K terrace's gentle eastward tilt). Subsequent loading by Haleakalā or earlier cessation of lava flows farther from East Moloka‘i Volcano might account for that difference, assuming that late in the morphologic shield stage subaerial flows continue to build the shield close to the summit while distal shorelines subside. Alternatively, the ridge may belong to an unrecognized volcano overlain by massive Haleakalā, much as Māhukona has been (largely) buried by Hualālai, Kohala, and Mauna Kea (Clague and Moore, 1991). Without petrologic sampling of the ridge we cannot rule out a non-Hawaiian origin (i.e., Cretaceous seamount), though we consider this less likely because the elongate ridge shares few morphologic characteristics with those seamounts (see Bridges, 1997).

3.6. ‘Ōpana Fan

‘Ōpana Fan is a deep-sea sediment fan that intervenes between Maui Deep and the Hawaiian trough, the two deepest parts of the moat encircling the Hawaiian Islands (Figs. 1 and 8). The fan is 42 km across, rises 350 m above the moat axis, and, at 1500 km^2 and ~300 km^3, is the largest deep-sea fan along the young end of the Hawaiian Ridge. It exhibits low sonar backscatter and, except for the bedforms and canyons described below, has a smooth surface inconsistent with the hummocky and blocky morphology of debris avalanche deposits (Moore et al., 1989). The fan was fed at its western margin by a 7- to 10-km-wide sediment chute south of, and parallel to, Pa‘uwela Ridge. Its source region appears to have been the lengthy northeastern margin of Haleakalā's H terrace and may therefore record the subaerial development of Haleakalā's shield stage prior to submergence of the H terrace and sediment-source cutoff. The close proximity of the fan with the Hāna slump raises many questions about its development, such as why sediment supply builds fans in some areas and slumps elsewhere, but we can infer that fan growth—because it extends passed and is not deformed by the slump—postdates the development and emplacement of the Hāna slump's frontal scarp, though it may have grown commensurate with other parts of the slump farther upslope.

The fan's northern flank exhibits asymmetric, contour-parallel bedforms that are slightly convex downslope (Figs. 2 and 8) and have ~1 km wavelength (900–1300 m) with 20–40 m of vertical relief between steps. A 3.5 kHz echo-sounder profile across this part of the fan (Fig. 10) shows the steps to consist of sedimentary layers that tilt towards the fan apex. Moore et al. (1994) termed similar features west of Kaua‘i, observed during the GLORIA surveys, ‘mud waves' after the nomenclature of Flood and Shor (1988). The ‘contour-parallel steps' of Fig. 10, however, are quite different from the

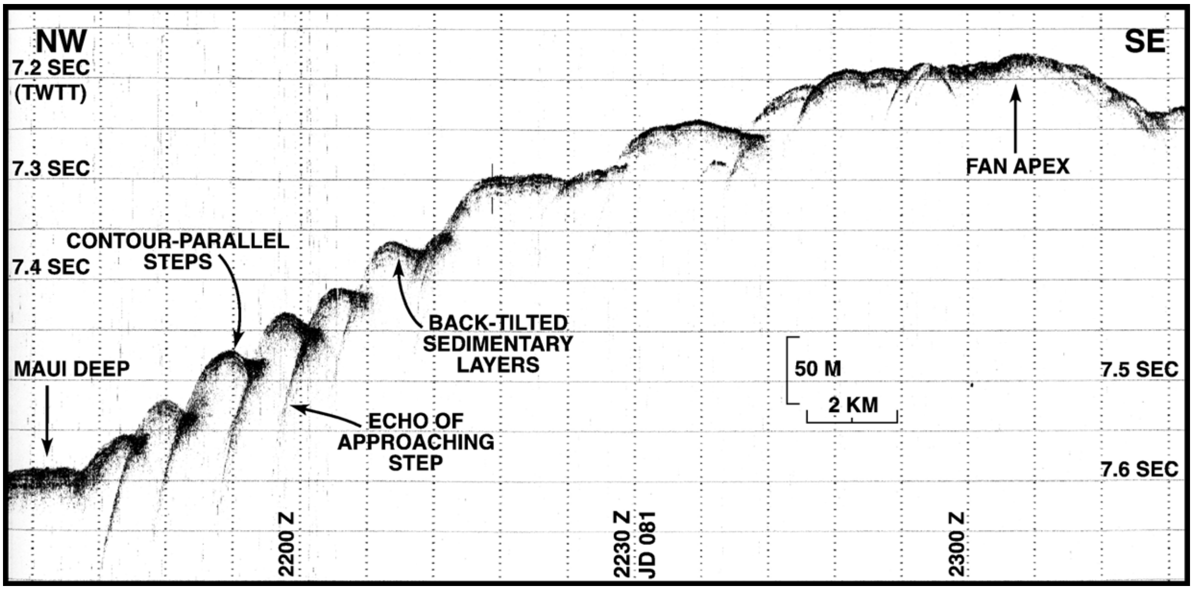

Fig. 10. 3.5 kHz echo-sounder profile across ‘Ōpana Fan. The contour-parallel steps of the northern fan margin, similar to those within the fan's sediment chute, are tentatively interpreted as sediment waves generated by turbidity currents. Vertical scale bar assumes two-way travel time (TWTT) of 750 m/s. Profile from GLORIA survey F-4-88-HW; location shown in Fig. 8.

features described by Flood and Shor (1988) in their 3.5 kHz profiles, which were interpreted as having formed via deposition on the lee side of sediment wave crests under steady bottom currents (Flood, 1988). The bedforms also do not appear to fit the criteria of Lee et al. (2002) for sediment waves built by intermittent turbidity currents (e.g., wave migration upslope, beds continuous across waves, overall wave field convex upward, wavelength decreases downslope) and, in plan, trend counterclockwise downslope (opposing the northern hemisphere Coriolis effect).

Similar contour-parallel steps are also found in the sediment chute that funneled sediments to ‘Ōpana Fan (Figs. 2 and 8, and Plate 1). Such features have also been identified upslope of the aforementioned bedforms described by Moore et al. (1994), which they inferred fed those features. Wynn et al. (2002) investigated morphologically similar bedforms in the confined, proximal parts of turbidity current channels offshore of the Canary Islands. They concluded that those features are coarse-grained sediment waves, and that they are common in gravel-rich turbidite systems and normally occur on erosive channel floors. Turbidity currents likely have incised five steep-sided, downslope-oriented canyons on the southern margin of ‘Ōpana Fan (Figs. 2 and 8, and Plate 1) but we have no information on sediment grain size anywhere in the fan or on the H terrace. Without more conclusive information on the contour-parallel steps on the northern fan margin and in the sediment chute, which nearly intersect at the fan apex (Fig. 8), we lean towards the sediment-wave interpretation to explain these features, though with the reservations noted above.

4. Discussion

4.1. Development of Hawaiian rift zones

One of the atypical morphologic expressions of Hāna Ridge, Haleakalā's submarine east rift zone, is the presence of two distinct, subparallel volcanic ridge crests, separated by 8 km, along the deeper, submarine-erupted part of the ridge (Fig. 3). At Kīlauea's east rift zone, volcanism—in the form of eruptive fissures, volcanic cones and pit craters—is confined to a long, narrow (1–3 km wide) topographic ridge, and is inferred to be representative of Hawaiian rift zones (Walker, 1999); the active part of its underlying plumbing system, along which magma from the summit reservoir is injected, is considered to be a few kilometers in width or less. Considering the 8-km distance between crestlines at Hāna Ridge, it seems likely that they were built sequentially, rather than concurrently at the margins of an exceptionally wide rift zone (Fig. 3). If the depth to the crestlines of the subparallel ridges is taken as a measure of relative age—with shallower crestlines being younger than deeper ones (having been constructed upon its neighbor's flank)—then Hāna Ridge's shallower northern crestline would be younger than its southern neighbor. Smith et al. (2002b), on the basis of higher sonar backscatter (i.e., less sediment cover), also concluded that the northern crest is youngest. If this age progression is indeed true, then the locus of volcanism on the ridge jumped (northwards) several kilometers, requiring a commensurate shift in the rift-zone plumbing system.

Mauna Loa's southwest rift zone has also migrated (westward) towards the heads of several major landslides (e.g., South Kona, ʻĀlika 1 and 2; Lipman et al., 1988; Moore et al., 1989, 1995). Lipman (1980) inferred that this migration was due to the landslide removal of confining material to the west, and to the buttressing effect of Kīlauea Volcano to the east. Alternatively, Clague and Moore (2002) argue that jumps would more likely occur into the volcanic pile as the stress field responds to landslides removing material (Fiske and Jackson, 1972). Smith et al. (2002b) follow a similar argument to suggest that the landslide amphitheater at the toe of Hāna Ridge might have influenced the northward shift in the volcanic zone. A third possibility is that pre-existing offsets in the ridge crest, such as have been identified on Puna Ridge by Lonsdale (1989), may migrate down rift and away from the feeding summit reservoir. Migration of nontransform offsets at oceanic spreading centers has been well documented (e.g., Hey et al., 1980, 1986, 1989; Kleinrock and Hey, 1989); along the Galapagos Ridge offsets migrate away from the Galapagos hotspot, which is thought to drive their downslope/downrift migration (Hey et al., 1980). On Hawaiian rift zones, similar lengthening of one ridge crest at the expense of its downrift neighbor, driven by magmatic pressure at the summit reservoir, might occur without requiring landslides to disrupt the local stress field; other similarities between Hawaiian rift zones and oceanic spreading centers have been previously noted and discussed (see Lonsdale, 1989; Borgia and Treves, 1992 and references therein). We favor this last hypothesis, as the conjugate flanks below Hāna Ridge's subparallel volcanic crests appear to be constructional in nature without evidence of large landslides embaying those flanks. The landslide at the ridge's distal toe, which may have influenced the northeastward deflection of the volcanic zones east of 155°05′ W, especially the southern one, is likely too distant to have affected the rift-zone plumbing system farther west (Fig. 3).

Landslides have also been identified on other submarine rift zones (e.g., Kīlauea's Puna Ridge, Hualālai's Kīholo Ridge, and Lōʻihi Volcano; Moore and Chadwick, 1995). They are generally small in spatial extent (5–10 km wide), have limited runout (10–15 km), and are recognizable by having a steep, arcuate slope—lacking the lobate morphology typical of submarine rift-zones—and hummocky floor (Moore and Chadwick, 1995). They may be caused by axial eruptions oversteepening and overloading the flanks; subsequent eruptions will anneal the slide scar, masking them in the long-term geologic record. We surmise that these submarine rift-zone landslides lack long runout because they are small, even though they may be single-event avalanches. There is no clear indication of incrementally moving, slump-type landslides on submarine-built ridges, which lack significant quantities of coastally generated fragmental basalt (i.e., the volcanic pile is mostly solid: built of submarine-emplaced pillow lava rather than shoreline-generated volcaniclastic sediment).

Ren et al. (2004) analyzed the petrology and geochemistry of 108 rock specimens (all tholeiitic basalts and picrites) collected during the six JAMSTEC dives on the submarine-built part of Hāna Ridge. Their results indicate that the relatively unaltered samples (compared to subaerial Honomanū basalts) are similar to Kīlauea shield-stage lavas in major and trace-element geochemistry, while the Honomanū are intermediate in composition between the Hāna Ridge samples and the postshield Kula and Hāna volcanics. This supports the supposition of Sherrod et al. (2003) that the Honomanū comprise basalt transitional between the shield and postshield stages, and are hence younger (1.1–0.97 Ma; Chen et al., 1991) than the submarine-emplaced Hāna Ridge lavas. Hāna Ridge therefore has probably been volcanically inactive for the past 1 m.y., as inferred by Moore et al. (1990), except for the pointed volcanic cones at the western end of the ridge (Fig. 2) that likely erupted in shallow water during the postshield alkalic stage (Clague et al., 2000).

4.2. Development of the Hāna slump

Without knowledge of the deeper subseafloor structure of the Hāna slump we can only infer landslide driving forces, and the location and orientation of the basal failure surface. However, that evidence of flank mobility and deformation is limited to that part of Haleakalā that lies downslope of its formerly subaerial shield (Figs. 1 and 2, and Plate 1) is, to our minds, significant. A key aspect of the volcanic-spreading hypothesis (Borgia and Treves, 1992; Borgia et al., 2000) is that the entire flank of a Hawaiian volcano would be mobile—driven by magmatic inflation at its rift zones that displaces the volcano along a basal decollement—irrespective of whether that flank is a sediment-rich slope generated by the quenching of lava flows at the coastline or part of a submarine rift zone. Alternatively, if flank mobility is driven primarily by downslope-oriented gravitational collapse then areas with abundant, unconsolidated hyaloclastite would be expected to exhibit the greatest degree of mobility and flank deformation; the dynamic, unstable nature of seafloor slopes below where shoreline-crossing lava flows enter the ocean is well illustrated by Sansone and Smith (2006-this issue). We therefore conclude—because deformation of Haleakalā's flank is limited to that part lying below its formerly subaerial shield (the H terrace)—that sliding of the entire volcanic edifice along a basal decollement was less significant than the gravitationally driven downslope migration of coastally generated unconsolidated to semi-consolidated volcaniclastic material within the slump, and that massive quantities of rapidly quenched basalt fragments generated by shoreline-crossing lava flows are integral to slump development and corresponding flank mobility.

Our interpretation of the structure and development of the Hāna slump downslope from Hāna Ridge, based upon the above conclusion, is presented in Fig. 11 and discussed in detail below. It is similar to the structural model of Moore et al. (1994) of Kīlauea's south flank but with the slump reaching the base of the volcanic edifice only near its distal end. We have drawn our basal failure surface within the thick pile of unconsolidated fragmental material, upon which the subaerial shield builds outward, and along slope-parallel bedding planes. Such bedding is observed in seismic reflection profiling of Kīlauea's south flank (Morgan et al., 2000, 2003) and at outcrop scale during submersible dives (Lipman et al., 2002). Landslide failure along these surfaces would result in a largely translational slide (Varnes, 1978) rather than the more purely rotational failure of a deeply rooted failure plane (e.g., Moore et al., 1994) expected in homogeneous (i.e., non-bedded) material. Upramping of the toes of the basal thrusts built transverse anticlinal ridges and back-rotated overlying basin strata. Sliding at the base of the volcanic edifice along a decollement (e.g. volcano spreading; Borgia and Treves, 1992; Borgia et al., 2000) is not necessary in our model, though seismicity 8 km underneath Kīlauea's south flank (Got et al., 1994) indicates that such a feature may exist there.

Seaward-dipping fault scarps at the head of the slump are not observed in the bathymetry or backscatter data. They have either been obscured by subsequent (post-slump) subaerial lava flows that helped build Haleakalā's H terrace—requiring that the slump ceased sliding while the volcano was still growing during its morphologic shield stage—or that the Hāna slump's basal failure plane did not rupture to the surface. Fault scarps on the Waiʻanae slump (southwest of O'ahu) are present only where a large block detached from the southern flank of Ka'ena Ridge, an event that likely occurred late in the development of that slump (Coombs et al., 2004). Seaward-dipping fault scarps are found along Kīlauea's subaerial southern flank, the Hilina Pali, but those features appear to be associated with a thin-skinned landslide, the Hilina slump, that is riding atop a larger, mobile (bench-forming) slump (Morgan et al., 2003). The evidence is thus more supportive of a slump's basal failure plane typically not reaching the surface (i.e., a blind normal fault). Such a blind failure plane would be consistent with incremen-

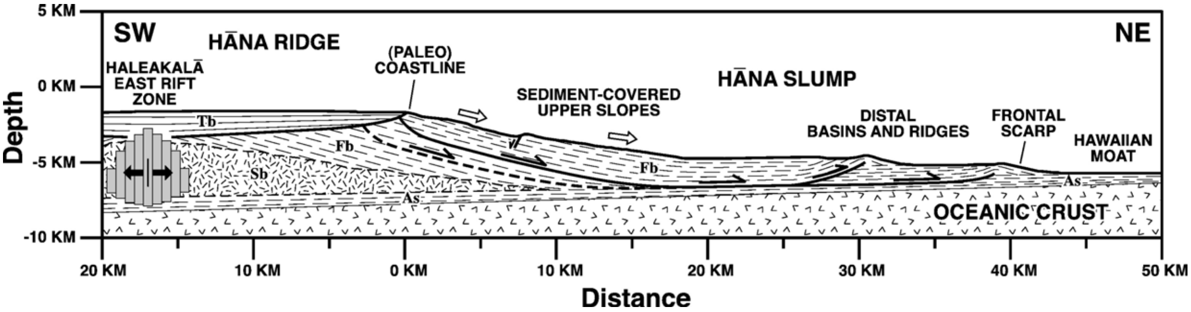

Fig. 11. Schematic profile illustrating the development of the Hāna slump. Principal failure planes are inferred to lie within the thick blanket of coastally generated fragmental basalt [Fb] that overlies a wedge of subaqueously erupted lava [Sb]. More than one such basal failure plane may have developed during the evolution of the slump, presumably along slope-parallel bedding surfaces, as continual lava fragmentation and downslope migration of surficial material (open arrows) thickened the slump. Upramping at the distal toe built the initial, distal-most anticlinal ridge (the slump's frontal scarp), and back-rotated overlying basin strata. Ongoing slump creep may have driven subsequent upthrusting and basin-and-ridge formation upslope while also thickening the slump. A thick, though compacted, sequence of abyssal sediment [As] is inferred to underlie the entire volcanic edifice. Gravitational failure due to the weight of the growing subaerial shield [Tb] was the primary force driving slump motion; edifice dilation at the rift zone (i.e., volcanic spreading) is considered to have been insignificant. Model profile location shown on Fig. 1, and approximately correlates with SCS profile 10-3 (Fig. 6).

tal motion, with increasing displacement downslope and rapid sediment supply in the source region.

Transverse ridges and basins of back-tilted sedimentary strata, similar to the toe of the Hāna slump, are found at the leading edges of accretionary prisms (e.g., Karig and Sharman, 1975; Moore and Karig, 1976). Morphologic mapping (multibeam swath sonar and seismic reflection profiling) of the distal parts of the eastern Mediterranean Ridge reveal a series of sinuous, asymmetric anticlinal ridges (7–12 km long) and 4- to 8-km-wide basins of back-tilted sediment at the leading edge of that accretionary prism (Huguen et al., 2001). The deformation front is defined by an undulating low (75–100 m high) scarp bounding the abyssal plain that Huguen et al. (2001) interpret as the youngest expression of thrusting during gradual, continual horizontal crustal shortening (i.e., subduction). Transverse basins and ridges (50–200 m high, 10–20 km long), with steep frontal scarps, are also found at the base of the Central Costa Rica volcanic range (Borgia et al., 1990) and are there interpreted to have formed by the gravity-driven slumping of the volcanoes' unstable flanks, forming asymmetric anticlines and related fault-propagation folds overlying low-angle blind thrusts. Leading-edge anticlines characterize thrusts that terminate by ramping upsection, and such anticlines are commonly asymmetric and convex (in plan) in the direction of transport (Boyer and Elliott, 1982). We conclude, therefore, that the transverse ridges found at the distal edge of the Hāna slump, morphologically similar to those at the leading edges of accretionary prisms, are the leading-edge anticlines of northeast-verging low-angle thrusts that moved incrementally as they gradually back-tilted the sediment-filling basins behind them.

At subduction zones, unconsolidated 'moat' material is accreted to the front of accretionary prisms, with the youngest thrusts at the distal toe; older thrusts become progressively back-tilted, uplifted, and marginalized. Slumps on Hawaiian and other ocean-island volcanoes, in contrast, have volcaniclastic material supplied from 'above' (i.e., gravitationally driven downslope) so that the youngest thrusts lay upslope. As the initial thrust extends out into the moat and builds an anticlinal ridge, bulldozing moat sediment ahead of it, it may be energetically preferable for the basal slip plane to cut through the overlying slump material and build a second ridge behind the first. Unconsolidated sediment cascading downslope would be trapped behind this ridge, and downslope basins would become sediment 'starved.' In this scenario, the farthest extent of the slump is dependent upon the initial distance the first thrust traverses. Subsequent slump motion will build the slump upward and landward (thickening it), though thrusting may in time overtake the first ridge. This process may explain how Kīlauea's southern flank, with its prominent mid-slope bench and high, steep frontal scarp has been built, because of its building high on the already-mobile flank of Mauna Loa (Smith et al., 1999; Lipman et al., 2006-this issue). We postulate that Mauna Loa's southeastern flank may have been in a stage of development similar to the Hāna slump before Kīlauea Volcano grew upon it and further contributed large volumes of volcaniclastic sediment and increased flank mobility without extending the slump significantly farther into the moat.

Along other parts of the Hawaiian trough (e.g., north of O'ahu; Rees et al., 1993) moat sediment is in excess of 2 km thick. Modeling of Pacific plate flexure (Watts and ten Brink, 1989), however, suggests ~800 m of sediment in the moat northeast of Haleakalā, significantly less than off of O'ahu, even though Haleakalā is one of the largest volcanoes in the Hawaiian Islands (see Robinson and Eakins, 2006-this issue). A large fraction of Haleakalā's sediment may therefore have been incorporated within the Hāna slump and 'Ōpana Fan rather than being shed to the moat. The moat also lacks large blocks as are found seaward of Kīlauea's and Wai'anae's slumps (Moore et al., 1989, 2000; Coombs et al., 2004). Those blocks are presumably derived from local collapse of steep frontal scarps (Morgan et al., 2000). Their absence seaward of the Hāna slump suggests that secondary landsliding at the slump toe, which requires local oversteepening, occurs after the slump has crossed some growth threshold; the Wai'anae and Kīlaeua slumps exhibit steeper, higher and more complex frontal scarps, and thus appear to have developed further than the Hāna slump. The 800-m thick sediment pile of archipelagic apron probably extends deep underneath its volcanic edifice (see Robinson and Eakins, 2006-this issue) and we have included such a (compacted) wedge in our schematic interpretation of the Hāna slump (Fig. 11). Material currently eroding from subaerial East Maui is probably being captured by the extensive H terrace (Fig. 2) with moat tilting, 0.5° towards the Island of Hawai'i, occurring after sediment supply to the moat was cutoff.

The Hāna slump may not have developed to the degree of the Wai'anae or combined Kīlauea and Mauna Loa slumps because it lay (mostly) downslope from Haleakalā's east rift zone, whereas the others are downslope from their respective summits. Haleakalā Volcano's extraordinary volume (Robinson and Eakins, 2006-this issue) and large shield extent (denoted by the margins of the H terrace, Fig. 2) indicate that sediment was probably created in excessive quantities but perhaps distributed less favorably to the Hāna slump. The slump's position in plan, with basins and ridges (thrust sheets) below the formerly subaerial part of Hāna Ridge and knolls (intact blocks?) below Haleakalā's summit, hints at a causal relationship between the structure of a volcano (thin rift-zone flows overlying hyaloclastite vs. thick superincumbent summit flows) and the type of landslide that ensues (slump or avalanche).

We emphasize one point concerning our model. Morgan et al. (2000) argued that development and uplift of Kīlauea's mid-slope bench requires some 24 km of horizontal shortening, which they inferred was "incompatible with modest overthrusting at the toe of a coherent slump." Our model potentially allows that magnitude of displacement at a Hawaiian-type volcanic slump by recognizing that downslope-migrating volcaniclastic sediment is continually replenished in the source region by quenching of shoreline-crossing lava flows. Slump-type landslides in other tectonic settings are typically not replenished in the source region and total slide displacement is less than the length of the slide; retrogression may occur through collapse of the unsupported headwall but this does not add substantially to the total displacement of the slide, although it does lengthen it. However, if replenishment occurs in the source region, and unconsolidated sediment cascades downslope on the surface of the slope while deeper faults accommodate coherent sliding, then the displacement observable at the slump toe will reflect 'modest overthrusting' between neighboring packets of strata (some or all deposited locally), especially if thrusting migrates upslope over time. In such a regime, the greatest degree of measurable fault displacement would be found near the middle of the slump's basal failure surface before it splays upward, building multiple transverse thrust ridges.

5. Summary

We present a reconnaissance geologic map of the submarine north and east flanks of Haleakalā Volcano and environs. Three principal features are the 135-km-long Hāna Ridge, the 3000 km^2 Hāna slump and the expansive, low-slope H terrace (Haleakalā's submerged shield) that wraps around East Maui, and probably captures most of the material currently eroding from it. Other features include: Pa'uwela Ridge, most likely a Hawaiian rift-zone ridge of unknown parentage that has its own low-slope terrace underlying the H terrace, therefore predating the growth of Haleakalā; and 'Ōpana Fan, a large deep-sea sediment fan.

We propose that subparallel volcanic crestlines on Hāna Ridge's deeper reach result from the downrift migration of offsets in the dike intrusion zone, similar to migrating nontransform offsets on oceanic spreading centers, with the northern ridge supplanting the older southern one. A short-runout landslide at Hāna Ridge's distal end, similar to those on other submarine rift zones (e.g., Puna Ridge and Lō'ihi), suggests that these avalanches may be inherently limited in size and runout as a result of the coherent nature of the pillow lavas that build these ridges. They may also be relatively common events along the subaqueously erupted parts of rift zones that are, however, likely quickly buried by subsequent eruptions and may not persist in the geologic record.

The distal toe of the Hāna slump exhibits transverse ridges and basins of back-tilted strata that morphologically resemble the toes of accretionary prisms and other thrust complexes, and are interpreted as a series of low-angle thrusts that are progressively younger upslope. The slump does not extend southeast past the downslope limit of Haleakalā's submerged shield (the H terrace), implying that development of the slump (i.e., flank mobility) was dependent upon the production of massive quantities of fragmental material generated by shoreline-crossing lava flows, and not on volcanic spreading driven by dilation at the rift zone. This in turn suggests that the gravitationally driven downslope migration of fragmental volcaniclastic material, which is created after volcano growth near or above sea level, plays an important, and perhaps even critical, role in large-scale flank destabilization and mobility (i.e., slump formation and growth).

'Ōpana Fan, fed by a sediment chute south of Pa'uwela Ridge, is the largest deep-sea fan identified along the young end of the Hawaiian Ridge. A staircase of contour-parallel steps on the fan's northern margin and within its sediment chute—similar to features seen elsewhere along the Hawaiian chain, though not yet studied in detail—is tentatively interpreted as a series of sediment waves generated by turbidity currents. The fan may record the geochemical evolution of Haleakalā's shield stage, and analysis of its sediments could therefore shed light on that poorly understood part of the volcano's history.

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