# Overthrusting and sediment accretion along Kīlauea's mobile south flank, Hawaii: Evidence for volcanic spreading from marine seismic reflection data

Julia K. Morgan*
Gregory F. Moore
Denise J. Hills
Stephen Leslie

Department of Geology and Geophysics, School of Ocean and Earth Sciences and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA

## ABSTRACT

**A large, intermittently active, submarine landslide known as the Hilina slump has been interpreted along the south flank of Kīlauea volcano. Seaward-dipping faults on land mark its headwall, and an offshore bench may define its uplifted toe. Geodetic data show that the entire south flank is also moving seaward, by a process referred to as volcanic spreading; this provides an alternative explanation for the bench, i.e., overthrusting along the edge of the sliding flank. The latter interpretation is consistent with new seismic reflection data across the submarine flank. A prominent reflection near the top of the oceanic plate suggests the décollement upon which the mobile flank slides. Landward-dipping reflections rise from this horizon and bound packages of bedded strata faulted and imbricated within the bench. The absence of correlative seaward-dipping faults and rotated strata on the upper flank suggests that the bench is not coupled to a slump. Moreover, kinematic reconstructions of the bench indicate that it has accommodated 15–24 km of displacement. This value is consistent with estimates for rift-zone extension but too high for shortening at the toe of a slump. We interpret the bench to result from overthrusting and accretion of volcaniclastic sediments to the edge of the mobile flank, and suggest that morphologic benches develop preferentially where landslide debris has accumulated near the base of the volcano and can be accreted to its sliding edifice.**

**Keywords:** Kīlauea volcano, volcanic processes, Hilina slump, landslides, volcanic spreading.

## INTRODUCTION

Oceanic volcanoes are recognized to undergo concurrent growth and degradation; massive submarine debris-avalanche tracks and deposits occur around many volcanic islands (Holcomb and Searle, 1991), including Hawaii (Moore et al., 1994), where tsunami deposits have been found high on nearby slopes (Moore and Moore, 1984). Elsewhere, upper flank extension and lower slope benches suggest coherent slumps still attached to the volcano (Fig. 1; Moore et al., 1994). The picture is complicated by lateral motions of volcanic flanks away from their eruptive centers by a process referred to as volcanic spreading (Borgia and Treves, 1992; Delaney et al., 1998); such flank displacement can also induce distal lateral compression, leading to overthrusting and bench development along the flank toe (e.g., Fig. 1; McGovern and Solomon, 1993; Denlinger and Okubo, 1995). If morphologic benches along volcanic flanks result from slumping, this suggests a potential for future catastrophic collapse. If they are generated by seaward sliding of the edifice, it implies a comparatively more stable deformation process. Distinguishing between the two possibilities has important implications for understanding volcanic evolution and related geologic hazards. A multichannel seismic survey onboard the R/V *Maurice Ewing* in 1998 along the south flank of Kīlauea volcano, Hawaii (Fig. 2), provides strong evidence that a morphologic submarine bench in this setting is a manifestation of volcanic spreading rather than slumping.

## KĪLAUEA SOUTH FLANK

Deformation along the south flank of Kīlauea volcano, on the island of Hawaii (Fig. 2), is evident from seismicity near the volcano base (i.e., 5–12 km depth; Got et al., 1994) and surface displacements as high as 10 cm/yr (Owen et al., 1995; Delaney et al., 1998). Ground motions and seismicity are explained by seaward sliding of the flank along a weak basal décollement (Denlinger and Okubo, 1995; Owen et al., 1995), and lead to rift-zone extension and dike intrusion (Fig. 1; e.g., Swanson et al., 1976).

Intermittent large earthquakes, such as the 1975 Kalapana earthquake (M 7.2), cause surface ruptures and ground subsidence, particularly seaward of the arcuate Hilina fault zone (Fig. 2); the pattern of coseismic deformation suggests a submarine landslide, i.e., the Hilina slump (Lipman et al., 1985). Both shallow and deep detachment geometries have been proposed for the slump (Fig. 3); the morphologic bench has been interpreted as a downdropped slump block (Fig. 3A) or the uplifted toe of the slump (Fig. 3B). Alternatively, the bench is unrelated to landsliding, but is an anticlinal ridge formed at the distal edge of the sliding edifice (e.g., Fig. 1; Borgia and Treves, 1992; Denlinger and Okubo, 1995). The seafloor in front of the deforming flank is characterized by hummocky morphology, protruding blocks, and local shallowing, suggesting the presence of avalanche debris as seen elsewhere around the islands (Moore et al., 1994). This material contributes to a broad volcanic apron surrounding the degrading volcano and implies recurring flank collapse.

## SEISMIC REFLECTION DATA

We collected 29 seismic lines across the south flank of Hawaii and applied a standard processing sequence to each line using ProMAX software (Appendix 1; see also Data Repository[1]). We present observations here by way of seismic line 2 that crosses the broad midslope basin and a distal block (Fig. 2); lines adjacent to line 2 show features similar to those noted here. Unless otherwise indicated, depths and traveltimes are referenced to sea level, and lateral positions are denoted by shot point (SP).

A strong set of reflections, labeled A, is identified at ~6.3–6.5 s beneath the midslope basin (Fig. 4A and 4B, SP 340) and can be followed landward with increasing traveltime below the seafloor. Horizon A shallows because of topography beneath the outer part of the bench (SP 450, ~6 s) and becomes difficult to follow beneath the outer slope (SP 500–650). A corresponding strong reflection occurs at ~7.5–8 s beneath sediments within the Hawaiian Deep (SP 700–800). A second prominent reflection, labeled B, overlies and diverges from reflection A at SP 220 (Fig. 4A and 4B, 5.5 s). The seismic unit between A and B exhibits reflections that parallel A and continue beneath the bench (Fig. 4A). The unit overlying and landward of B (northwest of SP 340) is characterized by irregular, discontinuous reflections. The outer part of the bench shows continuous, conformable reflections that define a broad fold (Fig. 4A). Two pronounced reflections, C and D, diverge near SP 370: C parallels horizon A, while D rises through the section

*Present address: Department of Geology and Geophysics, Rice University, 6100 Main Street, Houston, Texas 77005, USA.

[1]GSA Data Repository item 200070, Figure A, an unannotated version of Figure 4C enlarged ~215%, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

**Data Repository item 200070 contains additional material related to this article.**

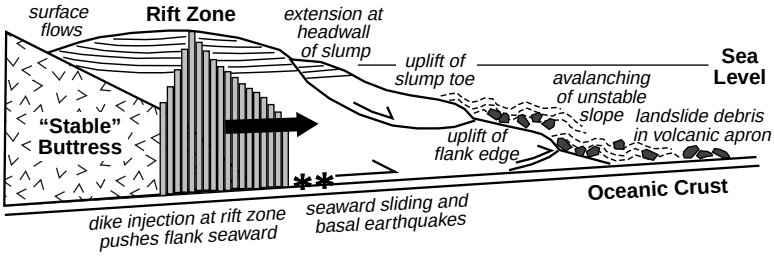


**Figure 1. Model for volcano growth and deformation. Magma intrudes at rift zone, feeding surface eruptions and dike intrusion, and flank moves away from rift zone. Seaward displacement of flank causes earthquakes along volcano base, and lateral compression and overthrusting along distal flank. Slumps may form on unstable slopes, causing extension along upper flank and uplift at slump toe. Collapse of unstable flank and uplifted bench leads to debris avalanches, which add material to volcanic apron surrounding volcano.**

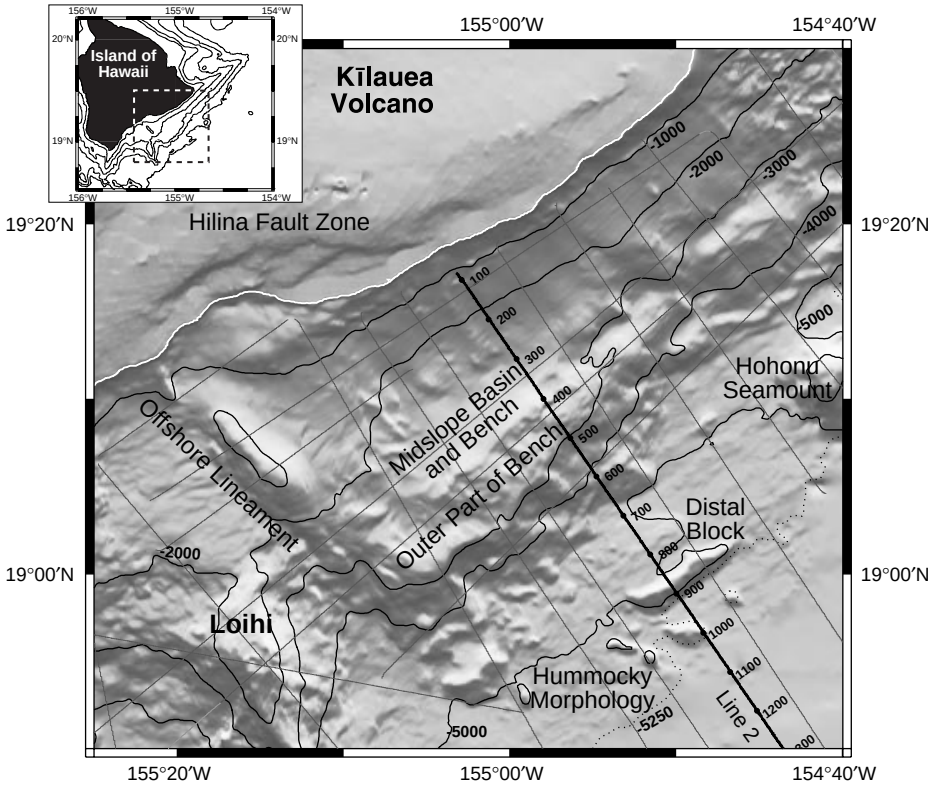


**Figure 2. Shaded-relief bathymetric and topographic map of Kīlauea volcano's south flank (white line denotes shoreline; 1000 m depth contours are plotted). 10°–15° slope is blanketed by hyaloclastic sediments, which yield to northeast to rougher terrain associated with submarine-erupted lavas. On-land Hilina fault zone, broad midslope basin and bench, and distinct offshore lineament to southwest bound interpreted Hilina slump. Arcuate scarps incise steep outer slope of bench. Debris-avalanche deposit is suggested seaward of flank (see deflected 5000 and 5250 m contours). Locations of line 2 (black, with annotated shot points) and nearby seismic lines (gray) are indicated. Illumination is from north. Bathymetry is from Smith et al. (1994).**

(Fig. 4B). Several low terraces at the toe of the slope (SP 600–700) are cored by narrow folds.

The upper flank is blanketed by ~1 s of highly reflective strata, which thicken in the midslope basin. The basin fill shows distinct landward rotation at its seaward edge, and stands high relative to the bench; bedding reflections terminate at the seafloor (Fig. 4A and 4B, SP 350–410), suggesting uplift or erosional truncation. A slightly less reflective unit defines a fold between SP 240, 4 s, and SP 330, 4.6 s; reflection E underlies the fold and projects to the seaward edge of the basin (Fig. 4B). The distal block shows dipping reflectors on its northwest side (Fig. 4A and 4B, SP 850, ~7.0 s). A highly reflective unit fills the intervening low, onlapping both the flank toe and distal block. The underlying unit, between 7 and 7.5 s, is comparatively chaotic.

## STRUCTURAL INTERPRETATION

The continuity of reflection A beneath the flank, its landward deepening, and the presence of correlative reflections within the Hawaiian Deep suggest that horizon A is near the top of the Cretaceous oceanic plate. The reflective character of horizon A beneath the flank implies a high impedance contrast across it, suggesting pelagic

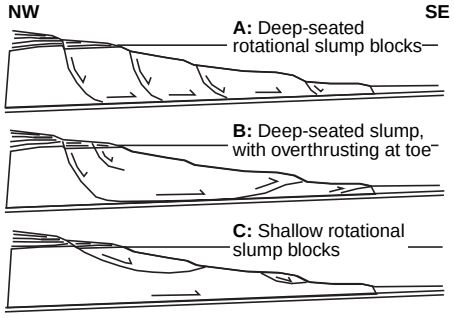


**Figure 3. Models for landsliding along south flank of Kīlauea. A: Deep-seated, rotational slump blocks (Lipman et al., 1985). B: Deep-seated slump block with overthrusting at toe (Moore et al., 1994). C: Shallow, rotational slump blocks (Swanson et al., 1976).**

or clastic sediments sandwiched between the volcano and the oceanic crust. Thin sediments in the Hawaiian Deep constrain the oceanic plate to be about 6 km deep along the northeastern edge of line 2. Assuming a landward dip of 2°–3° (Hill and Zucca, 1987; Got et al., 1994), the top of the oceanic plate projects to a depth of ~7 km at the landward edge of line 2. We used a smooth, downward-increasing velocity model for the volcanic edifice that yields the predicted crustal geometry, to construct the approximate depth section for line 2 interpreted in Figure 4C.

On the depth section, landward-dipping reflections D and E rise from the top of the oceanic plate in the seaward direction (Fig. 4C). Within the bench, deeper reflections parallel horizon A, whereas shallower ones parallel D. The angular discordance resembles thrust ramp and flat geometries developed in fold-and-thrust belts and accretionary prisms (Boyer and Elliott, 1982). The landward-dipping reflections D, E, and possibly C are interpreted to be reverse faults bounding packages of clastic sediments imbricated within the 4-km-high bench. Postdepositional uplift of the bench along the faults is implied by backtilting of the shallow sediments at the edge of the midslope basin.

The contrast in reflective character between units within the upper flank and the bench suggests a facies contact; we infer an interfingering transition from submarine-erupted volcanics in the flank to bedded sediments within the bench (Fig. 4C). Given the contrast in seismic character across reflection B, we interpret B to define the base of the primary volcanic edifice. The basin strata extend in depth almost to horizon B, confirming that the primary volcanic edifice does not extend into the bench.

Well-bedded sediments blanket the upper slopes and fill the midslope basin; they are assumed to be hyaloclastites generated by bench collapse and lava fragmentation at the shoreline (Moore and Fiske, 1969). The only seaward-dipping reflections on line 2 occur within and at the base of these shallow sediments (Fig. 4C); they are interpreted to denote bedding or lithologic interfaces. Landward-dipping reflections along the northwestern face of the distal block resemble sediment reflections in the bench.

On the basis of onlap relationships with the infilling sediments and the high velocities required for depth conversion, we interpret the block to be a landslide block derived from flank or bench collapse, as previously proposed (Moore et al., 1989).

## DISCUSSION AND CONCLUSIONS

On the basis of previous interpretations for the structure of the active south flank of Kīlauea volcano (Fig. 3), we sought to identify seaward-dipping detachment surfaces consistent with landsliding hypotheses. However, such reflections are not obvious on line 2 (Fig. 4). Instead, we image a series of landward-dipping reflections, particularly beneath the midslope bench, that rise from a basal reflection near the top of the oceanic plate. These reflections appear to be seaward-verging thrust faults that uplifted the morphological bench. We note that such compressional structures can form at the toe of a slump (e.g., Figs. 1 and 3B; Varnes, 1978), and the lack of correlative detachment reflections might be explained by a steeply dipping fault that does not extend beyond the shoreline or cannot be seismically imaged (e.g., Fig. 3A and 3B). However, extensional structures and stratal rotation expected near the headwall of a slump (e.g., Fig. 1; Varnes, 1978) are not observed here (Fig. 4). Consequently, we argue that shortening within the bench is not a result of slump displacement.

The general structure revealed along the south flank is consistent with models proposed for volcanic spreading (Fig. 1). The reflective character of horizon A implies a porous, weak layer along which slip occurs, similar to an accretionary-prism décollement (Moore, 1989; Shipley et al., 1994); this is a key element in volcanic spreading models (e.g., Borgia and Treves, 1992; Denlinger and Okubo, 1995). The pronounced landward-dipping reflections within the bench, and the stratal discordance across them, are consistent with overthrusting along the distal flank (e.g., Fig. 1) arising from lateral compression modeled along the edges of sliding volcanoes (McGovern and Solomon, 1993).

Another surprise in the new data is evidence that the bench is not composed of pillow lavas thought to compose the primary volcanic edifice (Lipman et al., 1985; Borgia and Treves, 1992). Instead, the bench appears to consist of sedimentary material, probably hyaloclastites and landslide debris that accumulated in the volcanic apron surrounding the volcano. This interpretation was confirmed by recent joint U.S.–Japanese submersible surveys, which recovered volcaniclastic sandstones and breccias from the outer slopes of the bench and distal block (Naka et al., 1998).

We propose that the bench defines a deformed wedge of sediments pushed by the comparatively strong flank sliding on a weak décollement. The wedge builds by overthrusting and preferentially incorporating slices of the weaker volcaniclastic apron (Fig. 5). The proposed process is analogous to the growth of an accretionary prism (Karig and Sharman, 1975). Slope sediments are trapped in a basin analogous to a forearc basin, and are rotated by subsequent uplift of the bench (Fig. 5). Deformation in front of the flank is ongoing, as evidenced by small folds at the base of the slope (Figs. 2 and 4).

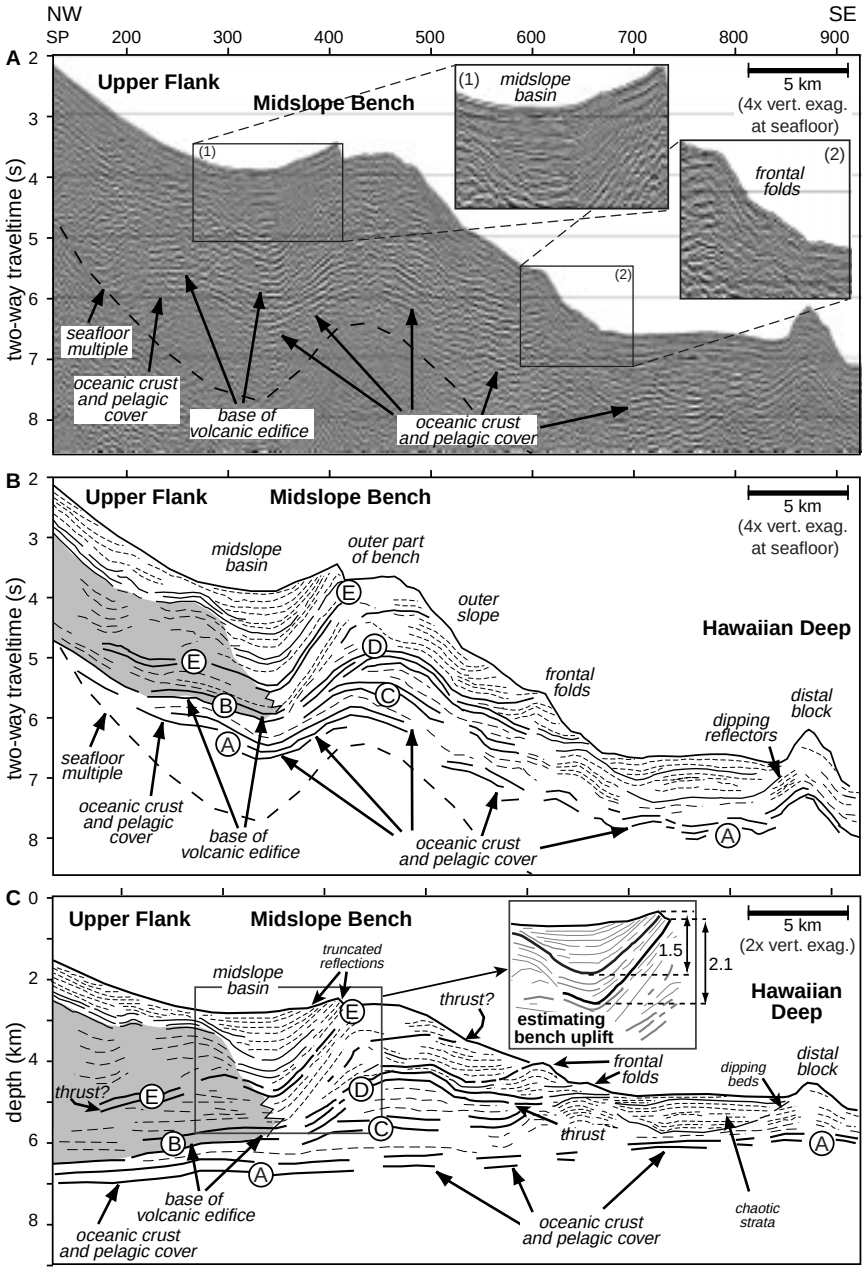


**Figure 4. Seismic line 2; location shown in Figure 2. A: Migrated time section, plotted at 4:1 vertical exaggeration at seafloor; automatic gain control (AGC, 500 ms operator) is applied to normalize reflection amplitudes. Insets show 150% enlargements of midslope basin and frontal folds (see footnote 1). B: Interpreted line drawing at same scale as A. Shaded zone denotes submarine volcanic edifice. C: Interpreted line drawing of depth section for line 2, plotted at 2:1 vertical exaggeration. Inset shows estimates for minimum bench uplift (in kilometers). See text for description.**

Vertical offset of the deeper tilted beds in the basin implies postdepositional bench uplift of ~1.5–2.1 km, approximately the thickness of the proximal apron (Fig. 4C and inset). Duplication of the apron strata within the deformed bench would imply a minimum displacement equal to the width of the bench, ~15 km. If we account for internal folding, faulting, and erosion of the uplifted strata, we obtain a displacement of ~24 km (Fig. 5). Displacements of 15–24 km are of the order of the 14-km-wide base of the dike zone beneath Kīlauea's summit inferred from seismic refraction data (Hill and Zucca, 1987). As dike injection is thought to accompany rift-zone extension (Fig. 1; Swanson et al., 1976; Delaney et al., 1998), the dike-zone width provides a minimum estimate for cumulative flank displacement. Such high flank displacements are consistent with volcanic spreading hypotheses but incompatible with modest overthrusting at the toe of a coherent slump.

Our model for the growth and development of the midslope bench along the south flank of Kīlauea

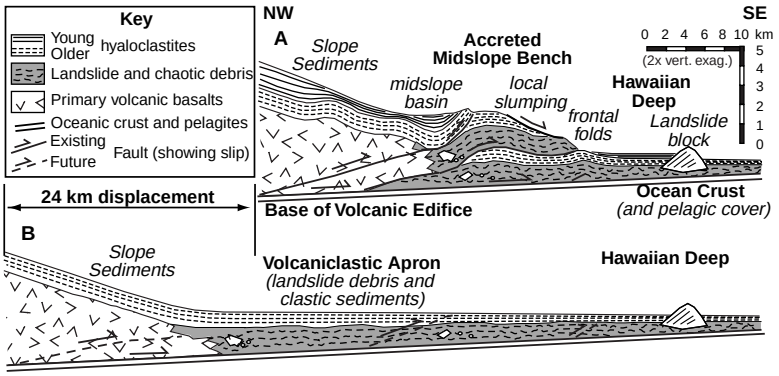


**Figure 5. A: Structural interpretation for deformed bench and flank on line 2, showing imbricate thrusting of volcaniclastic strata within bench, rotated sediments in midslope basin, and local slumping of bench recycling debris back to volcanic apron. B: Reconstruction of A, stripped of recent slope and basin sediments. Cumulative flank displacement is estimated to be ~24 km. Plots are shown with 2:1 vertical exaggeration.**

calls into question interpretations for benches elsewhere, e.g., along the flanks of Oahu, Molokai, Lanai, and Kauai. The benches are used as markers for the bases of coherent slumps still attached to the volcano flanks (e.g., Figs. 1 and 3B) and proximal debris fields are attributed to calving of material from unstable benches (Fig. 1; Moore et al., 1989). We propose that the relationship may in fact be reversed; i.e., the benches develop by accretion of preexisting sediments and landslide debris to the edges of the mobile flanks (Fig. 5). We expect to see well-developed benches in settings that have extensive debris-avalanche deposits, such as the north flanks of Oahu and Molokai and the south flank of Lanai, and poorly developed benches where this material is lacking, such as the south flank of the young Puna Ridge; this correlation appears to be borne out (Moore et al., 1989). Therefore, we argue that the development of the midslope bench is a fundamental characteristic of the lateral mobility of the flanks of the Hawaiian volcanoes and depends on the availability of sediment and debris in the volcaniclastic apron; such benches are less likely to be observed in settings where these factors do not coincide. Slumping and catastrophic flank collapse certainly occur throughout the area (e.g., Morgan et al., 1998), but we speculate that they occur as secondary processes induced by flank deformation arising from volcanic spreading.

## APPENDIX 1. SEISMIC DATA ACQUISITION AND PROCESSING PARAMETERS

Acquisition Parameters

| | |
|---|---|
| Source: | 15 airguns |
| | 4336 in$^3$ |
| Receivers: | 4000 m length |
| | 160 channels at 25 m |
| Shot Interval: | 50 m |
| Recording: | SEG-D format |
| | 2 ms interval |

Processing Sequence

Resample to 4 ms
Edit bad shots and channels
Sort to common midpoint (40 fold, 12.5 m)
Bandpass filter (4, 8, 72, 80 Hz)
Velocity analyses and dip moveout
Normal moveout correction
40-fold CMP (see footnote 1) stack
Lowpass filter for multiple attenuation (0, 0, 35, 45 Hz)
Migration in frequency-wavenumber (F-K) domain
F-K filter to remove steeply dipping noise
Depth conversion


## ACKNOWLEDGMENTS

Many people deserve credit for assisting in this study. In particular, we thank the friendly and professional shipboard and technical crew and the scientific party of the R/V *Maurice Ewing*, who ensured the success of the survey and quality of the data. Reviews by Roger Denlinger, Roland Burgmann, and Uri ten Brink led to significant clarification of the paper. This work was funded by National Science Foundation grant OCE-9711715. School of Ocean and Earth Sciences and Technology contribution 5163.


## REFERENCES CITED


Borgia, A., and Treves, B., 1992, Volcanic plates overriding the oceanic crust: Structure and dynamics of Hawaiian volcanoes, *in* Parson, L.M., et al., eds., Ophiolites and their modern oceanic analogues: Geological Society [London] Special Publication 60, p. 277–299.

Boyer, S.E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196–1230.

Delaney, P.T., Denlinger, R.P., Lisowski, M., Miklius, A., Okubo, P.G., Okamura, A.T., and Sako, M.K., 1998, Volcanic spreading at Kīlauea, 1976–1996: Journal of Geophysical Research, v. 103, p. 18,003–18,023.

Denlinger, R.P., and Okubo, P., 1995, Structure of the mobile south flank of Kīlauea volcano, Hawaii: Journal of Geophysical Research, v. 100, p. 24,499–24,507.

Got, J.-L., Fréchet, J., and Klein, F.W., 1994, Deep fault plane geometry inferred from multiplet relative relocation beneath the south flank of Kīlauea: Journal of Geophysical Research, v. 99, p. 15,375–15,386.

Hill, D.P., and Zucca, J.J., 1987, Geophysical constraints on the structure of Kīlauea and Mauna Loa volcanoes and some implications for seismomagmatic processes, *in* Decker, R.W., et al., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, p. 903–917.

Holcomb, R.T., and Searle, R.C., 1991, Large landslides from oceanic volcanoes: Marine Geotechnics, v. 10, p. 19–32.

Karig, D.E., and Sharman, G.F.I., 1975, Subduction and accretion in trenches: Geological Society of America Bulletin, v. 86, p. 377–389.

Lipman, P.W., Lockwood, J.P., Okamura, R.T., Swanson, D.A., and Yamashita, K.M., 1985, Ground deformation associated with the 1975 magnitude-7.2 earthquake and resulting changes in activity of Kīlauea volcano, Hawaii: U.S. Geological Survey Professional Paper 1276, p. 1–45.

McGovern, P., and Solomon, S., 1993, State of stress, faulting, and eruption characteristics of large volcanoes of Mars: Journal of Geophysical Research, v. 98, p. 23,553–23,579.

Moore, J.C., 1989, Tectonics and hydrogeology of accretionary prisms: Role of the décollement zone: Journal of Structural Geology, v. 11, p. 95–106.

Moore, J.G., and Fiske, R.S., 1969, Volcanic substructure inferred from dredge samples and ocean-bottom photographs, Hawaii: Geological Society of America Bulletin, v. 80, p. 1191–1202.

Moore, J.G., and Moore, G.W., 1984, Deposit from a giant wave on the island of Lanai, Hawaii: Science, v. 26, p. 1312–1315.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, p. 17,465–17,484.

Moore, J.G., Normark, W.R., and Holcomb, R.T., 1994, Giant Hawaiian landslides: Annual Review of Earth and Planetary Sciences, v. 22, p. 119–144.

Morgan, J.K., Moore, G.F., and Leslie, S., 1998, Seismic reflection lines across Papa'u Seamount, south flank of Kīlauea: The submarine expression of the Hilina Slump?: Eos (Transactions, American Geophysical Union), v. 79, p. 1008.

Naka, J., and Shipboard Scientific Party, 1998, Preliminary result of the KAIREI KR98-08,09 cruises around the Hawaiian Islands: Eos (Transactions, American Geophysical Union), v. 79, p. 1022.

Owen, S., Segall, P., Freymuller, J., Miklius, A., Denlinger, R., Arnadottir, T., Sako, M., and Burgmann, R., 1995, Rapid deformation of the south flank of Kīlauea volcano, Hawaii: Science, v. 267, p. 1328–1332.

Shipley, T.H., Moore, G.F., Bangs, N.L., Moore, J.C., and Stoffa, P.L., 1994, Seismically inferred dilatancy distribution, northern Barbados Ridge décollement: Implications for fluid migration and fault strength: Geology, v. 22, p. 411–414.

Smith, J.R., Shor, A.N., Malahoff, A., and Torresan, M.E., 1994, Southeast flank of Island of Hawaii, SeaBeam multibeam bathymetry, HAWAII MR1 sidescan sonar imagery, and magnetic anomalies: Hawaii seafloor atlas: Honolulu, Hawaii Institute of Geophysics and Planetology, sheet 4, scale 1:250 000.

Swanson, D.A., Duffield, W.A., and Fiske, R.S., 1976, Displacement of the south flank of Kīlauea volcano: The result of forceful intrusion of magma into the rift zones: U.S. Geological Survey Professional Paper 963, p. 1–30.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides, analysis and control: Washington, D.C., National Academy of Sciences Special Report 176, p. 11–33.



Manuscript received November 8, 1999
Revised manuscript received March 22, 2000
Manuscript accepted April 9, 2000