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Rapid mass wasting following nearshore submarine volcanism on Kilauea volcano, Hawaii

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Abstract

The rapid mass wasting of shallow submarine basalts was documented during SCUBA dives along the flanks of Kilauea volcano, Hawaii during the Kii lava entry of the current eruption (19°20.5′N, 154°59.8′W). Lava entered the ocean at this site from mid-February to late March 1990, with several pauses. Dives on 19–20 March 1990 confirmed the widespread formation of lava pillows at this site over a water depth range of 20–40 m, and visual observations suggested that the resulting volcanic deposits were generally stable, despite the steep (~40°) incline of the seafloor. (The pre-eruptive nearshore seafloor slope was ~14°.) However, dives on 2 April 1990 revealed that nearly all submarine volcanic features had been subject to mass wasting, as the offshore area had been transformed into a debris field composed of material ranging in size from fine sand to boulder fragments. This generally featureless seascape extended uniformly to beyond the visual range of divers (~60 m water depth). High-resolution multibeam bathymetry and sidescan imaging indicate that steeply sloped coarse sediment extends down the flanks of Kilauea in this area to abyssal depths, implying a linkage between nearshore submarine volcanism and deep-water deposits.

Keywords: lava; submarine; Kilauea; pillow; hyaloclastite; debris

1. Introduction

In this paper we discriminate between two types of coastal volcanic activity: *shoreline* volcanism (which occurs at or near the waterline along the shore) and *nearshore* volcanism (which occurs under water within a few hundred meters of shore). It is well known that shoreline volcanic activity can produce large quantities of glassy debris that can be transported along- or offshore (e.g., Moore et al., 1973; Peterson, 1976; Sansone and Resing, 1995). In this paper we demonstrate that nearshore submarine volcanism can also be a significant source of debris over very short time scales. The rapid mass wasting of shallow submarine basalts was documented during SCUBA dives along the flanks of Kīlauea volcano, Hawai'i.

This work, combined with other observations at Kīlauea, suggests that nearshore submarine volcanism does not generally result in the generation of stable submarine rock formations. Thus, observations of deep-water volcanic flows (e.g., Ballard et al., 1979; Davis, 1982; Embley et al., 1990; Chadwick et al., 1998), which describe the formation of coherent, stable rock formations, do not appear to apply to the nearshore Hawaiian environment.

2. Kīlauea shoreline and nearshore volcanic activity

Shoreline volcanism on Kīlauea has been described in detail by Moore et al. (1973), Peterson (1976), and

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Mattox and Mangan (1997). Molten lava is rapidly quenched and fractured by its contact with relatively cool seawater, resulting in the copious production of hyaloclastic debris, particularly where the shoreline is steep or significant surf is present (both are typical conditions along this shore). A large portion of the debris is black sand that is either transported by longshore currents to form black sand beaches or is discharged downslope as debris flows (Sansone and Resing, 1995). Mechanical abrasion of black beach sands produces fine suspended particles that can be transported long distances along- and/or off-shore, though it is unlikely that these particles are volumetrically significant to the overall sediment budget. Shoreline lava flows can also release numerous steaming rocks (typically a few tens of centimeters in length) that float offshore and sink to the bottom (Sansone et al., 1990; Sansone and Resing, 1995), contributing to the nearshore debris field. Finally, shoreline volcanism frequently results in the construction of lava benches (deltas) which are prone to catastrophic collapse (Kauahikaua, 1993; Mattox and Mangan, 1997). Such structures may be significant contributors to offshore debris flows, particularly during episodes of extended or highly active shoreline volcanism.

Nearshore volcanism on Kīlauea consists of two major extrusive processes fed by submarine lava tubes: pillow lava formation and the release of highly fluid, channelized lavas. Pillow lava formation at Kīlauea has been described in detail by Moore et al. (1973), Moore (1975), and Moore and Lockwood (1978), and are illustrated in Movie 1 in the Appendix of this paper. Tribble (1991) estimated that cooled pillows generally covered 10–20% of the bottom during nearshore eruptions, although coverage of 60–80% was observed on one occasion. Channelized submarine flows, which result from the underwater release of highly fluid lava from submarine lava tubes, were described by Tribble (1991) and can be seen in the video by Sansone et al. (1990) and in Movie 2. Hydrogen explosions within these thin submarine flows (Sansone and Resing, 1995) add to the production of rock fragments.

3. Observations

In this paper, visual observations by SCUBA divers during and after a nearshore extrusive event are used to describe the near-term fate (day-to-week scale) of the extruded pillow basalts. These observations were documented using an underwater 8-mm video camera; data files containing edits of the video documentation are available for downloading via the Appendix of this paper. The photographs presented in this paper (except Fig. 3) are video frame grabs, and consequently are not high resolution images.

This work was done during the Ki'i lava entry during Episode 48 (Kauahikaua et al., 1996) of the current Kīlauea eruption. Lava entered the ocean at this site (19°20.5'N, 154°59.8′W) (Fig. 1) from mid-February to late March 1990, with several pauses. Dives on 19–20 March 1990 confirmed the widespread formation of lava pillows over a water depth range of 20–40 m, with less than half of the bottom covered with talus (Sansone and Resing, 1995). Lava production rate at Kīlauea this time was $\sim 3 \times 10^5$ m^3 d^{-1} (Kauahikaua et al., 1996), with a highly variable amount entering the ocean.

Visual observations suggested that the resulting volcanic deposits were generally stable, despite the steep (~40°) incline of the seafloor; the latter was consistent with previous estimates of 25–40° (Tribble, 1991), ~30° (Kelly et al., 1989) and 30–45° (Moore et al., 1973) at other sites offshore of Kīlauea. The pre-eruptive nearshore seafloor slope at Ki'i was ~14°, as measured by a July, 1989 bathymetric survey (data not shown).

However, dives on 2 April 1990, two weeks after the end of the submarine volcanism episode, revealed that nearly all of the expansive submarine volcanic deposits had been subject to mass wasting, having been transformed into a debris field composed of material ranging from fine sand to large boulder fragments (Fig. 2). This generally featureless seascape extended uniformly to beyond the visual range of divers (~60 m water depth). The debris field was close to the angle of repose, as evidenced by the immediate sliding of surface material after any disturbance by divers (Movie 3).

Occasional intact rock outcrops were seen; some of these were intact lava pillows, but most were large, partially fractured basalt blocks (Fig. 3). However, none of these rocks were of a stable, coherent nature, in contrast to the pāhoehoe which dominates the subaerially extruded lava flows at Kīlauea. Instead, the outcrops were composed of friable rock with weak tensional strength (Fig. 4). Presumably this fragility is the cause of the “gravitational collapse” of pillow lavas originally noted by Jones (1966). It also contrasts with the greater apparent coherence of deeper basalts, suggesting that it is related to the shallow depth of our field site or the steepness of the seafloor.

4. Discussion

New observational techniques, such as high-resolution multibeam bathymetry, sidescan imagery and

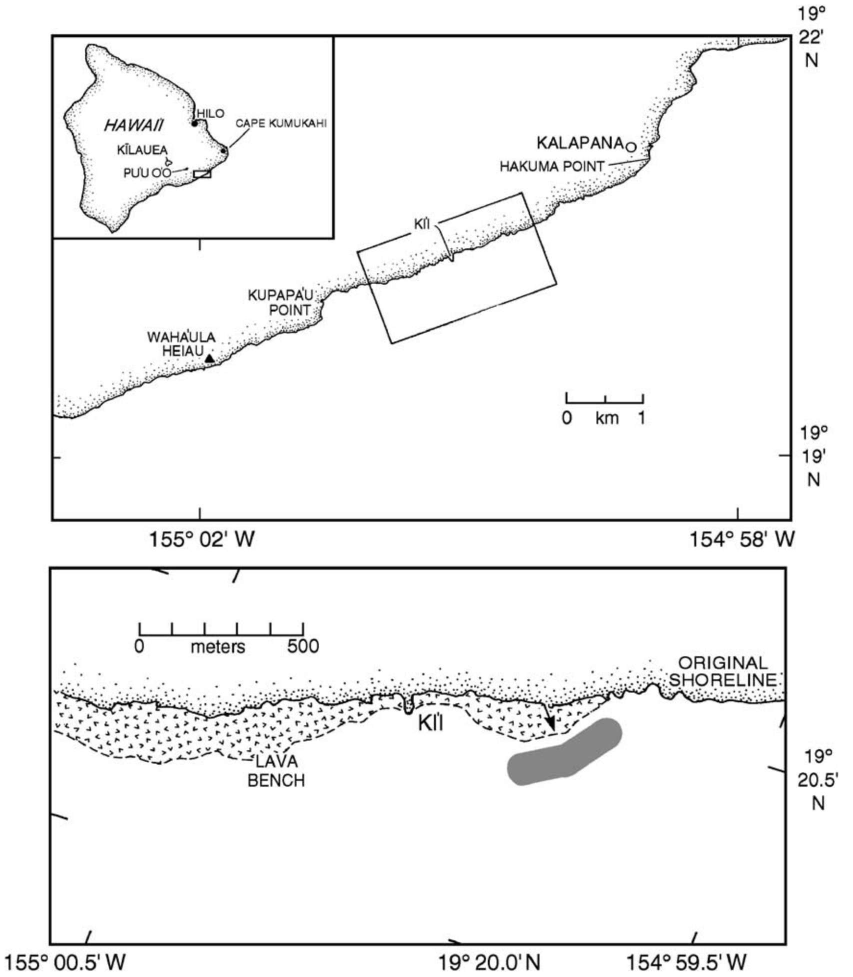

Fig. 1. Location maps of the study site. The upper panel shows pre-eruptive (pre-1990) features. The lower panel shows the original (pre-eruptive) shoreline, the lava bench (delta) produced by the eruption, the site of the Ki'i lava entry (arrow), and the approximate location of Figs. 3–5 (shading). Modified from Sansone and Resing (1995).

multi-channel seismic surveys provide a better understanding of the processes shaping the offshore margins of Kīlauea. For example, SeaBeam bathymetry and sidescan imaging indicate that steeply sloped talus fields extend down the flanks of Kīlauea in this area from the nearshore to abyssal depths (Fig. 5), implying a linkage between coastal volcanism and deep-water deposits. The observations presented above suggest that both coastline and nearshore volcanism may be responsible for the production of the loose material forming these debris fields.

The seafloor gradients offshore of Ki'i were measured by Lee et al. (1994). They found that the upper slope (nearshore) gradients are 25–40°, the gravitational angle of repose typical for coarse, loose sand. Similarly, Kelly et al. (1989) reported that the submarine slope averages ~30° over 75–230 m water depth. Downslope gradients are much shallower (10–15° at water depths of 700–2300 m) and are likely a "good measure of the seismic angles of response for this sand in the seismic environment of the Kīlauea margin" (Lee et al., 1994).

The smoothly sloping debris field flanking Kīlauea can be seen in the sidescan imagery shown in the lower panel of Fig. 5, indicated by the linear striations perpendicular to the shoreline. The striations continue down to 2500–3000 m water depth, ~15 km offshore, where they are interrupted by a 0.5–7 km wide mid-slope ridge (Smith et al., 1999). This is consistent with the observations of Lipman et al. (2002) that glassy sand deposits extend down to the midslope bench.

The multichannel seismic reflection survey lines of Hills et al. (2002) show that the surface debris field is composed of recent slope sediments (hyaloclastites) that extend down to the midslope bench (their lines 3

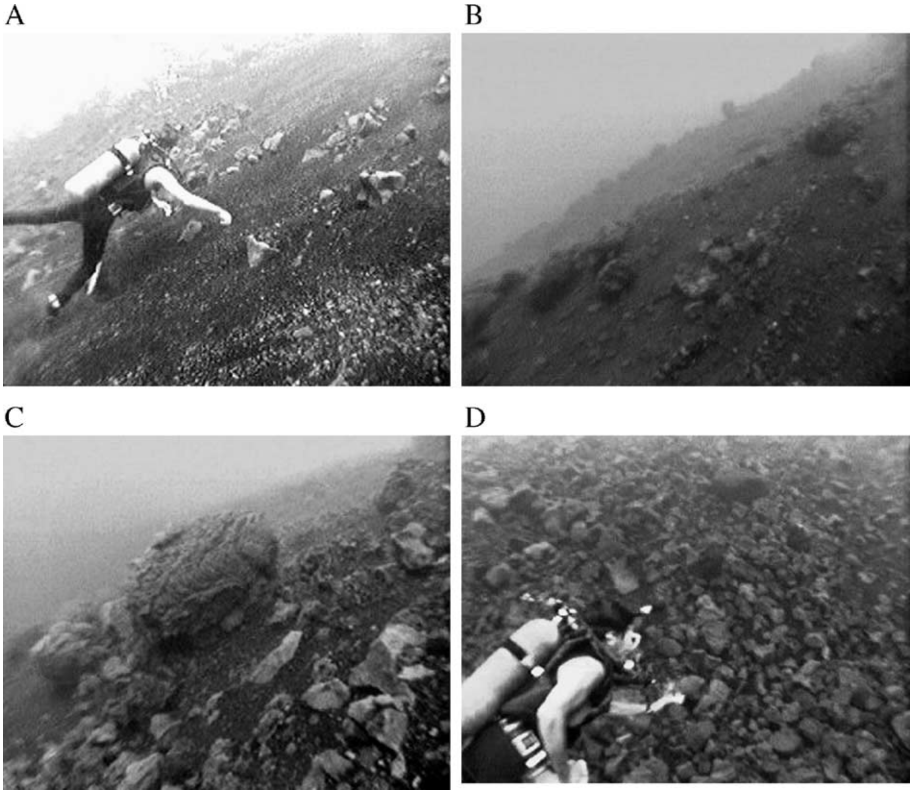

Fig. 2. Views of the post-eruptive debris field showing the range of materials observed: poorly sorted sand to boulder-sized rock fragments (frame grabs from Movie 3 in the Appendix). A) The diver's gentle contact with the seafloor sets off small sand landslides, an indication that the debris field in approximately at the angle of repose; depth ≈ 25 m. B) Field of view at mid-photograph is ~6 m; depth ≈ 25 m. C) Field of view at mid-photograph is ~4 m; depth ≈ 25 m. D) Upper slope rock field; depth ≈ 15 m.

and 16 correspond to our field study area). They interpret the uppermost sediments (their Unit 1 — "Recent slope sediments") as "primarily hyaloclastic sediments generated along the shoreline of Kīlauea by fragmentation of basalt flows as they enter the ocean that are then transported down the slope and into the basin by mass flow processes". We argue that, in addition, nearshore

Fig. 3. Post-eruptive rock outcrop. The block in the center of the photograph is ~2 m across. Depth ≈ 24 m.

Fig. 4. Post-eruptive lava pillow outcrop (frame grab from Movie 3 in the Appendix). The diver is removing a wedge of the pillow by gently leveraging a short crowbar inserted into a crack. This technique was also used to easily split open the pillow. Depth ≈ 12 m.

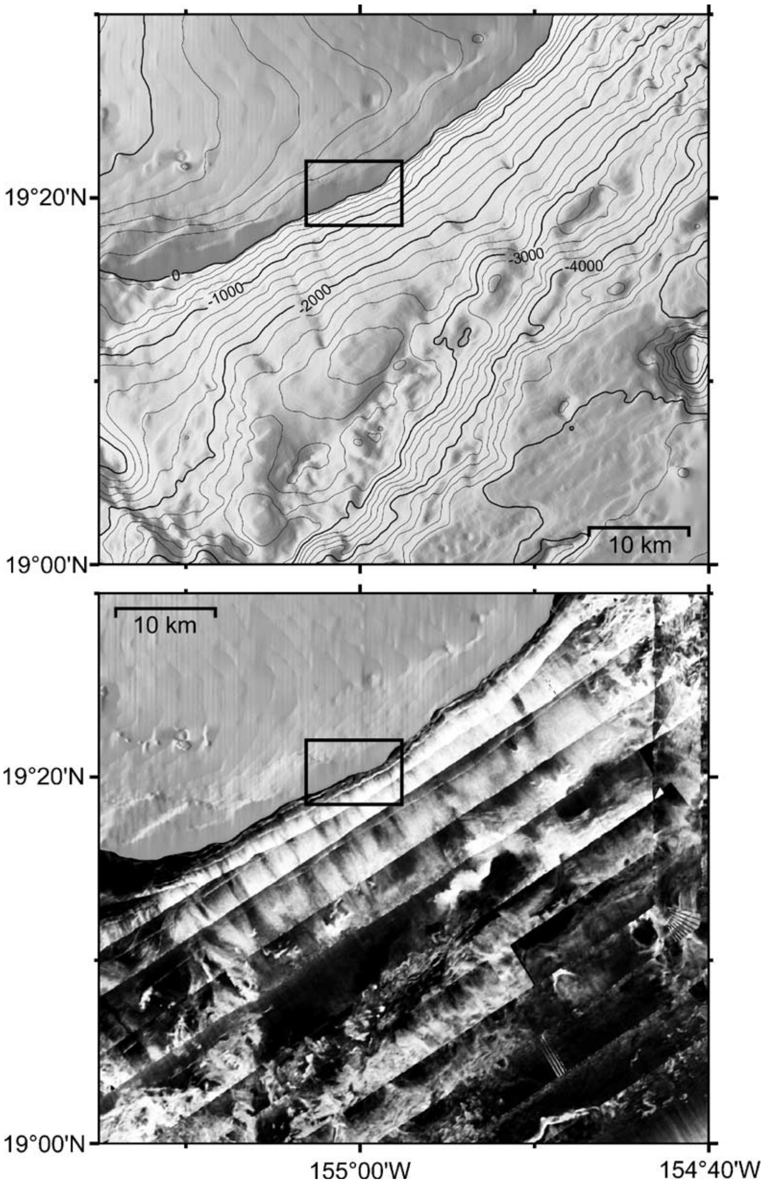

Fig. 5. Upper panel: shaded relief SeaBeam multibeam bathymetry of the southeast flank of Hawai'i island (illumination from east; 200-m contours). Lower panel: HAWAII MR1 sidescan sonar mosaic of the same area (high reflectivity=white). Both modified from Smith et al. (1999). Black rectangles correspond to the upper panel of Fig. 1.

(i.e., shallow submarine) volcanism can also be a source of hyaloclastic material for such debris flows, as previously suggested by Lipman et al. (2002).

Morgan et al. (2000) have proposed that the bench develops by the accretion of pre-existing sediment and landslide debris. Further, they hypothesize 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". This is consistent with the lack of such a feature on the Puna Ridge (Moore and Fiske, 1969; Moore and Chadwick, 1995), a flank area that is not subject to significant deposition of nearshore-derived hyaloclastic debris due to sharp inflection of the shoreline at Cape Kumukahi (Fig. 1). This lack of debris transport to the Puna Ridge can clearly be seen in the figures of Moore and Fiske (1969) and Moore and Chadwick (1995), in which the "lobate-hummocky" pillow lava flows of the ridge contrast with the sediment-draped slopes on either side of Cape Kumukahi. These authors argue that this difference is due to the ridge's isolation from shoreline volcanism, although it may also reflect the instability of pillow lavas erupted onto the much steeper slopes directly downslope from land as compared to the much gentler slope of the ridge (the cross-axis slope of the upper ridge is 10° (Moore and Fiske, 1969)).

Offshore slumps and landslides are relatively common geological features of the Hawaiian Island margins. Several models have been developed to explain how these result from the loading and failure of thick submarine beds of hyaloclastic debris on the flanks of Kīlauea (e.g., Moore and Fiske, 1969; Moore and Chadwick, 1995; Smith et al., 1999; Lipman et al., 2002; Morgan et al., 2003) and elsewhere in the Hawaiian Islands (e.g., Moore et al., 1989; DePaolo et al., 2001; Morgan and Clague, 2003). Such beds of volcanic debris were described by Fuller (1931) as resulting from subaerially erupted lavas entering shallow bodies of water, and this interpretation has been used by subsequent authors when discussing the flanks of the Hawaiian Islands.

However, the results presented here indicate that the "fragmental quenched lava" that form the debris flows on the submarine flanks of Kīlauea (Moore and Chadwick, 1995) is likely not solely the result of "subaerially erupted lava that crossed a shoreline and was subsequently quenched and fragmented" (quotation from Moore and Chadwick, 1995). Instead, it may also be due to nearshore submarine extrusion, either from (1) the direct production of basaltic debris when lava contacts seawater and then fractures, or (2) the rapid fracturing and collapse of the friable basaltic rock that, as demonstrated in this paper, is produced during shallow submarine eruptions. Note that this material from nearshore submarine extrusion originates from subaerial degassed (e.g., Gerlach, 1993) sources (i.e., the shoreline flows and lava tubes) and should be relatively depleted in magmatic volatiles despite its extrusion in a submarine environment. Hence, the lack of magmatic volatiles cannot be used as a strict indicator of subaerial emplacement when describing these kinds of debris flows.

McBirney (1963) speculated that "the fact that [thick submarine beds of hyaloclastite] are not uniformly developed around all oceanic volcanic structures suggests that their origin may be related to certain properties of the lavas or the physical environment that favors hyaloclastite flows". It seems apparent now that the latter is the case, with shoreline and/or nearshore volcanism being the formative processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jvolgeores.2005.07.026.

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