The Deformation of Ocean-Island Basaltic Volcanoes:
Ocean Drilling to Understand Growth, Collapse, and Associated Geohazards

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Abstract

Ocean island basaltic volcanoes experience large-scale sector collapse, and in unique cases such as Hawaii, more gradual seaward flank displacements accompanied by large earthquakes. Both modes of deformation have the potential to generate large tsunami that can cross the ocean basins, representing a substantial geologic hazard of global concern. In Hawaii, a long time series of subaerial deformation has been acquired, but the offshore contributions to flank deformation are very poorly known. Ocean drilling and borehole installations on active and older Hawaiian volcanoes offer the potential to clarify the modes of submarine flank deformation, constrain the lithologies, physical and mechanical properties, and rheologies of materials that govern flank deformation, and resolve flank stratigraphies that relate volcano growth and deformation with geochemical evolution. Drilling can yield a record of offshore turbidites that reflect the sources, magnitudes, and distributions of large landslides in the islands. Comparisons between Hawaii and other global ocean island basaltic volcanoes will help to explain why Hawaiian volcanoes exhibit contrasting flank deformation behavior compared to other settings, and the implications for global geologic hazards.

Ocean-island basaltic volcanoes are subject to large-scale sector collapses, resulting in enormous landslide and debris avalanche deposits on the surrounding seafloor (Moore et al., 1989, 1994; Urgeles et al., 1999; Masson et al., 2002). The type-locale for this process is Hawaii, where more than 38 landslides and debris avalanches have been identified [Figure 1]. Flank failures of this scale are certain to spawn tsunamis that cross the ocean basins, representing a substantial geologic hazard of global concern. Tsunami generated by Hawaiian landslides yield run-up estimates up to 100 m locally, and wave-heights of 10-20 m along the west coasts of North and South America (Satake et al., 2002; Ward et al., 2002).

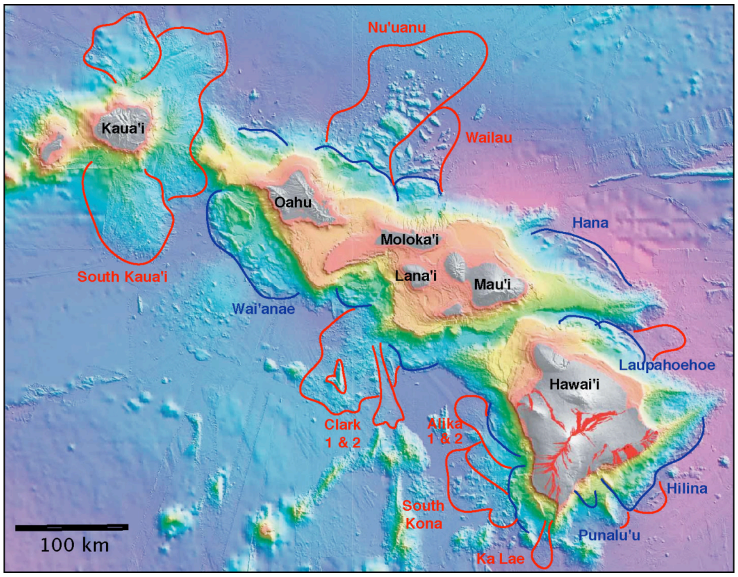

Figure 1. Landslides and slumps around Hawaii (Moore et al., 1989, summarized by T. Sisson). Red outlines are debris avalanche fields; blue outlines are slumps; islands are in gray. Bathymetry from Eakins et al. (2004). Modified from Morgan et al. (2009).

Infrequent sector collapse is just one manifestation of volcanic spreading. In Hawaii, volcanic spreading is also realized through more gradual flank displacements on the more active volcanoes. In the onshore region, Kilauea's south flank moves seaward at up to 8 cm/yr (Denlinger and Okubo, 1995; Owen et al., 2000; Miklius et al., 2006), the fastest known continuous displacement of any ocean island, and undergoes intermittent slow slip events on faults of uncertain geometry and depth (Cervelli et al., 2002; Brooks et al., 2006; Segall et al., 2006), large magnitude earthquakes (Lipman et al., 1985; Wyss, 1988), and local tsunamis (Ma et al., 1999). Recent seismic and submersible studies over the southern flanks of Kilauea and Mauna Loa have also revealed distinctive structures indicative of long-term flank displacements and accretion of volcanic aprons at the toes of the flanks (Morgan et al., 2000; Morgan and Clague, 2003). Slip occurs mainly along landward dipping decollements that correspond to the top of the oceanic crust; seaward verging thrust faults cut the flanks, resulting in uplifted benches near the toes (Swanson et al., 1976; Denlinger and Okubo, 1995). Geologic observations and bathymetric monitoring of Kilauea's south flank show that the submarine frontal bench uplifts as the subaerial south flank moves seaward and subsides (Phillips et al., 2008) [Figure 2].

Although little is known about the relative contributions, there appears to be a strong interplay between volcanic slope failure and flank displacement. Examples include evidence from Kilauea and Mauna Loa, where past slope failures contribute debris to volcanic aprons which are subsequently accreted to the toes of the mobile flanks (Morgan et al., 2000; Morgan and Clague, 2003), possibly slowing the rates of flank motions. However, subsequent landsliding can breach these benches, enabling renewed flank motions. This is interpreted for Mauna Loa's western flank (Morgan and Clague, 2003), where the Alika debris avalanche incised the frontal bench, transporting volcanic debris far into the Hawaiian Moat (Lipman et al., 1988). Kilauea currently supports an active slump that rides upon its mobile south flank, likely capable of similar detachment and rapid downslope displacement (Morgan et al., 2003).

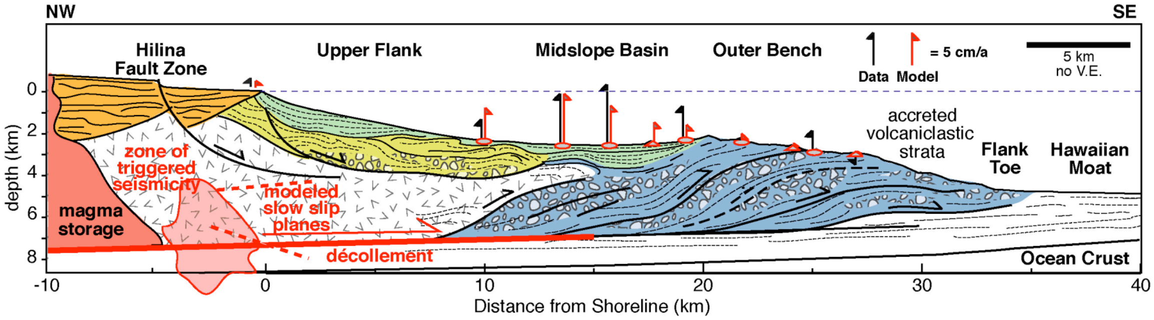

Figure 2. Cross-section through Kilauea's active submarine flank (after Morgan et al., 2003). Flank spreads seaward resulting in frontal sediment accretion and bench uplift. Aseismic slip along the active décollement (in red) can account for vertical displacement recently measured along the distal flank (data and slip interpretation from Phillips et al., 2008), and may be accommodated in part by repeated slow earthquakes, modeled to occur at or near the décollement plane and correlated with microseismicity (after Brooks et al., 2006). Modified from Morgan et al. (2009).

Volcanic activity at the summits and rift zones of deforming volcanoes is a key contributor to flank behavior, but is not the sole cause. Geodetic and geologic evidence for deep ductile cores of Hawaiian rift zones (Owen et al., 2000), and local high velocity and high density anomalies (Okubo et al., 1997; Kauahikaua et al., 2000), suggest the presence of cumulate bodies that contribute a push that drives the flanks outward within hot, active volcanoes (Clague and Denlinger, 1994). Seaward displacement of entire volcano flanks also requires the presence of deep decollement horizons, perhaps localized along a clay-rich layer at the oceanic crust – volcano interface, which may maintain high pore fluid pressures (Iverson, 1995). The transition from hot magmatic conditions beneath the summit to near seafloor temperatures near the toe of the flank also implies dramatic spatial transitions in fault properties and rheology.

Comparisons of actively deforming volcanoes and older volcanoes, both in Hawaii and around the world, can provide further insights into the processes that control volcano deformation and flank stability. As an example, most other ocean-island volcanoes exhibit little flank creep in comparison to Hawaii. Older Hawaiian volcanoes, however, likely experienced similar modes of deformation as occur on Kilauea and Mauna Loa today, and their eroded flanks provide unique access to the interiors of the resulting structures, and the stratigraphies and geochemistries of the rocks that compose them. Thus, it becomes possible to document the long-term evolution of volcanic materials that control flank stability. In particular, does the progressive alteration of glassy volcaniclastic sediments lead to increased induration and resistance to shear stresses (Clague et al., 2002), or does microbial activity during glass alteration reduce shear strength over time thereby favoring slope failure (Fisk et al., 2003)?

These preliminary hypotheses about the structure, behavior, and mechanisms of active ocean-island basaltic volcanoes are based on scant evidence, primarily from onshore observations and surveys. In general, the direct causes of volcano flank motions and slope instability are not well understood. Ultimately, deformation of the offshore portions of the flanks constitutes the greatest geologic hazard, with potential impacts across the ocean basins (e.g., Morgan et al., 2009); thus, it is imperative to deploy the tools offered through ocean drilling to understand the conditions, controls and frequencies of such deformational events. Integration of submarine observations with subaerial data, abundant in Hawaii, further enhances the value and relevance of submarine investigations.

The knowledge gained through deep ocean drilling will also contribute to our fundamental understanding of how ocean-island basaltic volcanoes grow and collapse. In particular, through drilling, it is possible to relate deformation stages of volcanoes to growth stages and geochemical evolution, providing key insights into the physical processes that govern their evolution

<u>Specific questions that can be addressed through ocean drilling include:</u>

- What are the conditions and/or triggers (e.g., composition, shear strength, pore pressure, thermal pressurization, earthquakes, explosive eruptions, sea level change) that lead to large-scale flank collapse in volcanic settings?
- What causes or enables more gradual volcano flank motions (e.g., seaward creep, aseismic slip, flank earthquakes), and what are the hazard implications?
- What are the frequencies, magnitudes, and distributions of large volcanic landslides on ocean island settings?
- What is the interplay between volcano growth, collapse, and geochemical evolution, and how does this influence volcanic evolution and geologic hazard potential through time?

The submarine flanks are clearly significant players in the deformation and evolution of ocean-island basaltic volcanoes, but to date, very few direct observations of submarine deformation exist in these settings. Ocean drilling is the only way to obtain a comprehensive view of the entire volcano flank and its substrate, in space and time. Moreover, the seafloors around ocean island volcanoes preserve a rich record of past events, but have yet to be completely sampled and analyzed. Ocean-island basaltic volcanoes thus define a rich target for future ocean drilling that will investigate some of these fundamental questions.

<u>Representative opportunities provided by ocean drilling include:</u>

- Drilling through flanks, landslide deposits, and “hanging walls” to determine lithologies, stratigraphies, geochemistries, physical and mechanical properties, alteration, biological content, fluid flow history, and structural evolution of these features.
    - Drilling at both active and older Hawaiian volcanoes will clarify the evolution in material properties that might favor or preclude slope failure, e.g., sampling at Kilauea, Mauna Loa, Kohala, and/or Haleakala.
- Deep drilling to sample deep fault materials and to constrain mechanical properties and frictional behavior of the basal decollement, internal thrusts and detachment faults that allow for flank deformation. Drilling through different parts of the decollement will be critical to constrain how and why strength and slip behavior vary.
    - Comparative studies in Hawaii and elsewhere would constrain why deformation processes differ in each setting.

- Deployment of offshore seismometers, tiltmeters, pressure gauges, and geodetic instruments to document the submarine contributions to flank motion, and to better constrain the modes and source regions for deformation. Such data could be readily integrated with onshore observations that constrain subaerial deformation.
- Drilling through distal turbidites that record past flank failures to constrain source area, frequency, and magnitude of events in a given setting.
    - Correlations of landslide-generated turbidites with known ash stratigraphy will test if large-scale slope failures accompany explosive eruptions.

A primary advantage of studying the offshore region of Hawaii Island through drilling is that intensive geodetic and seismic networks have long been in place onshore to monitor the activity of Kilauea and Mauna Loa volcanoes. Because of these networks, the deformation field and concentrations of seismicity are well established, and drilling targets can be selected with a high degree of certainty of detecting deformation. Intensive dive programs and marine seismic surveys have also been completed, particularly for Kilauea's submarine south flank, so that initial site characterization has already been accomplished, allowing depths and locations of structures to be estimated with confidence.

Future drilling and borehole installations will, of course, require preparatory studies, including well-designed 3D seismic surveys to better constrain the subsurface properties and structural geometries. Such surveys will be informed by existing detailed bathymetric surveys in Hawaii, and 2-D multichannel seismic profiles across key features of interest.

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