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An increment of volcano collapse: Kinematics of the 1975 Kalapana, Hawaii, earthquake

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Abstract

Earthquakes on Kilauea Volcano can be even more hazardous than volcanic eruptions. The most recent large earthquake was the 1975 Kalapana quake, which generated a locally damaging tsunami, over 8 m of horizontal surface displacement and 3 m of subsidence at the coast. The seismic magnitude estimates for this earthquake range from Ms 7.2 to Mw 7.7. The complexity of the seismic data is matched by the complex surface deformation that was observed with a combination of leveling, tilt and Electronic Distance Measurements (EDM). The geodetic data shows evidence of collapse of the caldera due to magma withdrawal, localized subsidence over the rift zone, normal faulting associated with shallow slumping along the Hilina Pali, and displacement on the basal detachment fault. We model the summit caldera, rift zones and basal detachment fault as dislocations in an elastic half-space to better quantify the sources of deformation related to this devastating event. Using inversion techniques that allow us to let the data constrain the geometry and magnitude of these sources, we find 0.04 km^3 of magma withdrawal at the summit, between 3–5 m of opening along the rift zone and 7.1 m of slip along the basal detachment at 8.3 km depth. Models that allow for finer spatial resolution of slip on the detachment show that the largest slip occurred west of the seismically recorded earthquake hypocenter, along the region of the fault below the coast, and that the majority of the fault slip occurred south of the region of microseismicity. Our best-fitting model has a geodetic moment of 4.1×10^{20} Nm (M_w 7.7), which is consistent with tsunami models and recent analysis of long period seismic data. The residual displacements of sites located in the hanging wall of the Hilina Pali slump system, which were not used in the inversion of the other sources, suggest that triggered shallow slumping contributed several meters of horizontal displacement to the coseismic displacement at these sites.

Keywords: Kilauea; volcanoes; earthquakes; rift zones; geodesy; trilateration; leveling; tilt

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1. Introduction

The active volcanoes of Hawaii are responsible for recurrent damaging earthquakes, the most recent being the events of 1975 and 1989. Both earthquakes occurred beneath the structurally unstable south flank of Kilauea Volcano, but also caused internal deformation of the south flank block and magma redistribution. Other volcanic flanks, especially those on oceanic shields, exhibit evidence for slumping and catastrophic gravity sliding during their growth. Benefiting from the dense seismometer network and rich geodetic database collected by the Hawaiian Volcano Observatory (HVO) (Lipman et al., 1985), we evaluate kinematic models of the 1975 Kalapana earthquake deformation to improve our understanding of the processes that cause large volcanic edifices to fail. We hope to better understand the seismic hazard of Kilauea's south flank through rigorous analysis of geodetic data spanning this largest Hawaiian earthquake of the past century.

2. Hawaiian earthquakes and Kilauea's edifice structure

The south flank of Kilauea Volcano, Hawaii, experienced significant historic earthquakes ($M>6$) in 1823, 1868, 1954, 1975, and 1989 (Fig. 1) (Wyss and Koyanagi, 1992a). These earthquakes caused significant damage with strong shaking, landsliding, coastal subsidence, and destructive tsunamis. Seismic, geodetic and tsunami data reveal that the 1975 $M_s=7.2$ earthquake (Ando, 1979; Lipman et al., 1985; Tilling et al., 1976) and the 1989 $M_s=6.1$ earthquake (Arnadottir et al., 1991; Bryan and Johnson, 1991) occurred primarily on sub-horizontal thrust faults near the base of the volcanic edifice at about 8–10 km depth (Fig. 1A,B) (Ando, 1979; Arnadottir et al., 1991; Crosson and Endo, 1982; Furumoto and Kovach, 1979; Hill and Zucca, 1987; Lipman et al., 1985). Coastal subsidence patterns and local tsunami heights during the $M \approx 8$ 1868 Kau earthquake resembled those of 1975 and suggest basal detachment below Kilauea as well as Mauna Loa (Ando, 1979; Hitchcock, 1912; Wood, 1914; Wyss, 1988).

The south flank of Kilauea is defined as the portion of the island of Hawaii that lies south of Kilauea's summit and rift zones. This region has been displaced seaward by magmatic intrusions, gravitational spreading of hot dense rock within the deep rift system and slip on the basal detachment fault (Clague and Denlinger, 1994; Crosson and Endo, 1982; Delaney et al., 1990; Denlinger and Okubo, 1995; Dieterich, 1988; Harvey and Wyss, 1986; Lipman et al., 1985; Ryan, 1988; Swanson et al., 1976; Thurber and Gripp, 1988). Detachment faulting and

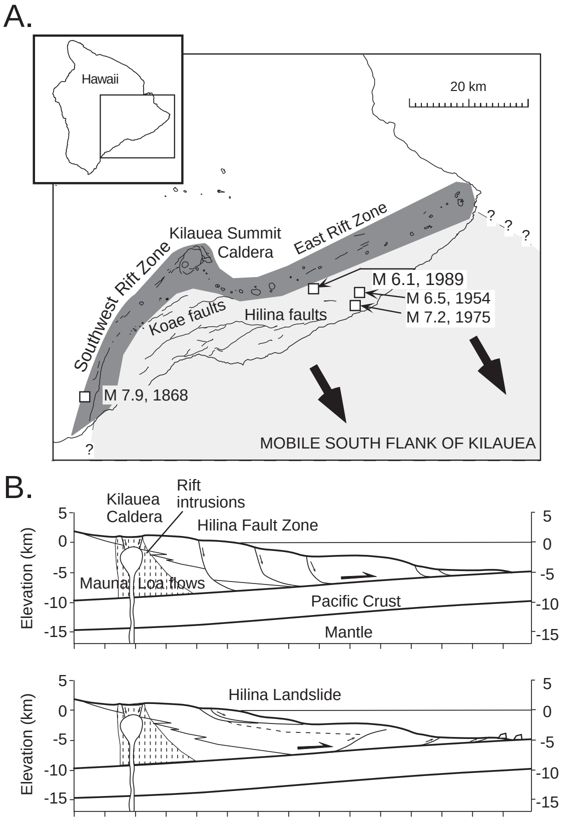

Fig. 1. (A) Location map of Kilauea's south flank. Historic $M>6$ earthquake epicenters are labeled with their magnitude and year. (B) Cross-sections across Kilauea's south flank showing two general interpretations proposed for the subsurface structure of the Hilina fault zone (based on Lipman et al., 1985; Hill and Zucca, 1987; and Morgan et al., 2003). The depth and dip of the Pacific plate, the inferred dike complex below the volcanic rift zones, and the stratigraphy of the south flank are based on gravity and seismic refraction data reviewed by Hill and Zucca (1987). A deeply rooted Hilina fault system is supported by microseismicity and seismic tomography results (Okubo et al., 1997). A shallow system, soling out at 2–4 km depth, is consistent with the surface geometry and offshore seismic reflection data (Cannon et al., 2001; Morgan et al., 2003).