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Volcanotectonic interactions between Mauna Loa and Kilauea: Insights from 2-D discrete element simulations

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Abstract

Numerical simulations using the discrete element method (DEM) are carried out to examine the dynamics and internal deformation of overlapping volcanoes constructed upon a weak décollement horizon, as analogs to the Kilauea–Mauna Loa system of volcanoes in Hawaii. Employing a frictional rheology, the DEM simulations capture much of the complex deformation behavior of Mauna Loa and Kilauea volcanoes, here referred to as the primary and secondary edifices, respectively. The models demonstrate incremental displacements of the outer flanks of the volcanoes and concurrent summit subsidence, leading to characteristic low slopes and inward dipping strata. Slip discontinuities that develop within the piles define steeply dipping normal faults along the upper flanks and beneath the edifice summits, that accommodate subsidence and flank spreading. Edifice overlap influences dynamic behavior significantly; even small topographic perturbations restrict the internal deformation and spreading of the confined flanks. The degree of buttressing depends on the relative positions of the two edifices. If the secondary edifice grows high upon the flanks of the primary edifice, outward spreading of the underlying flank is enhanced; if the secondary edifice is built low upon the primary flanks, spreading of the underlying flank is effectively prevented, or possibly reversed. Furthermore, as the second edifice grows, it subsides into the underlying flank, partitioning it into a mobile downslope region entrained by spreading of the second edifice, and a comparatively stable upper flank region. These results suggest that much of the mass of Kilauea volcano may lie deeply buried within the underlying flank of Mauna Loa, while older Mauna Loa rocks may lie far from their source beneath the mobile flank of the younger volcano.

Keywords: Mauna Loa; Kilauea; volcanotectonics; volcanic spreading; Hawaii; landslides; subsidence

1. Introduction

Kīlauea volcano is built upon the southeastern flank of the enormous edifice of Mauna Loa volcano, and together, these two volcanoes comprise ~70% of the area of the Big Island of Hawaiʻi (Fig. 1). Both volcanoes are subject to gravitational stresses that contribute to summit, rift zone, and flank deformation, resulting in substantial lateral spreading during their growth (e.g., volcanic spreading, Borgia et al., 2000). This spreading is manifested through seaward displacements of the volcano flanks (e.g., Owen et al., 1995, 2000; Delaney et al., 1998), distal shortening (Denlinger and Okubo, 1995; Morgan et al., 2003), and long-term summit subsidence (e.g., Walker, 1992; Delaney et al., 1993; Miklius et al., 1997; Quane et al., 2000). The three-dimensional configurations of these and adjacent volcanoes lead to complicated interactions as the volca-

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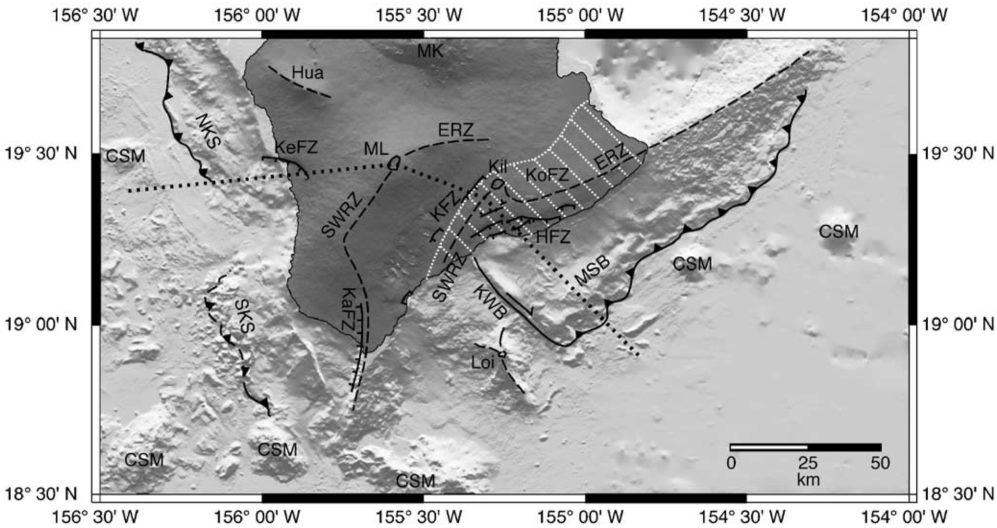

Fig. 1. Shaded relief map of the southern portion of the Island of Hawai‘i and offshore regions, showing relative positions of Mauna Loa (ML), Kīlauea (Kil), and Lō‘ihi (Loi) volcanoes, as well as Hualalai (Hua) and Mauna Kea (MK). Darker shaded region outlined in black denotes the island. Subaerial Kīlauea volcano, built along the flank of Mauna Loa, is indicated by inclined white lines. Dashed lines delineate volcanic rift zones, emanating from encircled calderas. Hachured lines indicate normal fault scarps, with the hachures pointing in the down dip direction. Lines decorated with teeth outline the boundaries of interpreted overthrust packages at the toes of the spreading volcanoes (dashed where less certain; teeth lie on the hanging wall). Arrows denote relative directions of strike-slip fault motion. Important subaerial and submarine features are labeled as follows: HFZ—Hilina fault zone; KFZ—Kaoiki fault zone; KoFZ—Koae fault zone; KaFZ—Kahuku fault zone; KeFZ—Kealakekua fault zone; MSB—midslope bench of Kīlauea's south flank; KWB—Kīlauea's western boundary; SKS—South Kona slump; NKS—North Kona slump; ERZ—East Rift Zones of Kīlauea and Mauna Loa; SWRZ—Southwest Rift Zones of Kīlauea and Mauna Loa; CSM—Cretaceous seamounts. Heavy dotted line traversing the mapped area marks the position of interpretive cross-section in Fig. 12. Bathymetry gridded at 100 m from Smith et al. (1994).

noes grow and deform. Due to their proximity, Kīlauea and Mauna Loa buttress each other, restricting faulting and displacement of their adjoining flanks. Their seaward flanks, however, show evidence for substantial past deformation, in the form of extensive seaward dipping normal faults along their upper flanks, and uplifted midslope benches along the submarine flanks (e.g., Swanson et al., 1976; Lipman et al., 1985, 1988; Moore et al., 1989, 1994). Present-day motions of Kīlauea's south flank are also substantial, and include seaward creep of up to 10 cm/yr in recent years, and possibly even higher in previous decades (e.g., Swanson et al., 1976; Delaney et al., 1993, 1998; Denlinger and Okubo, 1995; Owen et al., 1995, 2000; Delaney and Denlinger, 1999), as well as intermittent damaging flank earthquakes (e.g., Ando, 1979; Furumoto and Kovach, 1979; Crosson and Endo, 1981; Bryan, 1992). Mauna Loa's flanks are much less active, showing lower displacement rates and fewer large earthquakes (e.g., Wyss, 1988; Wyss and Koyanagi, 1992; Gillard et al., 1992; Miklius et al., 1995, 1997). The contrasting behaviors of the two volcanoes raise the question as to what degree the two edifices influence each other dynamically, both today and in the past.

Numerical simulations can be used to investigate gravitationally induced stresses that influence volcanotectonic deformation. In a previous study using the discrete element method (DEM), the self-similar growth and gravitational deformation of symmetric granular piles were simulated as analogs for natural volcanoes subject to Coulomb rheology (Morgan and McGovern, 2005-a,b). These preliminary simulations successfully reproduced structural and morphologic features recognized at several basaltic volcanoes, including their low surface slopes, deep-seated and surficial detachment faults, and distal overthrusting at the toes of the flanks (Morgan and McGovern, 2005-a). Although magmatic processes are no doubt important, the results demonstrate that gravitational stresses alone can explain much of the observed deformation at natural volcanoes. Furthermore, the mode of edifice deformation proves to be highly dependent upon the strength of the volcanic substrate (Morgan and McGovern, 2005-b). Surface slopes and dips of detachment faults that develop during steady state volcano growth are directly predicted by the basal strength conditions, yielding distinct layer geometries that can be compared with natural analogs