Influence of volcanic activity at Mauna Loa, Hawaii, on earthquake occurrence in the Kaoiki Seismic Zone

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[1] The Kaoiki Seismic Zone at Mauna Loa's east flank is the locus of some of the largest earthquakes on Hawaii. In this paper we examine the link of those earthquakes to volcanic activity at Mauna Loa. We calculate the changes of Coulomb failure stress along the Kaoiki faults for typical volcanic events at Mauna Loa volcano. We simulate the dislocation associated with the 1950 eruption at the Southwest Rift Zone, the 1984 eruption at the Northeast Rift Zone, and the subsequent replenishment of the shallow magma chamber. Our model calculations suggest that the earthquake occurrence in the Kaoiki Seismic Zone strongly depends on the type of volcanic activity. Kaoiki earthquakes are encouraged by dike intrusions into the Southwest Rift Zone of Mauna Loa, but discouraged by dike intrusion into the Northeast Rift Zone. Inflation of a shallow magma chamber may again encourage earthquakes. *INDEX TERMS:* 1242 Geodesy and Gravity: Seismic deformations (7205); 7223 Seismology: Seismic hazard assessment and prediction; 8164 Tectonophysics: Stresses—crust and lithosphere; 8434 Volcanology: Magma migration; 8499 Volcanology: General or miscellaneous. **Citation:** Walter, T. R., and F. Amelung (2004), Influence of volcanic activity at Mauna Loa, Hawaii, on earthquake occurrence in the Kaoiki Seismic Zone, *Geophys. Res. Lett.*, *31*, L07622, doi:10.1029/2003GL019131.

1. Introduction

[2] There is increasing evidence that earthquakes and volcanoes interact. Earthquakes change the state of stress in magmatic systems and may trigger eruptions, and reversely, volcanic activity alters the stress along faults and may trigger earthquakes [*Thatcher and Savage*, 1982; *Nostro et al.*, 1998; *Hill et al.*, 2002]. It has been found that even small stress changes (<3 bar) can trigger earthquakes [*Stein*, 2003].

[3] On the Island of Hawaii, volcanic eruptions are commonly accompanied by significant earthquakes. In this paper we examine how volcanic activity at Mauna Loa volcano changes the stress field in the Kaoiki Seismic Zone (*KSZ*) on Mauna Loa's east flank. We consider three different scenarios of volcanic activity. First, we consider a dike intrusion into the Southwest Rift Zone (SWRZ) of Mauna Loa to simulate the 1950 eruptive fissure. Second we consider a dike intrusion into the Northeast Rift Zone (NERZ) to simulate the 1984 eruptive fissure. Third, we consider magma chamber inflation to simulate doming periods. The models suggest that earthquakes in the *KSZ* may be encouraged or discouraged, depending on the type of volcanic activity at Mauna Loa.

2. Geological Background

[4] The *KSZ* is a heavily faulted and seismically active zone on the eastern flank of Mauna Loa volcano (Figure 1A). Two types of earthquakes occur in the *KSZ* [e.g., *Endo*, 1985; *Wyss et al.*, 1992; *Got and Okubo*, 2003]: The first types of earthquakes are right-lateral strike-slip events along SW-NE striking vertical faults at 5–9 km depth. The second types of earthquakes are low angle thrust events along a décollement fault between the volcanic edifice and the paleo-seafloor at 9–11 km depth (Figure 1B). The décollement fault is slightly inclined towards the centre of Mauna Loa because of the bending of the oceanic crust under the volcano load. In the northern *KSZ* strike-slip earthquakes dominate, while in the south décollement-type earthquakes dominate [*Got and Okubo*, 2003]. The strike-slip events may have some décollement-type slip component (see below). The seismicity in the *KSZ* is probably related to flank instability of the volcano edifice and to lateral expansion perpendicular to the rift zones [*Endo*, 1985]. Mauna Loa's east flank slides southeastward and Kilauea's south flank moves to the south [*Bryan and Johnson*, 1991], promoting strike-slip faulting between Mauna Loa and Kilauea. Similar strike-slip structures were recently reproduced experimentally [*Walter*, 2003].

[5] Earthquake mainshocks in the *KSZ* occurred in 9/1941 (M_S 6.0), in 8/1951 (M_S 5.5), in 6/1962 (M_S 6.1), 11/1974 (M_L 5.5), and in 11/1983 (M_L 6.6) [*Endo*, 1985; *Wyss*, 1986; *Klein and Wright*, 2000]. Based on the periodicity of 10.5 ± 1.5 years, *Wyss* [1986] noted that an event is likely between 1993 and 1996. This earthquake did not occur, nor did it during the subsequent decade (Figure 1C).

3. Static Stress Field Changes

[6] Volcanic or tectonic deformation is associated with stress transfer that can influence near and distant faults [*Nostro et al.*, 1998; *Stein*, 1999]. Fault slip may occur if the shear stress acting on the fault plane exceeds the frictional resistance, or if the stress normal to this fault is reduced (unclamping). The sum of these stress components defines the static Coulomb failure stress. The changes of static Coulomb failure stress is given by $\Delta CFS = \Delta\sigma_s + \mu(\Delta\sigma_n + \Delta P)$, where μ is the coefficient of internal friction, ΔP is the change in pore-fluid pressure, $\Delta\sigma_s$ is the change in

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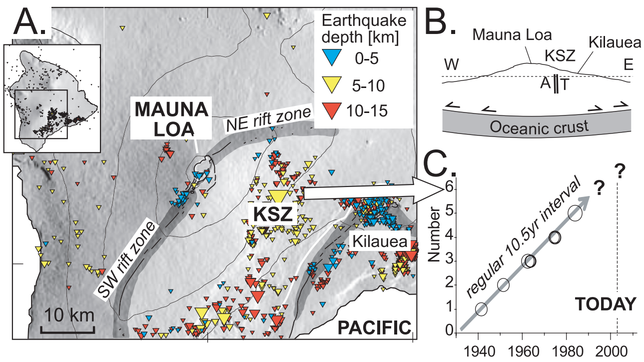

Figure 1. A. Location map of Mauna Loa volcano and seismicity since 1970 (M > 3). Earthquakes at Kaoiki Seismic Zone (KSZ) occur at vertical SW-NE oriented strike-slip faults, and at subhorizontal décollement faults. B. Sketch of section through southern Hawaii with both major fault types. Strike-slip motion: A-away from observer, T-toward observer. C. Kaoiki earthquakes after Wyss (1986). Note that since 20 years no mainshocks occurred.

shear stress in direction of fault slip, and $\Delta\sigma_n$ is the change in normal stress. Following *Toda and Stein* [2002], we assume a positive correlation between the change in pore pressure and the change of tensional normal stress, and use the effective coefficient of friction μ':

$$\Delta CFS = \Delta\sigma_s + \mu'\Delta\sigma_n.$$

Several studies have shown that areas with increase in ΔCFS match well with areas of aftershocks and seismicity rate increases [e.g., *Reasenberg and Simpson*, 1992; *Stein*, 1999, 2003; *Troise*, 2001; *Dieterich et al.*, 2003]. Triggering may occur for several months to years following the mainshock.

[7] We determine the changes in Coulomb failure stress (ΔCFS) at the *KSZ* fault planes in Mauna Loa's east flank, computed in a uniform elastic half-space. The half-space approximation is appropriate for Mauna Loa volcano, which has a height-to-length ratio of 1:20. We assign a Young's Modulus of E = 50 GPa and a Poisson's ratio of ν = 0.25, and μ' = 0.7. The models are loaded by an opening dike, or by an expanding magma reservoir. We evaluate ΔCFS on receiver planes oriented subparallel to the Kaoiki strike-slip faults (strike/dip/rake 40°/90°/180° at 7 km depth), and on receiver planes parallel to the subhorizontal décollement plane (45°/0°/−90° at 10 km depth). The fault plane orientation and slip direction is based on focal mechanism solutions by *Endo* [1985], *Wyss et al.* [1992], and *Got and Okubo* [2003]. In the next sections we investigate how intrusions at Mauna Loa encourage or discourage earthquakes.

3.1. Stress Changes Due to the 1950 Eruptive Dike

[8] The June 1950 eruption of Mauna Loa volcano was one of the largest ever reported eruptions on Hawaii. Initiated near the summit, fissures propagated rapidly to the southwest. Over 3.7 × 10^8 m^3 Lava erupted from a ~20 km long linear fissure in the SWRZ [Figure 2A, *Lockwood and Lipman*, 1987].

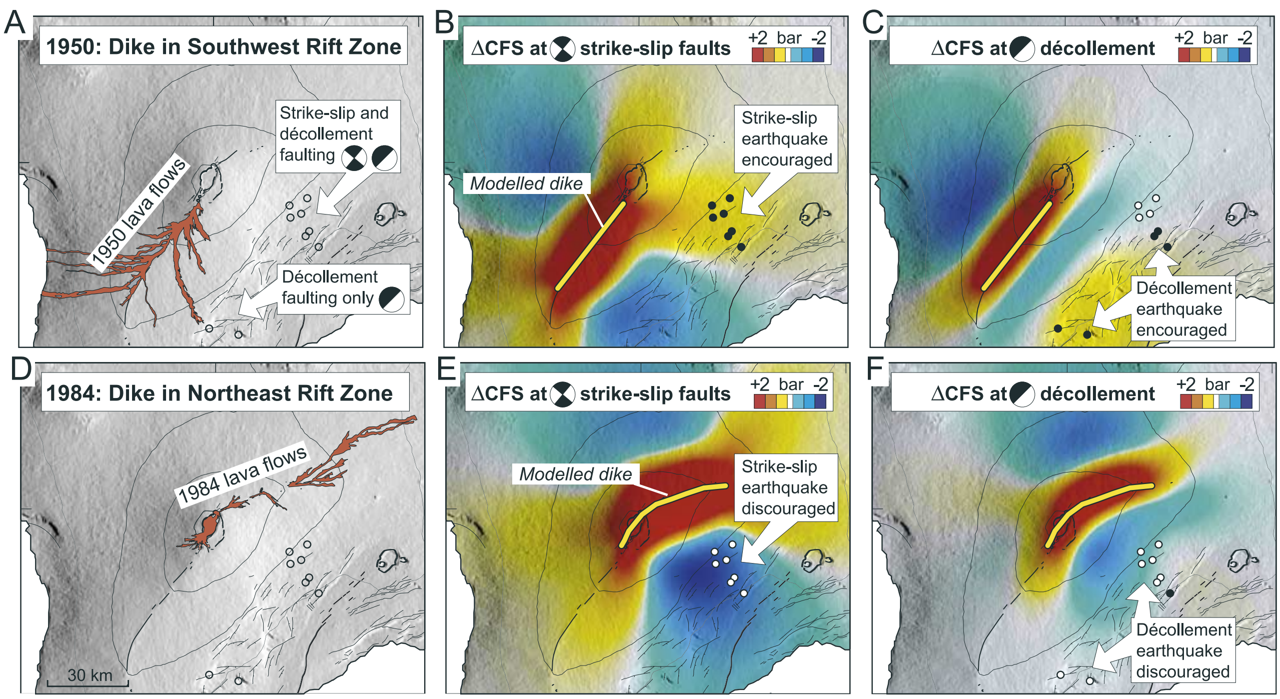

Figure 2. ΔCFS at Kaoiki faults caused by the 1950 eruptive fissure in the SWRZ (A, B, C) and by the 1984 eruptive fissure in the NERZ (D, E, F). ΔCFS is calculated at receiver planes parallel to the vertical right-lateral strike-slip faults (B, E strike 40° at 7 km depth) and parallel to the subhorizontal déllement faults (C, F, 10 km depth). Failure is encouraged if ΔCFS is positive (red color) and discouraged if negative (blue). Circles indicate earthquakes epicenters M > 4.8 after *Endo* [1985], where filled (open) circles denote encouraged (discouraged) earthquakes.

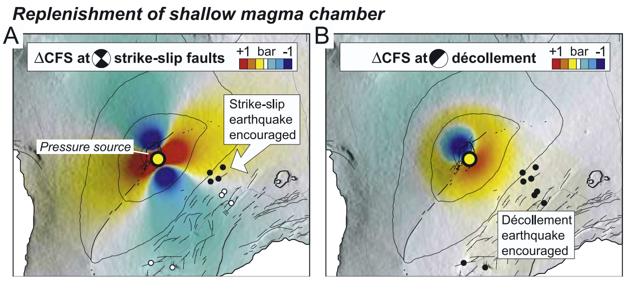

Figure 3. Mogi source simulating inflation of the shallow magma chamber. Magma chamber inflation may trigger Kaoiki earthquakes.

[9] We investigate how the eruptive dike along the SWRZ changed the stress field in the *KSZ*. We assume a dike thickness of 1 m, a dike length of 20 km and dike height from 4 km depth to the surface, similar to other recent dikes on Mauna Loa [cf. *Johnson*, 1995]. The dike was simulated by a uniform dislocation. ΔCFS is positive along Kaoiki-type strike-slip faults (Figure 2B). ΔCFS is also positive for décollement faulting at the southern *KSZ*, but negative in the northern and northwestern *KSZ* (Figure 2C). The increase of Coulomb stress is more significant at the Kaoiki-type strike-slip faults (about 0.5 bar) than at the décollement (less than 0.4 bar). Right-lateral strike-slip earthquakes are encouraged in the entire *KSZ*. Décollement-type eartquakes are encouraged in the southern *KSZ* (black circles in Figure 2C), but discouraged in the northern and northwestern *KSZ* (open circles).

3.2. Stress Changes Due to the 1984 Eruptive Dike

[10] The March–April 1984 eruption of Mauna Loa started with the opening of a crack in the summit caldera. Eruptive fissures then propagated along the rift zones to the NE and to the SW (Figure 2D). While activity in the SW died rapidly, the main eruptive fissures migrated in segments into the NERZ [*Lockwood et al.*, 1985]. Geodetic measurements showed that the NERZ extended by 0.8–1 m and was consistent with a shallow dike intrusion [*Lockwood et al.*, 1987; *Lockwood and Lipman*, 1987; *Johnson*, 1995].

[11] We model the 1984 dike by a segmented uniform dislocation, with a length of 22 km and opening of 1 m, with a depth between 0–4 km. ΔCFS along the Kaoiki-type strike-slip faults is negative on the southeast flank of Mauna Loa (−1 to −2.3 bar), thus Kaoiki-type strike-slip earthquakes are discouraged (Figure 2E). The ΔCFS along subhorizontal décollement-type faults is also mostly negative (−0.5 bar), thus décollement events are also discouraged (Figure 2F). Only in the area of Kilauea's Southwest Rift Zone ΔCFS is slightly positive. In general, the 1984 dike caused at both fault types a stress drop, more significant at the strike-slip faults. The calculations show that shallow dike intrusions into the NERZ discourage the occurrence of both, Kaoiki-type strike-slip and of décollement-type earthquakes in the *KSZ*. The 1984 dike could be responsible for the 20-year time period without major Kaoiki earthquakes.

3.3. Stress Changes Due to the Magma Chamber Inflation

[12] The magma chamber of Mauna Loa was replenished since the 1984 eruption during two main periods. A first period of inflation started directly after the 1984 eruption and lasted for about 10 years. The pattern of surface deformation suggested a ~3.7 km deep pressure source, which was slightly offset relative to the summit caldera and subjected to an annual volume increase of about 3.5×10^6 m^3 [*Miklius et al.*, 1995]. The total amount of extension across the caldera was ~200 mm. This phase was followed by almost 10 years of slight deflation. Since May 2002, Mauna Loa's magma chamber is inflating again with an extension rate of more than 50 mm/year [*Miklius and Cervelli*, 2003]. At the time of this writing (Feb, 2004) inflation continues. The geodetic data shows both, swelling of the summit and southeastward movement of the east flank [*Miklius and Cervelli*, 2003].

[13] We simulate the post-1984 magma chamber inflation using a Mogi point source that expands by 35×10^6 m^3, a volume which approximates the total volume of inflation since 1984 [*Miklius et al.*, 1995]. The location of the source is at 3.5 to 4 km depth, southeast under the outer caldera wall. The ΔCFS at Kaoiki-type strike-slip faults is positive in the northeastern (+0.1 bar), but negative in the southwestern *KSZ* (Figure 3A). The area of positive ΔCFS matches well (i) the locations of surface fractures related to right-lateral fault displacements and (ii) of the previous earthquake epicenters of 1962, 1974 and 1983 [black filled circles in Figure 3A; after *Jackson et al.*, 1992]. The ΔCFS for décollement faulting is positive throughout the *KSZ*, encouraging earthquakes (Figure 3B). Magma chamber inflation thus encourages strike-slip events in the northeastern KSZ and décollement faulting in the entire KSZ.

4. Discussion

[14] The model calculations suggest that volcanic events at Mauna Loa volcano influence, if not control, the occurrence of earthquakes in the *KSZ*. In general, dike intrusions into the SWRZ of Mauna Loa (such as in 1950) encourage the occurrence of Kaoiki earthquakes (Figures 2B and 2C). Dike intrusions into the NERZ (such as in 1984) discourage the occurrence of Kaoiki earthquakes (Figures 2E and 2F). Inflation of Mauna Loa's shallow magma chamber encourages the occurrence of décollement earthquakes and of strike-slip earthquakes in the northeastern KSZ (Figure 3A).

[15] We also tested the influence of poorly constrained model parameters. For effective friction coefficients $0.2 < \mu' < 0.7$ and greater dike depths we obtained in general similar patterns of ΔCFS. The only difference is that décollement faulting may be encouraged for a dike intrusion along the NERZ or SWRZ, if the dike originates at a much greater depth than the present magma chamber. The Young's modulus affects only the magnitude of the stress changes but not the pattern. Additional stress changes may be caused by active processes at Kilauea volcano.

[16] Our results are consistent with the observed earthquake history in the *KSZ* [*Klein and Wright*, 2000]. Six significant Kaoiki earthquakes occurred at regular intervals of ~10.5 years. The last event in this series occurred in 1983 [Figure 1C, *Wyss*, 1986]. The dike intrusions into the SWRZ associated with the 1950 Mauna Loa eruption encouraged Kaoiki earthquakes. However, the dike intrusion into the NERZ associated with the 1984 eruption may explain the non-occurrence of Kaoiki earthquakes since this last eruption.

[17] ***Mechanism of Kaoiki earthquakes.*** The mechanism of the Kaoiki earthquakes is not well understood. The first motion and teleseismic focal mechanism for the 1962, 1974 and 1983 Kaoiki earthquakes indicate right-lateral strike-slip [*Jackson et al.*, 1992; *Koyanagi et al.*, 1984; *Endo*, 1985]. The surface-wave derived moment tensor (MTS) and Harvard centroid solutions, however, indicate décollement-type thrust-slip [*Koyanagi et al.*, 1984; *Endo*, 1985; *Sipkin*, 1987]. A possible explanation for this difference is that some earthquakes may initiate as right-lateral strike-slip events in the volcanic edifice and then continue as décollement-type faulting. This explanation is consistent with our model calculations which all show that the most important positive change in Coulomb failure stress occurs along the Kaoiki-type strike-slip faults (Figure 3).

[18] In this paper we only have examined how volcanic events at Mauna Loa volcano may influence earthquake occurrence in the KSZ (uni-directional volcano-earthquake interaction). We have not examined how Kaoiki earthquakes may influence volcanic processes at Mauna Loa. Earthquake occurrence in the KSZ is complex. Kaoiki earthquakes sometimes precede and sometimes follow Mauna Loa eruptions. The 1974 and 1983 earthqaukes, for example occurred only a few month prior to the eruptions in 1975 and 1984. This may be a consequence of bi-directional volcano-earthquake interaction.

5. Conclusion

[19] Model calculations suggest that Coulomb failure stress changes associated with volcanic episodes of Mauna Loa influence the earthquake occurrence in the *KSZ*: (1) Dike intrusions into the SWRZ encourage Kaoiki earthquakes. (2) Dike intrusions into the NERZ discourage Kaoiki earthquakes. (3) The magma chamber inflation which continues at the time of writing (Feb, 2004) is bringing the Kaoiki faults closer to failure.

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