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The use of earthquake rate changes as a stress meter at Kilauea volcano

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Stress changes in the Earth's crust are generally estimated from model calculations that use near-surface deformation as an observational constraint. But the widespread correlation of changes of earthquake activity with stress[1–5] has led to suggestions that stress changes might be calculated from earthquake occurrence rates obtained from seismicity catalogues. Although this possibility has considerable appeal, because seismicity data are routinely collected and have good spatial and temporal resolution, the method has not yet proven successful, owing to the non-linearity of earthquake rate changes with respect to both stress and time. Here, however, we present two methods for inverting earthquake rate data to infer stress changes, using a formulation for the stress- and time-dependence of earthquake rates[6]. Application of these methods at Kilauea volcano, in Hawaii, yields good agreement with independent estimates, indicating that earthquake rates can provide a practical remote-sensing stress meter.

The inversions use a formulation for earthquake rate changes[6] derived from laboratory observations of rate- and state-dependent fault strength[6–8], which constrain the earthquake nucleation process to be dependent on both time and stress. Previously, this formulation has been applied to model the spatial and temporal characteristics of earthquake clustering phenomena, including foreshocks and aftershocks[6,7], and to evaluate earthquake probabilities following large earthquakes[9]. The effectiveness of the formulation for forward modelling of earthquake phenomena, and its derivation from observed fault properties, provide the basis for its use to estimate stress changes from earthquake rate data. This approach yields stresses that drive the earthquake process. As such, it is distinct from other seismological methods that yield measures of stress changes resulting from earthquakes.

The formulation of Dieterich[6] for rate of earthquake activity R (in a specified magnitude range) can be written in the condensed form

$$R = \frac{r}{\gamma \dot{S}_r}, \text{ where } d\gamma = \frac{1}{A\sigma}[dt - \gamma dS] \qquad (1)$$

where γ is a state variable, t is time, and S is a modified Coulomb stress function defined below. The constant r is the steady-state earthquake rate at the reference stressing rate $\dot{S}_r$. A is a dimensionless fault constitutive parameter with values usually in the range 0.005–0.015 (refs 6–8). The modified Coulomb stress function is defined as

$$S = \tau - [\mu - \alpha]\sigma \qquad (2)$$

where τ is the shear stress acting across fault planes that generate earthquakes (positive in the slip direction), σ is the normal stress (less pore fluid pressure), μ is the coefficient of fault friction and α is a constitutive parameter[6,10] with an assigned value in this study of 0.25 (refs 6, 10). In equation (1), the term $A\sigma$ is a constant (that is, changes in σ are negligible relative to total σ). For a stress step, equation (1) yields the characteristic aftershock sequence, which consists of an immediate jump of seismicity rate followed by decay that obeys the Omori t^{-1} aftershock decay law with aftershock duration $t_a = A\sigma/\dot{S}$ (ref. 6).

We use two methods to estimate stress changes from earthquake rate data. The first gives stress as a function of time in a specified volume. From equation (1), the observed rate R is used to directly calculate γ as a function of time (that is, $\gamma(t) = r/R(t)\dot{S}_r$). This requires an estimate of $\dot{S}_r$, which can be obtained from independent

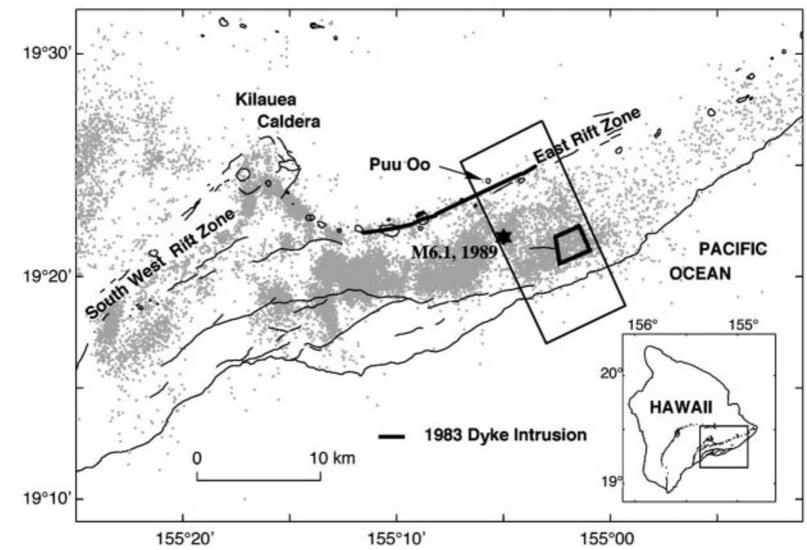

Figure 1 Map of Kilauea volcano showing earthquakes of magnitude $M \approx 1.5$ from 1976 to 1983. Intrusion of magma into the southwest and east rift zones of Kilauea causes rift expansion, and results in motion of the south flank to the SSE. Eruptive fissures initiated the Puu Oo eruption, which started 1 January 1983 and continues to the present. The small polygon is the region of analysis of Fig. 2; the large rectangle gives the region of analysis of Figs 3 and 4.