Insights into Caldera Collapse and Fault Friction from the 2018 Kilauea eruption

Paul Segall (Stanford University) Kyle Anderson (U.S.G.S. Volcano Science Center)

Abstract

The 2018 eruption of Kilauea volcano, Hawai`i, caused 62 repeatable collapse events in which the summit caldera dropped several meters, accompanied by M_W 4.7-5.4 VLP earthquakes. Collapses were exceptionally well recorded by GPS and tilt instruments, and represent unique in situ kilometer-scale friction experiments. We develop a lumped parameter model of a piston collapsing into a magma reservoir. Pressure at the piston base and shear stress on its margin, governed by rate and state friction, balance its weight.

Downward motion of the piston compresses the underlying magma, driving flow to the eruption vents (see Figure 2). We identify initial conditions and ranges of material and magma-system parameters that lead to episodic caldera collapse, revealing that small differences in the elevation of eruptive vents can lead to major differences in eruption volume and duration. Most historical basaltic caldera collapses were, at least in part, episodic implying that the conditions for stick-slip derived here are commonly met in nature.

Monte Carlo estimation of the system parameters validates laboratory friction parameters at the kilometer scale, including the magnitude of steady-state velocity weakening. The absence of accelerating pre-collapse deformation constrains d_c to be less than 10 mm, potentially much less. These results support the use of laboratory friction laws and parameters for modeling earthquakes under similar conditions.

Details available in Segall and Anderson, 2021 Proceedings of the National Academy of Science.

Data

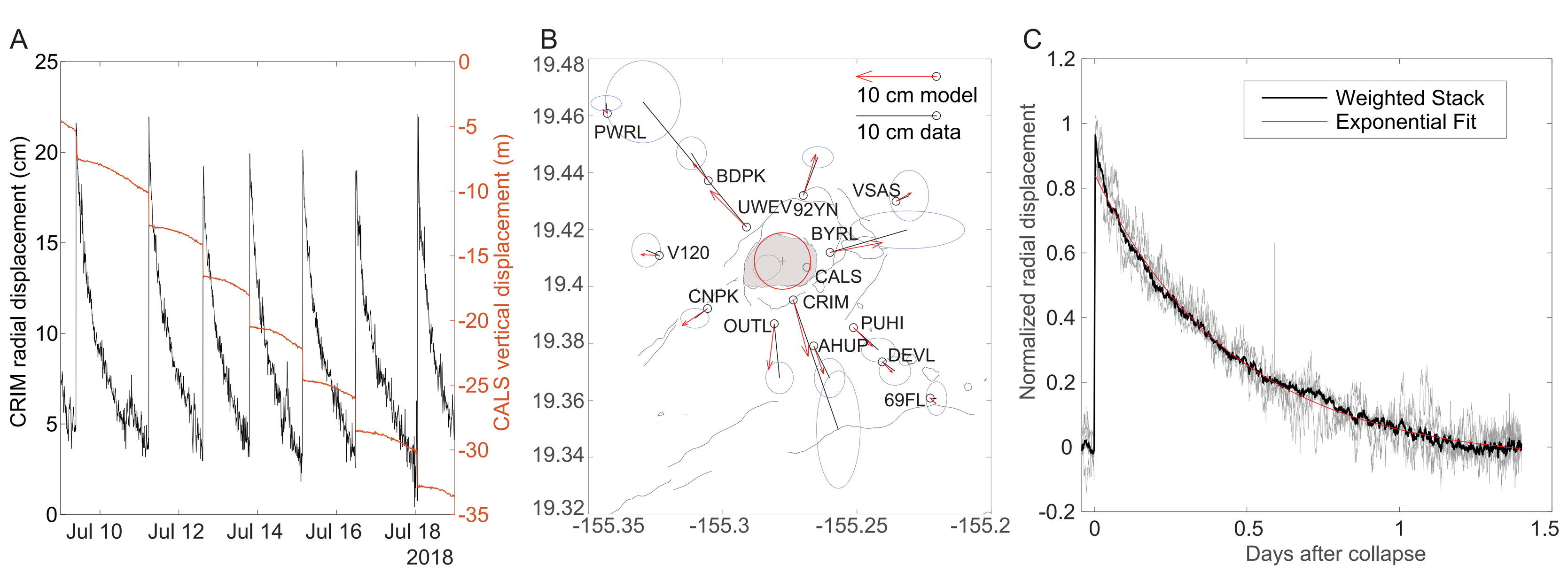


Figure 1. (A) Time series of caldera-radial GPS displacement at BYRL and vertical displacement at CALS. Radial is positive away from the caldera. Station locations shown in part B. B) Co-collapse horizontal displacements. Black vectors: average of last 32 events, with 95% confidence ellipses. Red vectors: predicted by model with 90 degree fault dip and magma compressibility of 3×10^{-10} 1/Pa (Segall et al, 2020, GRL). Collapse structure is shaded. Red circle: model ring-fault. C) Weighted stack of radial GPS displacements for stations external to collapse. Gray curves show stations with offset over 40 mm. Red: exponential fit with decay time of 0.46 days.

Model

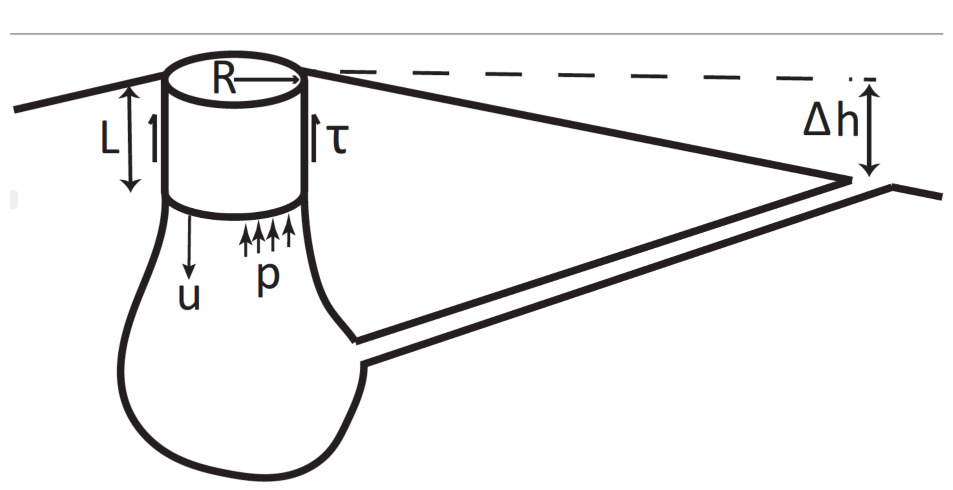


Figure 2. A cylindrical caldera block of radius R and length L with density ρ_c is supported by pressure p at its base and shear stress τ on its sides, undergoes downward displacement u. The underlying chamber with initial volume V_0 contains magma with density ρ. The elevation difference between the top of the caldera block and the eruptive vent is Δ h.

Governing Equations

$$\frac{R\rho_c g}{2} - \frac{R}{2L}p(t) - \tau(t) = \frac{R\rho_c}{2}\frac{dv}{dt}, \qquad [1]$$

Equation [1] represents momentum balance of the caldera block, on a per area basis: the first term is the block weight, the second pressure on its base, the third shear stress -- modeled by rate and state dependent friction -- on its sides.

$$\frac{dp}{dt} = -\frac{k}{\rho\bar{\beta}(t)V(t)}\left[p(t) - p_e - \rho g u(t)\right] + \frac{\pi R^2}{\bar{\beta}(t)V(t)}v(t), \qquad [2]$$

Equation [2] combines conservation of mass (of magma) with an equation stating that mass flux is proportional to excess pressure $p - p_e$. The last term represents the pressurization of the reservoir due to downward velocity, v(t) of the plug. Here β is the total compressibility (magma + reservoir).

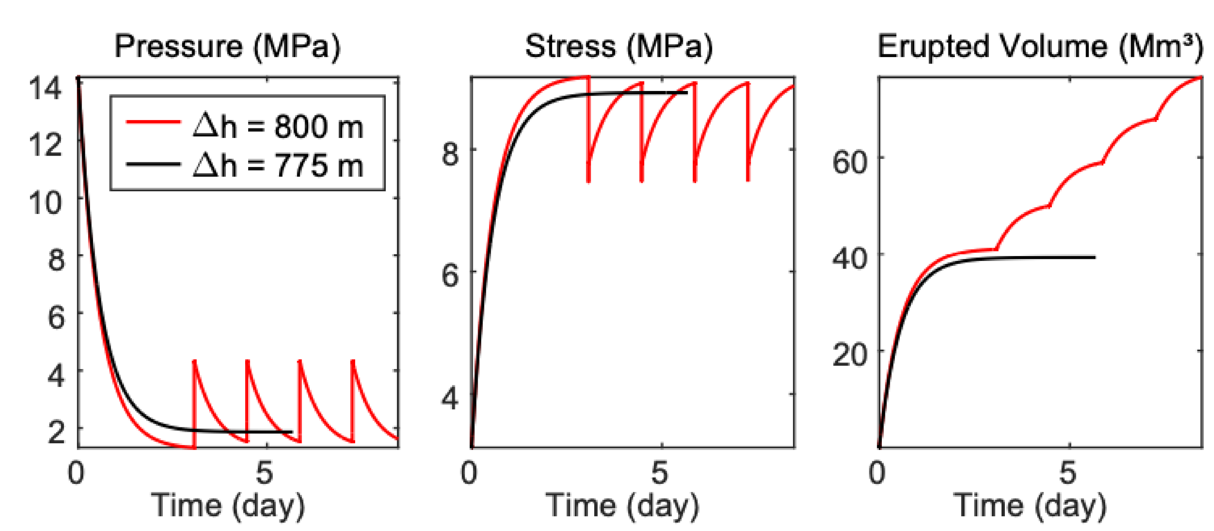
Predicted Behavior

The model exhibits a wide range of behavior. Depending on parameter values and initial conditions the system can: 1) decay to magmastatic pressure, possibly following one or more collapse events; 2) evolve to steady-state subsidence, either monotonically or via decaying non-inertial oscillations; or 3) produce a sequence of repeating stick slip cycles. A linearized stability analysis shows that stick slip cycles occur only when d_c is less than a critical value given by

$$(d_c)_{crit} = \sigma(b-a)\left[\frac{\pi R^3}{2LV\bar{\beta}} + \frac{\sigma a}{v_{ss}t^*}\right]^{-1}.$$

b-a is the steady state friction dependence on log v, σ is effective normal stress, v_{ss} and t^* are steady-state slip speed and characteristic drainage time.

The elevation difference between the caldera and the eruptive vents (800 m for Kilauea in 2018) plays an important role in determining whether collapse initiates. Figure 3 below shows that for other parameters held fixed, increasing the elevation of the eruptive vents by 25 m prevents collapse from occurring - the shear stress on the block never exceeds the nominal static friction. Pressure reckoned at the piston base; erupted volume in million cubic meters.



Indeed, the 2007 Piton de la Fournaise eruption began at the volcano's summit, but collapse only initiated when the eruption shifted ~1,300 m lower. The summit of Bardarbunga, Iceland is over a kilometer above the eruptive vents during the 2014 collapse, and the 2000 Miyakejima collapse was accompanied by a deep submarine dike intrusion. In contrast, Kilauea erupted for 35 years from the Pu`u`o`o vent -- 600 m higher than the 2018 vents -- without causing caldera collapse.

References

Anderson, K.R., Johanson, I.A., and others, Magma reservoir failure and the onset of caldera collapse at Kilauea volcano in 2018, Science, 366 (6470), 2019.

Segall, P., K.R. Anderson, and others, Caldera collapse geometry revealed by near-field GPS displacements Kilauea volcano in 2018, Geophysical Research Letters, 2020.

Zhang, L., C. He, Y. Liu, and J. Lin. Frictional properties of the South China Sea oceanic basalt and implications for strength of the Manila subduction seismogenic zone. Marine Geology, 394:16–29, 2017.

MCMC Estimation of Parameters

We use a Markov Chain Monte Carlo routine to sample the posterior distribution of parameters consistent with observations of: recurrence time (1.4 day), event duration (5-10s), pressure change (3 MPa), collapse displacement (2.5-5 m), and pressure decay time (0.5 day). Distributions for 2.2 million samples are shown in Figure 4. Also shown are *a priori* estimates of these parameters, subjected to the constraint that the parameters exhibit stick-slip cycles. The friction parameters, particularly b-a are remarkably consistent with laboratory experiments on basalt at 45 - 51 MPa effective normal stress and temperatures up to 600 C (Zhang et al, 2017). Estimates of chamber volume are largely consistent with those of Anderson et al (2019) from pre-collapse deflation data.

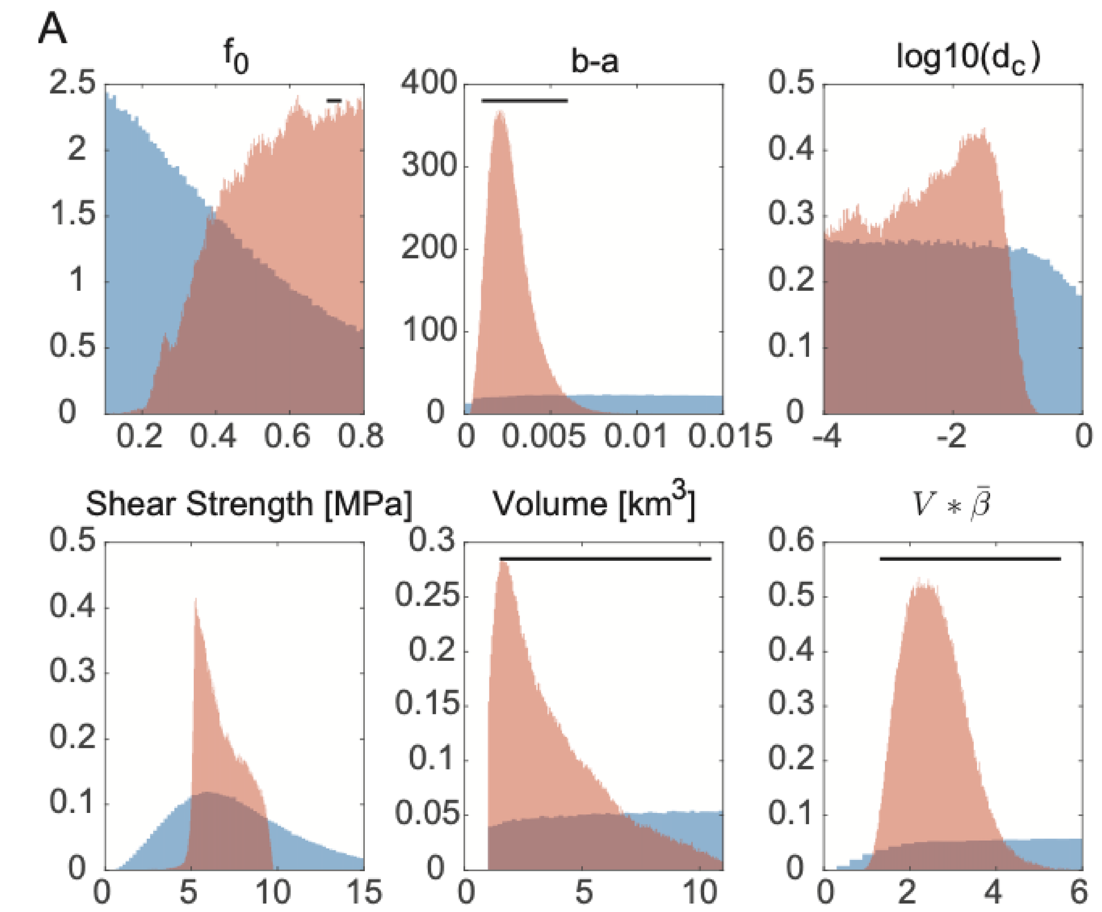


Figure 4. Posterior distributions based on 2.2 million samples (red). A priori distributions conditional on the existence of linearly unstable steady-state solutions (blue). Black horizontal lines mark the range of values from lab experiments (Zhang et al, 2017) for friction parameters, and from Anderson et al (2019) for the magma chamber parameters.

MAP Predicted Time Series

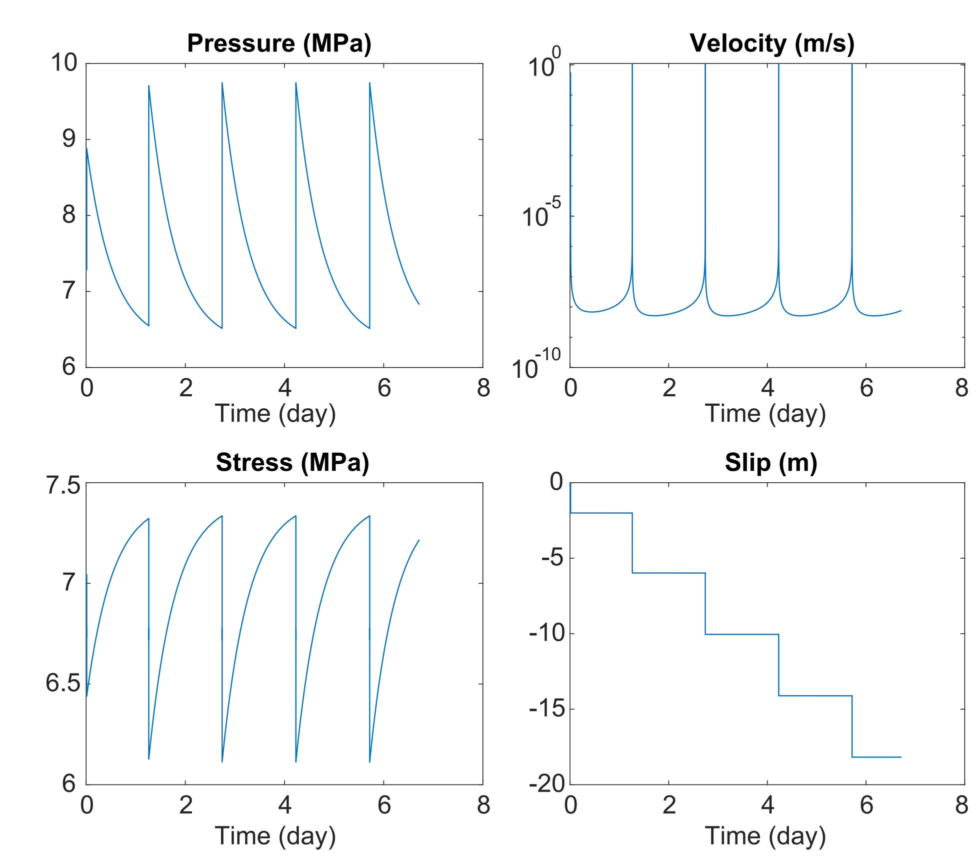


Figure 5. Predicted pressure, slip velocity, shear stress and piston displacement for the Maximum a Posteriori (MAP) model with dc < 10 mm, to be consistent with absence of pre-collapse deformation (not shown). Pressure is reckoned at the top of the magma chamber.

Conclusions

- Simple model consistent with many aspects of the 2018 caldera collapse events.
- Low elevation eruptive vents promote collapse onset.
- Linearized stability analysis predicts combinations of parameters that give rise to stick slip behavior.
- Friction parameters estimated from km scale collapse consistent with laboratory experiments on vastly smaller samples.