Modeling of volcanic tremor as repeating earthquakes

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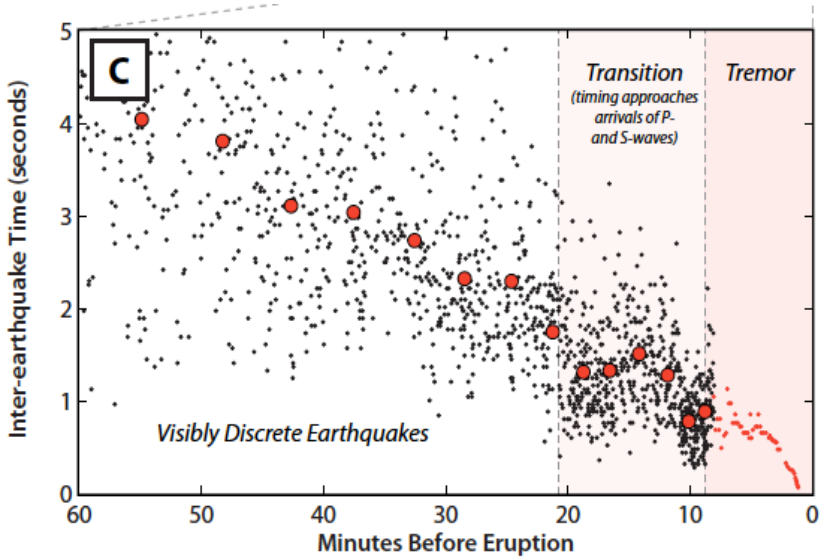
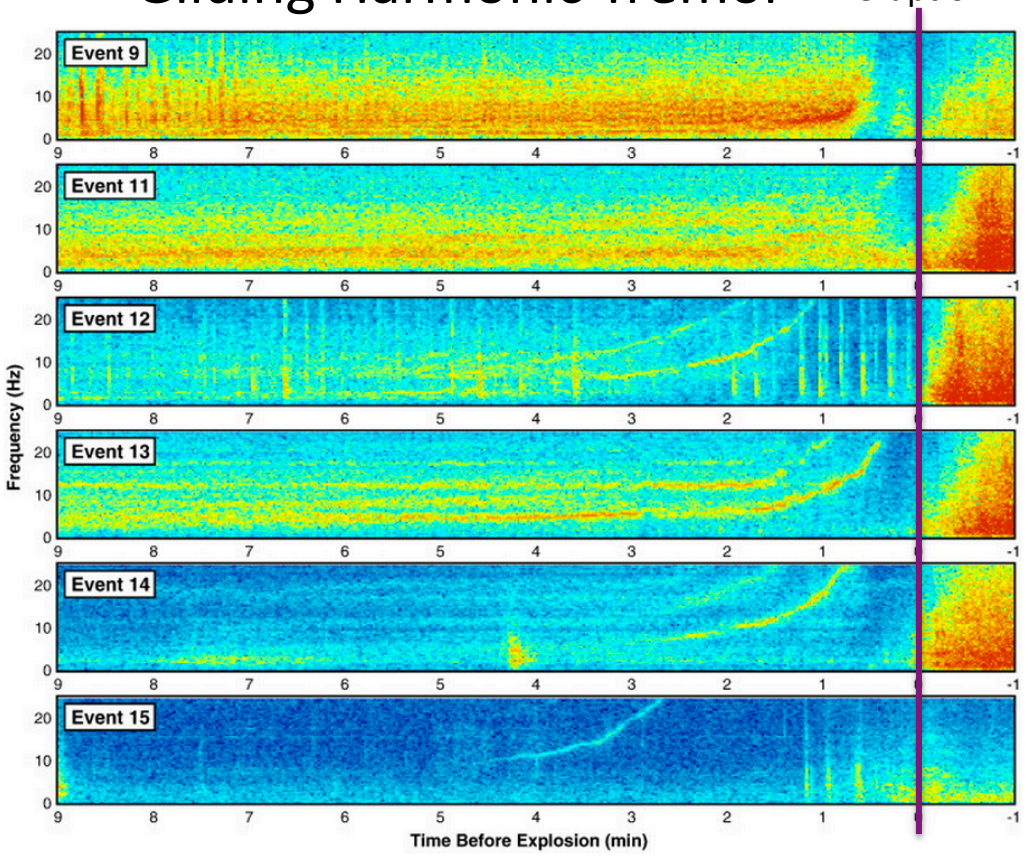
2009 Eruption of Redoubt Volcano

- repeating earthquakes magnitude ~ 1
- 1-3 km beneath the active vent

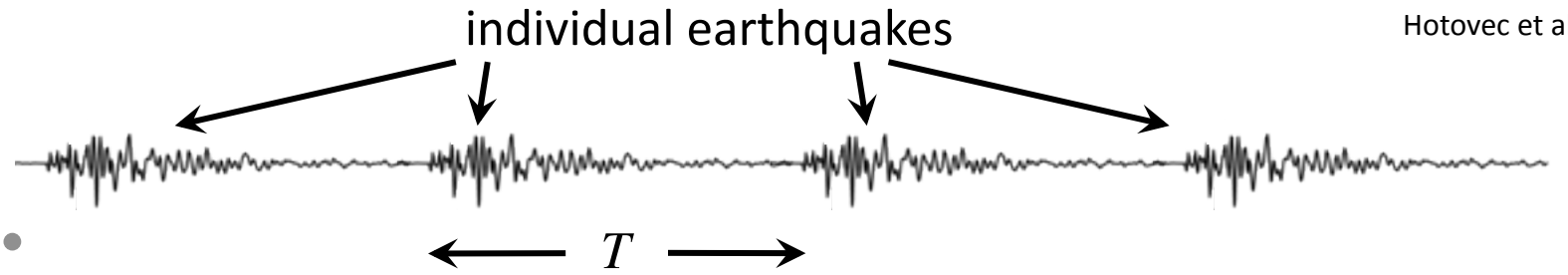


Hotovec et al., 2012

Gliding Harmonic Tremor



spectrum has peaks at frequencies $1/T$, $2/T$, $3/T$,… even if signals from individual events overlap



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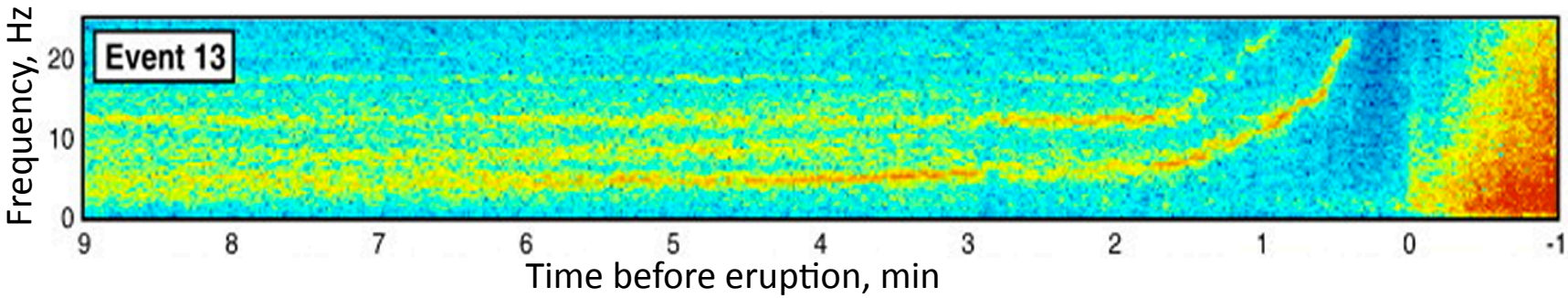
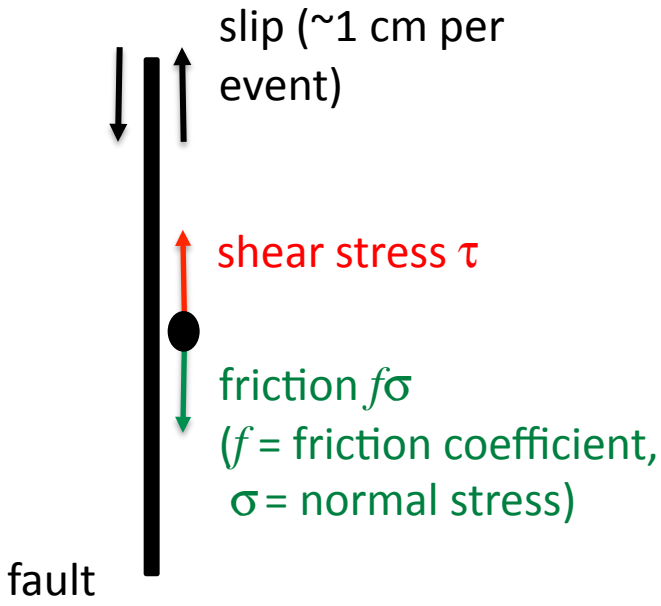


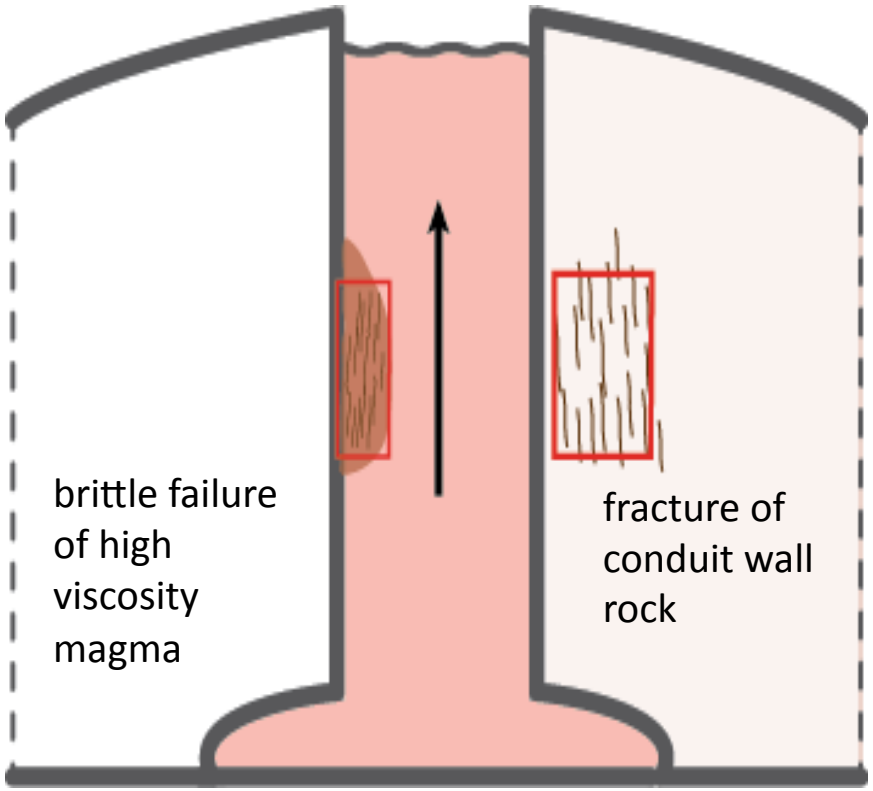
Observation	Explanation
Repeating quakes & gliding tremor	?
Maximum frequency	?
Seismic quiescence/silence	?

Force balance



force balance: $\tau = f\sigma$

Model set up



obstruction in conduit => increase in shear stress τ on faults, relaxed by slip

Earthquake cycle

on San Andreas Fault:

$$\alpha \sim 10^{-2} \frac{\mathrm{MPa}}{\mathrm{Yr}} \Rightarrow T \sim 100\mathrm{yr}$$

on Redoubt Volcano:

$$\alpha \sim 10 \frac{\mathrm{MPa}}{\mathrm{Sec}} \Rightarrow T \sim 0.1\mathrm{sec}$$

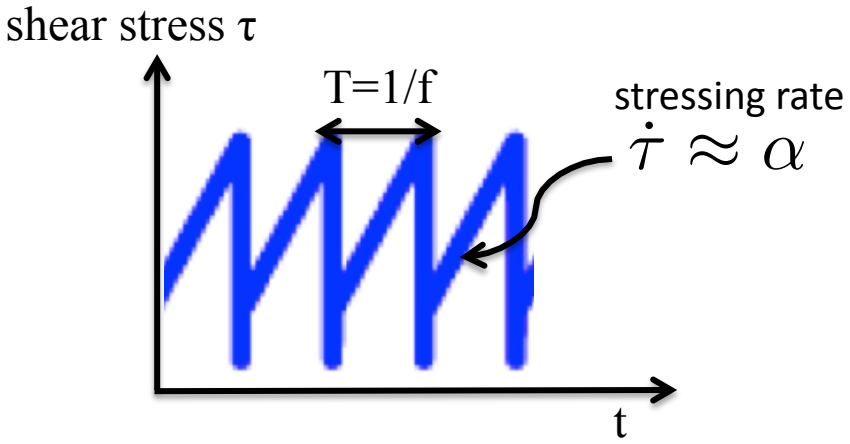
10 orders of magnitude higher!

Necessary to consider inertial effects

Rate and state friction

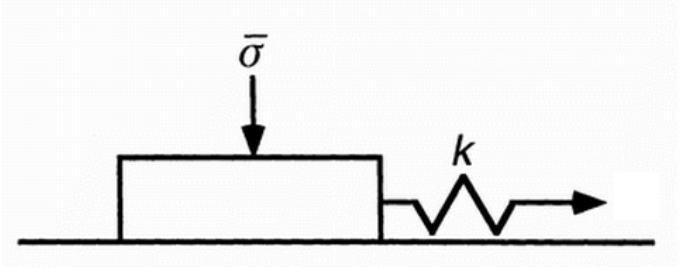
$$\tau = \sigma \left(f_0 + a \ln \frac{V}{V_0} + b \ln \frac{\theta V_0}{L} \right)$$

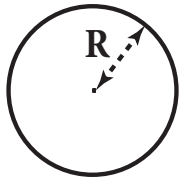
$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$



Stress accumulation and relaxation

$$\tau = \alpha t - k\Delta u - \eta V$$



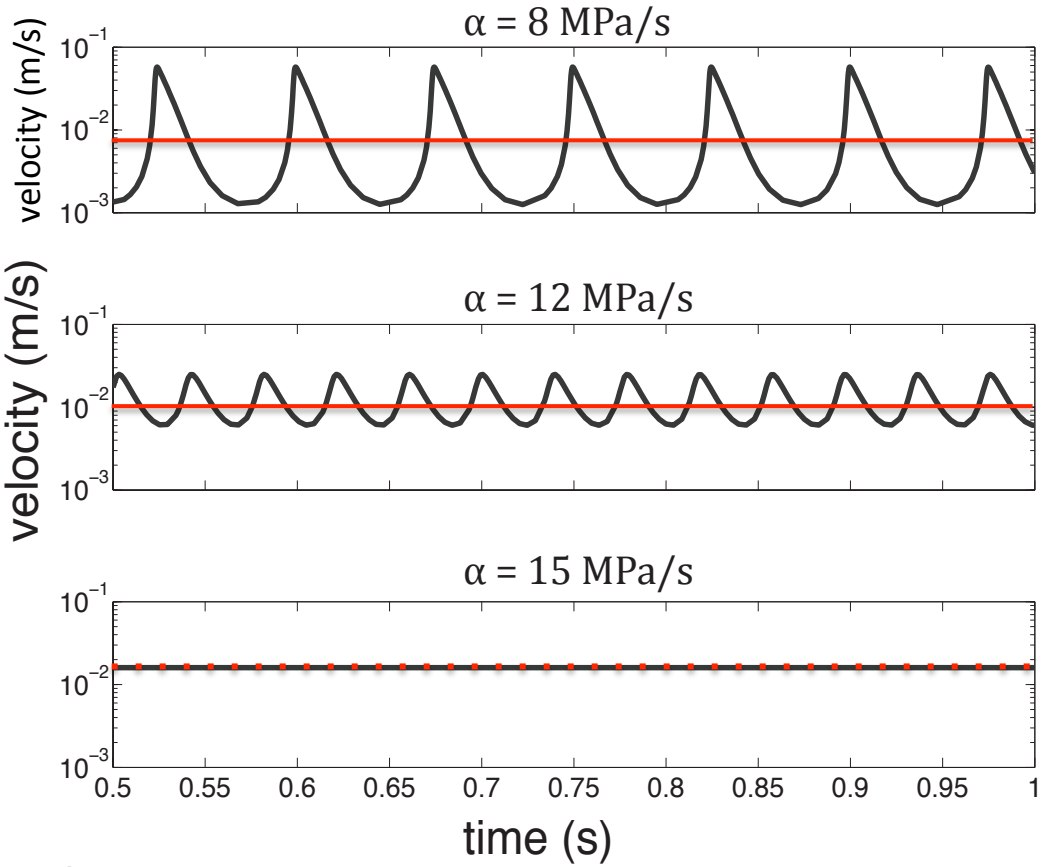


$$k \sim \mu / R$$

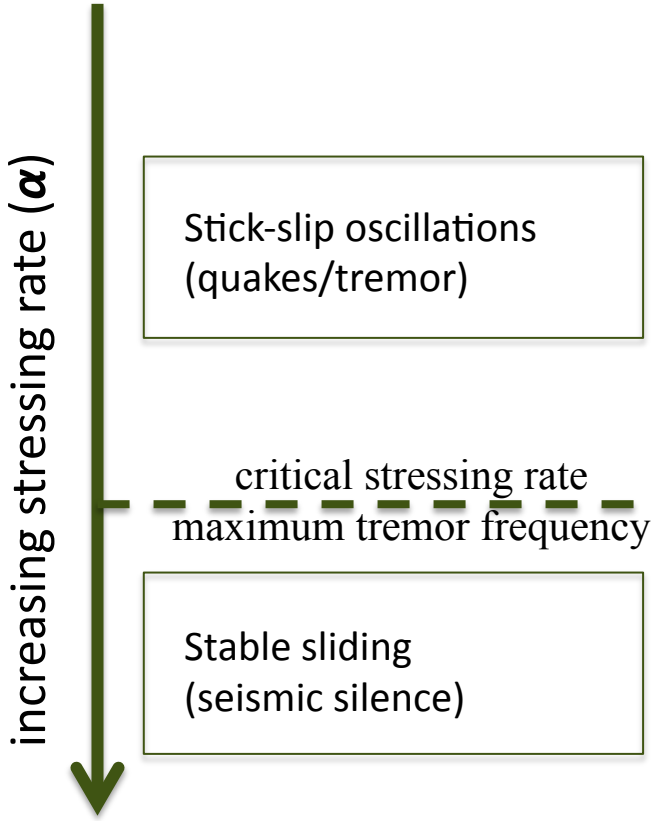
Response of fault to constant stressing rate (α): steady state sliding or stick-slip oscillations

Steady state solution – always exists for a constant velocity. Not always stable.

$$V_{ss} = \alpha / k$$



Under certain conditions – stick-slip oscillations

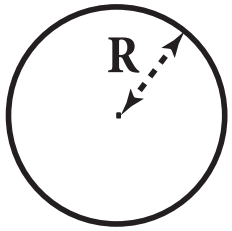


Conditions for instability (stick-slip oscillations)

Stiffness:

$$k < k_{crit}$$

k~*μ*/*R*, so for instabilities there is a minimum fault dimension (~ 1 m)



Stressing rate:

$$\alpha < \alpha_{crit}$$

At high stressing rates the inertial effects (neglected for tectonic settings) stabilize the system.

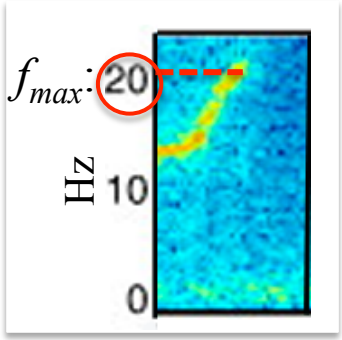
Critical values

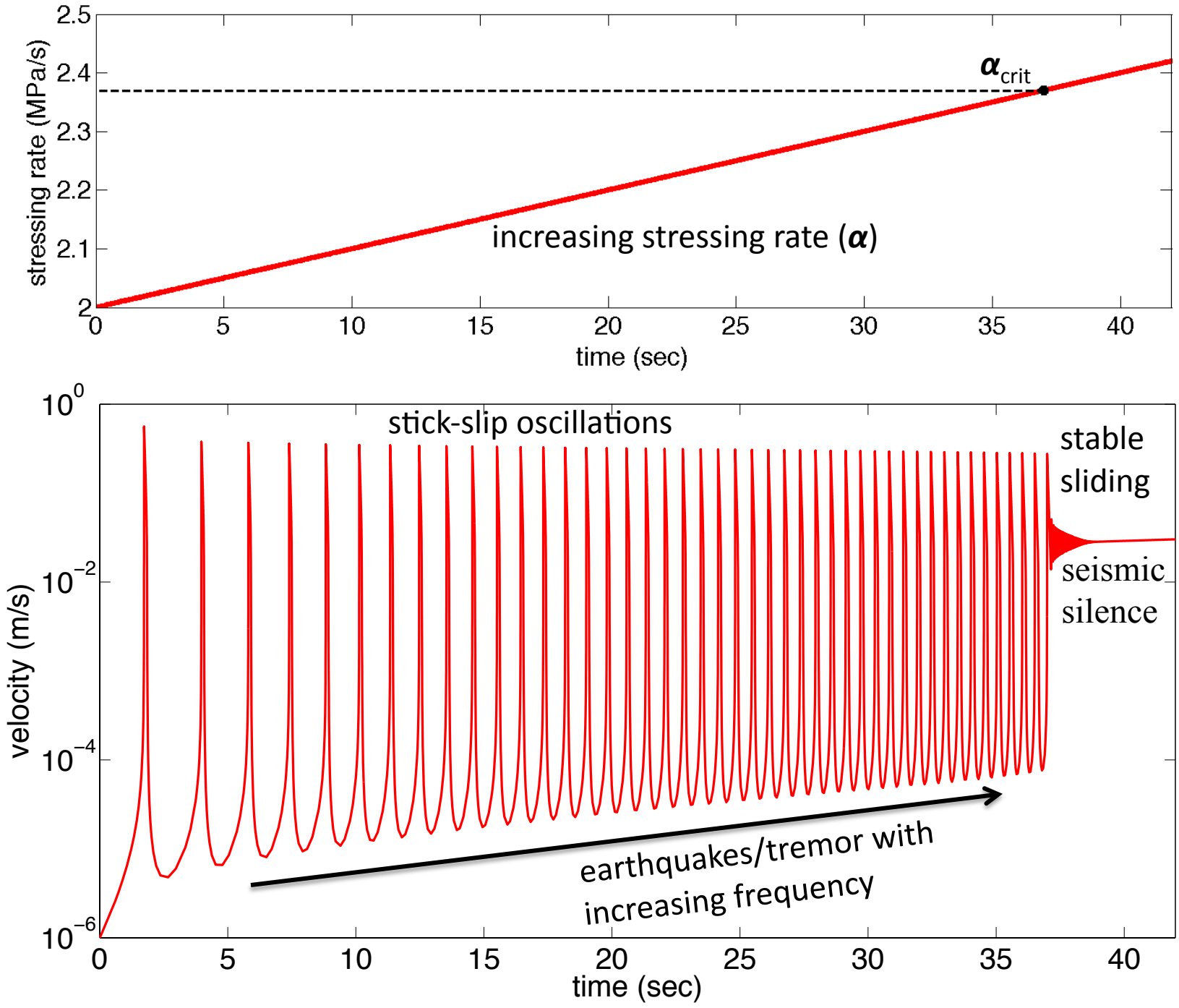
Critical stressing rate:

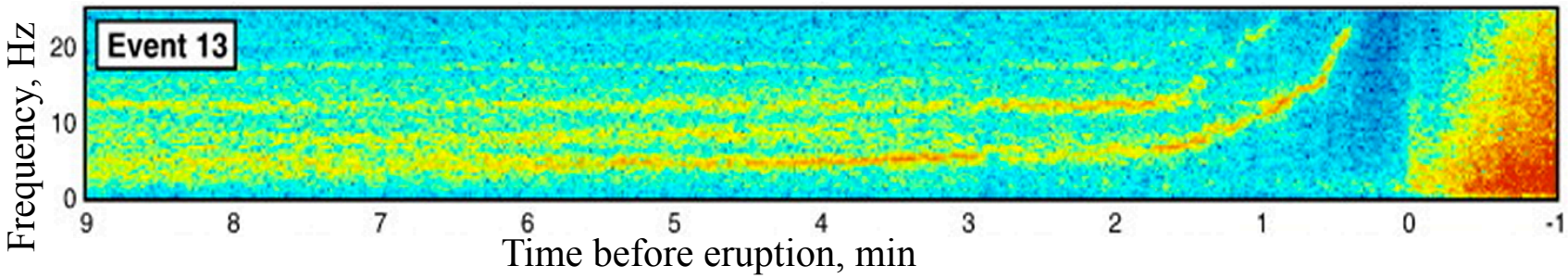
$$\alpha_{crit} \sim \frac{\mu L/R}{R/c} \sim \frac{\text{stress drop}}{\text{duration of quake}}$$

Maximum frequency (at $\alpha=\alpha_{crit}$) :

$$f_{max} \sim \frac{1}{R/c} \sim \text{corner frequency}$$




stressing rate (MPa/s)
2.5
2.4
2.3
2.2
2.1
2
α_{crit}
increasing stressing rate (α)
0
5
10
15
20
25
30
35
40
time (sec)
velocity (m/s)
10^{0}
10^{-2}
10^{-4}
10^{-6}
stick-slip oscillations
stable sliding
seismic silence
earthquakes/tremor with increasing frequency
0
5
10
15
20
25
30
35
40
time (sec)



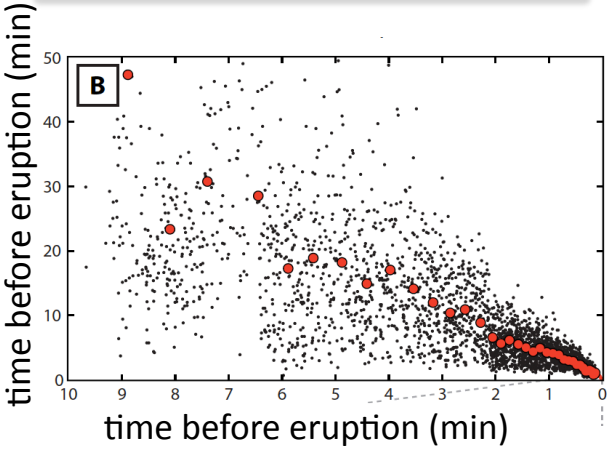
Observation	Explanation
Repeating quakes & gliding tremor	(Unstable system) Stick-slip oscillations with increasing stressing rates
Maximum frequency	Frequency at critical stressing rate
Seismic quiescence/silence	(Stabilized system) stressing rate higher than critical

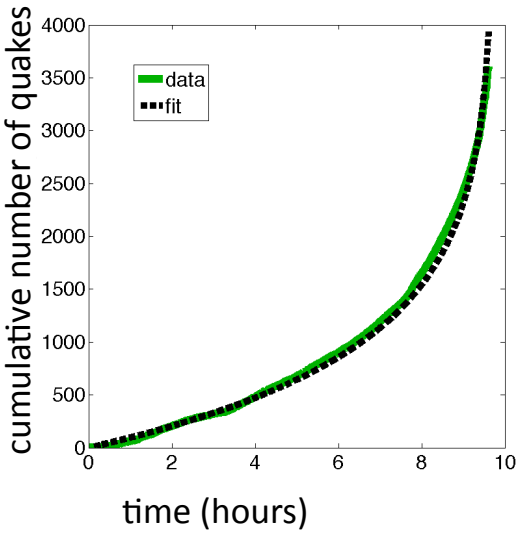
Infer stressing rates from observations

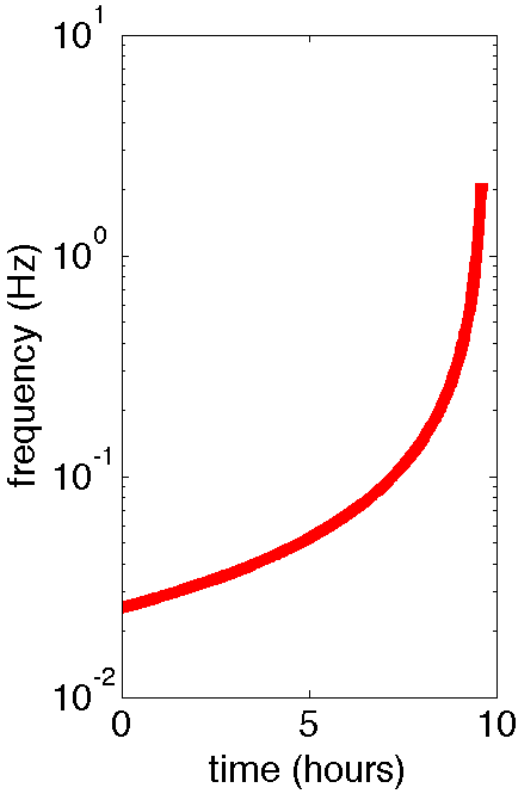
cumulative number of events (data)

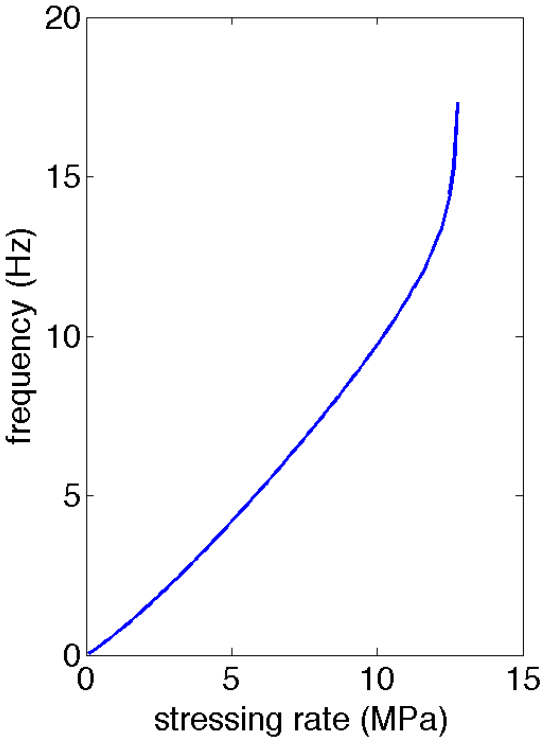
frequency vs time (data)

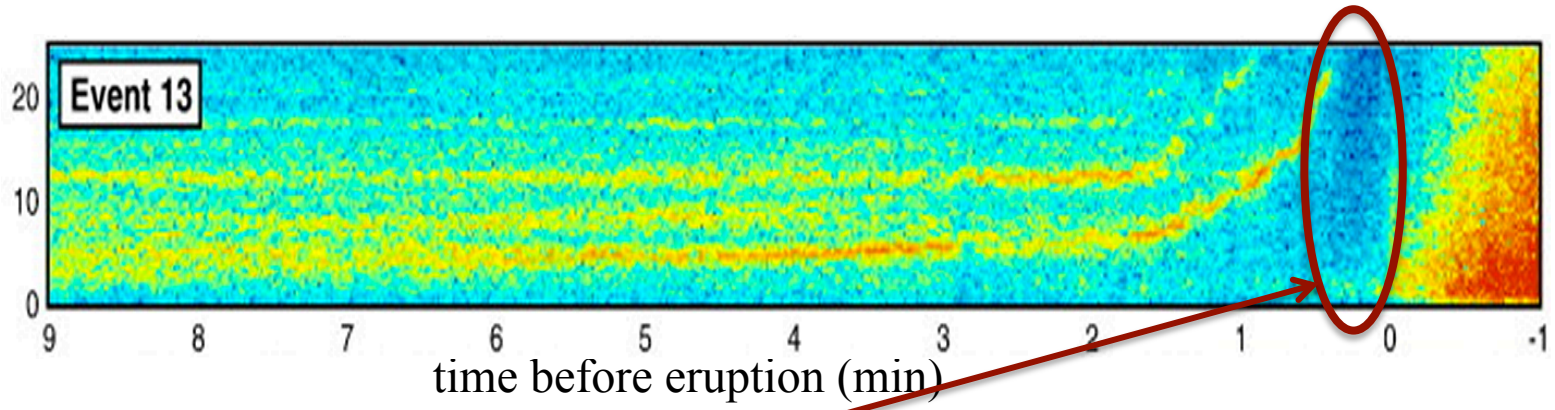
frequency vs stressing rate (model)



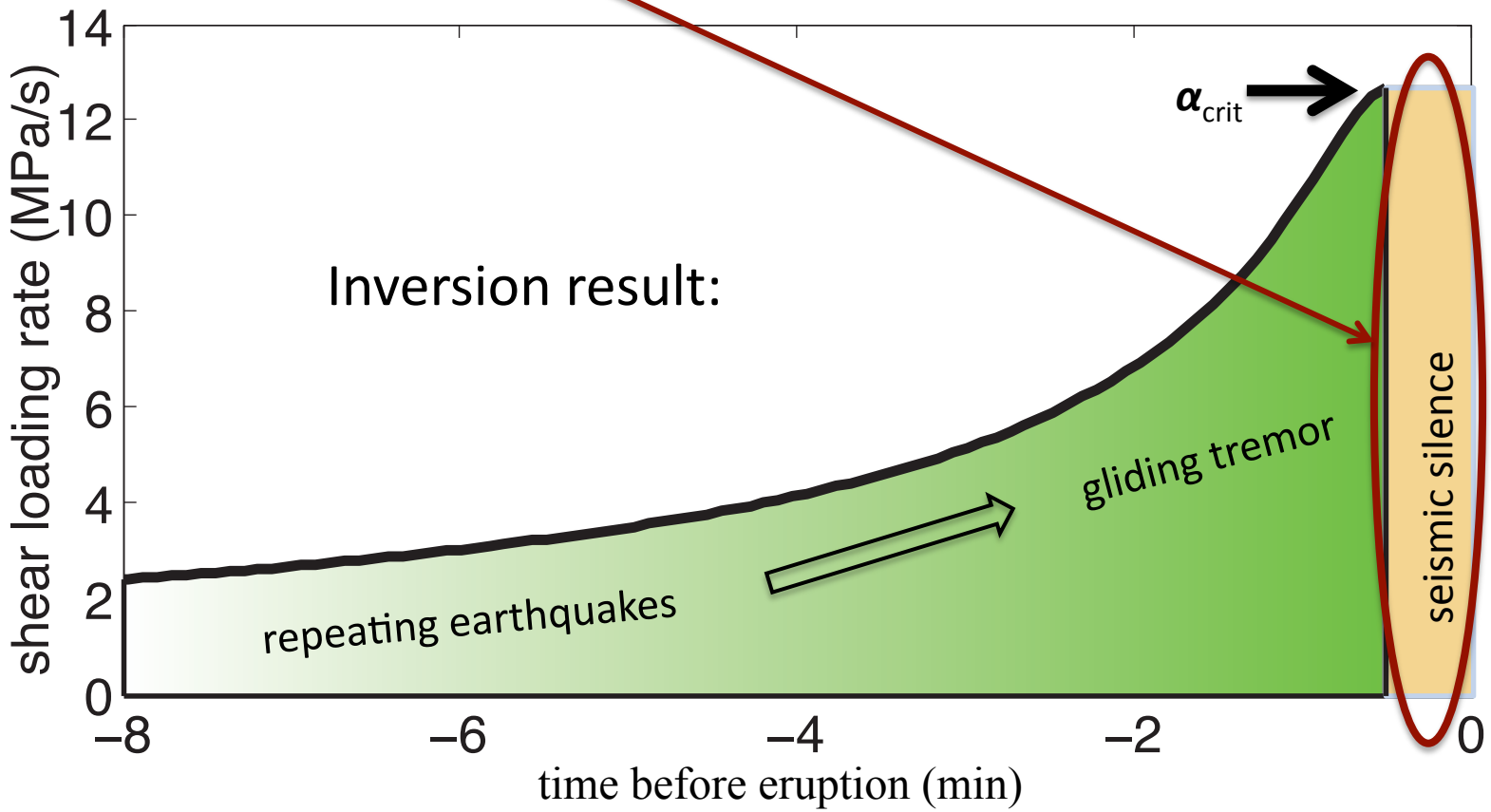


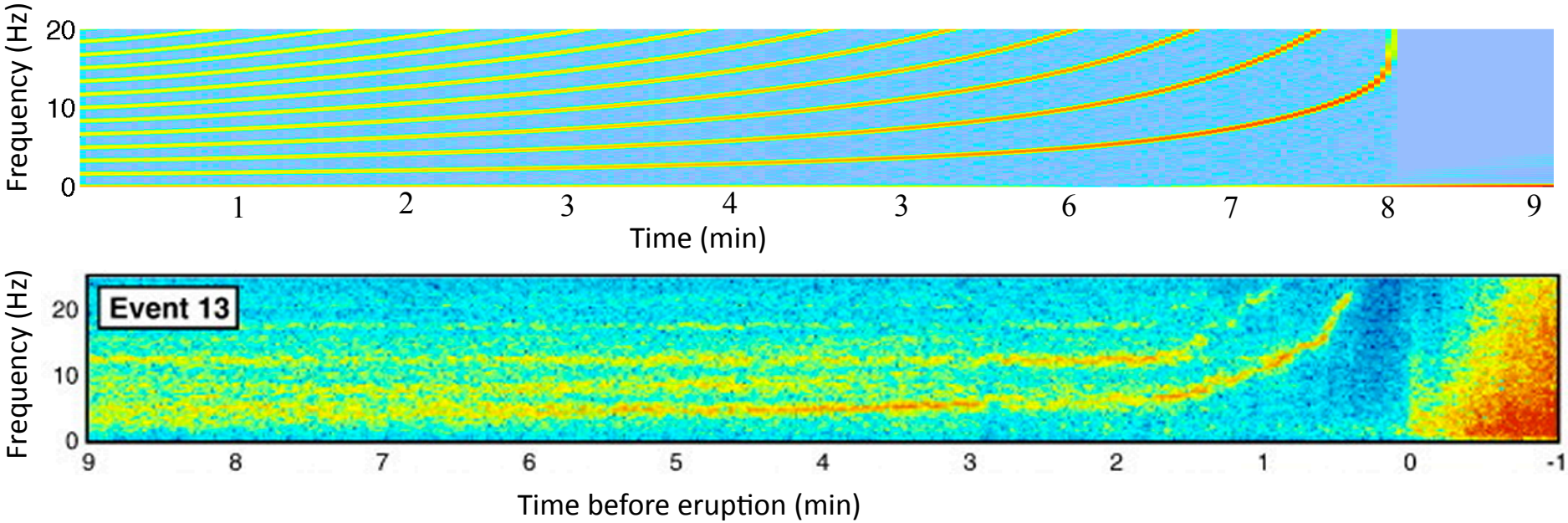






Seismic silence ~ 30 sec





Conclusions

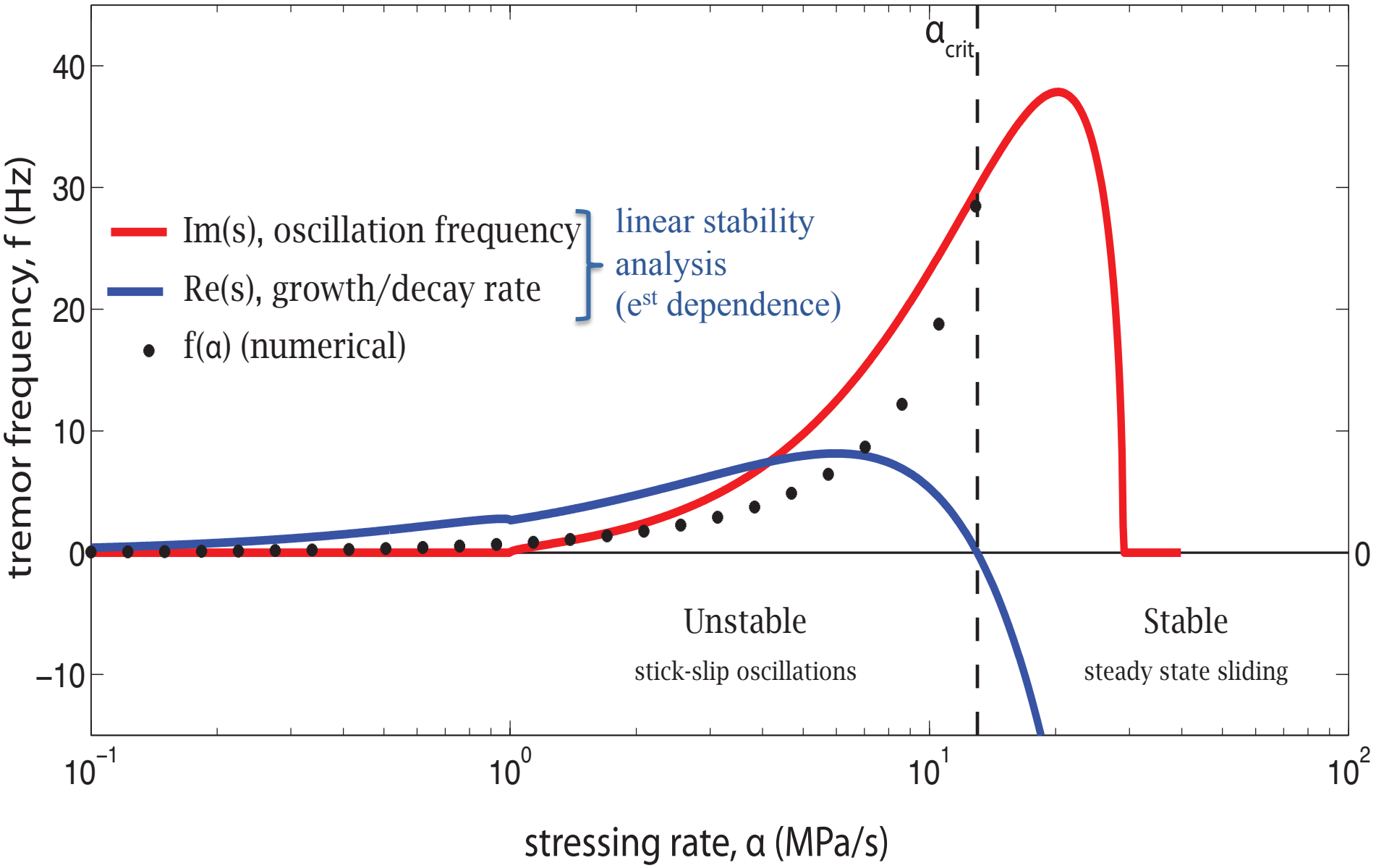
- Repeating EQs can explain harmonic gliding tremor
- Model constrains stressing rates (up to ~10 MPa/s)
- What volcanic processes could cause these stressing rates?
- Need to explore parameter space (using moment, corner frequency and other observations) – Monte Carlo simulations

Extra slides

Parameters of the model

normal stress (σ) 35 MPa (1 - 50 MPa)
fault dimension (R) 40 m (10 - 100 m)
state evolution distance (L) 10e-6 m (10e-6 - 10e-3m)

shear wave velocity (c) 2000 m/s
shear modulus (μ) 10 GPa
rate-and-state direct effect (a) 0.01
rate-and-state healing (b) 0.014
stiffness ($k=\mu/R$) 250 MPa/m (1000 – 10 MPa/m)
radiation damping parameter ($\eta=\mu/2c$) 2.5 MPa s/m
reference friction coefficient (f_0) 0.6
reference velocity (V_0) 1e-6 m/s


α crit
40
30
20
10
0
−10
tremor frequency, f (Hz)
Im(s), oscillation frequency
Re(s), growth/decay rate
f(α) (numerical)
linear stability analysis (e^st dependence)
Unstable
stick-slip oscillations
Stable
steady state sliding
10^−1
10^0
10^1
10^2
stressing rate, α (MPa/s)