Determining the nonlinear elastic properties of rocks using the ambient seismic field

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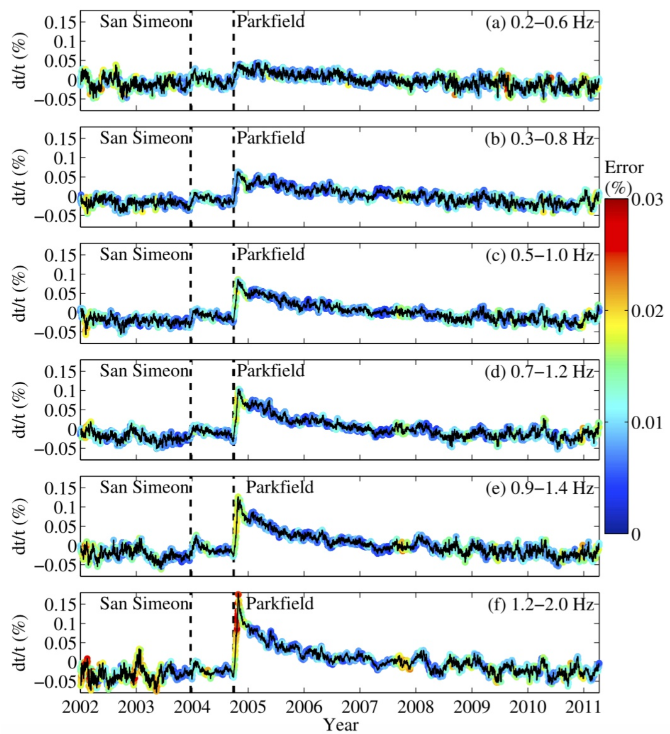
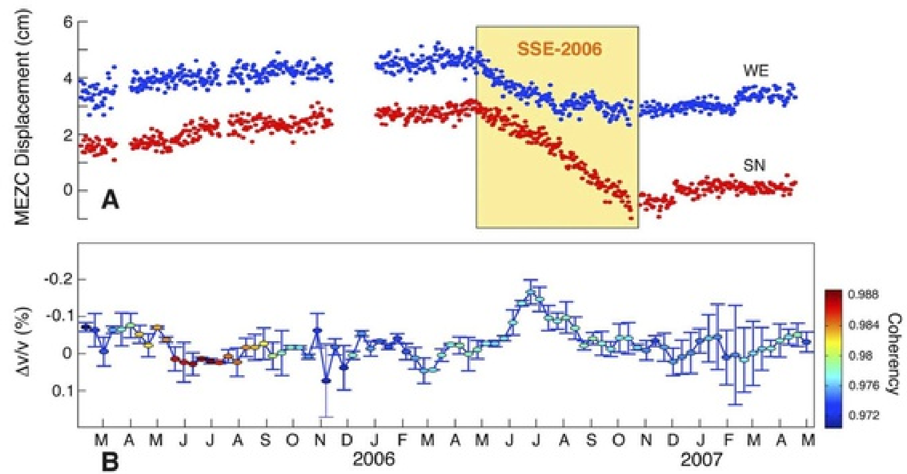
With many others: Charles Lieou, Robert Guyer, Paul Johnson, Andrew Delorey, Chunquan Wu, Michel Campillo

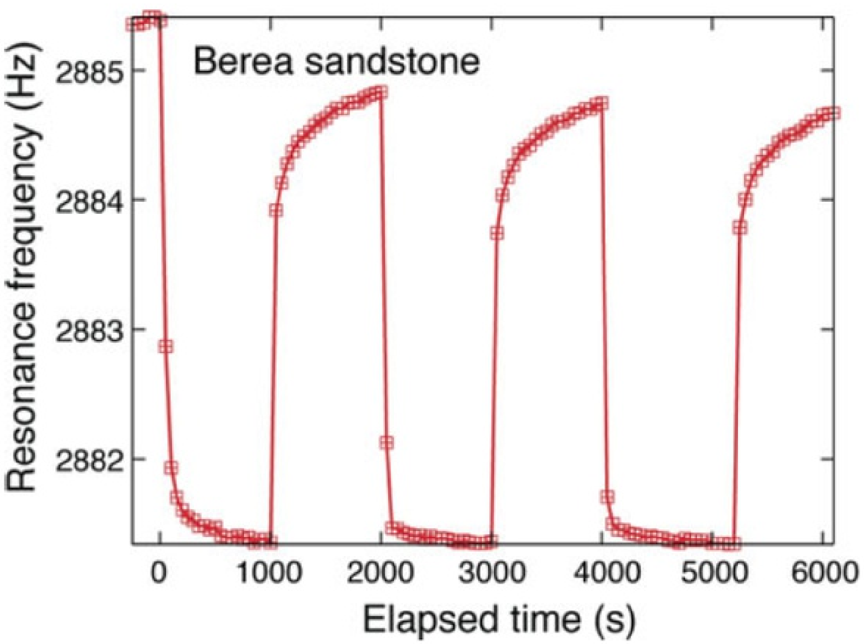




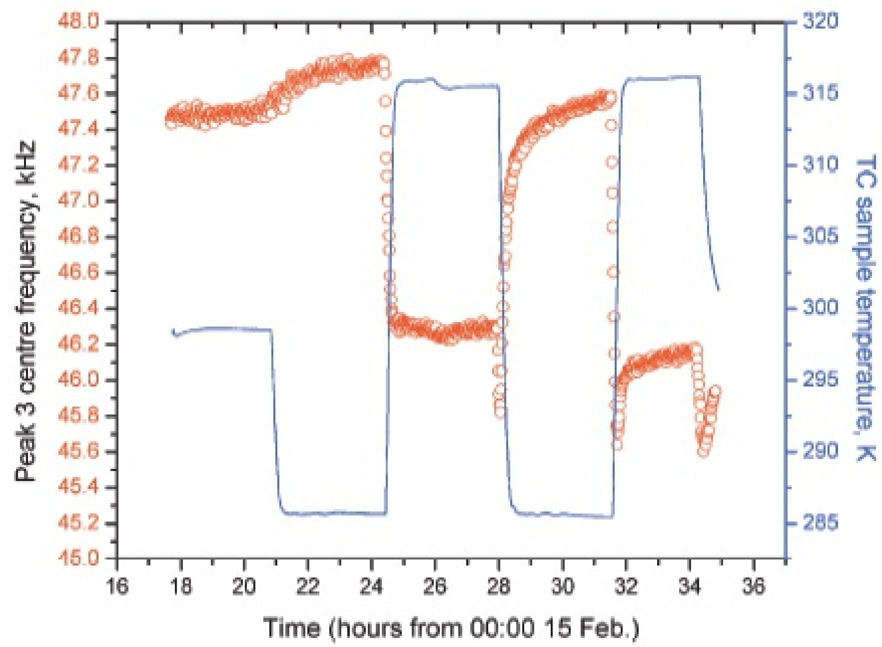
Nonlinear Elastic Behavior of Rocks

Elastic properties of rocks change with stress/strain. Use laboratory measurements and seismic observations to understand dynamics.

Short Time Scales
Dynamic softening with recovery
(e.g. Ten Cate and Shankland, 1996)

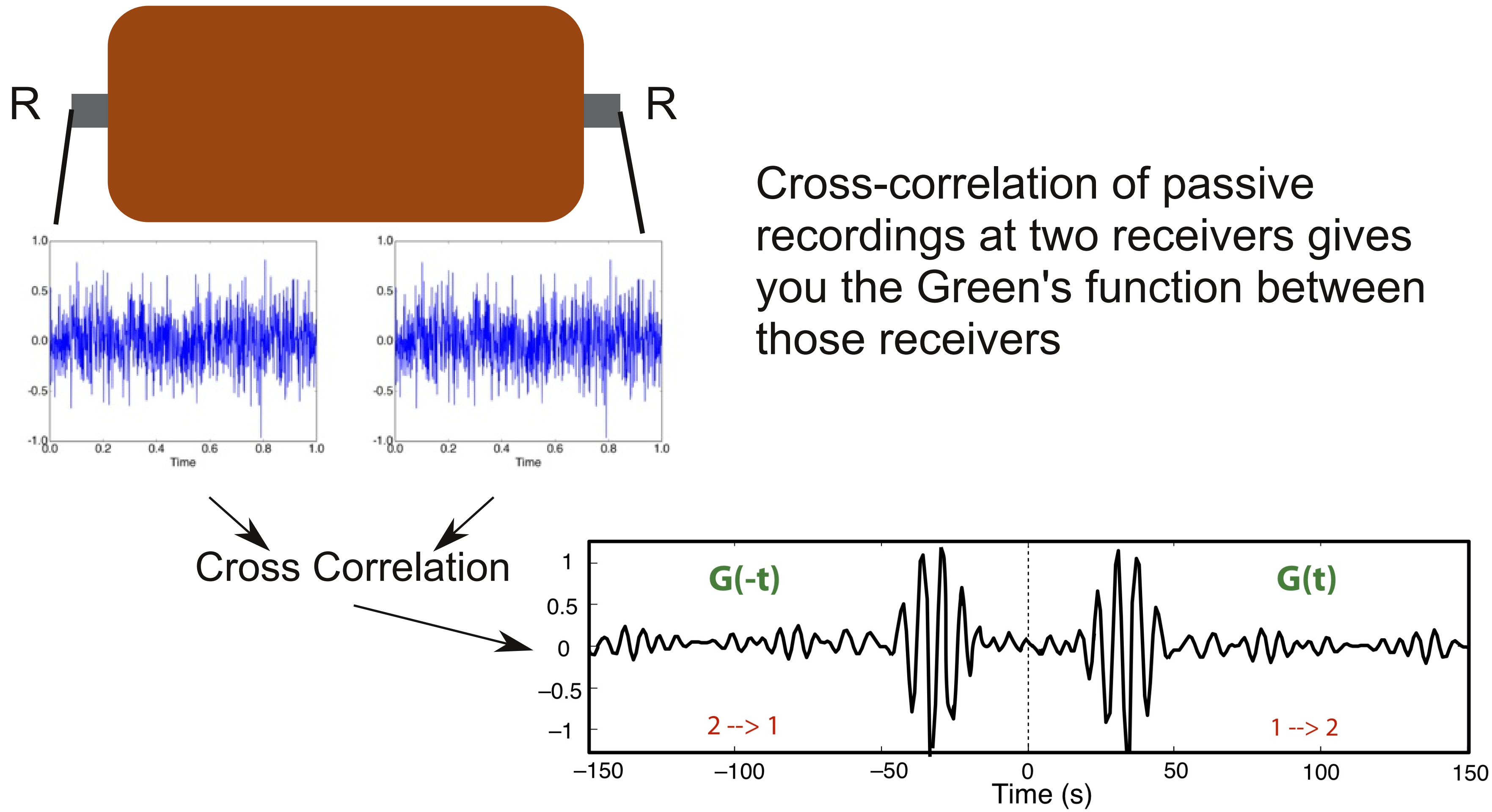


Long Time Scales
Softening with change in temperature
(plot courtesy of Ten Cate)



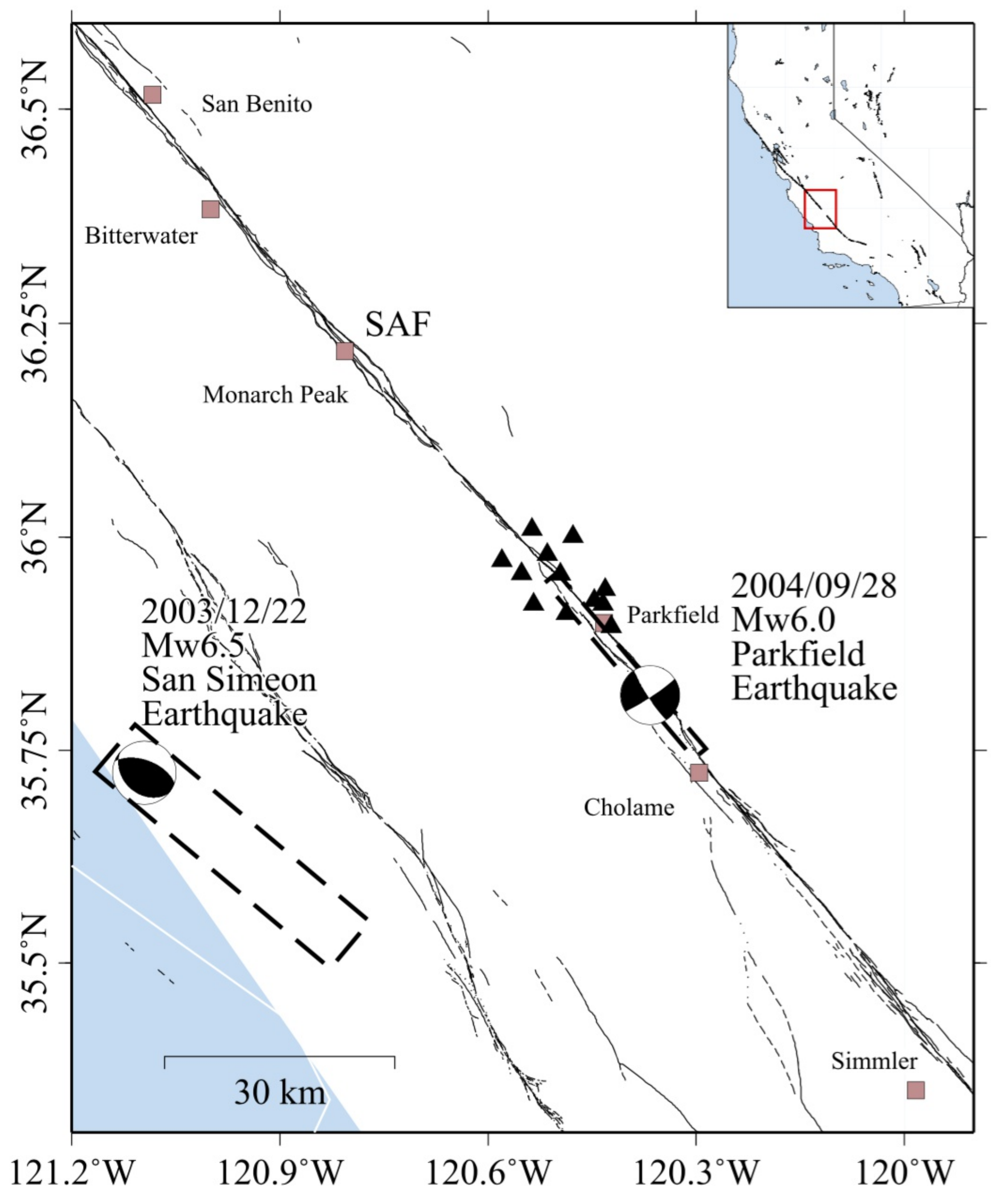
Making Measurements in the Earth

Measure propagation velocity continuously using ambient seismic field cross correlation (more details in many talks this week)

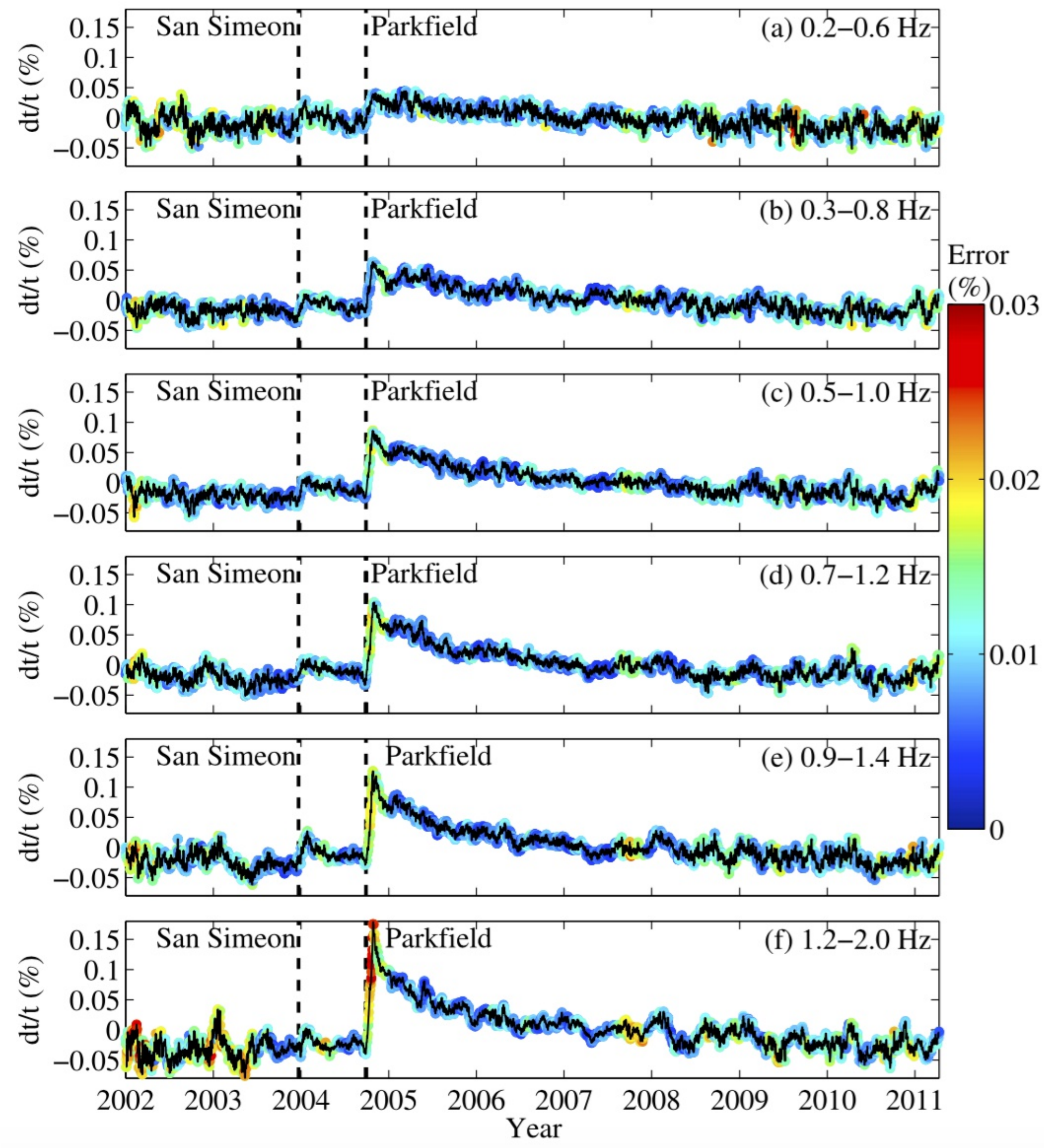


Cross-correlation of passive recordings at two receivers gives you the Green's function between those receivers

Study Area in Parkfield, CA



Time-Dependence at Parkfield, CA



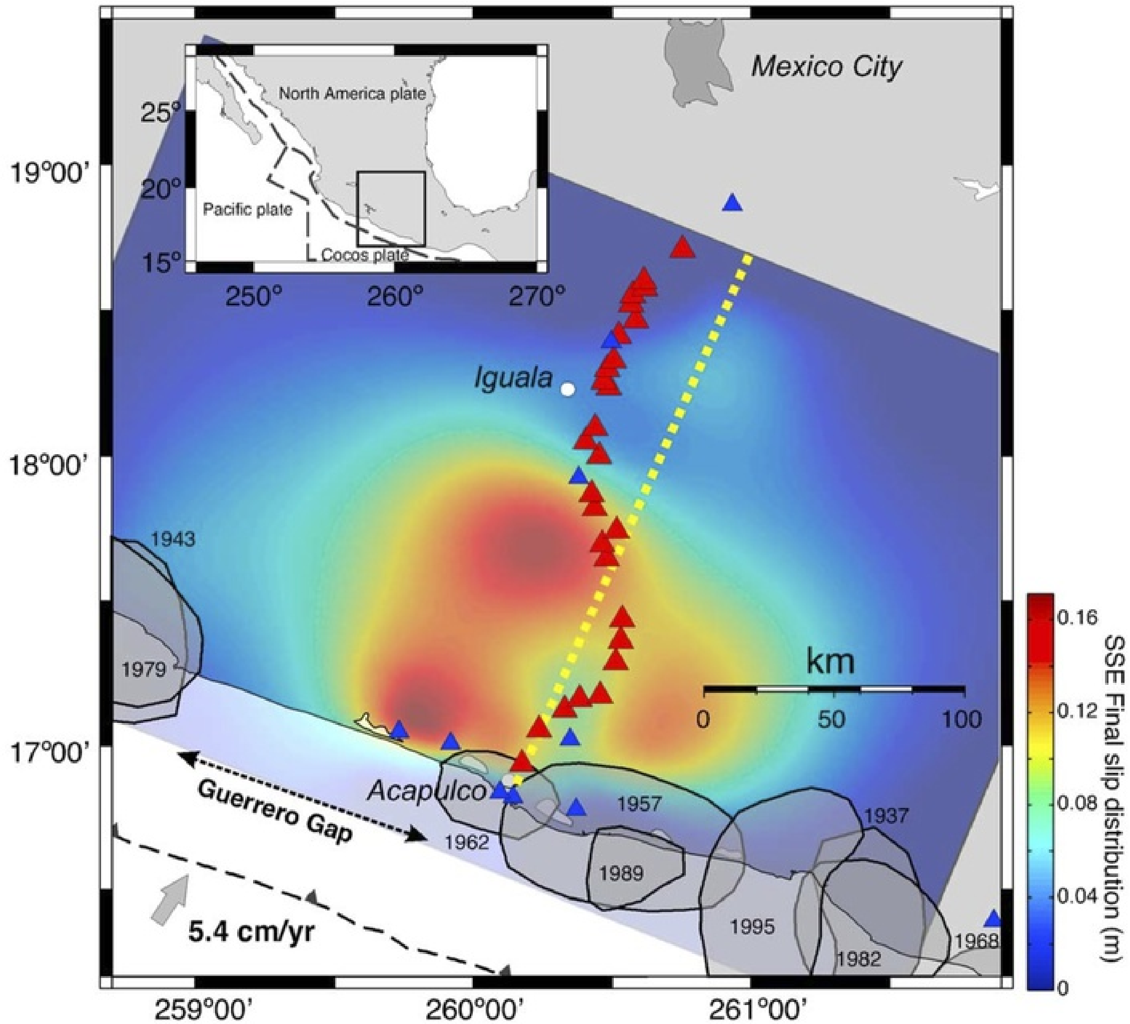
See velocity decrease after 2004 Parkfield earthquake, followed by slow recovery process. Change is largest at high frequencies, which are most sensitive to shallow changes in the upper few km (interpreted to be due to strong seismic shaking)

Wu et al., 2016

Slow Slip, Guerrero, Mexico

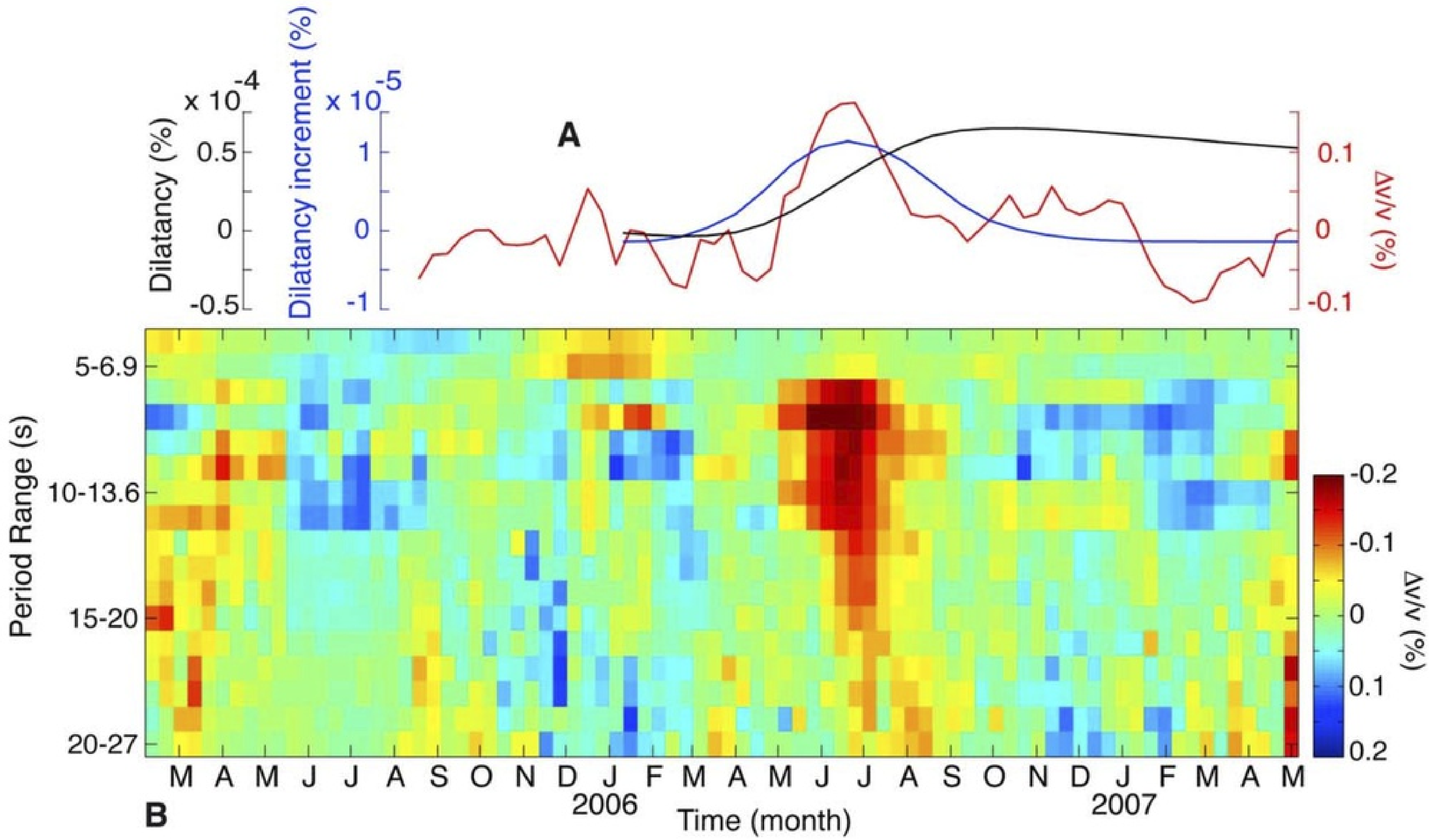
What about a different type of event? Slow slip event in Mexico. No strong shaking, slow deformation

Rivet et al., GRL, 2011



Example: Slow Slip, Guerrero, Mexico

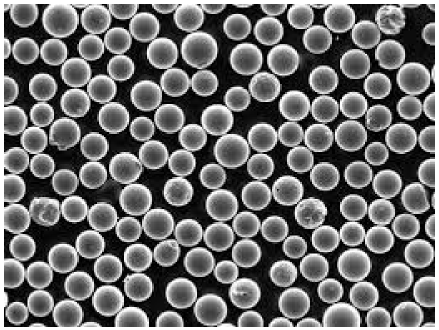
Velocity decrease during slow slip. Using different frequency bands, can localize velocity change to lower crustal layers where deformation occurs

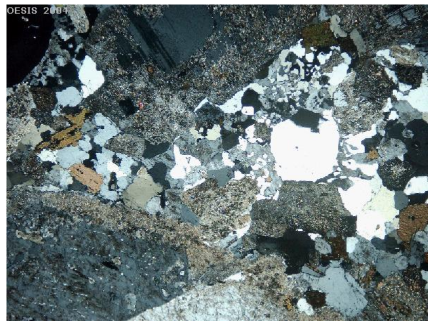


Rivet et al., GRL, 2011

Time-Dependent STZ Model

Big idea: nonlinearity is due to structural features. Means in principle you can tell how nonlinear something is entirely from a picture of it



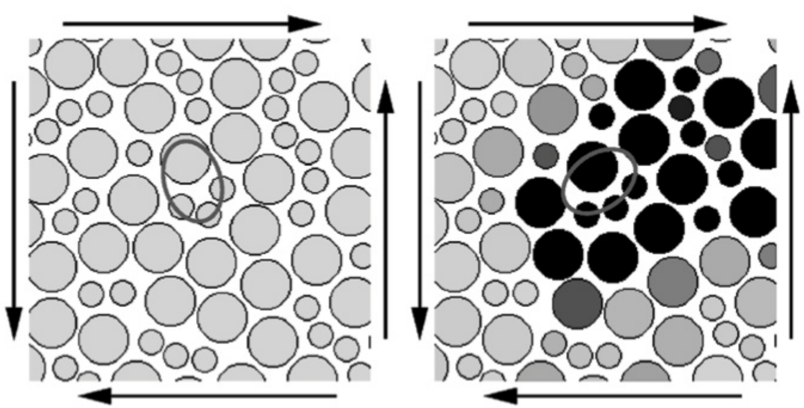


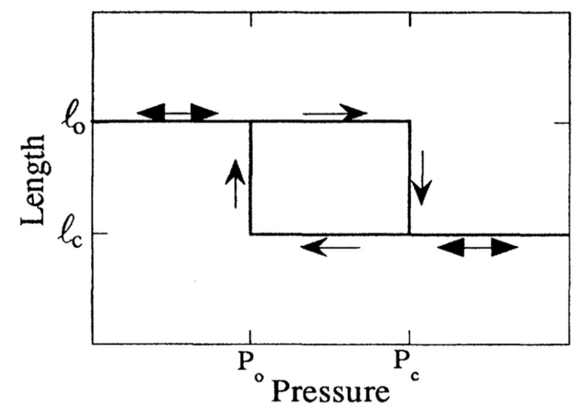
STZ = Shear Transformation Zone, defect that can undergo inelastic deformation

More specific assumptions:

(1) 2-state system, each of which is susceptible to deforming in opposite directions (like PM)

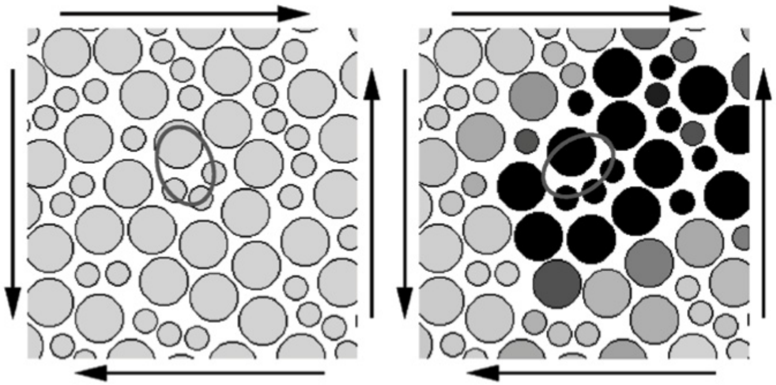
(2) Number of defects controlled by effective temperature (quantifies structural disorder in the material)





Time-Dependent STZ Model

Time dynamics of nonlinearity related to evolution of effective temperature. Higher effective temperature, more soft zones, greater modulus decrease



$$\frac{d\chi}{dt} = \frac{|\dot{\gamma}\sigma|}{c_0}\left(1 - \frac{\chi}{\hat{\chi}}\right) - R\exp\left(-\frac{E_r}{\chi}\right)$$

Excitation drives towards steady state

Time dependent relaxation

Time dependent term gives rise to slow dynamics (easy to show evolution depends on the logarithm of time).

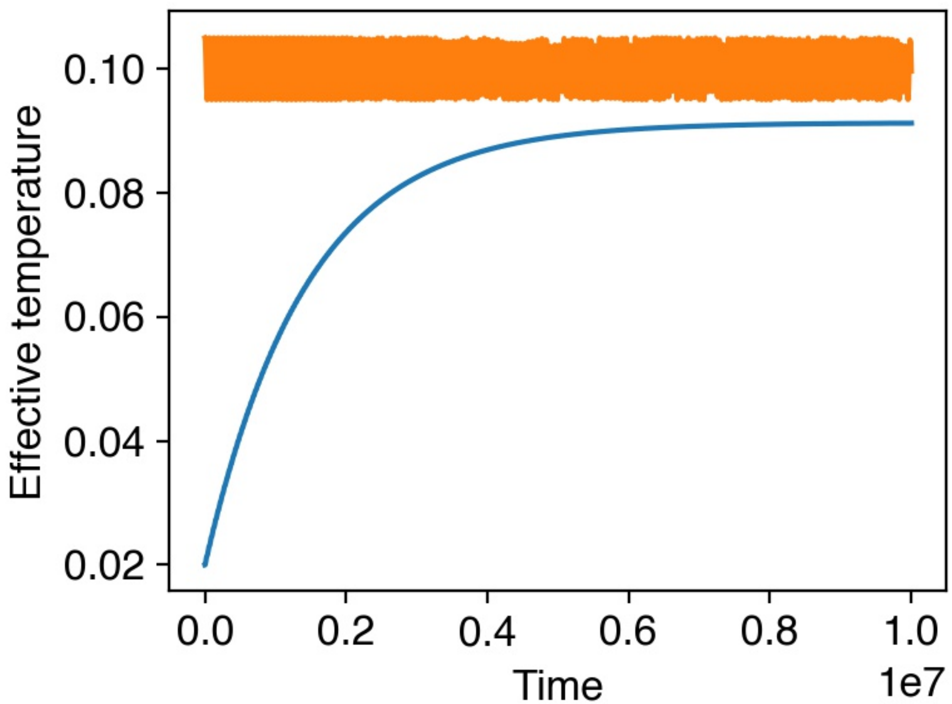
Excitation more complex, and responsible for everything else. Assume we have an oscillating drive. Then two relevant time scales: drive frequency, and strain rate (normalized by stress/specific heat parameter)

Time-Dependent STZ Model

Dynamics depend on relative values of drive frequency and strain rate:

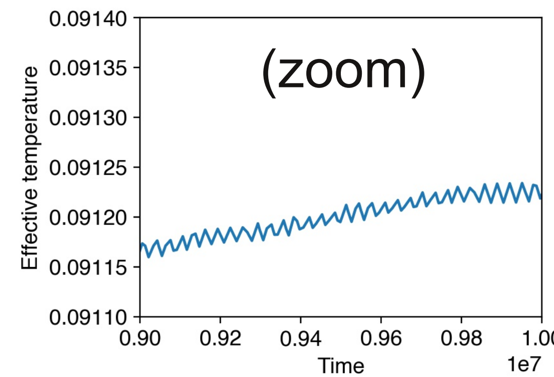
$$\omega > \dot{\gamma}\sigma / c_0$$

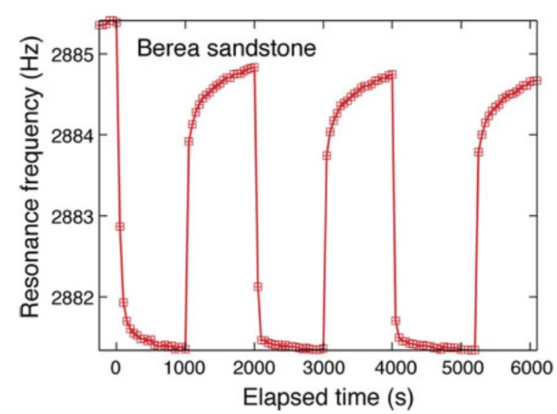
Drive is much faster than intrinsic time scale. System cannot keep up with the drive oscillations, and takes a long time to approach steady state



Softer

Stiffer



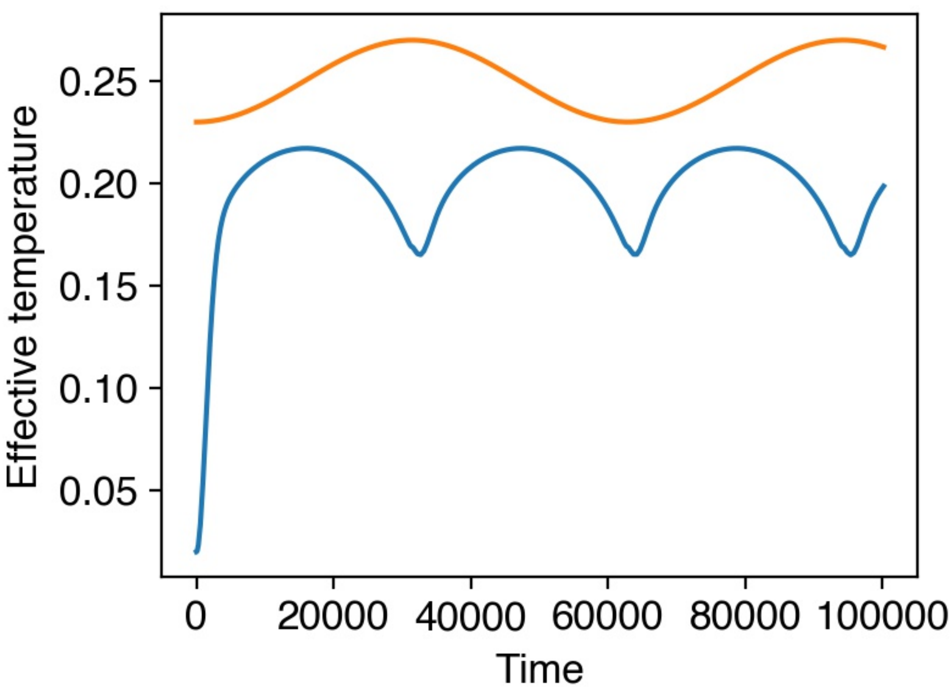


Time-Dependent STZ Model

Dynamics depend on relative values of drive frequency and strain rate:

$$\omega < \dot{\gamma}\sigma / c_0$$

Drive is much slower than intrinsic time scale. System oscillates about steady state with large fluctuations coincident with highest strain rate



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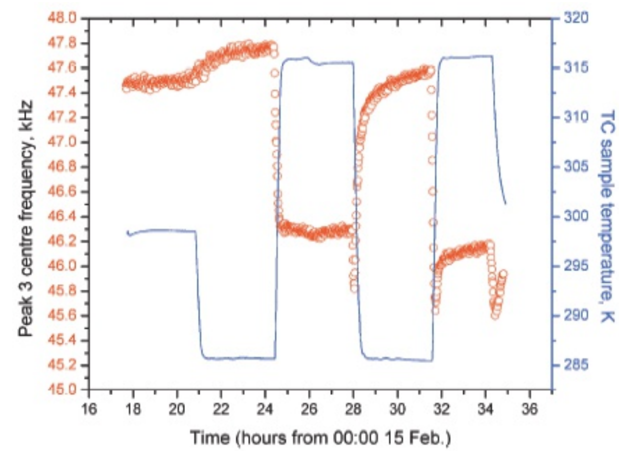

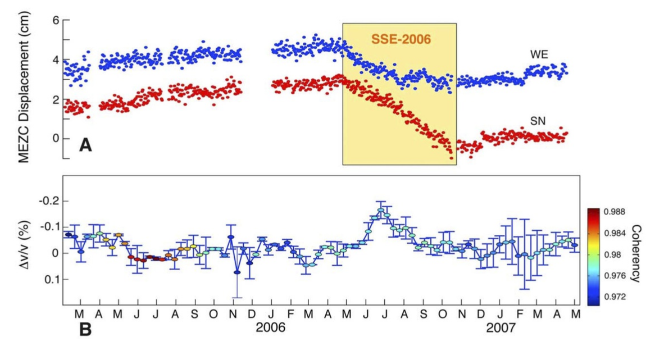

Recap

Using ambient noise, see many of the effects seen in laboratory experiments.

Qualitative model for dynamics based on ideas of effective temperature, working on quantitative version.