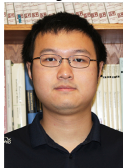


Continuous seismic monitoring of hydraulic fracturing and relaxation

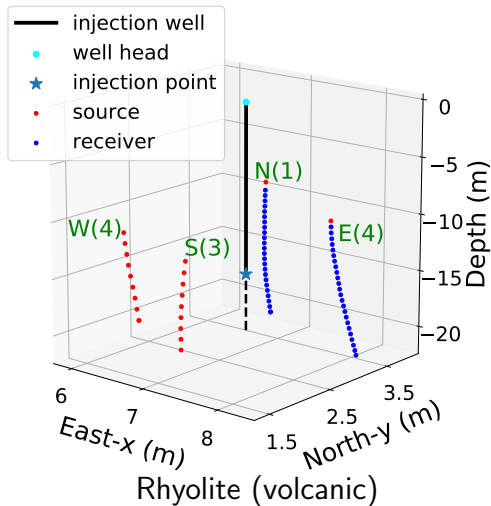
**Xun (Jack) Li¹; Roel Snieder¹;
Christoph Sens-Schönfelder²; Jonathan Ajo-Franklin³**

- 1. Center for Wave Phenomena**
- 2. GFZ German Research Centre for Geosciences**
- 3. Lawrence Berkeley National Laboratory**



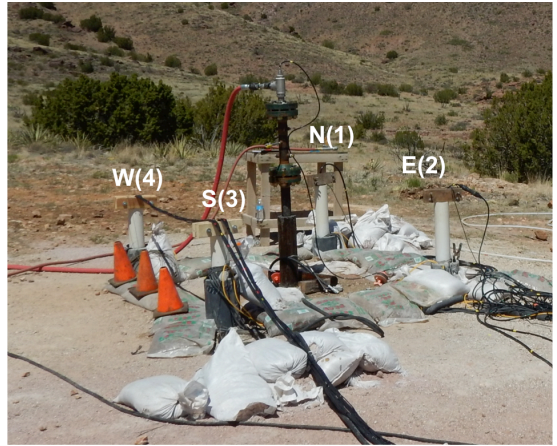
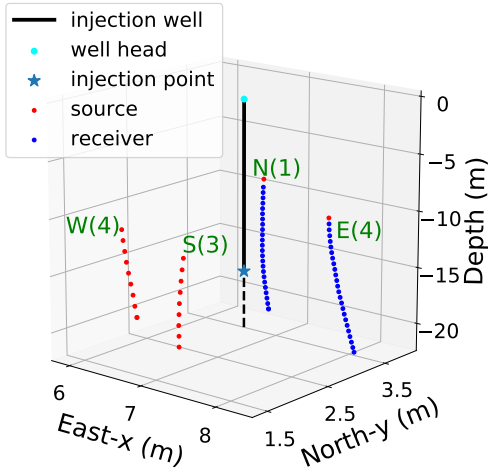
Introduction

► Continuous Active Source Seismic Monitoring (SNL+LBNL)



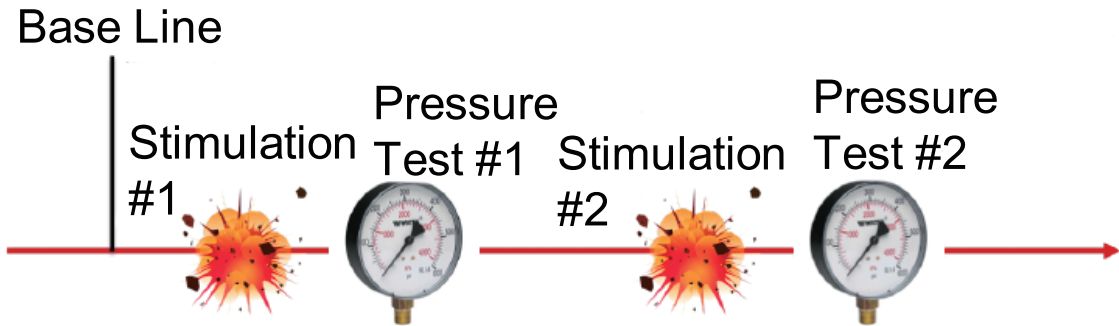
Introduction

► Continuous Active Source Seismic Monitoring (SNL+LBNL)



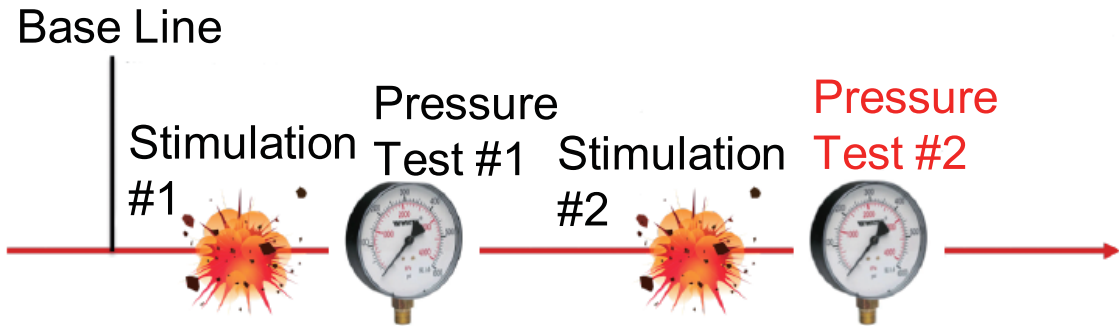
Field test

- ▶ hydraulic fracturing (HF) operations



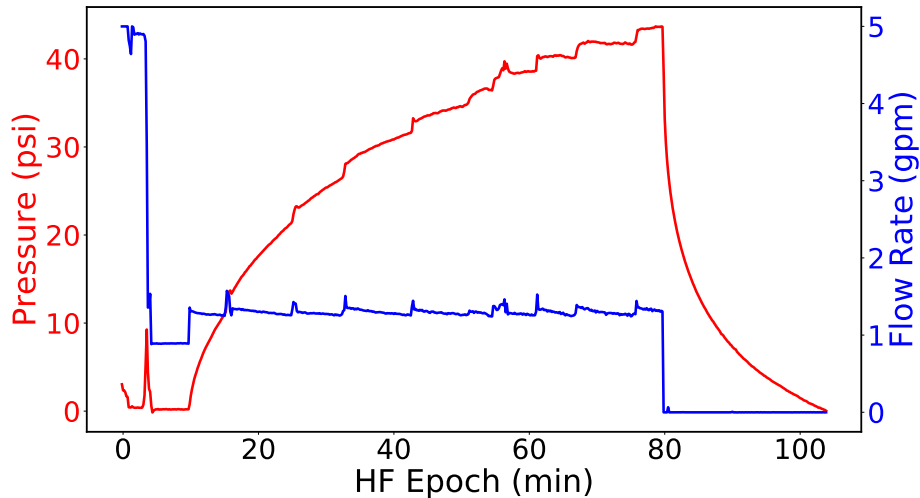
Field test

- ▶ hydraulic fracturing (HF) operations



Field test

► pressure test #2

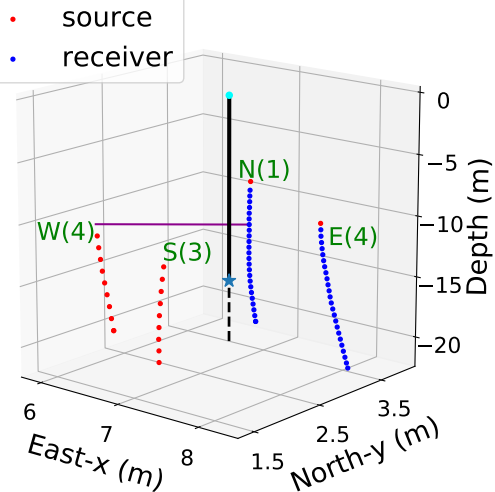


Data

- ▶ continuous monitoring; resolution: 1 min

Data

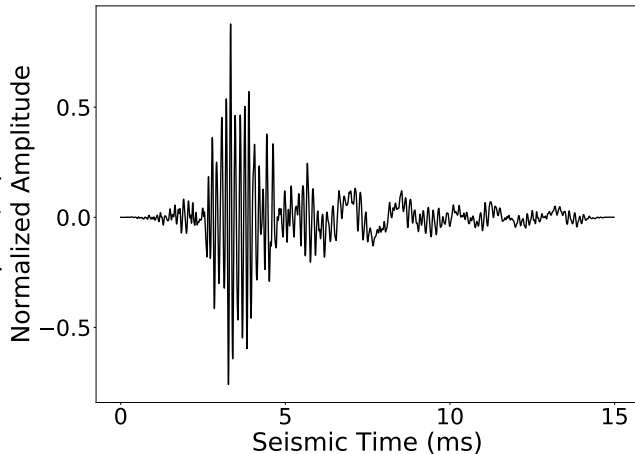
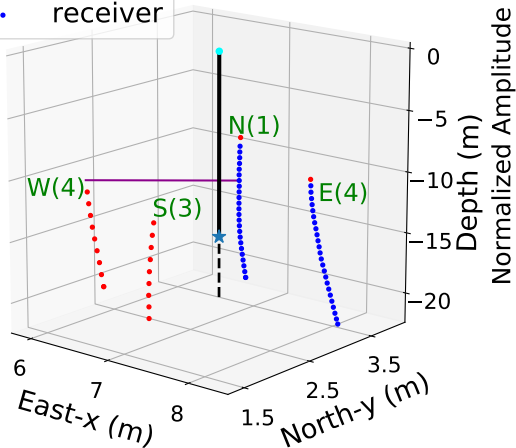
- ▶ continuous monitoring; resolution: 1 min



Data

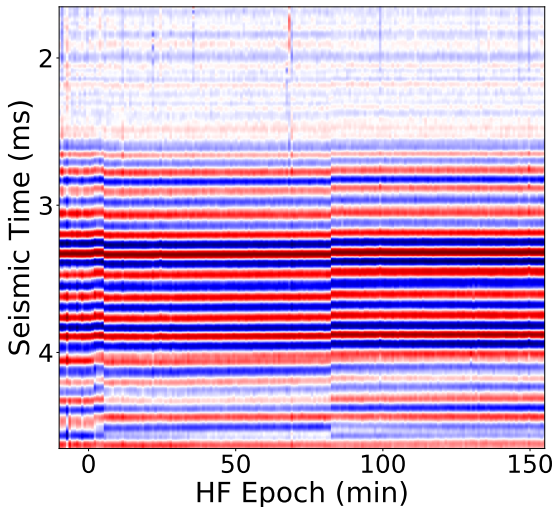
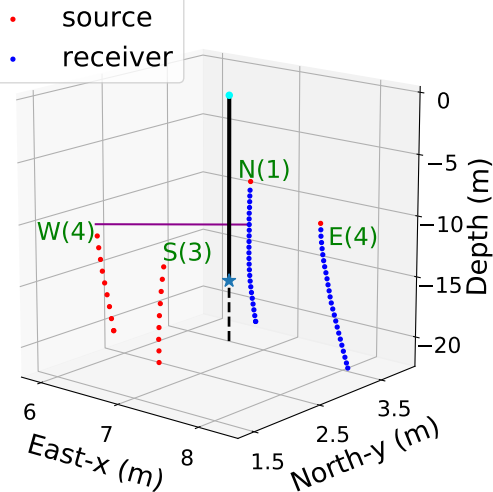
- ▶ continuous monitoring; resolution: 1 min

- source
- receiver



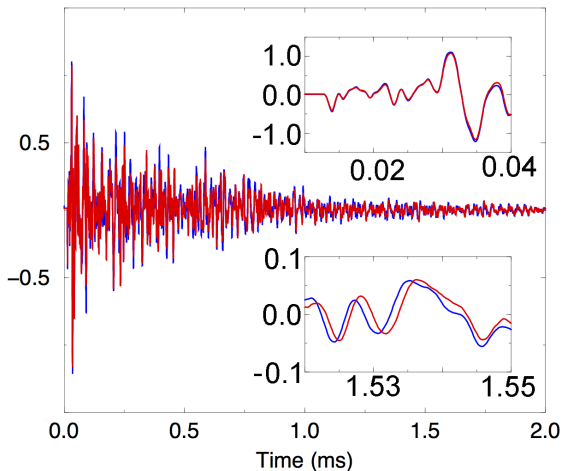
Data

- ▶ continuous monitoring; resolution: 1 min



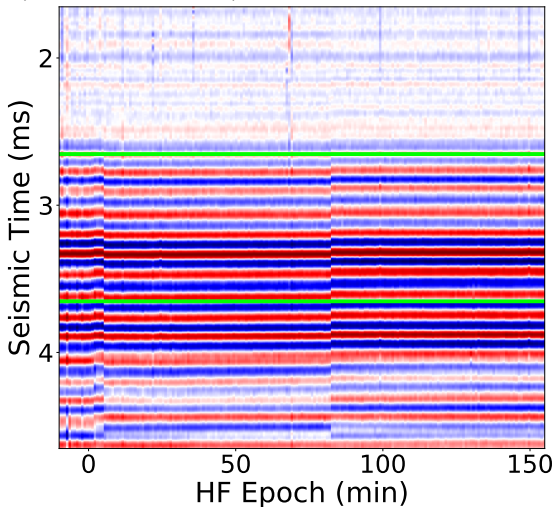
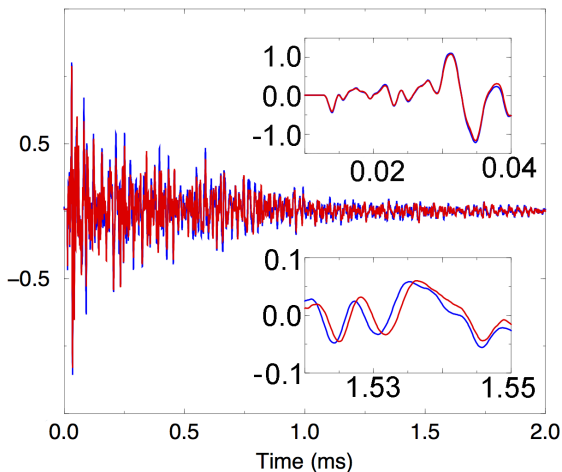
Seismic monitoring

- ▶ coda wave interferometry: $\Delta V/V = -\Delta t/t$



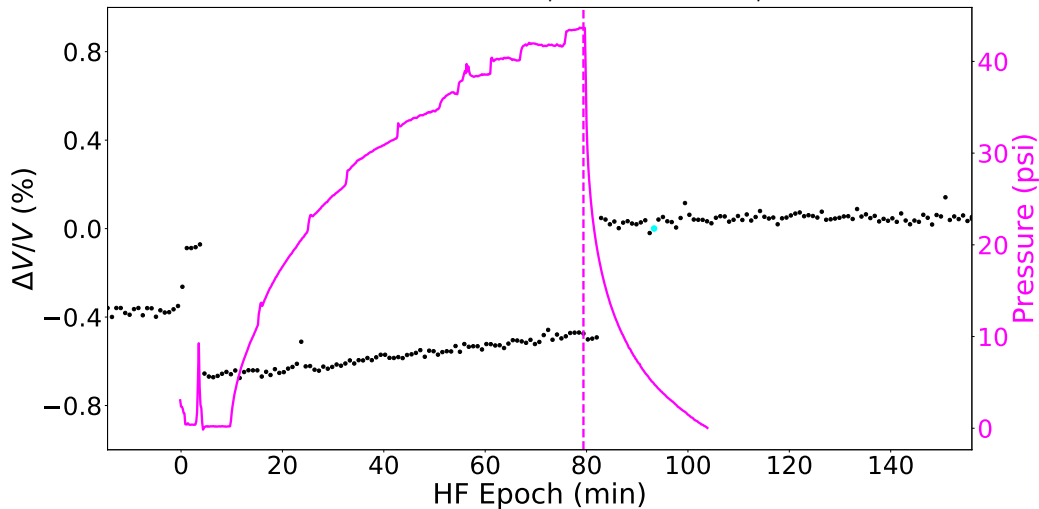
Seismic monitoring

- ▶ coda wave interferometry: $\Delta V/V = -\Delta t/t$



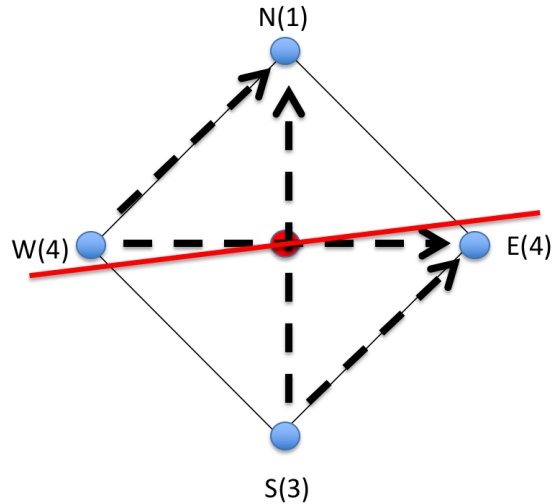
Seismic monitoring

- ▶ coda wave interferometry: $\Delta V/V = -\Delta t/t$



Fractures

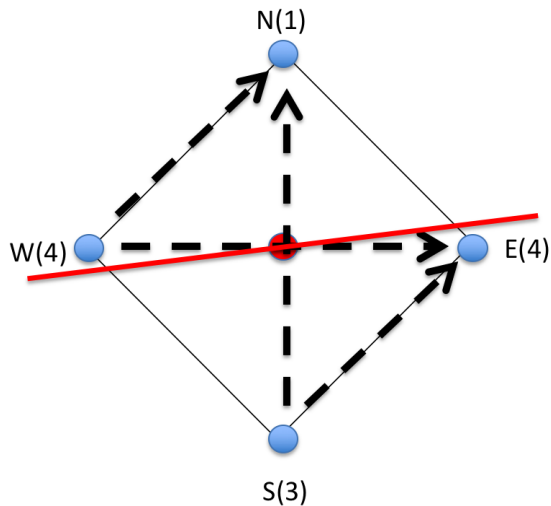
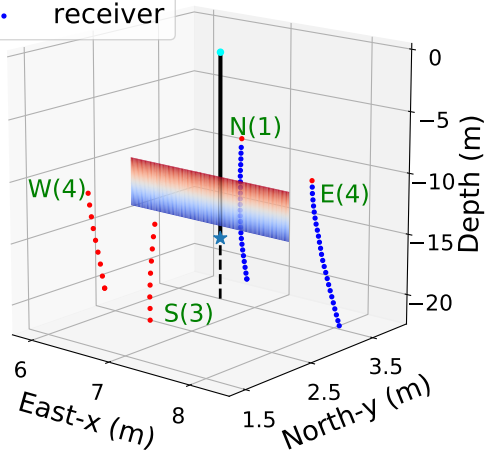
- ▶ W-E vertical fracture (crack)



Fractures

► W-E vertical fracture (crack)

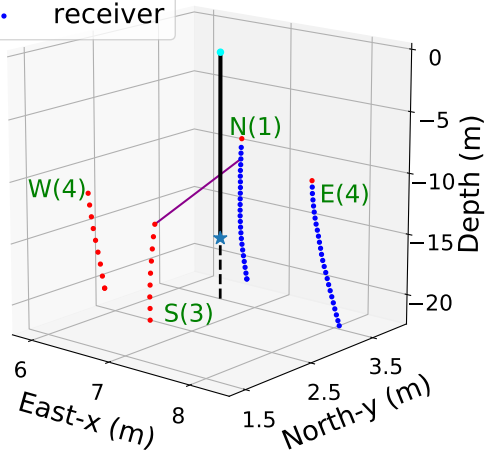
- source
- receiver



Relaxation

- ray path across main crack

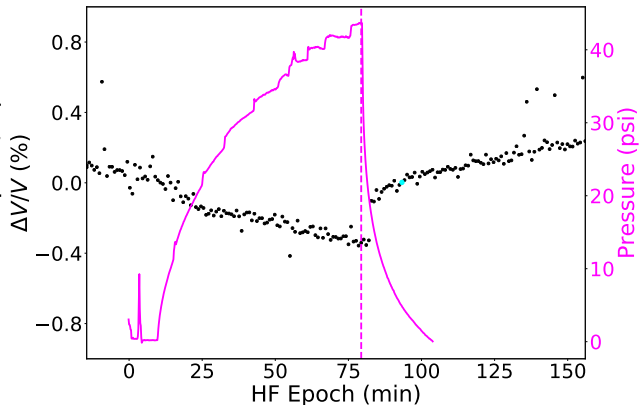
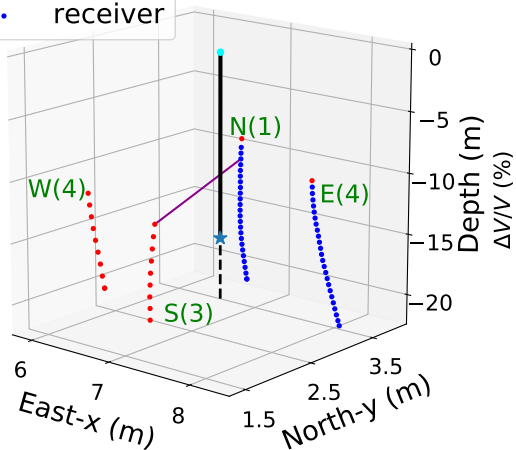
- source
- receiver



Relaxation

► ray path across main crack

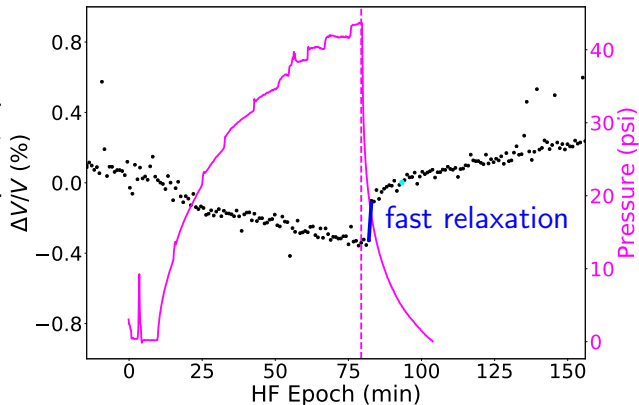
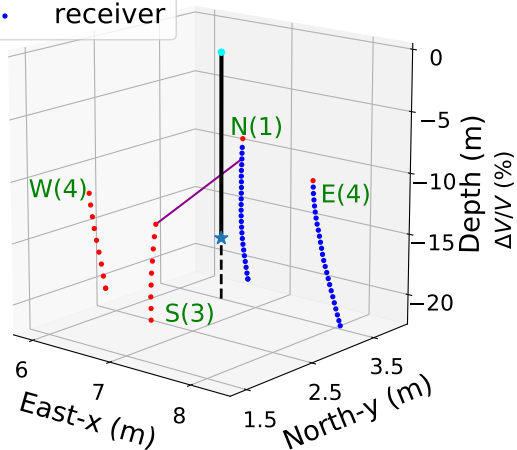
- source
- receiver



Relaxation

- fast (instantaneous) relaxation?

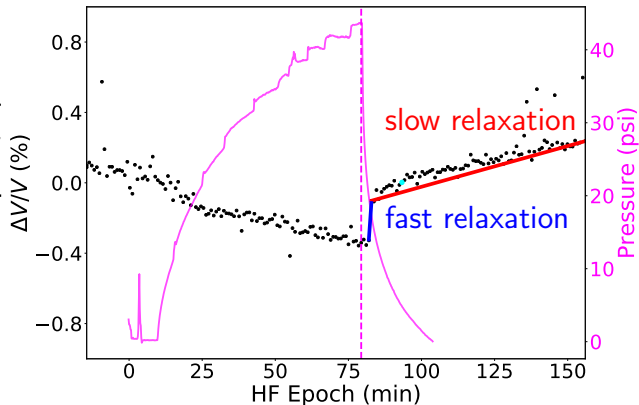
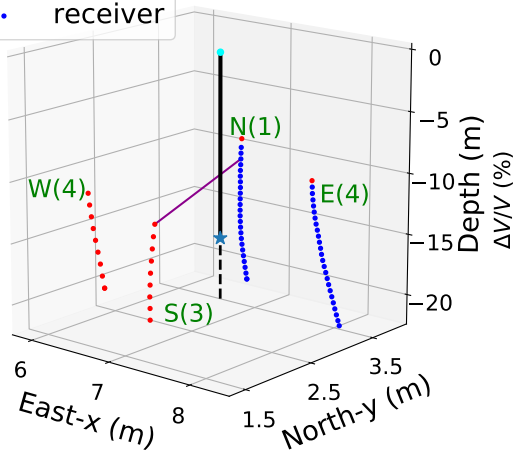
- source
- receiver



Relaxation

► slow relaxation?

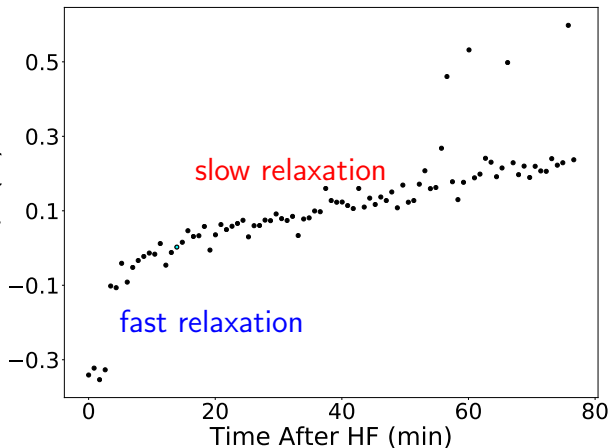
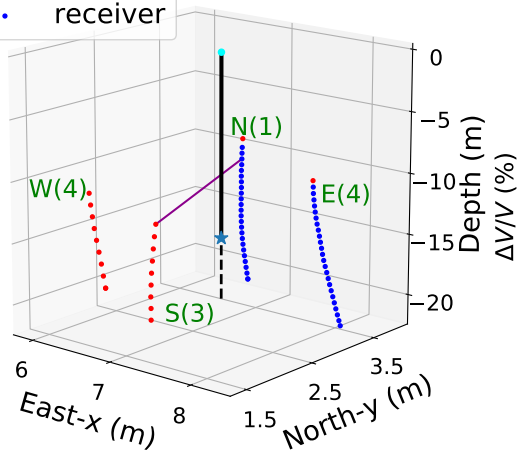
- source
- receiver



Relaxation

- ▶ two relaxation mechanisms?

- source
- receiver

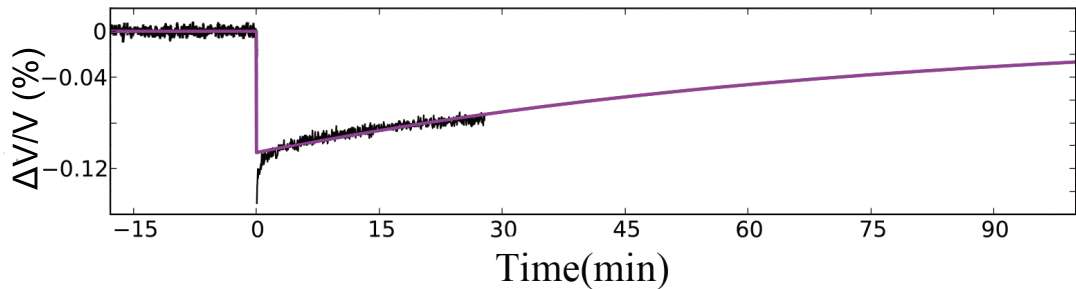


Lab

- ▶ deformation-dependent seismic velocity

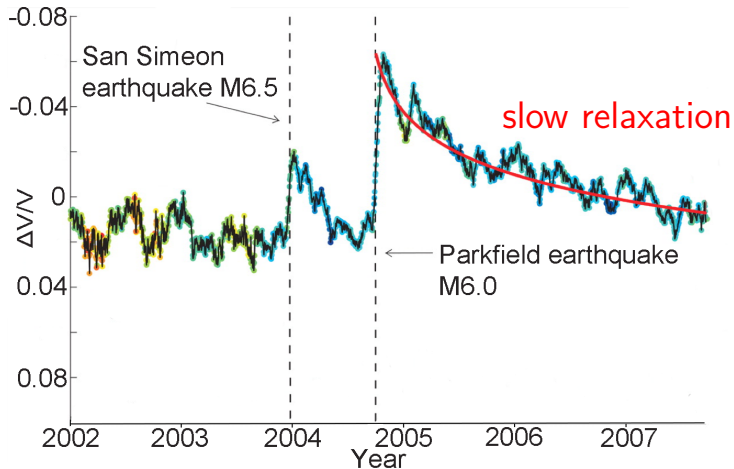
Lab

- ▶ deformation-dependent seismic velocity; **slow relaxation**



Field

► near-surface relaxation



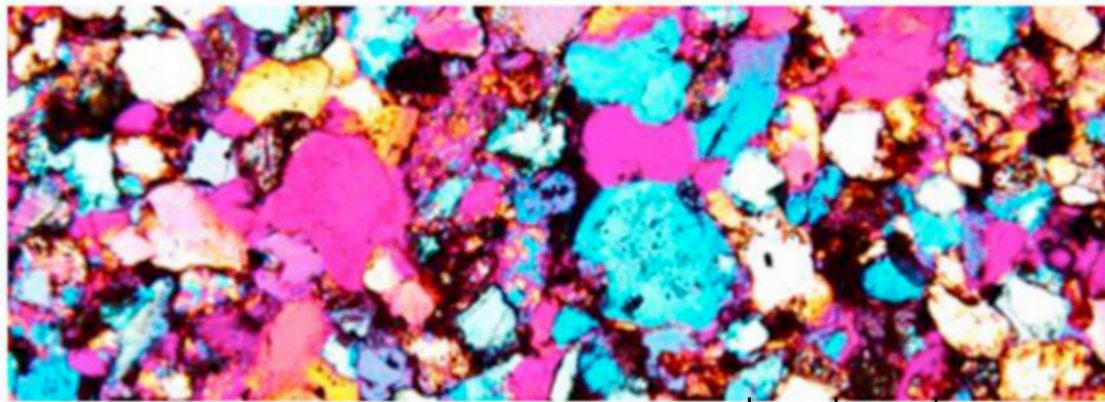
Damage & healing

- ▶ slow relaxation?

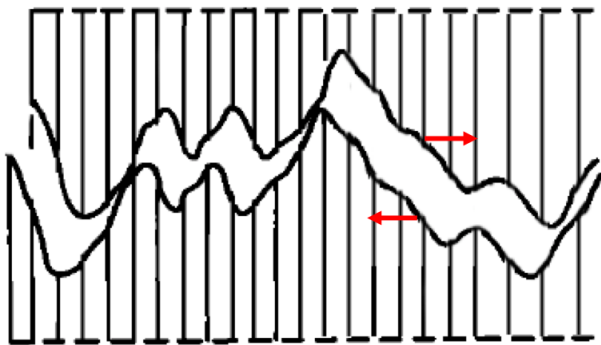
Damage & healing

- ▶ slow relaxation?
- ▶ granular contacts/fractures

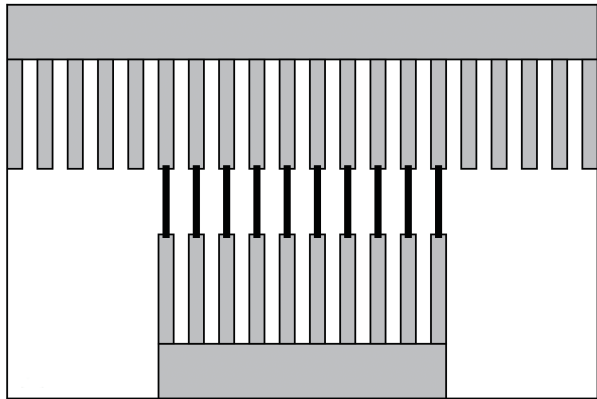
400 μm



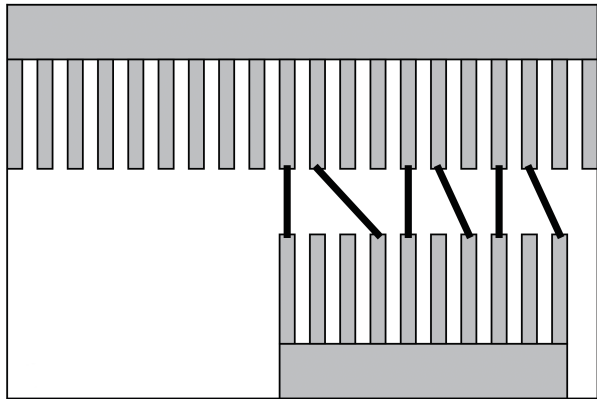
Damage & healing



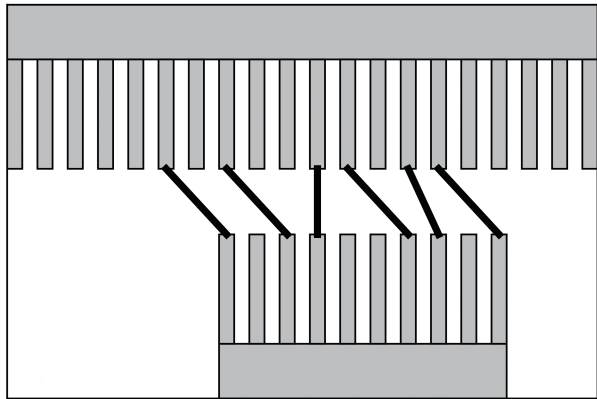
Damage & healing



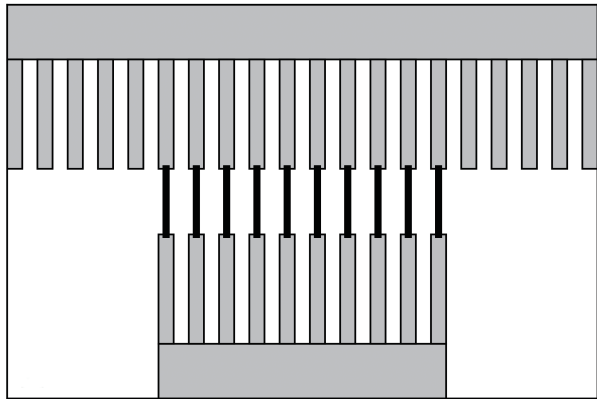
Damage & healing



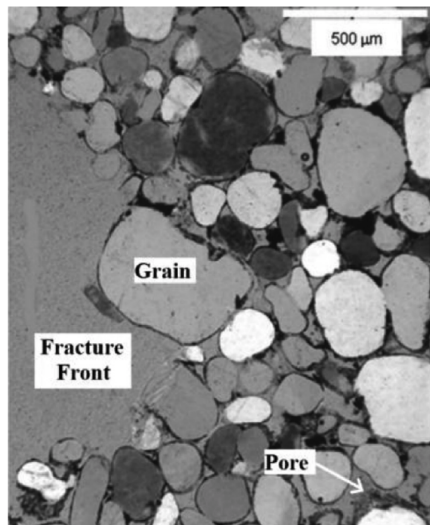
Damage & healing



Damage & healing

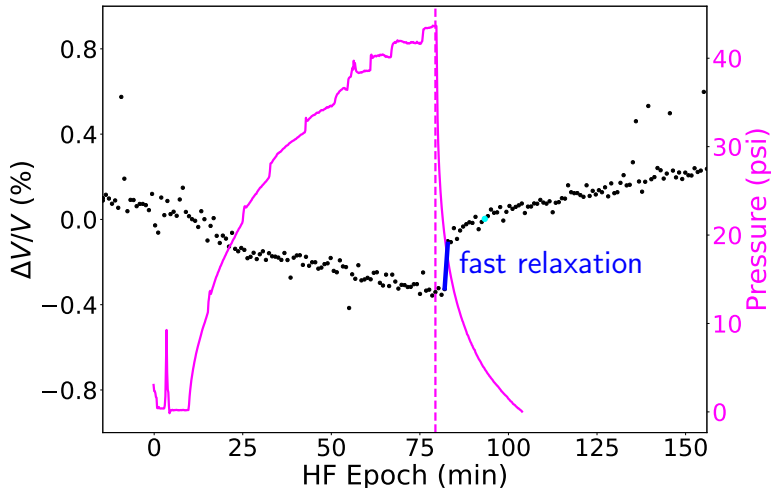


Damage & healing



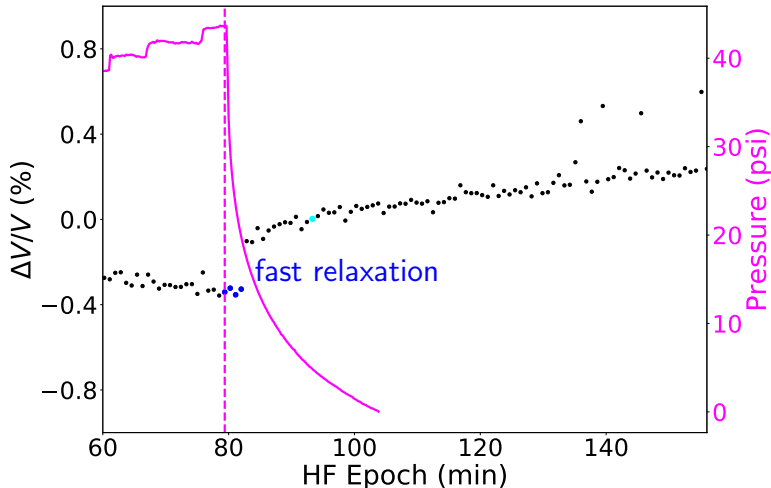
Relaxation mechanisms

- fast relaxation



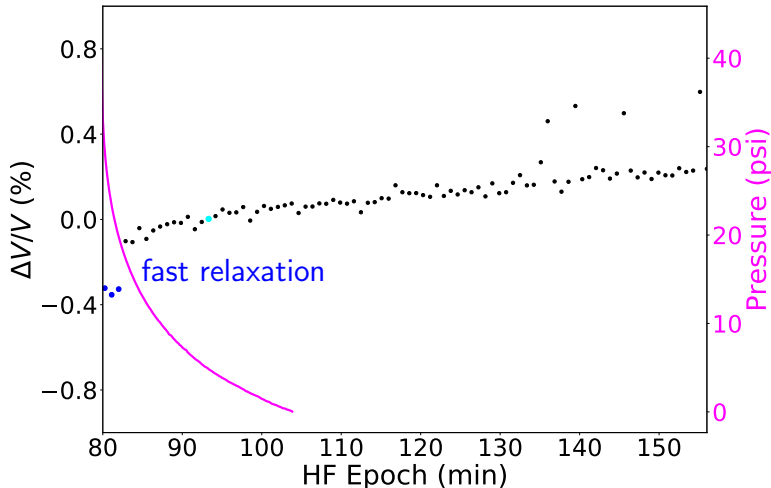
Relaxation mechanisms

- fast relaxation



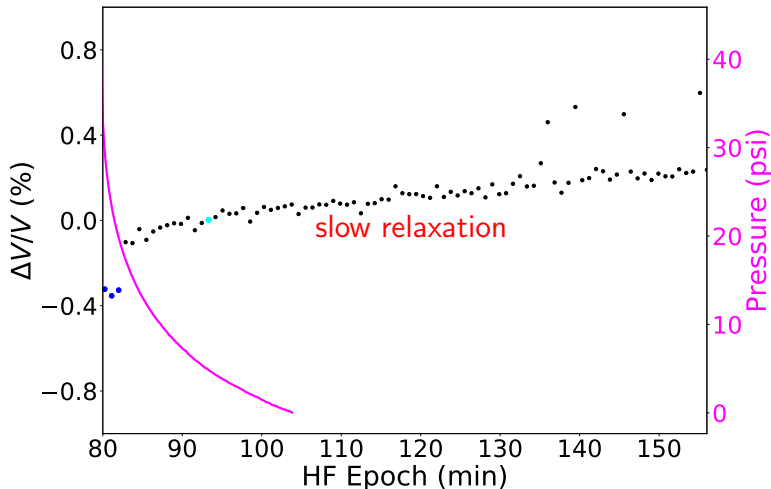
Relaxation mechanisms

- crack closure



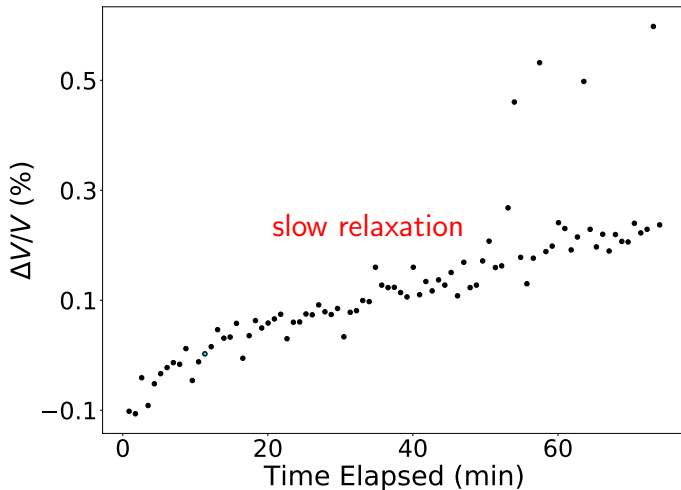
Relaxation mechanisms

- ▶ **slow** relaxation



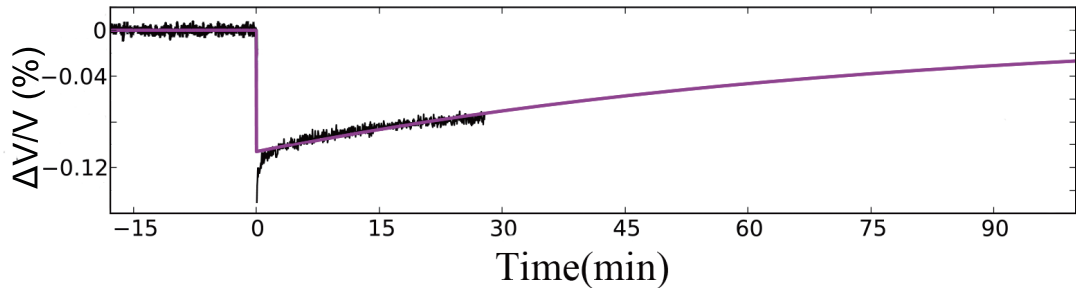
Relaxation mechanisms

- slow relaxation



Relaxation mechanisms

- ▶ slow relaxation (lab)



Insights

Insights

- ▶ fast relaxation: crack closure

Insights

- ▶ fast relaxation: crack closure
- ▶ slow relaxation: healing

Acknowledgements

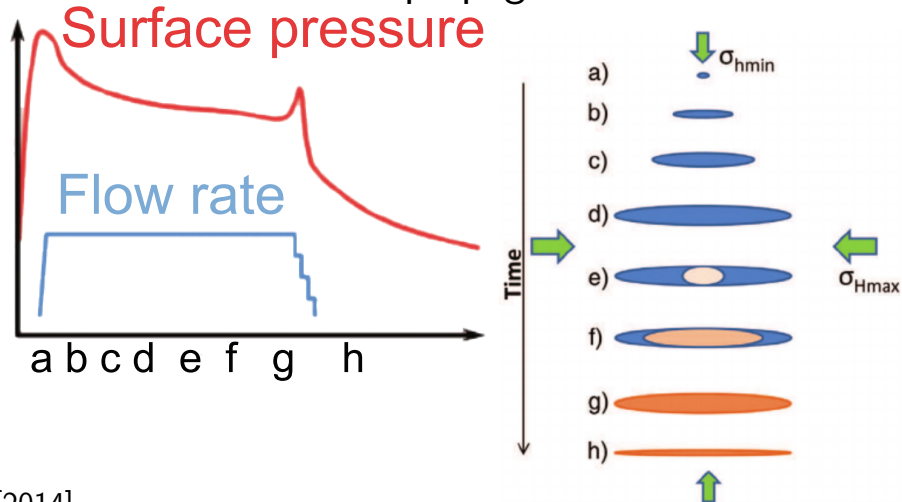
- ▶ CWP sponsors
- ▶ CWP colleagues

Reference

- Brenguier, F., M. Campillo, C. Hadziioannou, N. M. Shapiro, R. M. Nadeau, and E. Larose, 2008, Postseismic Relaxation Along the San Andreas Fault at Parkfield from Continuous Seismological Observations: *Science*, **321**, 1478–1481.
- Brown, S. R., and C. H. Scholz, 1986, closure of rock joints: *Journal of Geophysical Research: Solid Earth*, **91**, 4939–4948.
- Gassenmeier, M., 2015, Observation of dynamic processes with seismic interferometry: PhD thesis.
- Knox, H., J. Ajo-Franklin, T. Johnson, J. Morris, M. Grubelich, S. James, A. Rinehart, L. Preston, V. Vermeul, C. Strickland, J. Knox, D. King, and C. Ulrich, 2017, Imaging fracture networks using joint seismic and electrical change detection techniques: Technical report, Sandia National Laboratories.
- Li, Q., H. Xing, J. Liu, and X. Liu, 2015, A review on hydraulic fracturing of unconventional reservoir: *Petroleum*, **1**, 8 – 15.
- Li, X., C. Sens-Schönfelder, and R. Snieder, 2018, Nonlinear elasticity in resonance experiments: *Phys. Rev. B*, **97**, no. 14, 144301.
- Maxwell, S., 2014, Microseismic imaging of hydraulic fracturing: Improved engineering of unconventional shale reservoirs: Society of Exploration Geophysicists. SEG Distinguished Instructor Series No. 17.
- Rivière, J., P. Shokouhi, R. A. Guyer, and P. A. Johnson, 2015, A set of measures for the systematic classification of the nonlinear elastic behavior of disparate rocks: *Journal of Geophysical Research: Solid Earth*, **120**, 1587–1604.
- Sens-Schönfelder, C., R. Snieder, and X. Li, 2018, A physics-based model of nonlinear elasticity of rocks for reversible damage, slow dynamics, hysteresis and dynamic acoustoelastic testing (DAET). ((unpublished)).
- Snieder, R., A. Grêt, H. Douma, and J. Scales, 2002, Coda wave interferometry for estimating nonlinear behavior in seismic velocity: *Science*, **295**, 2253–2255.
- TenCate, J. A., 2011, Slow dynamics of earth materials: An experimental overview: *Pure and Applied Geophysics*, **168**, 2211–2219.
- TenCate, J. A., E. Smith, and R. A. Guyer, 2000, Universal slow dynamics in granular solids: *Physical Review Letters*, **85**, 1020–1023.

Hydraulic fracturing

- ▶ stress-controlled fracture propagation

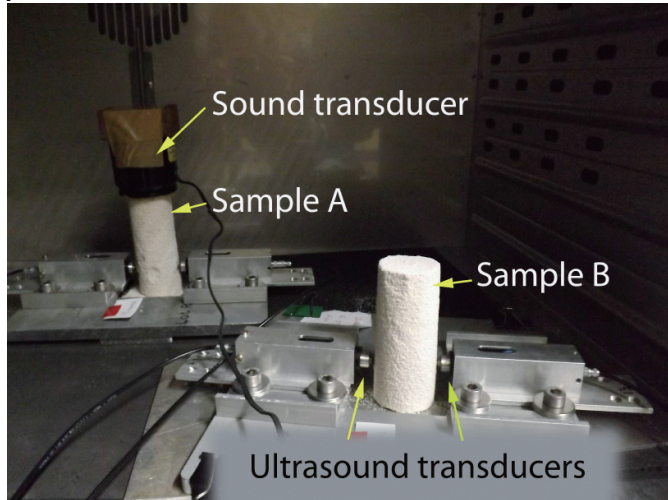


Introduction

- ▶ resonance experiment

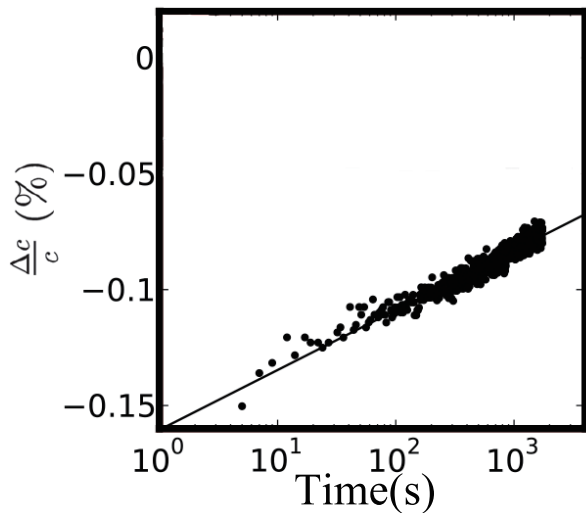
Introduction

- ▶ resonance experiment



Introduction

- ▶ log-time relaxation

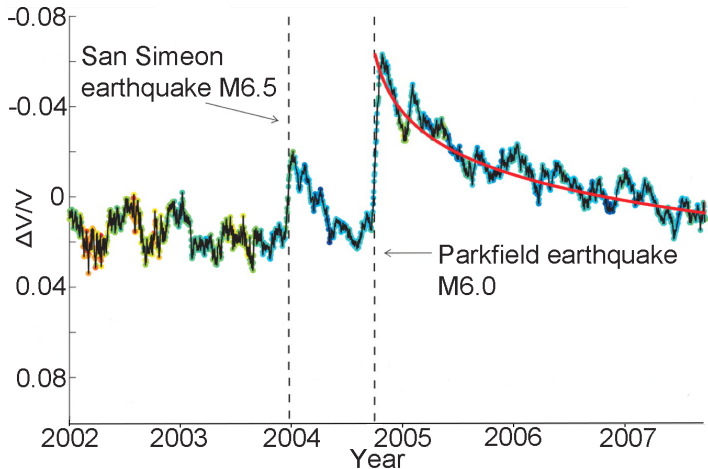


Introduction

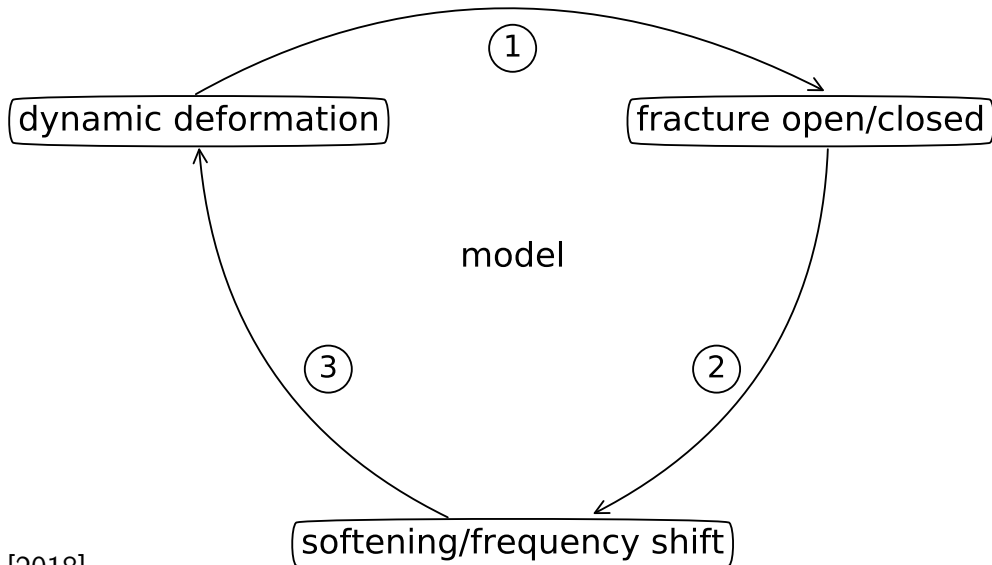
- ▶ near-surface relaxation

Introduction

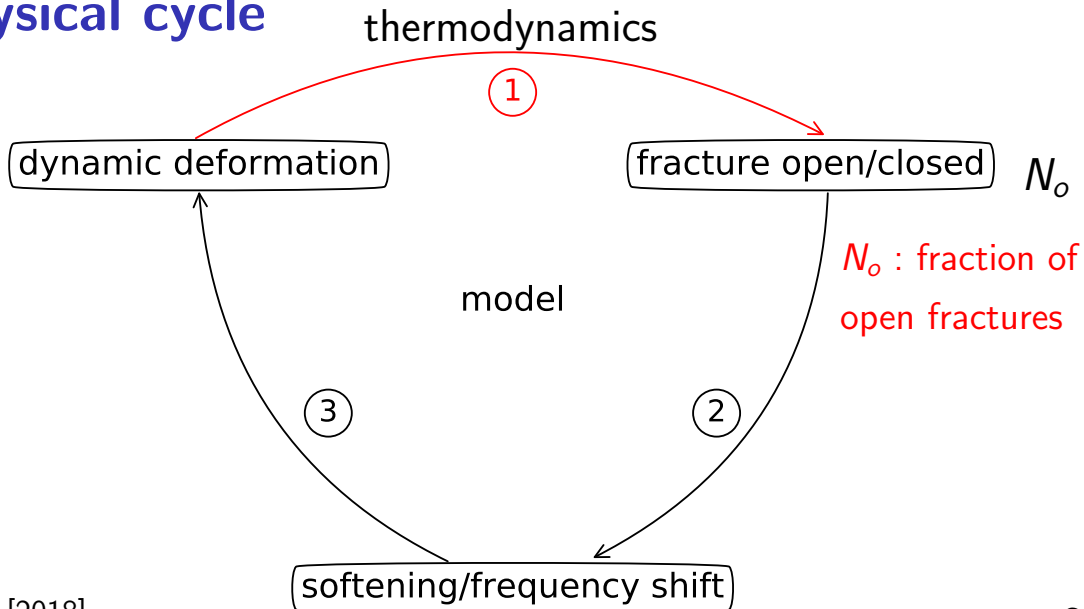
- ▶ near-surface relaxation



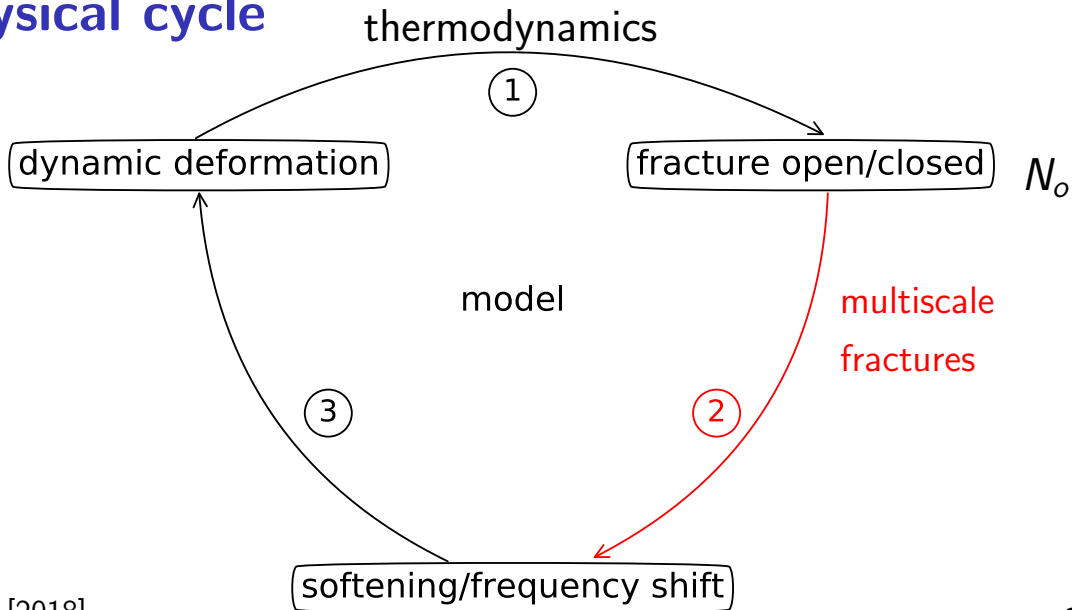
Physical cycle



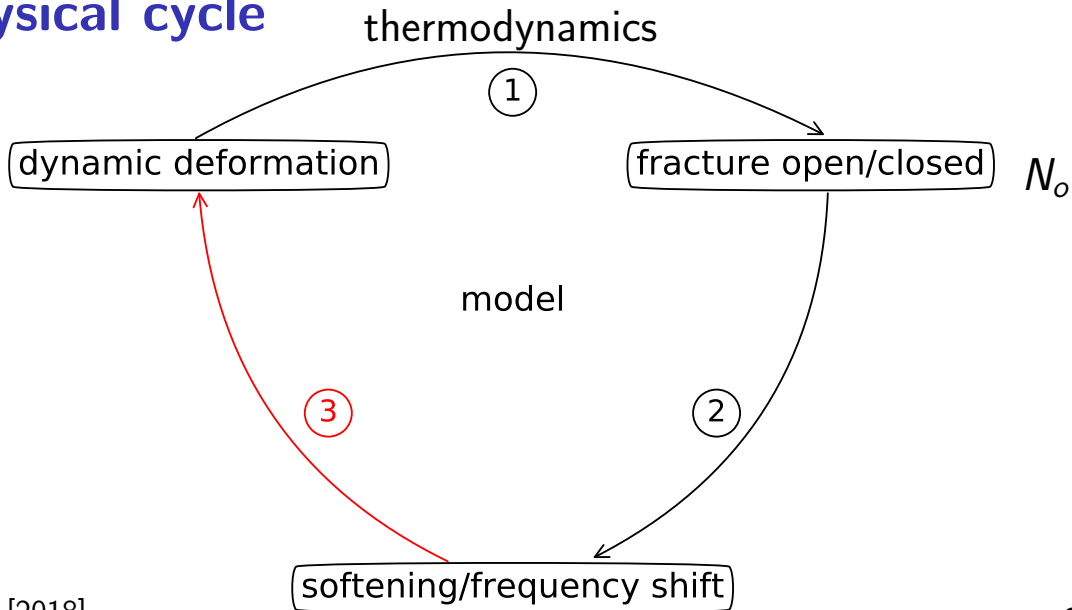
Physical cycle



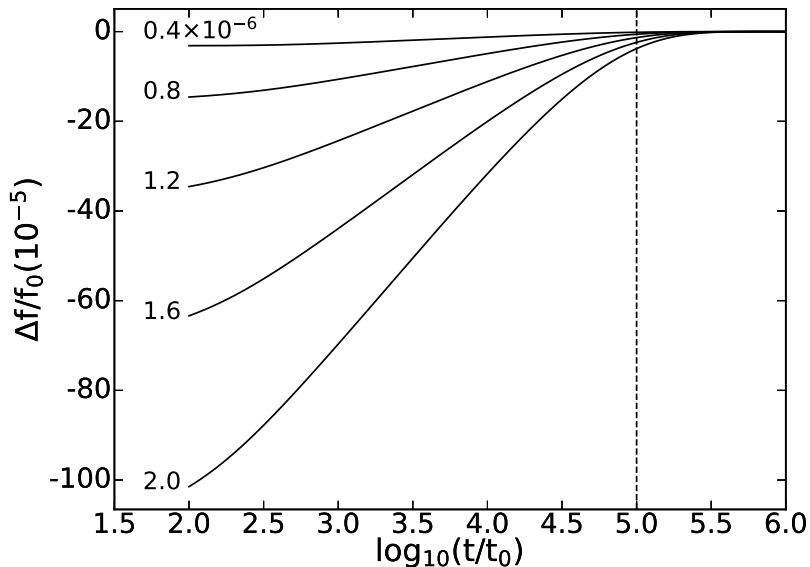
Physical cycle



Physical cycle

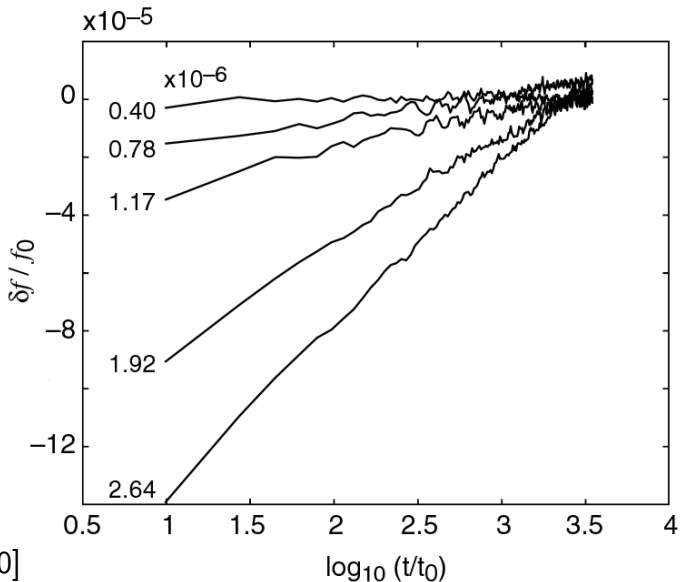


Simulated relaxation



simulation

Simulated relaxation



Lab

PHYSICAL REVIEW B **97**, 144301 (2018)

Nonlinear elasticity in resonance experiments

Xun Li,^{1,*} Christoph Sens-Schönfelder,² and Roel Snieder¹

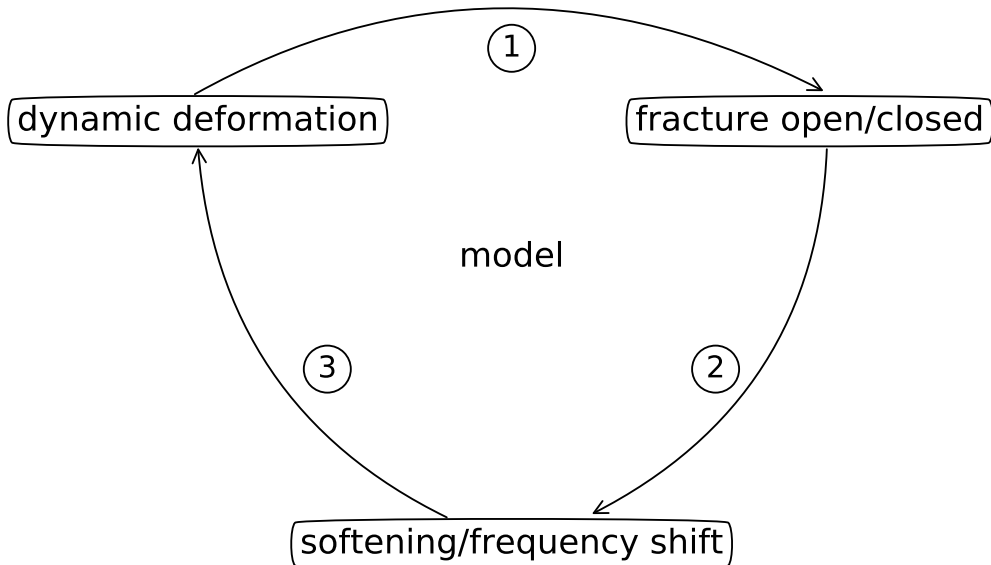
¹*Center for Wave Phenomena, Colorado School of Mines, Golden, Colorado 80401, USA*

²*GFZ German Research Centre for Geosciences, Potsdam, Germany*

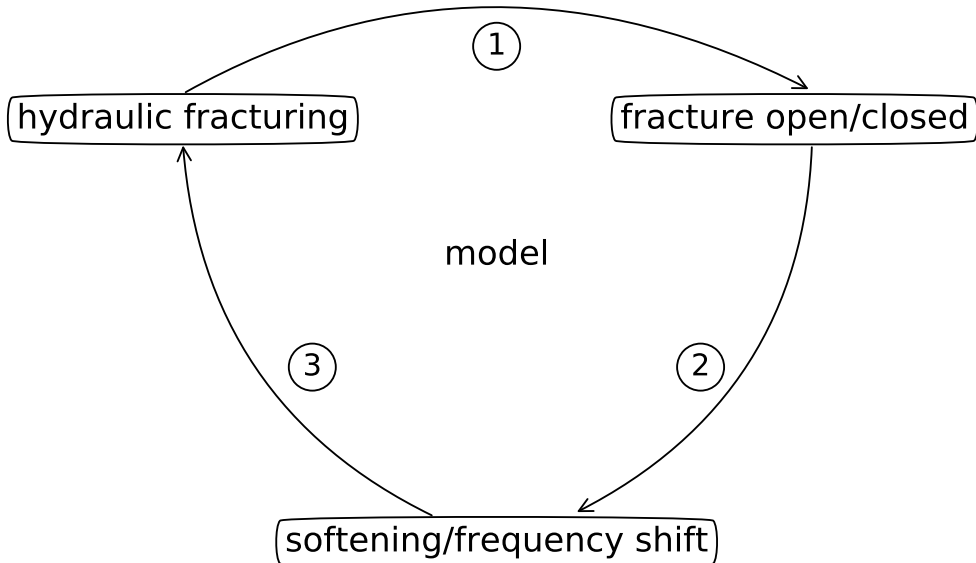


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Hydraulic fracturing



Hydraulic fracturing



Introduction

► log-time relaxation

