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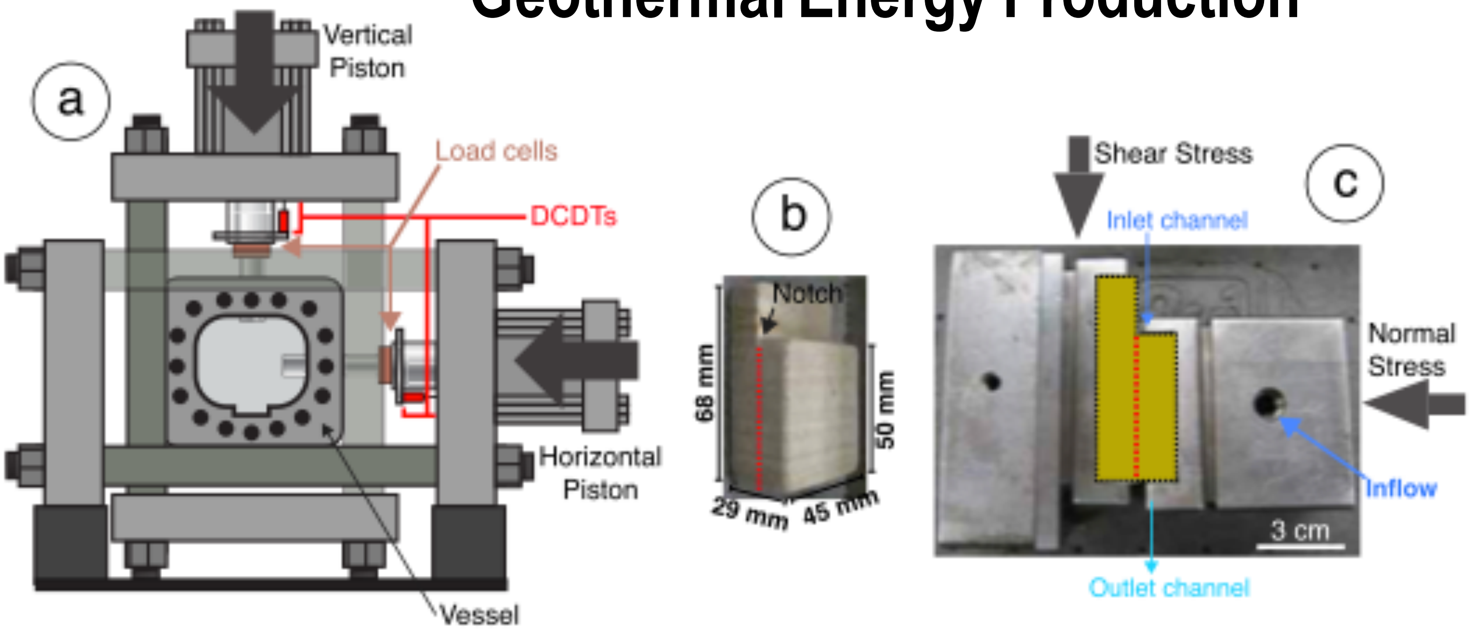
Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production



Project Officer: William Vandermeer ;

Project Funding: $858k;

Nov 14, 2017

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Penn State University

EE0006762; Reservoir Fracture Characterization & Fluid Imaging

Relevance to Industry Needs and GTO Objectives

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Challenges

- Prospecting (characterization)
- Accessing (drilling)
- *Creating reservoir*
- *Sustaining reservoir*
- *Environmental issues (e.g. seismicity)*

Observation

- Stress-sensitive reservoirs
- Effective stresses influence
  - Permeability – hydroshear and propagation
  - Heat-transfer area
  - Elastic Properties (proxy for state of stress)
  - Induced Seismicity (IS)

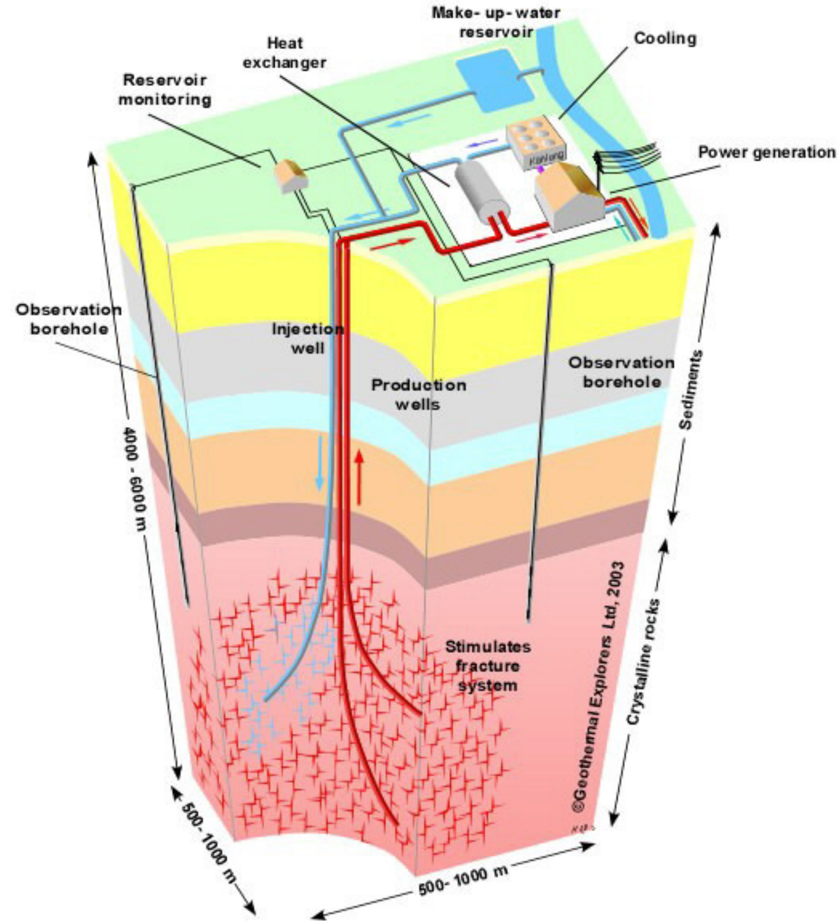
Understanding IS-permeability linkage is key:

- Aseismic/seismic permeability modes
- Mechanisms of dynamic stressing
  - Permeability gain (short-term)
  - Permeability loss (long-term)
- Complex THMC interactions
- Control to “engineer” the reservoir

Permeability
Reactive surface area
Induced seismicity

Resource

- **Hydrothermal (US:10^4 EJ)**
- **EGS (US:10^7 EJ; 100 GW in 50y)**



Relevance/Impact of Research
Dynamic Stressing and Permeability

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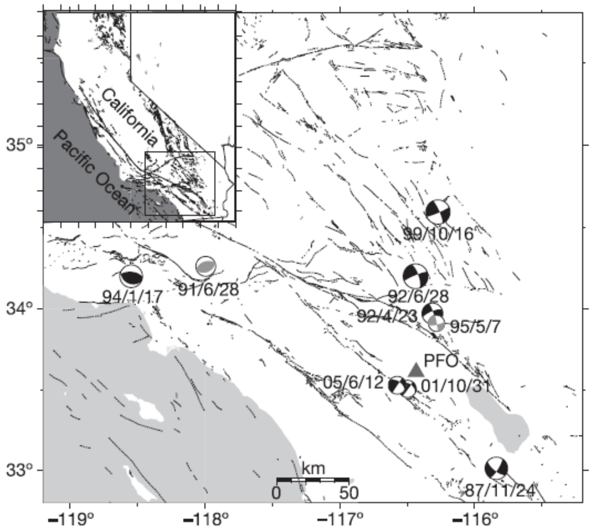
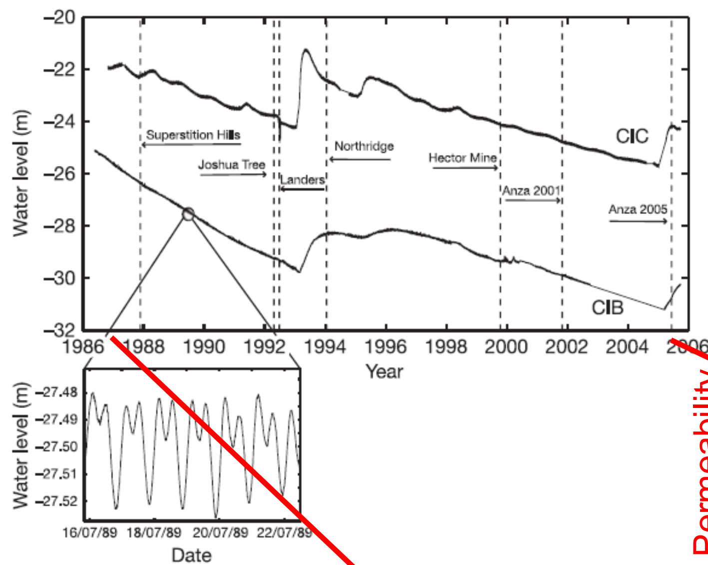
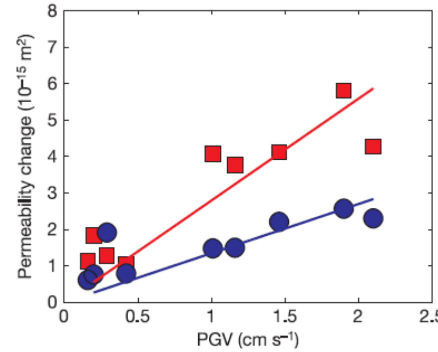
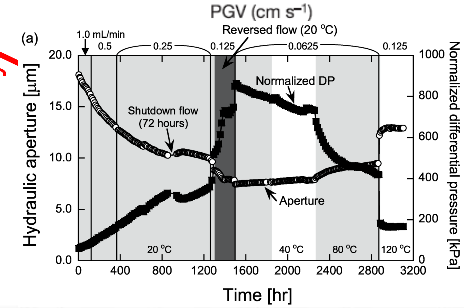




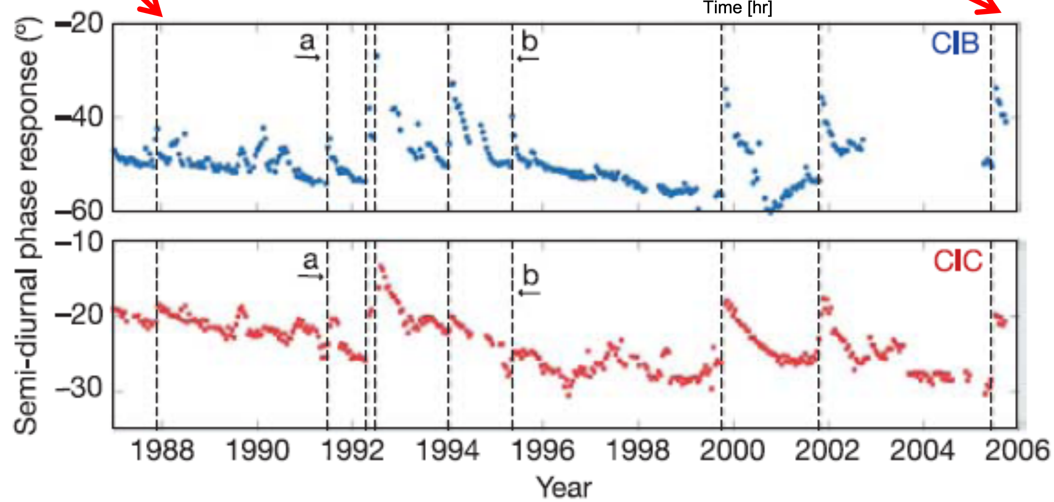


Permeability



- Remote earthquakes trigger dynamic changes in permeability
- Unusual record transits ~8y
- Sharp rise in permeability followed by slow "healing" to background
- Scales of observations:
  - Field scale
  - Laboratory scale
- Mechanistic understanding and control? Can this be employed in an EGS setting?

Permeability



[Elkhoury et al., Nature, 2006]

Relevance/Impact: Inferring Critical Stress State via Elastic Properties

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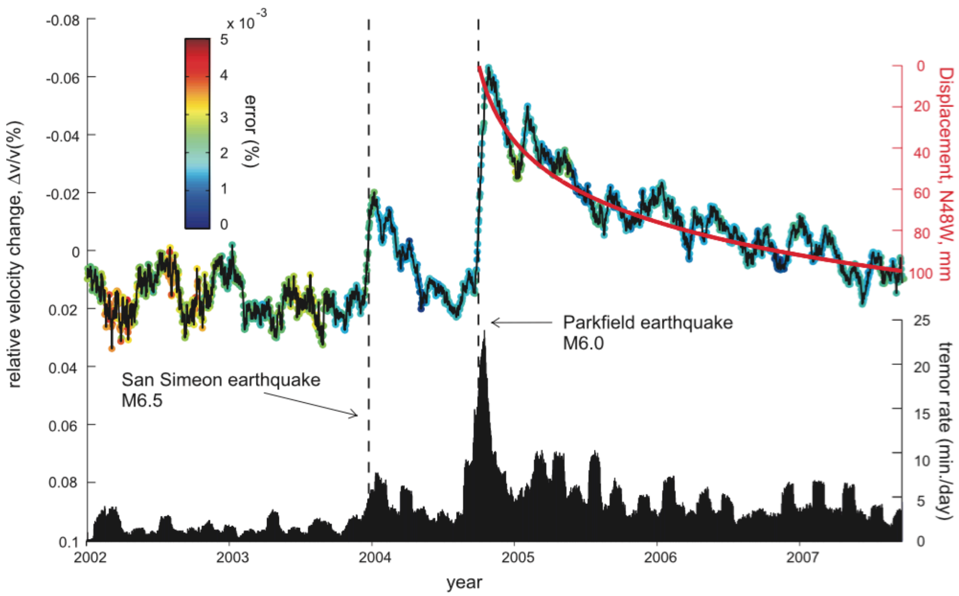
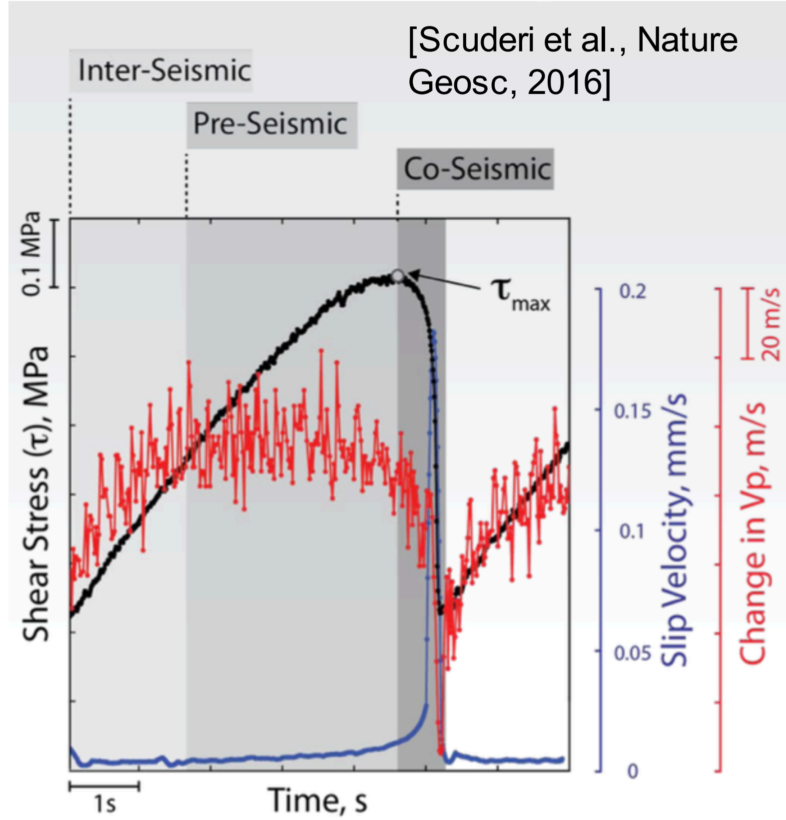
Transient softening following earthquakes



[from Brenguier et al, Science, 2008]



- Seismic waves trigger transient changes in elastic properties
- Elastic softening coincides with increased permeability (e.g., see previous slide)
- Lab observations of precursors to earthquake-like failure (i.e., elastic wave speed)
- Monitoring to assess the critical stress-state in Earth's crust
- Potential for management of induced seismicity to maximize geothermal energy production

Scientific/Technical Approach

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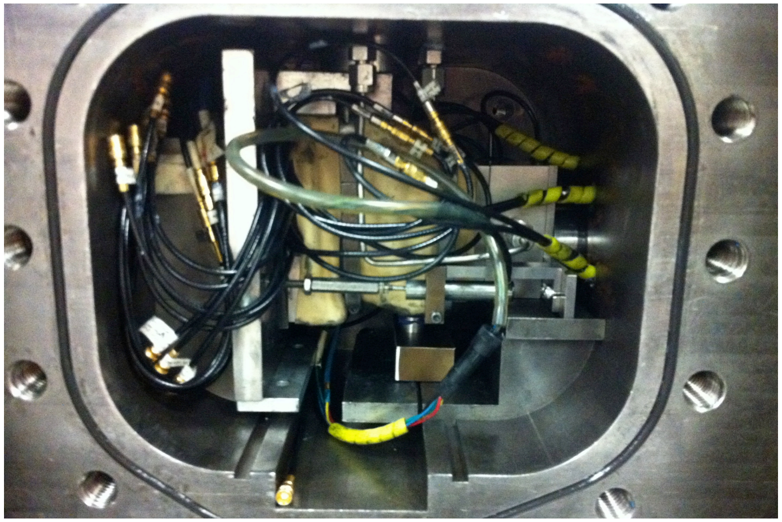
Addressing four broad areas:

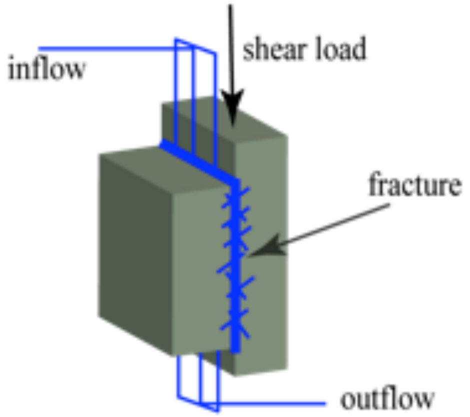
1. Fracture formation and the relationship between fluid flow and shear failure.
2. Improved understanding of the relationship between fracture permeability, fluid flow, and induced seismicity in geothermal reservoirs.
3. Precursors to failure: changes in elastic properties prior to lab earthquakes
4. Development of process based models for using elastic properties and induced seismicity to assess the critical stress-state in Earth's crust.

Fracture formation and the relationship between fluid flow, shear failure, and dynamic stressing

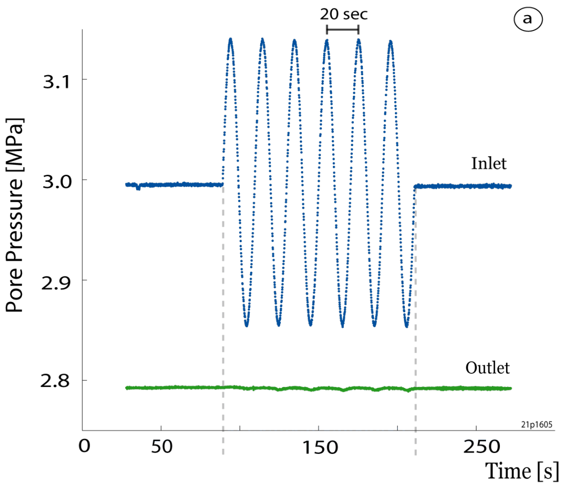


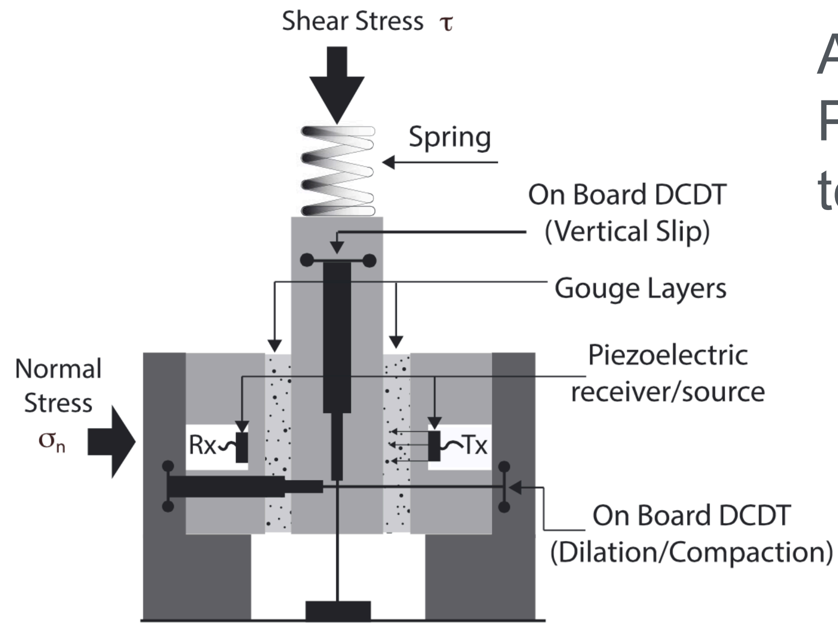
Madara et al., 2016, *Rivière et al.*, 2017

Fracture Formation and Permeability Measurement



Dynamic Stressing





Acoustic Precursors to failure

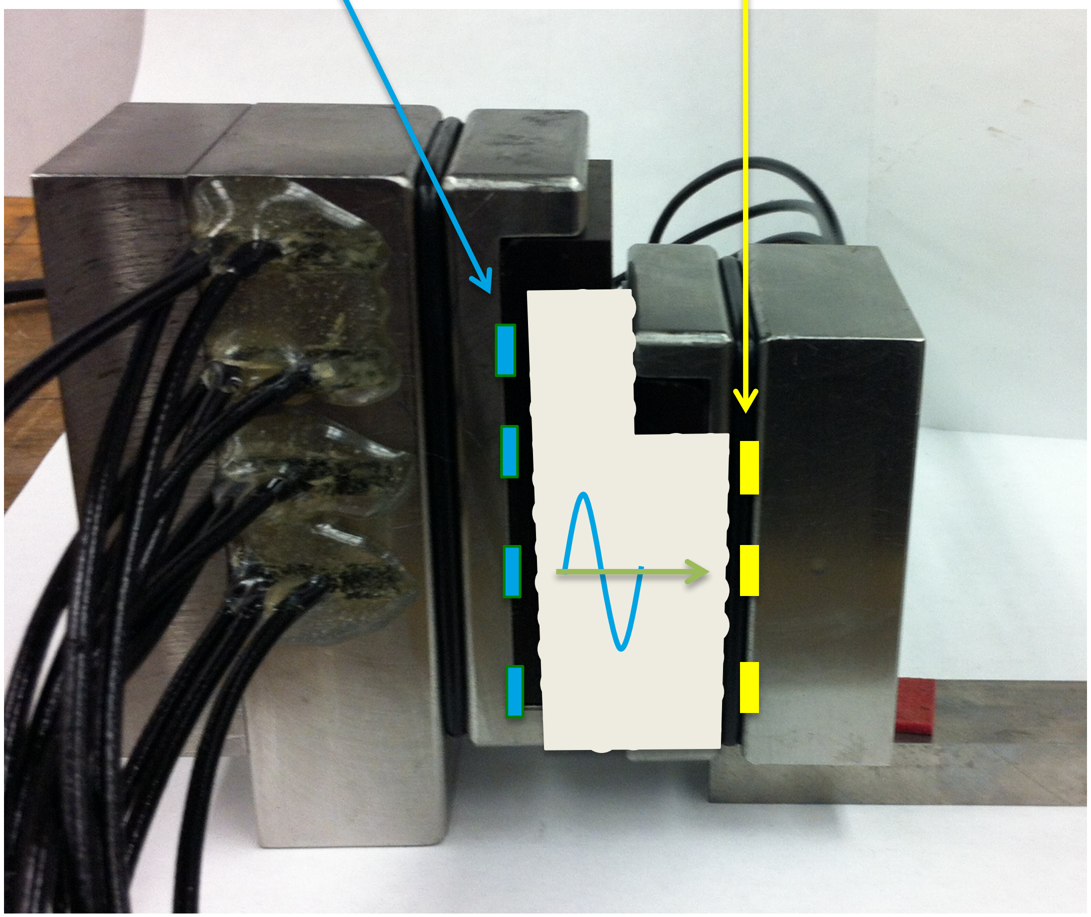
Scuderi et al., 2016
Tinti et al., 2016

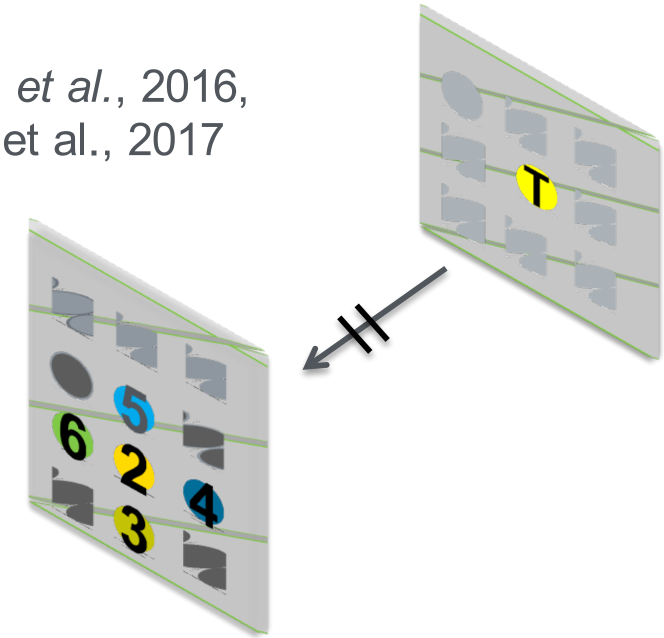
Assessment of Fracture Properties and Permeability Enhancement via Elastic Monitoring (Dynamic Stressing, Precursors to Failure and Induced Seismicity)

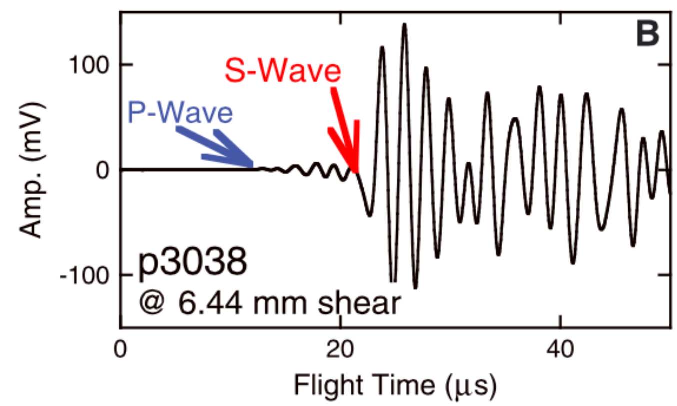
Receivers

Transmitters

Madara et al., 2016,
Rivière et al., 2017

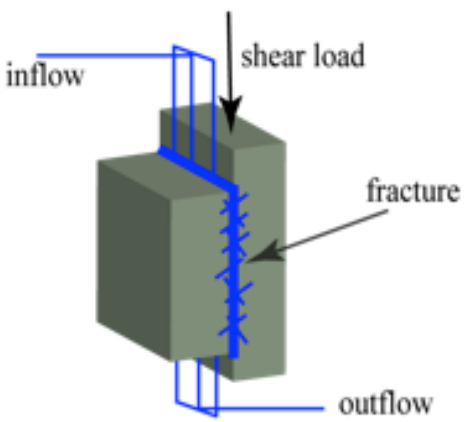


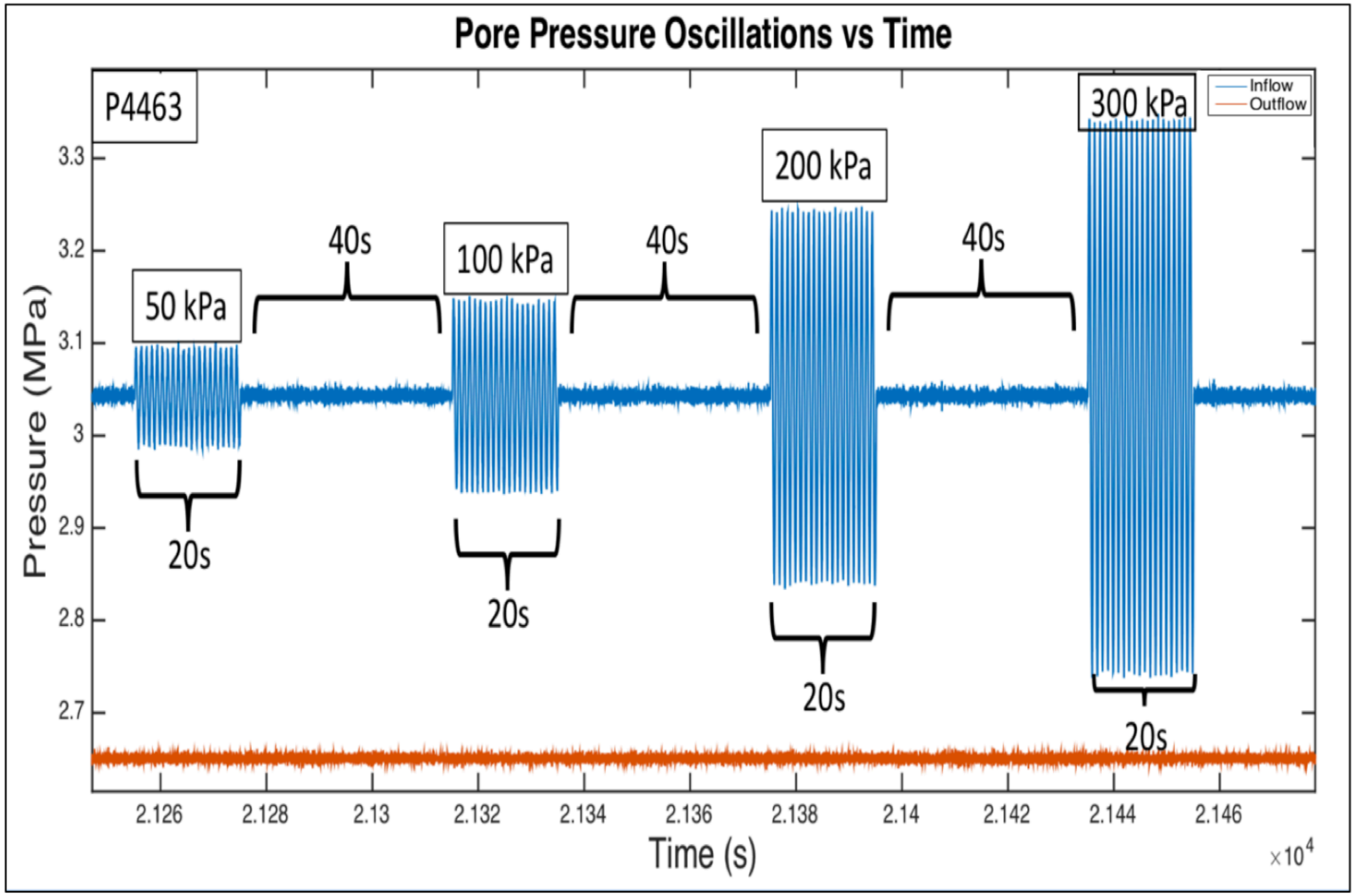




Dynamic stressing

Assess the effects of stressing amplitude and frequency on permeability enhancement and induced seismicity

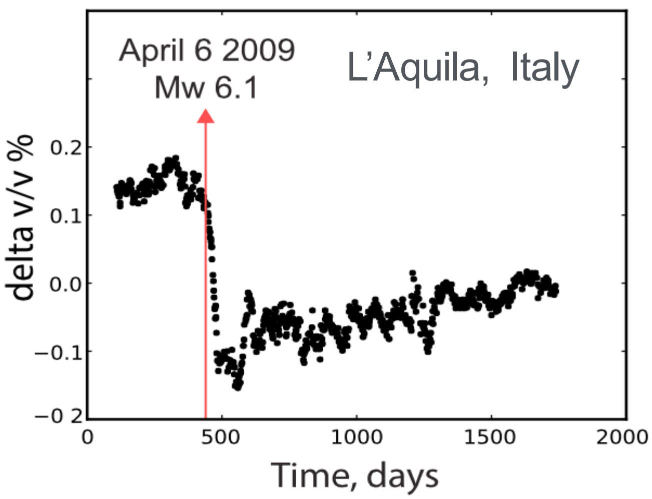


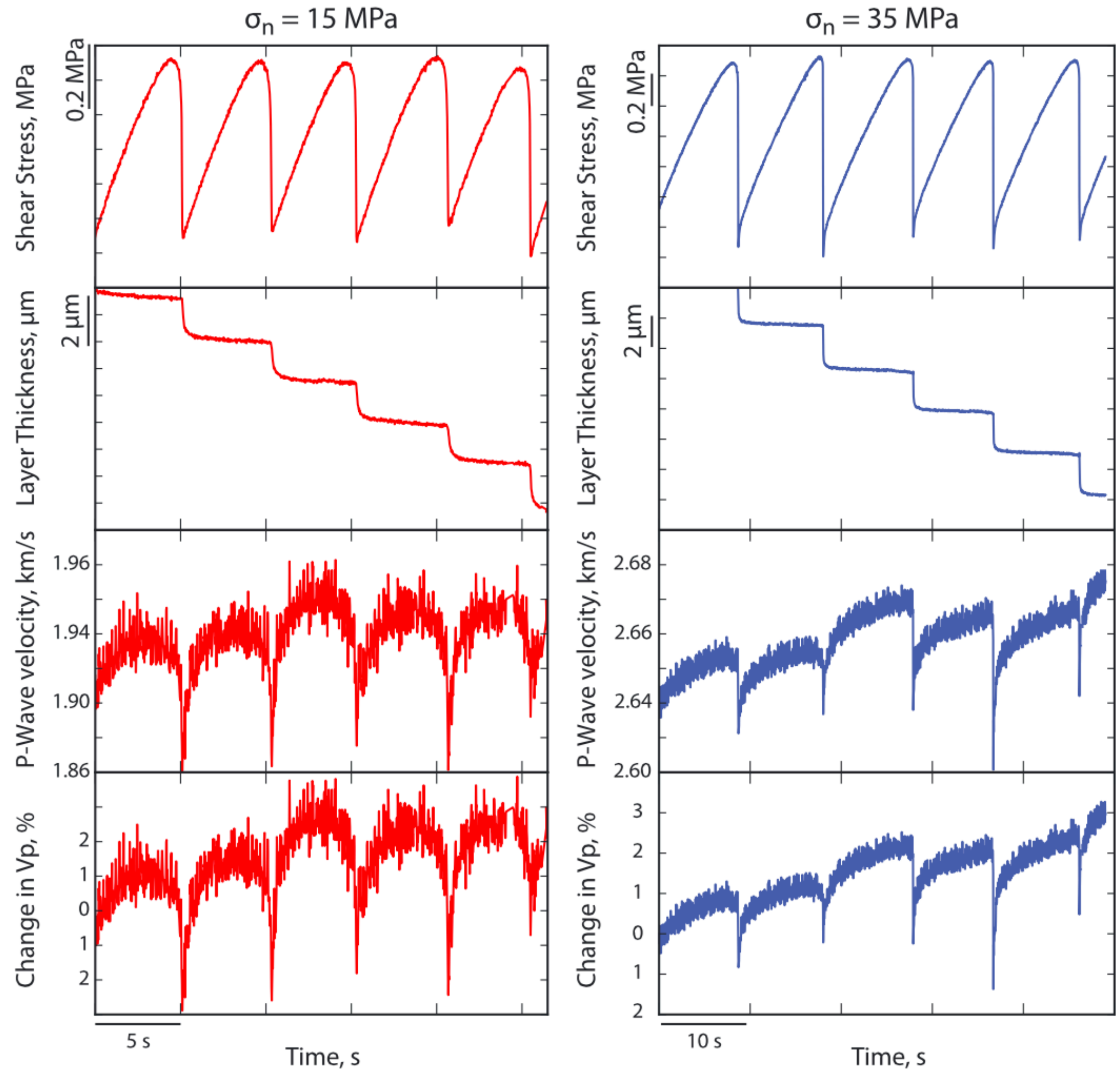


Candela et al., 2014, 2015; *Madara et al.*, 2016, Rivière et al., 2016, 2017

Acoustic precursors to failure

- Clear observations of changes in elastic properties prior to earthquake-like failure
- Precursors observed for slow and fast failure –laboratory equivalent of slow earthquakes and dynamic rupture in seismic events
- Elastic wave speed decreases prior to failure
- Lab data show similar pattern as field observations for coseismic and postseismic slip.



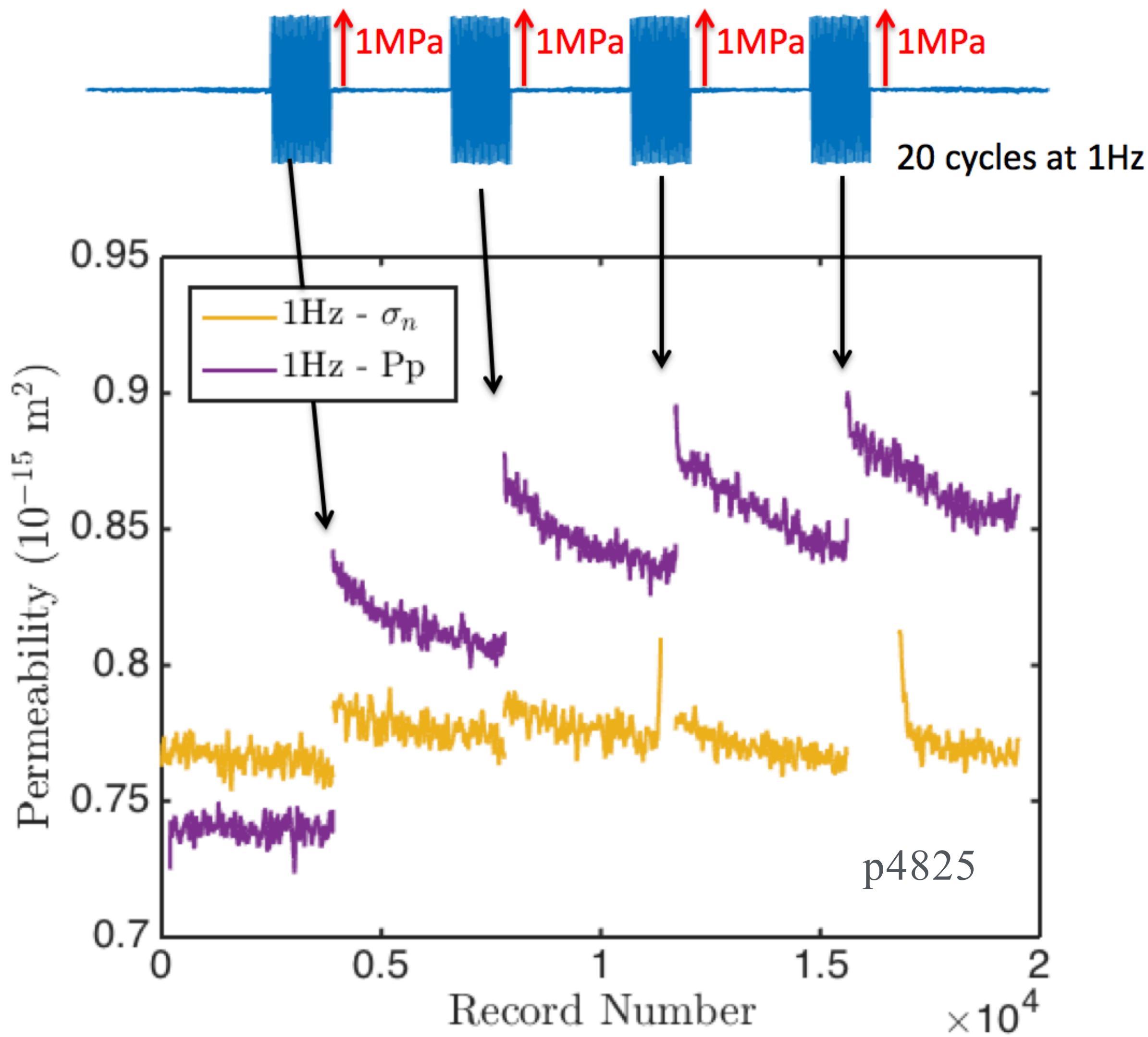


Tinit et al., 2016; Scuderi et al., 2016

Transient Changes in Permeability: Assessment of Stressing Amplitude and Mode

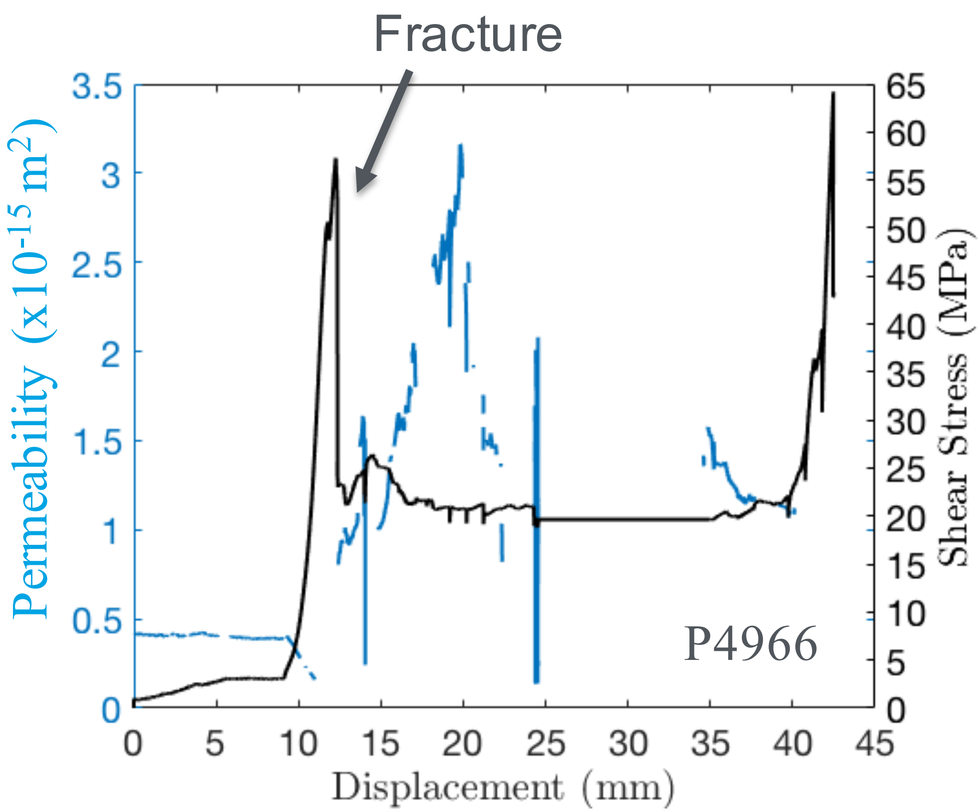
- Flow (ΔPp)
- Applied stress ($\Delta\sigma_n$)

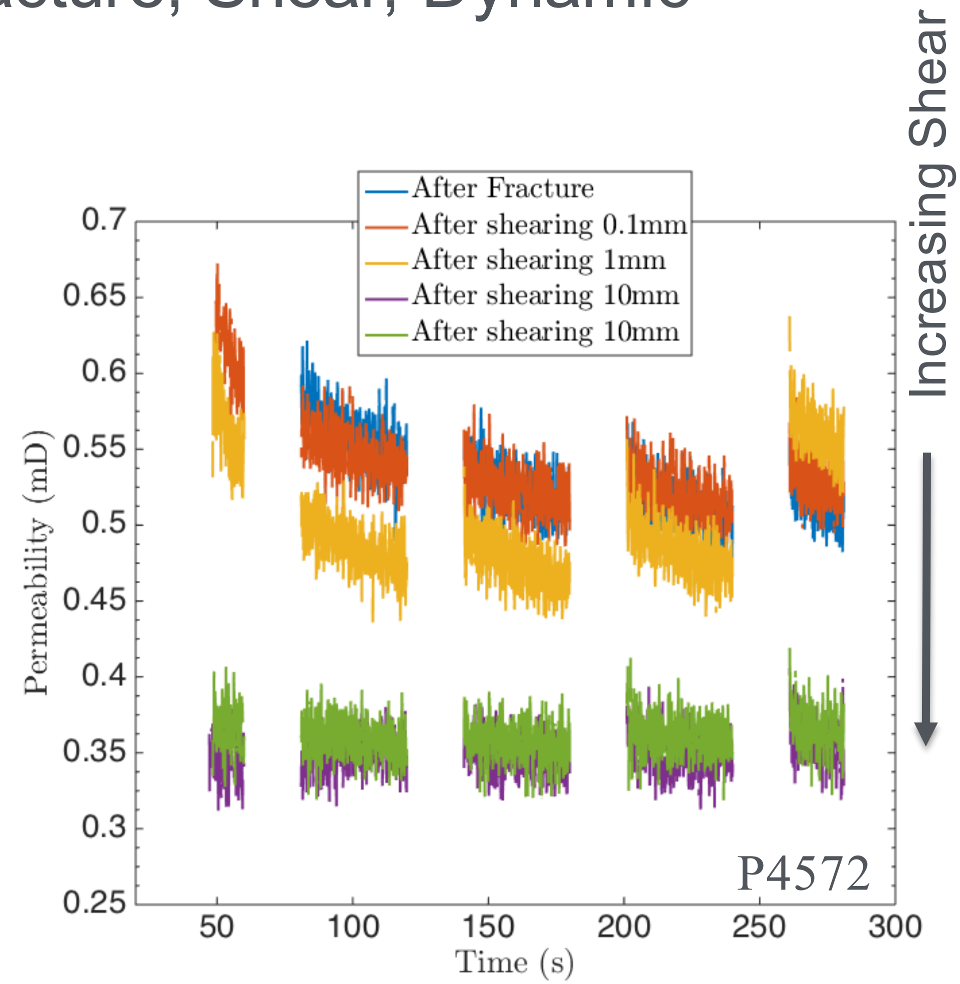
Implication: fluid flow (clogging/unclogging) is the primary cause of transient changes in permeability.



Rivière et al., 2017

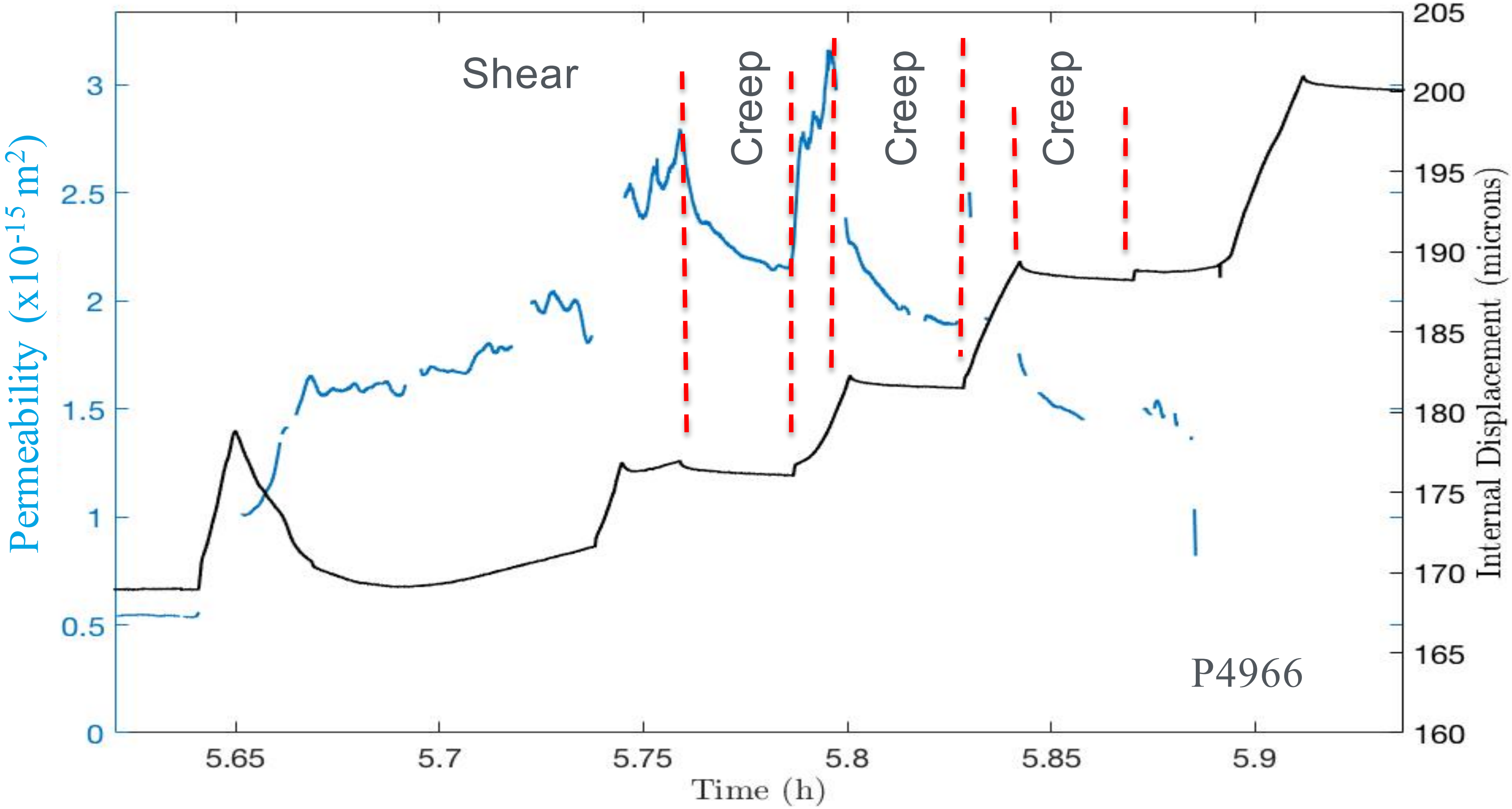
Permeability Changes During Fracture, Shear, Dynamic Stressing, and Healing





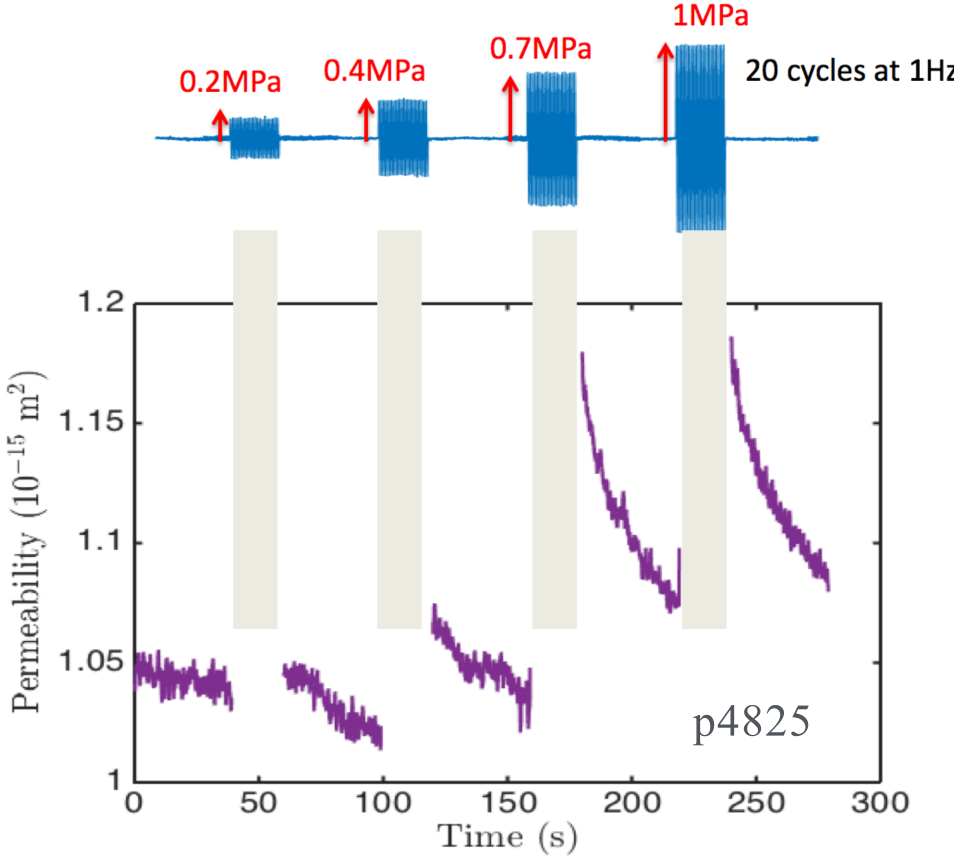
Madara et al., 2016, Rivière et al., 2017

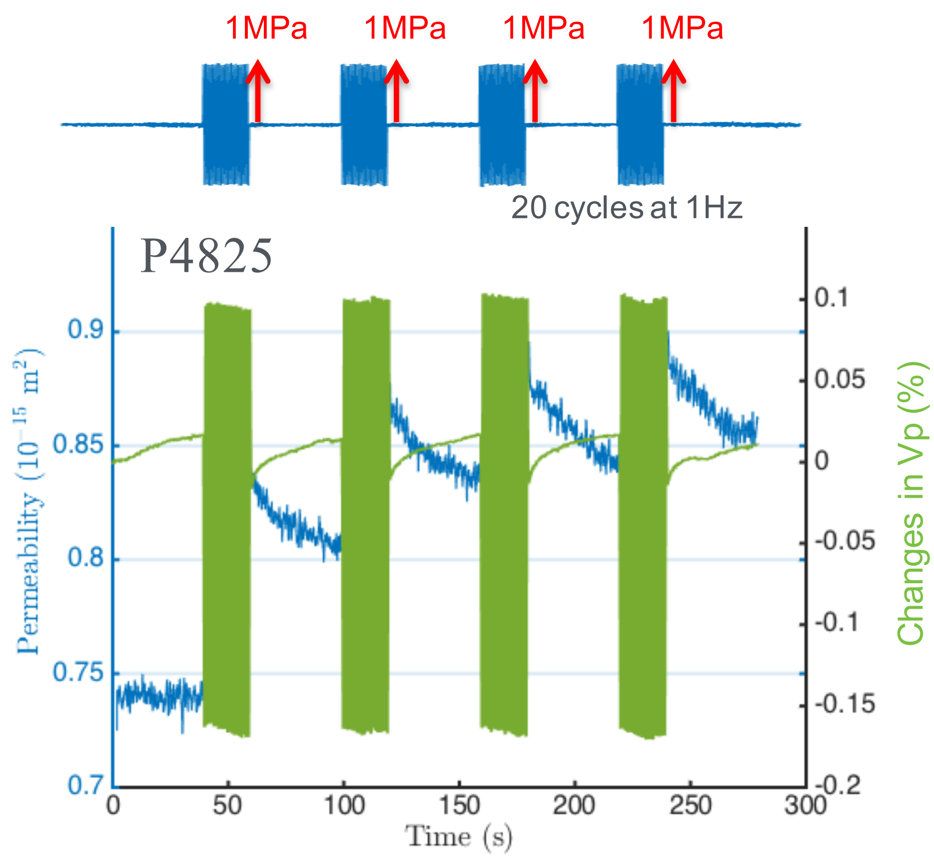
Fracture permeability increases during shear and decreases during hold periods (Creep induced healing and sealing)



Madara et al., 2016, Rivière et al., 2017

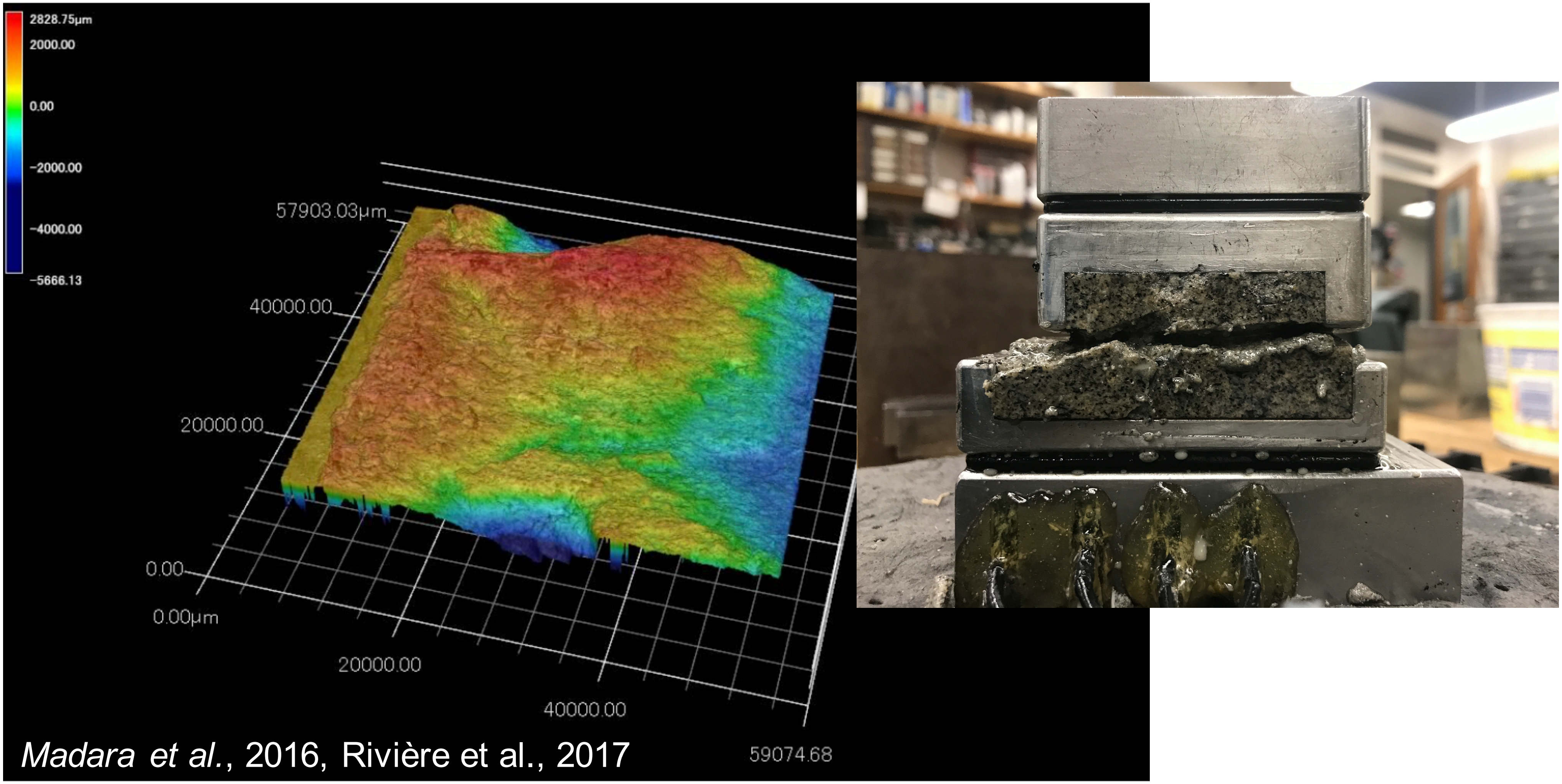
Acoustic imaging of changes in fracture permeability during dynamic stressing and shear





Madara et al., 2016, Rivière et al., 2017

The role of roughness for shear induced permeability change



Madara et al., 2016, Rivière et al., 2017

Research Collaboration and Technology Transfer

- We are participating in the EGS Collab deployment (LBNL-lead) at the Sanford Lab examining seismicity-permeability relations from fractures.
- We are working to migrate observations from laboratory scales to field scale - BES proposal with LBNL (Guglielmi) in review; also Guglielmi, Elsworth et al., Science, 2015.
- We are exploring linkages between permeability evolution and non-linear elasticity and acoustics (PSU/Grenoble/LANL) (Shokouhi-BES-funded).
- We are working to use data on dynamic earthquake triggering to infer the critical stress state in Earth’s crust. We are particularly interested in the role of fluid injection and associated changes in stress state and fault zone frictional strength.

Future Directions

- Field and laboratory results show that dynamic stressing modifies rock permeability.
- Lab data show that clogging/unclogging via fluid flow is the primary agent of transient permeability change via dynamic stressing.
- Perform field tests to determine if dynamic stresses can be used to manage fracture permeability in an EGS.
- We have shown that elastic wave speed and amplitude vary systematically during the cycle of stick and slip, which is an analog for the earthquake cycle, and we see that P- and S-wave speeds decrease prior to and during fault slip and recover with log time during interseismic restrengthening.
- Field results also show transient changes in elastic properties associated with earthquake failure.
- Expand the laboratory database and perform field tests to determine if techniques can be developed to assess hazard associated with induced seismicity and avoid damaging seismic activity in association with geothermal production

Summary Slide

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- Our work addresses the fundamental role of facture permeability, fluid flow and shear failure in geothermal energy production.
- Our results illuminate the relationships between fracture permeability, heat transfer via fluid flow, and induced seismicity, with potential for improved management and safety of geothermal energy production.
- We have developed methods to understand how the seismic behavior of geologic faults and their susceptibility to hydraulically-induced shear failure can be used to inform drilling and production with the goal of mitigating damaging seismic failure in critical cases.