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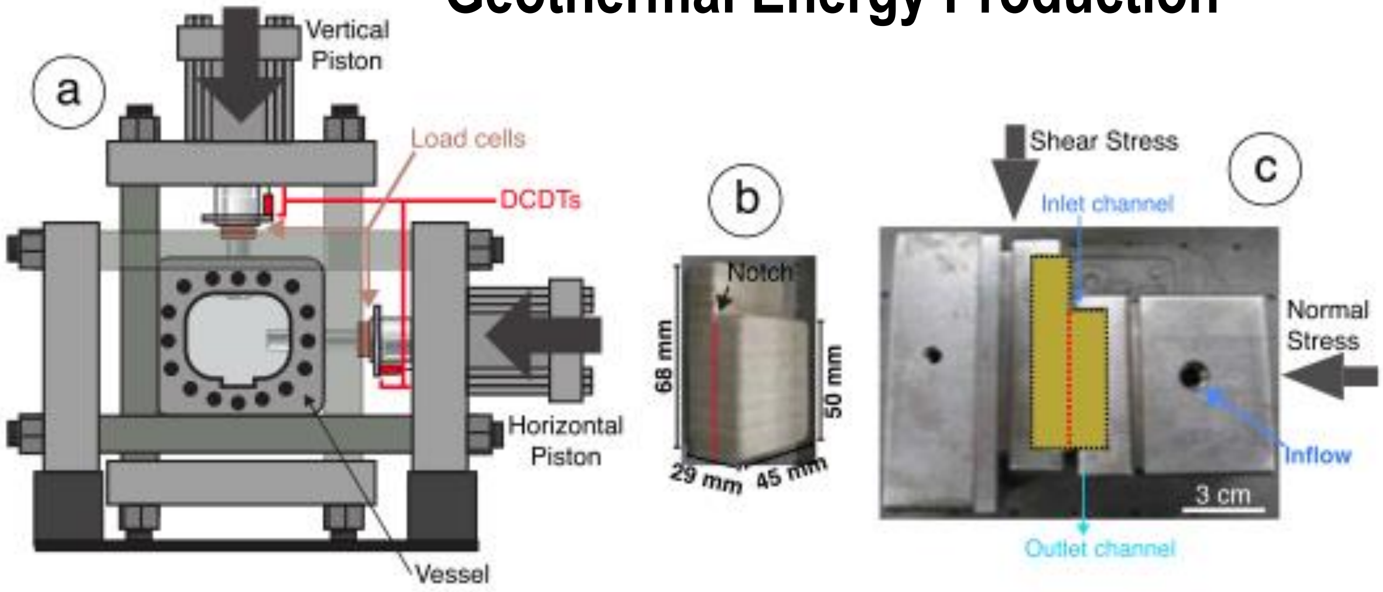
Leveraging a Fundamental Understanding of Fracture Flow, Dynamic Permeability Enhancement, and Induced Seismicity to Improve Geothermal Energy Production



Project Officer: William Vandermeer ;

Project Funding: $858k;

May 11, 2015

PI: Chris Marone
Co Pis: D. Elsworth (PSU), P. Johnson (LANL)
Presenter: Derek Elsworth
Penn State University

EE0006762; Reservoir Fracture Characterization & Fluid Imaging

Relevance/Impact of Research [Challenges]

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
  - Induced Seismicity (IS)

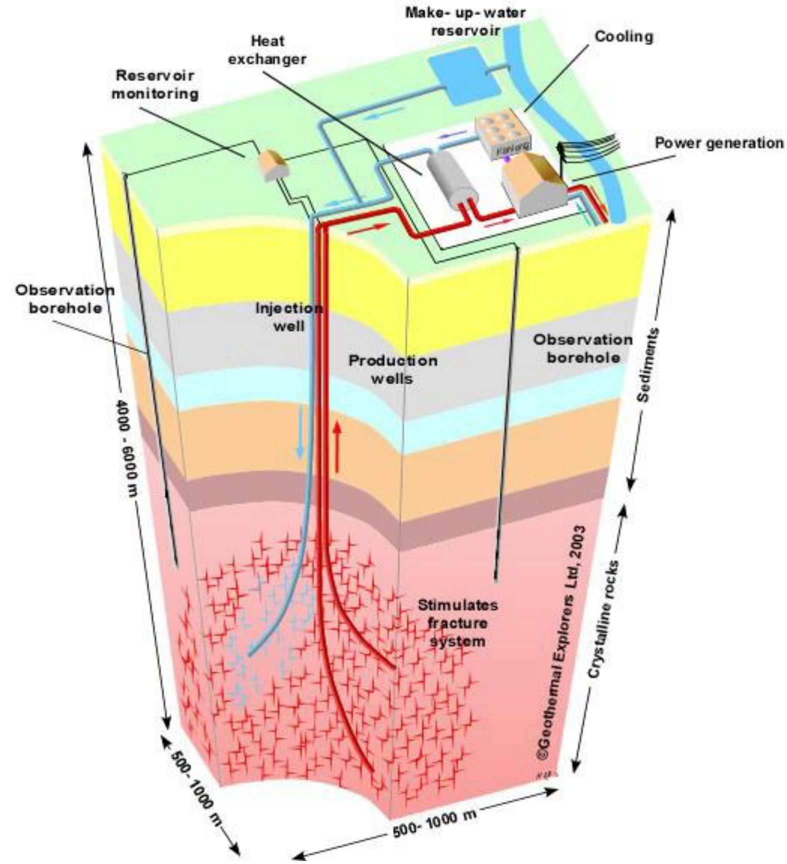
Understanding IS-permeability linkage is key:

- 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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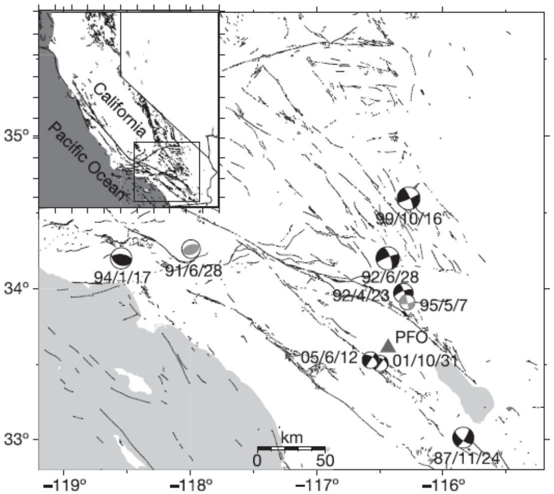
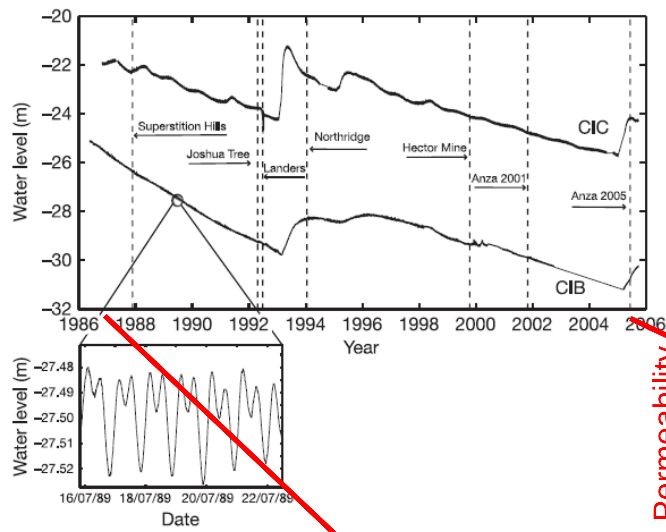
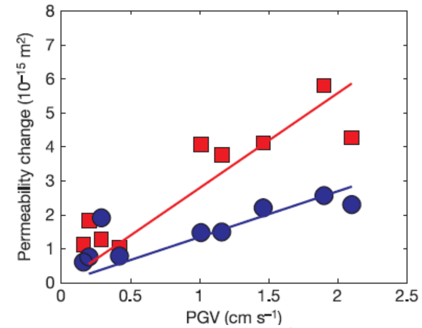
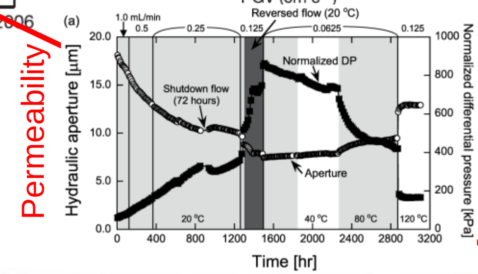
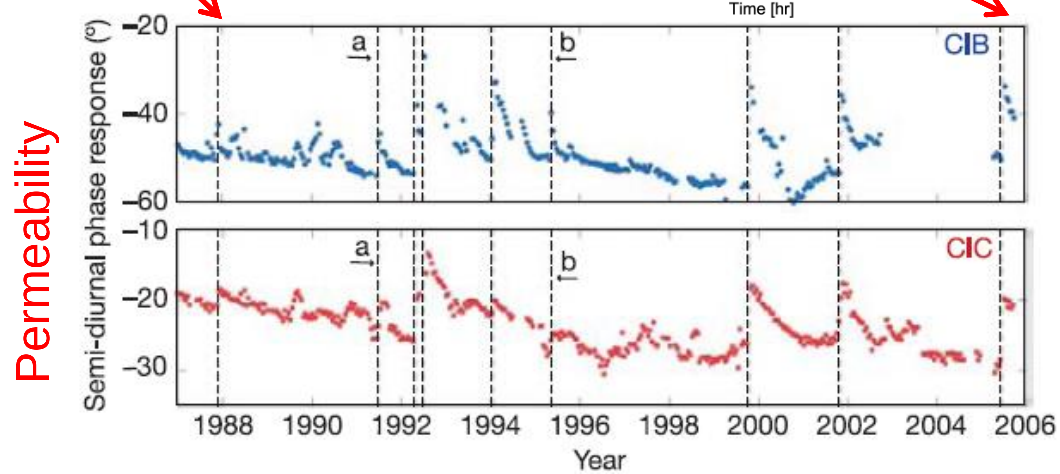








- <u>Remote</u> earthquakes trigger dynamic changes in permeability
- Unusual record transits ~8y
- Sharp rise in permeability followed by slow "healing" to background
- Scales of observations:
  - Field scale
  - Laboratory scale
- <u>Mechanistic understanding and control</u>?



[Elkhoury et al., Nature, 2006]

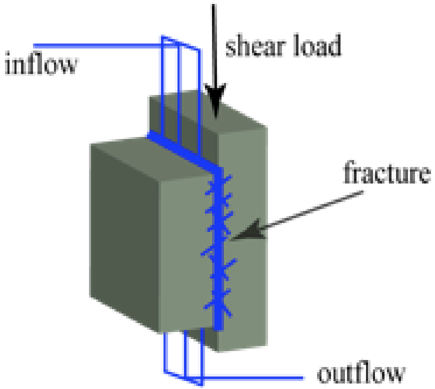
Scientific/Technical Approach

Addressing four broad areas:

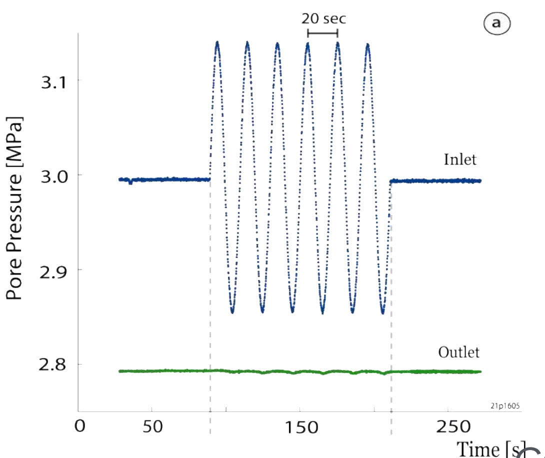
1. Fracture formation and the relationship between fluid flow and shear failure,
2. Assessment of fracture geometry and fluid permeability using novel acoustic measurements,
3. An improved understanding of how drilling, injection and geothermal production influence local seismicity, and
4. Development of process based models for using induced seismicity to assess the critical stress-state in Earth’s crust.

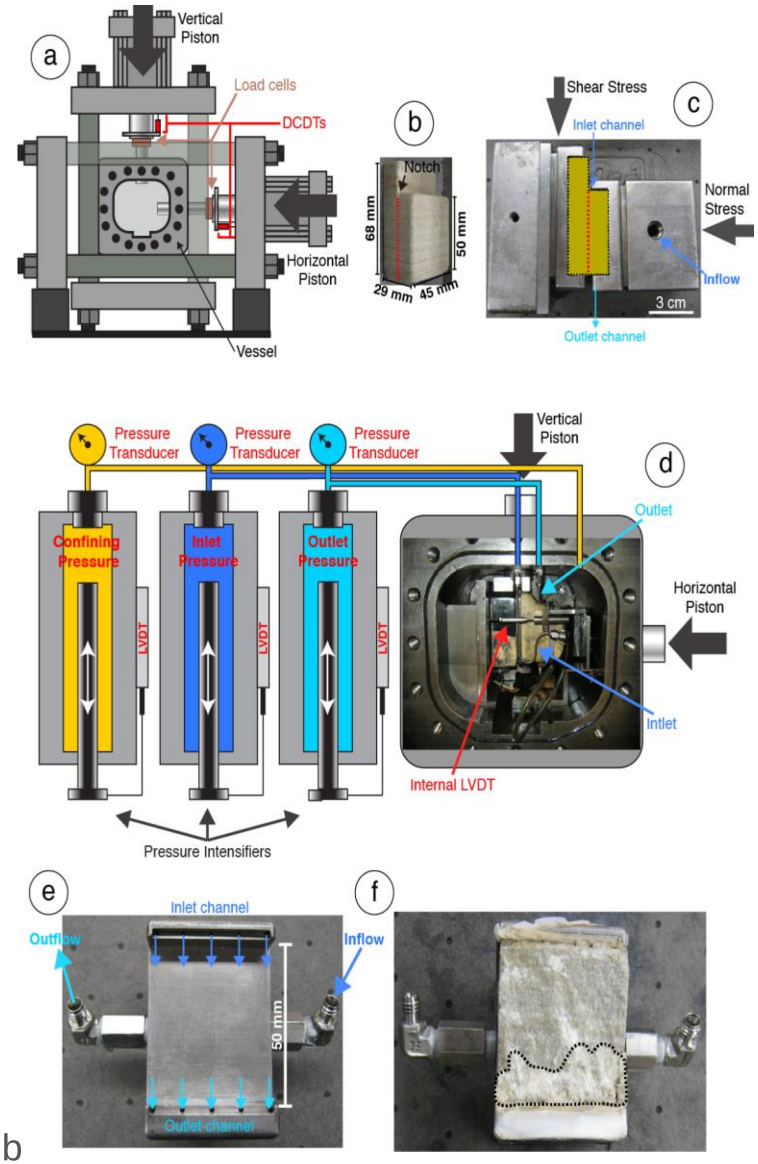
Fracture formation and the relationship between fluid flow, shear failure, and dynamic stressing

Fracture Formation and Permeability Measurement



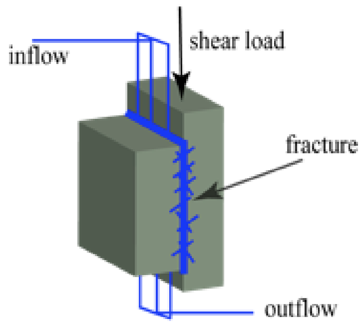
Dynamic Stressing

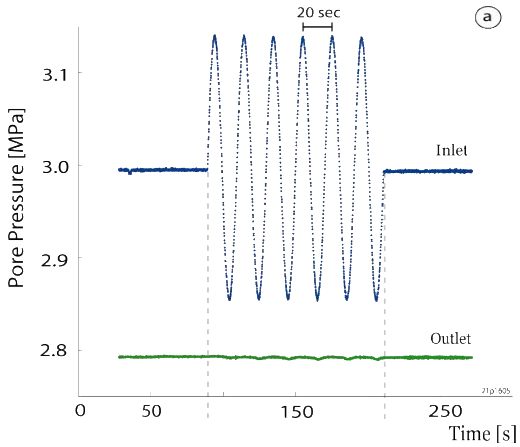


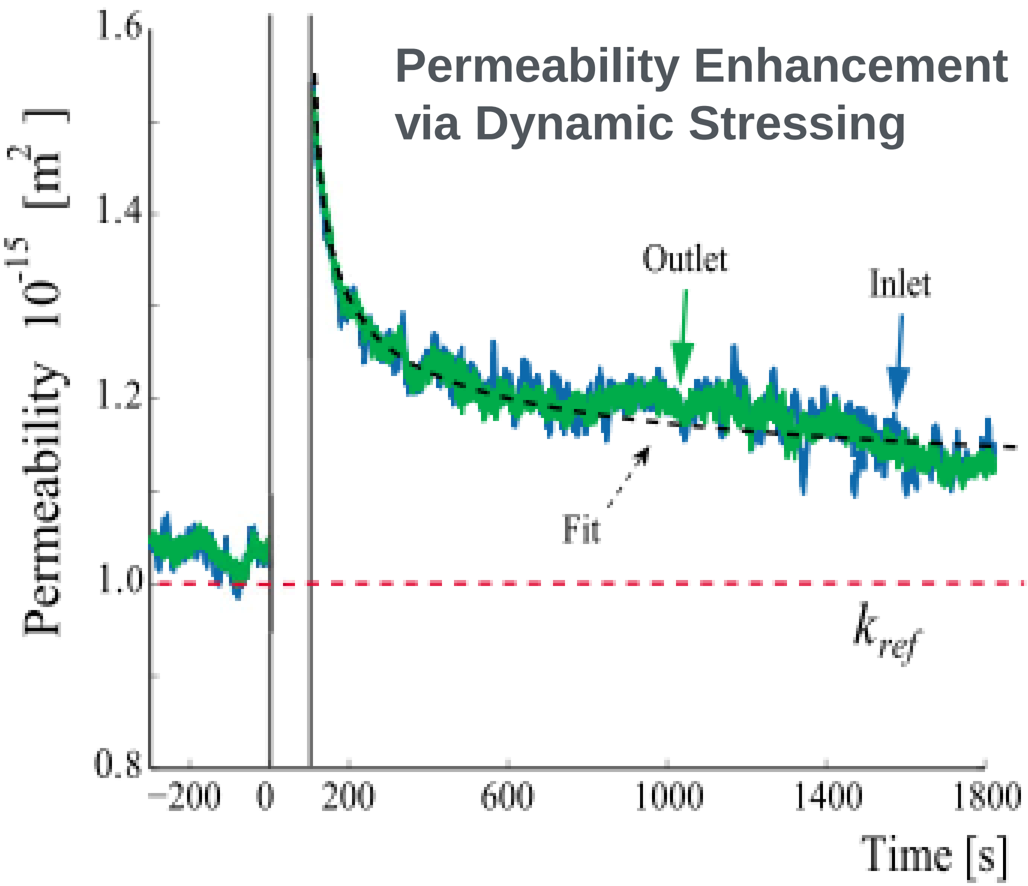


Candela et al., 2014a,b

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



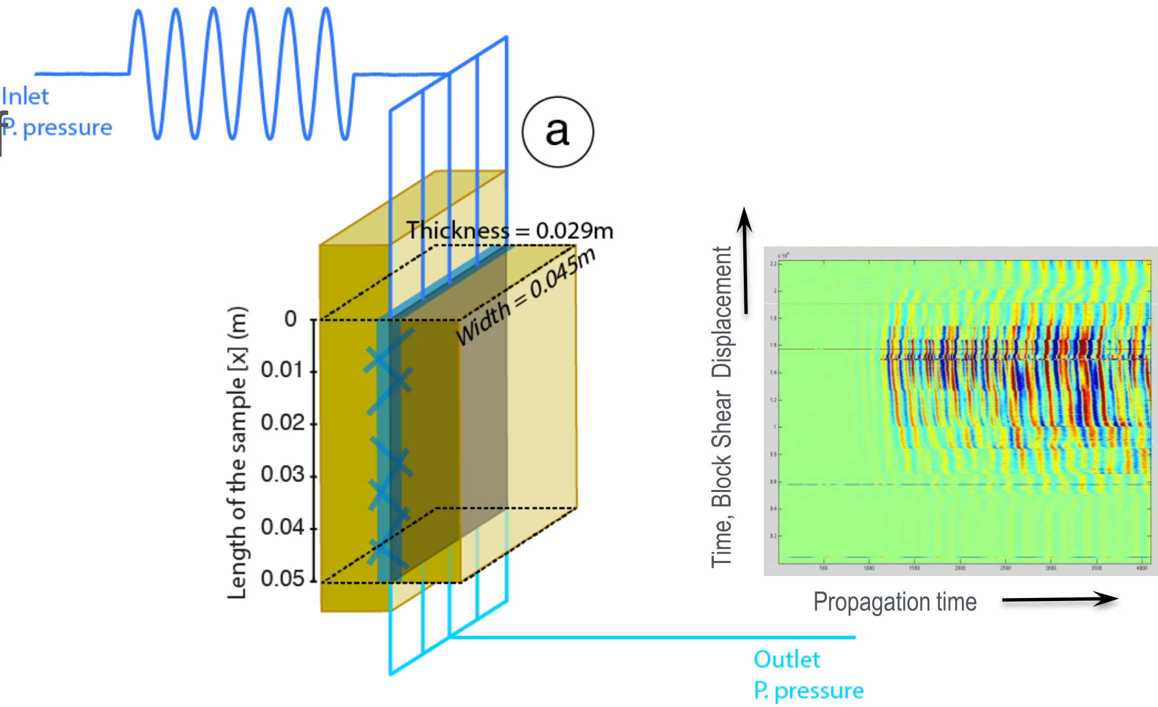


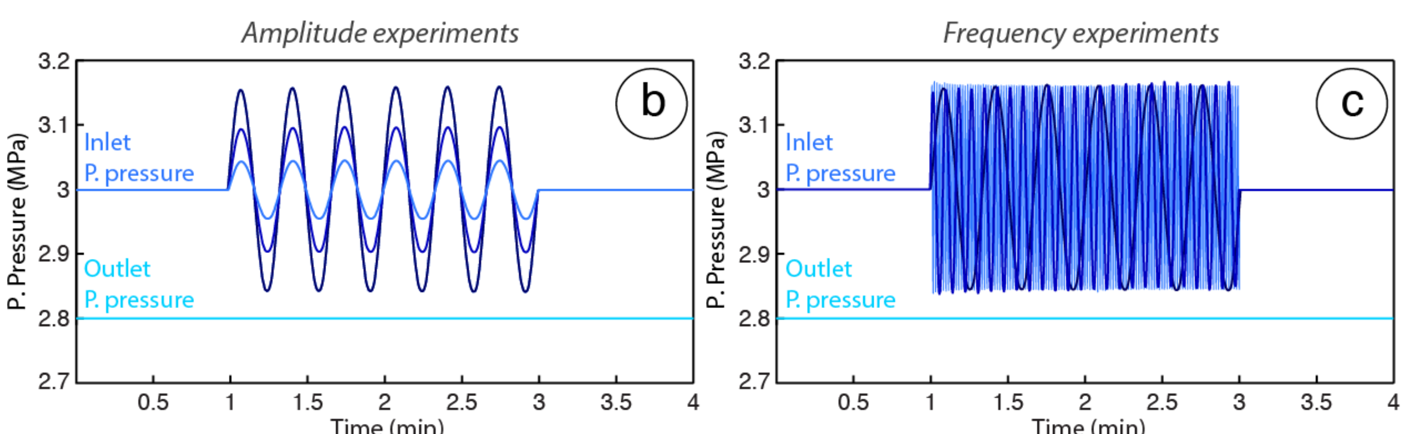


Candela et al., 2014a,b

Dynamic stressing

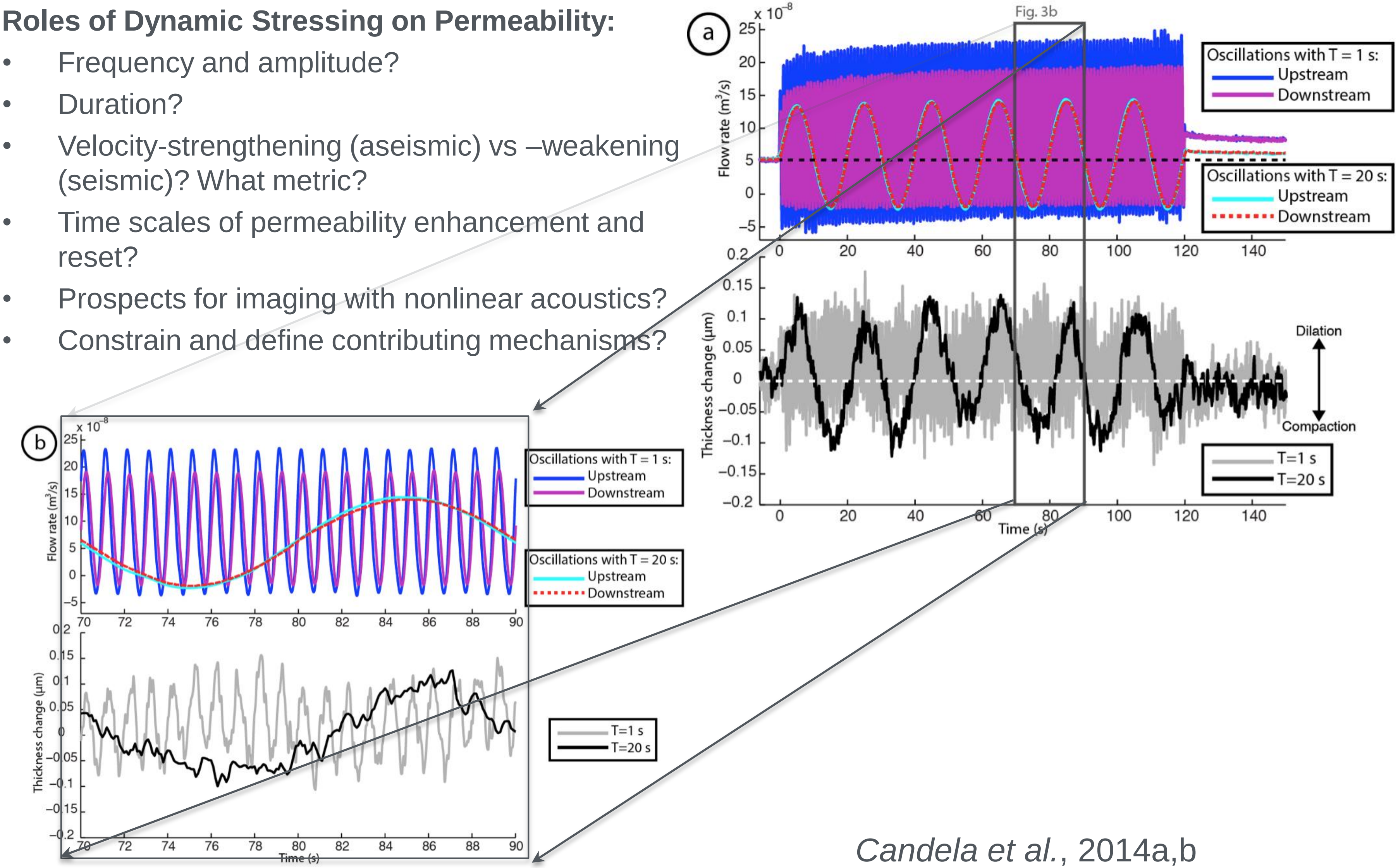
Assess the effects of stressing amplitude and frequency on permeability enhancement





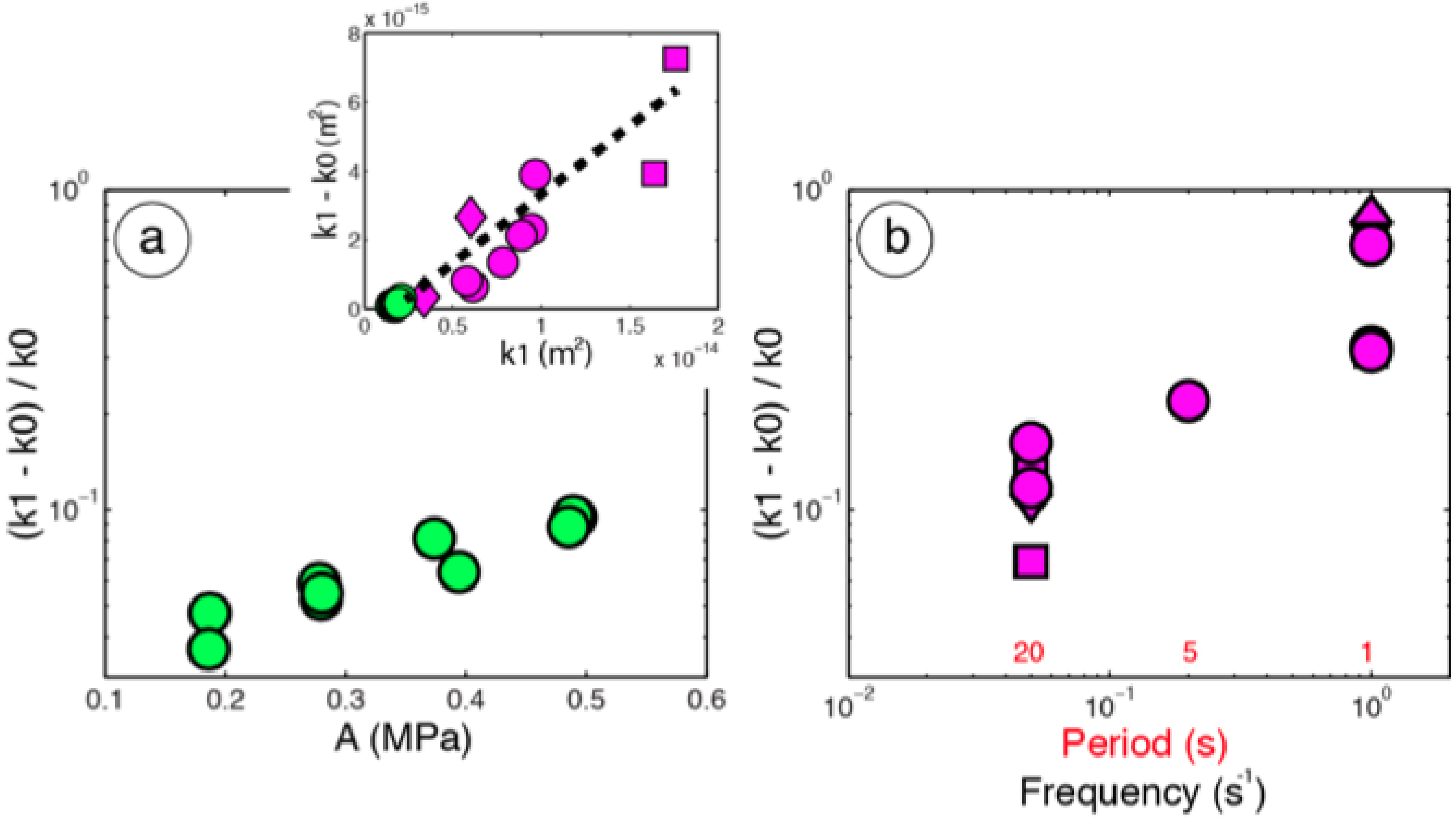
Roles of Dynamic Stressing on Permeability:

- Frequency and amplitude?
- Duration?
- Velocity-strengthening (aseismic) vs –weakening (seismic)? What metric?
- Time scales of permeability enhancement and reset?
- Prospects for imaging with nonlinear acoustics?
- Constrain and define contributing mechanisms?



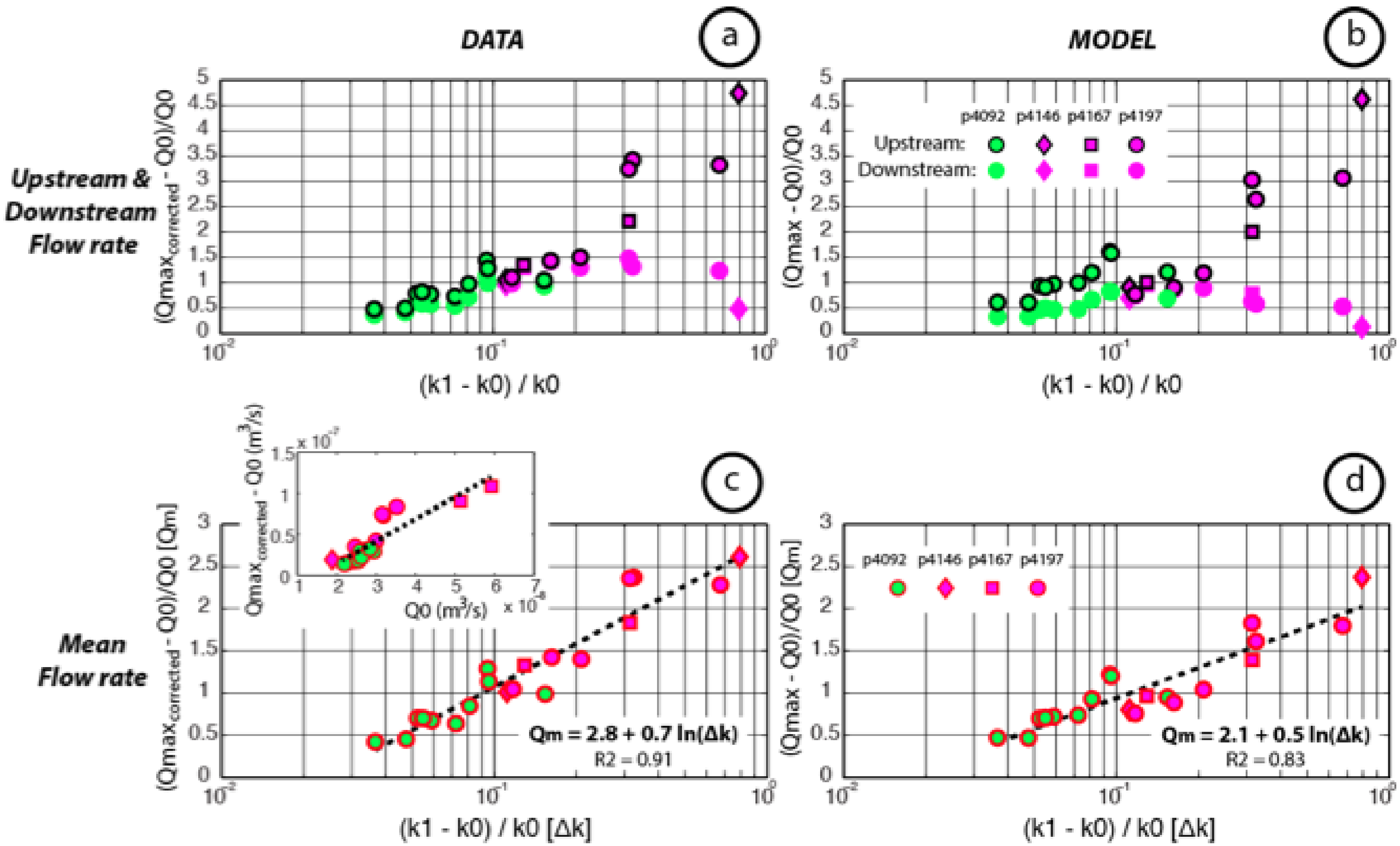
Candela et al., 2014a,b

Assessment of stressing amplitude and frequency



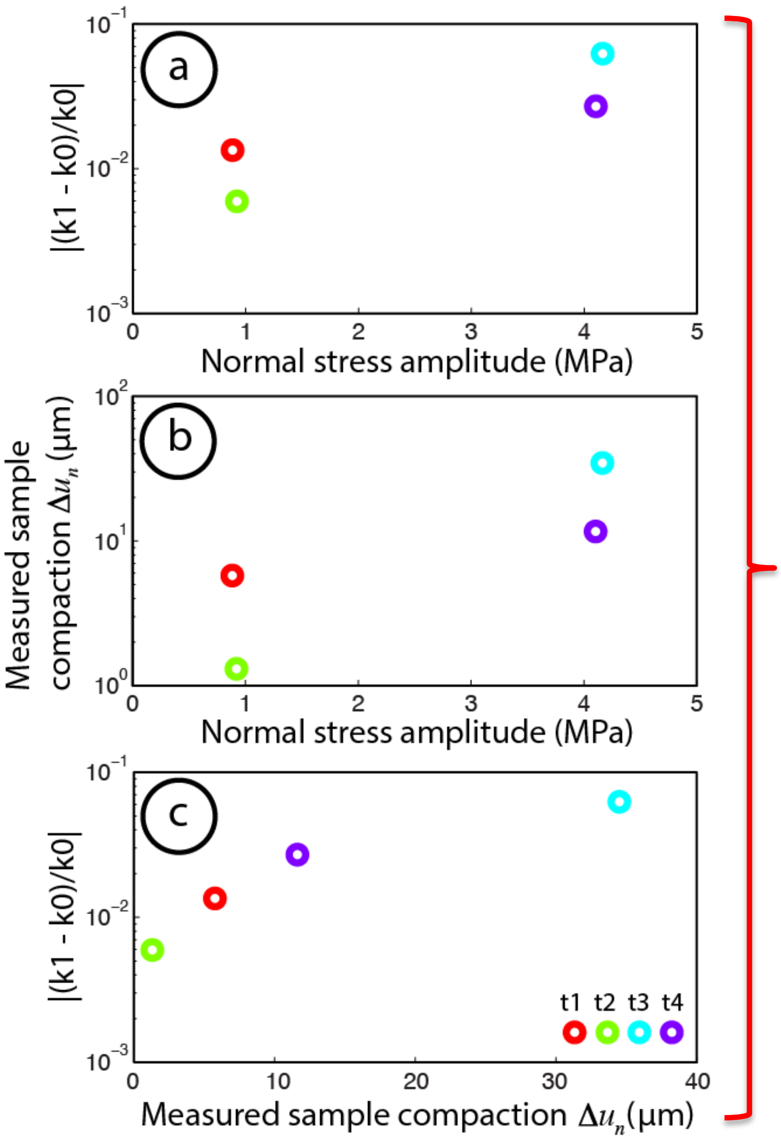
Candela et al., 2014a,b

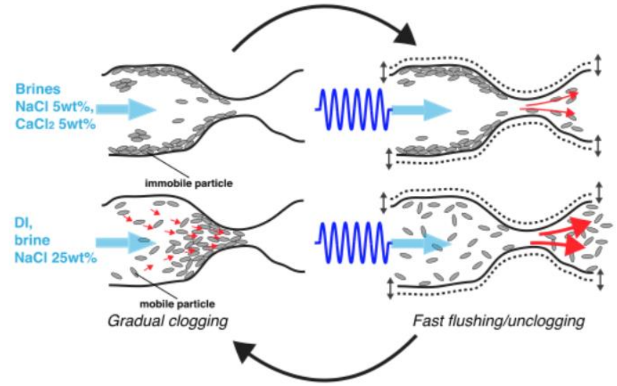
Permeability Changes Induced by Dynamic Stressing are Dictated by Flow Rate

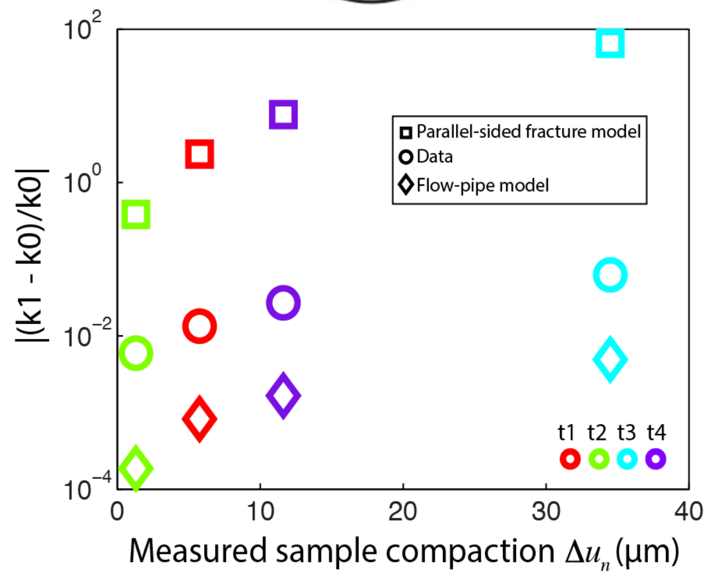


Candela et al., 2014a,b

Permeability changes induced by dynamic stressing are not dictated by compaction but are dictated by flow rate



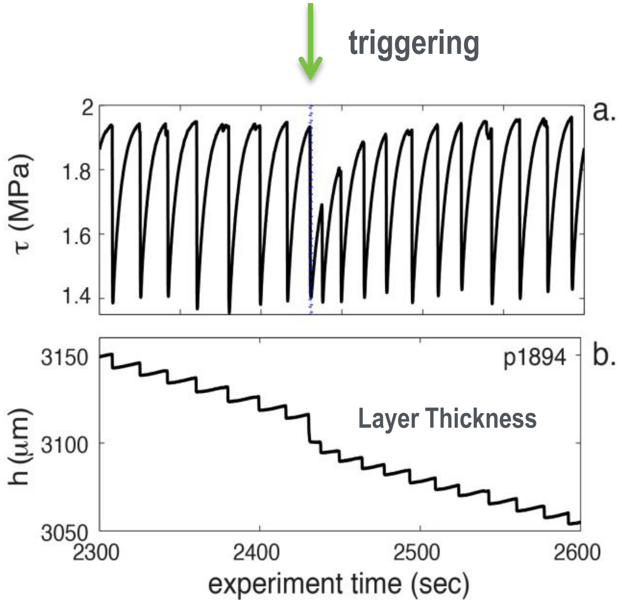




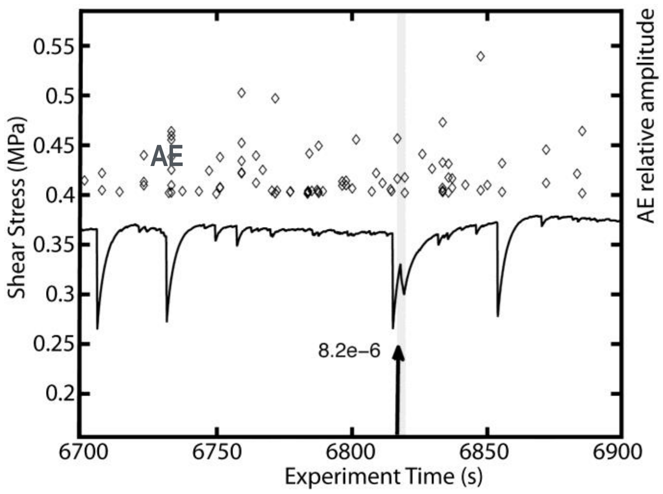
Candela et al., 2014a,b

Using Triggered Earthquakes as a Probe of the State of Stress in EGS Reservoirs

Dynamic triggering only occurs when the system is critically stressed.



Triggered stick slip in dry gouge at 4 MPa applied load



Triggered slow slip in dry gouge at 0.37 MPa applied load

Johnson et al., 2015

Accomplishments, Results and Progress

- We are analyzing laboratory data, developing laboratory techniques and capabilities, and training project personnel.
- Our analysis of recent results shows that fluid flow rate dictates permeability enhancement during fluid pressure oscillations [*Candela et al.*, 2014a,b] where clogging particulates are remobilized, which has important implications for 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 during fault slip and recover with log time during interseismic restrengthening [*Kaproth and Marone*, 2014].
- 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.

Accomplishments, Results and Progress

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Schedule of Tasks and Milestones

*Milestones M1 at end of Quarter Q1, etc

	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 0 Cost and resource allocation for GDR/NGDS	x											
Task 1 -Permeability Evolution and Fracture Flow Management via Dynamic Stressing												
1.1 *Examine dynamic stressing on permeability evolution*												
1.1.1 Role of fluid pressures and effective stresses	M1											
1.1.2 Amplitude and frequency dependence of permeability evolution			M3	G/NG								
1.1.3 Scaling rates of permeability recovery					M5							
1.2 *Develop permeability-seismicity relations*												
1.2.1 Represent freqeuncy dependent modes of particle transport								M8				
1.2.2 Ionic and geochemical effects												
1.2.3 Chemical healing effects and permeability resetting											M11	
1.3 *Upscaled models for permeability seismicity coupling*												
1.3.1 Micro-modeling of laboratory experiments						M6						
1.3.2 DEM models for permeability evolution and upscaling												
1.4 *Linkage with field observations*									*M9*			
Task 2 -Acoustic Fracture Characterization and Frictional Stability												
2.1 *Development of acoustic microscope for fracture instability studies*		*M2*										
2.2 *Dynamic triggering under static stress conditions*				*M4*								
Task 3 - Dynamic Triggering												
3.1 *Dynamic triggering under direect shearing conditions*												
3.2 *Develop frictional constitutive models for triggered slip*							*M7*	*G/NG*				
3.3 *Develop process-based models for observed response*										*M10*		
3.4 *Develop predictive models for observed behavior and test with experimentation*												
Reports				Y1				Y2				Y3

Future Directions

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- How can we 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.
- 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 during fault slip and recover with log time during interseismic restrengthening [*Kaproth and Marone*, 2014].
- A post-doc has recently joined the project and is focused on the use of acoustic measurement to image fracture development and permeability evolution.

Milestone or Go/No-Go	Status & Expected Completion Date
Laboratory observations of fracture, permeability evolution during well stimulation, and monitoring of acoustic signals	On track for completion during Budget period 1

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 have transformative potential for management of fracture permeability, heat transfer, and induced seismicity.
- An overarching goal is to develop methods for using the seismic behavior of geologic faults, and their susceptibility to hydraulically-induced shear failure, to forecast drilling and flow-induced seismicity, with the opportunity to take mitigating steps in critical cases.

Additional Information

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- **Publications and Presentations, Intellectual Property (IP), Licenses, etc.**
-

- Candela, T., Brodsky, E. E., Marone C., and D. Elsworth, Flow rate dictates permeability enhancement during fluid pressure oscillations in laboratory experiments, *in Press, J. Geophys. Res. Solid Earth*, 2014b.
- Candela, T., Brodsky, E. E., Marone C., and D. Elsworth, Laboratory evidence for particle mobilization as a mechanism for permeability enhancement via dynamic stressing, *Earth and Plan. Sci. Lett.,* **392**, 279-291, 10.1016/j.epsl.2014.02.025, 2014a.
- Elsworth, D., Gan, Q., Marone, C., Connolly, P., Alpern, J., Lu, Y., Culp, B., Im, K.J., Wang, J., Zhu, W., Liu, J., Guglielmi, Y. 2014. Controls on gas-fracturing in unconventional reservoirs. China University of Petroleum. Beijing. November 23, 2014. [Invited]
- Elsworth, D., Marone, C., Guglielmi, Y. 2014. Mechanical and transport properties of rocks, reservoirs and faults – evolution of fault rheology, stability and permeability. Total, Pau, France. October 14, 2014. [Invited]
- Fang, Y., den Hartog, S.A.M., Elsworth, D., Marone, C., Cladouhos, T. (2015) Anomalous distribution of microearthquakes in the Newberry geothermal reservoir: mechanisms and implications. Submitted for publication. Geothermics. 40 pp.
- Ferdowsi, B., Griffa, M., Guyer, R. A., Johnson, P. A., Marone, C., and J. Carmeliet, Three-dimensional discrete element modeling of triggered slip in sheared granular media, *Physical Review* E, 002200, 2014.
- Kaproth, B. M., and C. Marone, Evolution of elastic wave speed during shear-induced damage and healing within laboratory fault zones, *J. Geophys. Res. Solid Earth*, 119, 10.1002/2014JB011051, 2014.