Evaluating the State of Stress Beyond the Borehole

Project Number FWP-FE-617-15-FY15

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Mastering the Subsurface Through Technology, Innovation and Collaboration:
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Presentation Outline

- Project Overview
- Stress and Reservoir Management
- Project History
- Stress Calculations
- Critical Stress Behavior

Benefit to the Program

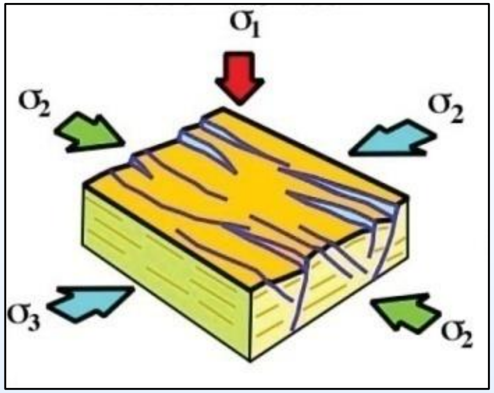
- Monitor and ensure containment of CO_2 reservoir.
- Minimize induced seismicity.
- Understand and monitor interaction between injection operations.

This research project is developing techniques to calculate the stress tensor and changes to the stress tensor at the reservoir scale combining tectonic and local contributions to ensure containment and monitor interactions between injection operations. Additionally, we are developing a technique to identify triggered earthquakes and quantify critical state behavior to minimize induced seismicity for the purposes of reducing hazard and risk of containment failure.

Project Overview: Goals and Objectives

- Algorithm to obtain regional stresses used in calculating the stress tensor.
- Algorithm for obtaining the differential stress
- Metrics for gravity and seismic station emplacement to optimize resolution of the stress inversion
- Metrics for determining if a fault is critically stressed
- A fluid flow code appropriate to determine permeability applying the differential stress

The state of stress in rock results from a summation of forces that vary in space and time.



Glossary of Terms

Gravitational (F_G)—vertical forces due to overburden

Tectonic ($F_{Tectonic}$)—lateral forces due to far-field geologic processes

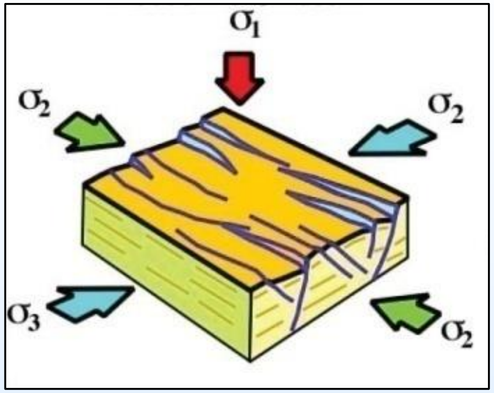
Pore Pressure (F_{pore})—internal forces due to fluid-filled pore spaces; exerts pressure on rock matrix

Frictional—internal forces inhibiting slip within a rock body

Temporal, external—periodic forces arising from various external processes, such as remote earthquakes, lunar tides, trains, thumpers, etc.

Stress Tensor (σ_T)—Matrix describing spatial variation in the balance of forces

The state of stress in rock results from a summation of forces at a point that vary in space and time.



Our Approach to Stress Tensor (σ_T):

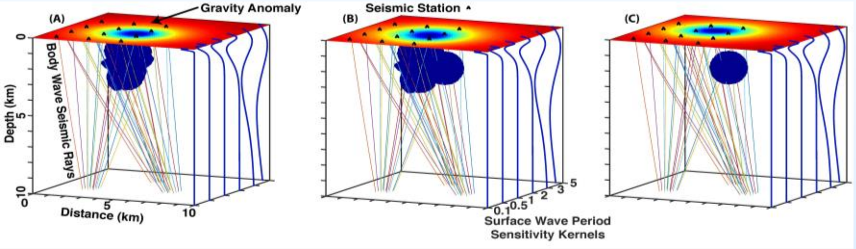
$$\sigma_T = \overbrace{F_G + F_{Tectonic}}^{\textit{primary drivers of stress}} + \overbrace{F_{pore} + F_{dynamic}}^{\textit{modulators of stress}}$$

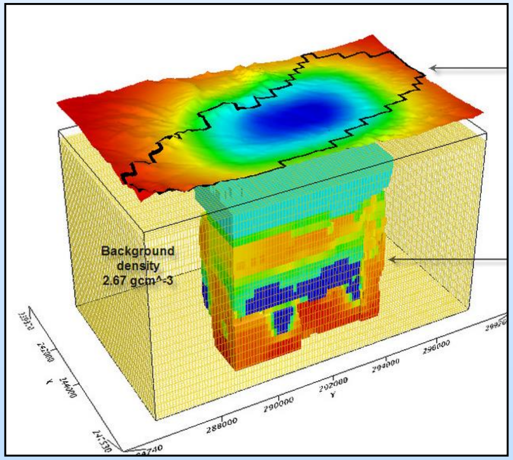
- derive stress tensor from a combination of gravitational (F_G) and background tectonic stresses ($F_{Tectonic}$)
- $F_G + F_{Tectonic}$ derived from joint inversion of seismic and gravity data to quantify/image volumetric elastic modulus and density
- $F_{Tectonic}$ derived from plate-scale finite-element modeling combined with updated field data for North America
- $F_{dynamic}$ used to probe critically stressed faults
- F_{pore} derived from simulation of injection/production to couple flow with stress

Project History

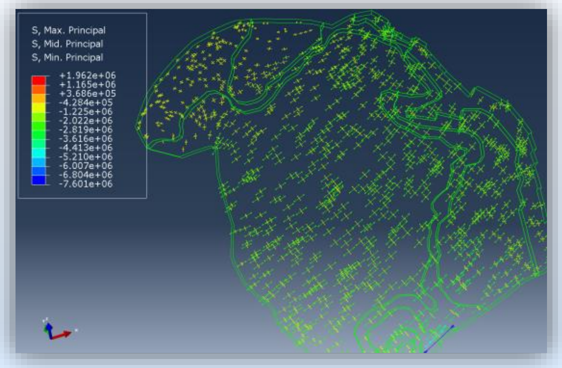
SubTER LANL Seedling (FY15, $250k)

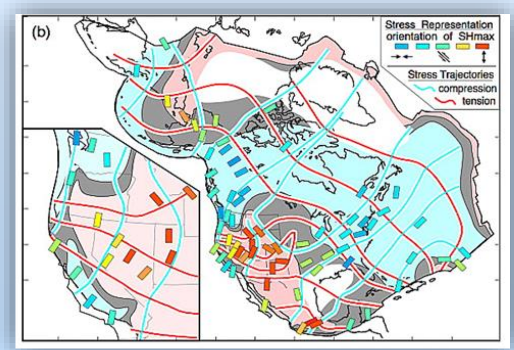
A. **Image volumetric elastic modulus and density based on joint-inversion of seismic & gravity data (initiate algorithm development)**





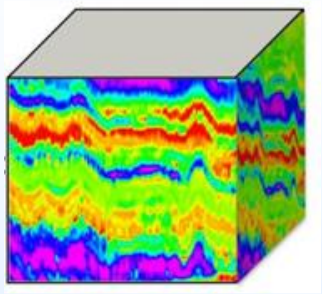
B. **Calculate background tectonic stress via fusion of new data and simulation (update North American stress map)**





SubTER Sapling (FY16, $900k)

A. Image volumetric elastic modulus and density



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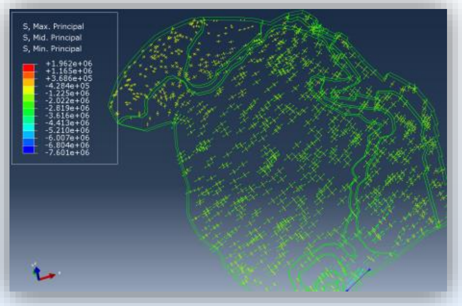
Sandia National Laboratories

Berkeley Lab

Lawrence Livermore National Laboratory

B. Calculate background tectonic stress



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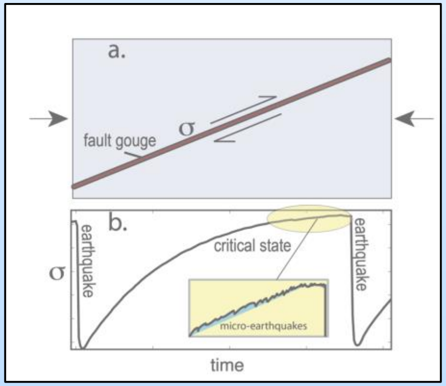
NETL National Energy Technology Laboratory

C. Identify critically stressed faults using low-magnitude, µ-seismic events



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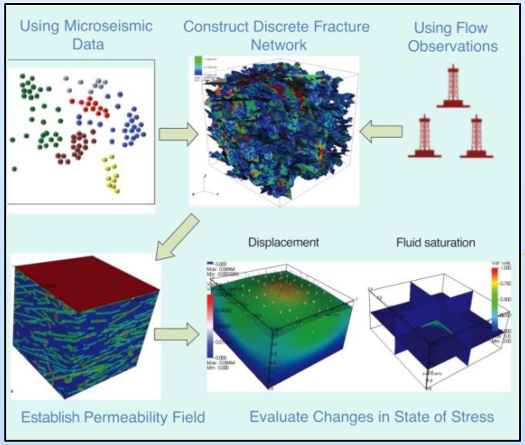
D. Develop linkage between stress & permeability on fracture networks



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Final products from effort will be a suite of computational tools for reservoir management.

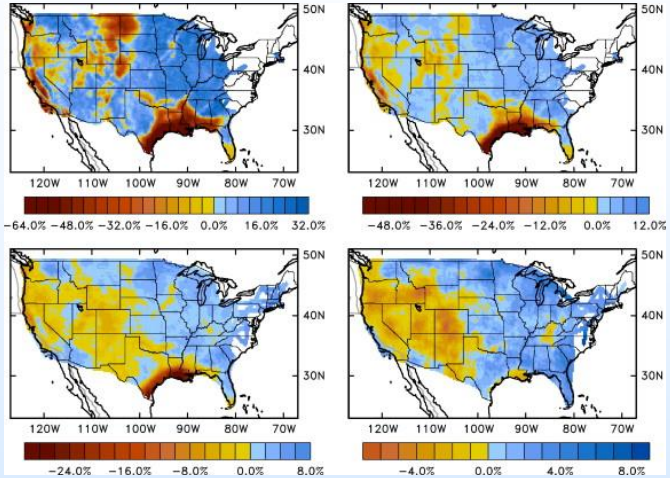
MONITORING ANALYSIS SYSTEM FOR STRESS AND CRITICAL FAULTS

input data	***modules***	***output***
• conventional seismic • gravity survey	Monitor stress and stress change	• dynamic images of reservoir stress
• real-time micro-seismic • real-time injection/production data (volumes and pressures) • tidal cycles	Monitor and determine if faults are near failure	• identification of critically stressed faults during initial site characterization • quantitative "stop-light"
• real-time micro-seismic data • real-time injection/production data (volumes and pressures) • reservoir model	Predict coupled flow and stress within reservoir	• micro-seismic data, • injection/production data • reservoir model

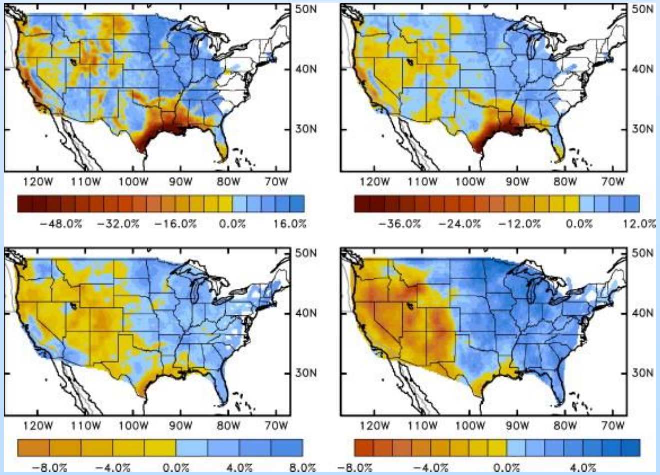
Stress Calculations

Advanced Multi-Physics Tomography

Love Waves

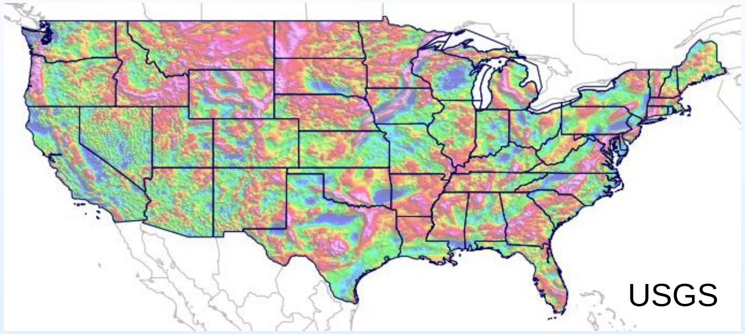


Rayleigh Waves



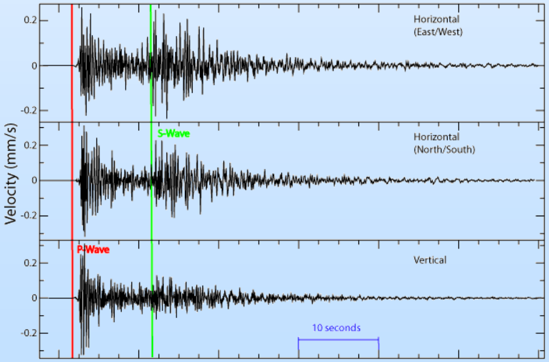
Ekstrom, 2013

Gravity

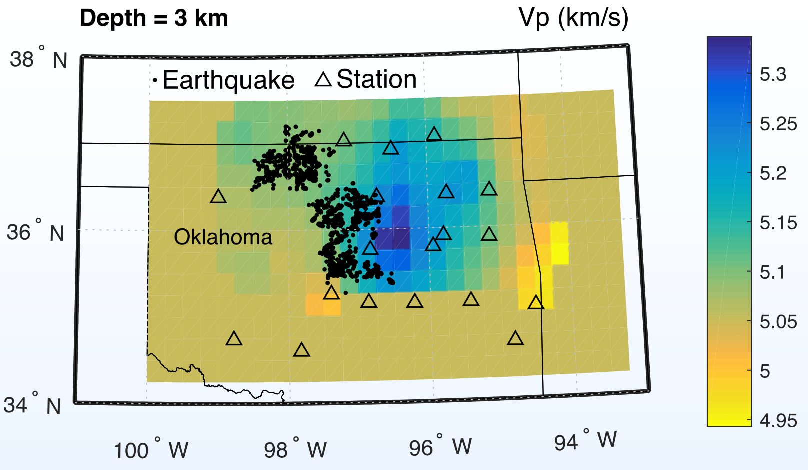


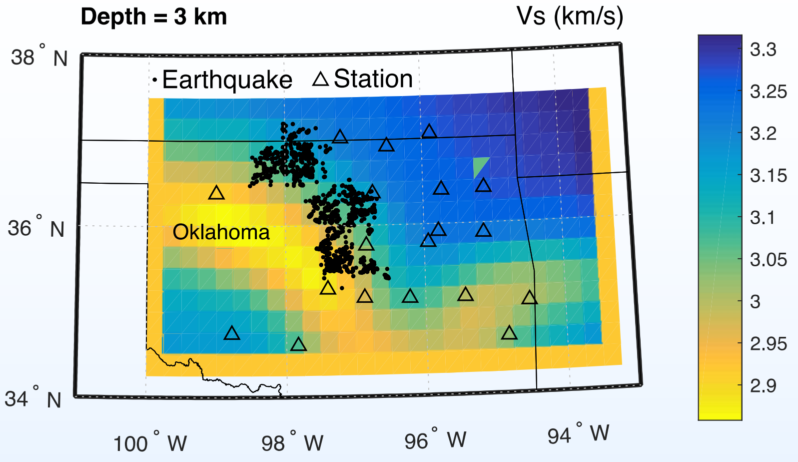
USGS

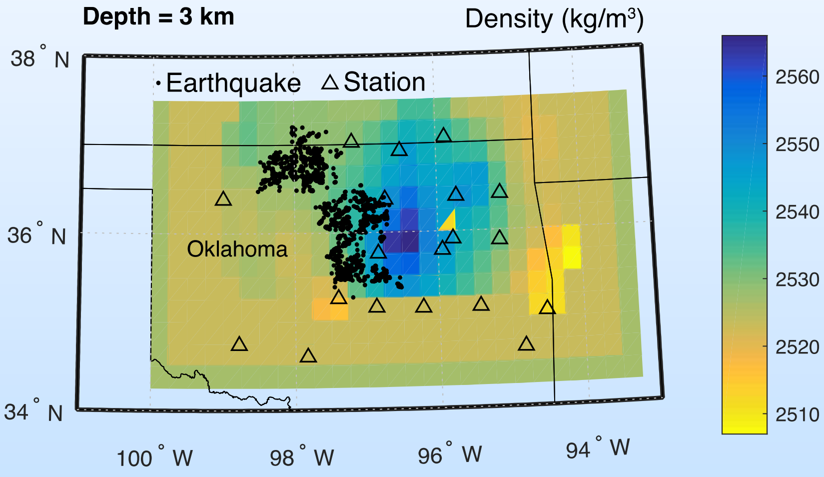
Body Waves

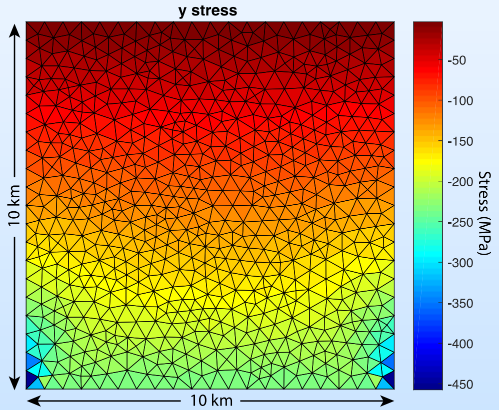


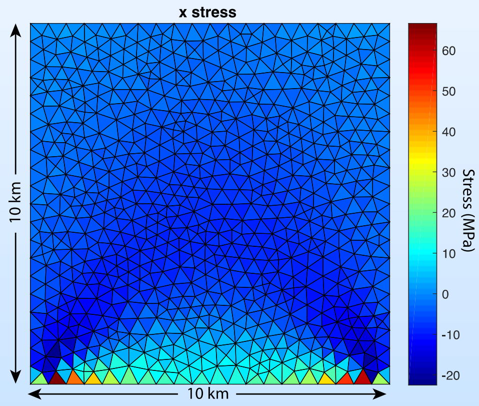
Oklahoma Results

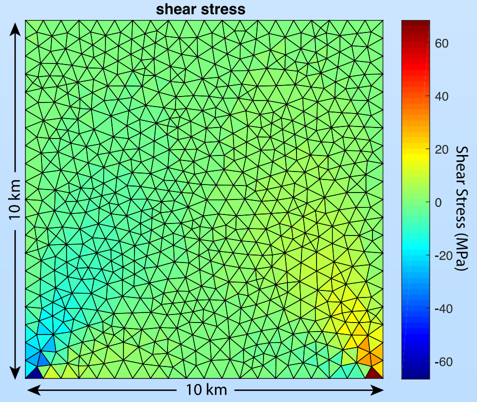




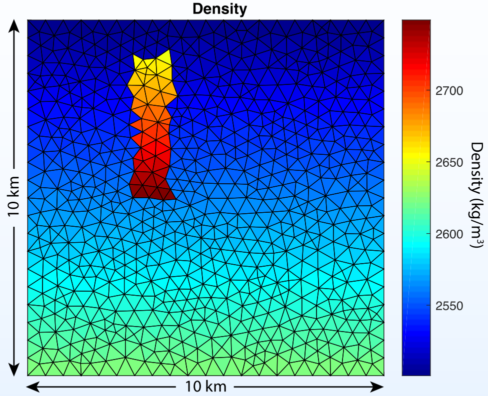


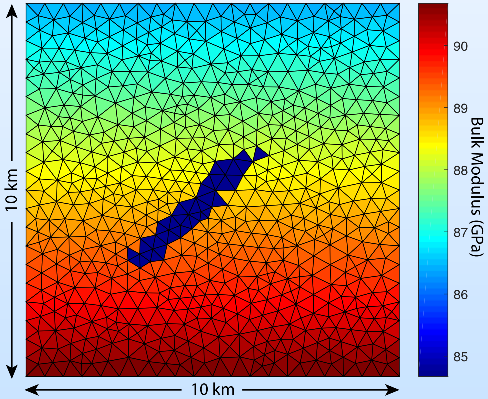


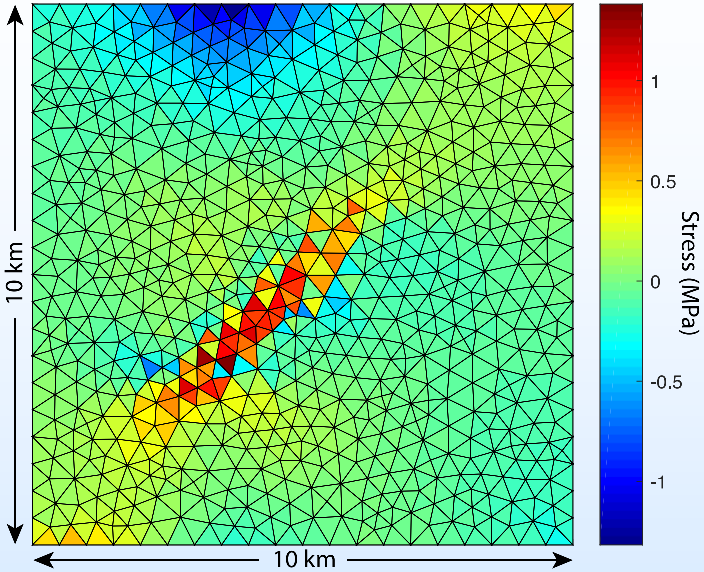


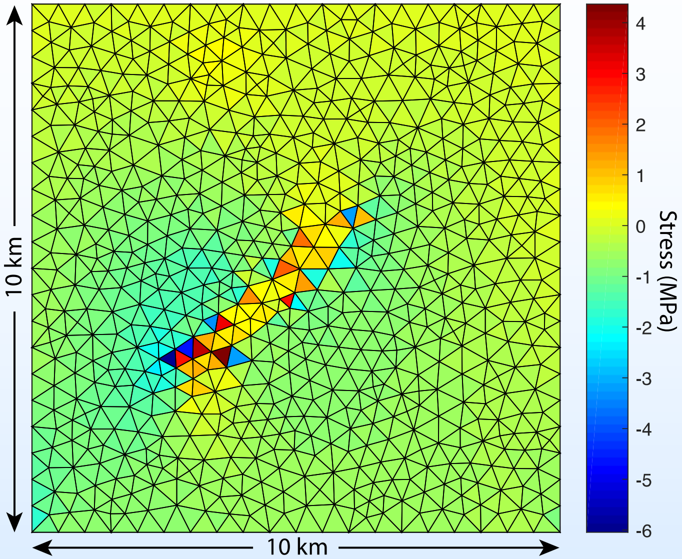


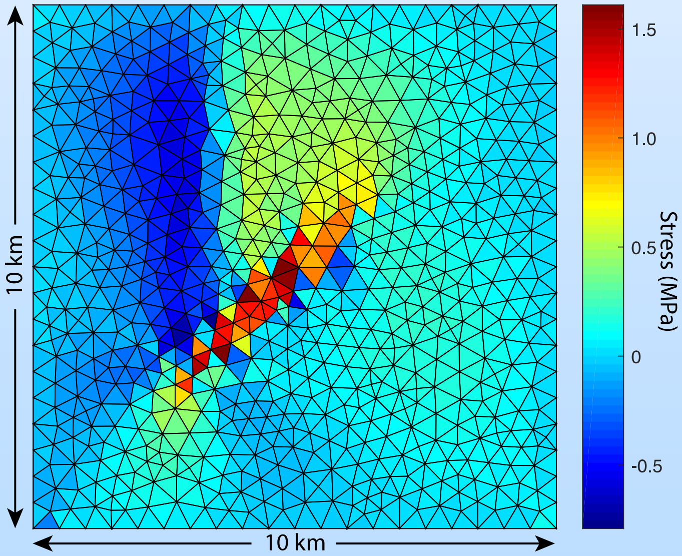
Differential Stress Field


Density


bulk modulus


x stress


y stress

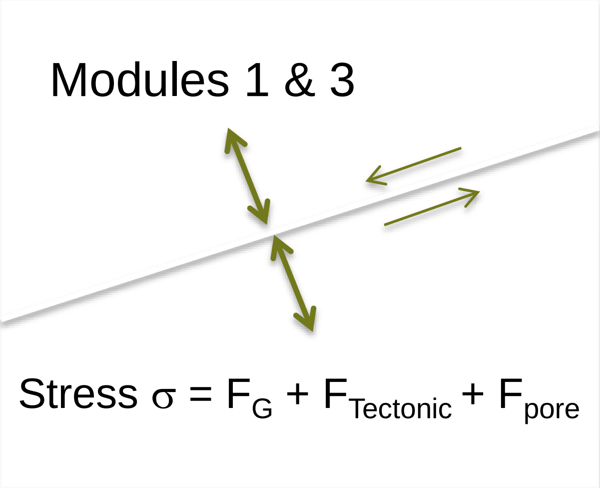

shear stress

Critical State Behavior

The Physics behind Critically Stressed Faults

Stress Field

$\sigma=\kappa\varepsilon$

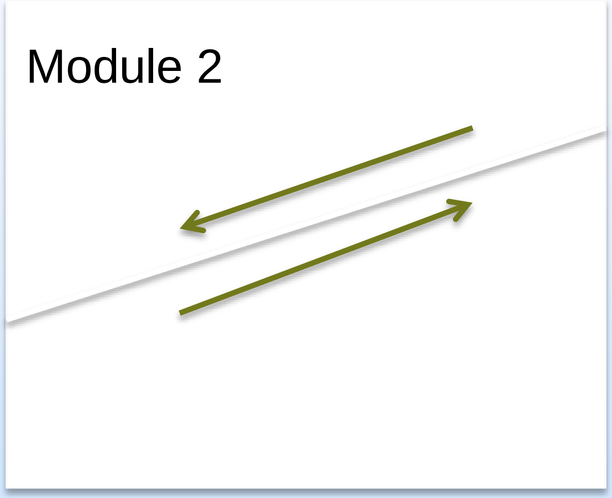


Modules 1 & 3

Stress $\sigma = F_G + F_{Tectonic} + F_{pore}$

- Which way will a hydraulic fracture propagate?
- Will a fracture open? Or close?
- How does the stress field evolve as fluids are injected?

Induced Seismicity



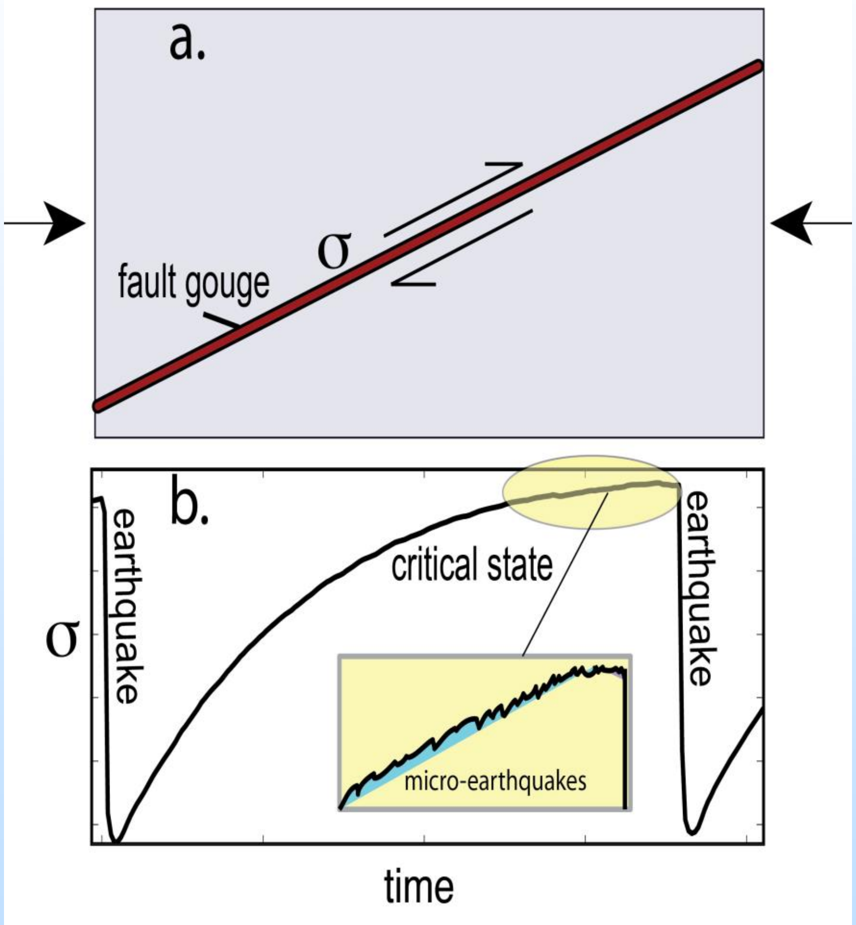
Module 2

- During fluid injection will a fault slip? When?

The Science behind Critically Stressed Faults

Our first hypothesis (based on our lab data):

All earthquakes are preceded by precursor events—small slips.



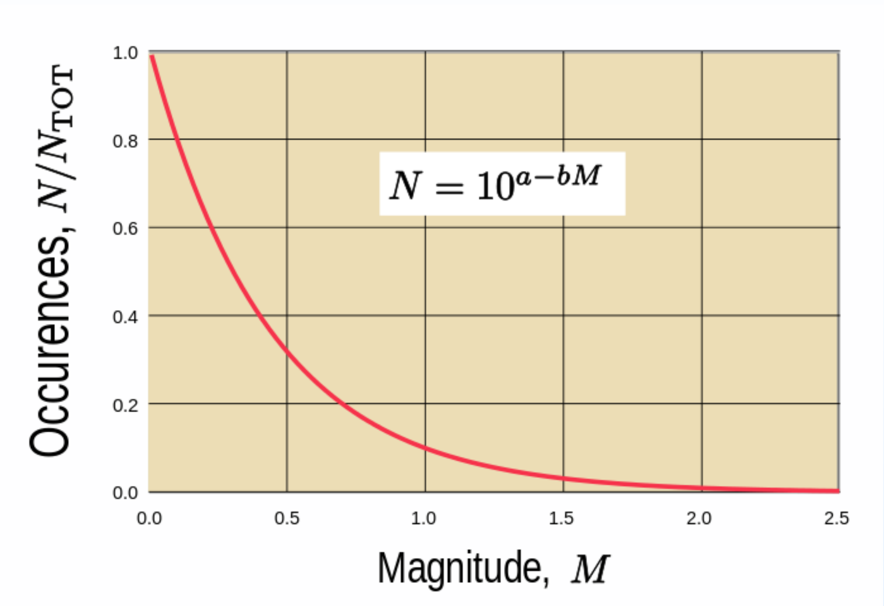
Some, but not all, field observations confirm this hypothesis.

Hence, our second hypothesis:

Many precursor events remain undetected due to their small size (M < –2).

We have also found that faults are only triggered by dynamic stresses when they are in the critical stressed

The Science behind Critically Stressed Faults



Small earthquakes can provide a more statistically robust path:

- for testing our hypotheses
- for a practical field monitoring approach

But, small earthquakes pose a challenge:

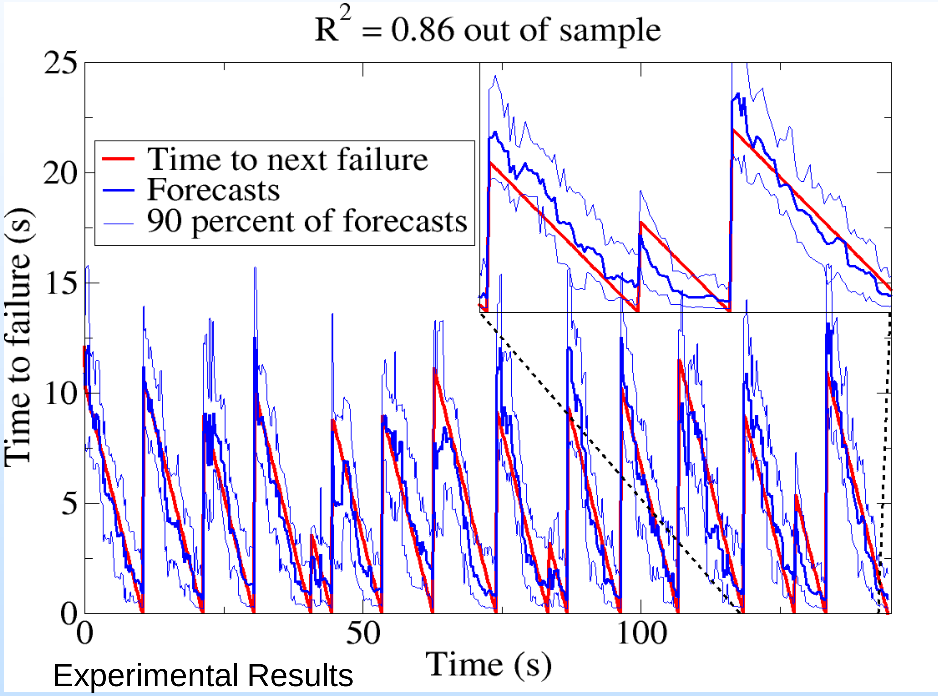
Rapid detection of small signals in a noisy background

The empirically observed Gutenberg-Richter (GR) law is a logarithmic relationship between number of earthquakes (N) and magnitude (M) for a system in a given state.

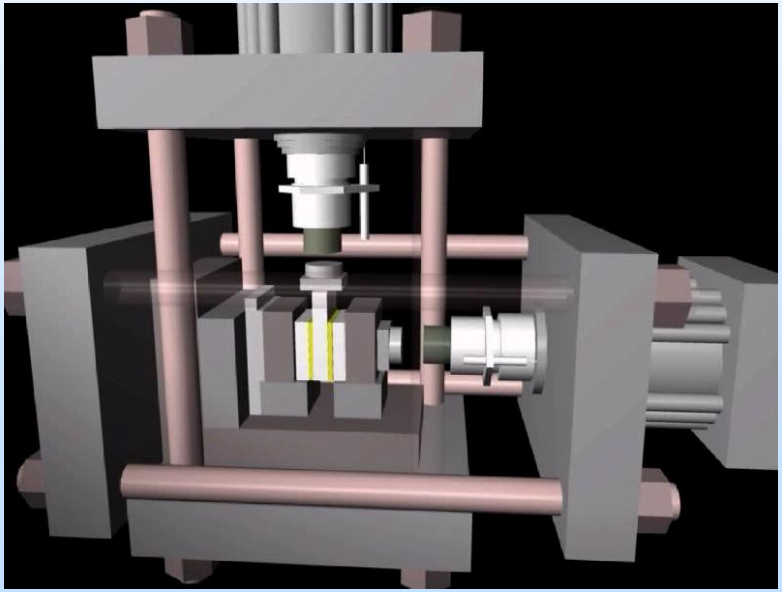
There is a 10x increase in earthquakes for each lower magnitude point.

New LDRD Results: Machine learning can offer path to rapid (real-time) detection of small μ-seismic signals.

- First time ML applied to lab or field successfully.
- Proxy for complicated system; extracting interesting physics.
- Material ‘knows’ when it will fail.
- If true in this system why not in Earth.



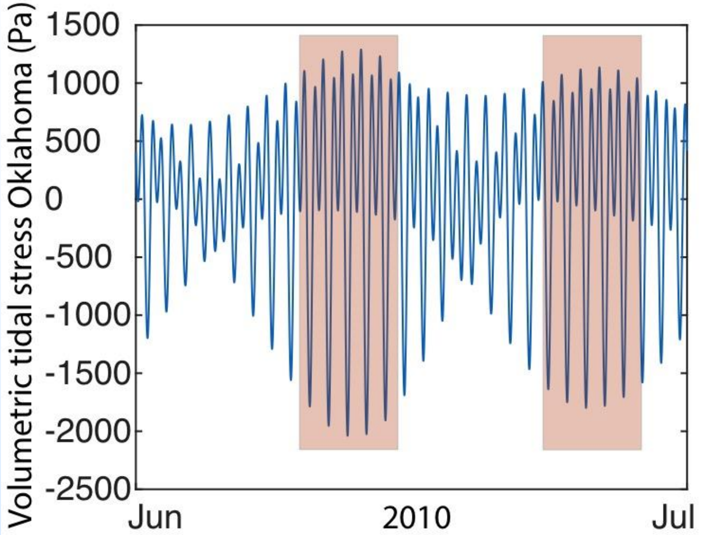
Experimental Results



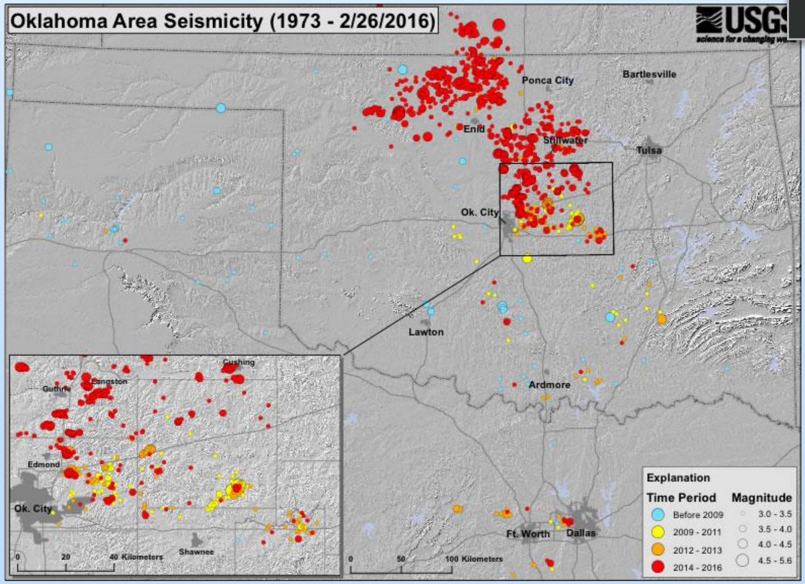
The blue solid line shows the regression model from each window and the shaded region shows the 5 and 95 percentile—90 percent of the trees that compose the forest gave a forecast within these bounds.

Critical State Behavior in Oklahoma

17 Months prior to 11/05/2011 M5.6 Prague Earthquake



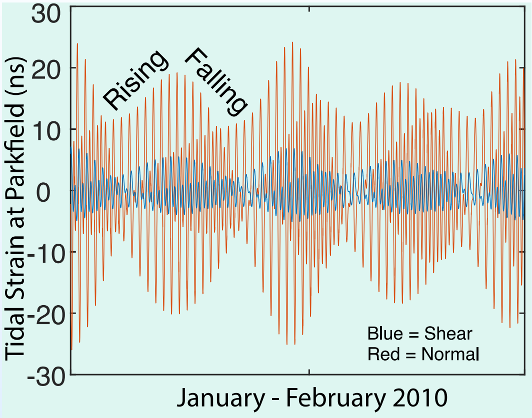
Observed / Expected During Positive Volumetric Stress	All	Middle Third
2010/06/01-2010/12/31	787 / 793	257 / 246
2011/01/01-2011/11/02	1673 / 1605 1%	549 / 500 < 1%
2010/06/01-2011/11/02	2460 / 2398 6%	806 / 748 < 1%

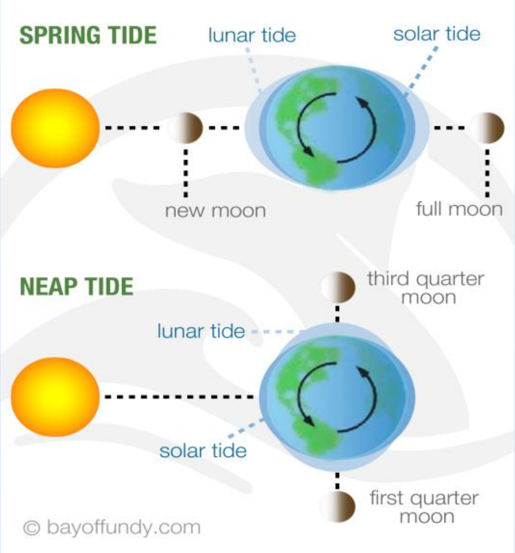


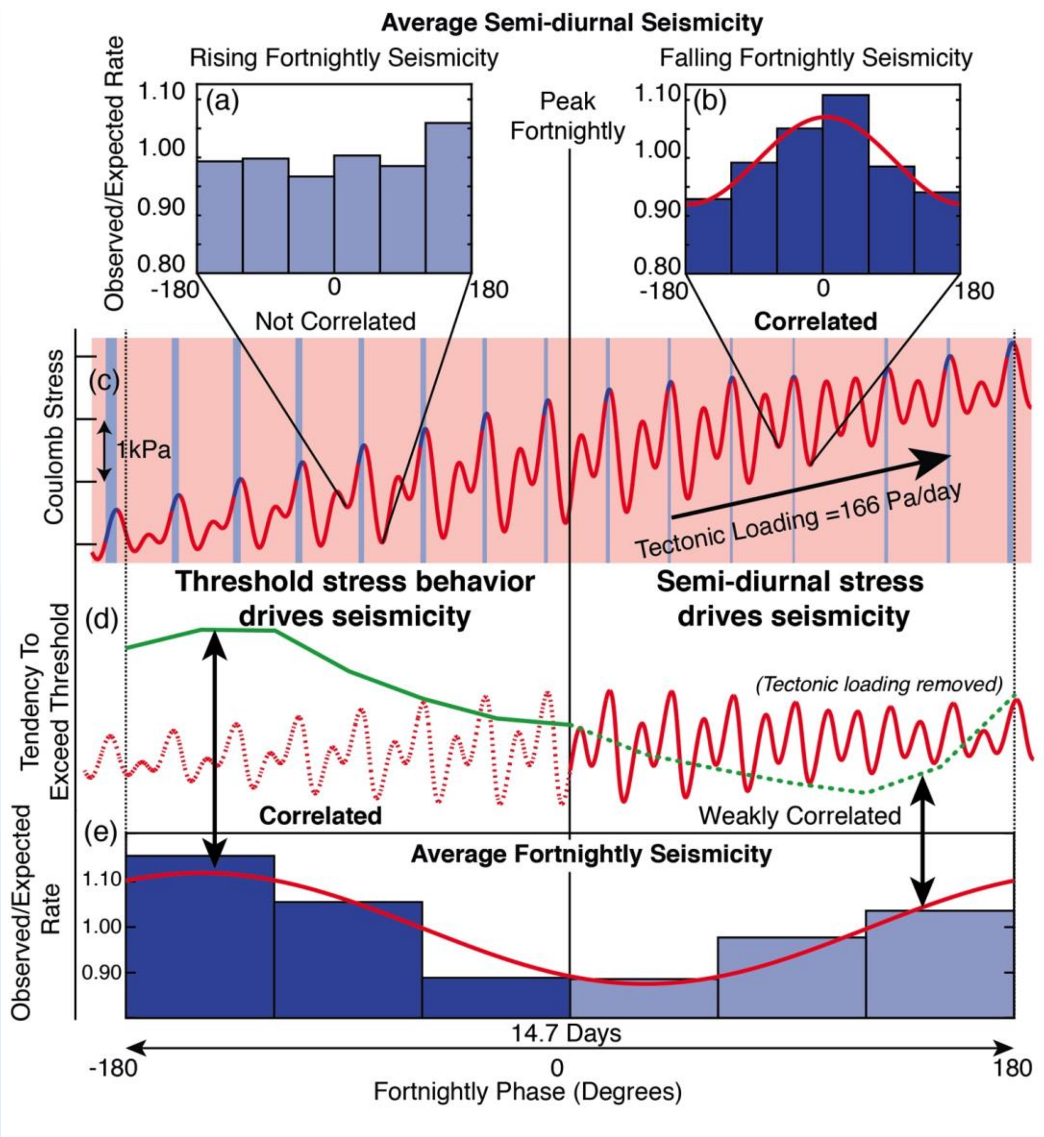
(Percentage values are how often the distribution would occur randomly.)

Critical state behavior increases as Prague earthquake is approached.

Triggered Seismicity, California







Accomplishments to Date

- Continental scale stress calculations
- Algorithm development for joint inversion
- Stress calculation algorithms
- Joint Inversion applied to Oklahoma
- Triggered seismicity identified in Oklahoma and Parkfield

Synergy Opportunities

Stress, the change in stress, and the identification of critical state behavior are central to subsurface engineering. Permeability, hazard, fluid flow, and containment all depend upon stress conditions.

Our project is primarily observational and therefore has synergy with both modeling and other observational projects within the SubTER and “Mastering the Subsurface” family of projects.

Appendix

- These slides will not be discussed during the presentation, but are mandatory

Summary

- Key Findings
  - We can model stress at reservoir scale with regional and local observations.
  - We can measure and observe critical state behavior using Earth tides.
- Lessons Learned
  - Even with improved seismic networks more data is needed to sufficiently image a typical reservoir
  - Gravity time series data improves differential stress calculations. More is needed.
- Future Plans
  - We will continue to improve our stress calculations by adding new data as it becomes available, or seek funding for additional instrumentation.
  - We will apply our microseismicity detector to additional study areas.
  - We will spend additional effort looking at changes in seismicity and stress over longer periods of time.

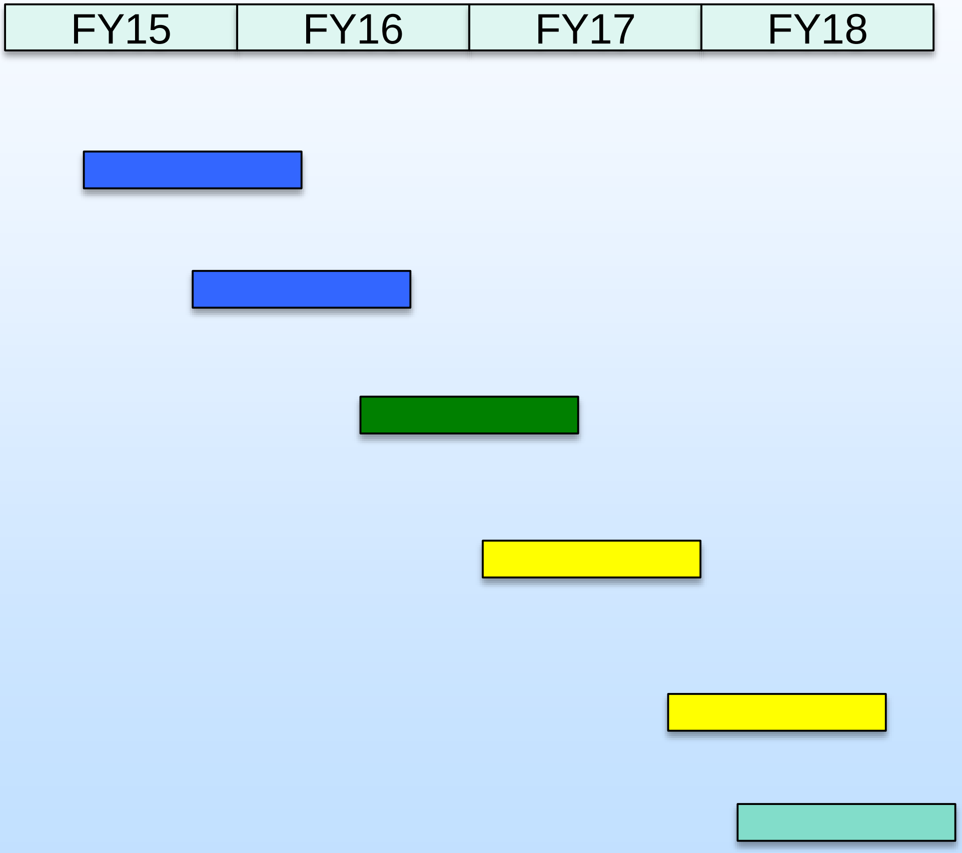
Organization Chart

PIs: P. Johnson & D. Coblentz (LANL)

Research Team:

- **LANL—**A. Delorey, S. Karra, M. Maceira
- **LBNL—**T. Daley
- **LLNL—**S. Myers
- **NETL—**K. Rose
- **SNL—**D. Aldridge, T. Dewars, M. Lee

Gantt Chart



Develop interstation waveform coherence for extraction of signals from small μseismic events

Demonstrate proof of principle at laboratory scale

Demonstrate proof of principle at field scale for large, natural systems using historical data

Demonstrate proof of principle at field scale for small, anthropogenic systems using historical data

Deploy preliminary system at active field site

Develop automated algorithm proof of principle at field scale for small, anthropogenic systems

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- van der Elst, Nicholas J., **Andrew A. Delorey**, David R. Shelly, and **Paul A. Johnson**, Fortnightly modulation of San Andreas tremor and low-frequency earthquakes PNAS 2016 113 (31) 8601-8605; published ahead of print July 18, 2016, doi:10.1073/pnas.1524316113
- **Delorey, A. A.,** van der Elst, Nicholas J., **Paul. A. Johnson,** Tidal Triggering of Earthquakes Reveals Poroelastic Behavior on the San Andreas Fault, *under review EPSL.*