CHARACTERIZING AND INTERPRETING THE IN SITU STRAIN TENSOR DURING CO_2 INJECTION

Project NumberDE-FE0023313

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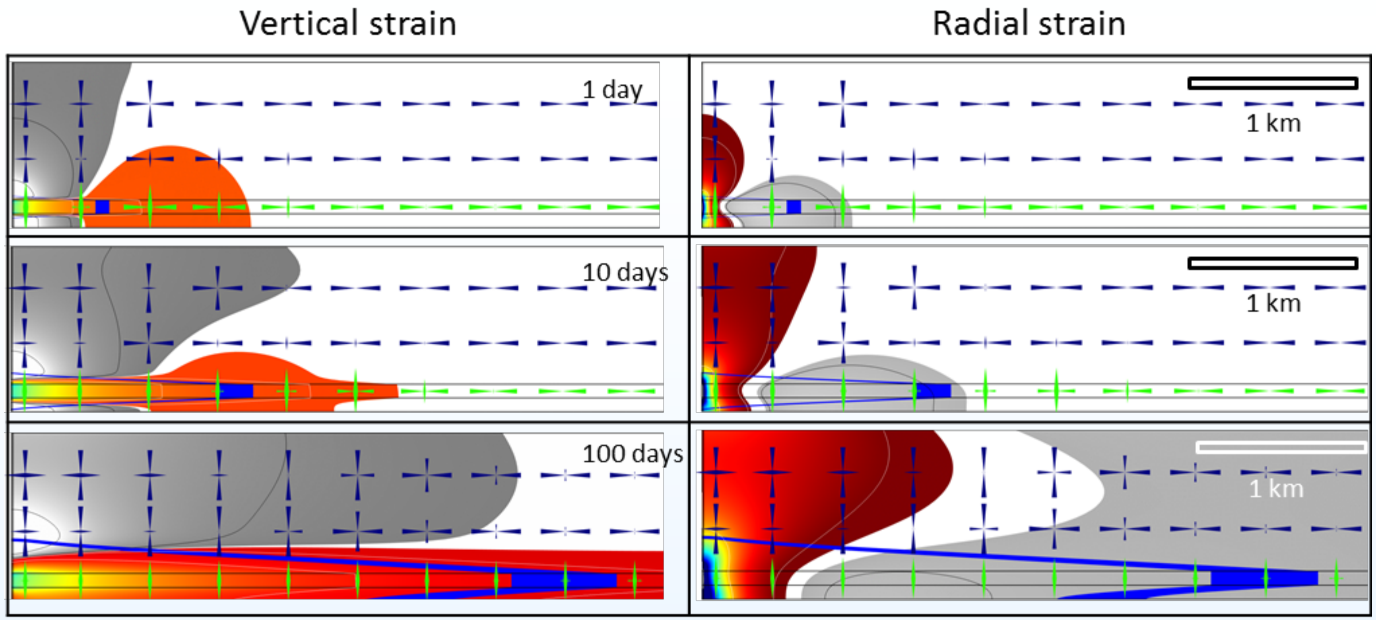
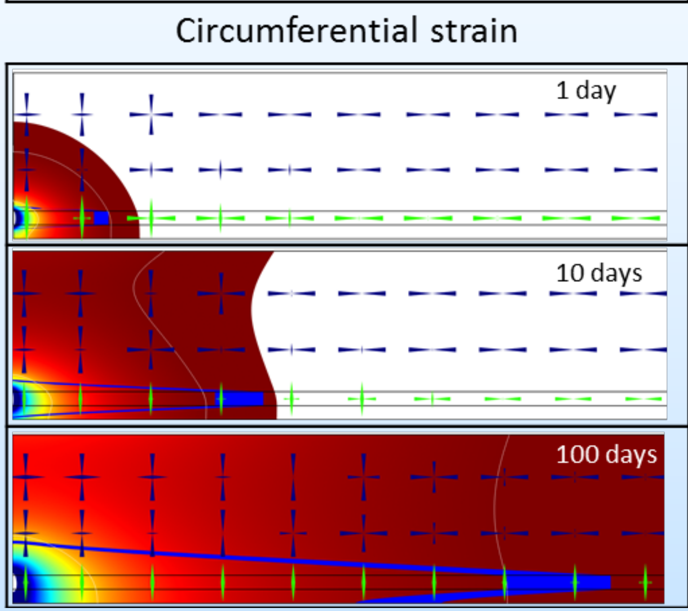
U.S. Department of Energy

National Energy Technology Laboratory

DE-FOA0001037 Kickoff Meeting

November 12-13, 2014





Strains near a well with time

- Color = positive (tensile) strain
- Grey = negative (compressive) strain
- Color cutoff: +/-0.05 $\mu\varepsilon$
- Blue band = pressurized

Strain scales with max pressure

Presentation Outline

Overview

- Benefits, Goals

Technical Status

- Instrumentation
- Analyses
- Field demonstration

Accomplishments

Summary

Benefit to the Program

Contribute to *Area of Interest 1 – Geomechanical Research* by developing and demonstrating innovative instrumentation and theoretical techniques for characterizing the strain field resulting from injection (Research Need 3)

Carbon Storage Program goal to support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Benefits Statement: The proposed project will contribute to *Area of Interest 1 – Geomechanical Research* by developing and demonstrating innovative instrumentation and theoretical techniques for characterizing the strain field resulting from injection (Research Need 3). The field data and inversion method will advance characterization of geomechanical properties and evaluation of stress change throughout the formation, including in the vicinity of faults and lithologic contacts. These contributions will improve the reliability of theoretical models, thereby advancing estimates of storage capacity and assisting in future monitoring decisions and risk assessment. Preliminary analyses of the proposed method demonstrate an improvement in accuracy of property estimates by an order of magnitude (from 25% to a ~1%) and a reduction in uncertainty by more than 50%, relative to baseline methods. These improvements contribute to the Carbon Storage Program goal to support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Project Overview:
Goals and Objectives

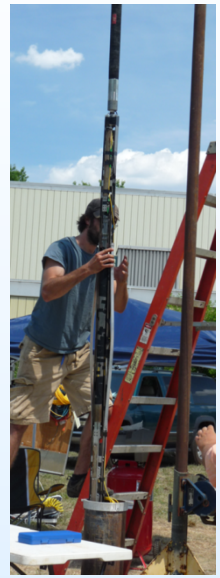
- Overall Goal: evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO2 storage.
  - **Instrument Development Task** Design/build instrumentation for measuring the in-situ strain tensor and evaluate performance characteristics relative to the existing state of the art.
  - **Theoretical Analysis Task** Develop theoretical analyses for characterizing the strain field associated with injection in the vicinity of critical features, such as contacts and faults, and then develop and demonstrate innovative methods for inverting these data to provide a quantitative interpretation.
  - **Field Demonstration Task** Demonstrate the best available strain measuring instrumentation during a field injection test, interpret the result data, and compare the interpretation with currently available information.

Strain Measurement

Overview

Geodetics | *Geomechanics* | *Borehole Stability*

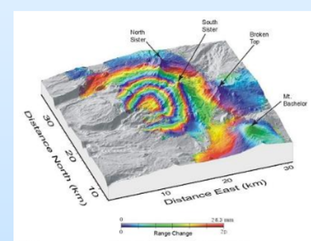
Gladwin Borehole Strain Meter (BSM)
- 4 axis, horizontal
- ~0.001 με resolution
- Grouted in place
- Tectonic strain



Clemson *5DX*
- 3D + shear
- ~0. 1με resolution
- Optical
- Removable
- Well testing

Clemson *Tilt-X*
- Axial+tilt
- ~0. 01με resolution
- Electrical
- AGI tiltmeter
- Removable
- Well testing

Baker Hughes *WIRE*
- Multicomponent
- ~1 με
- Optical
- Part of casing

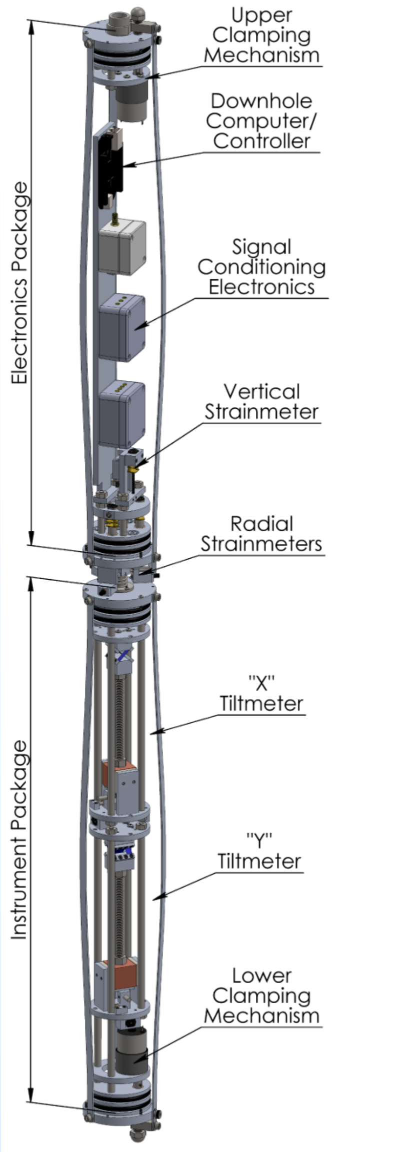


In SAR

Geodetic GPS

Instrument Design

- Multiple components of strain
- Geodetic resolution (~nε)
- Cost
  - Commercial sensors
  - Removable or disposable

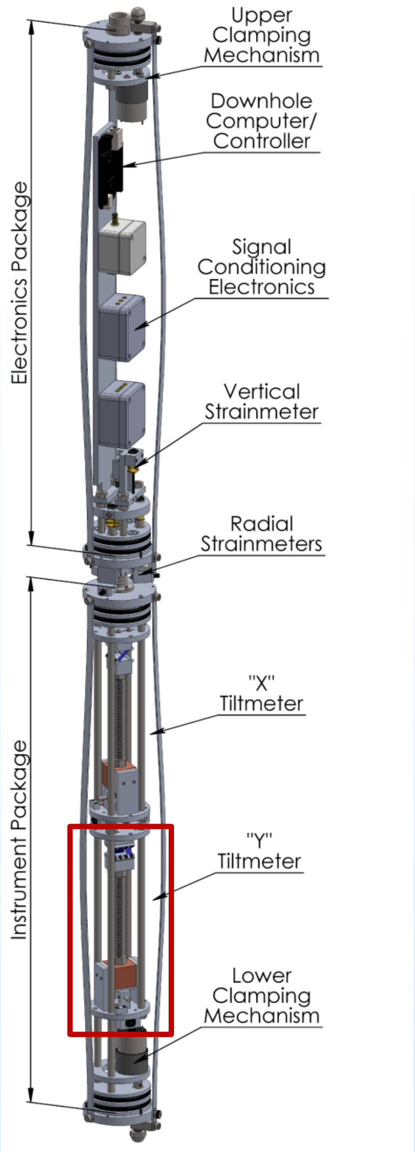


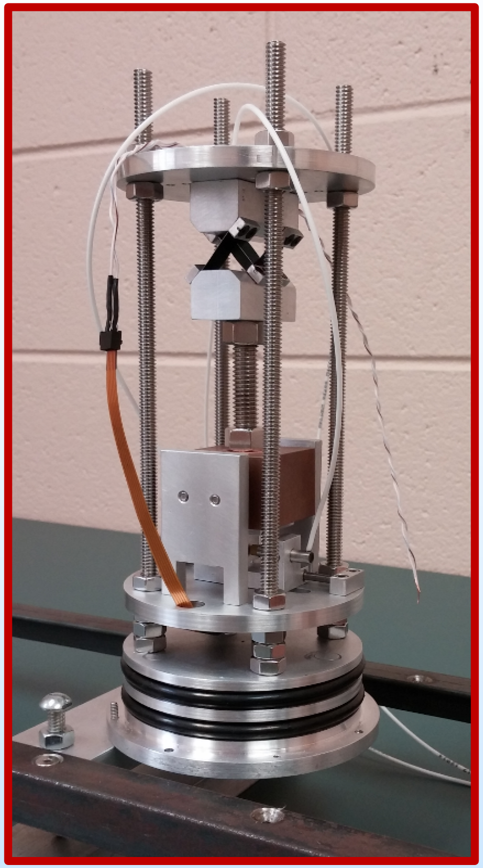
Tensor Borehole Eddy Current Strainmeter With Two-Axis Physical Pendulum Tiltmeter (Acronym?)

Scott DeWolf

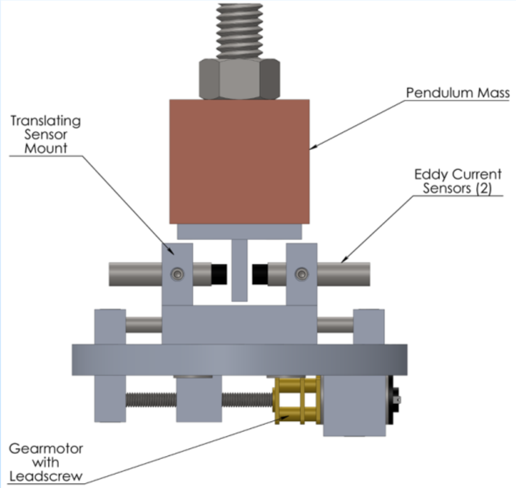
- Two packages: electronics package and instrument package
  - Each is 24" long
- Separate clamping mechanisms
- Isolates most sensors from electronics
- Packages are allowed to "float" along the vertical axis
- Removable!

Prototype Tiltmeter

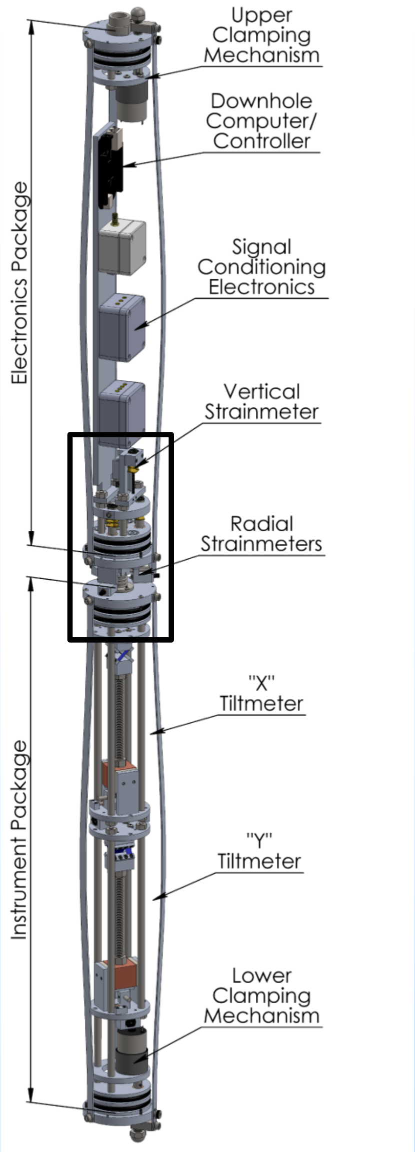




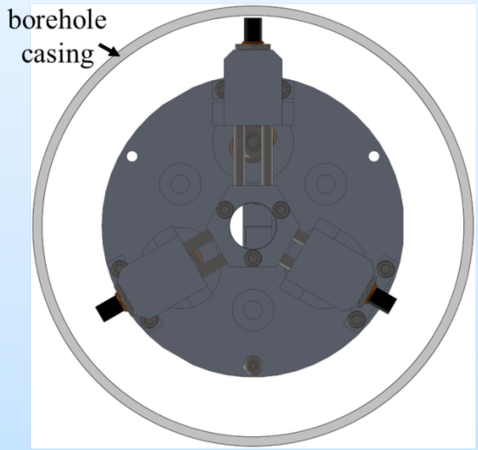
- Crossed flexure design
- Offset hinge +/- 11.5°
- Re-zero sensors +/- 4.2°
- Conductive mass with magnetic damping
- Differential eddy current sensors <1nm

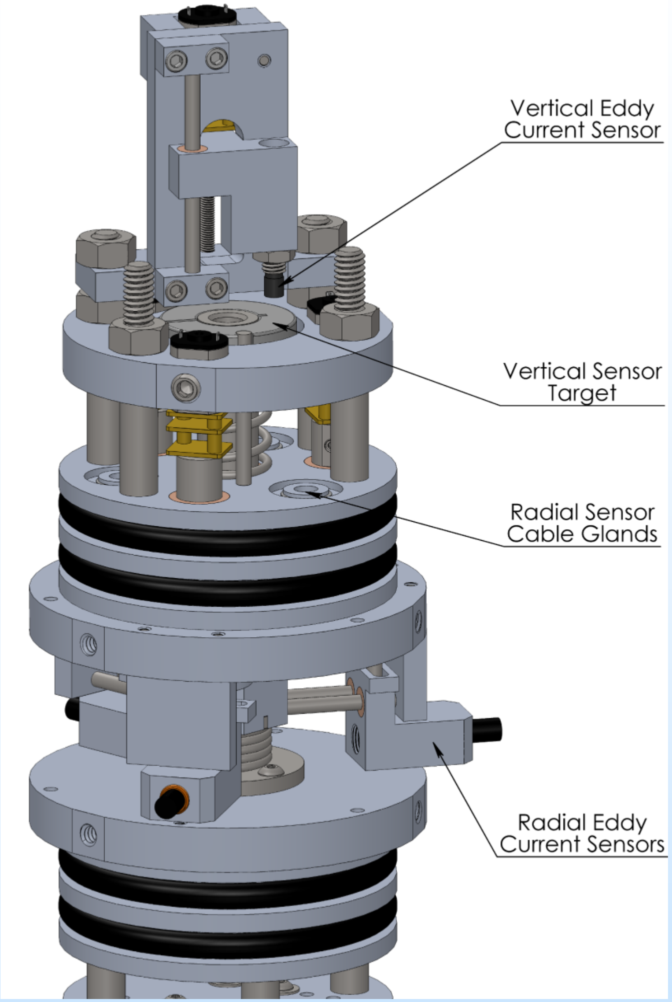


Radial and Vertical Sensors

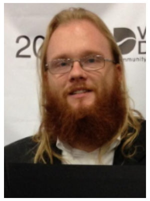


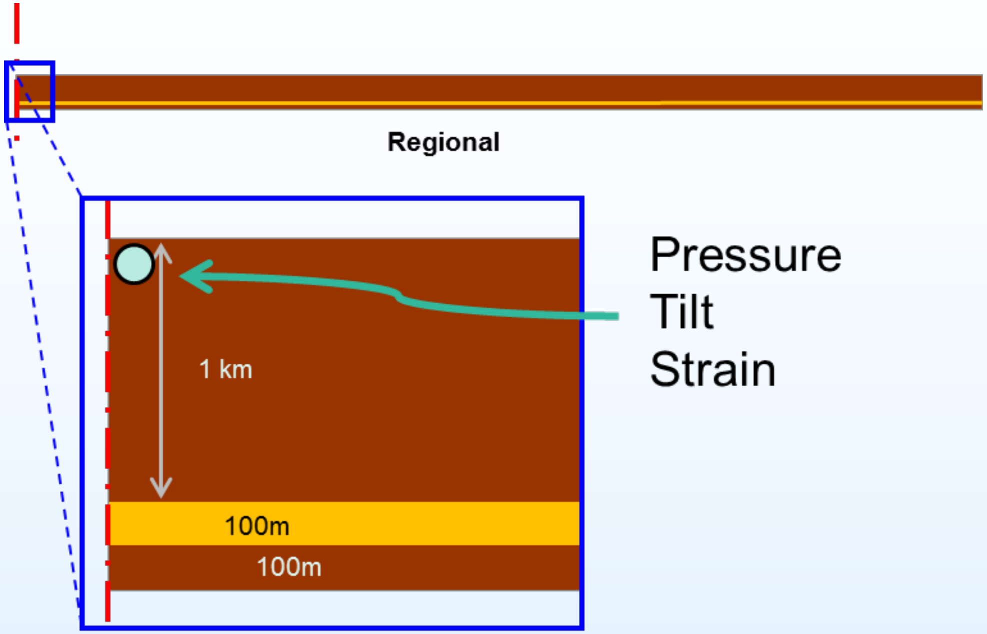
- Three radial displacement
  - From 3.25” to 4.56”
  - Scotch yoke mechanism
- One vertical
  - Measures displacement between packages
  - Linear actuator





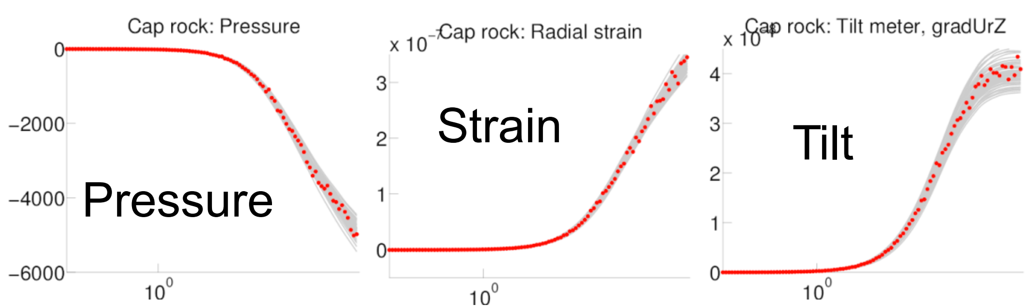
Interpretation



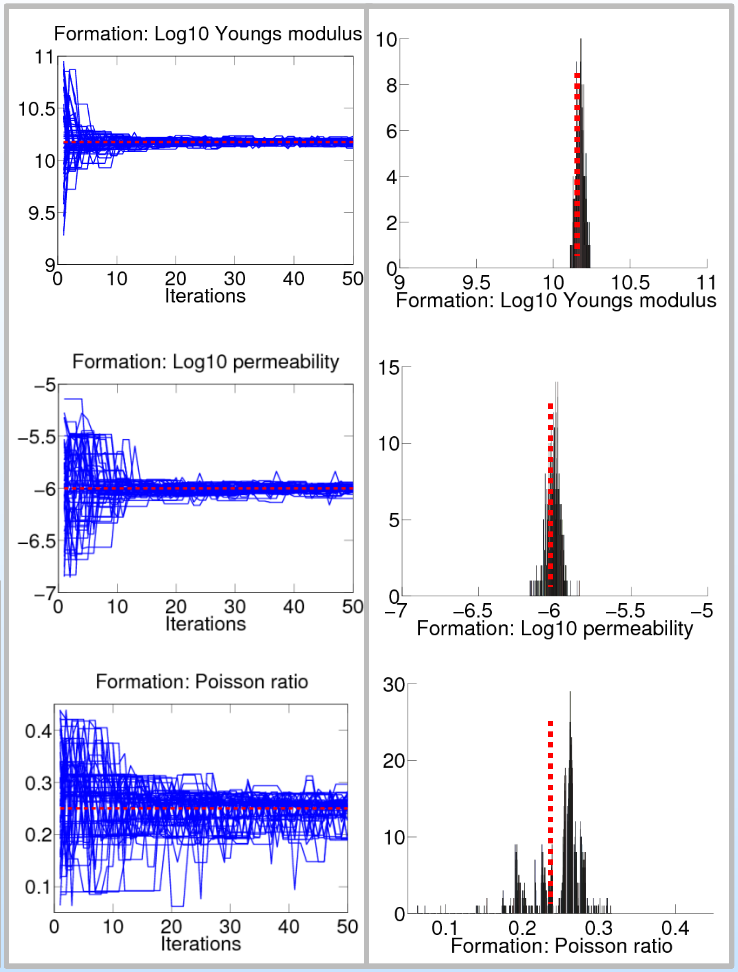


Poroelastic Forward Model

Data (Observed + Fit)

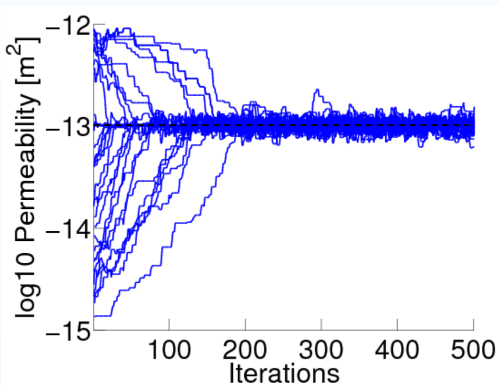


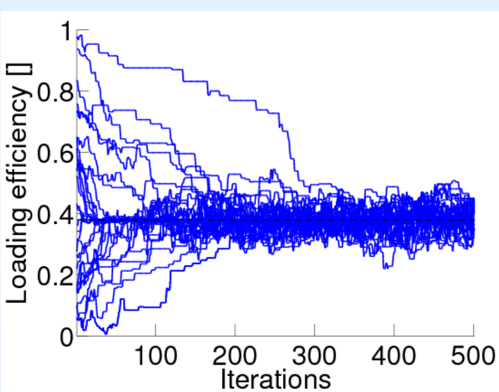
Iterations	Estimated Parameters



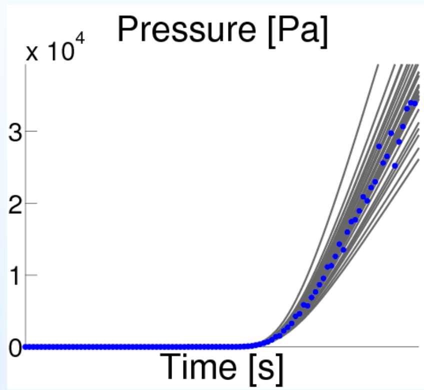
Interpreting Strain and Pressure Signals

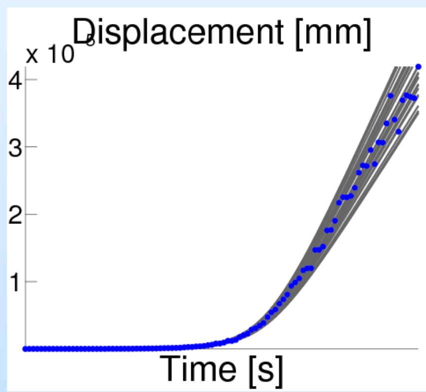
Reservoir Parameters

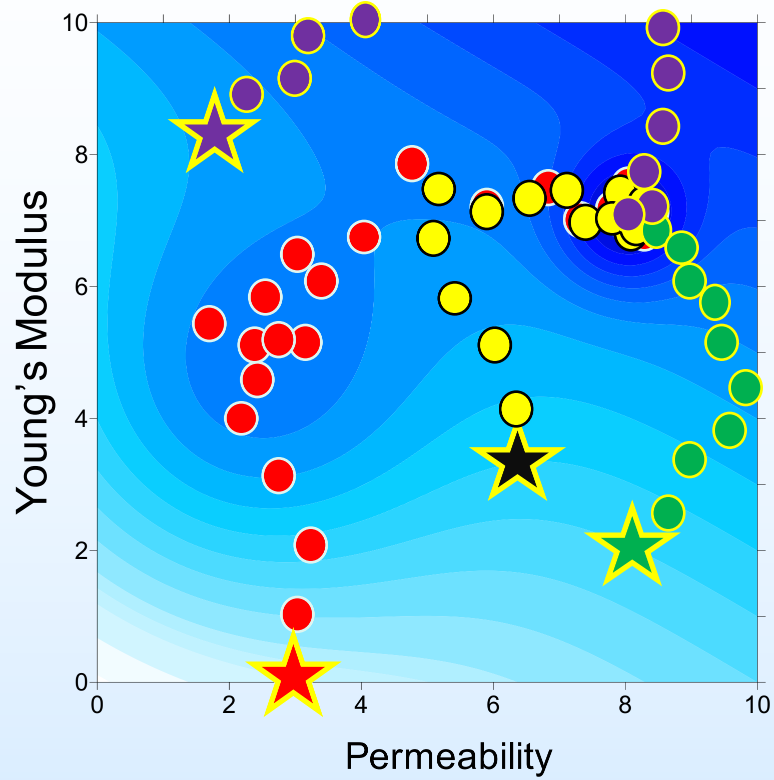




Geomechanical Signals

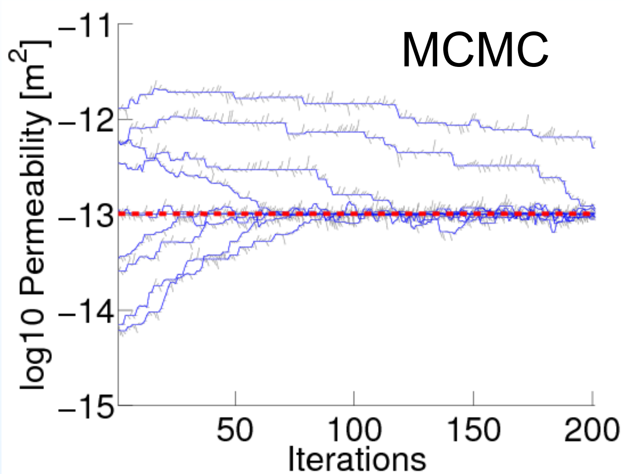


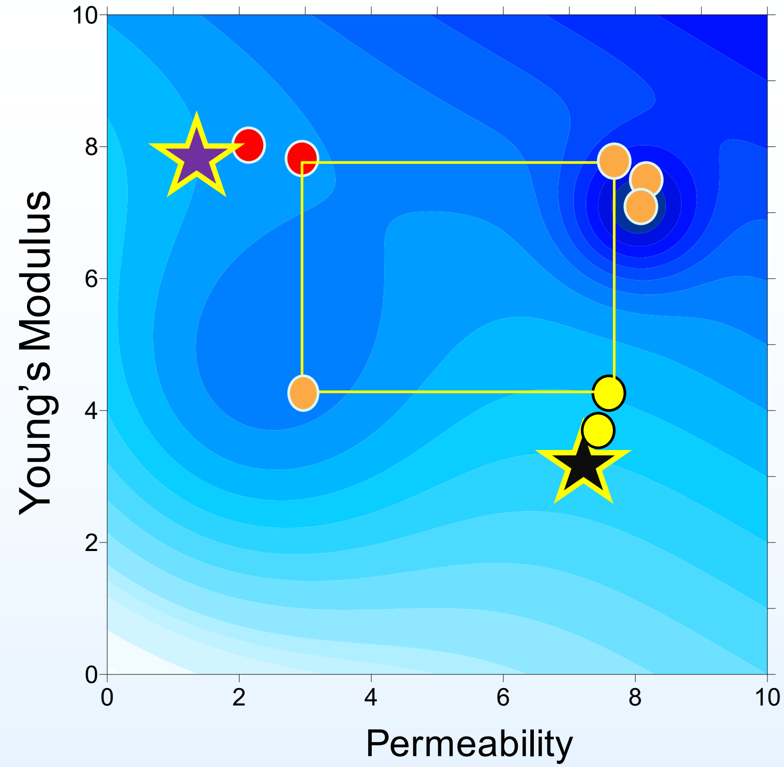


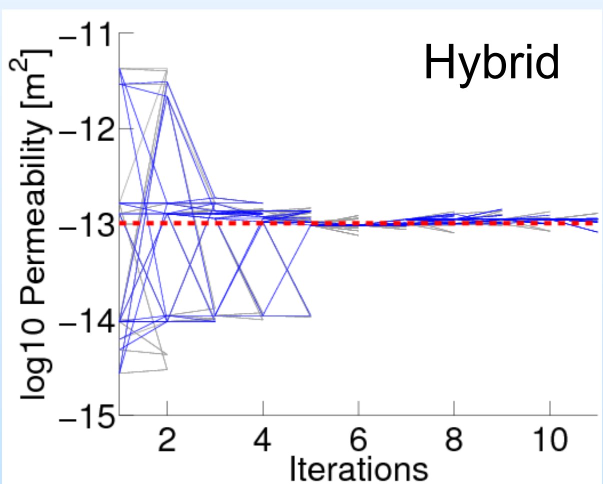


MCMC: Good search of parameter space. Avoid traps in local minima.

MCMC+Genetic → Hybrid Optimization



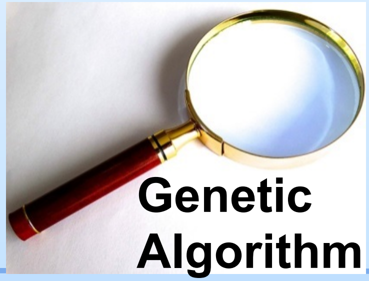




Exploration vs Exploitation

Search large region quickly

Search most promising region carefully



Algorithms in Hybrid Optimization

Space Filling

- Monte Carlo
- Sparest sampling (Voronoi)

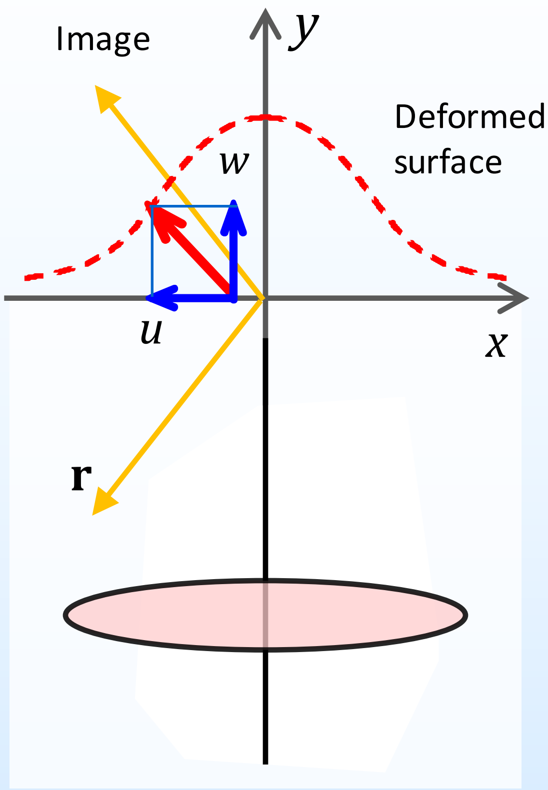
Uncertainty Evaluation (Exploration)

- Markov chain Monte Carlo (McMC)
- Reversible jump McMC *(heterogeneous reservoirs)*

High Efficiency Minimization (Exploitation)

- Genetic Algorithms (NSGAII, SPEA2) - global
- *Gradient descent* - local

Analytical solutions to Poroelastic Problems



- Displacements in infinite space [*Goodier*, 1937]

$$\varphi_0(x,y,z) = \frac{1+\nu}{1-\nu}\int_V \frac{\varepsilon_0(\mathbf{r}_1)d^3\mathbf{r}_1}{|\mathbf{r}-\mathbf{r}_1|}$$

$$w_0(x,y,z) = -\frac{\partial}{\partial z}\varphi_0(x,y,z)$$

ε_0: transformation strain distribution, from poroelasticity

- Use image points [*Mindlin and Cheng*, 1950] to get displacements in half space

$$w(x,y,z) = w_0(x,y,z) + (3-4\nu)w_0(x,-y,z) - 2z\frac{\partial}{\partial z}w_0(x,-y,z)$$

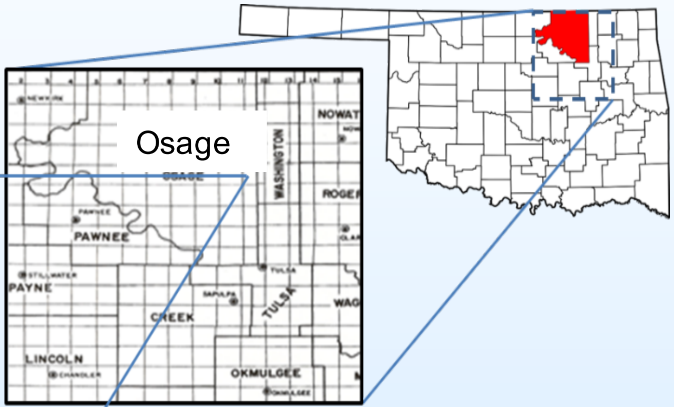
- Analytical expressions developed using Mushkelishvili potentials for nearly any shape in 2-D and for some shapes in 3-D (e.g., ellipsoidal or rectangular inclusions)

→Use analytical expression for deformation to start inversion process. Quickly identify important regions of parameter space. Use numerical after that.

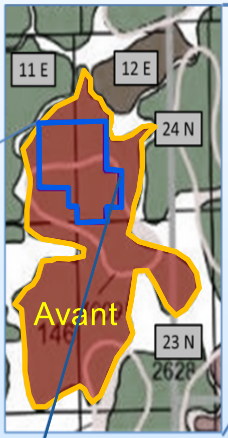
Field Demonstration

Josh Smith

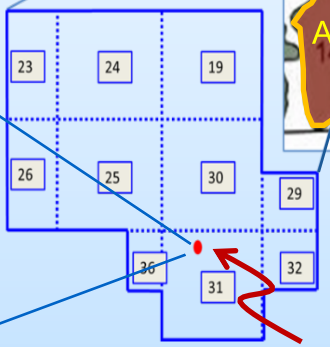
- Measure/interpret strain during waterflood as analog to CO2 injection
- North Avant Field, Osage County, OK
- 100+ years of production
- Vicinity of Section 31, T24N dormant recently



Counties



From: Oil fields in OK



Field Test Site

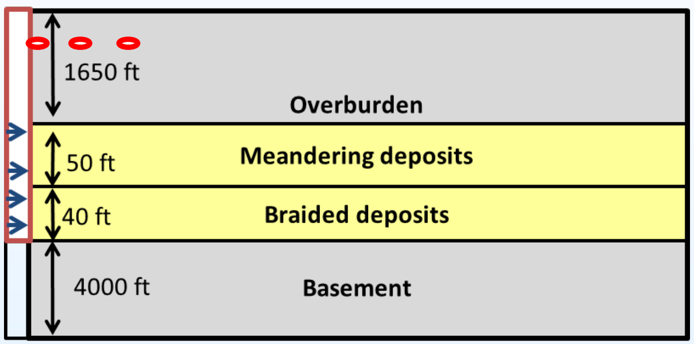
CLEMSON UNIVERSITY GEORGIA TECH UNAVCO U.S. DEPARTMENT OF ENERGY

Field Experiment

- Work Plan, Design, Dec 2015
- Install Geodetic Strainmeter, Spring 2016
- Install Clemson Strainmeter, Fall 2016
- Water flooding, Winter-Spring 2017
- Interpretation, Spring-Summer 2017

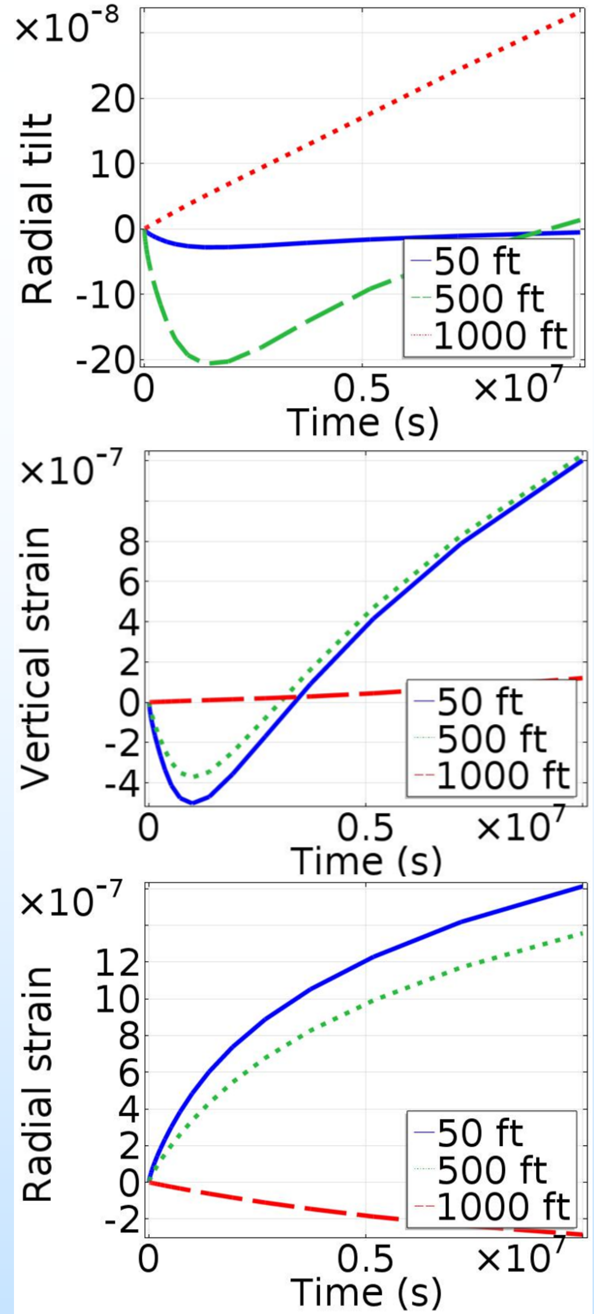
Preliminary Design

Expected strains?



- Q = 30 gal/ min

Domain	ϕ	k_horiz [mD]	k_vert [mD]	ρ [kg/m³]	E [Gpa]	ν	α
Overburden	0.12	1	1	2500	30	0.2	0.75
Meandering	0.16	25	3.6	2400	30	0.25	0.75
Braided	0.18	75	21	2400	30	0.25	0.75
Basement	0.12	1	1	2600	30	0.2	0.75



Accomplishments to Date

– Strain instrument v1.0 designed
– Prototype components, full system being fab’d
– Hybrid inverse method developed
– Poroelastic elliptical inclusion sol’n tested
– Field site recon
– Geologic model taking shape
– Expected deformation at site feasible to measure

Synergy Opportunities

– Anyone need to measure strain?

Summary

Measure and interpret strain tensor during injection

– New instrument

- high rez, removeable
- Under construction

– New hybrid inversion method

- fast and thorough
- Evaluate using various geo-scenarios

– Field demo

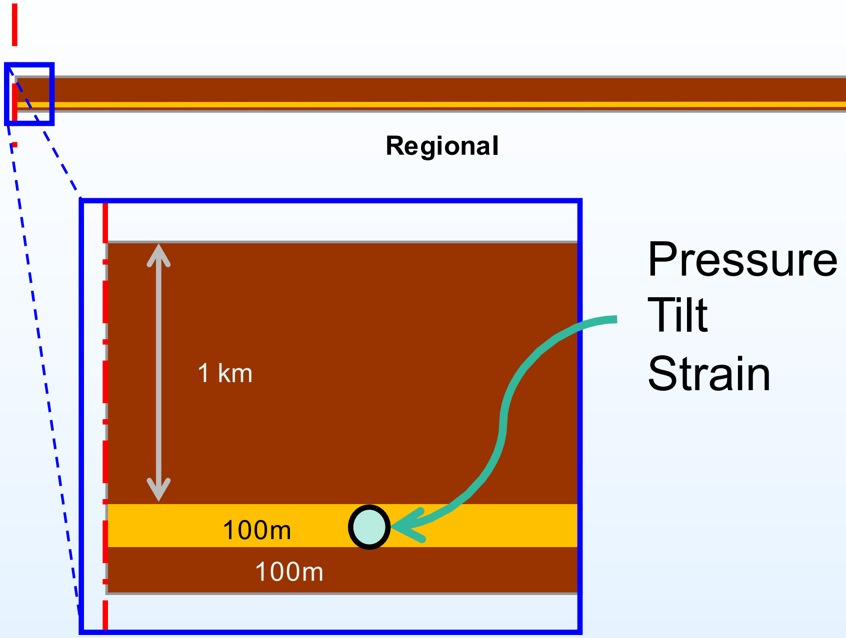
- Being designed
- Field work starting in 2017
- Field data at my talk next year??

Field Experiment Design

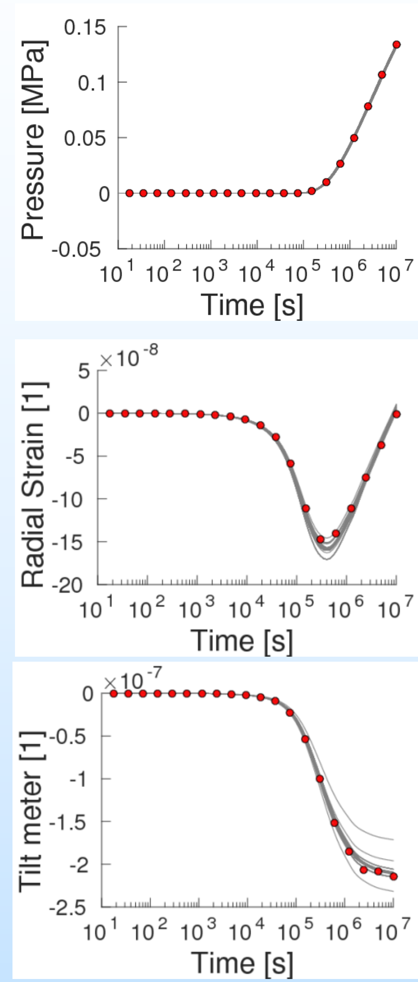
- Geology
- Predicted strains
- Location of sensors
- Evaluate inversion

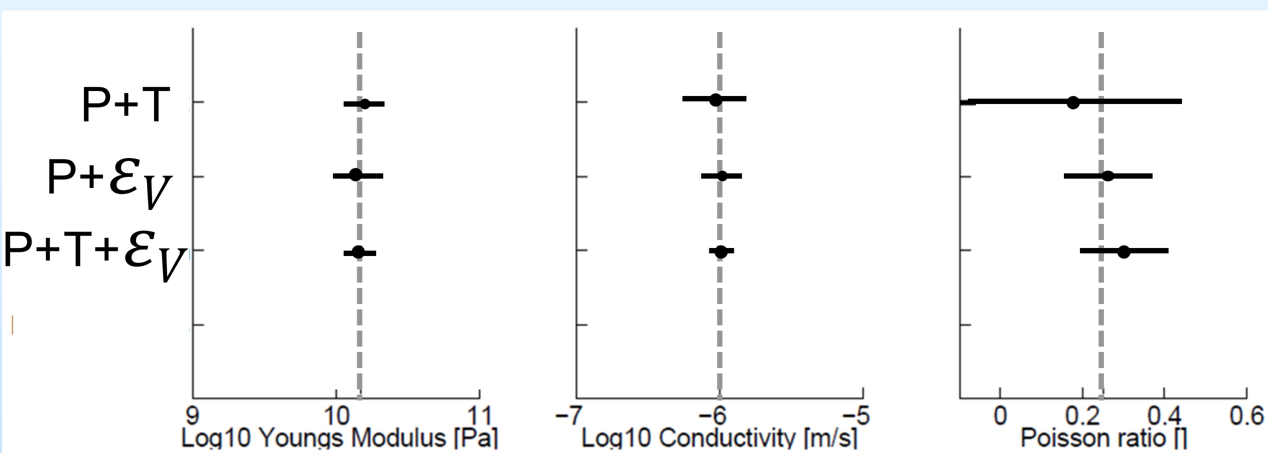
Applications

Measurement Type



Data (Observed + Fit)

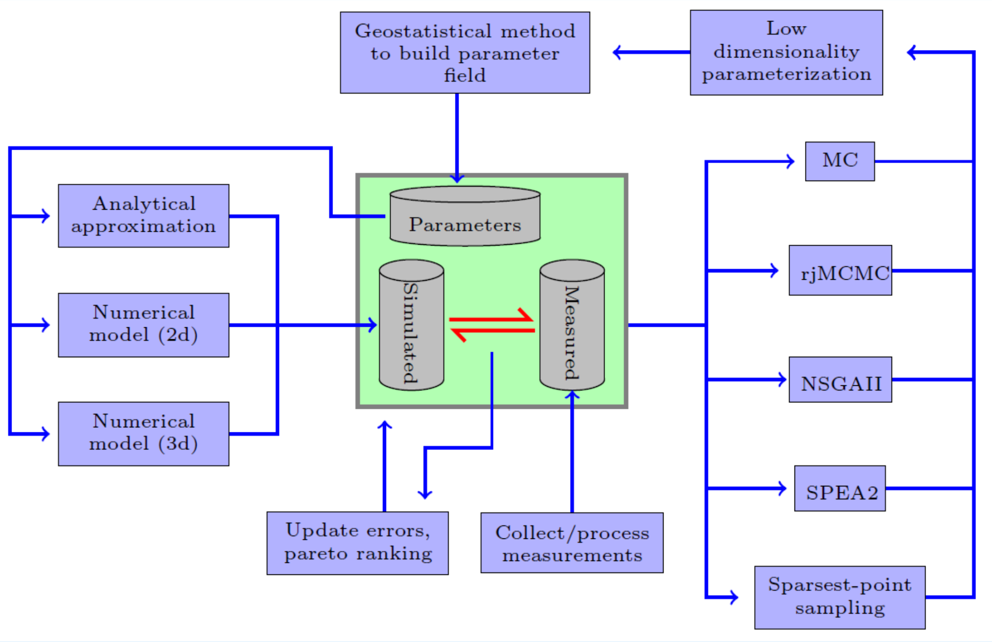




Task 3 Theoretical Analysis

Develop theoretical analyses for characterizing the strain field associated with injection in the vicinity of critical features, such as contacts and faults, and then demonstrate innovative methods for inverting these data to provide a quantitative interpretation.

Alex Hanna



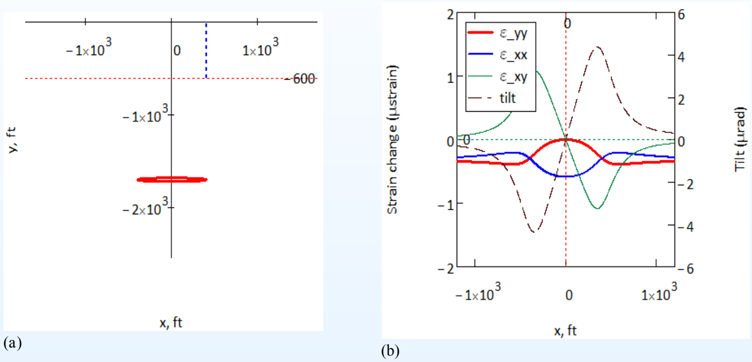


Figure 7. (a) Meandering-fluvial reservoir of elliptical geometry. Red is the pressurized zone. Blue line is the borehole and red line is the depth of the profile shown to the right. (b) Normal and shear strain and tilt as functions of distance at a depth of 600 ft above a pressurized inclusion representing a channel.

Open Science Grid:

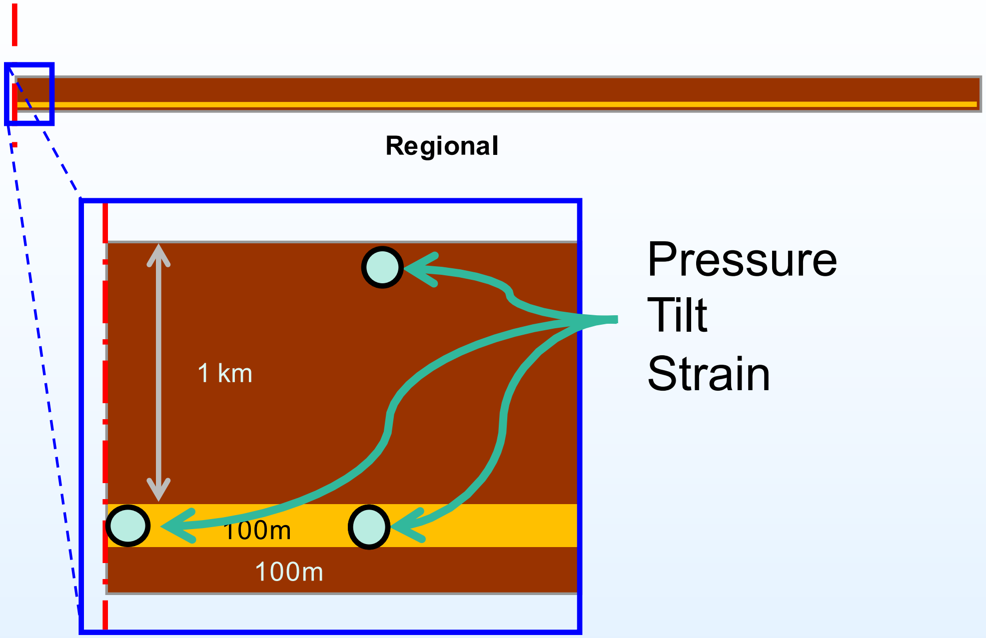
- Postprocessing
- Geostatistical Assessment
- Analytical Solutions
- Albany

Palmetto

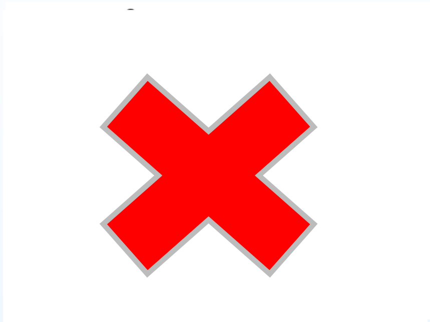
- Comsol (2d,3d)
- Abaqus

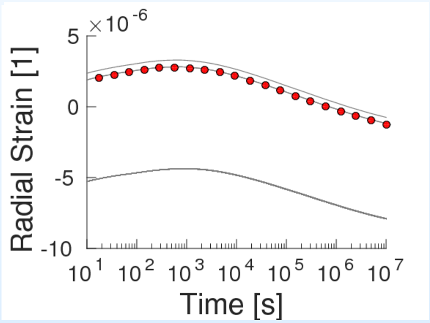
Applications

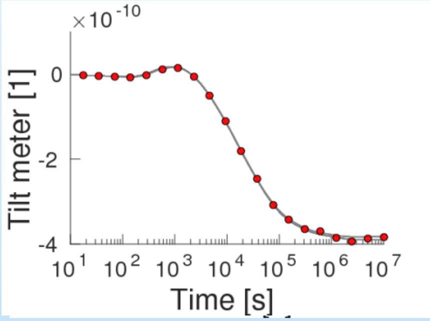
Data Location, Measurement Type

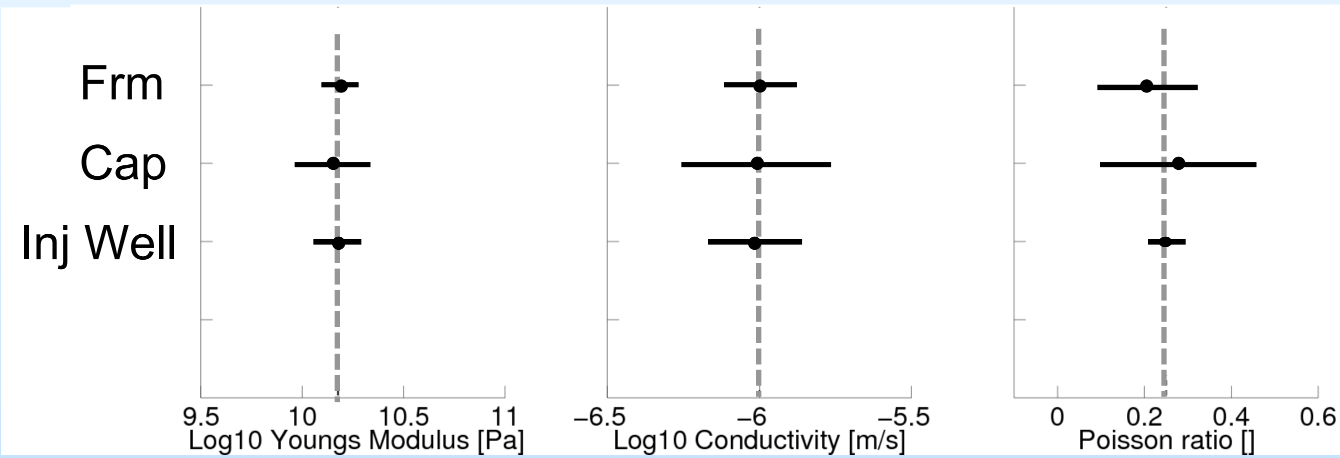


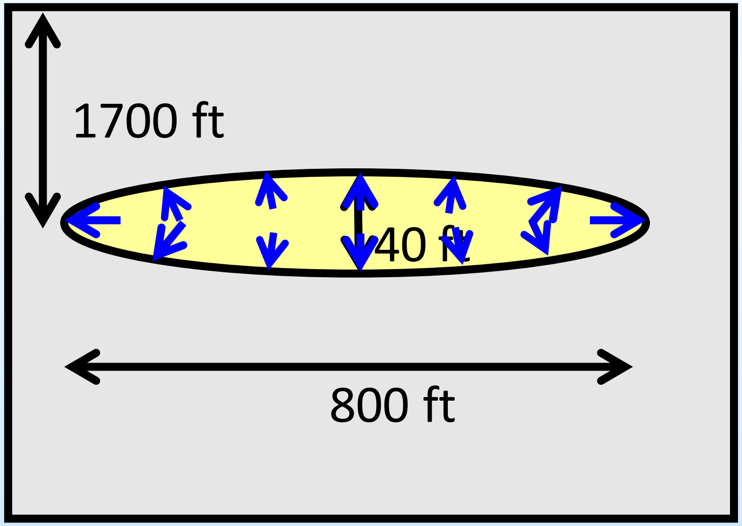
Data (Observed + Fit)



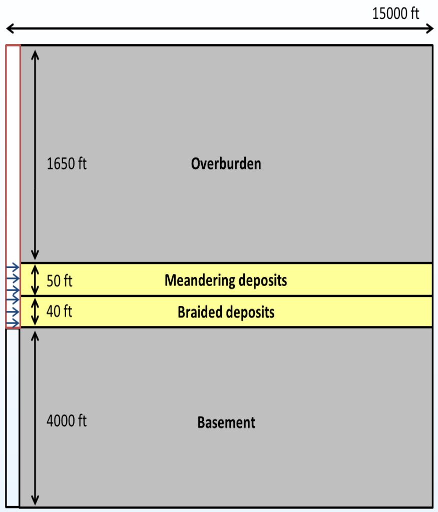


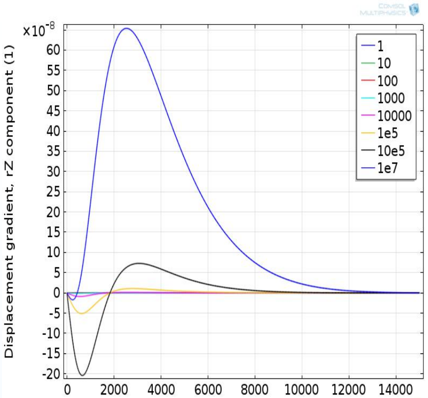


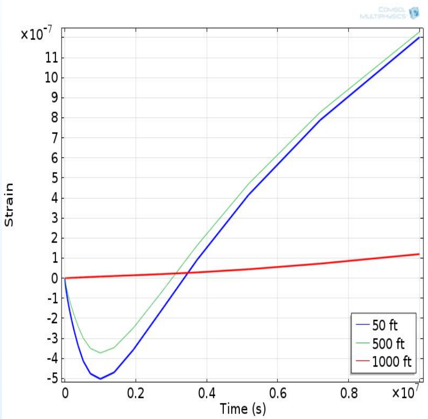


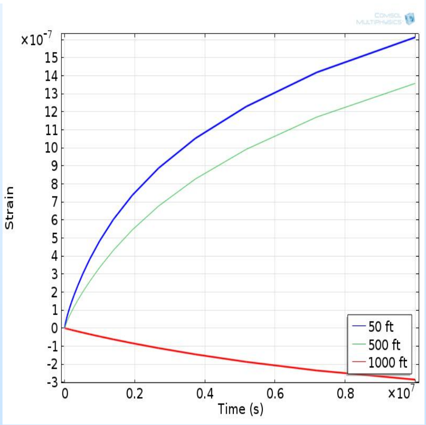

1700 ft
40 ft
800 ft

2-D model of Field Test Waterflood









- Wellbore pressure = 300 psi
    - Q = 30 gal/ min

Domain	ϕ	k_horiz [mD]	k_vert [mD]	ρ [kg/m³]	E [Gpa]	ν	α
Overburden	0.12	1	1	2500	30	0.2	0.75
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Basement	0.12	1	1	2600	30	0.2	0.75

Technical Status

- Use the remaining slides to logically walk through the project. Focus on telling the story of your project and highlighting the key points as described in the Presentation Guidelines.
- When providing graphs or a table of results from testing or systems analyses, also indicate the baseline or targets that need to be met in order to achieve the project and program goals.