Characterizing and Interpreting the In Situ Strain Tensor During CO_2 Injection

Project NumberDE-FE0023313

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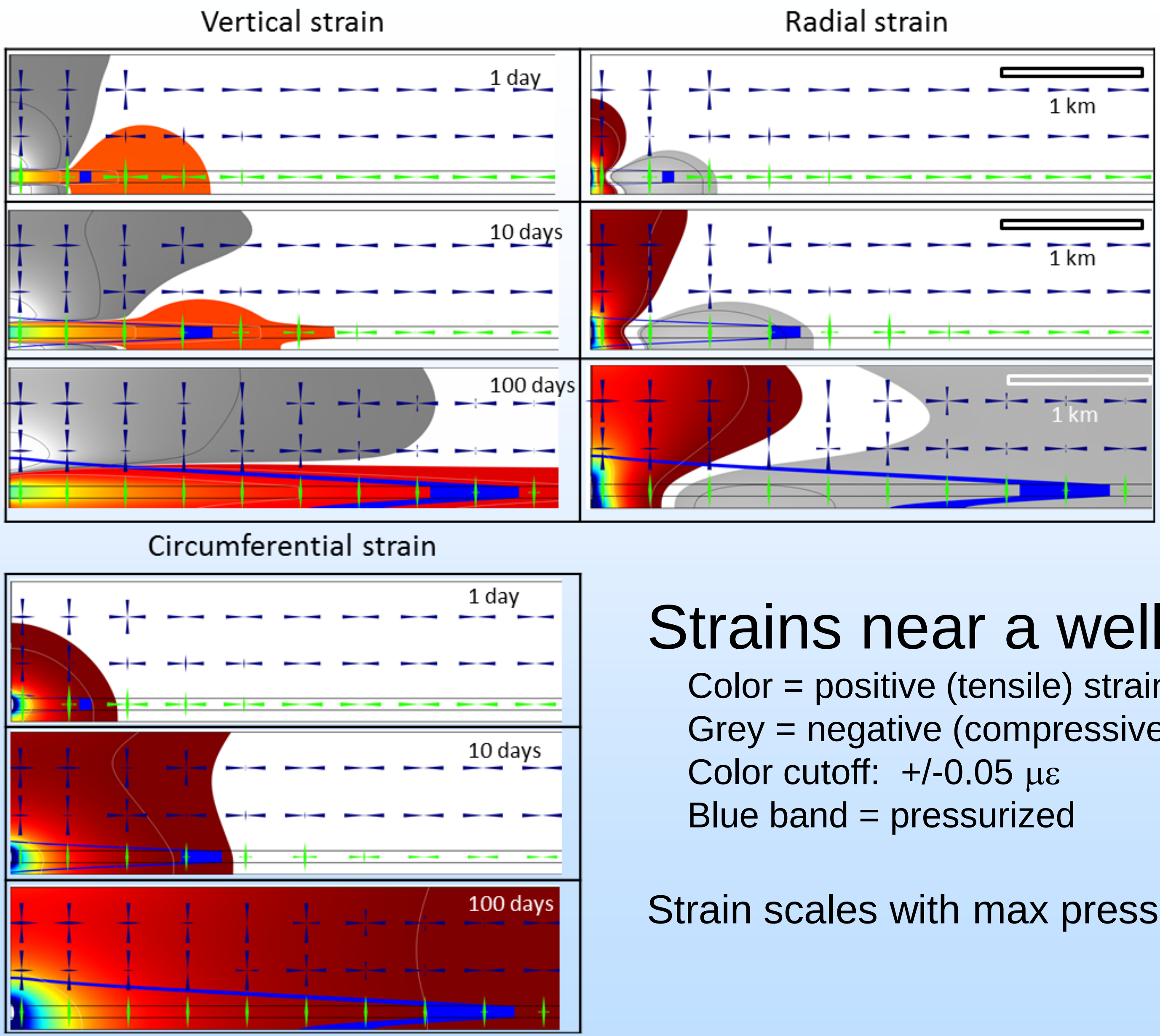
U.S. Department of Energy

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

Benefit to the Program

Project 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.

Carbon Storage Program goals

- support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop and validate technologies to ensure for 99 percent storage permanence

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)

Project Overview: Goals and Objectives

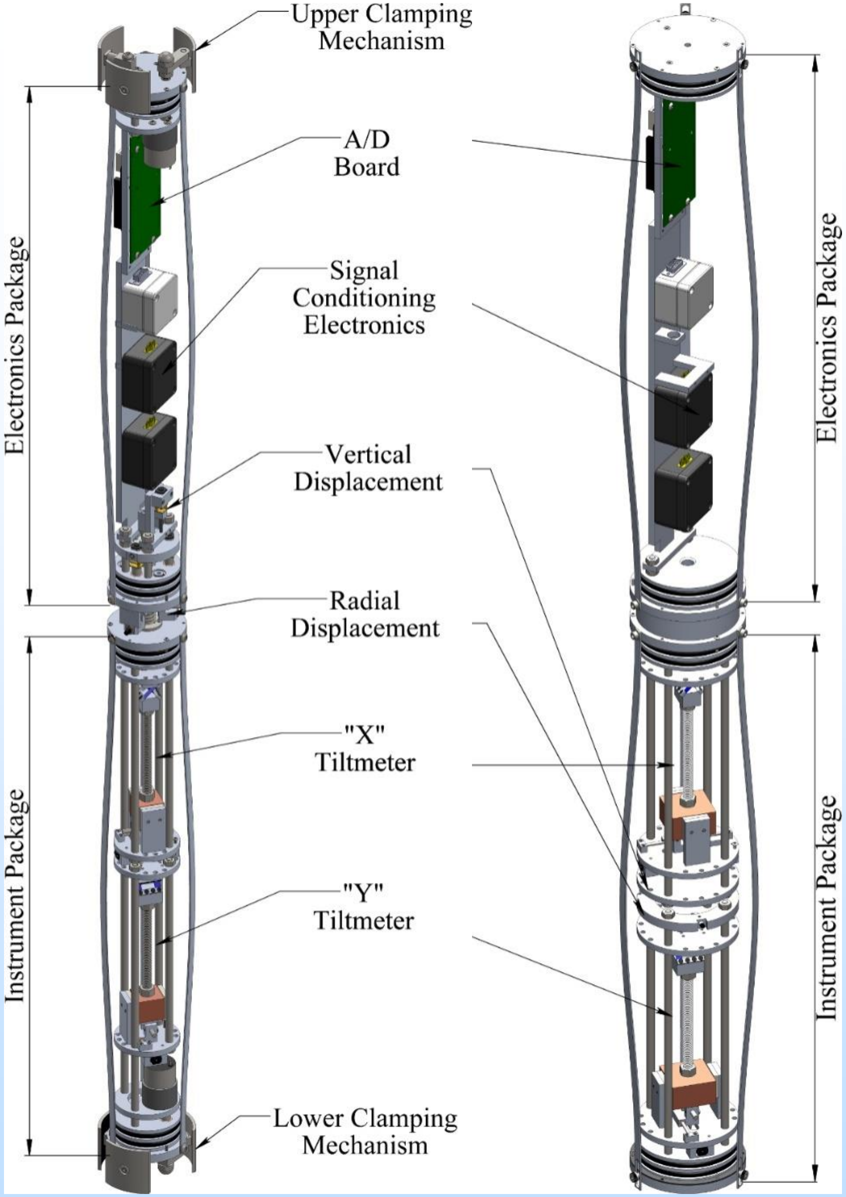
- Overall Goal: evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO2 storage.
  - **Instrument Development Task** Design/build instrumentation for measuring the 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.

Instrument Design

- Multiple components of strain, vector tilt
- Geodetic resolution (~nε, <nrad)
- Cost

→Prototypes

- Removable multicomponent
- Expendable, grout-in multicomponent
- “Smart” casing, single component but cheap



Removable

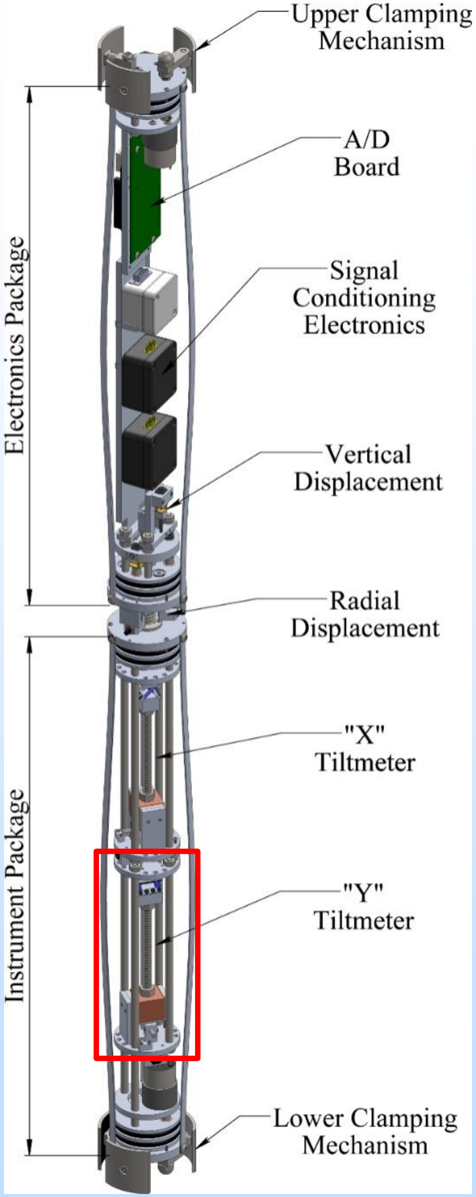
Expendable

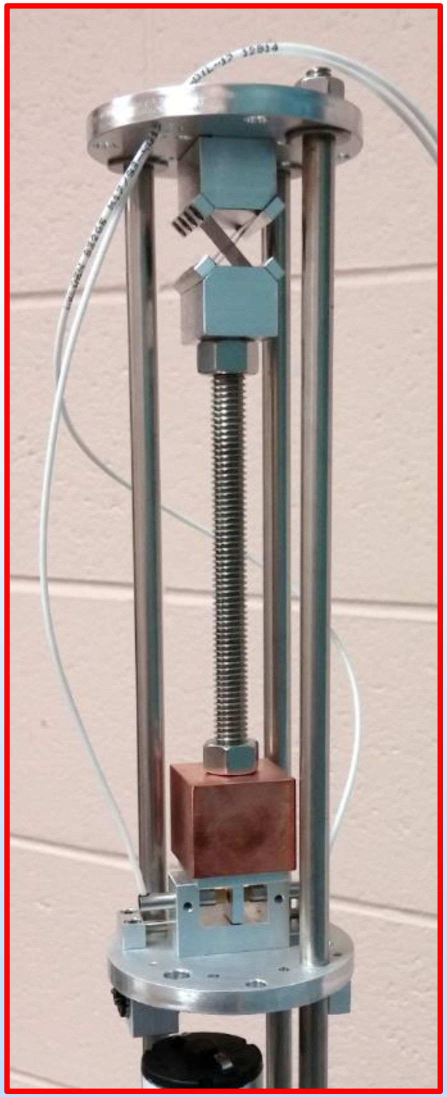
Tensor Borehole Eddy Current Strainmeter with Two-Axis Physical Pendulum Tiltmeter (TBECS-TAPPT)

Scott DeWolf

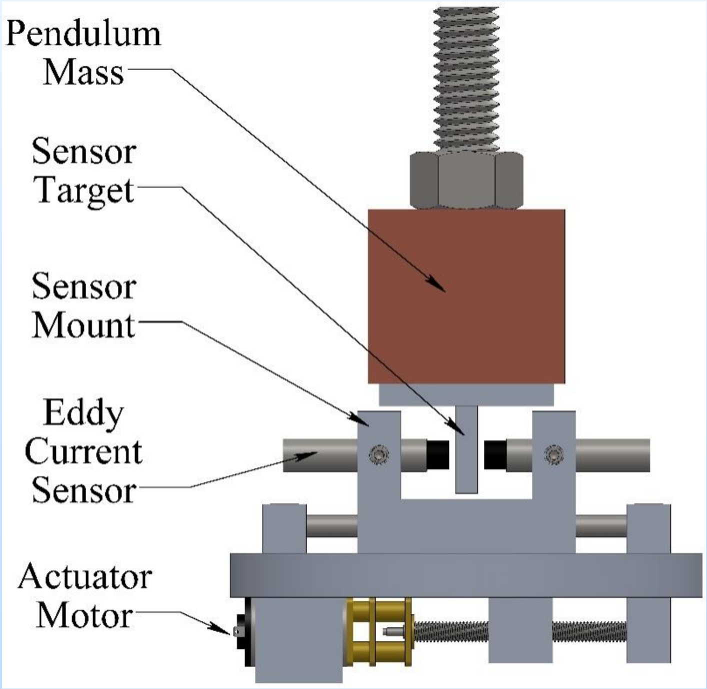
- Removable and expendable (grout-in) configurations
  - Removable→ deformation casing
  - Expendable → deformation of instrument pressure case
- Two packages: electronics package and instrument package
  - Each is 24” long
  - Isolates most sensors from electronics
  - Removable packages are allowed to “float” along the vertical axis
  - Expendable packages are coupled directly to formation via expanding grout

Two-Axis Tiltmeter

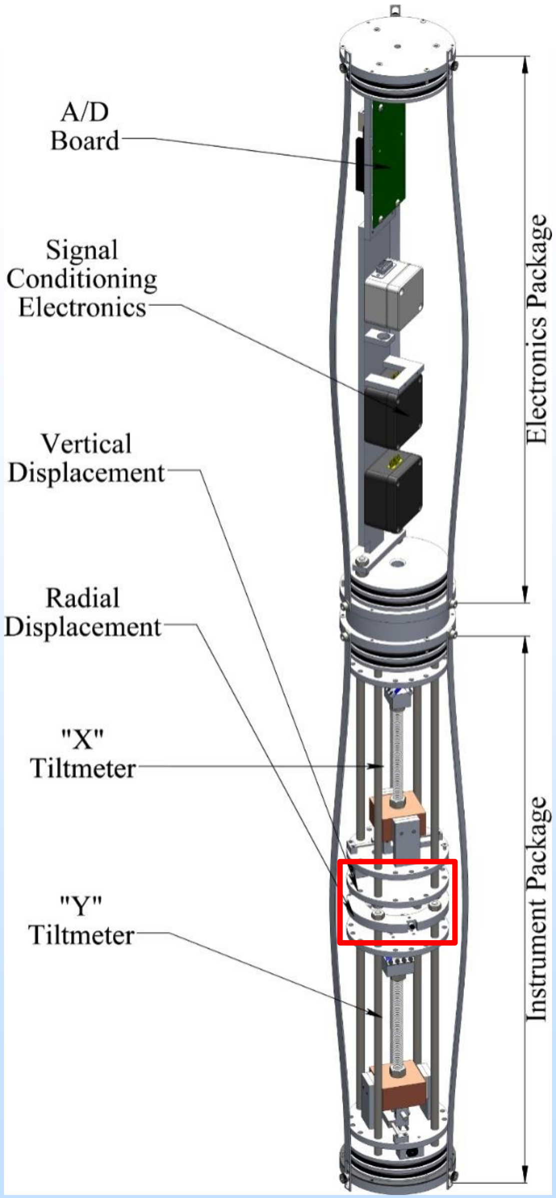




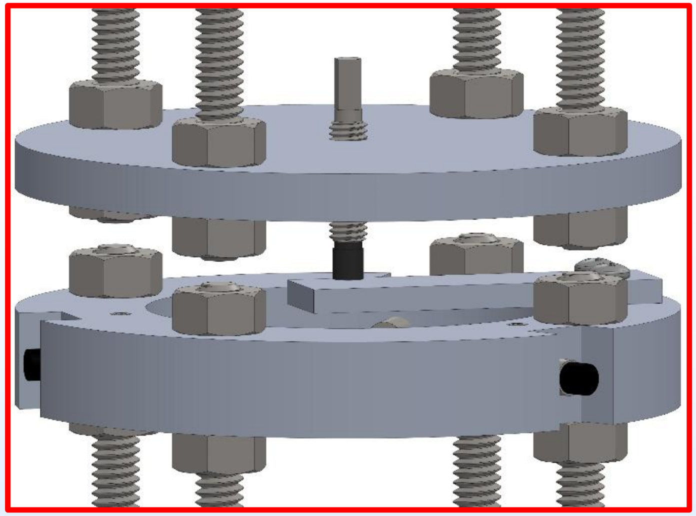
- Crossed flexure hinge design
- Re-zero sensors w/actuator:
  - Removable: ±4.2º
  - Expendable: ±12.9º
- 0.17 m baseline, ~5 s free period
- Differential eddy current sensors ~0.1 nm for nrad resolution



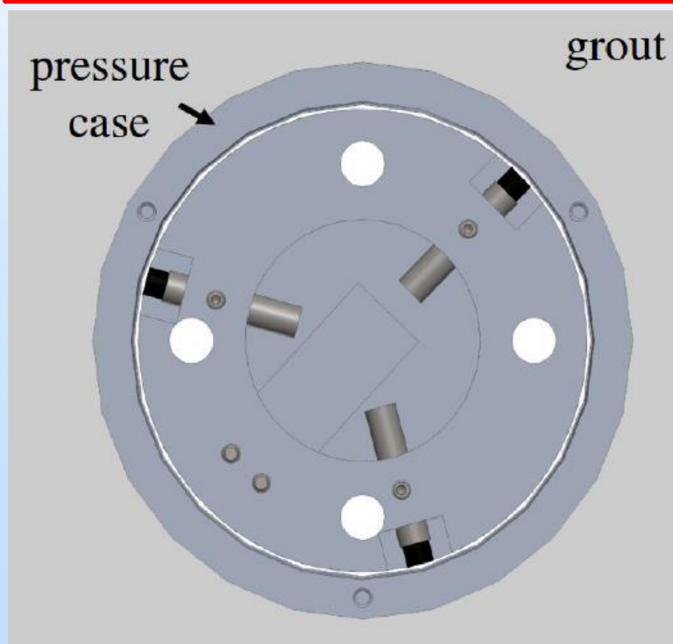
Radial and Vertical Sensors



Expendable

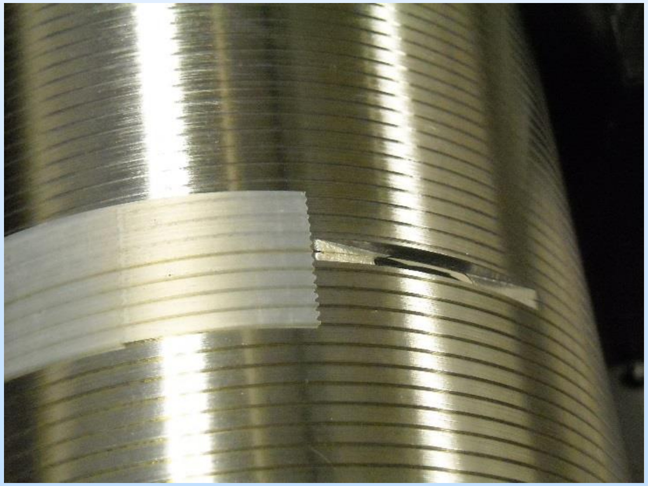


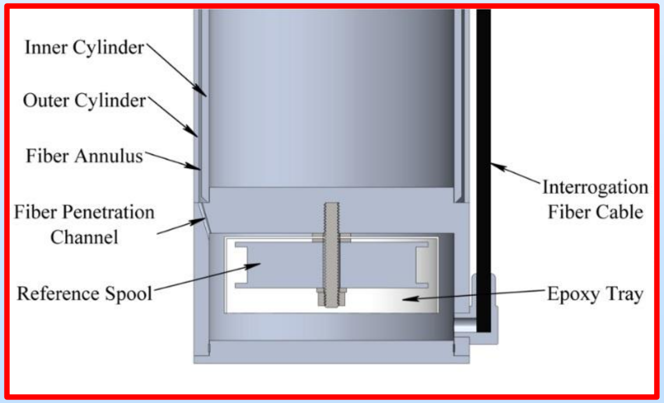
- 4.5” OD for 6” boreholes
- Three radials at 120º
  - Measures pressure case inner diameter
  - Axially collocated
- One vertical
  - Measures pressure case length



Volumetric Optical Fiber Strainmeter

- 250 m of optical fiber embedded between two cylinders
  - Final dimensions = Schedule 40 pipe
- Can be used to complete 6” wells, leaving ID open
  - Designed to deploy removable system within
- Highly sensitive interferometer with $\sim 10^{-12}$ resolution
- Inexpensive, passive and very robust
  - $1,000 parts, $2,500 interrogation/logging
  - No downhole moving parts or electronics





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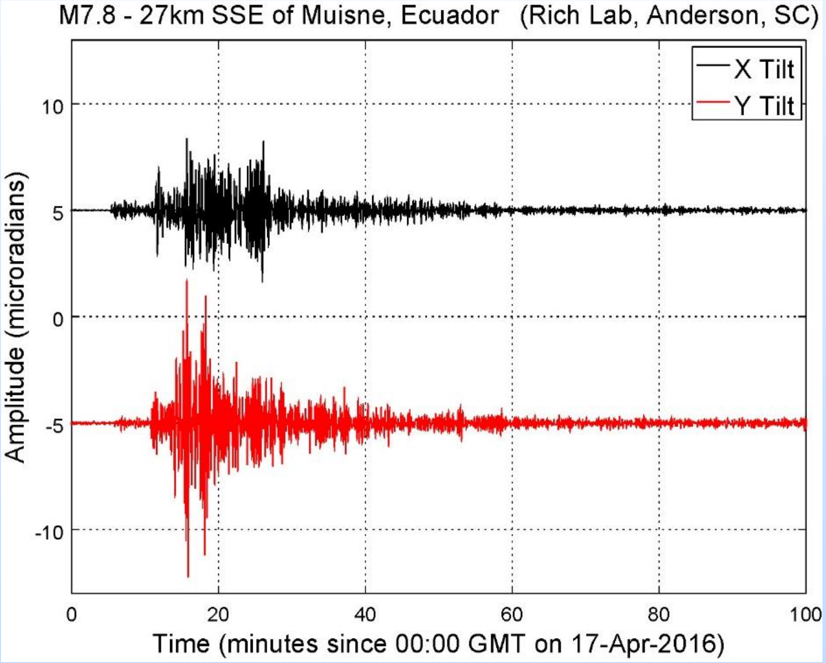
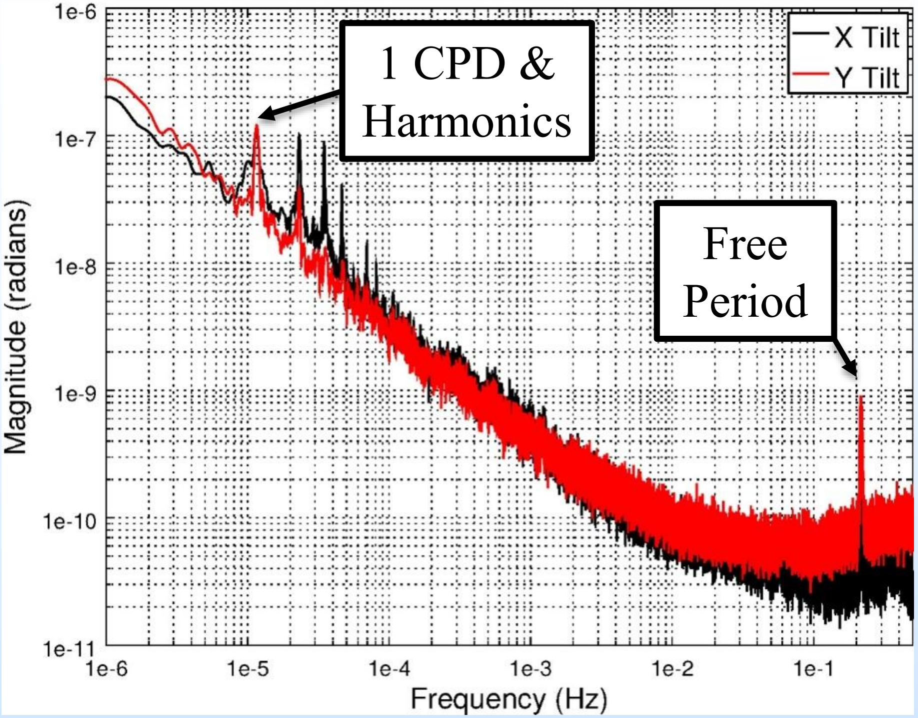
Test Deployment

- Deployed expendable instrument in 20' hole for two months
  - Null test for radial and vertical
  - Near-surface effects for tilts
- Recorded surface wave tilts from several large teleseismic events
  - M7.8 Ecuador on 17-Apr-2016

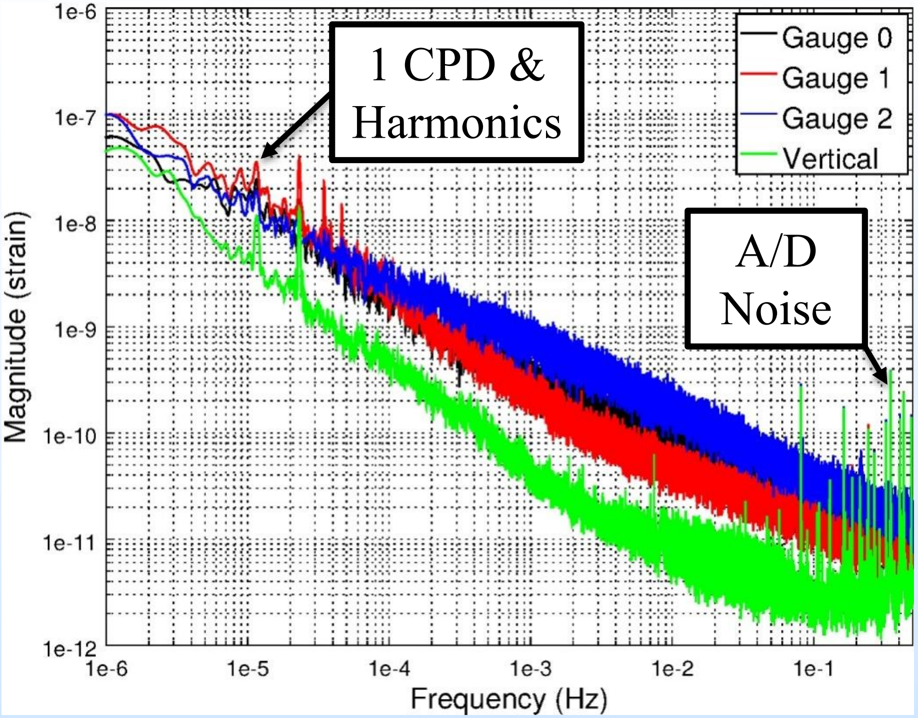


Test Deployment Spectra

Tilts



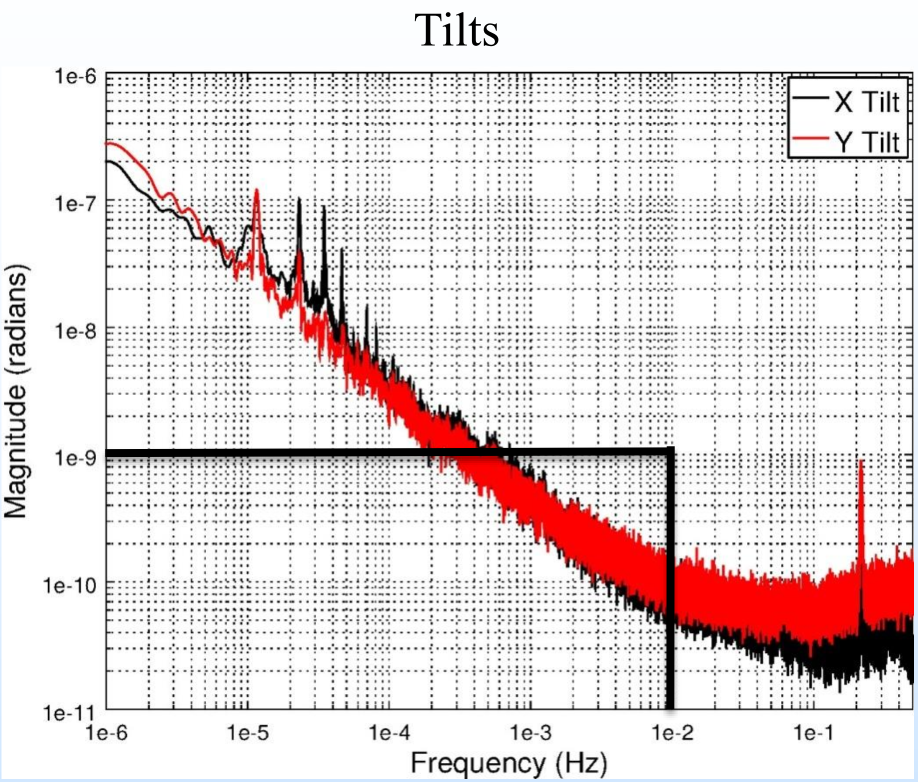
Strains

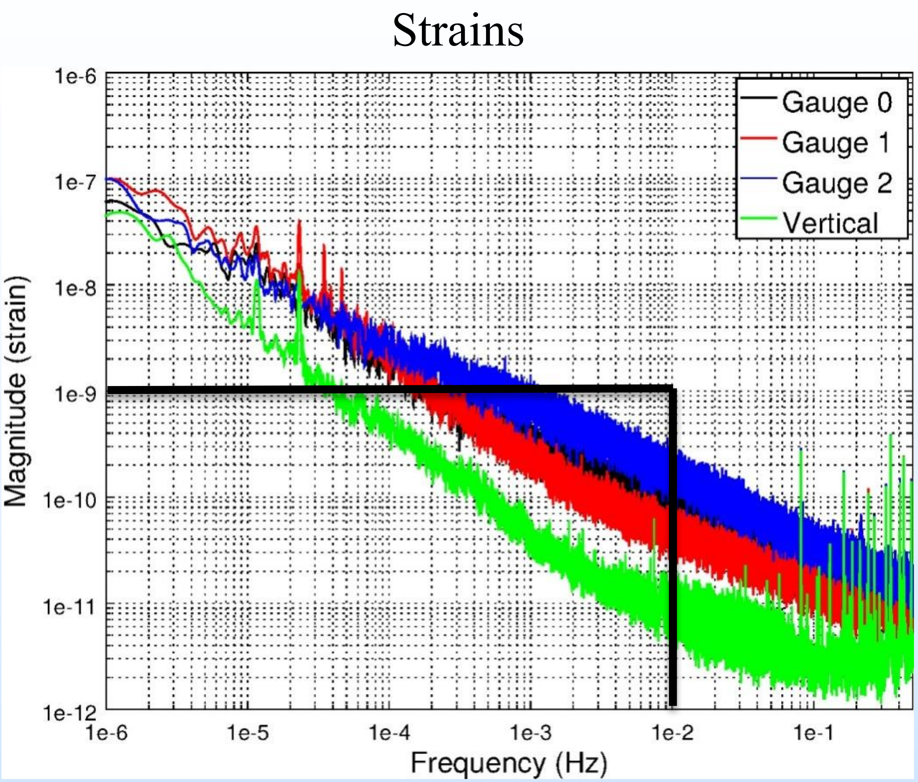


- Loosely coupled to surface
- Clear free period signal
  - Remove using deconvolution
- Large 1 cycle-per-day (CPD)
  - Thermoelastic
  - Barometric

- Uncoupled from surface
- Analog/Digital converter noise
  - Resolution limit of sensor and A/D
- Also 1 cycle-per-day (CPD)
  - Barometric
  - Residual temperature?

Test Deployment Spectra

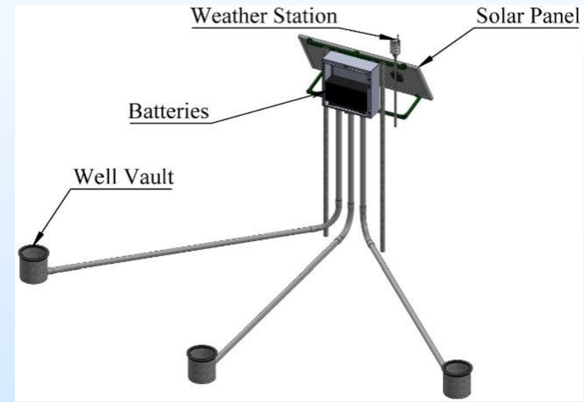




All sensors exceed their design goal of 10^{-9} at 0.01 Hz!

Clemson Full-Scale Deployment

- Three 150 foot wells
  - Cased to rock, ~100 feet
  - Open from 100 to 150 feet for instruments
  - Intended to match final field demonstration



- Flush-mounted well vaults
- Above-ground enclosure
  - Batteries
  - Solar panel
  - Low-power computer
  - Cellular telemetry
  - Weather station

Interpretation

- **Numerical**: strain field in various scenarios, design Avant Field demo
- **Analytical**: new solution of 3D poroelastic rectangular inclusion
- **Inversion**: New algorithm to enhance efficiency on many processors, move to cloud

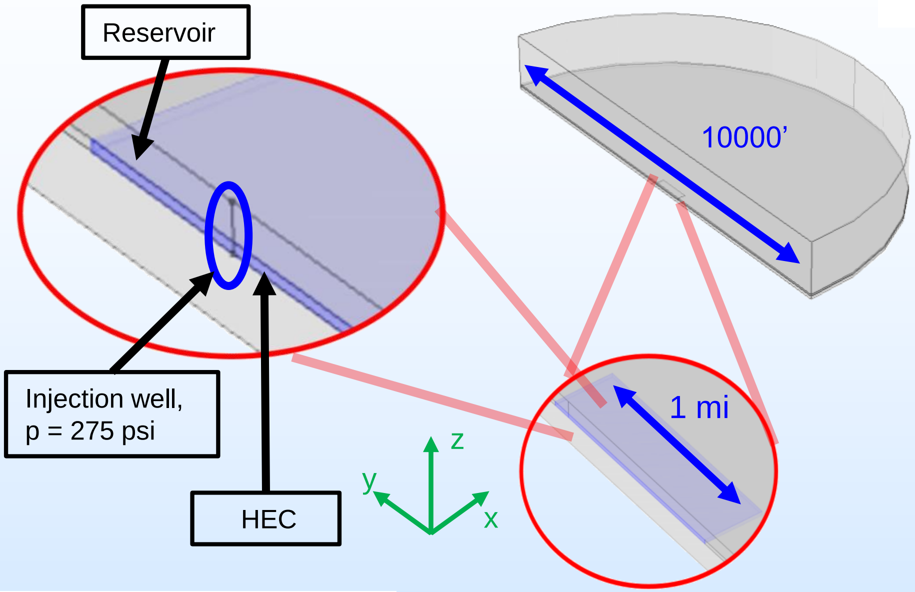
Effect of lens on deformation

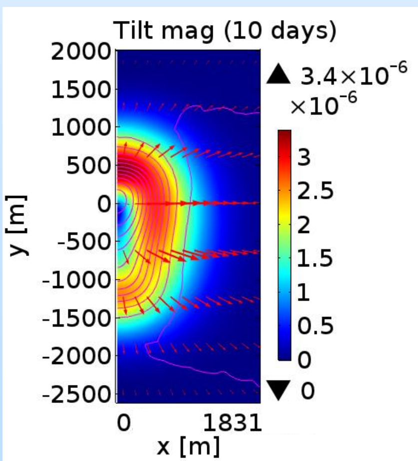
Idealized Avant Field model

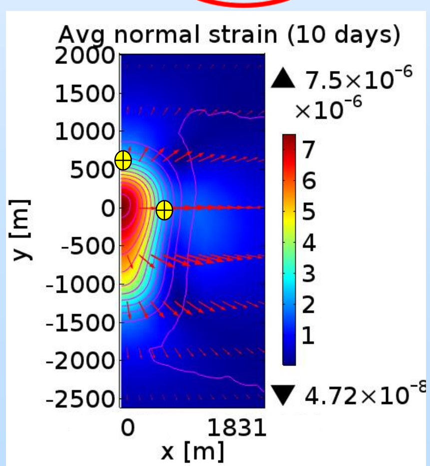
Reservoir: k = 10 mD; Φ = 0.15

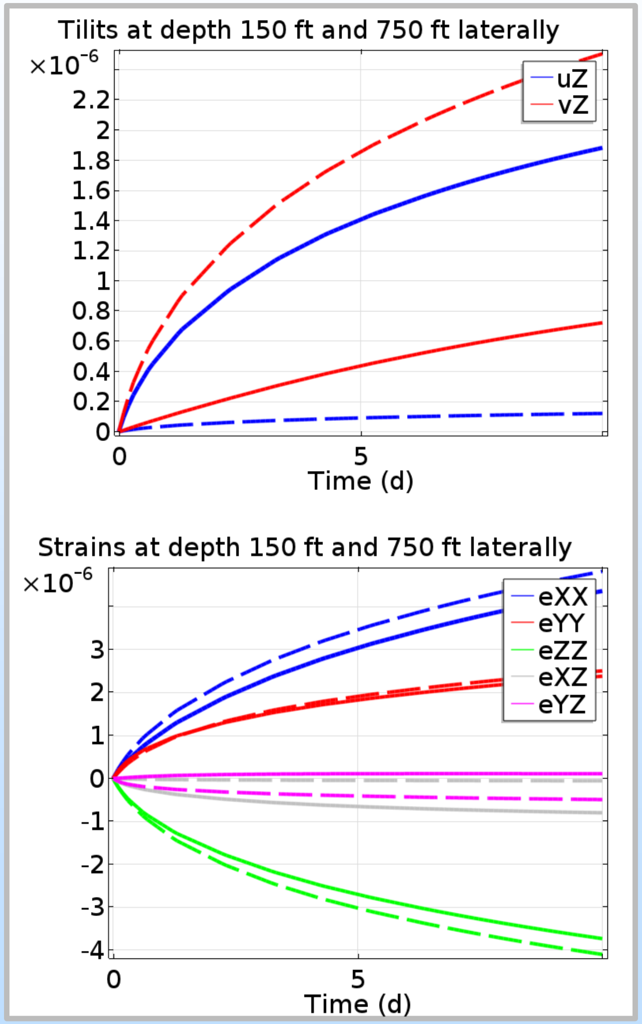
Confining: k = 0.01 mD; Φ = 0.15

HEC: k = 1000 mD; Φ = 0.25

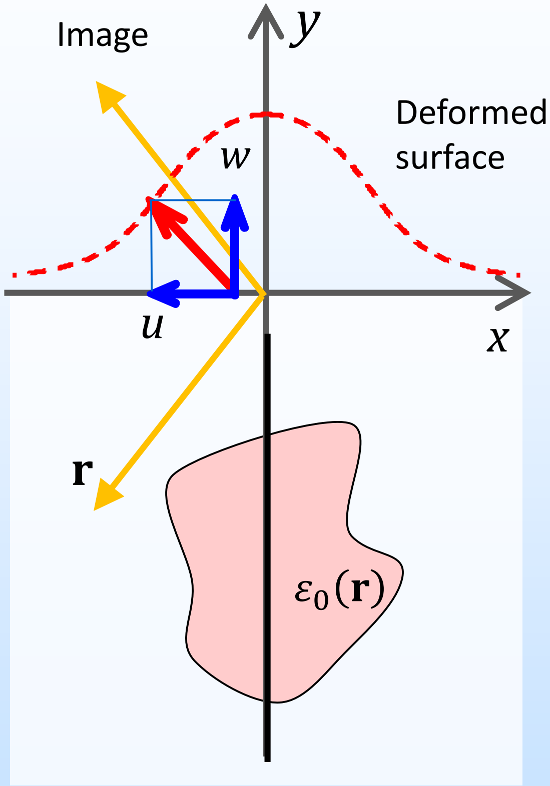








Analytical solutions to poroelastic inclusions



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

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

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

ε_0: transformation strain distribution, from poroelasticity

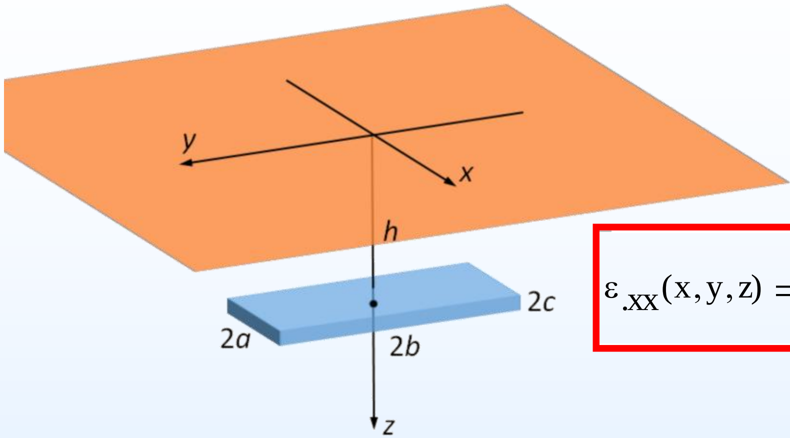
- Use image points [*Mindlin and Cheng*, 1950] to get displacements in half space

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

- 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.

Analytical solutions to poroelastic inclusion



$$\varepsilon_{xx}(x,y,z) = \varepsilon_{xx\_\infty}(x,y,z) + (3-4\cdot\nu)\cdot\varepsilon_{xx\_\infty}(x,y,-z) + 2\cdot z\cdot\frac{\partial}{\partial z}\varepsilon_{xz\_\infty}(x,y,-z)$$

Strain in infinite space:

$$F(x,y,z,z_1,a,b) = \mathrm{sign}(x+a)\cdot\mathrm{sign}(y+b)\cdot\mathrm{atan}\left[-\frac{(z-z_1)\cdot\sqrt{(y+b)^2}}{\sqrt{(x+a)^2}\cdot\sqrt{(x+a)^2+(y+b)^2+(z-z_1)^2}}\right]$$

$$\varepsilon_{xx\_\infty} = -\frac{1}{4\cdot\pi}\cdot\frac{1+\nu}{1-\nu}\cdot\delta_0\cdot\begin{pmatrix} F(x,y,z,h+c,a,-b) - F(x,y,z,h-c,a,-b) - F(x,y,z,h+c,-a,-b) + F(x,y,z,h-c,-a,-b)\ \ldots \\ +F(x,y,z,h+c,-a,b) - F(x,y,z,h-c,-a,b) - F(x,y,z,h+c,a,b) + F(x,y,z,h-c,a,b) \end{pmatrix}$$

Vertical strain gradient:

$$\Omega(x,y,z,a,b,d) = \frac{d-z}{\left[b-y+\sqrt{(x-a)^2+(y-b)^2+(z-d)^2}\right]\cdot\sqrt{(x-a)^2+(y-b)^2+(z-d)^2}}$$

$$\frac{\partial}{\partial z}\varepsilon_{xz\_\infty} = -\frac{1}{4\cdot\pi}\cdot\frac{1+\nu}{1-\nu}\cdot\delta_0\cdot\begin{pmatrix} -\Omega(x,y,z,a,b,h+c) + \Omega(x,y,z,a,b,h-c) + \Omega(x,y,z,a,-b,h+c) - \Omega(x,y,z,a,-b,h-c)\ \ldots \\ +\Omega(x,y,z,-a,b,h+c) - \Omega(x,y,z,-a,b,h-c) + \Omega(x,y,z,-a,-b,h-c) - \Omega(x,y,z,-a,-b,h+c) \end{pmatrix}$$

Optimization

→Cloud-based Analysis

Goals:
- Estimate model parameters that fit data
- Evaluate uncertainty in parameters
- Forecast range of reservoir behavior

workflow

data passing

Parameterization
- Zones
- Geostats

Forward Models
- Comsol
- Albany
- Geocentric
- Analytical
- Other…

Database
- Forward results
- Field observations
- Parameters

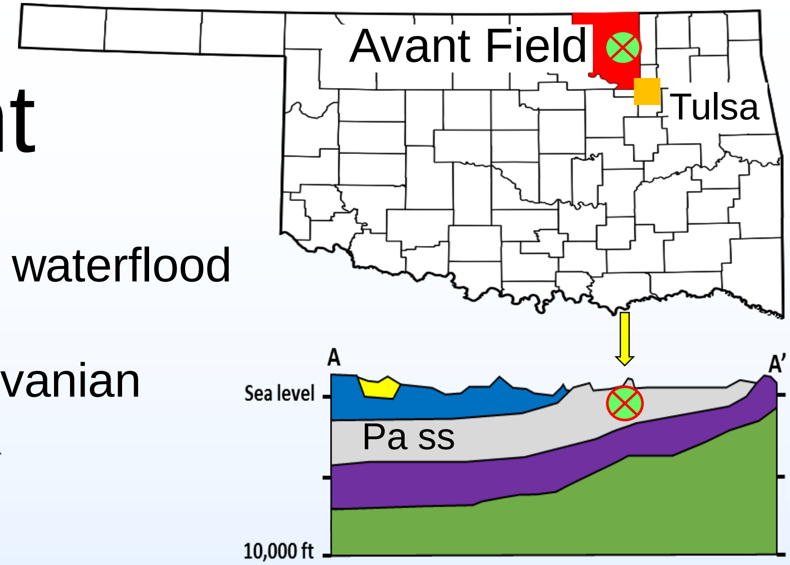
Sampling
- MC
- rjMCMC
- NSGAII
- SPEA2
- Sparsest point
- Other…

Data Assessment
- Multi-objective
- Adaptive

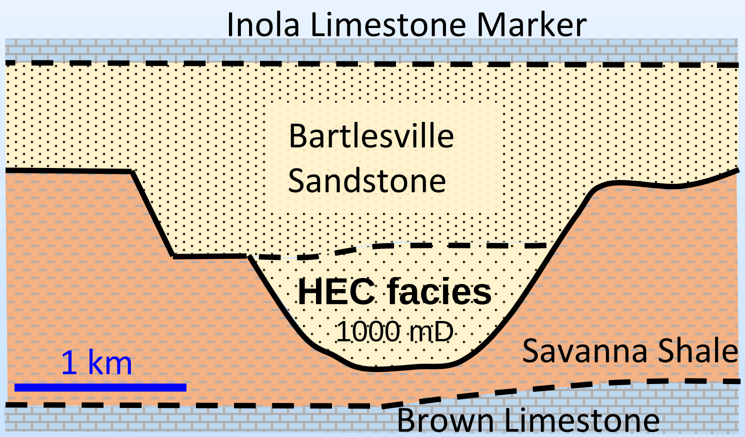
- Methods diverse, flexible
- Each compute job runs independently, on any computer, anywhere (Palmetto, OSG, cloud…
- Information passed on demand
- Scalable

Josh Smith

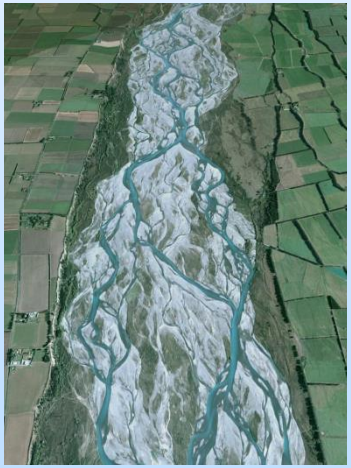
Field Experiment



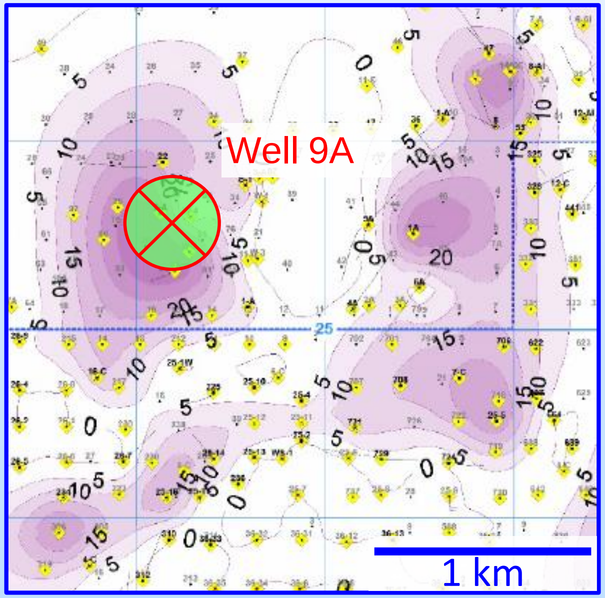
- **Objective**: Measure/interpret strain during waterflood as analog to CO_2 injection
- **Location**: Bartlesville Sandstone, Pennsylvanian
  North Avant Field, Osage County, OK
  100+ years of oil production



Stratigraphic Conceptual Model



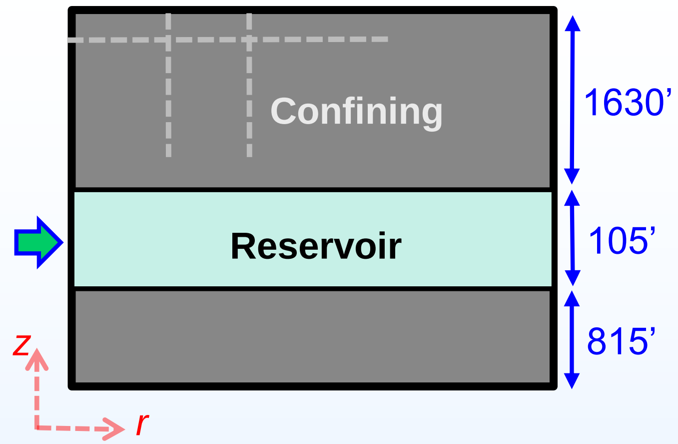
HEC Analog
Rakaia River, NZ

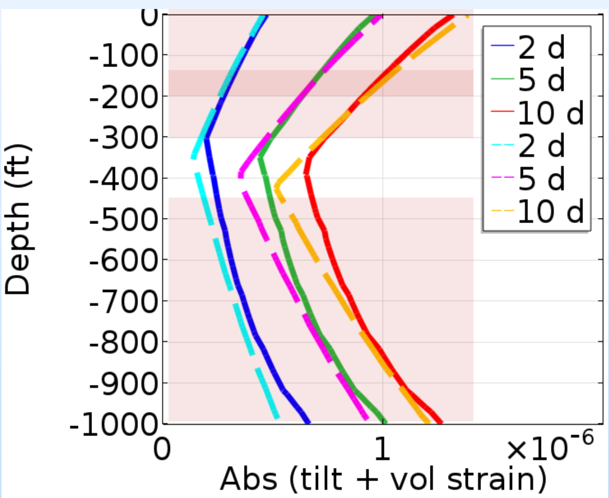


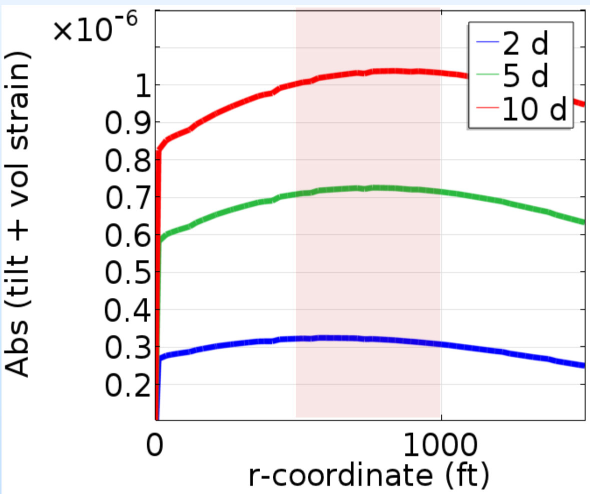
HEC isopach, N Avant Field

Siting Strain Instruments

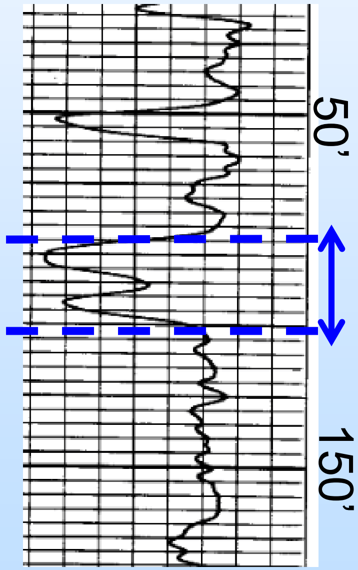
- Strain Magnitude
- Rock Coupling
- Cost
- Access







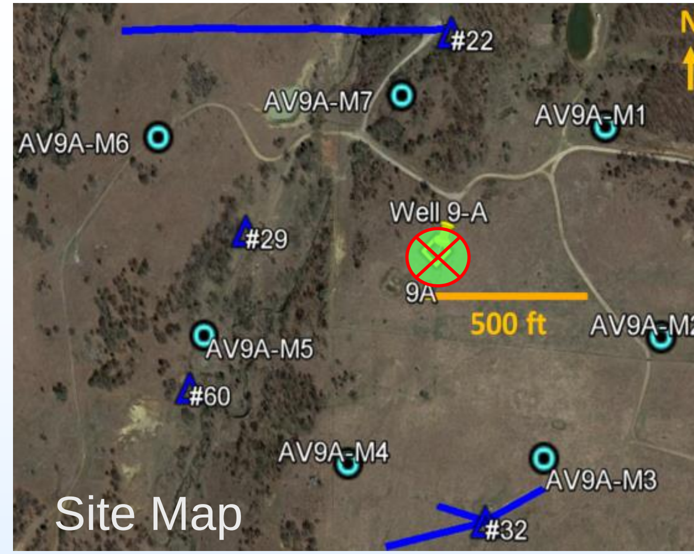
Gamma Log



10 - to 15 ft thick limestone at well 9C, 1.5 mi to the SE of 9A

Reservoir: k = 80 mD Φ = 0.25; **Confining**: k = 0.01 mD Φ = 0.15
E = 15 GPA α = 0.75 ν = 0.23 ρ = 2500 kg/m³

Field Experiment



- Work Plan, Design, July 2016
- Install Geodetic Strainmeter, Sept 7-12 2016
- Install Clemson Strainmeters, Nov 2016
- Water flooding, Winter-Spring 2017
- Interpretation, Spring-Summer 2017

Accomplishments to Date

- Instruments
  - Portable, grout-in instruments designed, built, tested
  - Optical smart casing designed, built
  - Prototypes field operational, meet design specs
  - Full-scale installation ongoing
- Analyses
  - Cloud-based optimization method developed
  - Poroelastic 3D analytical sol’n tested
- Field demo
  - Workplan finished
  - Instrument locations optimized
  - Installation of Gladwin strainmeter Sept 2016
  - Expected deformation at site feasible to measure

Synergy Opportunities

– In-situe strain measure/interpret
– Other monitoring methods at Avant Field demo

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Summary

Measure and interpret strain tensor during injection

– Instruments

- high rez, removeable, grout-in, smart casing
- Prototypes built, field testing underway, specs look good

– Analysis

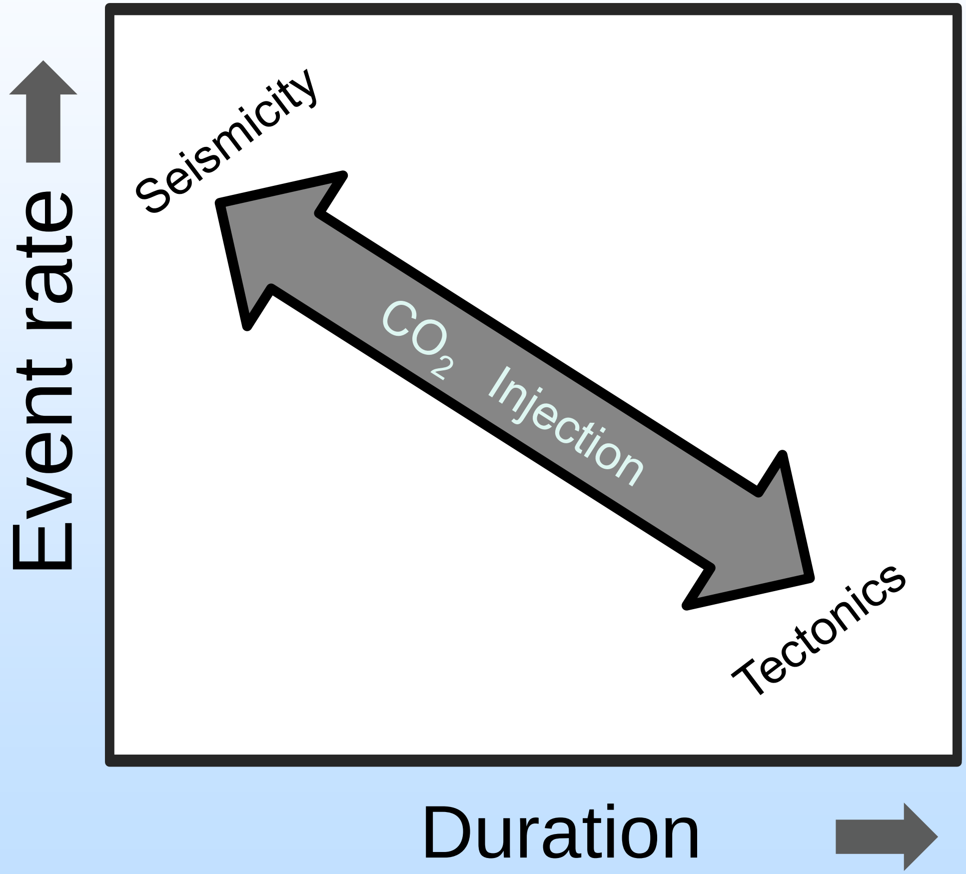
- Cloud-based inversion method
- Numerical and analytical poroelastic solutions

– Field demo

- Avant Field test designed
- Field deployment on going

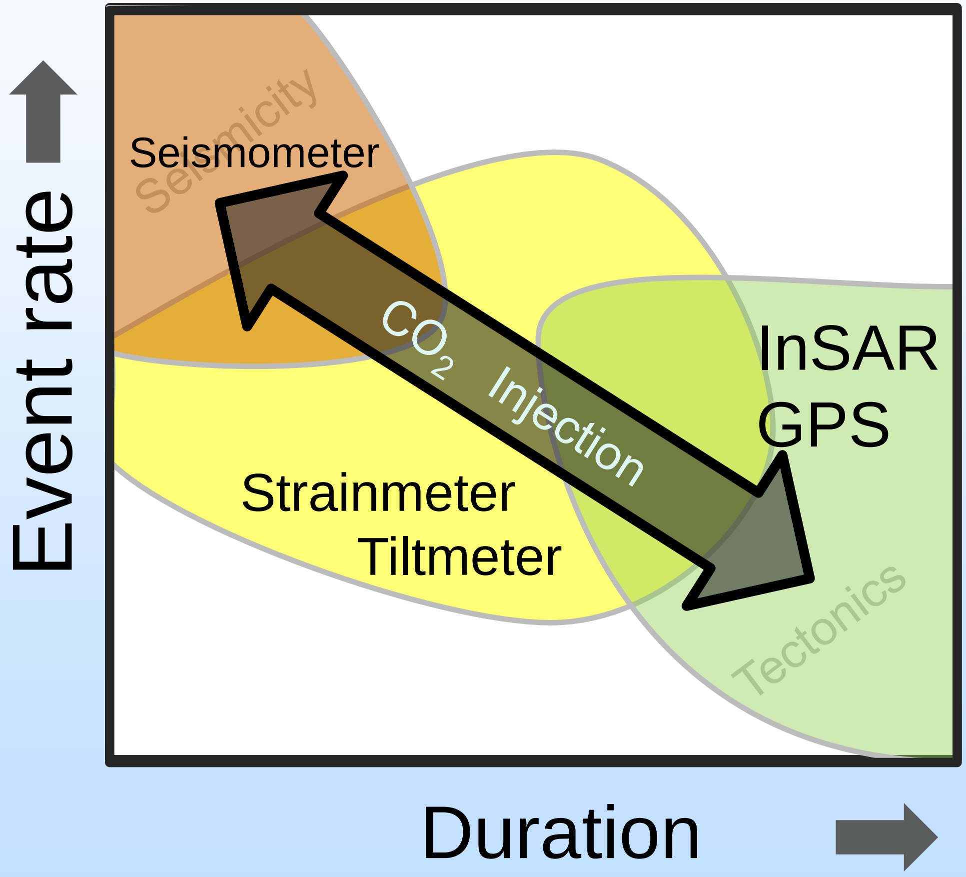
In Situ Strain

Instrumentation

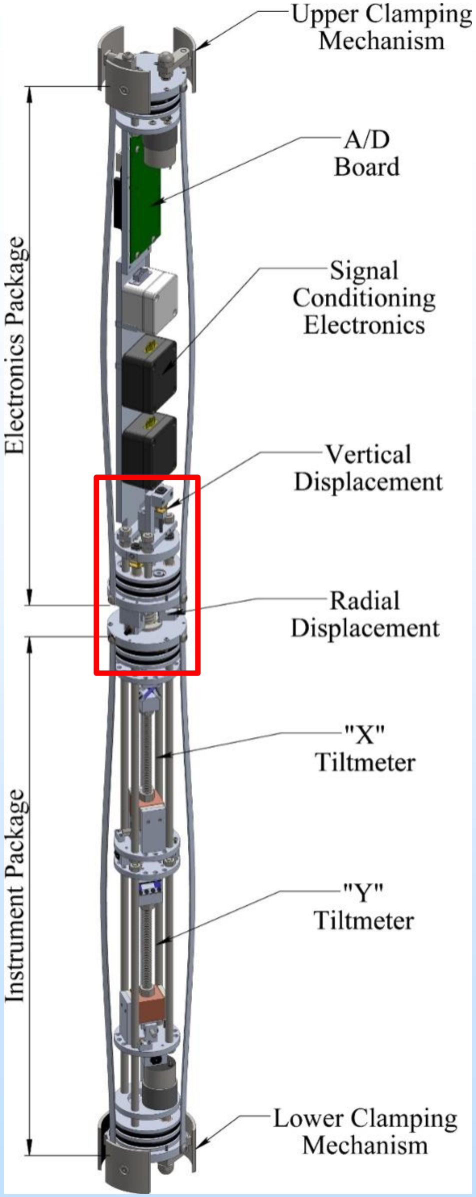


In Situ Strain

Instrumentation

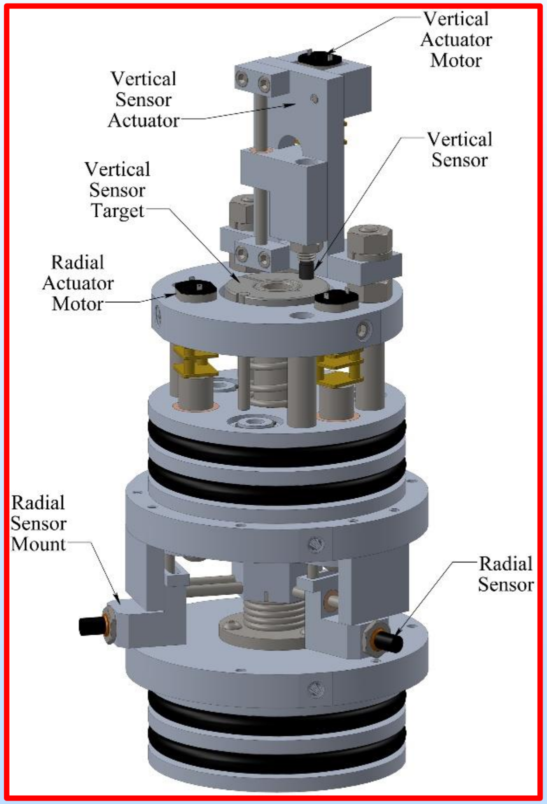


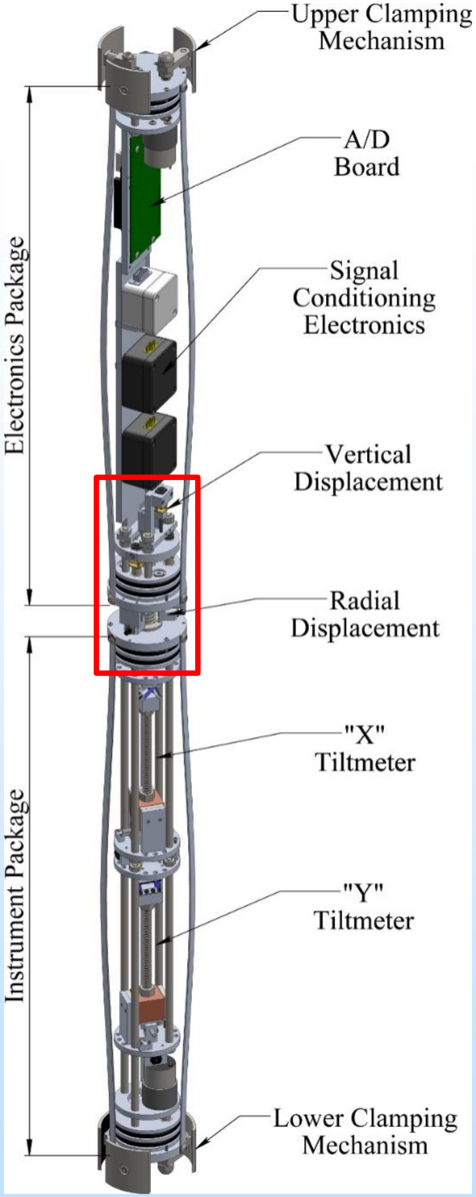
Radial and Vertical Sensors



Removable

- Three radial displacement transducers
  - Deployable in casings from 3.50” to 4.56” diameter
  - Scotch yoke mechanism to deploy and retract sensors
- One vertical
  - Measures displacement between clamped packages
  - Linear actuator to zero vertical sensor





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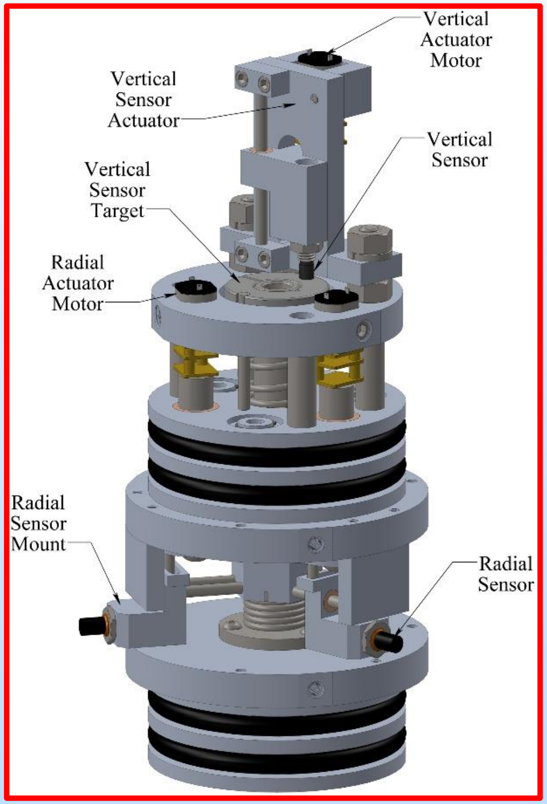
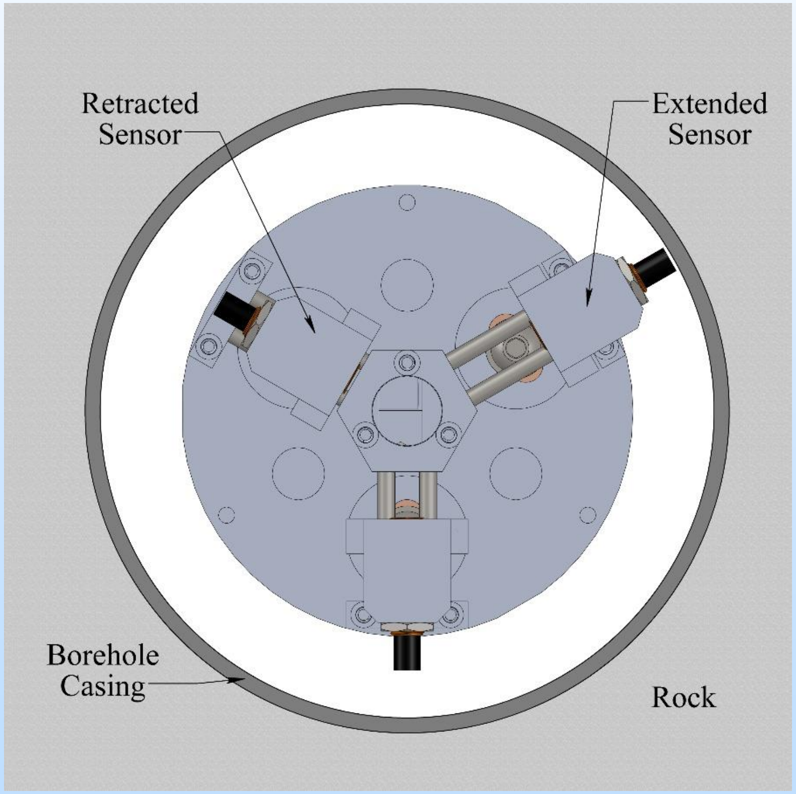
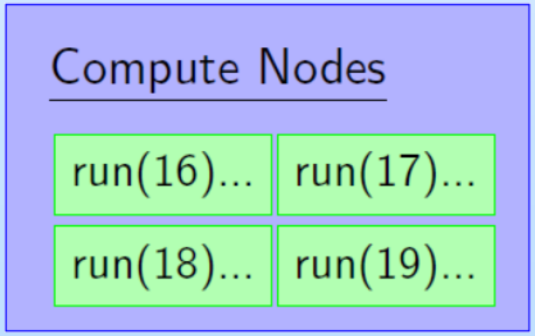
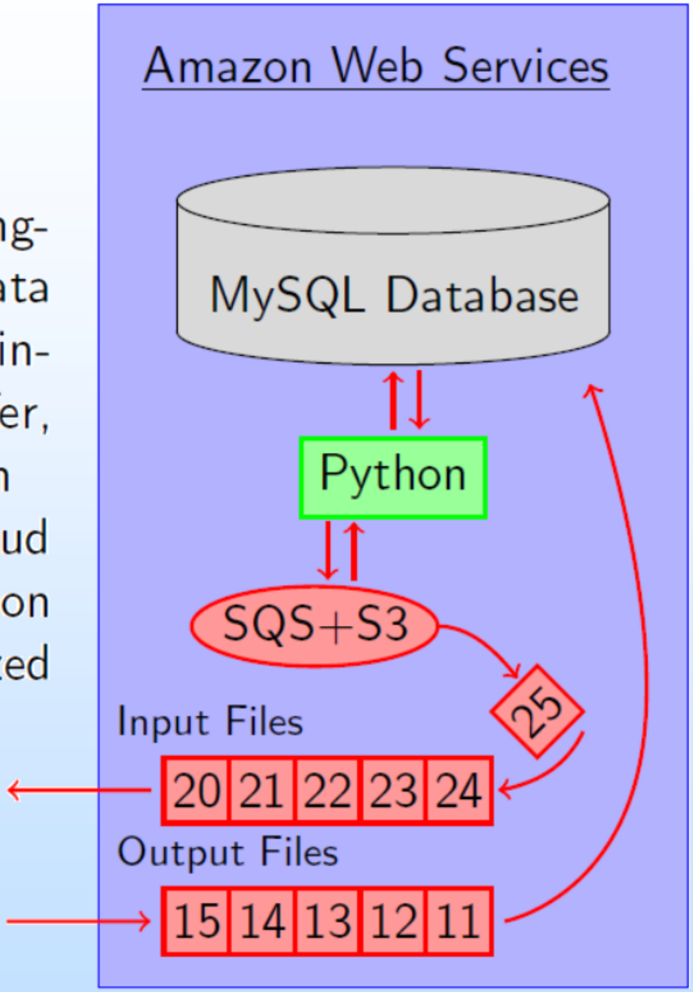




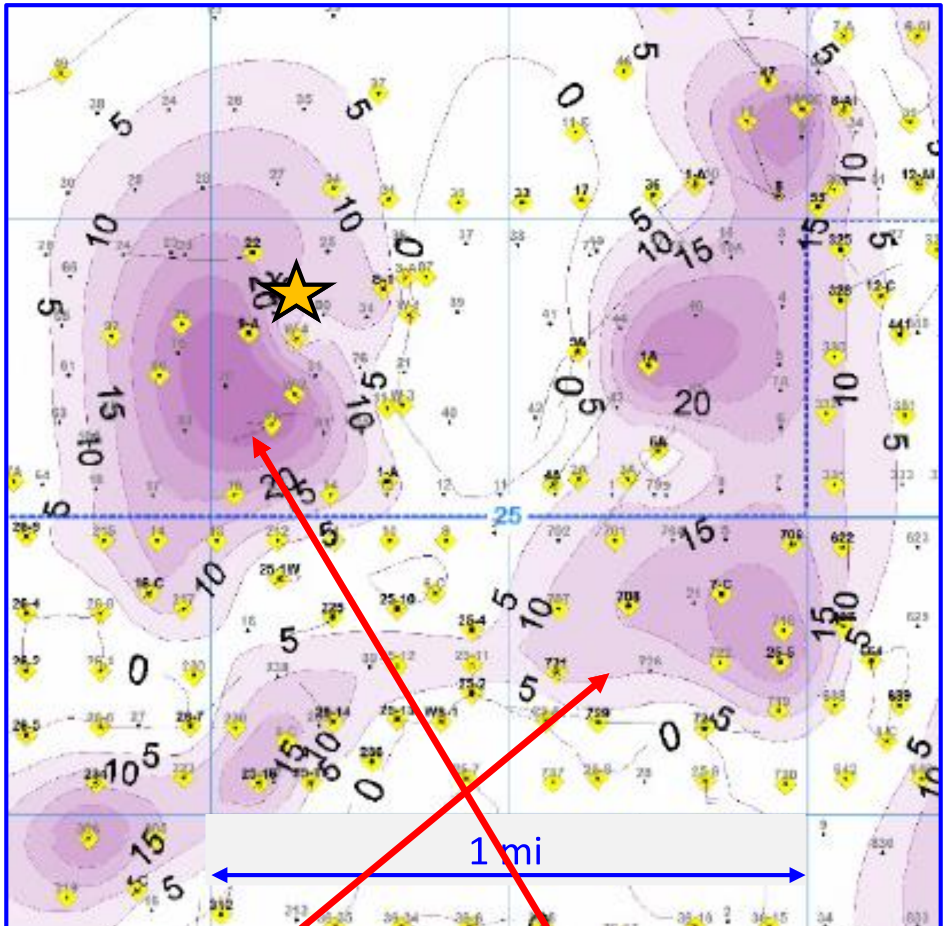
Inversion Workflow

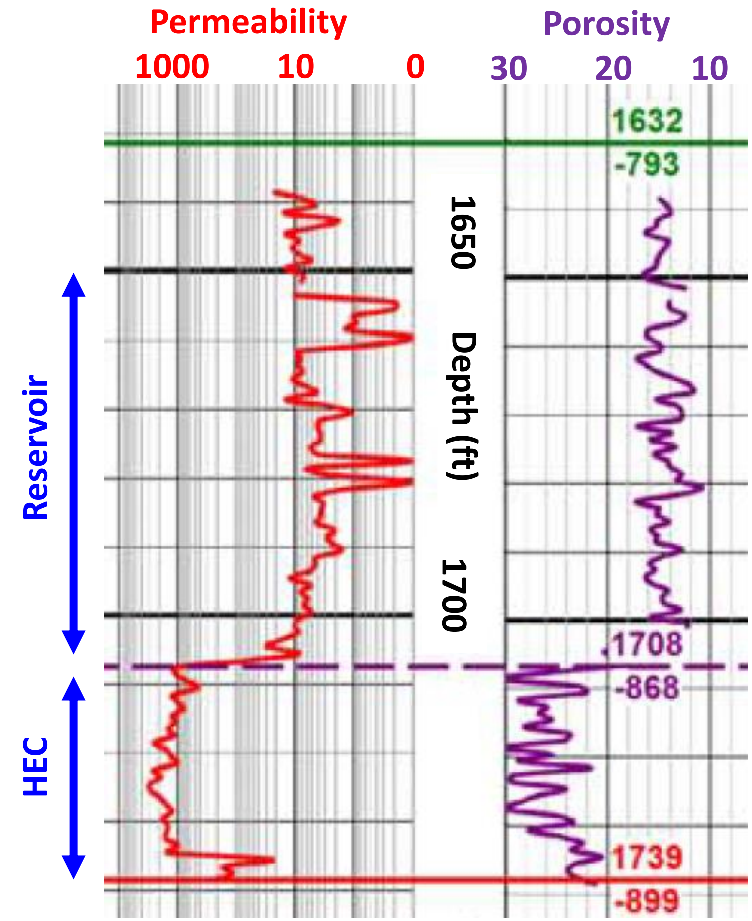
- MySQL: Centralized, long-term storage of structured data
- Python: Inverse methods, input file assembly, data transfer, post-processing, visualization
- SQS/S3: Temporary cloud storage for efficient distribution of input files to decentralized pool of compute nodes

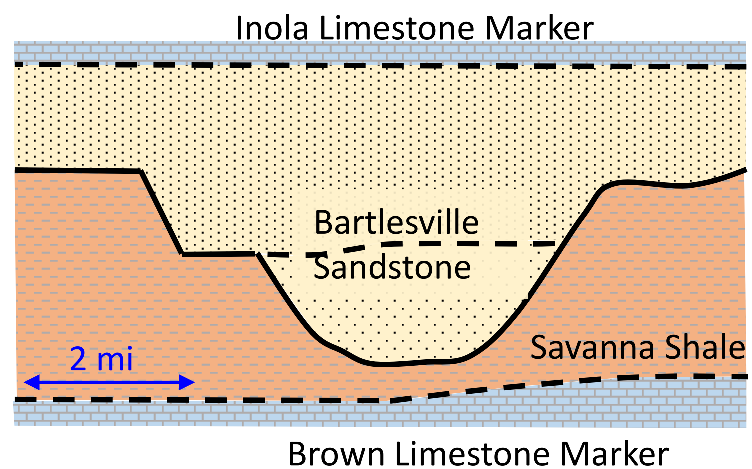




Local geology: High energy channel (HEC)







- Channels of high permeability (1000 mD)?