CHARACTERIZING AND INTERPRETING THE IN SITU STRAIN TENSOR DURING CO_2 INJECTION

Project Number DE-FE0023313

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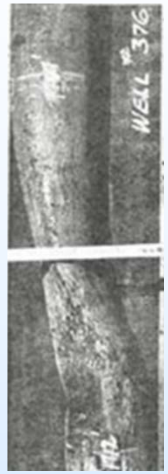
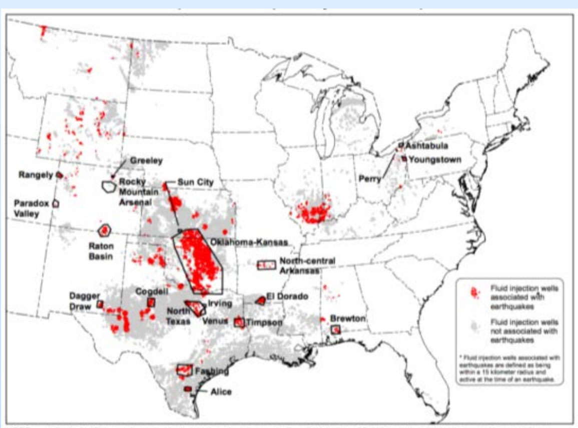
U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 1-3, 2017

Strain from Fluid Injection/Recovery

Damaged home, Prague, OK

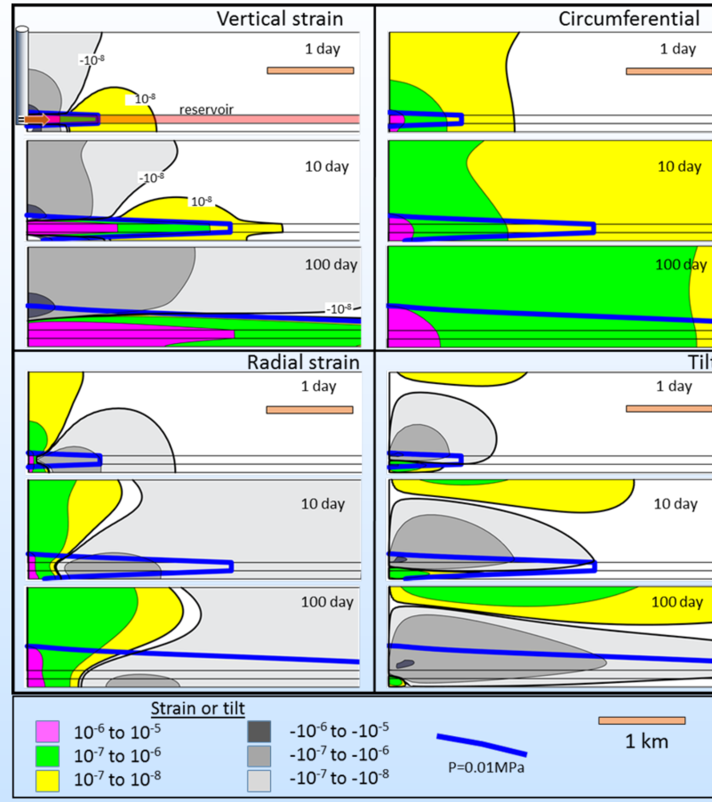


Deformed well casing



Earthquakes (red) and injection wells (grey)

Subsidence, Central Valley CA



Strain field in the vicinity of an injection well

Project Overview
Goals and Tasks

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 CO_2 storage.

Tasks

1. **Instrument Development**
2. **Theoretical Analysis**
3. **Field Demonstration**

Outline

Technical Status
Accomplishments
Lessons Learned
Synergy
Summary

Instrument Development

Scott DeWolf

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

→Prototypes

- – Removable multicomponent
- – Expendable, grout-in multicomponent
- – Expendable single component, cheap

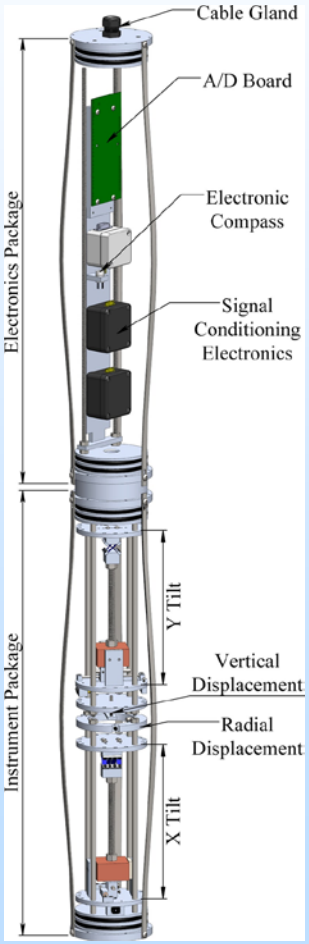
Instrument Development

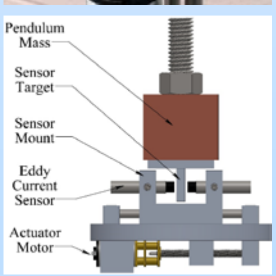
Grout-In Eddy Current System

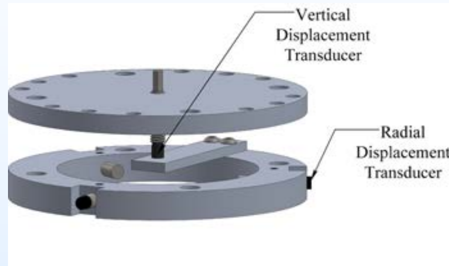
- Commercial sensor integration
- 2 tilts, 3 horizontal & 1 vertical strain
- ~1 part-per-billion resolution

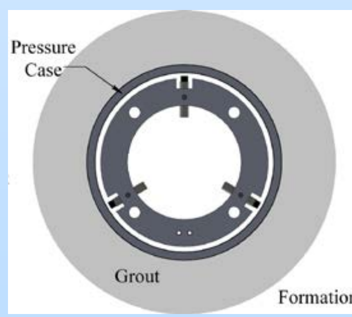
Volumetric Optical Interferometer

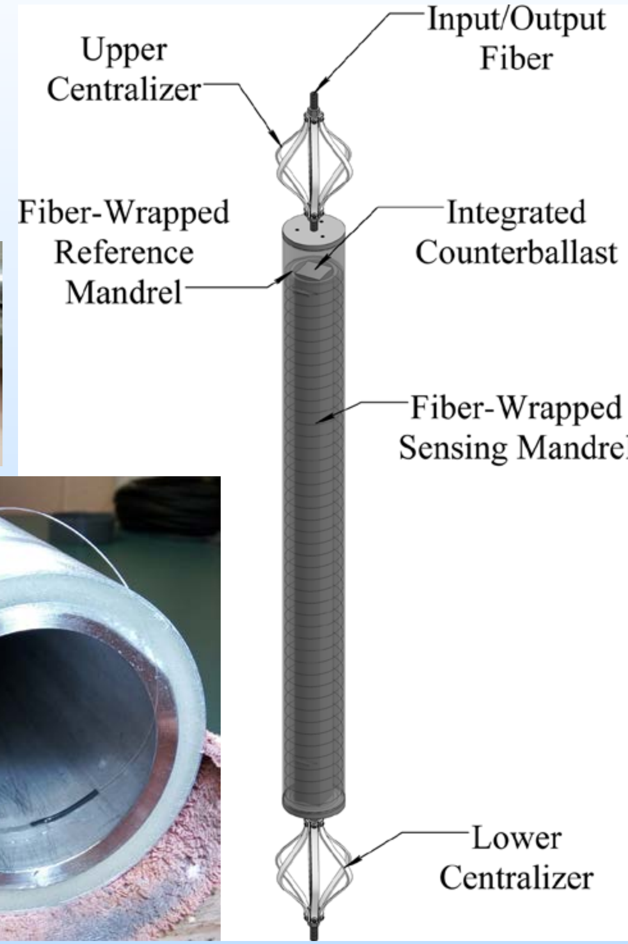
- Pair of 220 m wrapped fibers
- Welded exterior, fully potted interior
- ~1 part-per-trillion resolution











Instrument Deployments

Local Field Site (Clemson, SC)

Injection Analog Site (Avant, OK)

Tensor & Tilts

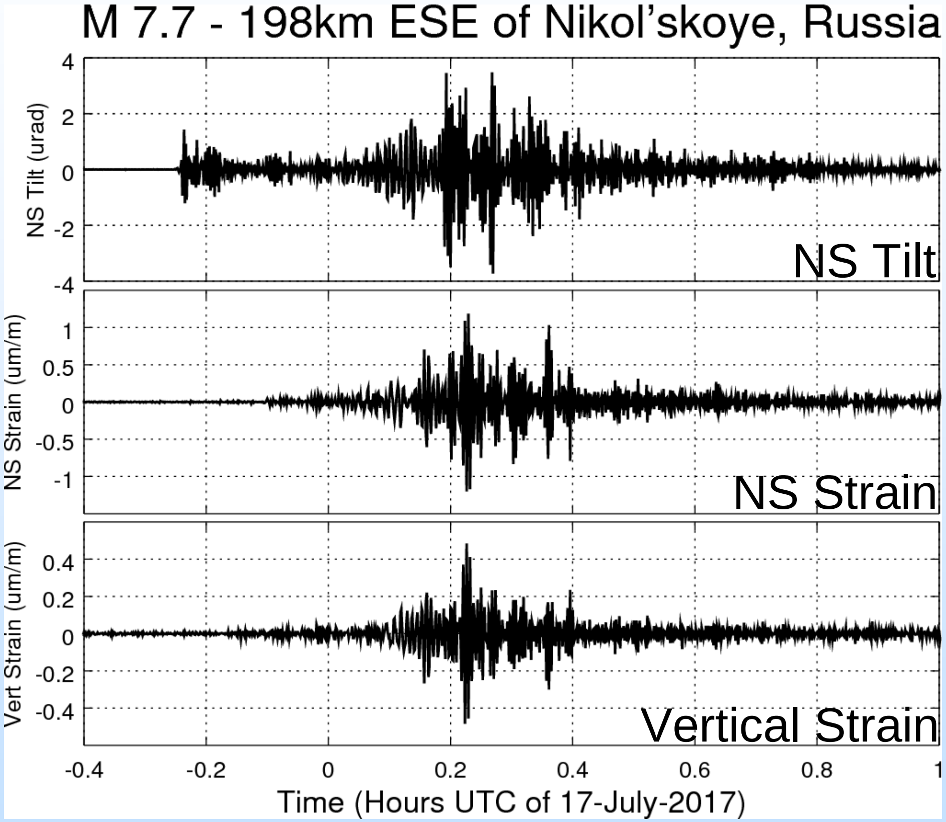
Volumetric

Gladwin Tensor

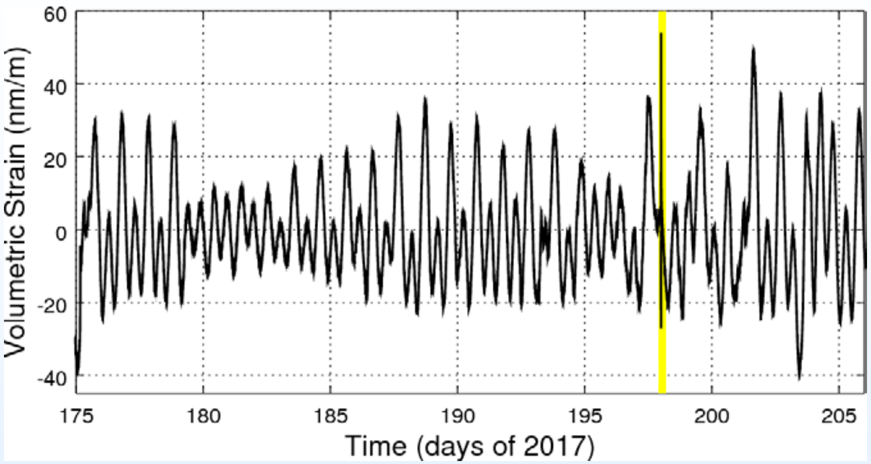
Tensor & Tilts

Volumetric

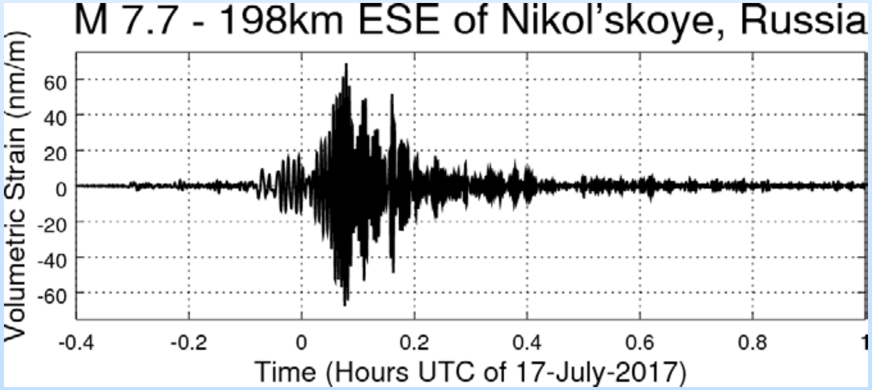
Instrument Development



Teleseisms on tensor strainmeter (Avant, OK)

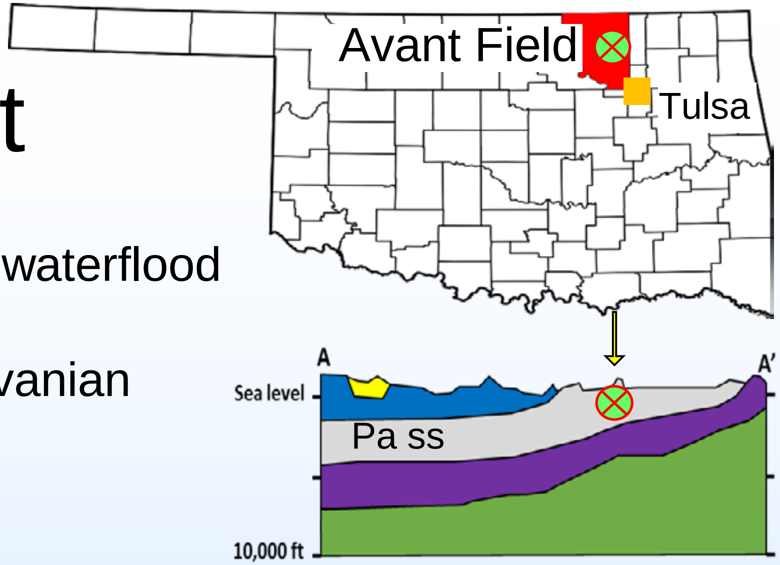


Tides on volumetric strainmeter (Clemson, SC)

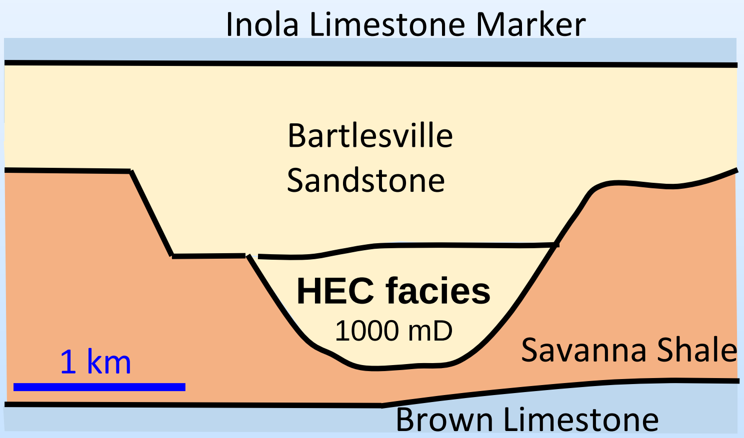


Teleseisms on volumetric strainmeter (Clemson, SC)

Field Experiment



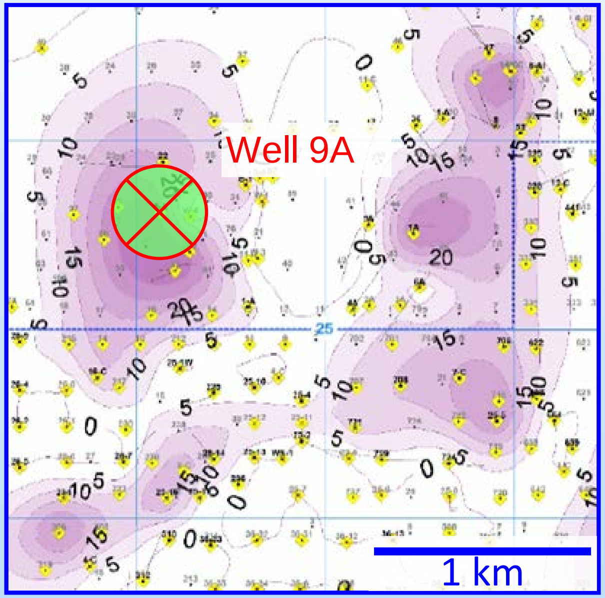
- **Objective**: Measure/interpret strain during waterflood as analog to CO_2 injection
- **Location**: Bartlesville Sandstone, Pennsylvanian North Avant Field, Osage County, OK 100+ years of oil production



Stratigraphic Conceptual Model

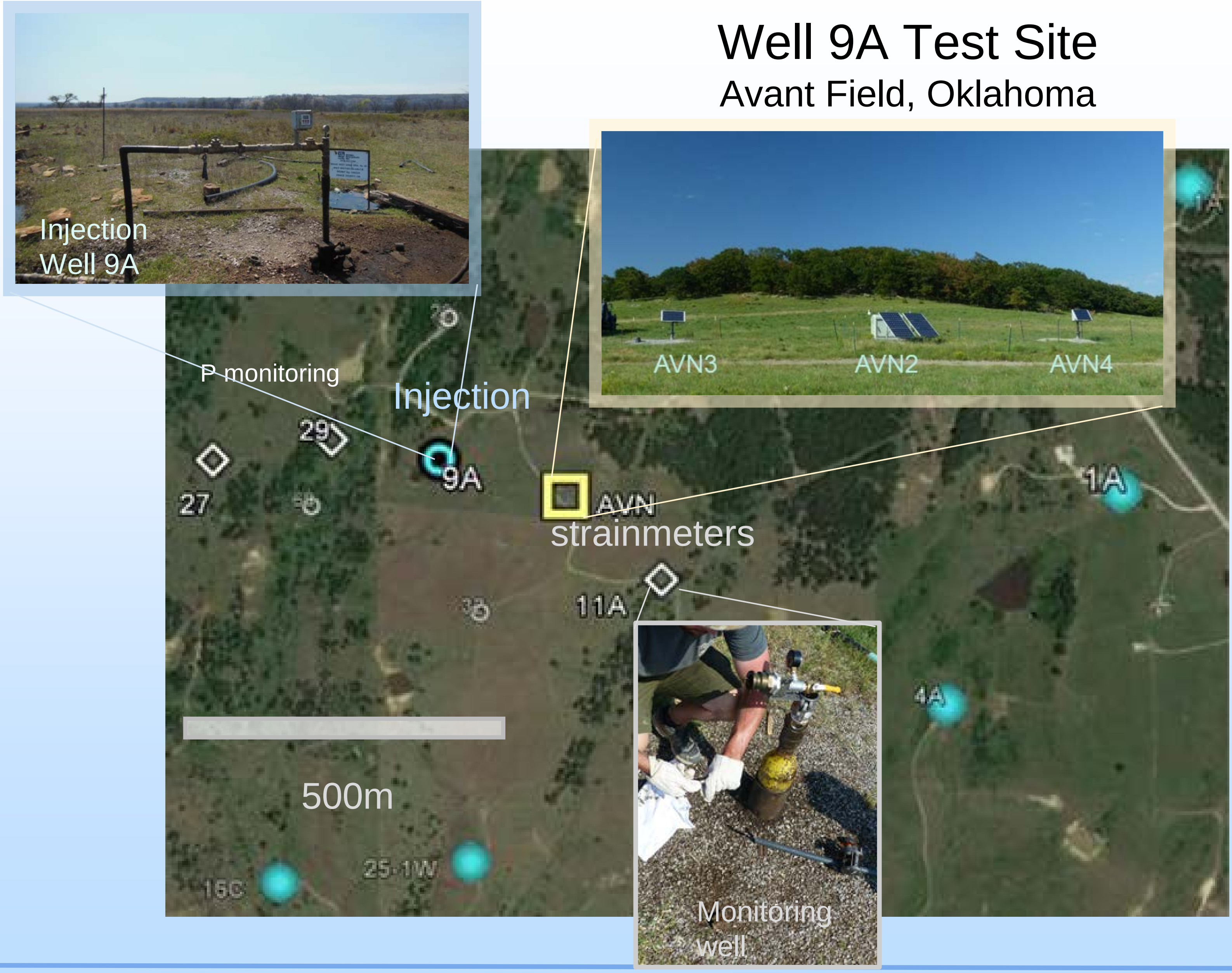
HEC Analog

Rakaia River, NZ

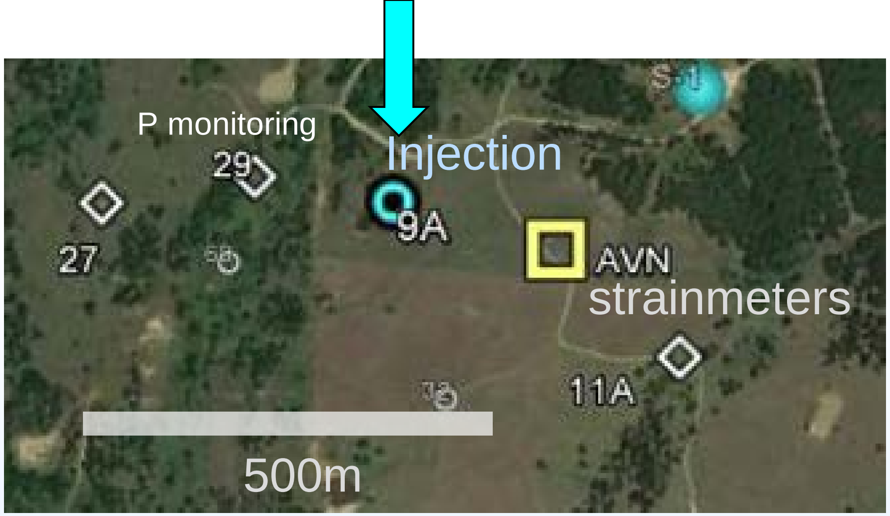


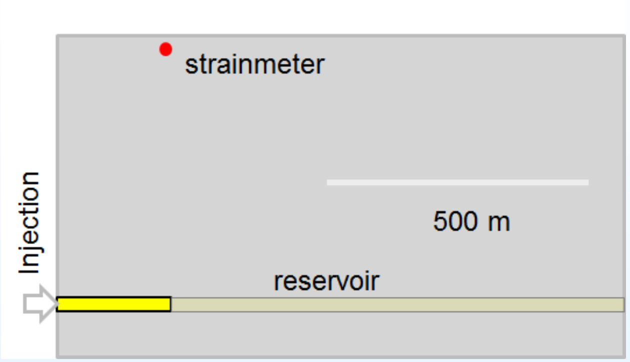
Permeable sand isopach

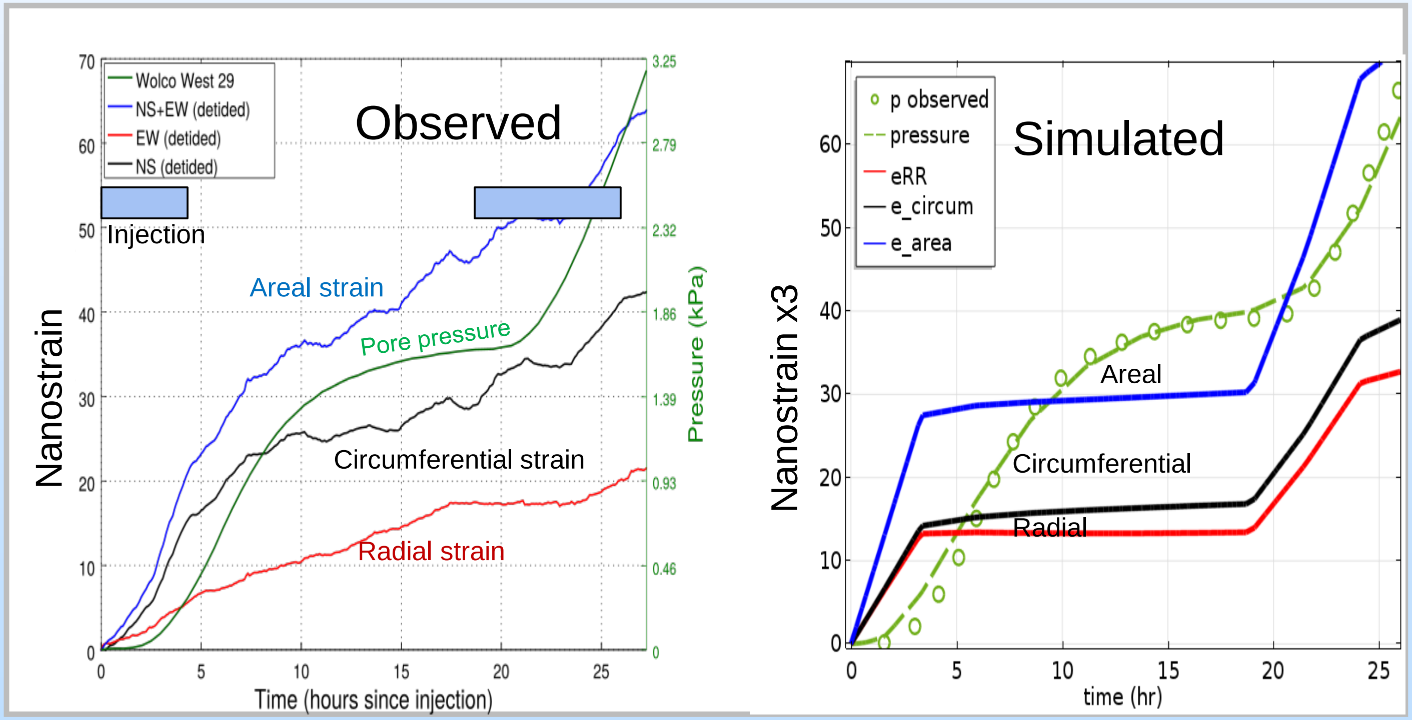
Well 9A Test Site
Avant Field, Oklahoma



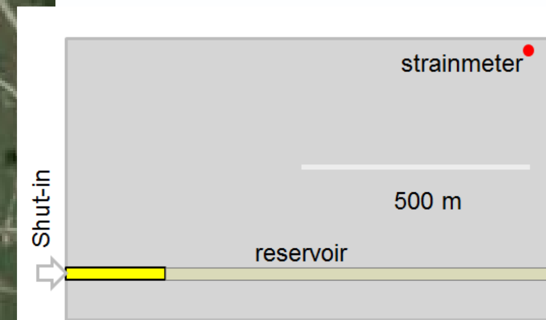
Injection Test at 9A

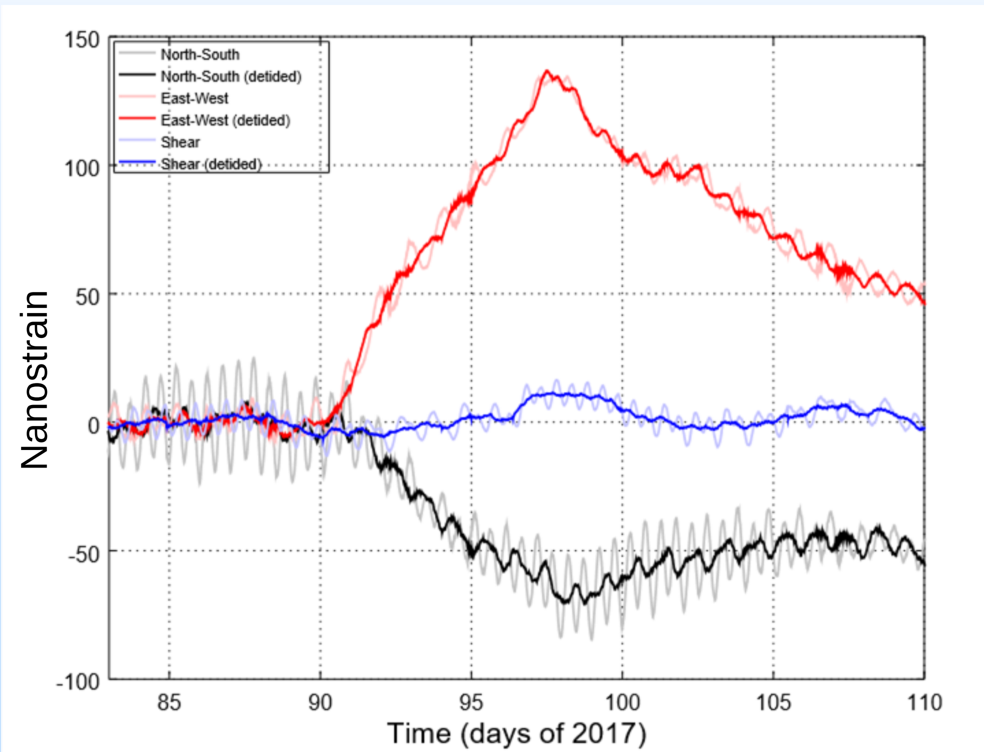


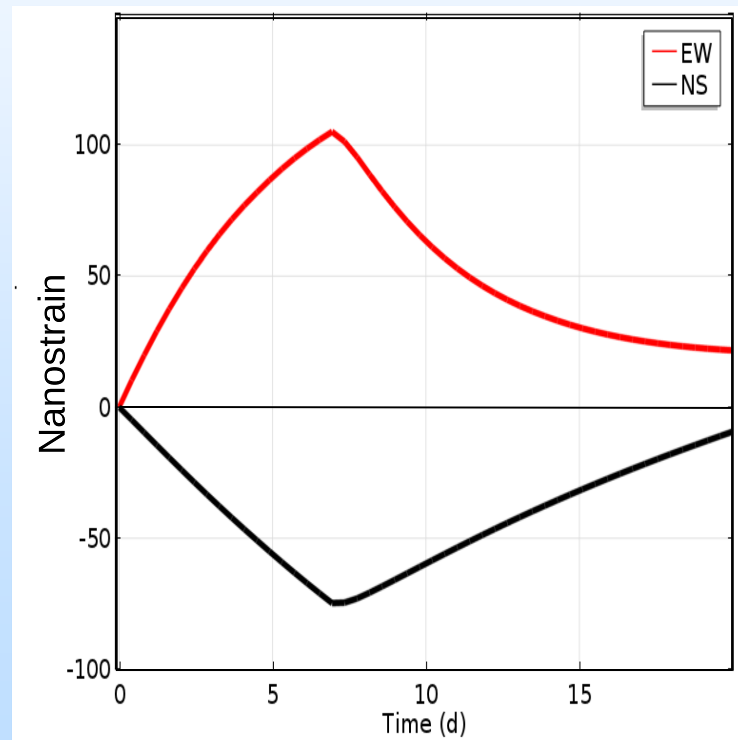




Shut-in Test at 1A







Stephen Moysey

Inversion Approach

Space Filling

- Monte Carlo
- Sparsest sampling (Voronoi)

High Efficiency Minimization (Exploitation)

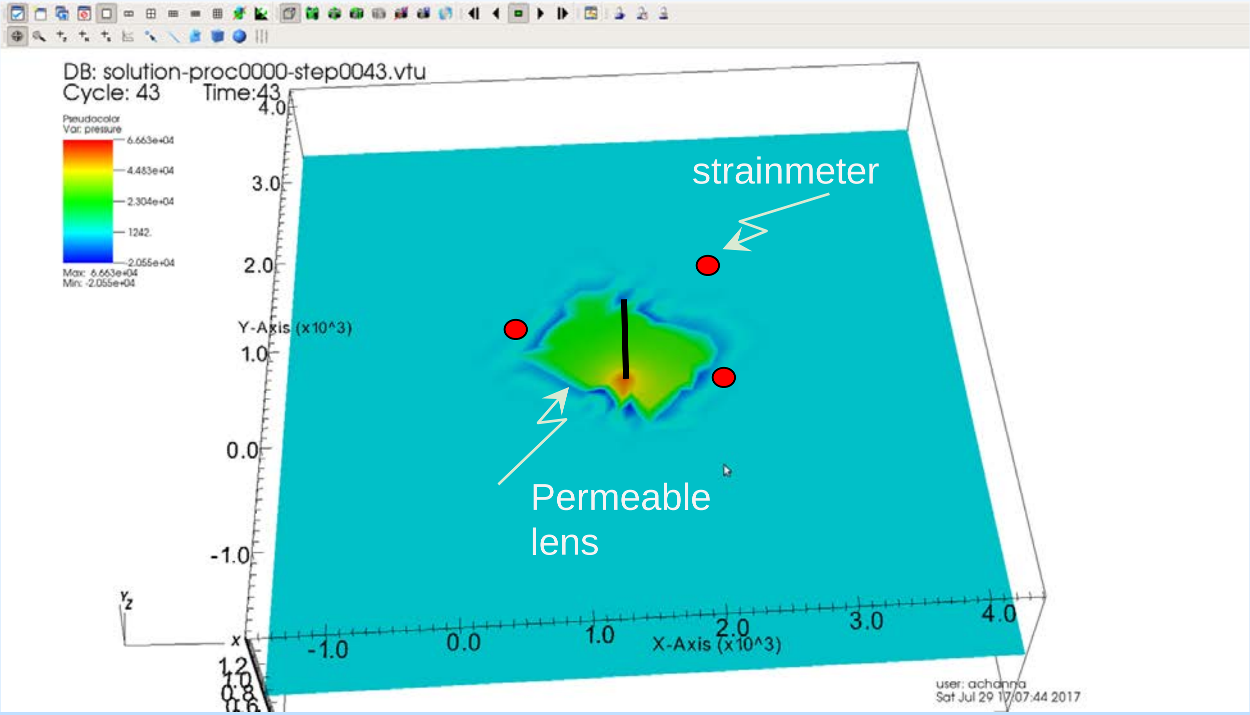
- Delayed rejection sampling
- Genetic Algorithms (NSGAII, SPEA2) - global
- Gradient descent – local

Uncertainty Evaluation (Exploration)

- Markov chain Monte Carlo (McMC)
- Reversible jump McMC

Avant Field Forward Model

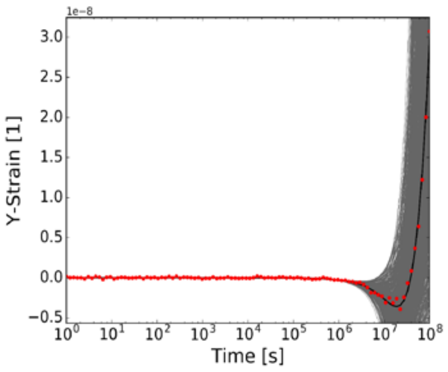
- Code: Poroelastic, single phase, FEM, GeoCentric (Josh White)
- Geometry: Depth, thickness, wells from site data
- Mesh generation: Automated scripts with 30+ wells
- Heterogeneities: Idealized lens similar to known features
- Data: Strain at 3 shallow locations representing strainmeters

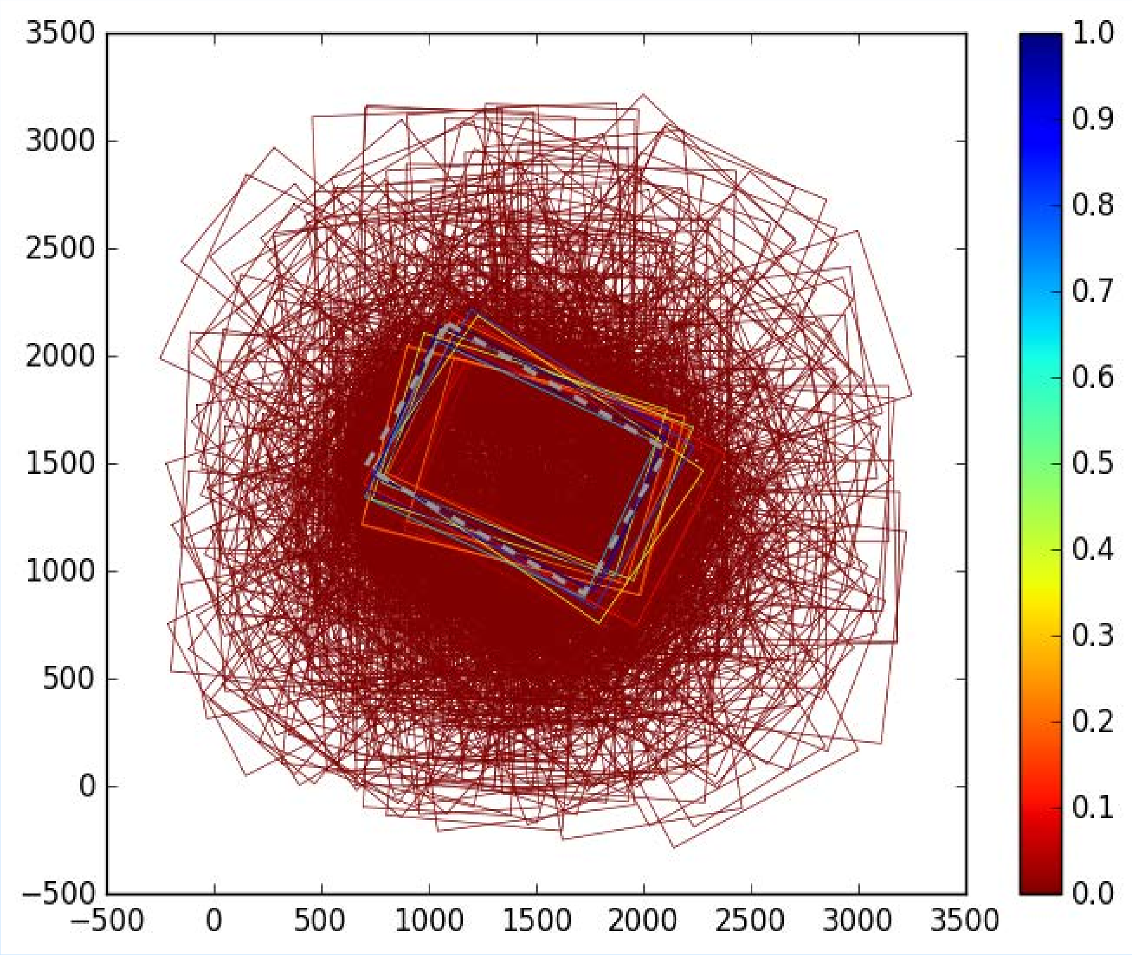


Locating Permeable Lens
using data from 3 shallow strainmeters

1. Space filling algorithms (eg Voronoi) begin by running simulations with diverse set of zone geometries

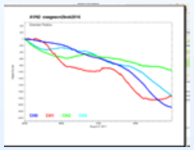
1. Delayed rejection algorithm selects best data-fits and runs simulations with similar geometries





Accomplishments to Date

- Instruments
  - 4 new strainmeters designed, built, deployed, working
  - Gladwin strainmeter deployed, working
  - Data available, https://www.unavco.org/instrumentation/networks/status/pbo/overview/AVN2
  - Removable instrument under development



1 Aug 2017

- Analyses
  - Cloud-based optimization method developed
  - Inversion of synthetic field case promising
- Field demo
  - Gladwin, volumetric, tensor strainmeters working at Avant Field
  - 3 pressure transducers deployed, measuring ambient
  - Brief injection test
  - Shut-in detected, field operation may be used to characterize

Lessons Learned

Technical

- Coupling to rock
- Grouting
- Calibration

Logistics

- Well field operation
- Accessibility
- Land owner, mineral rights

Communication

- Multiple PIs, Industry partners

Synergy Opportunities

- Strain monitoring demonstrations at other sites
- Other monitoring methods at Avant Field site
- Oklahoma earthquakes
- Stress change

Summary

Measure and interpret strain tensor during injection

–Instruments

- high rez, removeable, grout-in, volumetric
- Prototypes built, installed, working. Data available

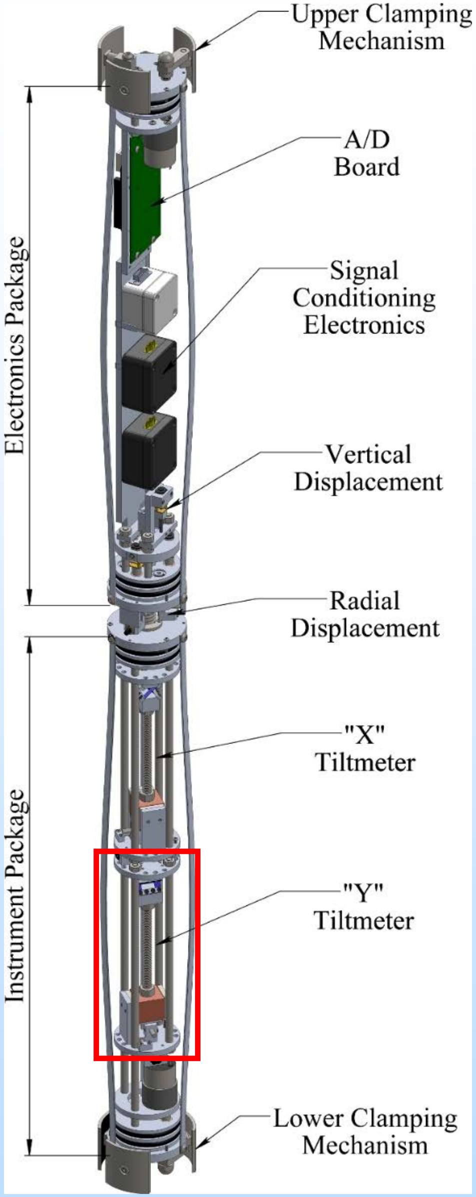
–Analysis

- Cloud-based inversion method
- Application using synthetic data looks good

–Field demo

- Working strainmeters at Clemson site, Avant Field site
- Preliminary data from injection encouraging
- Longer injection tests August-January
- Fluid handling operations may be used for characterization

Two-Axis Tiltmeter



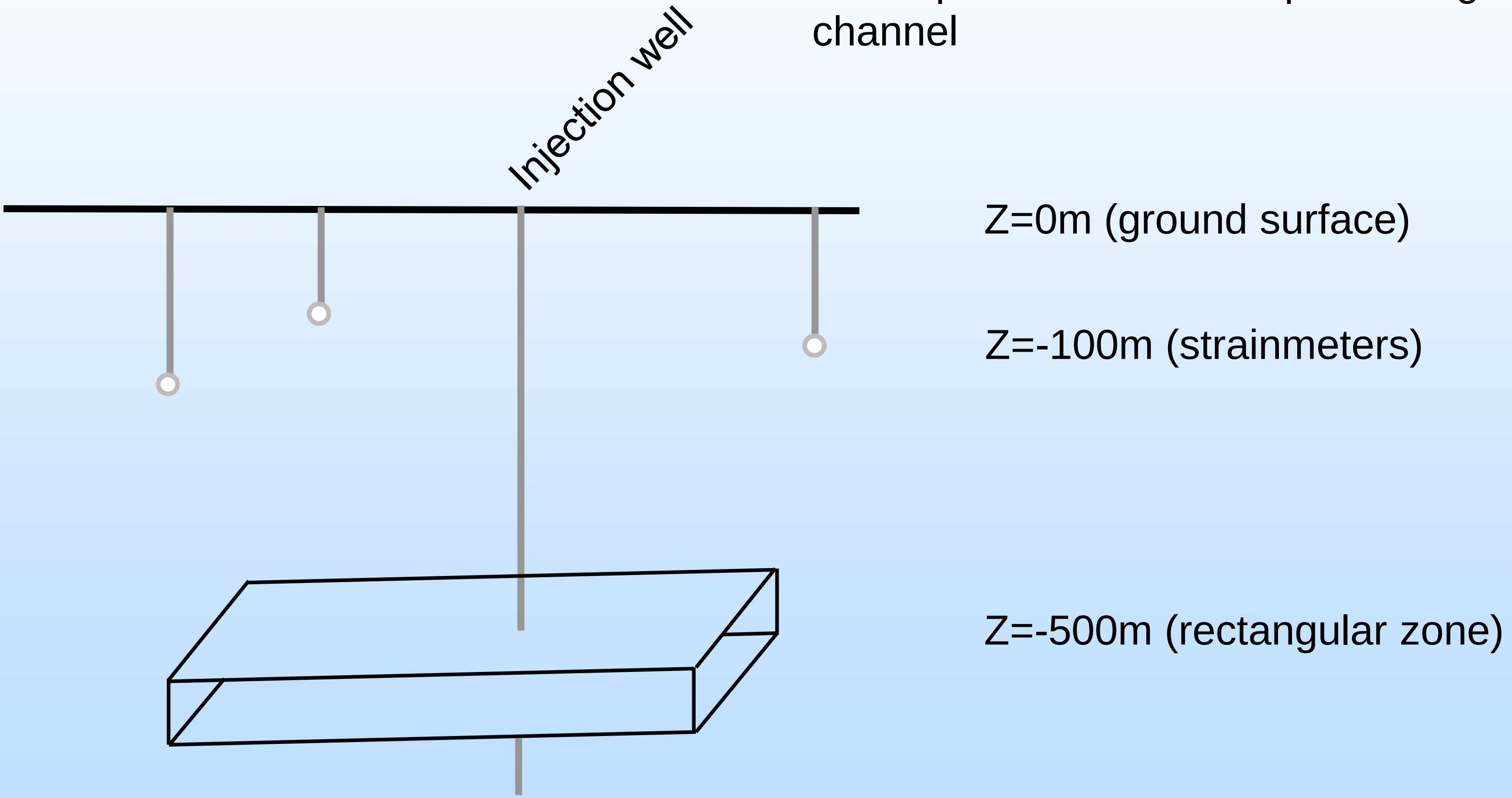
- Crossed flexure hinge design
- Re-zero sensors w/actuator:
  - Removable: $\pm 4.2^{\circ}$
  - Expendable: $\pm 12.9^{\circ}$
- 0.17 m baseline, ~5 s free period
- Differential eddy current sensors ~0.1 nm for nrad resolution

Scott update of instruments

Fiber instrument
Volumetric and casing

Permeable Channel Identification

Preliminary Avant field inversion:
•Uses synthetic strainmeter data to locate permeable zone representing a channel



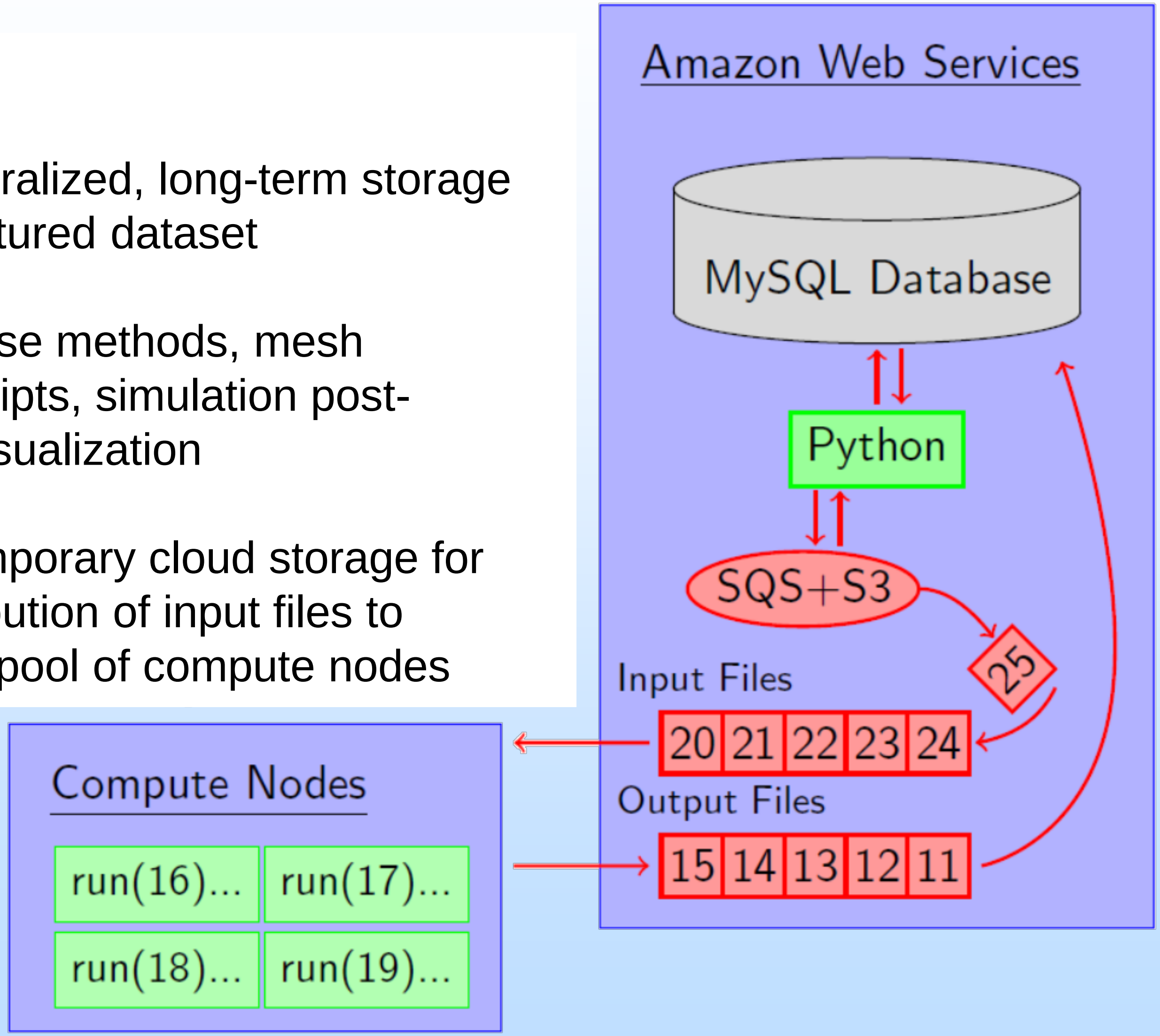
Inversion Methods

Workflow

•MySQL: Centralized, long-term storage of highly-structured dataset

•Python: Inverse methods, mesh generation scripts, simulation post-processing, visualization

•SQS/S3: Temporary cloud storage for efficient distribution of input files to decentralized pool of compute nodes



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

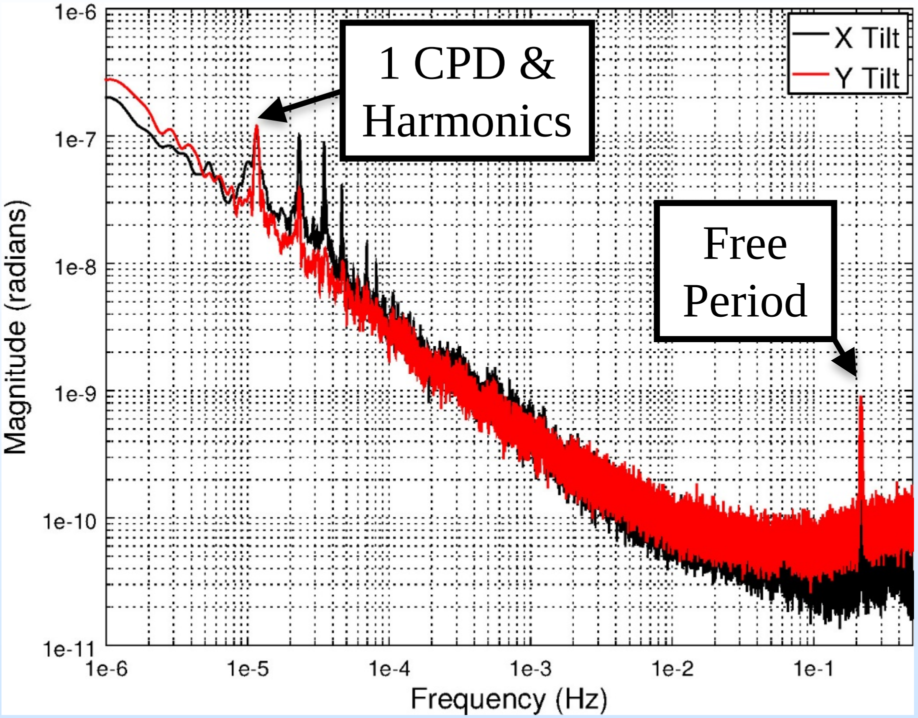
Contribute to *Area of Interest 1 – Geomechanical Research* by developing and demonstrating innovative instrumentation and theoretical techniques for characterizing the strain field resulting from injection (Research Need 3)

Theoretical Analysis

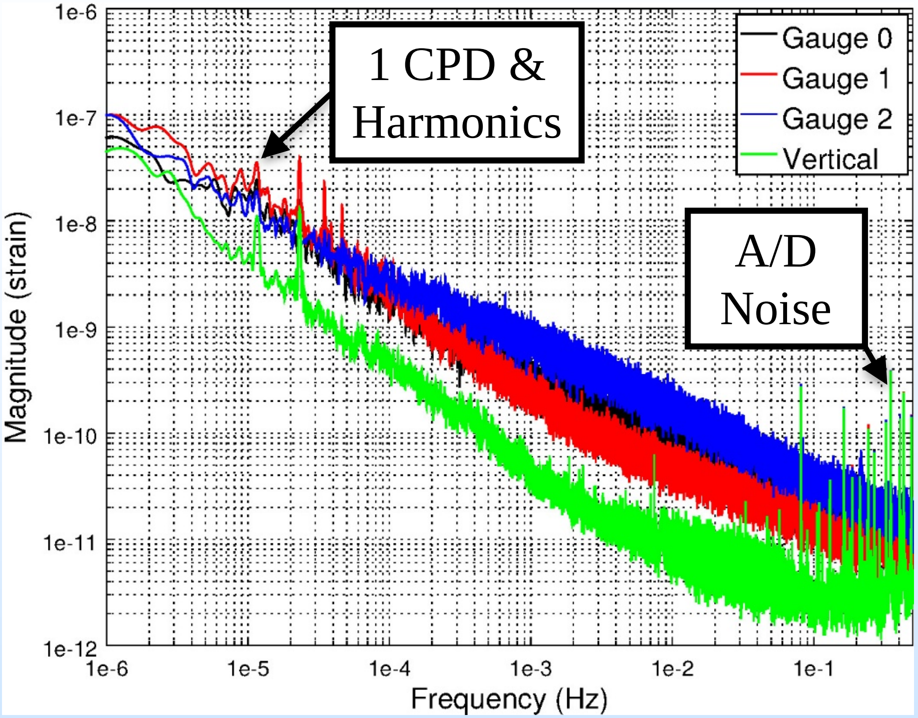
- **Numerical**: strain field in various scenarios, Avant Field demo
- **Analytical**: new solution of 3D poroelastic inclusions
- **Inversion**: New algorithm to enhance efficiency on many processors, move to cloud

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?

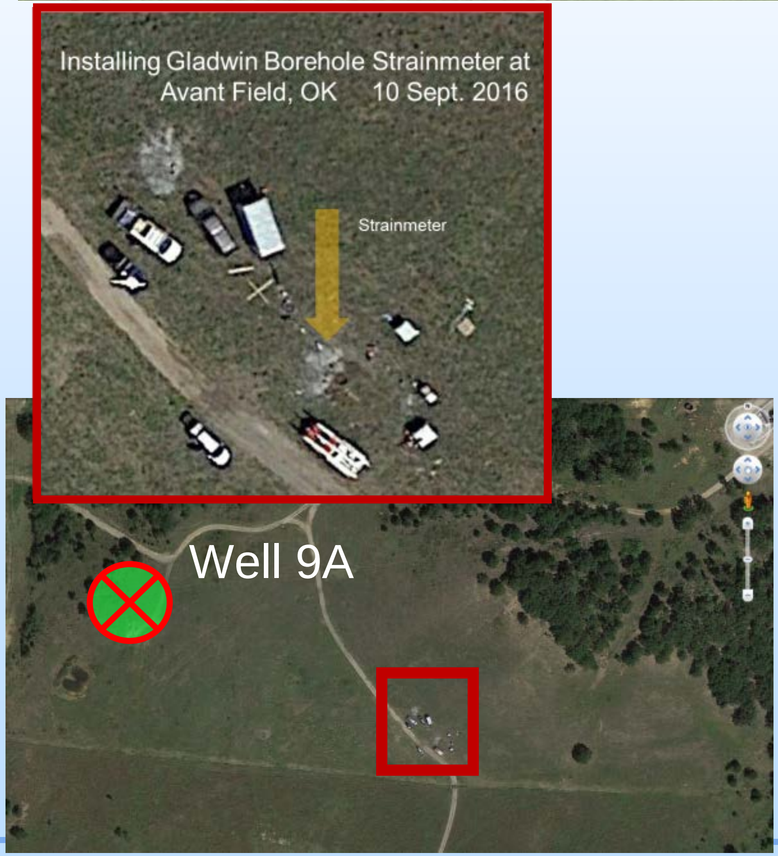
Field Sites

Avant Field
North of Tulsa, Oklahoma
Sedimentary rock

Clemson Site
western South Carolina
Saprolite over xtln rock

Strainmeter Installation

North Avant Field, Sept 2016



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.