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

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

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

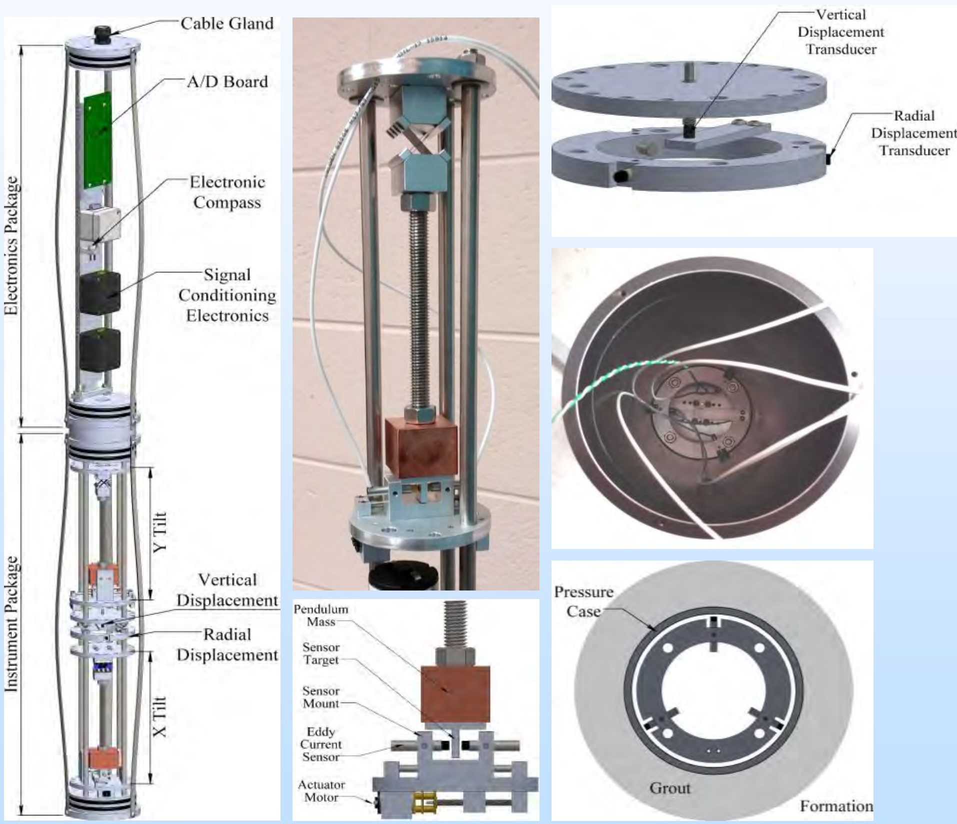
- Multiple components of strain, tilt vector
- Geodetic resolution (~nε, nrad)
- Cost

⟶Prototypes

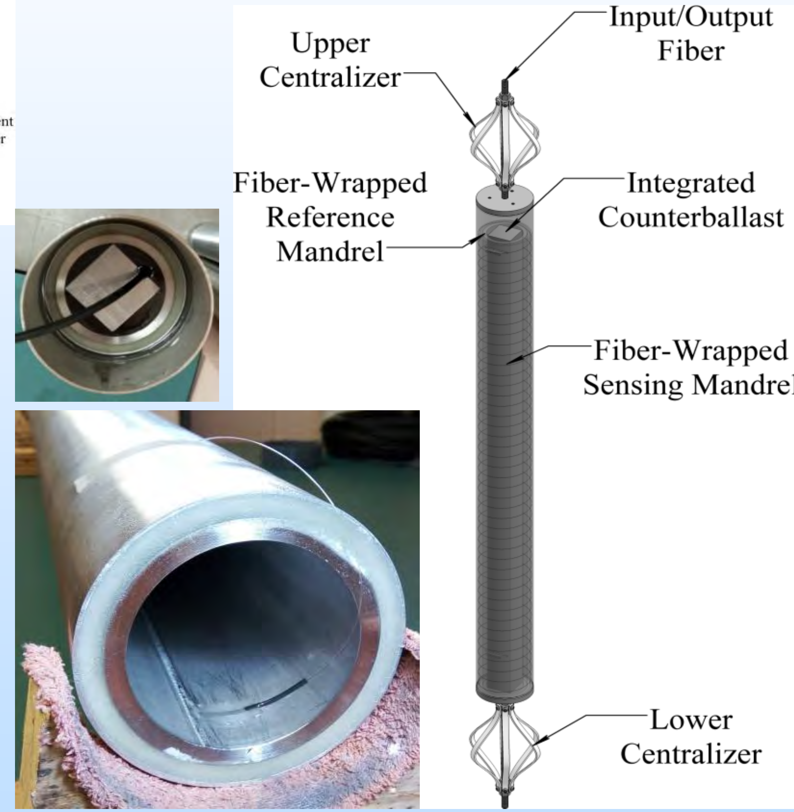
- – Removable multicomponent
- – Expendable, grout-in multicomponent
- – Expendable single component, cheap

Instrument Development

Grout-In Eddy Current System
- Commercial sensor integration
- 2 tilts, 3 horizontal & 1 vertical strain
- ~1 part-per-billion resolution



Areal 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

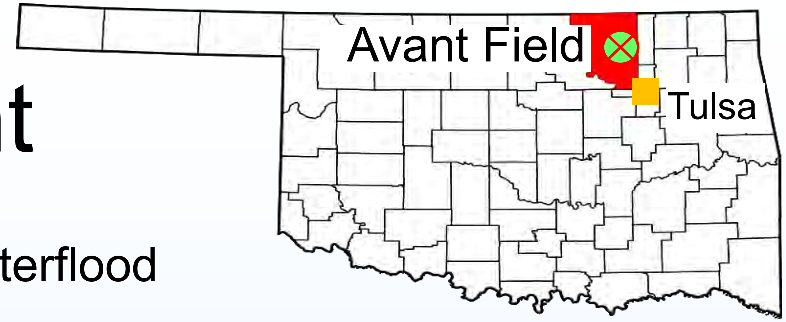
Areal

Gladwin Tensor

Tensor & Tilts

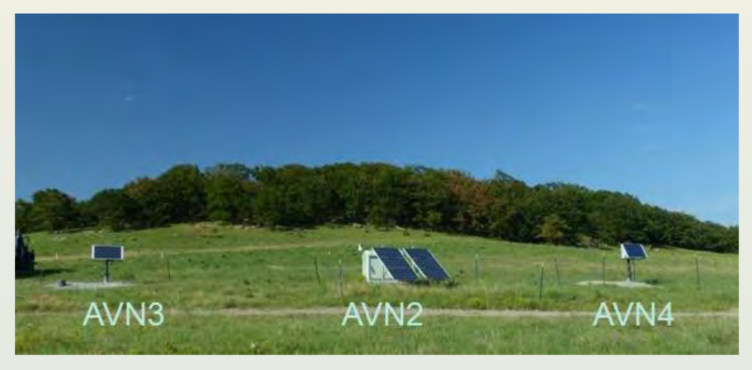
Areal

Field Experiment

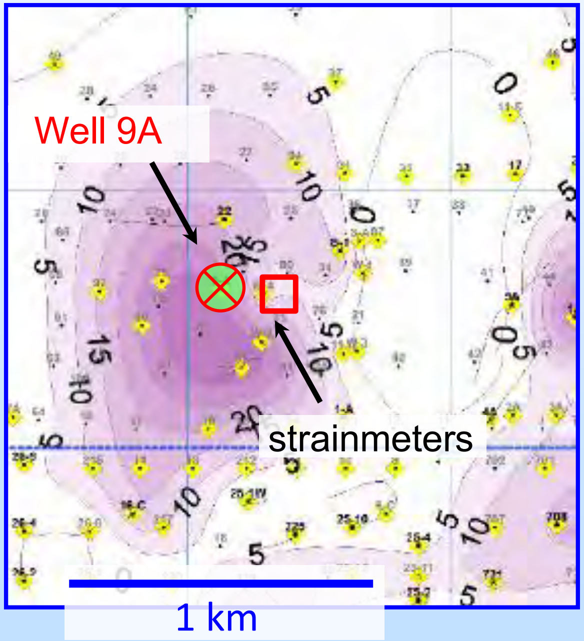


Objective: Measure/interpret strain during waterflood as analog to CO_2 injection
Location: North Avant Field, Osage County, OK
100+ years of oil production
Reservoir: Basal sand lens, Bartlesville Sandstone
Resevoir Depth: 530 m
Strainmeters: Gladwin, Optical Areal, Eddy Tensor
Strainmeter depth: 30m, 220m E of injection well

Permeable Lens Analog



AVN Strainmeters



Permeable sand isopach

Field Tests

Shakedown tests

April, 2017 Shut-in at Well 1A, 1km from strainmeters
July, 2017, 4-hr-long injection into well 9a, shakedown
Aug, 2017, 4-day-long injection into well 9a, shakedown

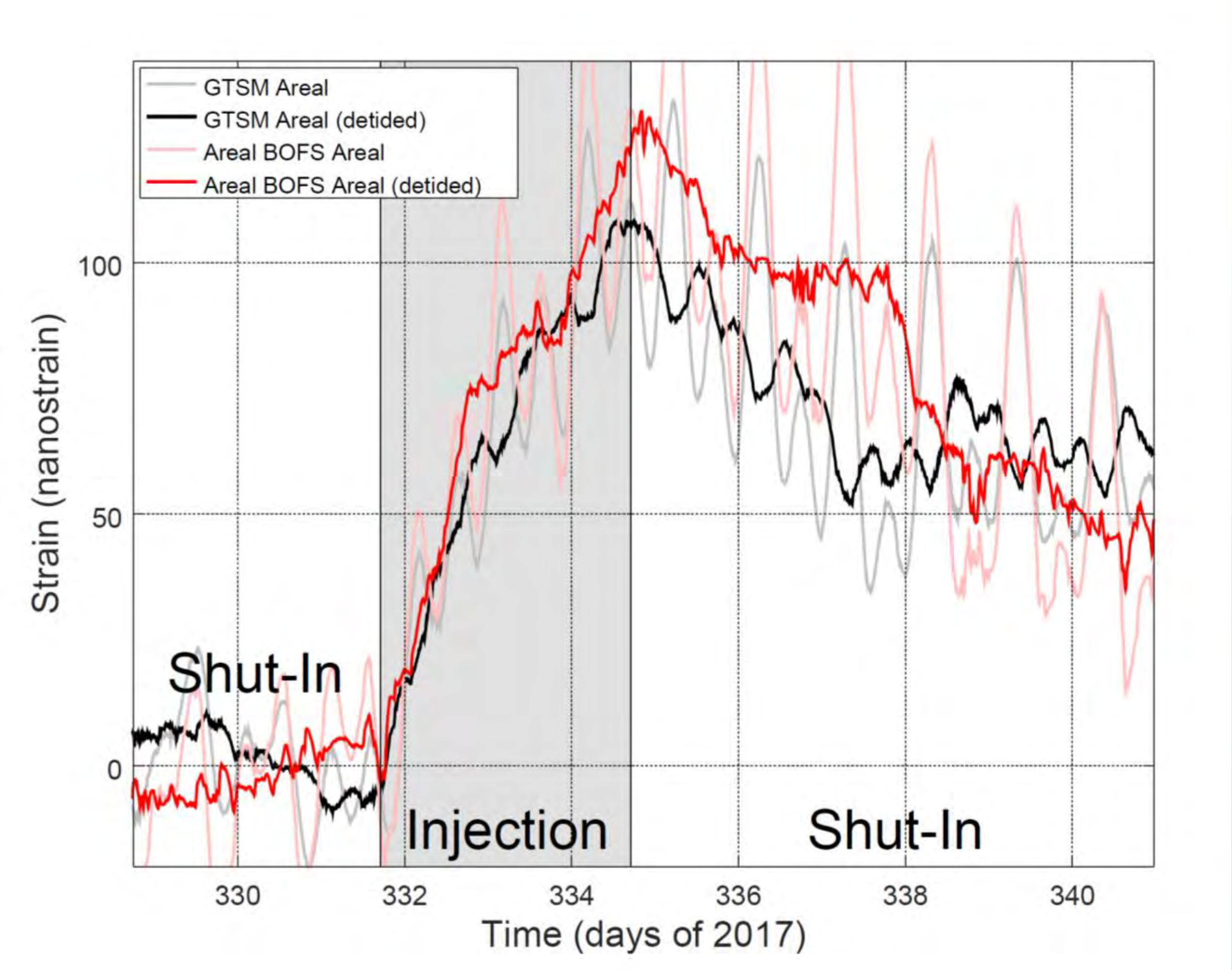
Full Tests

Injection into Well 9A, multi-components of strain, reservoir pressure

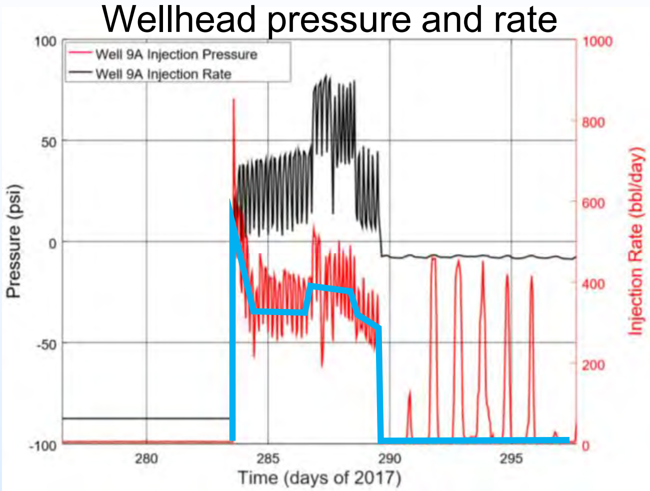
Start Date	Inject days	Recover days	Rate (bbl/d)	Wellhead Pressure (psi)
Oct 2017	6	7	300-800	20-50
Nov 2017	3	6	300-700	60-30
March 2018	60	10	50-500	60-130
June 2018	24	20	350-550	5-20

Data Processing: Calibration, tidal correction, barometric correction
Evaluate data: Manual calibration, stochastic inversion, analytical

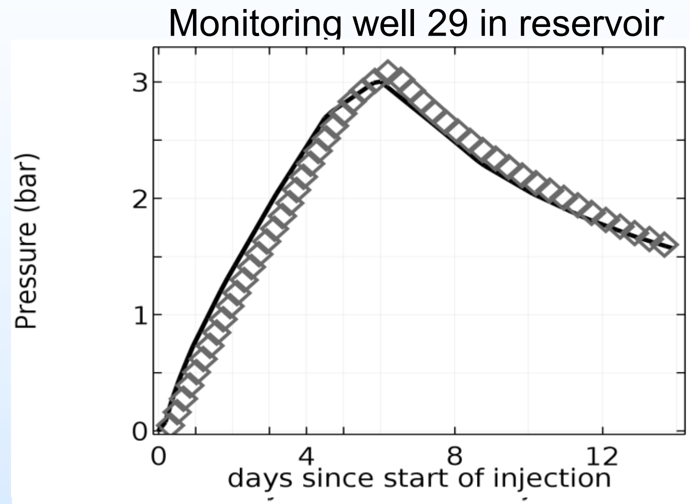
Data Comparison
Gladwin—Areal BOFS

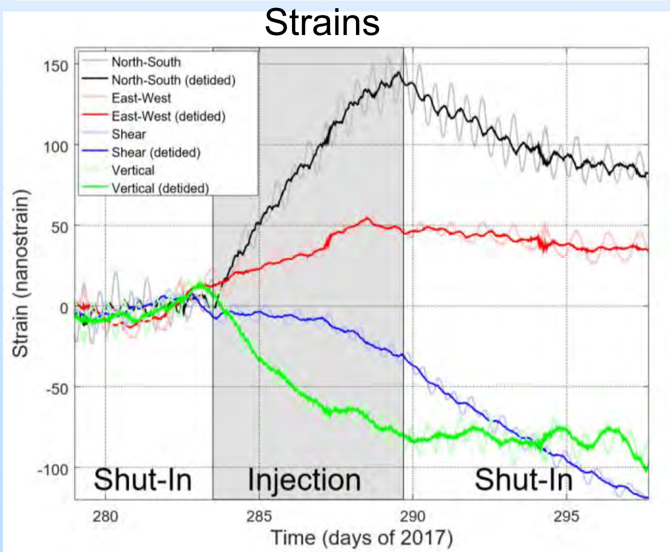


Oct 2017 Injection Test



a.





b.

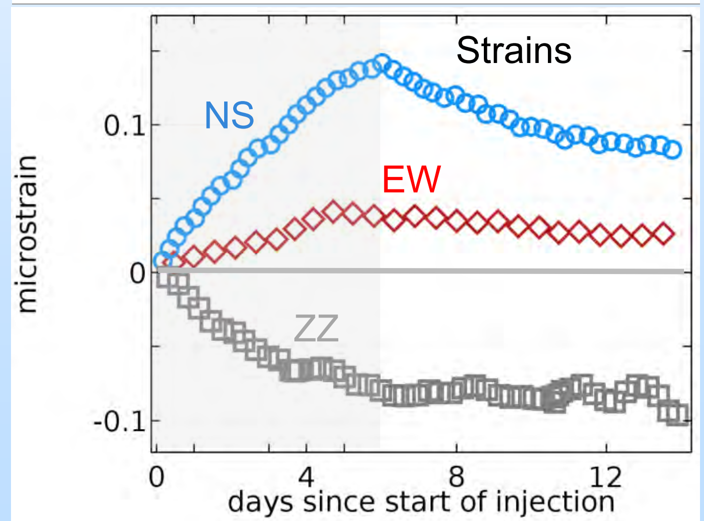
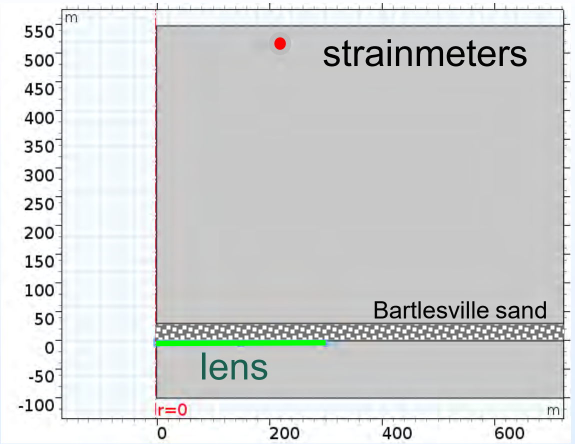


Figure 1. a.) Pressure and injection rate during well 9a injection test in Oct 2017 (upper). Blue line is the rate used in the simulation. b.) Normal strain, shear strain, and areal strain from Gladwin strainmeter at AVN2, vertical strain from Eddy Current instrument from Oct 2017 injection test

Oct 2017 Injection Test

Axisymmetric model



3D Model

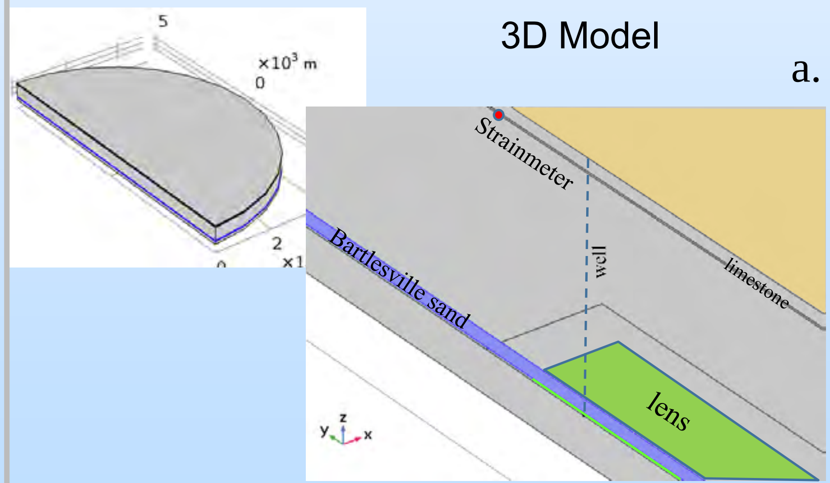
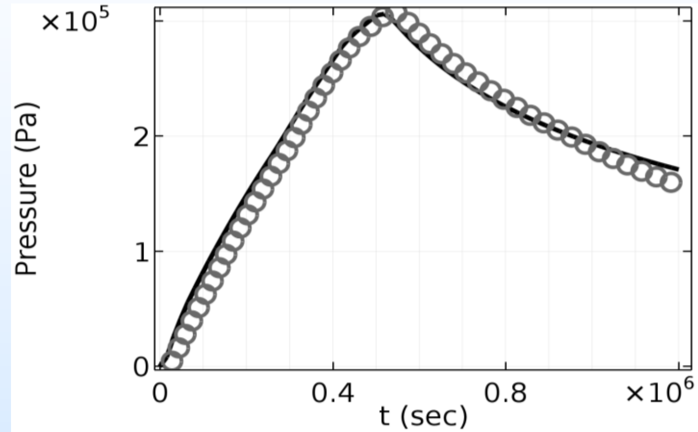
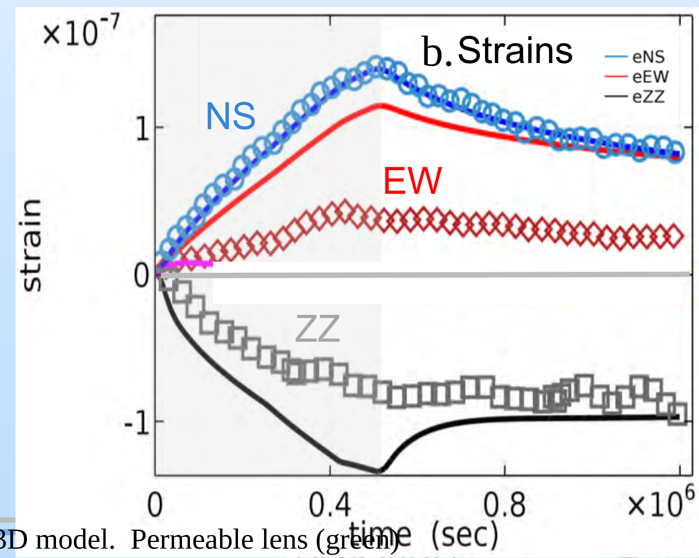


Figure 5. Configuration a.) and FEM mesh b.) used in 3D model. Permeable lens (green) under Bartlesville sand (purple). Strainmeter (red dot) in a limestone layer at 30m depth. Path of the well is shown as a dashed line.

Axisymmetric Model Results

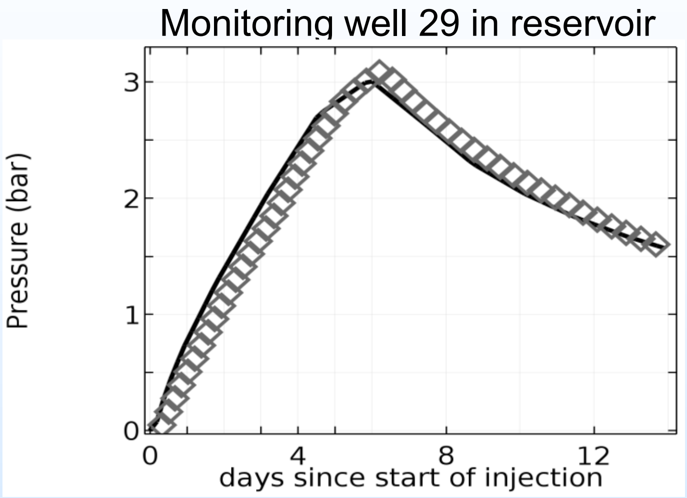
Monitoring well 29 in reservoir

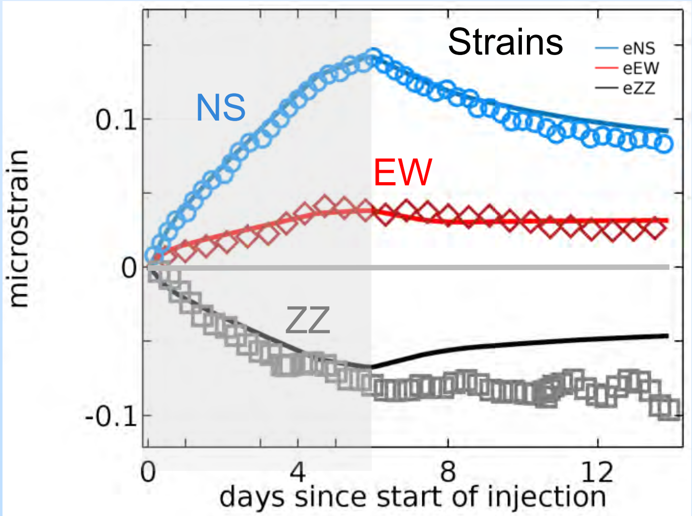




Oct 2017 Injection Test

		3D Manual	
Youngs Modulus	Lens	2	GPa
	Bartlesville	8	GPa
	Confining	2.9	GPa
	Instrument	42	GPa
Poisson's ratio		0.25	–
Permeability	Lens	500	mD
	Bartlesville	5	mD
	Confining	0.01	mD
Lens Thickness		5	m
Lens long axis		580	m
Lens short axis		300	m
Well to boundary1		80	m
Boundary to instrument		140	m





Sensitivity Analysis

Controls on strain

<u>Observations</u>

ε ~ 1/E lens

ε ~ E confining

ε ~ P, lateral extent, D_h

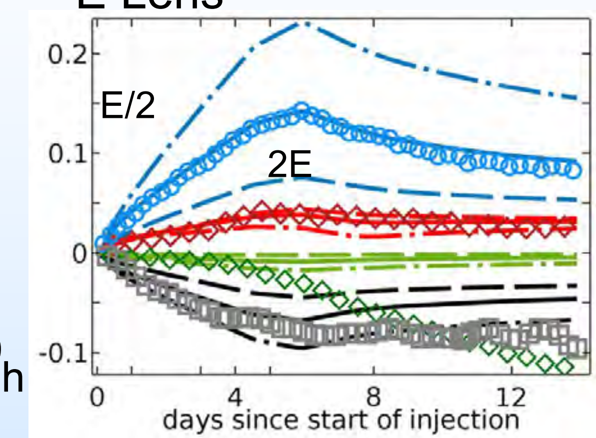
$\varepsilon_{xx} / \varepsilon_{yy}$ ~ boundary

$\varepsilon_{xx} / \varepsilon_{yy} < 0.7 \rightarrow$ boundary

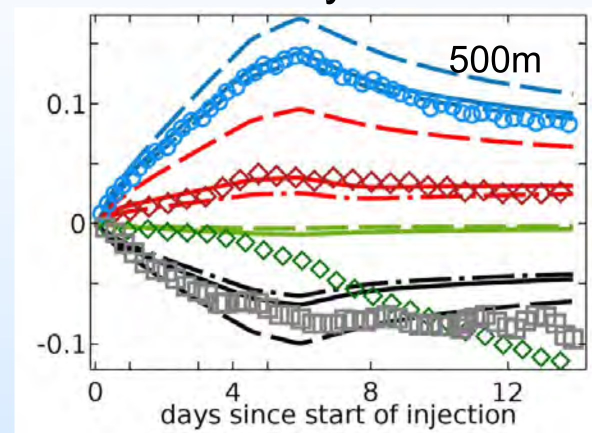
ε_{zz} ~ local E

$\varepsilon_{xx}, \varepsilon_{yy} \nsim$ local E

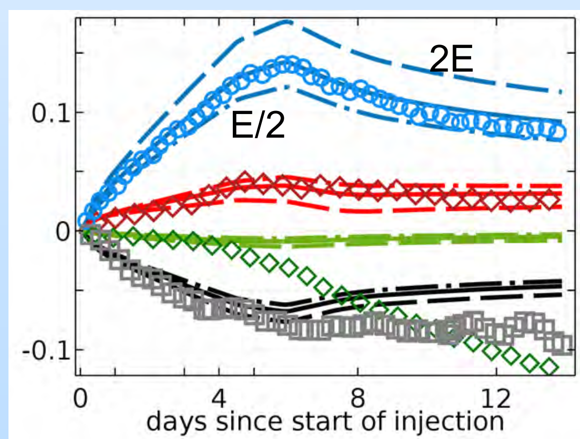
E Lens



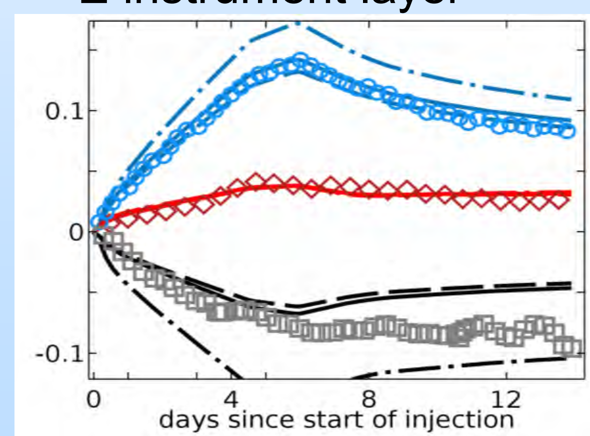
L boundary



E confining



E instrument layer

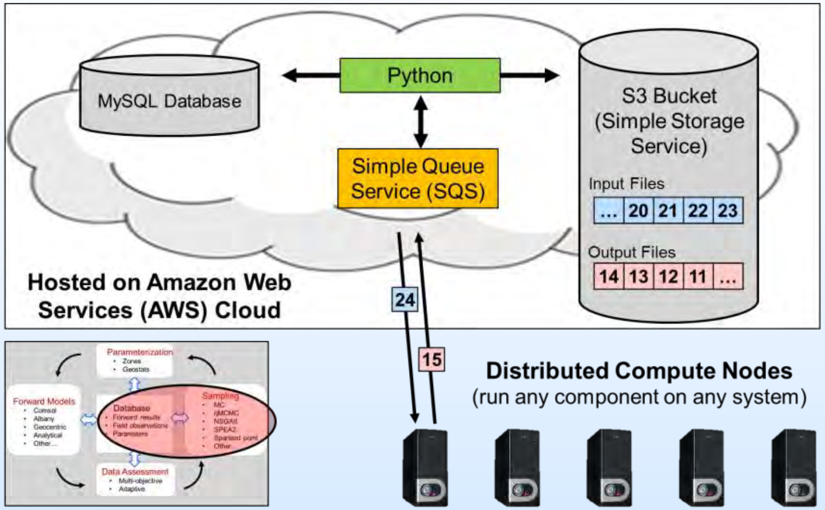


Stephen Moysey

Inversion Approach

Alex Hanna

- infrastructure for parameter estimation using large models w long run times
  - HTC
  - Cloud storage, computing



Current Implementation

Space Filling (exploration)

•Latin Hypercube, Monte Carlo

High Efficiency Minimization (Exploitation)

•Genetic Algorithms (NSGAII, SPEA2) - global

•Gradient descent – local

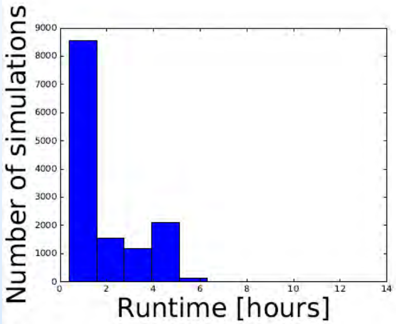
Uncertainty Evaluation (Exploration)

•Markov chain Monte Carlo (McMC)

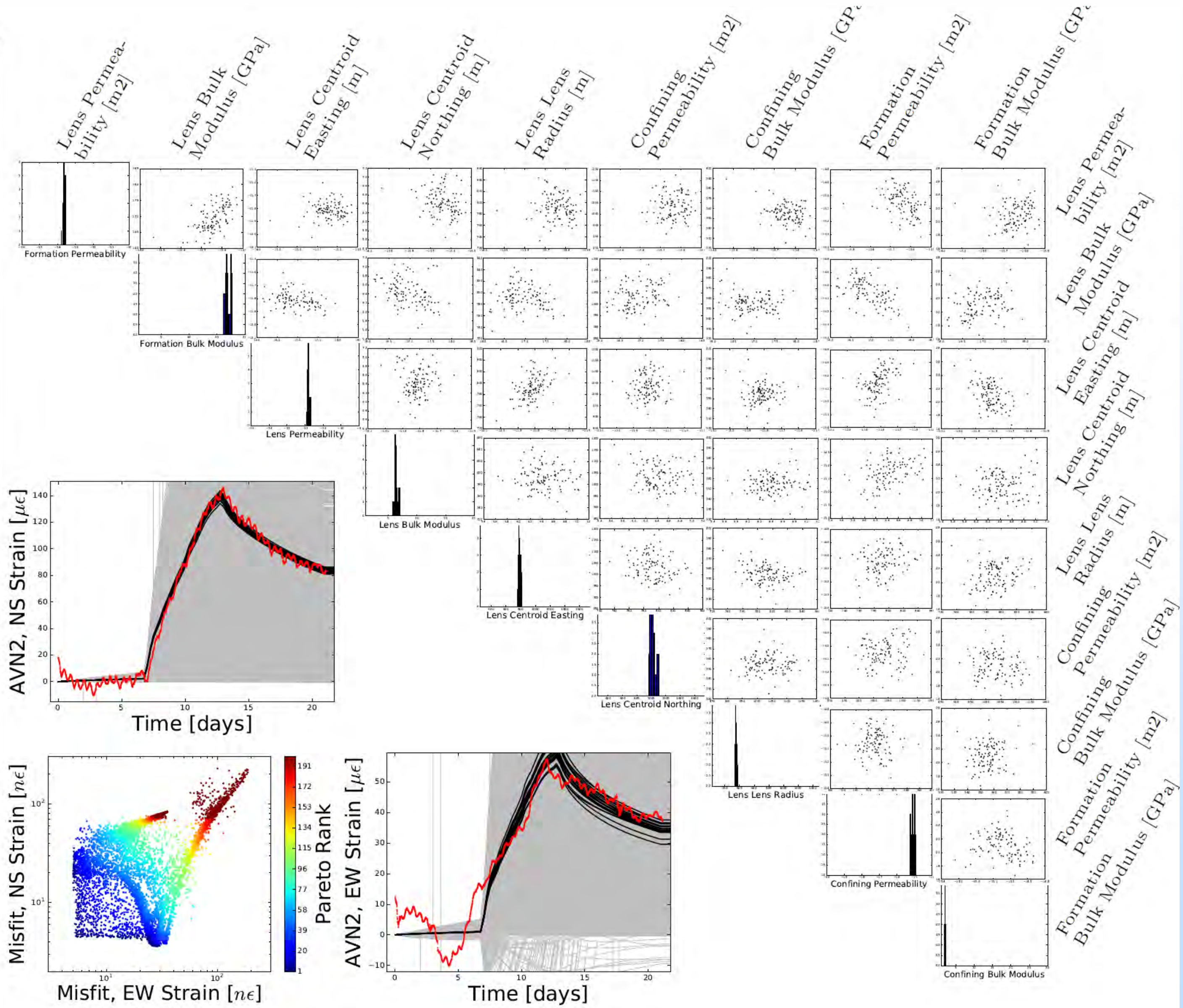
•Reversible jump McMC

Example Results from Stochastic Inversion of Strain Data from Oct 17 Field Test

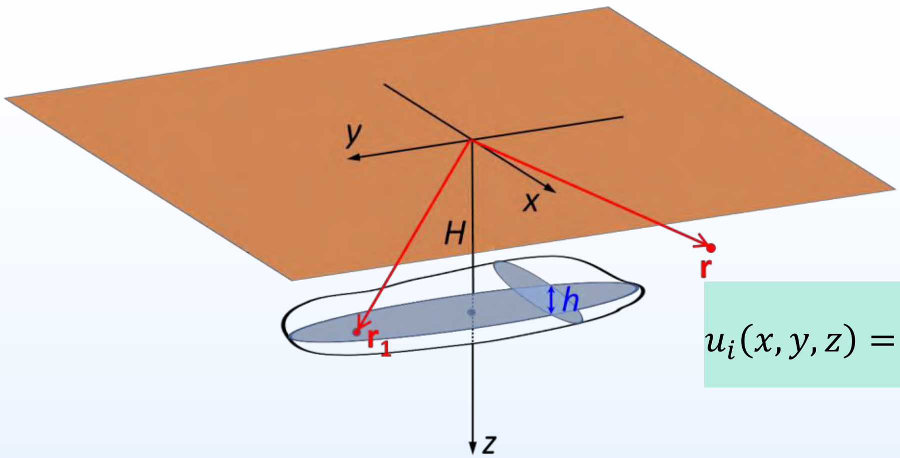
Forward model Geocentric
Thnx to J. White



Simulations: 13,520
Runtime: 6 hrs
Cores: 1000
Memory: 1.5 TB



Analytical solutions to poroelastic inclusions



$$\varphi_\infty(x,y,z) = \frac{1}{12\pi}\frac{1+\nu}{1-\nu}\int_V \frac{\varepsilon_0(\mathbf{r}_1)d^3\mathbf{r}_1}{|\mathbf{r}-\mathbf{r}_1|}$$

$$u_i^\infty = -\frac{\partial\varphi_0}{\partial x_i}$$

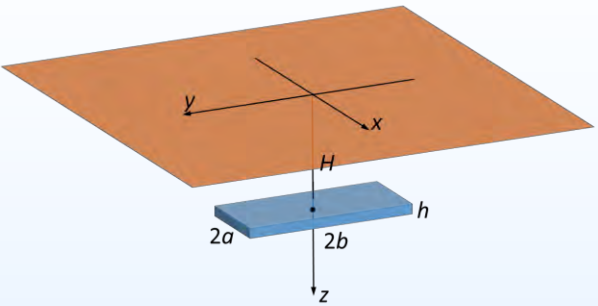
$$u_i(x,y,z) = u_i^\infty(x,y,z) + (3-4\nu)u_i^\infty(x,y,-z) + (-1)^\delta 2z\frac{\partial}{\partial z}u_i^\infty(x,y,-z)$$

($\delta = 1$ for $i = 1, 2,$ and $\delta = 0$ for $i = 3$)

$$\varepsilon_0 = \frac{3(1-2\nu)}{E}\Delta p$$

- Inclusion with transformation strain represents pressurized reservoir
- Transformation strain distribution from poroelasticity
- Analytical expressions for arbitrary shape of pressurized poroelastic inclusion
- In 2-D, using Mushkelishvili potentials
- In 3-D, using Goodier potential for *infinite* space and Mindlin-Chen dilation source in *half-space*
- Baseline analysis
  - inclusion of same properties (E, ν) as matrix
- This year
  - arbitrary pressure distribution
  - inclusion and matrix of different properties
  - dimensionless analysis

Analytical solutions for parameter estimation

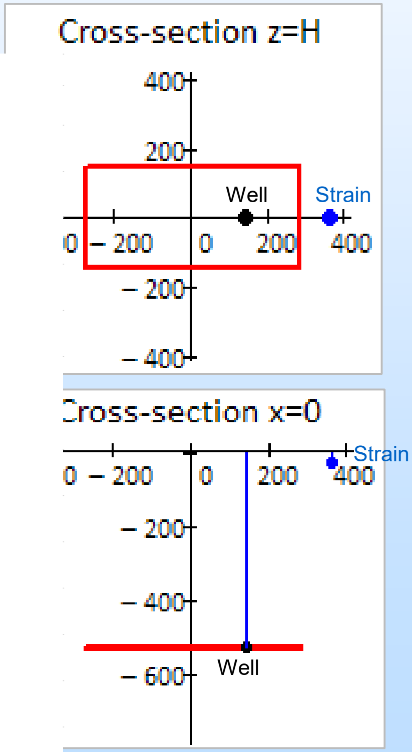


- Pressure spatially equilibrates for $t \gtrsim$ hours
- Uniform P = Measured pressure $\Delta p = 0.3$ Mpa (by the end of injection period)
- Measurement coordinates $x = 0,\ y = 360$ m, $z = 30$ m
- Assumed Poisson ratios $\nu_{incl} = 0.25,\ \nu_{matrix} = 0.25$
- Data from end of injection
- Levenberg-Marquardt t<1s

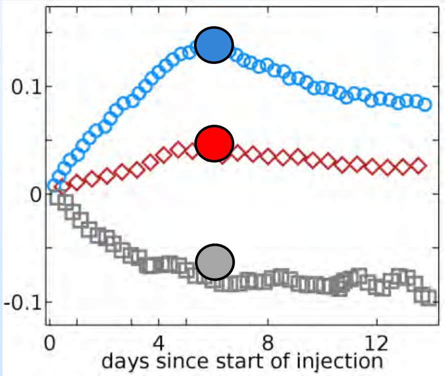
Parameters

		3D Manual	Analytical	
Youngs Modulus	Lens	2	2	GPa
	Bartlesville	8	--	GPa
	Confining	2.9	3.1	GPa
	Instrument	42	--	GPa
Poisson's ratio		0.25	0.25	–
Permeability	Lens	500	--	mD
	Bartlesville	5	--	mD
	Confining	0.01	--	mD
Lens Thickness		5	5.2	m
Lens long axis		580	590	m
Lens short axis		300	290	m
Well to boundary1		80	--	m
Boundary to instrument		140	70	m

Geometry



Strains



	Measured	Simulated
ε_{NS}	138	143
ε_{EW}	39	46
ε_{ZZ}	80	62

Accomplishments to Date

- Instruments
  - 4 new strainmeters designed, built, deployed
  - Data available, https://www.unavco.org/instrumentation/networks/status/pbo/overview/AVN2
- Analyses
  - Understanding factors affecting strain signal
  - Cloud-based optimization method developed
  - Inversion of field data demonstrated
  - Analytical solution derived, demonstrated
- Field demo
  - Gladwin, areal, tensor strainmeters working at Avant Field
  - 4 injection tests with full strain and pressure data
  - Simulations match field data, geologic model
  - Strain data used to advance understanding of properties, heterogeneity, pressure.

Synergy Opportunities
with other talks in the session

- Strain during injection→fault slip
  - Critical stess
  - Reactivation
  - Rheology
  - Leakage along faults
- Field projects
  - Fluid injection
  - Fault slip
  - Hydraulic fracturing
- Knowledge from Noise

Summary

Measure and interpret strain tensor during injection

–Instruments

- Multiple Prototypes built, installed, working. Data available

–Analysis

- Interpret using inversion of numerical simulations, analytical solution soon

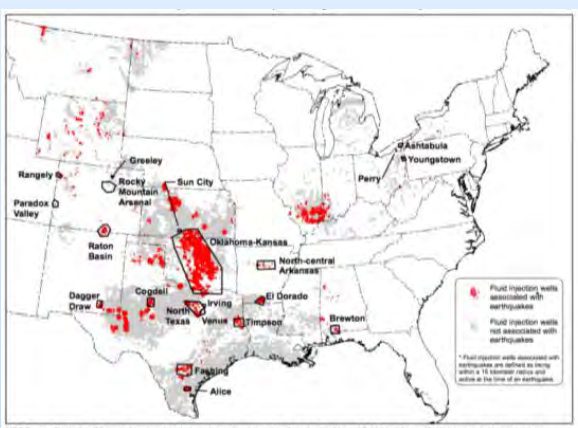
–Field demo

- Working strainmeters at Avant Field site
- 4 injection tests, data obtained, results similar to simulations, interpretation ongoing

Strain from Fluid Injection/Recovery

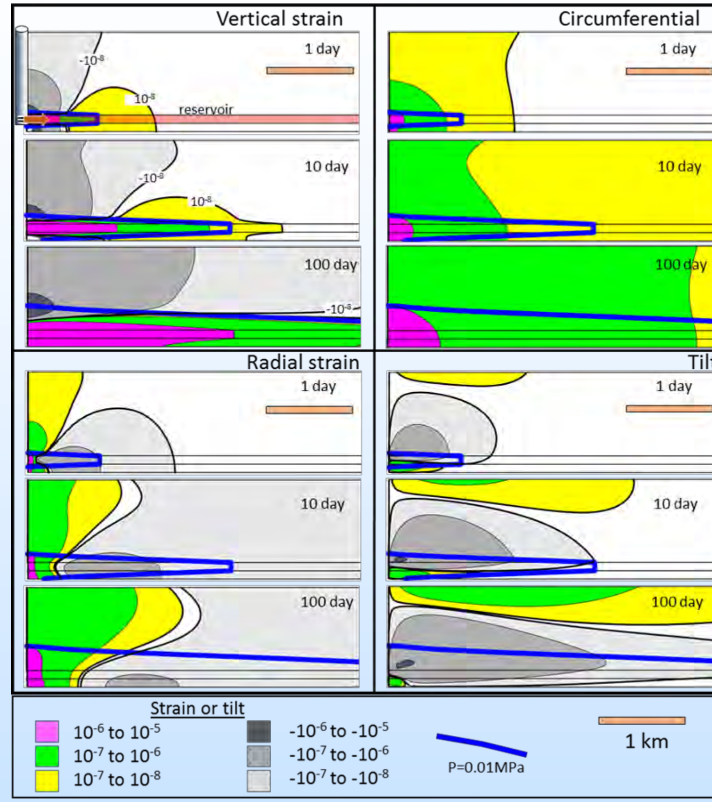
Damaged home, Prague, OK

Deformed well casing



Earthquakes (red) and injection wells (grey)

Subsidence, Central Valley CA



Strain field in the vicinity of an injection well

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Lessons Learned

Technical

- Background signals
- "Robust" instrumentation

Logistics

- Well field operation
- Accessibility, SC←→OK
- Land owner, mineral rights

Communication

- Multiple PIs, Industry partners

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

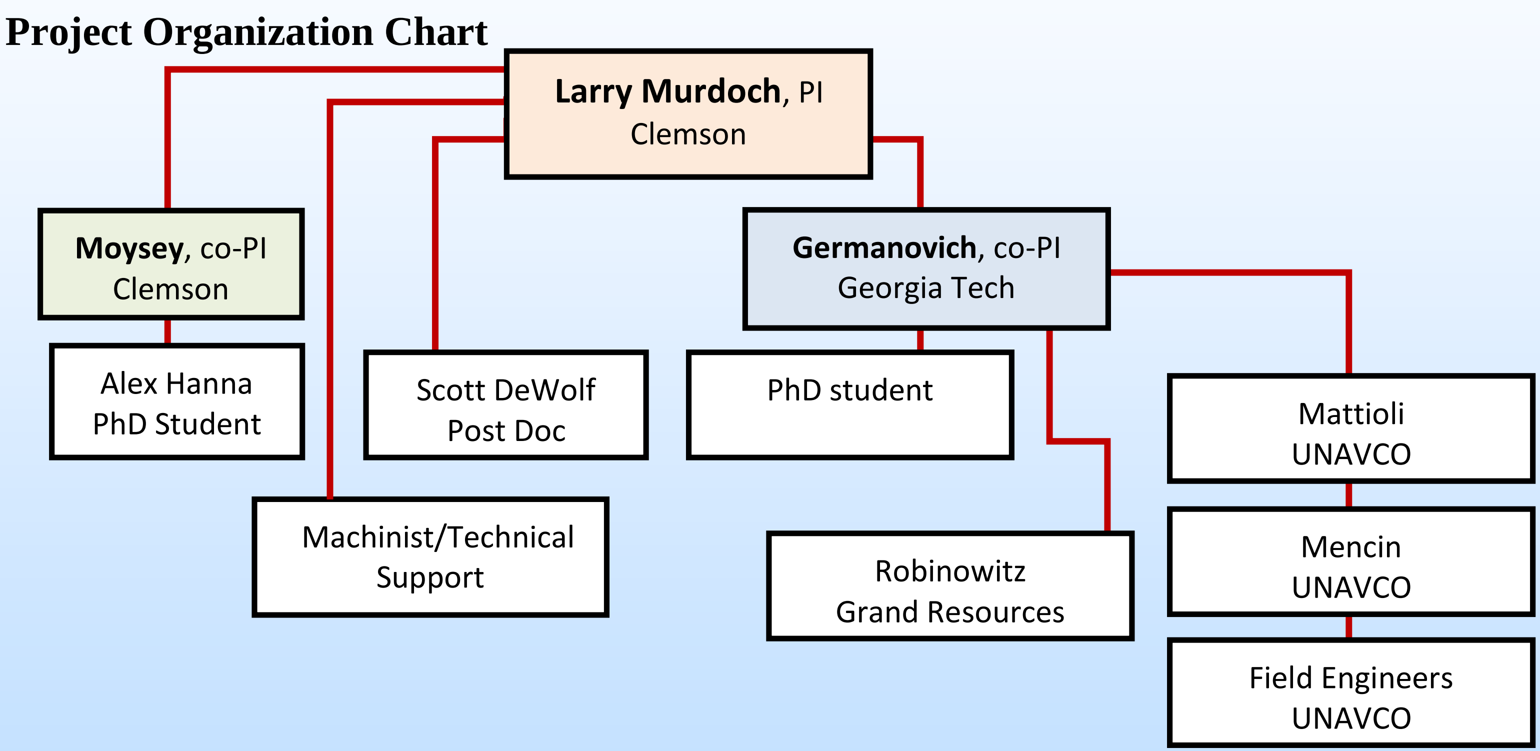
Overall Goal: evaluate how subsurface strain measurements can be used to improve the assessment of geomechanical properties and advance an understanding of geomechanical processes that may present risks to CO2 storage.

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.

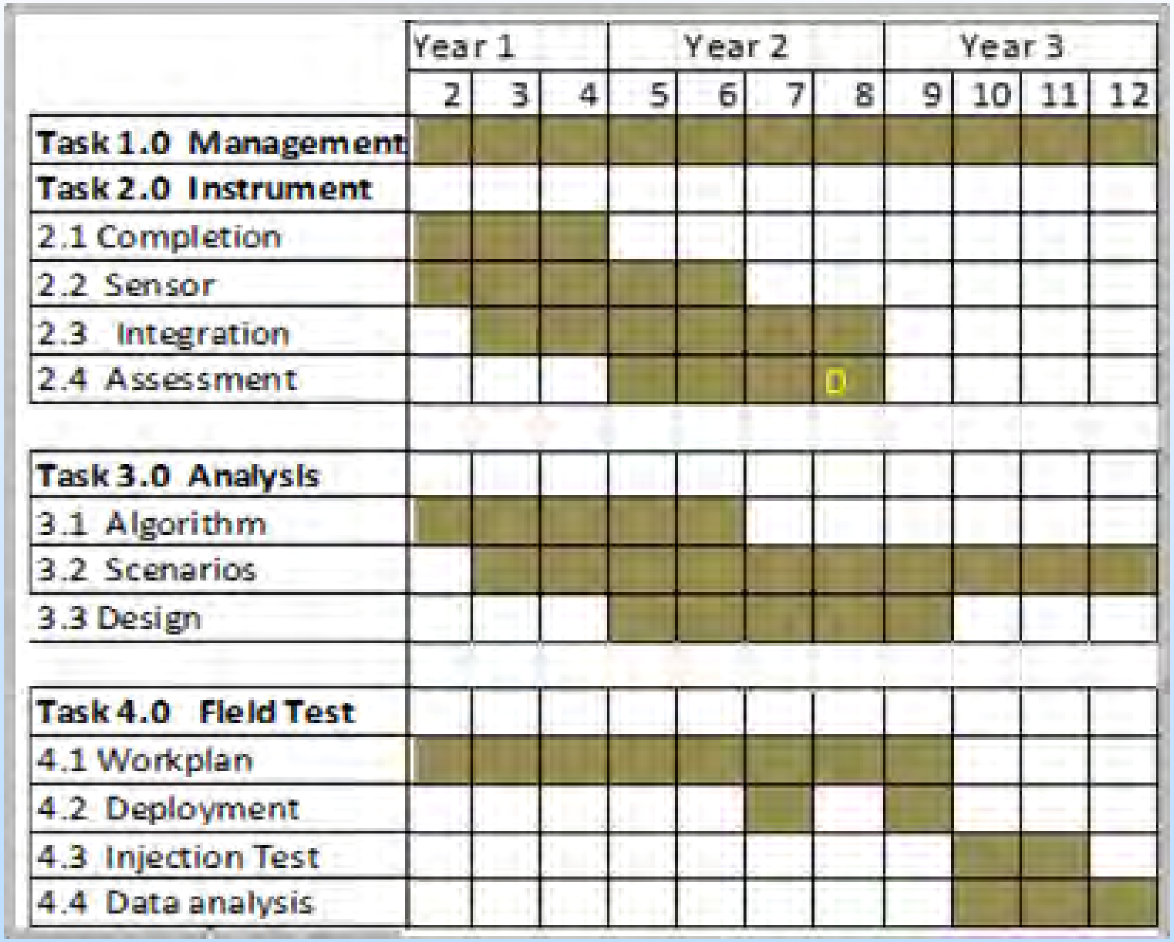
Theoretical Analysis Task Develop theoretical analyses for characterizing the strain field associated with injection in the vicinity of critical features, such as contacts and faults, and then develop and demonstrate innovative methods for inverting these data to provide a quantitative interpretation.

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.

Organization Chart



Gantt Chart


Year 1
Year 2
Year 3
2
3
4
5
6
7
8
9
10
11
12
Task 1.0 Management
Task 2.0 Instrument
2.1 Completion
2.2 Sensor
2.3 Integration
2.4 Assessment
D
Task 3.0 Analysis
3.1 Algorithm
3.2 Scenarios
3.3 Design
Task 4.0 Field Test
4.1 Workplan
4.2 Deployment
4.3 Injection Test
4.4 Data analysis

Bibliography

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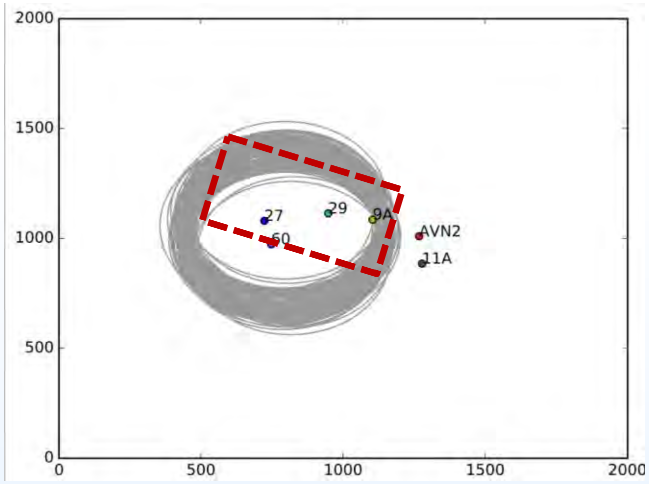

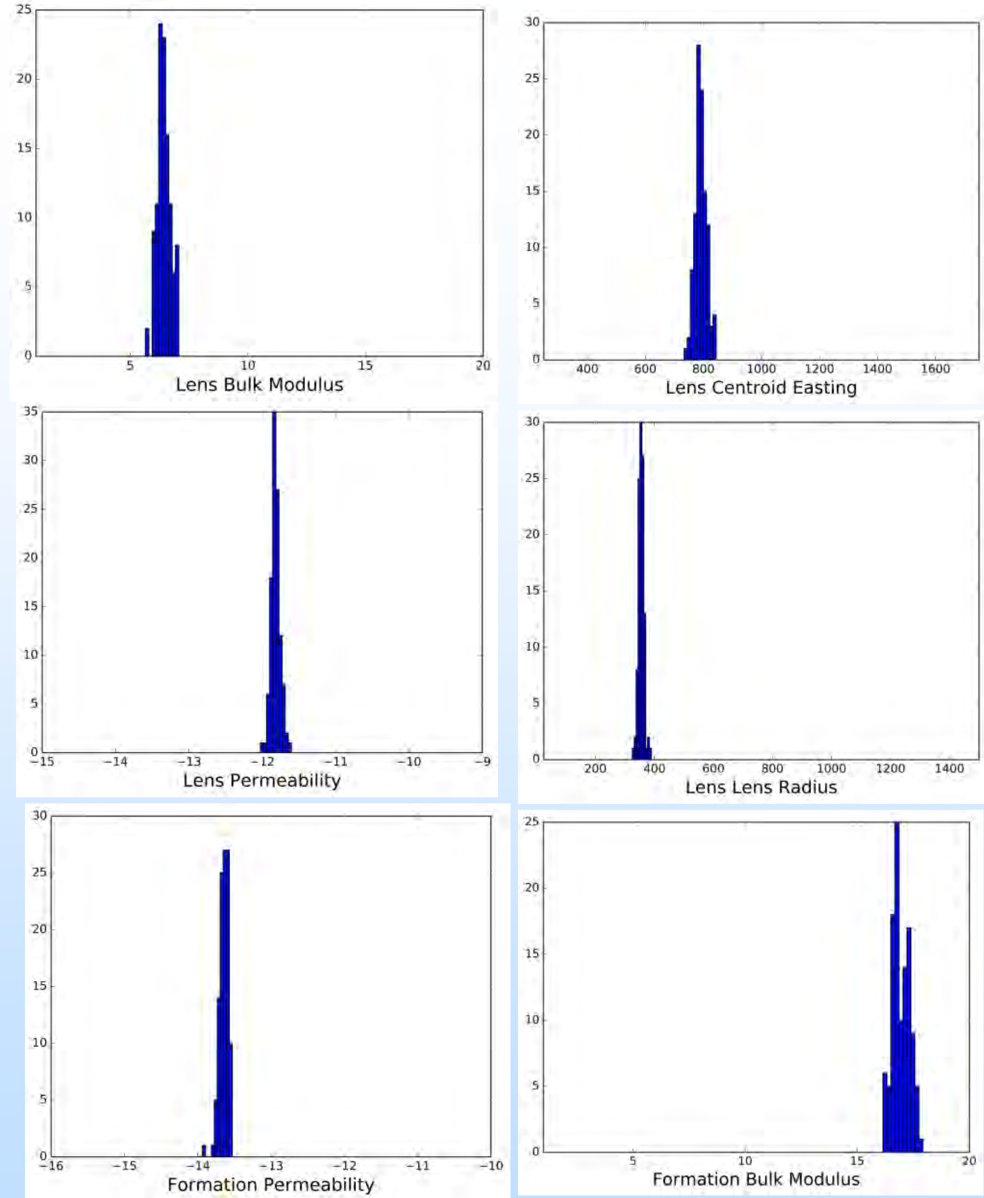

Results using horizontal strain

Distribution of parameters

E, k

Size, location lens

Next

Update forward model

Include other data

vertical strain, tilt, p

Include pilot points

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Well 9A Test Site
Avant Field, Oklahoma