ROBUST IN SITU STRAIN MEASUREMENTS TO MONITOR CO_2 STORAGE

Project Number FE0028292

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U.S. Department of Energy
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Addressing the Nation's Energy Needs Through Technology Innovation – 2020 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting
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Project Goals and Tasks

Develop and demonstrate in-situ strain measurement during injection

1. Instrumentation
   - Point strain; ultra-high resolution, multi-component strain + tilt
   - Distributed strain; high resolution, spatial distribution
   - Temporal; DC→kHz; Tectonic ←→ seismic

Michelson Interferometer

Microwave Photonics

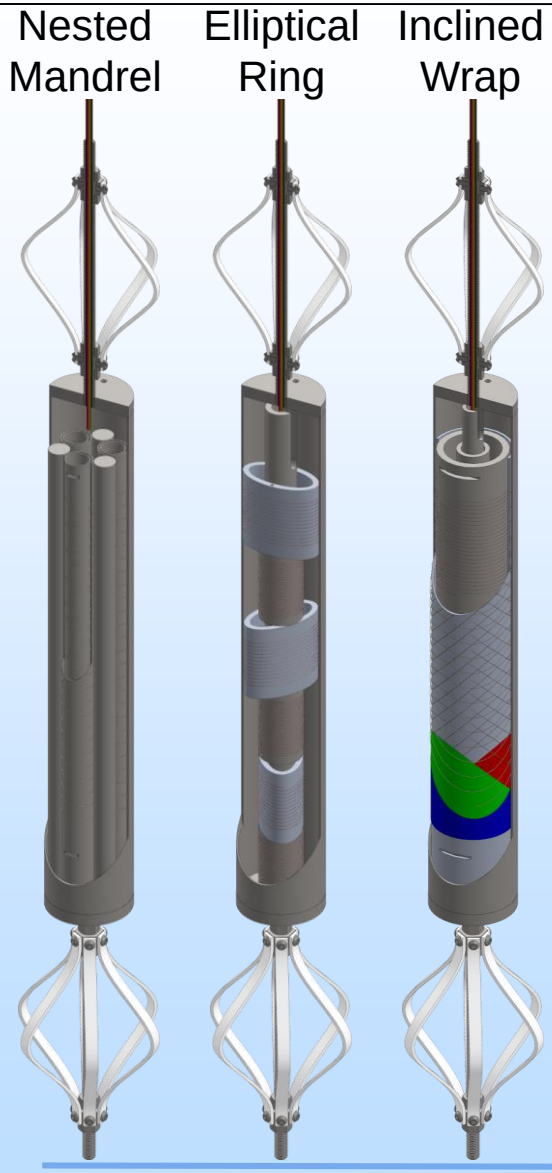
2. Strain Interpretation
   - Leaks, ambient processes
   - Analytical solution
   - Inversion applications

3. Field Demonstration
   - Deploy instruments in field injection setting
   - Acquire data, interpret

BP2→BP3

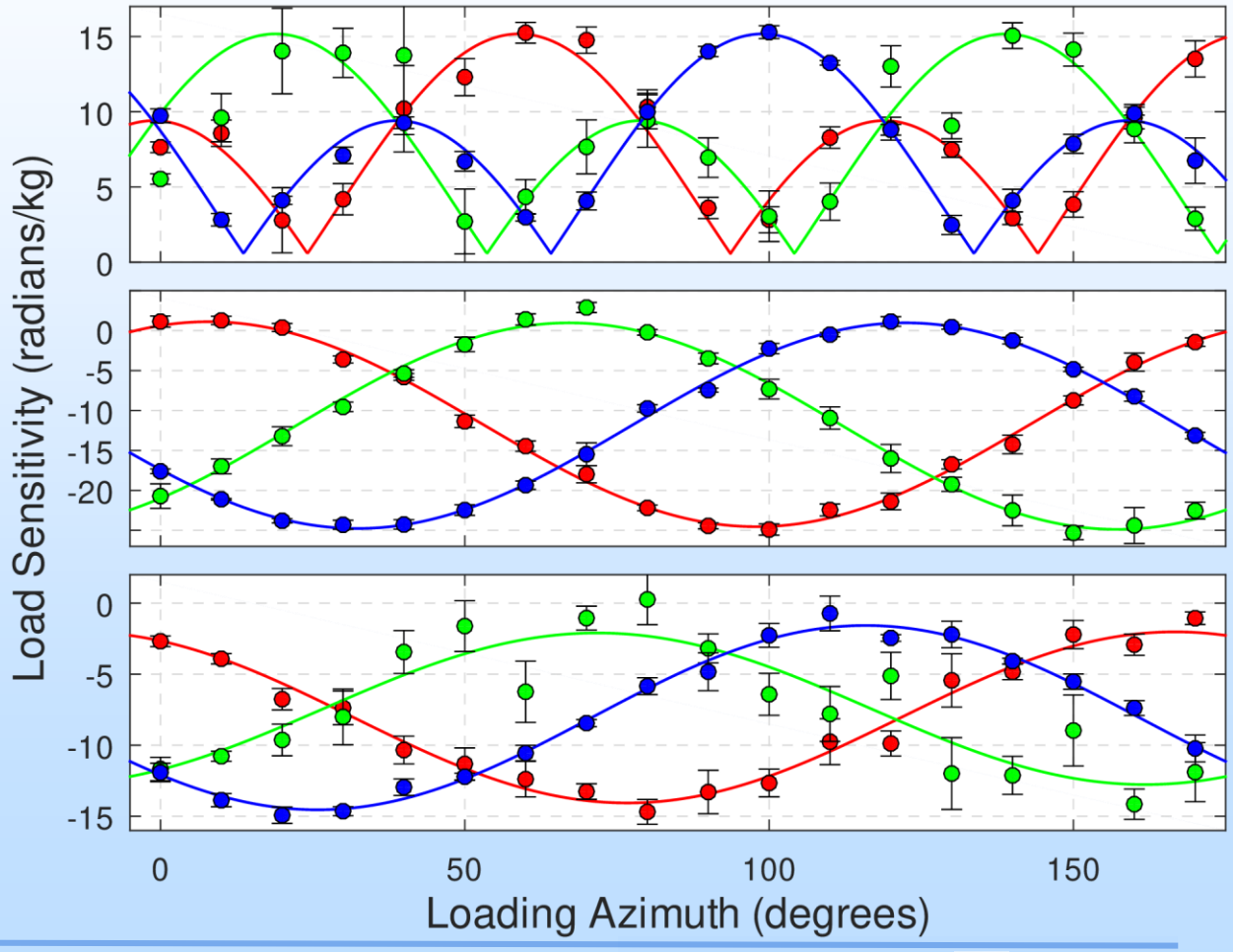
- Instruments
  - Horizontal Tensor Strainmeters, Michelson Interferometer
  - Discrete-distributed sensors, Microwave photonics
- Strain Interpretation
  - Leaks
  - Inversion--analytical solution, surrogate for numerical
  - Signal processing
- Field Tests
  - Clemson
  - Avant Field, OK

Optical Strain Instruments



3 Horizontal Tensor Strainmeters

- Designed, built and lab calibrated



Optical Strain Instruments

3 Horizontal Tensor Strainmeters

- Deployed at our local field site

Nested Mandrel

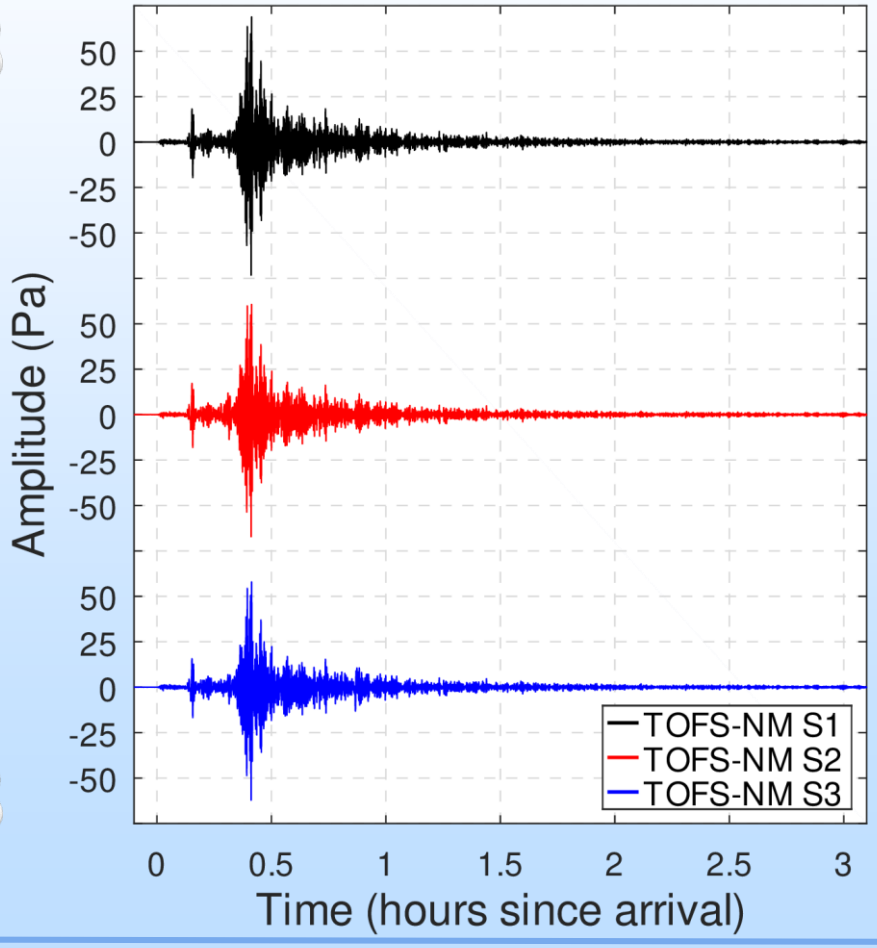
Elliptical Ring

Inclined Wrap

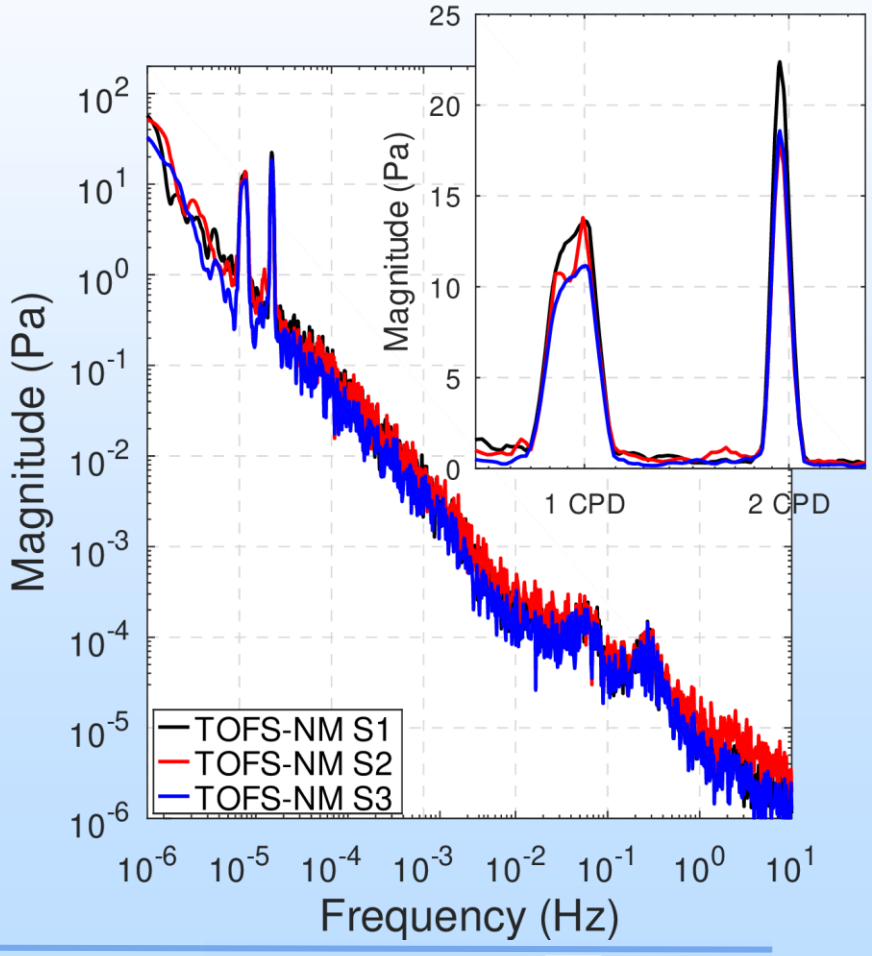
Optical Strain Instruments

3 Horizontal Tensor Strainmeters

Teleseisms



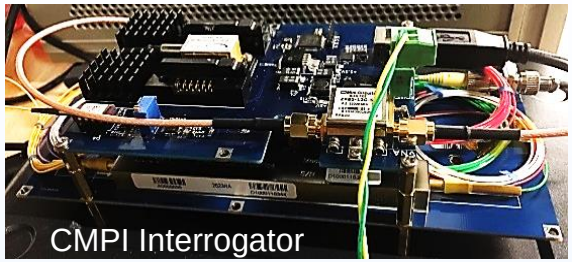
Solid Earth Tides



CMPI Distributed Strain Sensor

Microwave photonics

CMPI Interrogator: New transmitter design for better reliability, lower cost.

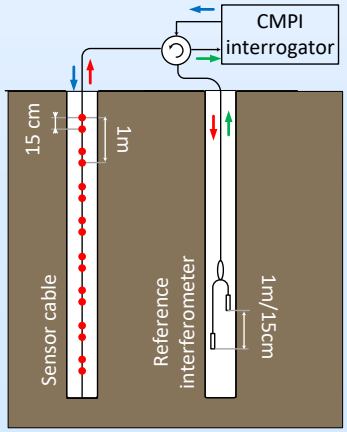


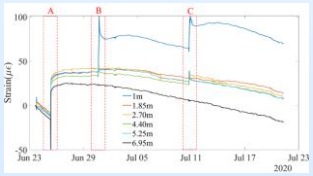
Field sensor: Fiber packaged in composite material for field deployment. Strain ribbon, DDM strain sensor.

Strain ribbons

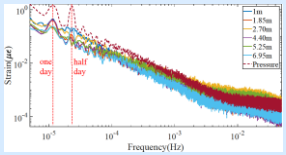
Strain ribbon fabrication

Field testing: Strain ribbon to 8m in vadose zone, reflectors every m. Ambient noise, vehicle moving, rain, tides, seismic wave, well testing



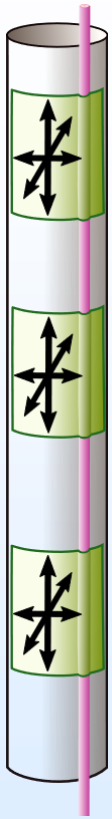


Strain time series



Ambient noise

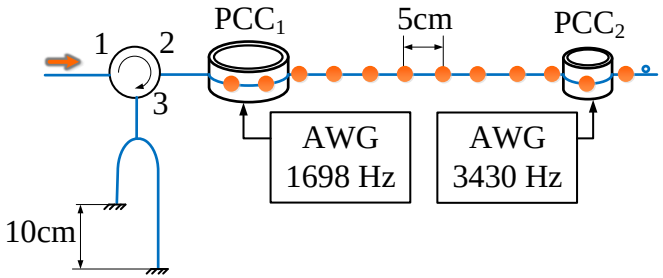
Fiber embedded in composite shell



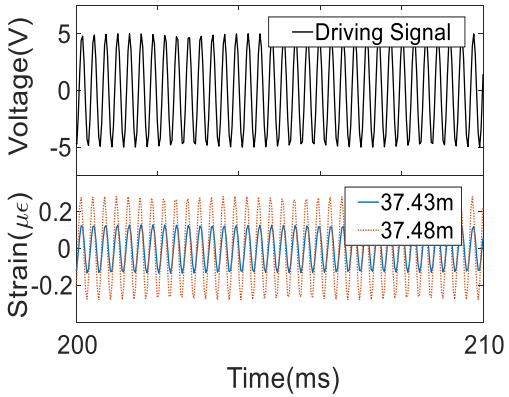
Discrete, distributed, multi-component (DDM) strain sensor outside of casing.

CMPI Distributed Acoustic Sensing

Lab

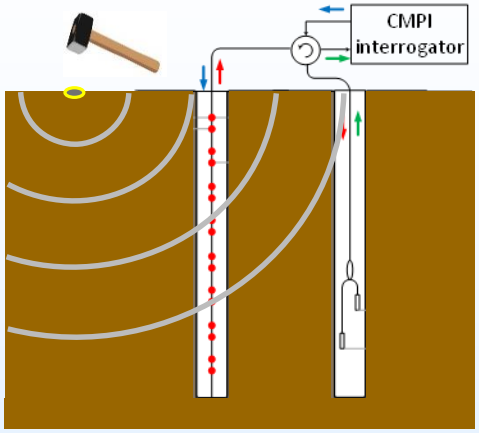


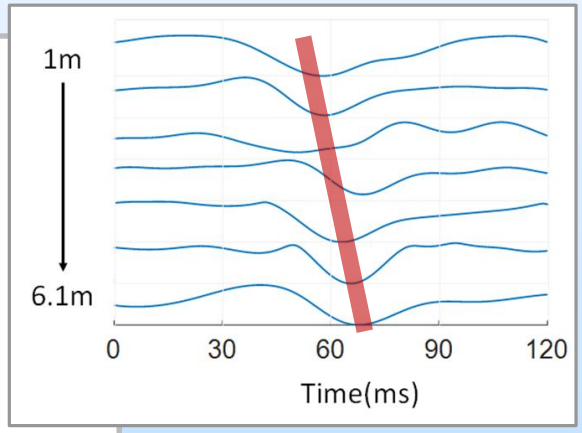
- 5 cm spatial resolution
- Multiple points kHz acoustic vibration sensing
- Recover the temporal signals with high fidelity



Field

- Surface impulse, detect at strain ribbon
- Slight delay of strain response between top sensor and bottom sensor, v~ 450 m/s

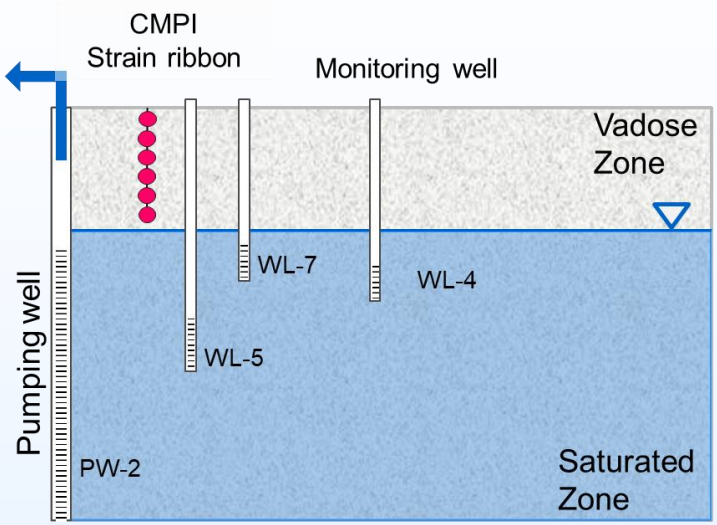




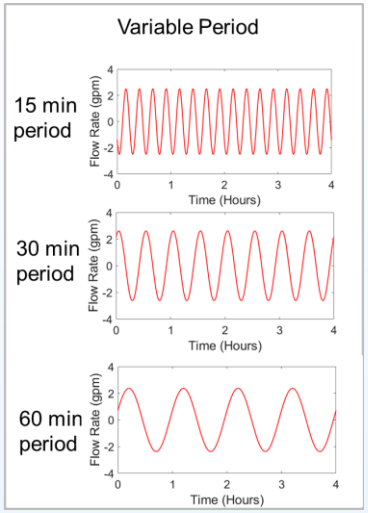
Transient strain at different depths after impulse

Strain during periodic-rate well tests

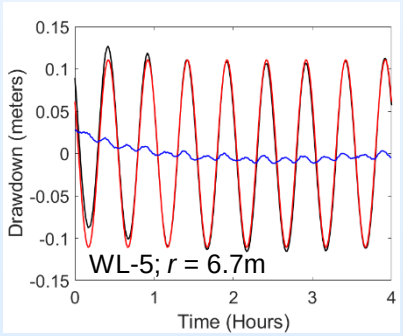
Field site cross-section

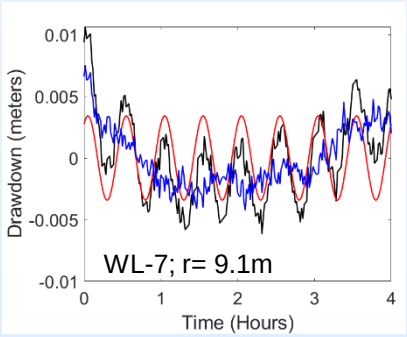


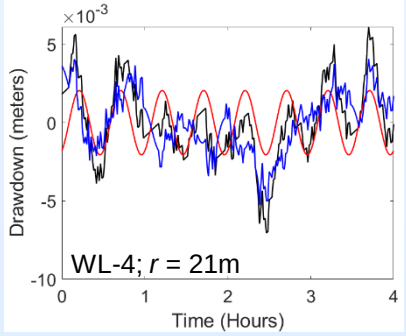
Pumping rates



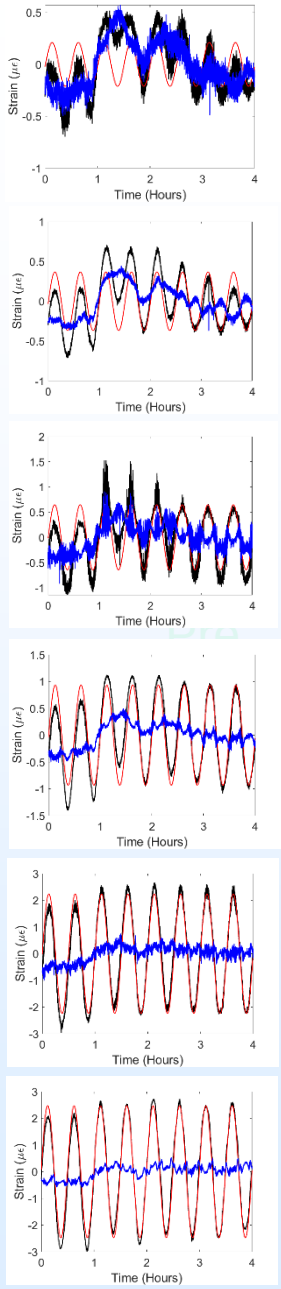
Pressure in formation







Strain in vadose zone



Increasing depth ↓

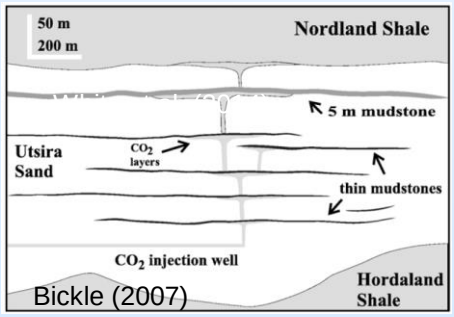
Task 2. Strain Interpretation

Identifying leaks from strain

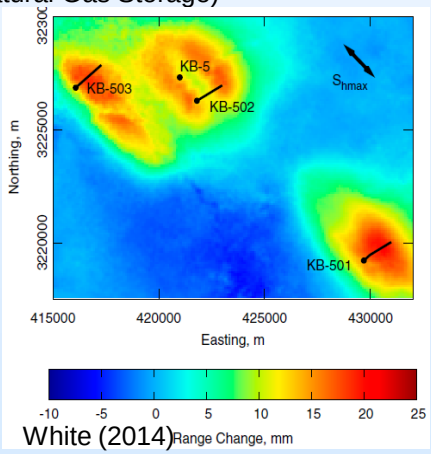
Detect?
Recognize?

Crystal Geyser
(Natural CO_2 Leakage)

Surface fracture, Elk City Blowout
(Natural Gas Storage)

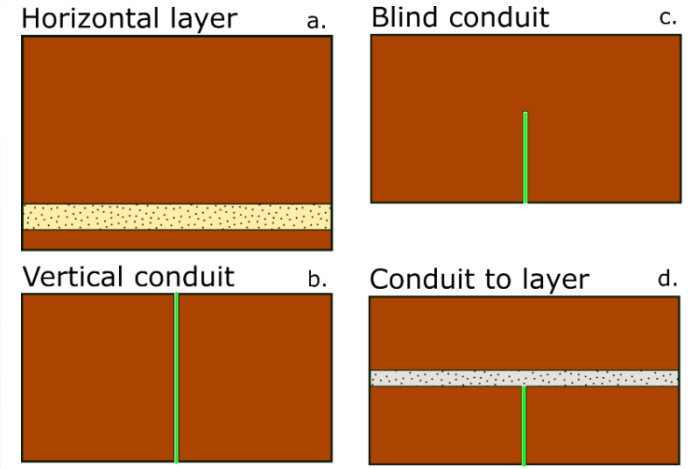


Cross-section, Sleipner
(CO_2 Storage)

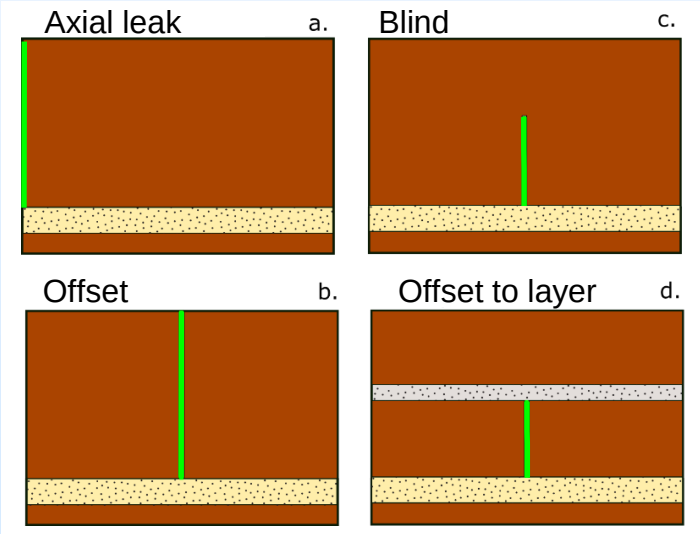


Uplift at In Salah
(CO_2 Storage)

Components



Composite→Leak + reservoir



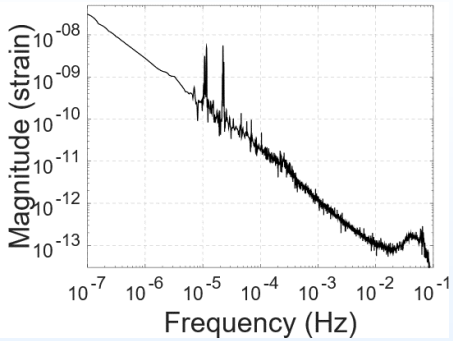
Task 2. Strain Interpretation

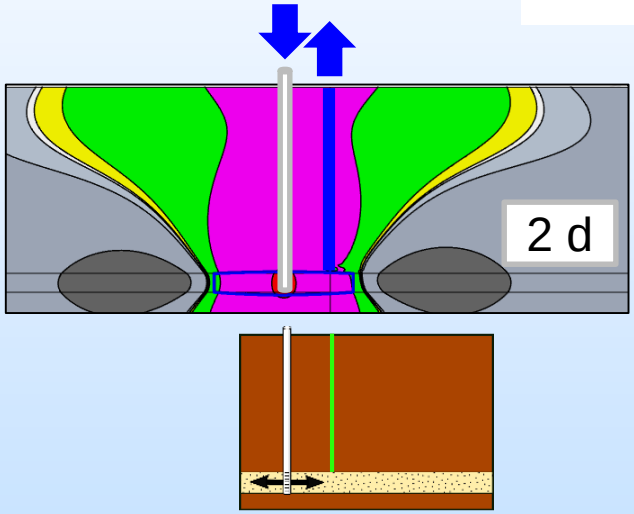
Identifying leaks from strain

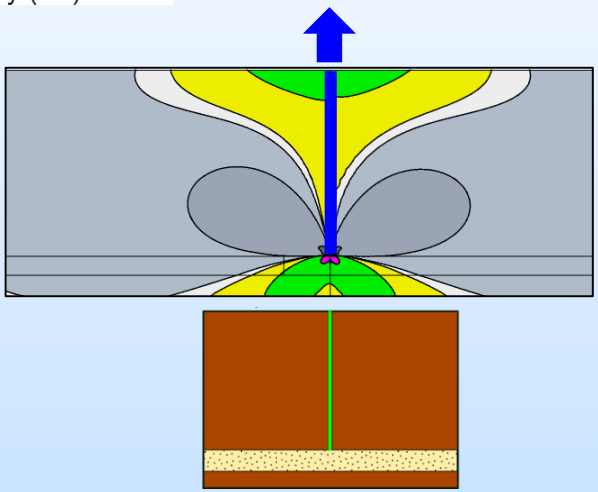
Detect?

Recognize?

Ambient strain magnitude spectra







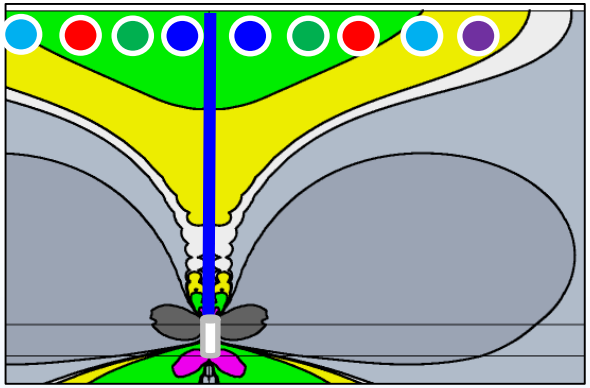
Horizontal strain field in cross-section during injection into reservoir; 35μm offset fracture

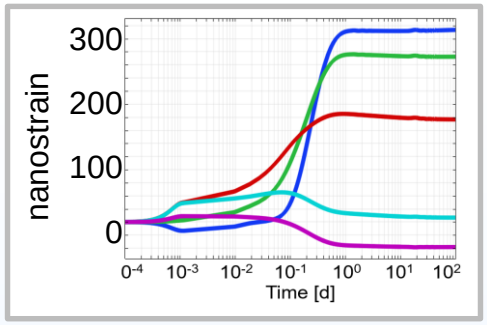
Horizontal strain field with strain from the reservoir pressure removed

1000	100	10	-10	-100	-1000

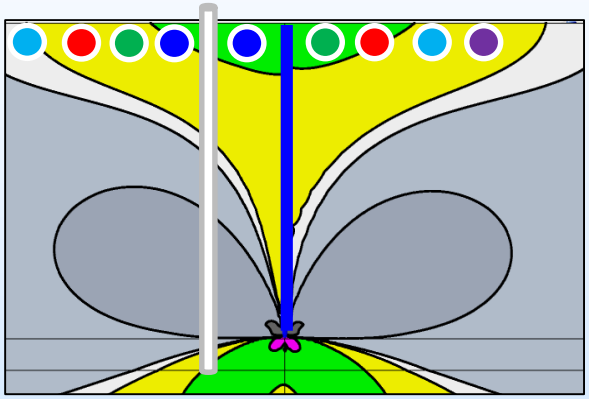
nanostrain, nε:

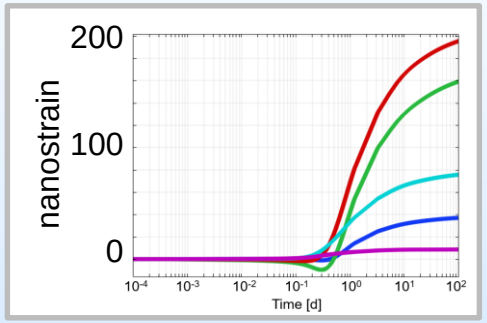
Axial Leak



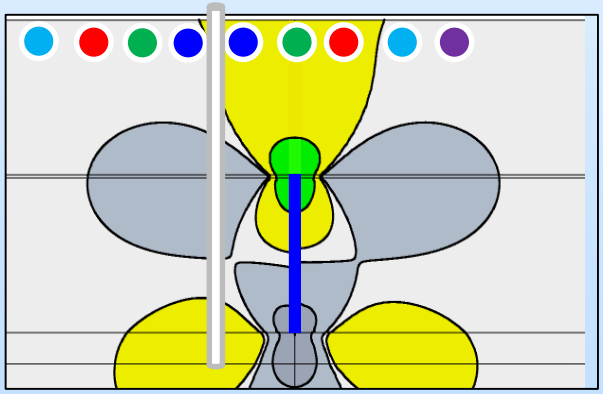


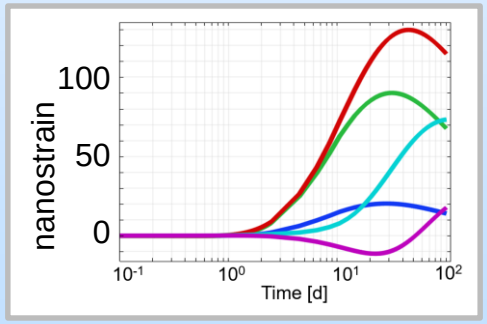
Offset Leak

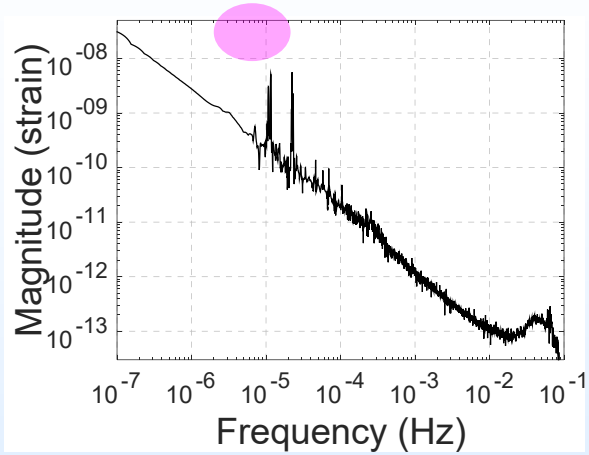




Offset Leak to Layer







nε: 10 | 100 | -10 | -100

Task 2. Strain Interpretation

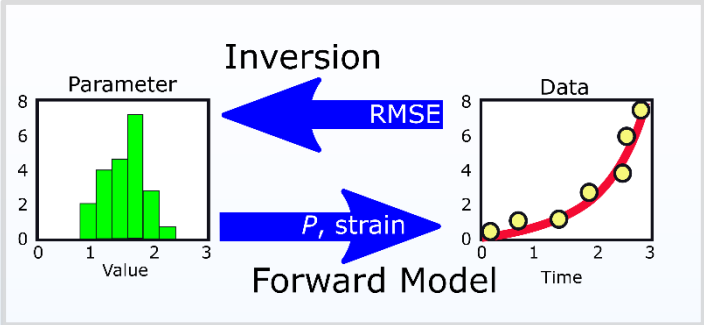
Interpretation: Characterize reservoir properties, geometries, etc. using strain and pressure data measured during well testing/operation. Forward model←→ Inversion

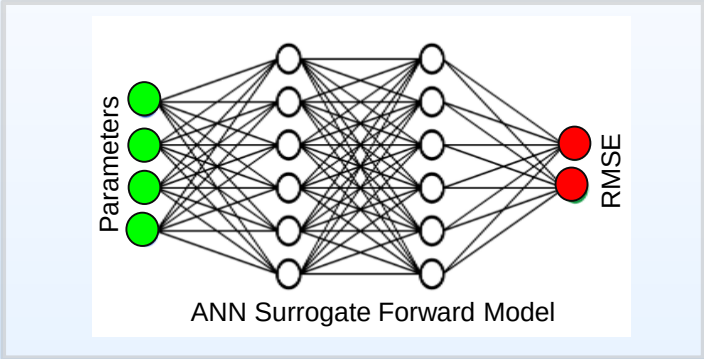
Forward Models

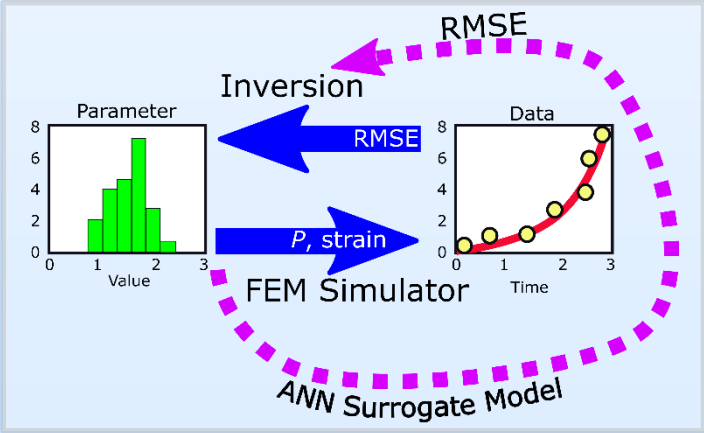
Analytical solution: simplified, very fast
FEM Simulator: details, slow
*Surrogate Model?***:** details, faster

Surrogate with Artificial Neural Network: ANN identifies complex patterns between inputs and outputs using a process that mimics how neurons analyze the information in the human brain.

Inversion Application: Train ANN surrogate using output from FEM Simulator. Run inversion with ANN to predict RMSE. Reduce RMSE, then run FEM to check & update ANN, repeat until converged.

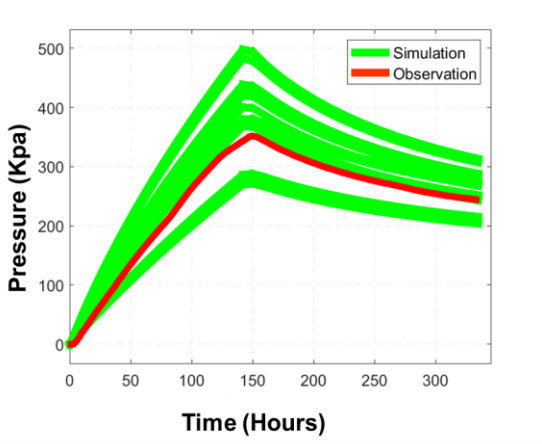


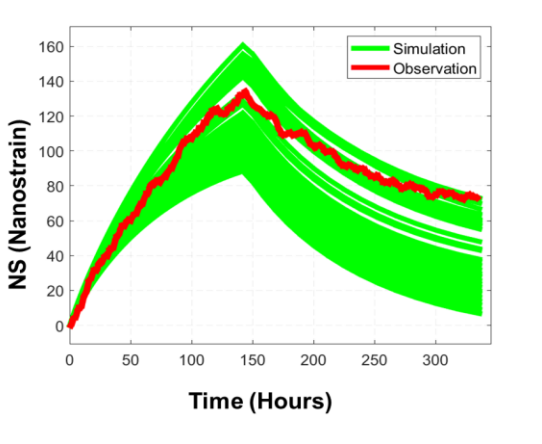


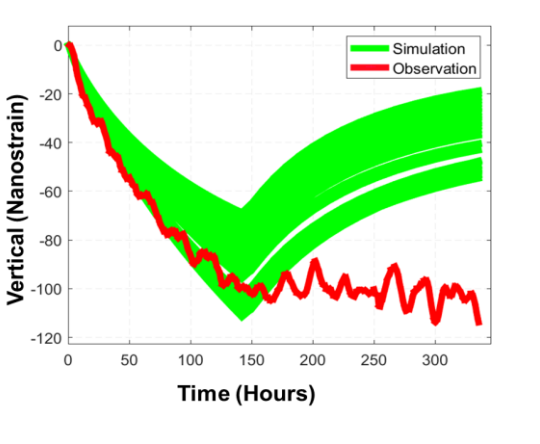


Task 2. Strain Interpretation

Test case: ANN Inversion of well test from Avant Field, OK







Performance

ANN surrogate w/ FEM: 20 core hrs (7E4 seconds)

FEM Simulator only: 410 core hrs (1.4E6 seconds)

ANN reduced by computation by ~20, with same results

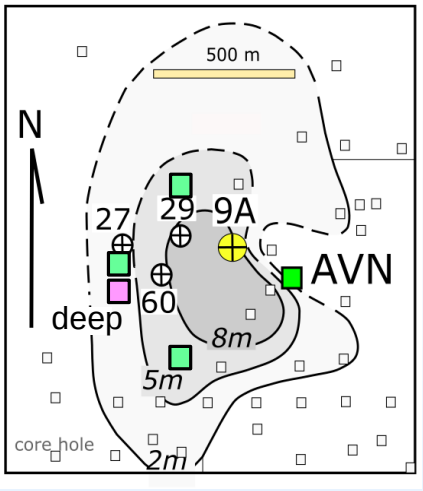
3D Analytical Solution: 1 core second; similar geometry and elastic parameters as FEM

Task 3. Field Experiments

✓ Workplan submitted

1. Avant
   - Build out shallow strainmeter array
   - Deep strainmeter in reservoir
   - Constant and periodic-rate tests
   - Improve resolution of inversion

2. Clemson
   - CMPI
   - Periodic-rate pump/inject
   - Shallow seismic
   - Ambient strain

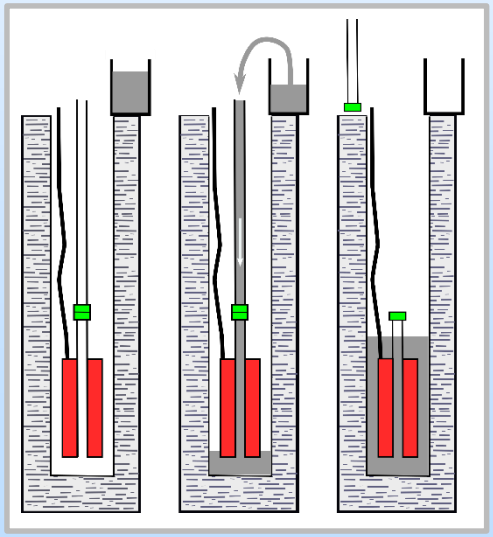


Planned Strainmeter Array


Surface infrastructure (unobtrusive)




Open axis for deep completion


Deep strainmeter deployment

Accomplishments

–Strain Instruments, Fiber interferometer

- Monolithic tiltmeter designed, built, lab tested, deployed
- 3 tensor strainmeters designed, built, lab tested, deployed
- 2 areal “smart casing” strainmeters designed, built, lab tested

–Distributed strain, Microwave photonics

- New interrogator field tested
- Field sensors—Ribbon; Discrete, Distributed, Multicomponent
- Field deployment, ambient strain, well tests, acoustic/seismic

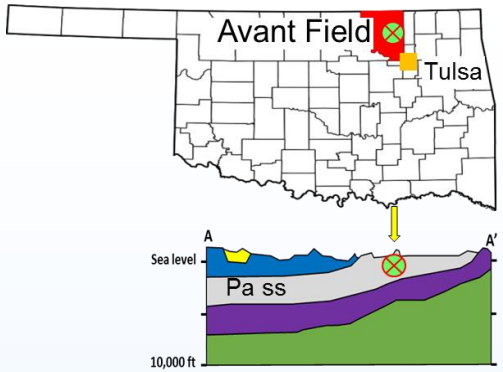
– Interpreting Strain

- Leaks--encouraging results
- Inversion--surrogate, analytical

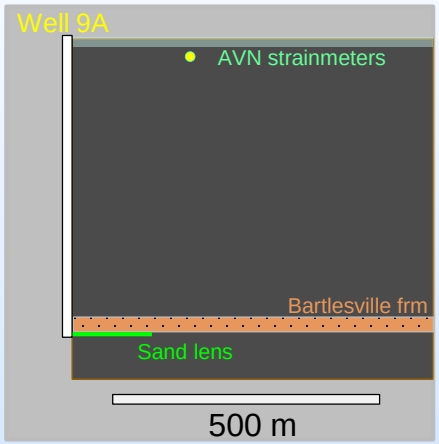
– Field Demonstration

- Planning Fall and Spring instrument deployments
- Shallow array + deep strainmeter at reservoir depth

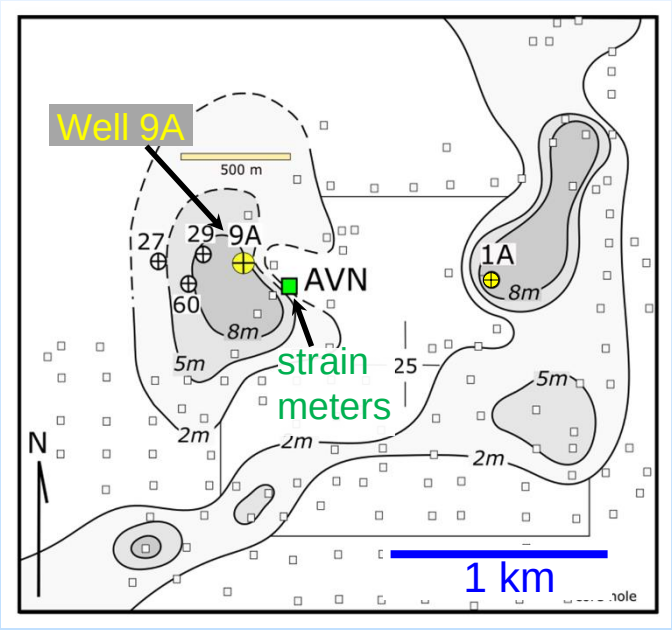
Analyzing Strain during Injection Field Tests



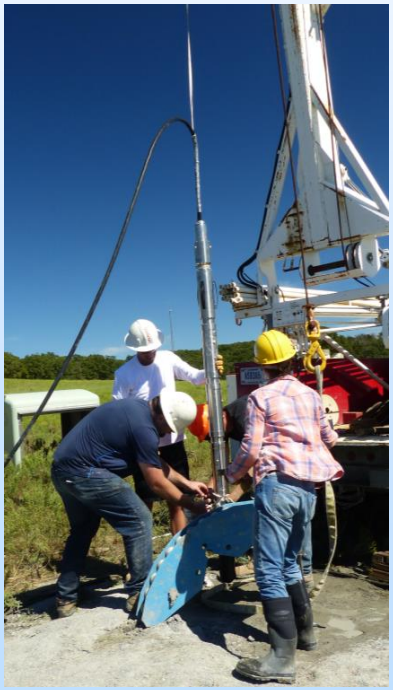
- **Objective**: Measure/interpret strain during waterflood as analog to CO_2 injection
- **Location**: Bartlesville Sandstone, Pennsylvanian North Avant Field, Osage County, OK 100+ years of oil production



Schematic cross-section



Permeable sand isopach



Installing strainmeter

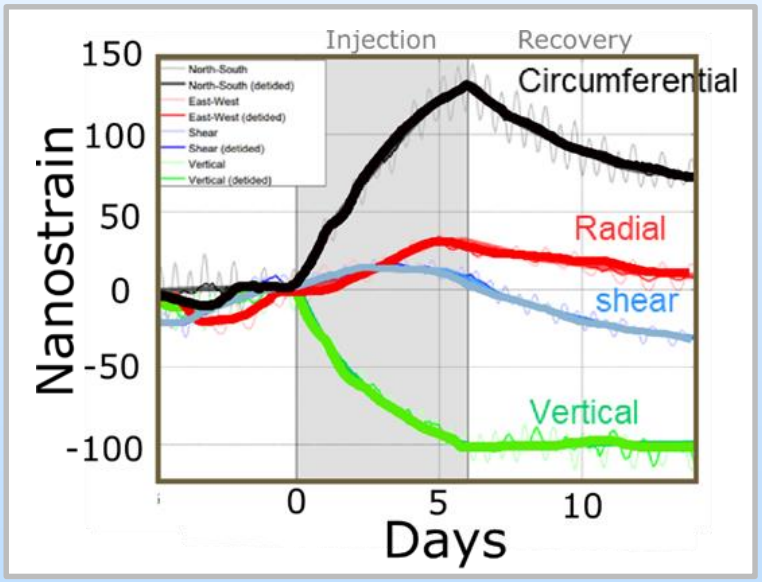
Strainmeters at Avant Field

Results

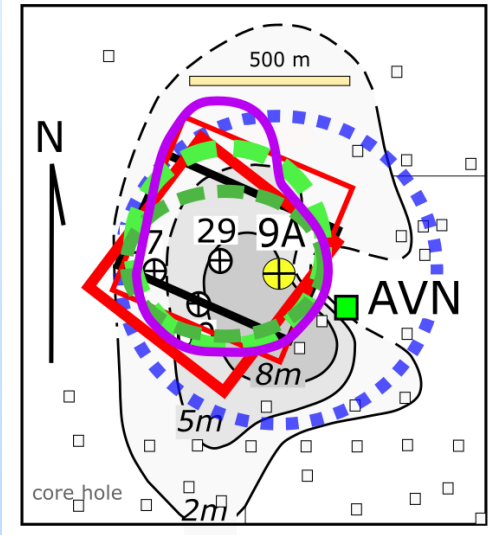
1. Strain from injection measured at shallow depths with geodetic strainmeter, repeatable
2. Inversion→reservoir properties and geometry
3. Geodetic strainmeter expensive, unavailable. Need new instrument

Reservoir properties from inversion

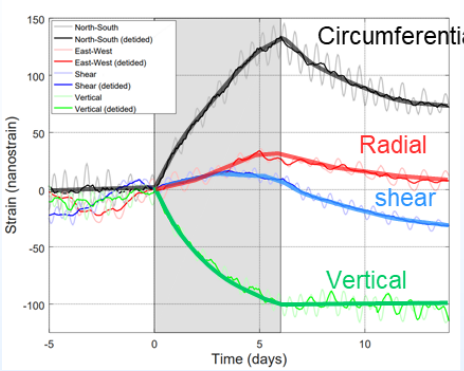
	Forward model Inversion		Type Curve Graphical	Inclusion Gradient	3D Manual Manual	Ellipse Stochastic	Pilot Stochastic
Parameter	Location	units					
Young's Modulus	Lens	E (GPa)		2	2	2-3,4-6	6
	Bartlesville	E (GPa)			8	17-22	33
	Confining	E (GPa)			2.9	17-22	33
Poisson's ratio		ν		0.23-0.4	0.26		
Permeability	Lens	k (mD)	100		500	250	150
	Bartlesville	k (mD)			5	0.1	0.1
	Confining	k (mD)			0.01	0.003	0.003
Thickness	Lens	m		7	5	5[a]	5[a]
Fluid Compressibility	Bartlesville	B(1/GPa)			11	0.45[a]	0.45[a]
	Lens	B (1/GPa)			3.5	0.45[a]	0.45[a]
Hydraulic Diffusivity[d]	Lens	$D_h(m^2/s)$	0.5	-	0.6	0.9	0.8
	Bartlesville	$D_h(m^2/s)$			0.004		
Distance to boundary	E	m	500	120	80	100	120
Distance to boundary	N	m	500	225	150	200	400
Distance to boundary	S	m	500	345	150	150	150
Distance to boundary	W	m	500	390	500	400	400

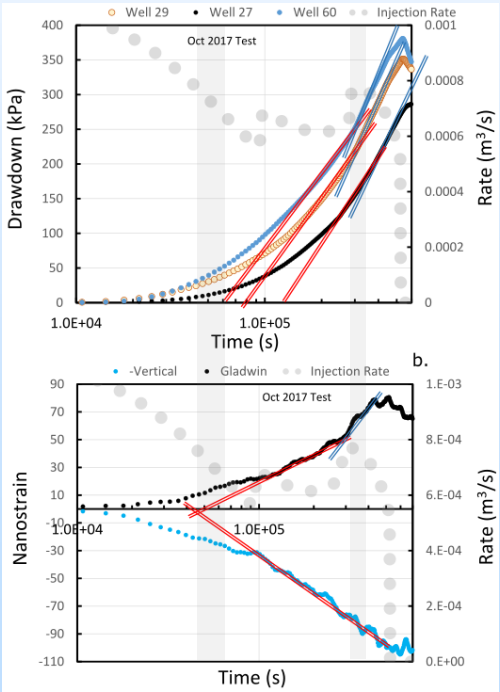


Estimated reservoir geometry



Observations





Injection: ~15 gpm @ 500m depth, 2 to 20 days

Shallow strain: Horizontal tension
Circumferential > radial
Vertical compression

Strain rates: initial 100 nε/d
first day 30 nε/d
few days 10 nε/d

Total strain: 10s to 100s nε

Strain log slope: 50-75 nε
Strain log time intercepts: 12 +/- 3 hrs; 46 +/- 6hrs
Pressure log time intercepts: 13 hrs +/-3 hrs