ROBUST IN SITU STRAIN MEASUREMENTS TO MONITOR CO_2 STORAGE

Project Number FE0028292

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U.S. Department of Energy

National Energy Technology Laboratory

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Project Goals and Tasks

Develop and demonstrate in-situ strain measurement during injection

Michelson Interferometer

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

Microwave Photonics

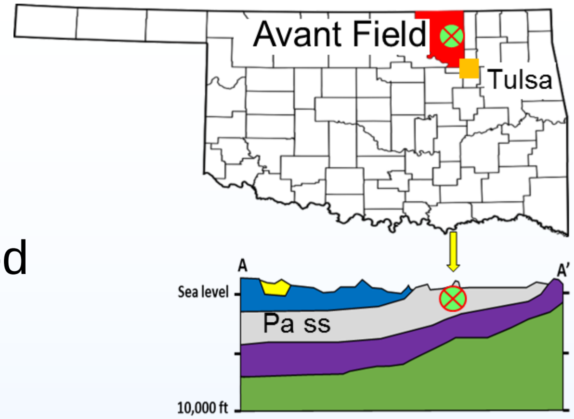
2. Strain Interpretation
   - Leaks, ambient processes
   - Analytical solution
   - Inversion applications
3. Field Demonstration
   - Deploy instruments in field injection setting
   - Acquire data, interpret

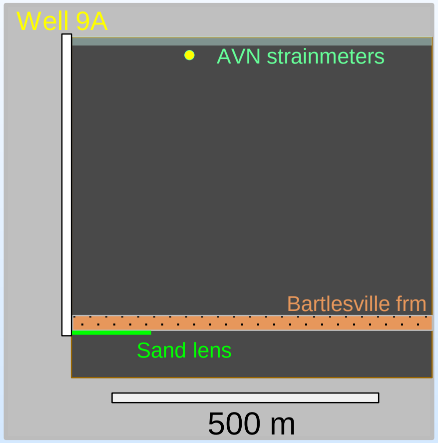
<u>Outline</u>

- Technical Status
- Accomplishments
- Lessons Learned
- Synergy
- Summary

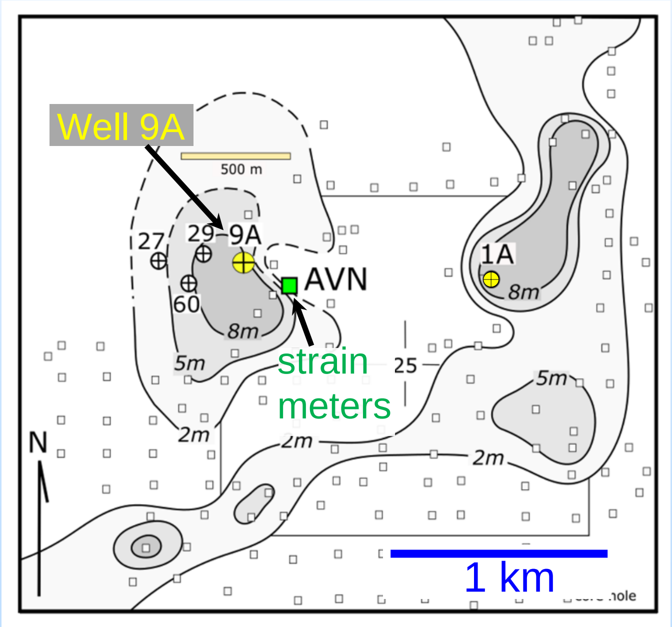
Analyzing Strain during Injection Field Tests

- **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

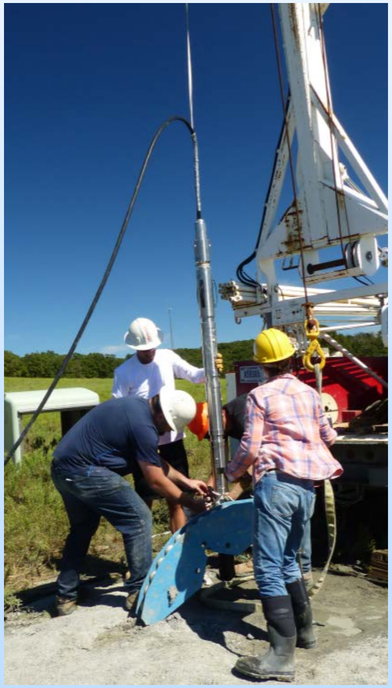




Schematic cross-section



Permeable sand isopach

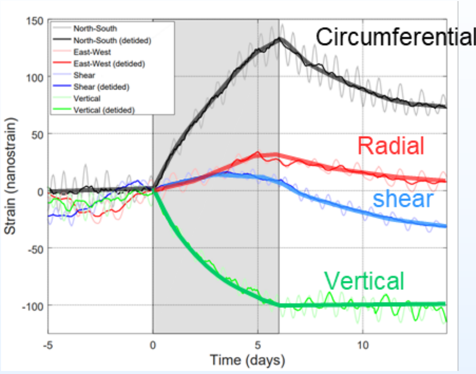


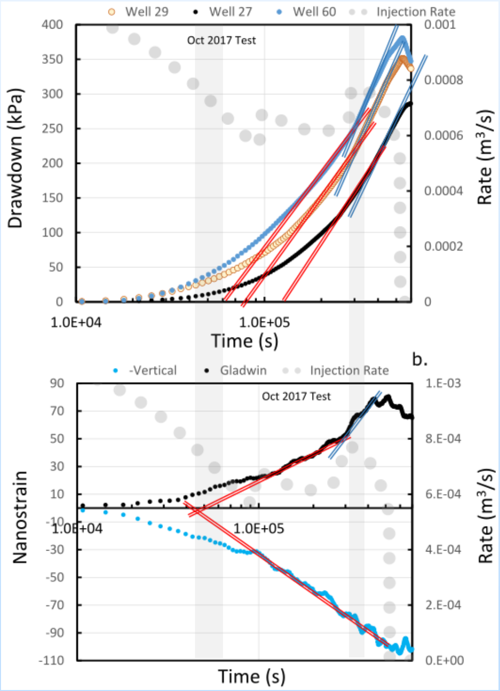
Installing strainmeter

Strainmeters at Avant Field

CLEMSON UNIVERSITY
U.S. DEPARTMENT OF ENERGY

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

Results

Interpretation Methods

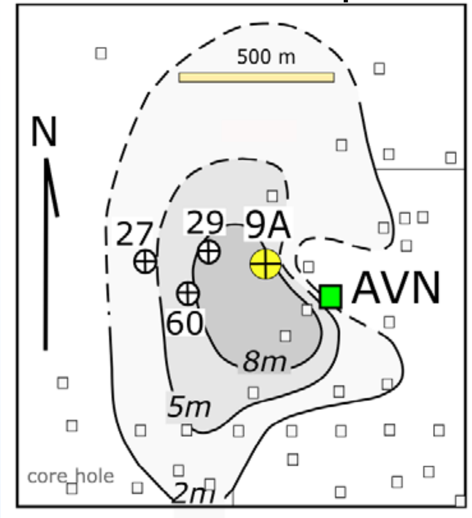
1. Strain type-curve method
   - Based on well testing,
   - Simple, fast, hydraulics and mechanics
2. Poroelastic inclusion
   - Advanced analytical solution
   - Fast, mechanics
3. Stochastic inversion
   - Numerical, intense computations
   - Detailed

Scaling

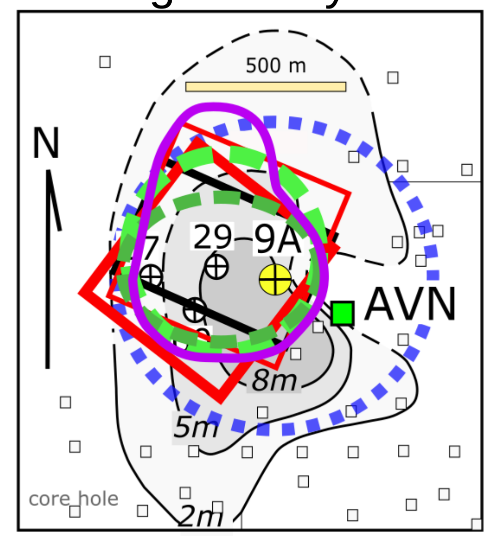
$$\varepsilon^* = \frac{\alpha \mu Q}{Kkd}$$

$$\frac{\varepsilon^*}{t^*} = \frac{\alpha Q M}{K d^3}$$

Reservoir isopach



Estimated reservoir geometry



Estimated Properties from strain inversion

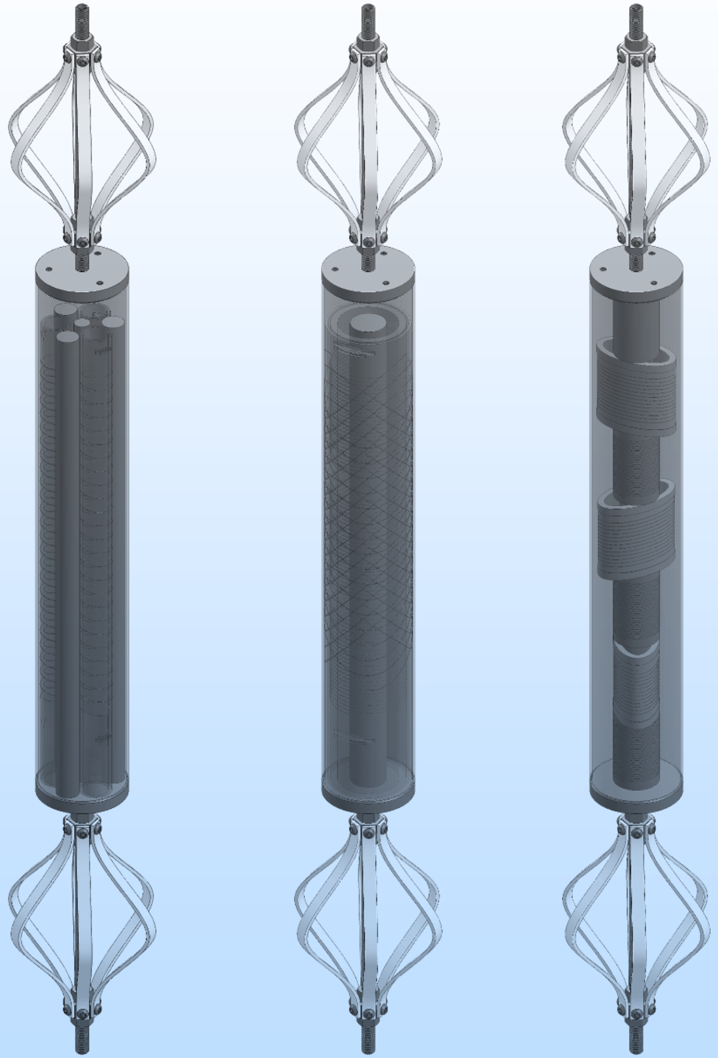
Parameter	Location	units	Type Curve / Graphical	Inclusion / Gradient	3D Manual / Manual	Ellipse / Stochastic	Pilot / Stochastic
	Forward model		Type Curve	Inclusion	3D Manual	Ellipse	Pilot
	Inversion		Graphical	Gradient	Manual	Stochastic	Stochastic
Young's Modulus	Lens	E (GPa)		2	2	2-3,4-6	6
	Bartlesville	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

BP1→BP2

One instrument: Shallow strain → reservoir properties and geometry

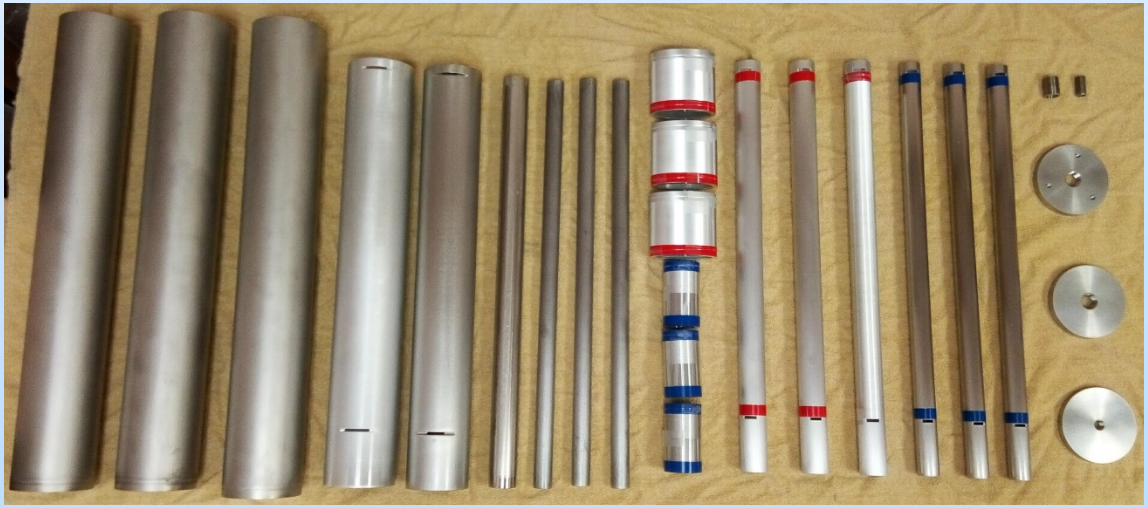
- Instrument Array
  - Strainmeters, Michelson Interferometer
  - Distributed sensors, Microwave photonics
- Strain Interpretation
  - Stability
  - Leaks
  - Ambient processes
  - Signal processing
- Field Tests
  - Clemson
  - Avant Field, OK

Optical Strain Instruments

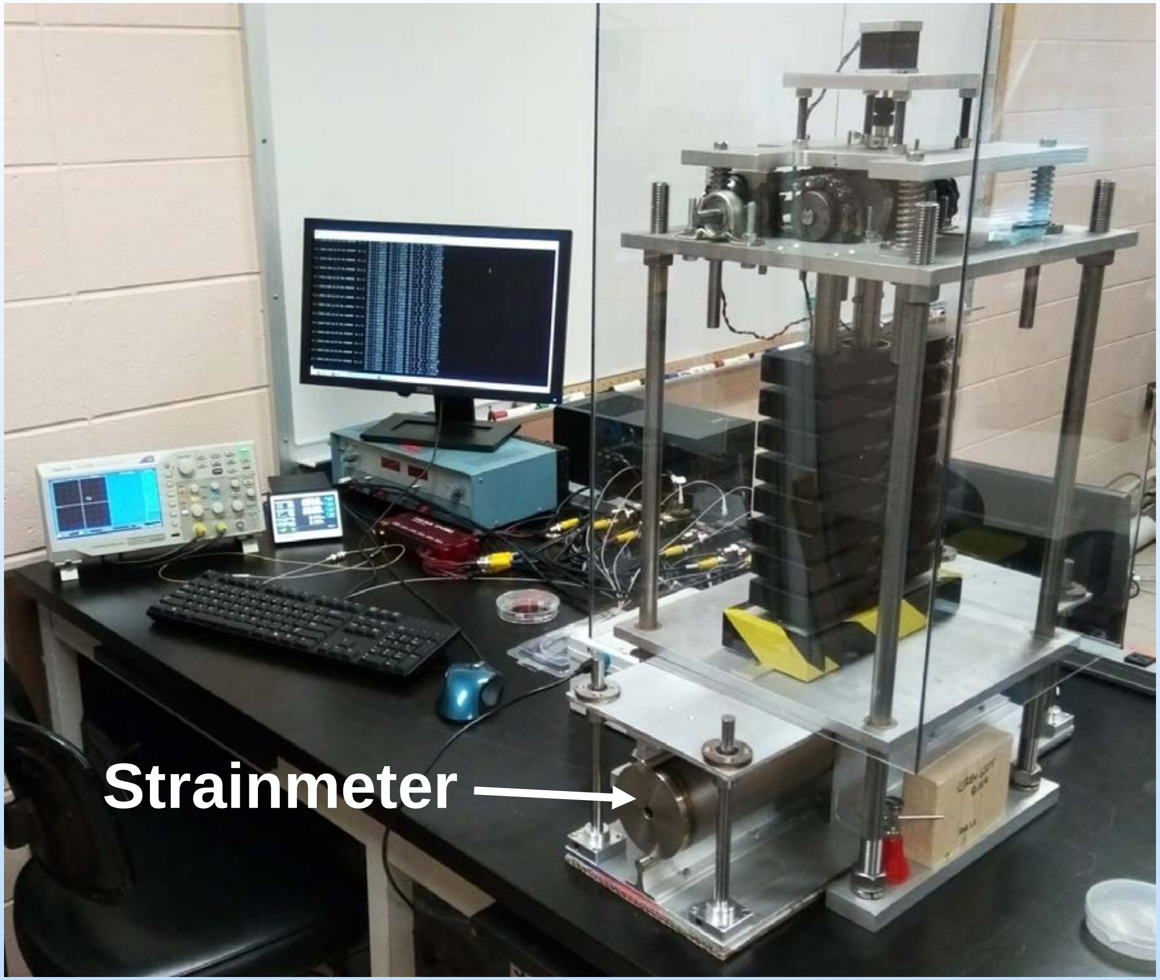


3 Horizontal Tensor Strainmeters

- Designed and being assembled
- Different measurement styles
  - Multi-tube, inclined wrap, elliptical element
  - Sub picostrain ($<10^{-12}$) resolution
- Deployed in tandem (i.e., stacked)

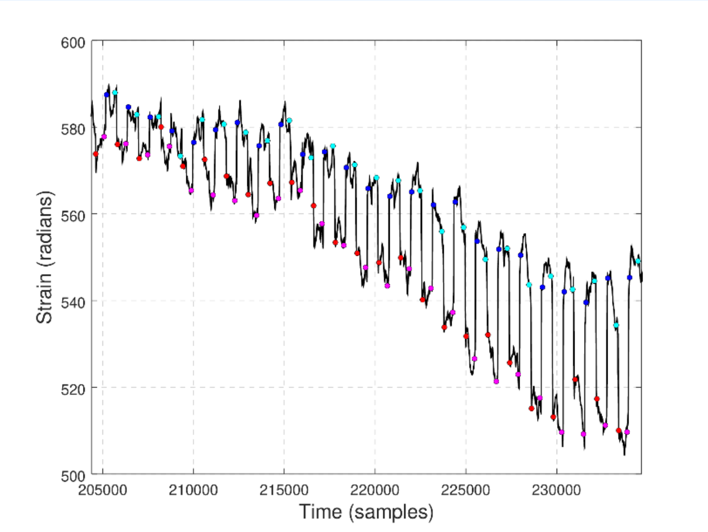


Optical Strain Instruments



Automated Dead-Weight Calibration

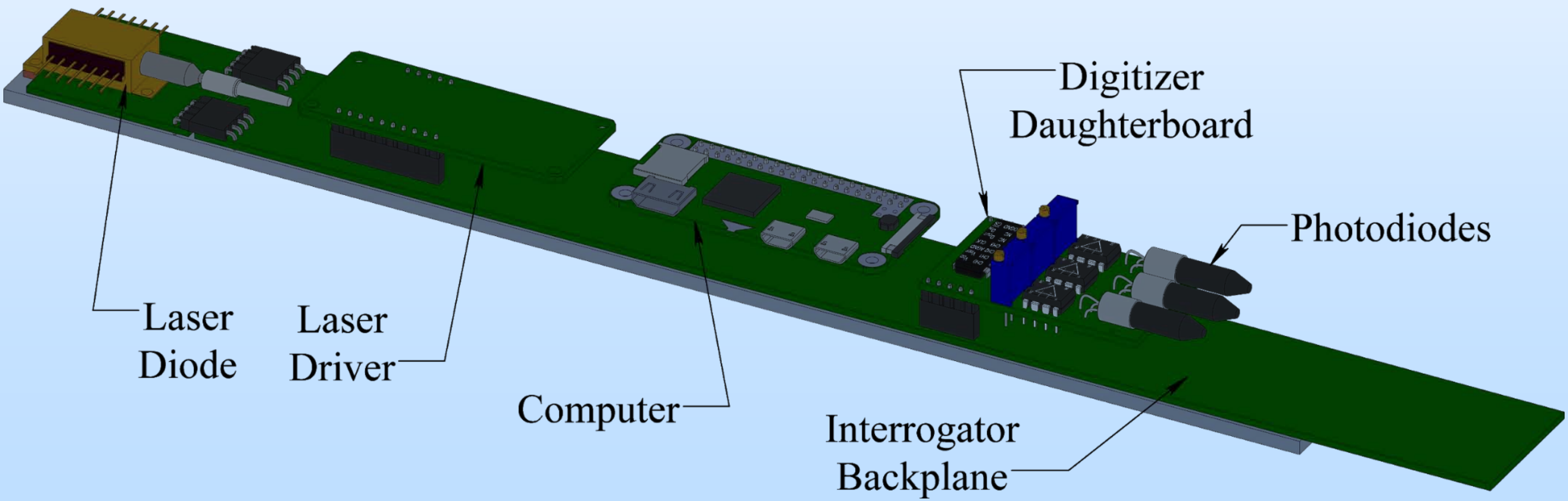
- Programmable loading
  - Up to 10 @ 5 lbs
- Manual azimuth index



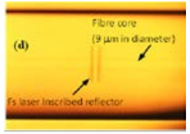
Optical Strain Instruments

New Optical Fiber Michelson Interrogation System

- Up to 128 interferometers
- Fits inside 2” pressure case
- >2.5 Watts (without wireless)
- 16-bit @ 1.5 MHz
- Coming soon:
  - GPS disciplined oscillator
  - 4G LTE modem



Field Testing Distributed Strain Sensor



Reflector in optical fiber

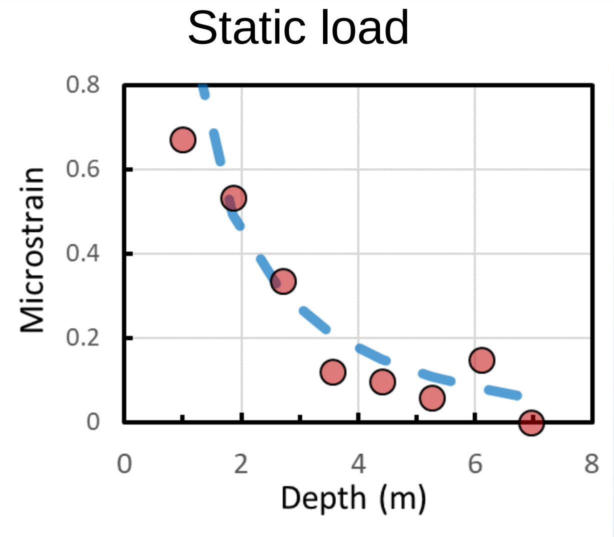
Sensing: Microwave photonics for strain and acoustics, CMPI. Non-proprietary interrogator

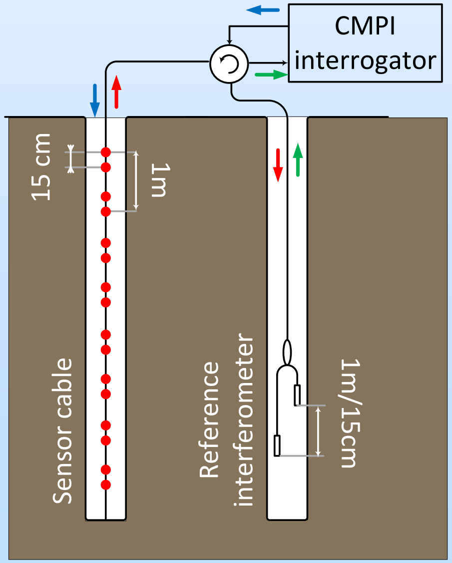
Fiber packaging: friction coupling to formation: high compliance, large surface area

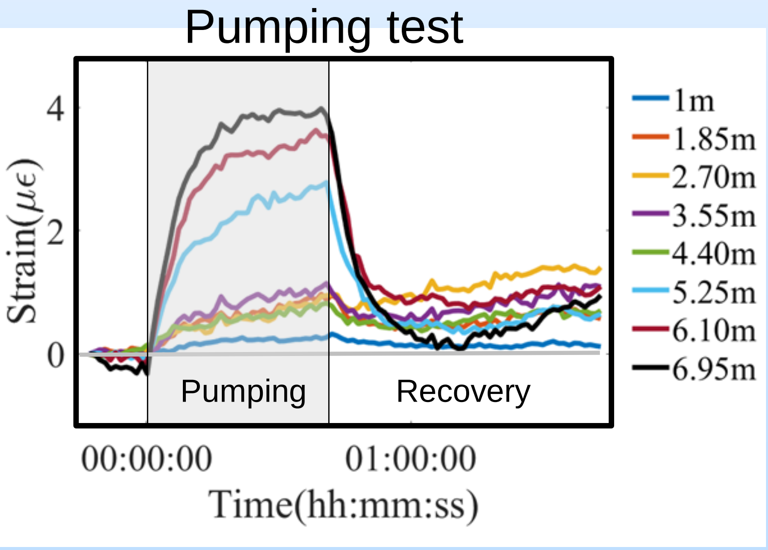
Field testing: Fiber to 8m in vadose zone. Reflector spaced 15 cm every m. Field interrogator with telemetry. Tested with static surface load and pumping in underlying aquifer.

Field deployment. Fiber packaging for friction coupling to formation

Interrogator

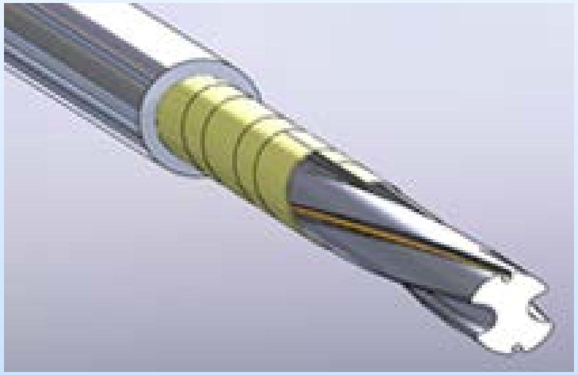






Field Testing Distributed Strain Sensor

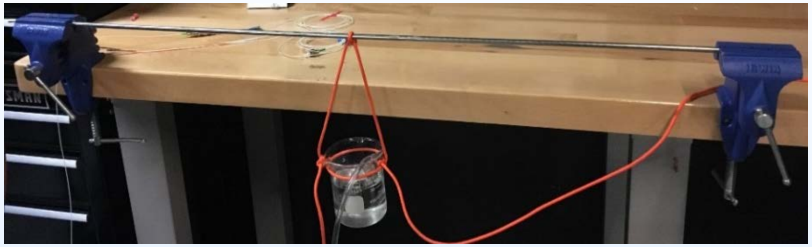
Packaging: WIRE cable (Baker Hughes): contains close spaced (2cm) weak FBGs, helically attached to metal rod, sealed in ¼" metal tubing. Multi-dimension strain, ~10 $\mu\varepsilon$ resolution, good for protecting well integrity. Commercial product.

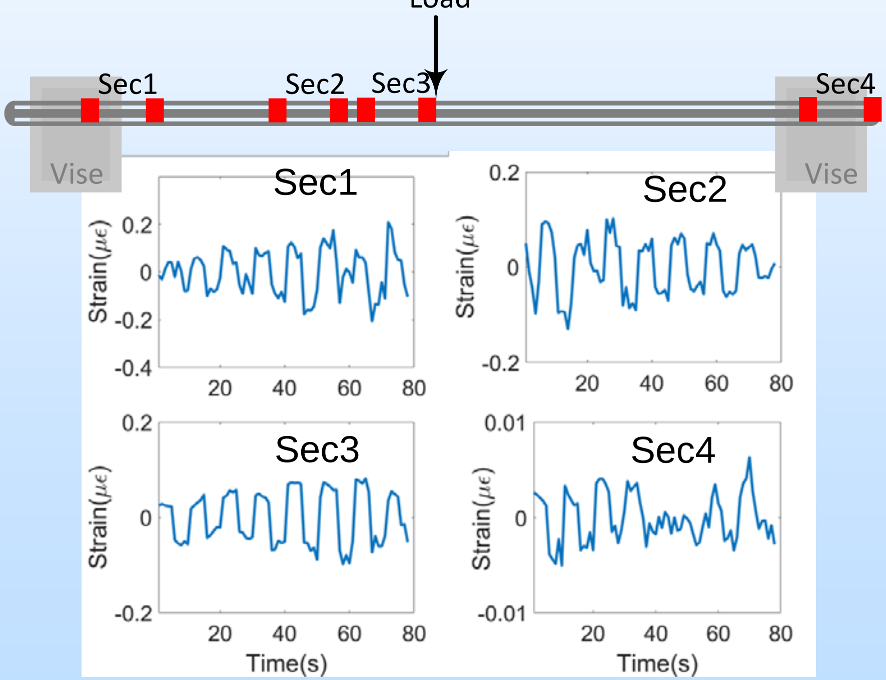


Question: Can WIRE be used with CMPI → High resolution, multi-component distributed strain?

Proof of Concept Test

Clamped WIRE cable, load by +/- 10 gm increments





Strain resolution ~0.01 $\mu\varepsilon$ using CMPI

Task 2. Strain Interpretation

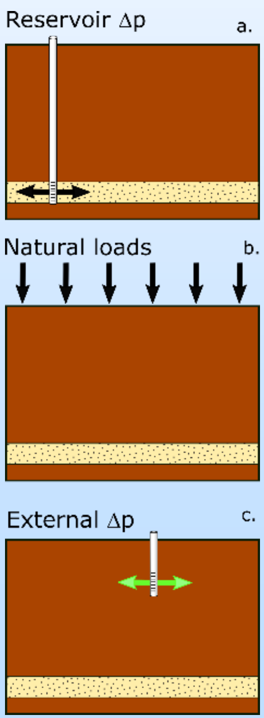
Identifying leaks from strain

1. Conceptual model of strain from leaks?
2. Expected strain signals?
3. Can expected signals be measured?
4. Can measurements be identified as leaks?

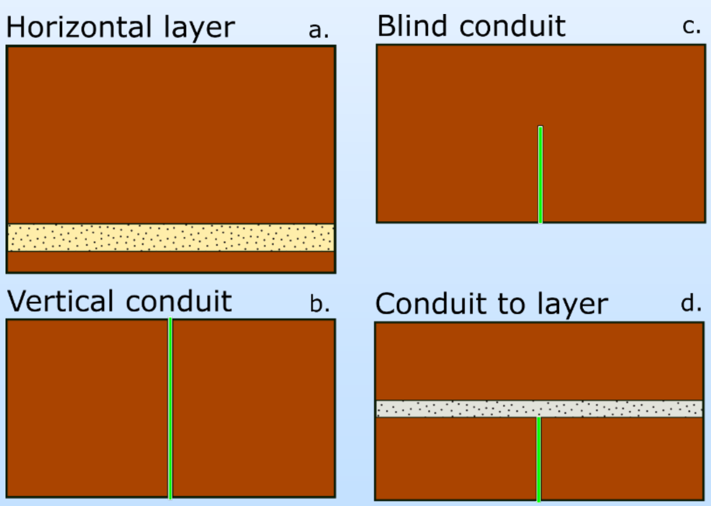
Conceptual Framework

- Loads that cause strain
- Geometric components
- Geometry composites

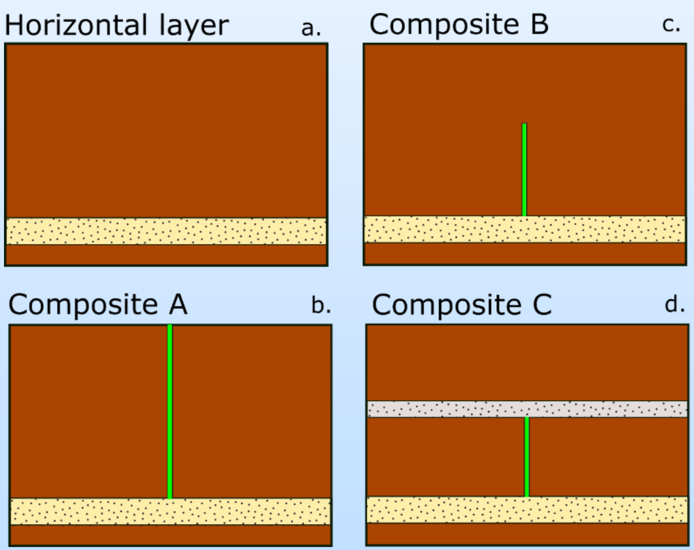
Load Type



Components



Geometries



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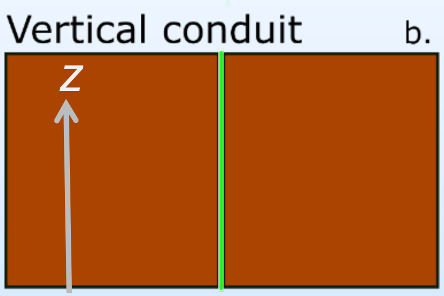
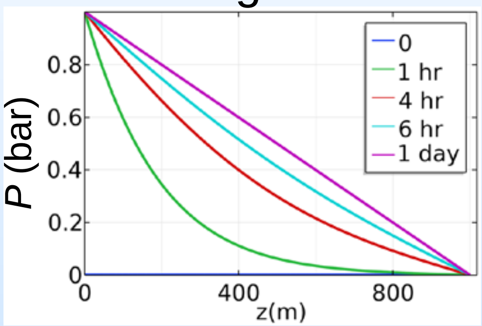
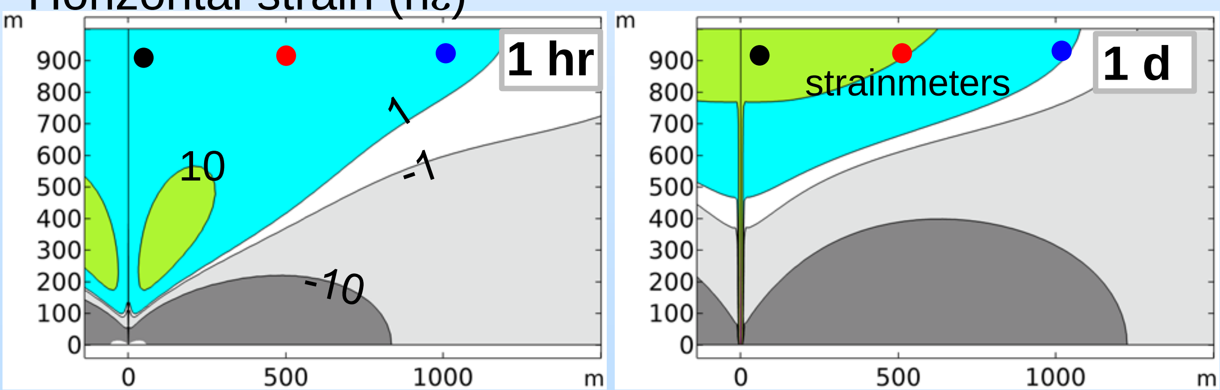


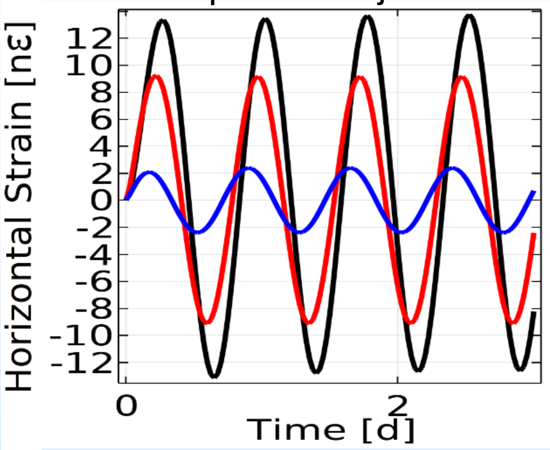
P along conduit



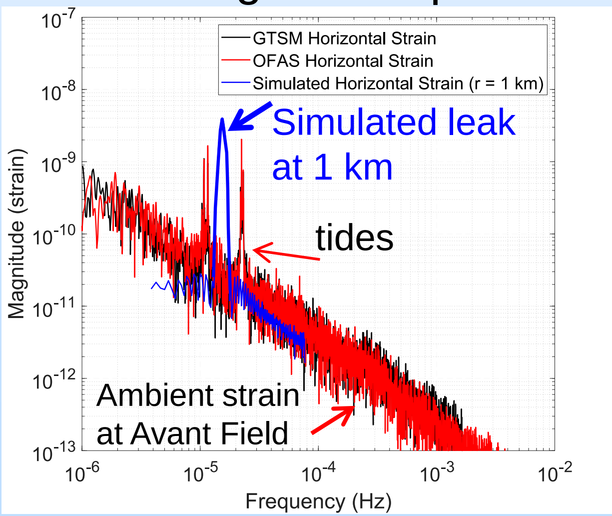
Horizontal strain (nε)



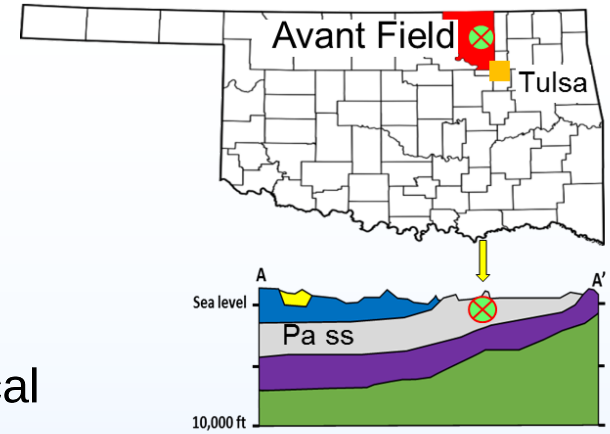
ε_h at strainmeters from periodic injection



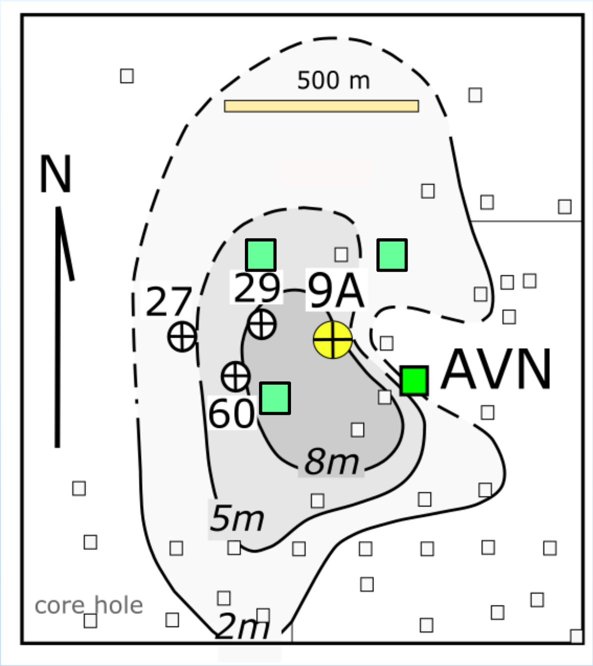
Strain magnitude spectra



Task 3. Field Experiments



1. Clemson
    - Strain instruments, Inclined, 3-tube, elliptical
    - CMPI in vadose zone and rock
    - Periodic pumping
2. Avant
    - Tiltmeter
    - Build out strainmeter array
    - Constant and variable rate tests
    - Improve resolution of inversion



Accomplishments to Date

– Strain Instruments, Fiber interferometer
  - Monolithic tiltmeter designed, built, lab tested, deploy Sept 9th in OK
  - 2 areal "smart casing" strainmeters designed, built
  - 3 tensor strainmeters designed and being assembled
    - – Deployment this fall!

– Distributed strain, Microwave photonics
  - High resolution strain, static → 20 kHz
  - Non-proprietary field interrogator
  - Packaging; high coupling, WIRE
  - First field demo

– Interpreting Strain
  - Reservoir characterization, Scaling
  - Leaks

Synergy Opportunities

- Demonstrate at CO_2 injection sites
- Evaluate at leak experiments
- Integrate with other monitoring methods, joint inversion

Project Summary

Strain Instruments, Fiber Interferometers

- Monolithic tiltmeter, biaxial, high resolution
- Tensor Strainmeters: Wrapped tube, Inclined wrap, elliptical element
- Field testing underway

Distributed Strain, Microwave Photonics

- High resolution static strain → seismic frequency, Non-proprietary gear
- Fiber packaging for shallow and deep applications
- Shallow field tests encouraging

Next Steps

- Field demo at Clemson
- Prep for build out at Avant Field
- Theoretical analyses; strain from leaks, analytical inversion, data processing, filtering

Lessons Learned

High sensitivity

- Fiber packaging — armoring/coupling
- Noise — detect everything
- Calibration — limit noise

Scaling to:

- Multiple instruments
- Multiple components per instrument
- Field-based interrogator

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Technical Status

- Prepare as many technical status slides as needed, but recognize the limits of the allocated presentation time.
- Use these 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.
- Include specific information to show how your project is advancing the state-of-the-art; be as quantitative as possible in describing improvements in the performance of your technology compared to the state-of-the-art.

Accomplishments to Date

- Bullet List of Accomplishments (see Presentation Guidelines for examples).
- Multiple slides can be used if needed.

Lessons Learned

- Research gaps/challenges.
- Unanticipated research difficulties.
- Technical disappointments.
- Changes that should be made next time.
- Multiple slides can be used if needed.

Benefit to the Program

- Identify the program goals being addressed.

- Insert project benefits statement.
  - See Presentation Guidelines for an example.

Project Overview

Goals and Objectives

- Describe the project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives.
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.

Organization Chart

- Describe project team, organization, and participants.
  - Link organizations, if more than one, to general project efforts (i.e., materials development, pilot unit operation, management, cost analysis, etc.).

- Please limit company specific information to that relevant to achieving project goals and objectives.

Gantt Chart

- Provide a simple Gantt chart showing project lifetime in years on the horizontal axis and major tasks along the vertical axis. Use symbols to indicate major and minor milestones. Use shaded lines or the like to indicate duration of each task and the amount of work completed to date.

Bibliography

– List peer reviewed publications generated from the project per the format of the examples below.

- Journal, one author:
  – Gaus, I., 2010, Role and impact of CO_2-rock interactions during CO_2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  – MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  – Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.