Proof-of-Feasibility of Using Wellbore Deformation as a Diagnostic Tool to Improve CO2 Sequestration

DE FE0004542

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
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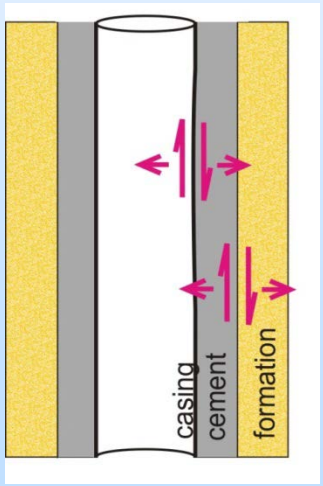
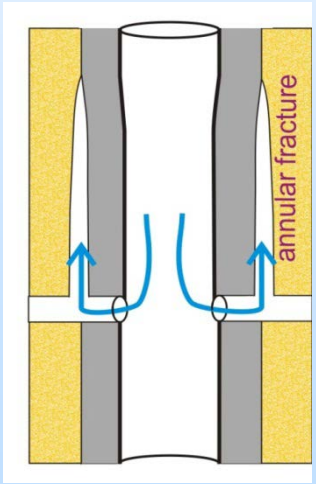
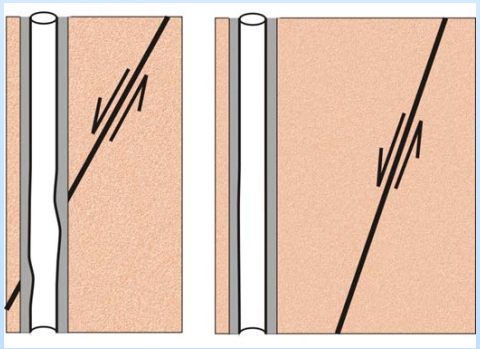
Presentation Outline

- Preliminaries
- Current project status
- Plans







Improve characterization

Anticipate problems

Benefit to the Program

Measuring and interpreting casing deformation should improve the ability to characterize flow and geomechanical properties of injection zones and confining units, as well as remotely estimate pressure in the storage reservoir, and help identify problems with wellbore integrity that could lead to leakage.

Program Goal:

Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent

Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones

Project Overview:
Goals and Objectives

Evaluate feasibility of using wellbore deformation as a diagnostic tool.

1. What deformation should be expected?
   - FEM analyses, Task 2
2. Can that deformation be measured?
   - Instrument development and testing, Task 4
3. Can the measurements be interpreted?
   - Inverse analyses, Task 3

What can be measured?

Task 4

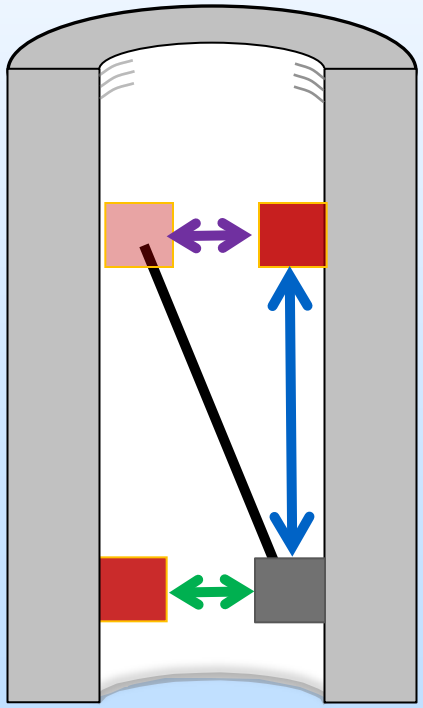
Goal: Assess capabilities to measure deformation of wellbores under field conditions.

Downhole Tools

- Axial displacement/strain
- XZ, YZ shear (tilt)
- Radial displacement

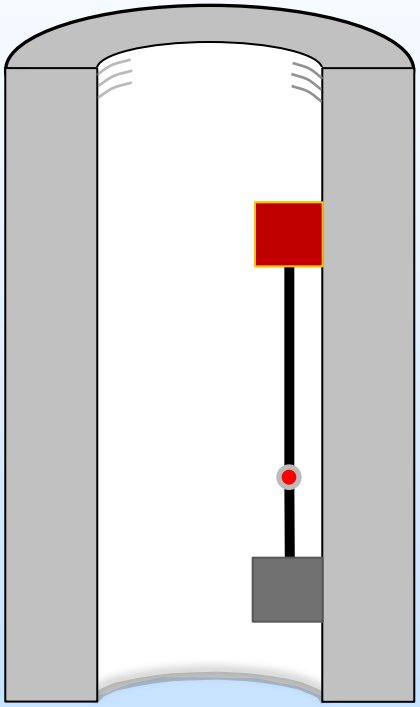
Sensors

- Displacement/strain
  - LVDT, DVRT
  - Optical Fiber Bragg Grating (FBG)
  - Capacitance gauge
- Acceleration
  - MEMS accelerometer
- Tilt
  - Electrolytic bubble



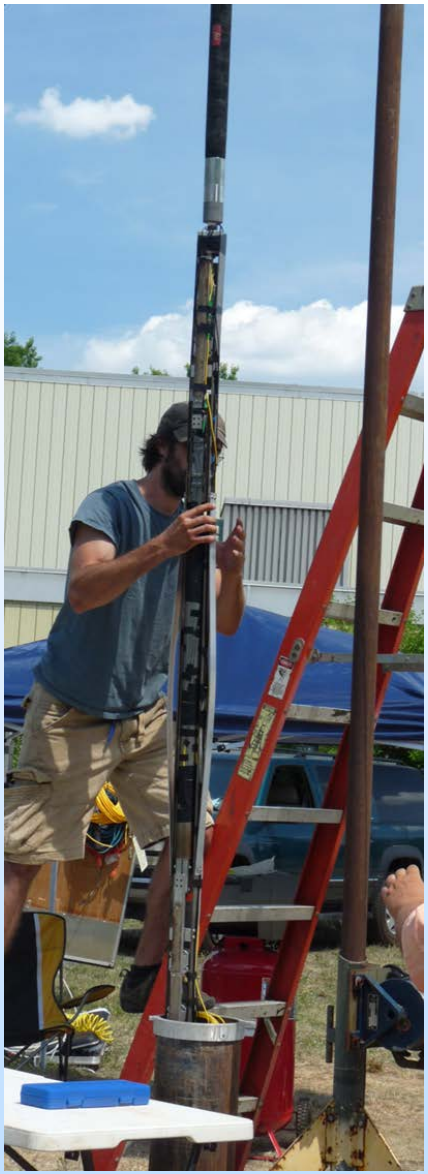
3D Borehole Displacements

Optical Fiber Sensor



Fiber Bragg Grating Strain Gauge

+ Immune to EM interference
+ Immune to supercrit CO2
+ No downhole electronics
+ Many gauges per fiber
- Fragile



Field Testing in Newark Basin, July 2012

3D Borehole Displacements

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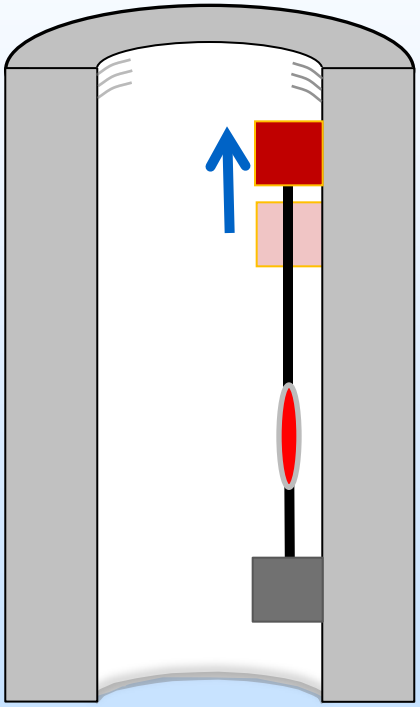

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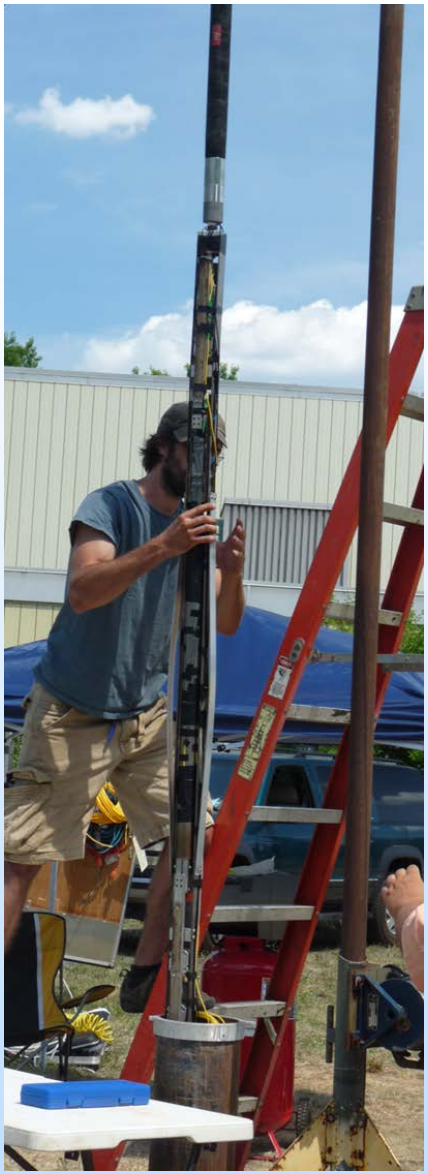

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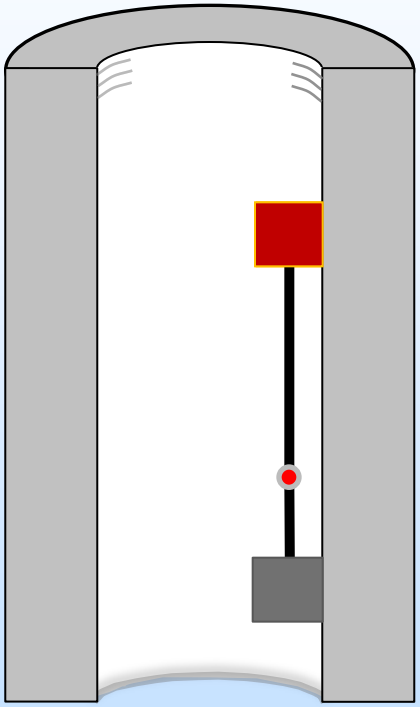

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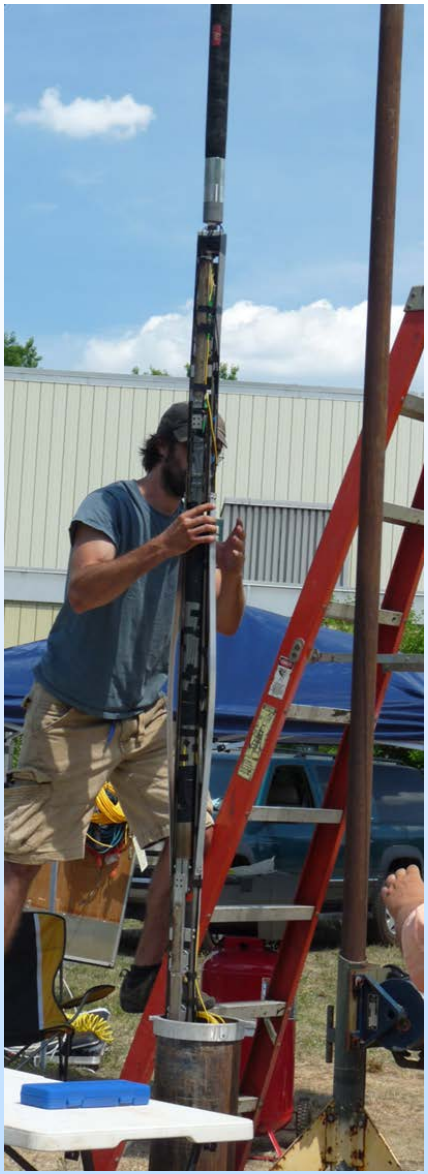

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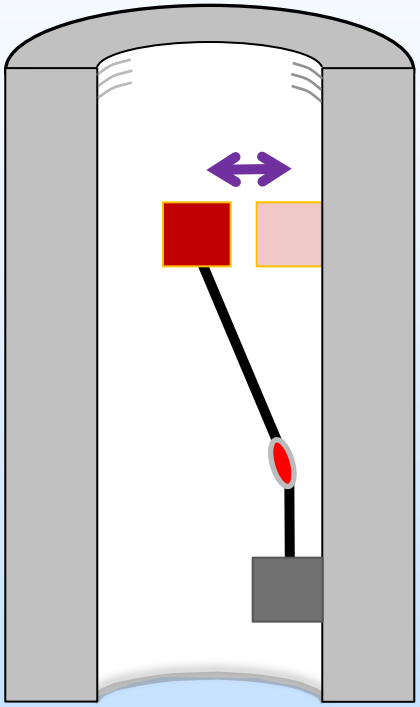

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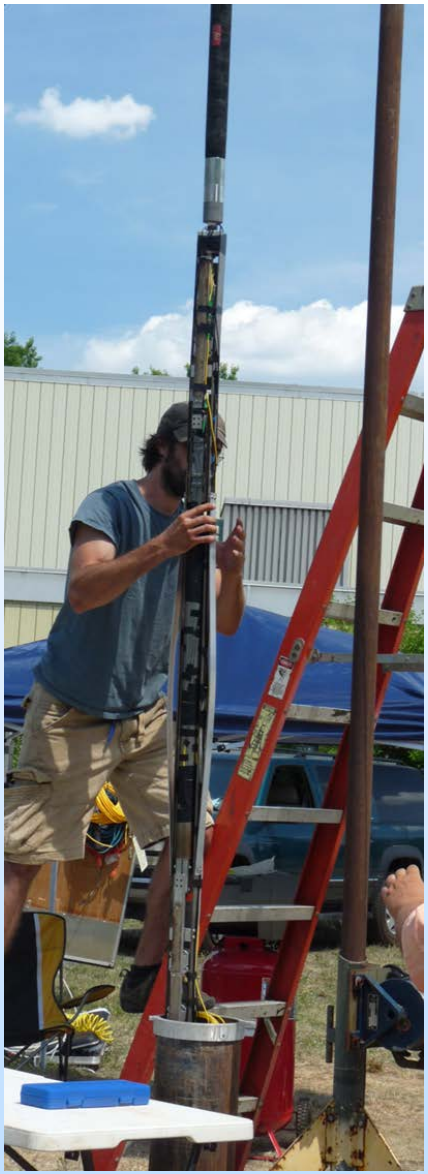

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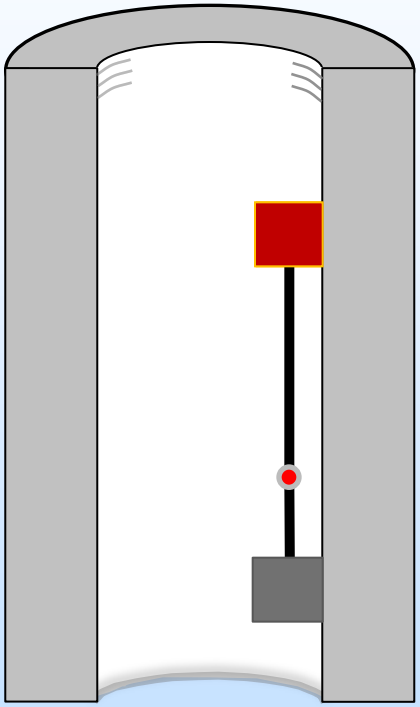

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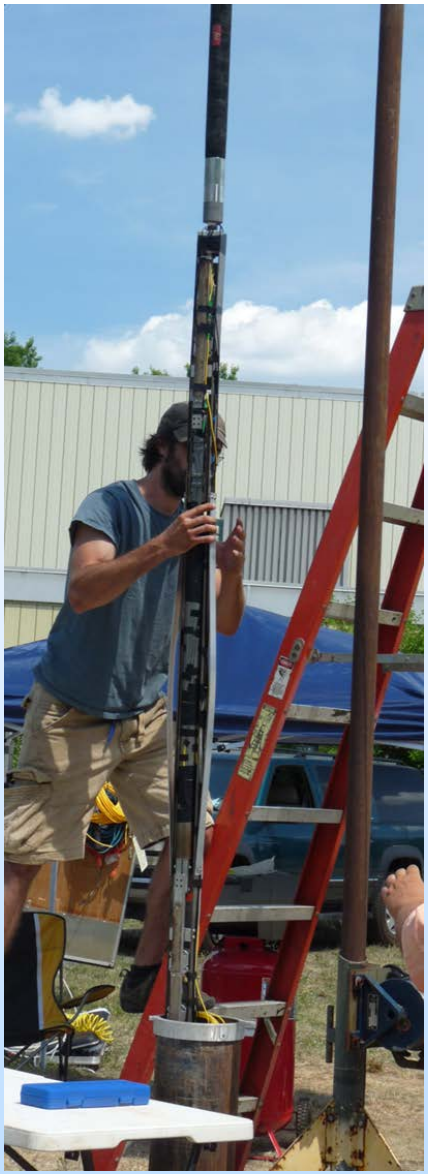
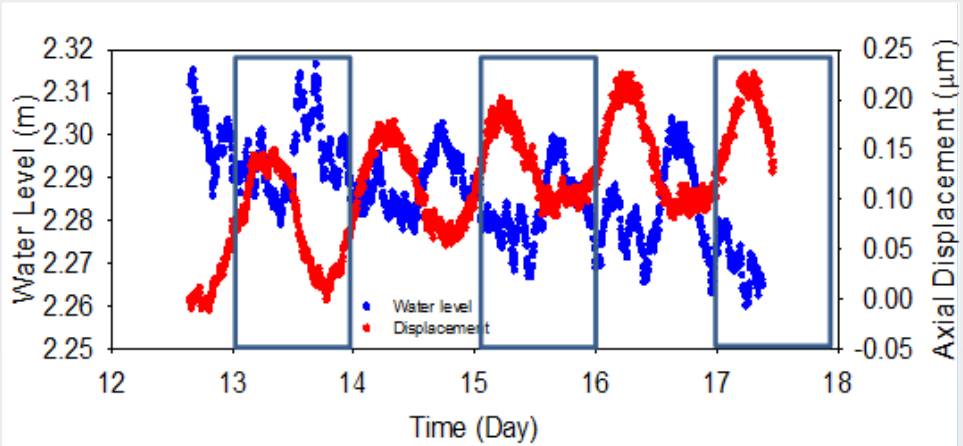


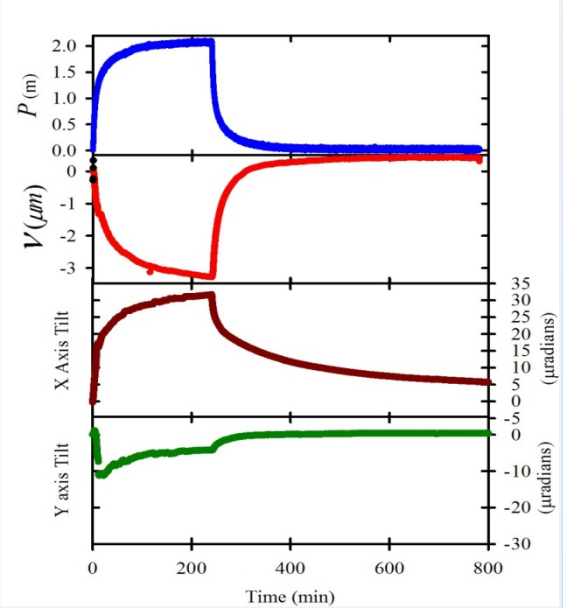
Field Testing in Newark Basin, July 2012

Field Data

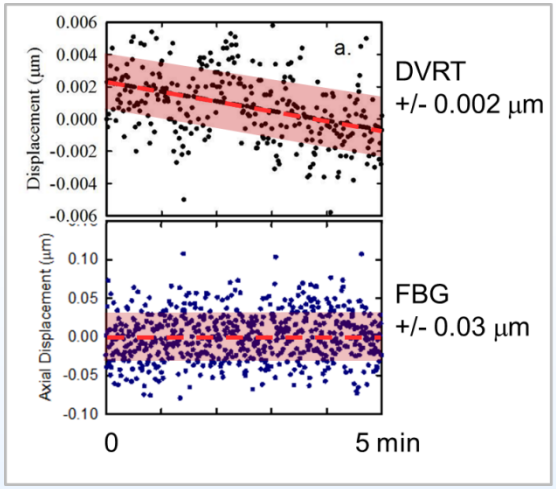
Ambient



Pumping



In-situ noise



Status

- ✓ Axial, radial, 3D
- ✓ Field testing at shallow depths
- ✓ Mobilization

Resolution

- Axial displacement: 0.01 μm
- Axial strain: 0.01 με
- Tilt: 0.03 μrad
- Shear strain: 0.2 με
- Strain Rate: $<10^{-12}$ s^{-1}

Other Borehole Strain Measurement Systems

Gladwin Strainmeter

- 4 axis, horizontal
- <0.001 με
- resolution
- Grouted in place
- Tectonic strain

Baker SureView

- Multicomponent
- 10 με
- Part of casing
- Compaction/failure

What deformation is expected? Task 2

Goal: characterize deformation in the vicinity of wellbores used for sequestration.

- Benchmark simulations
  - FLAC, Abaqus, Comsol
- Response Scenarios
  - Reservoir types
  - Heterogeneities
  - Wellbore completion

Example: Regional-to-Wellbore-Scale

Geometry

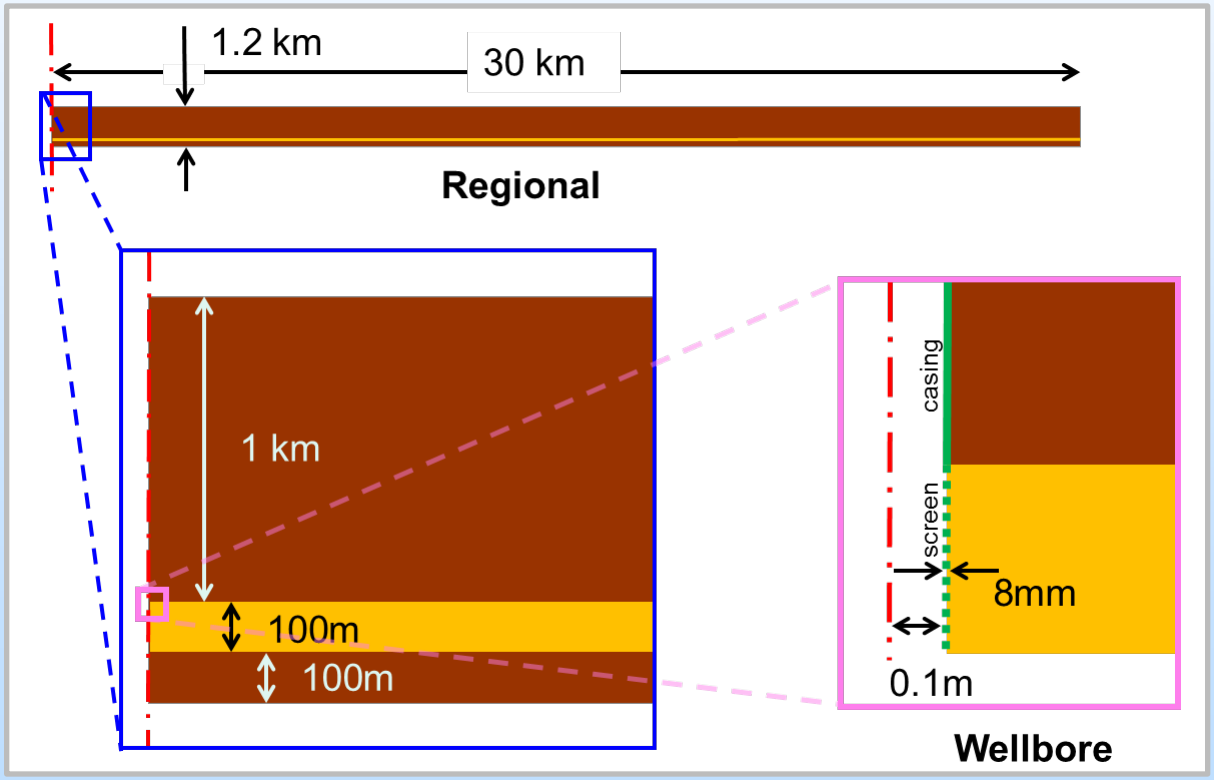
Constant *Q* injection, 6 lps ~100gpm, Axial symmetry

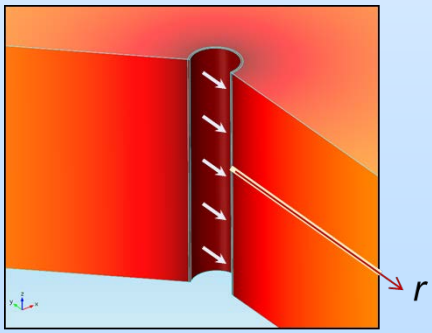
Aquifer: *k*: $10^{-13}m^2$, *b*: 100m, *E*: 15GPa , *R* = 30km

Confining : *k*: $10^{-16}m^2$, *b*: 1000 m; *E*: 15GPa

Casing: *k*: 1nd; 8-inch, 8mm wall, *E*: 200GPa

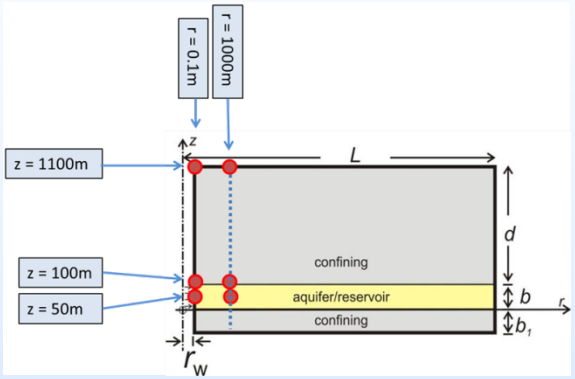
Screen: *k*: $10^{-13}m^2$; 8-inch, 8mm wall, *E*: 200GPa

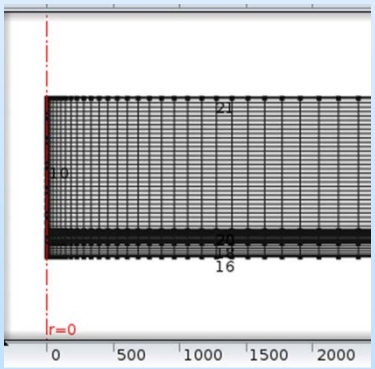


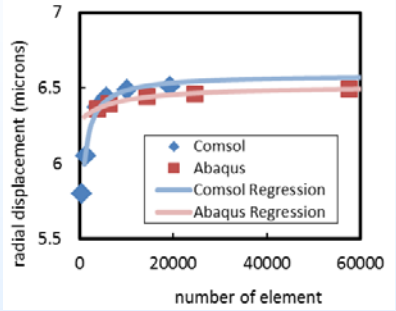


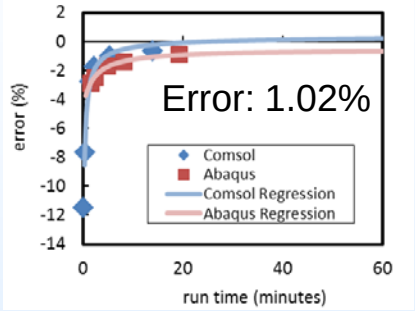
Verification and Mesh Effects

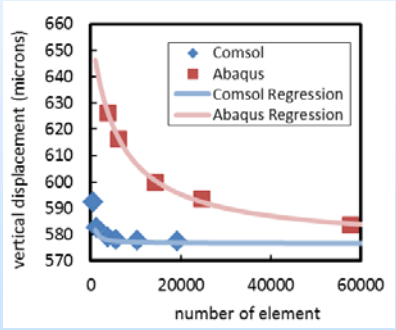
Code Intercomparison

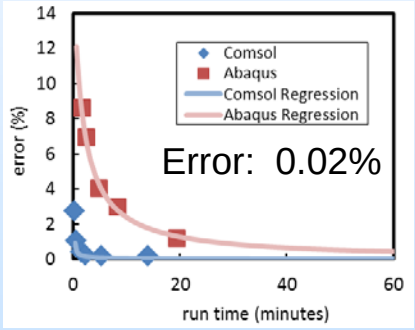


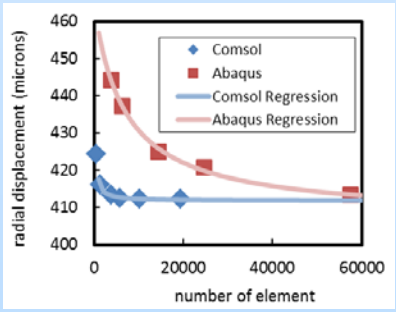


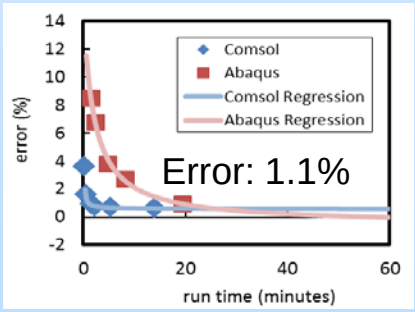






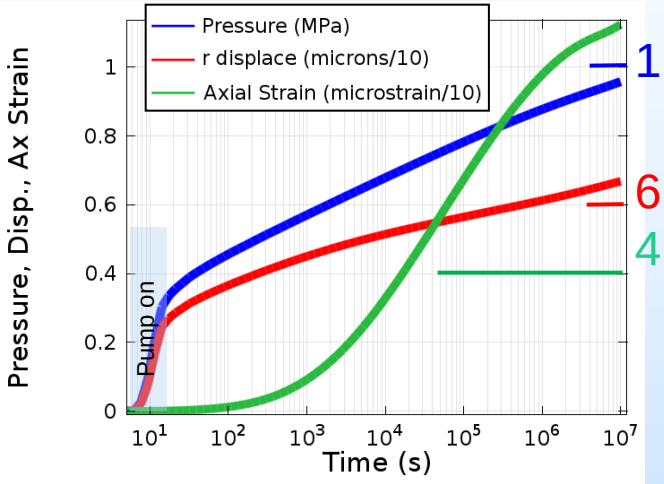




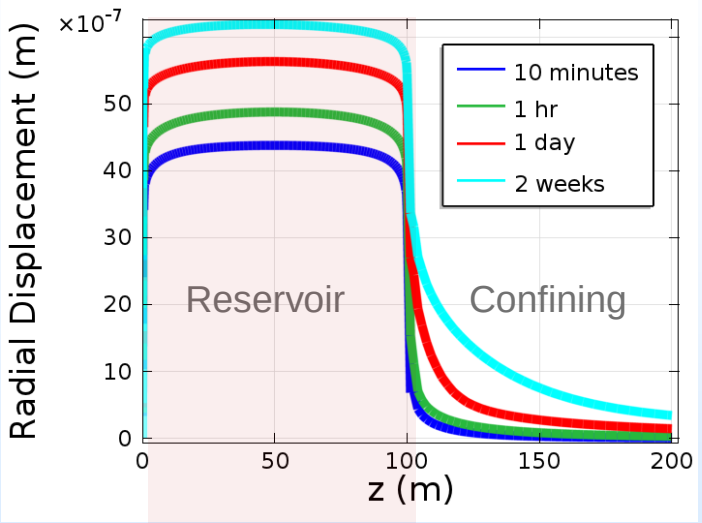


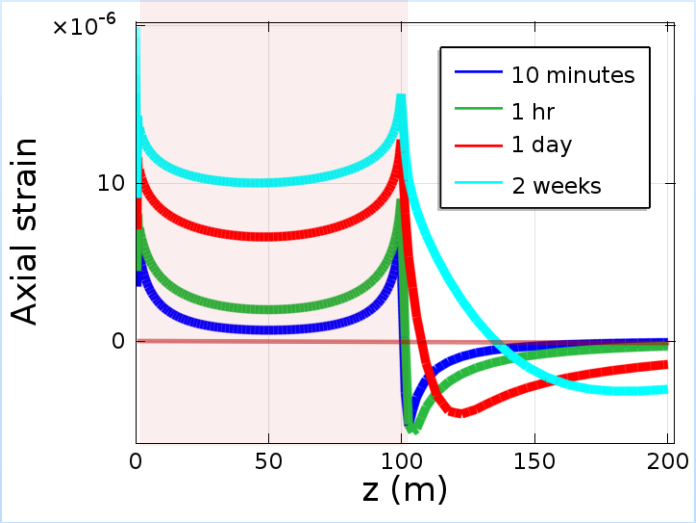
Response in Injection Well

Hydromechanical type curves



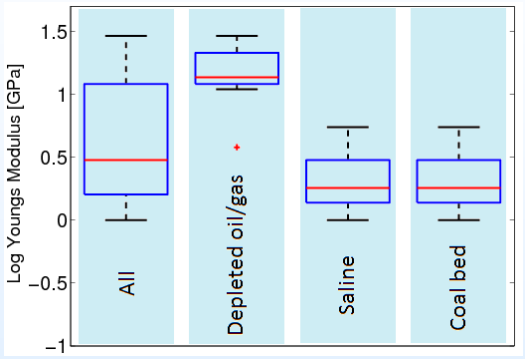
Vertical Profiles on Wellbore

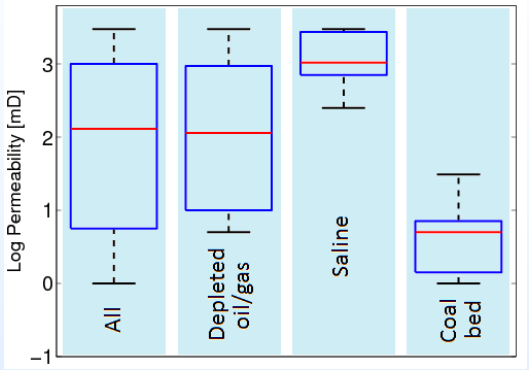


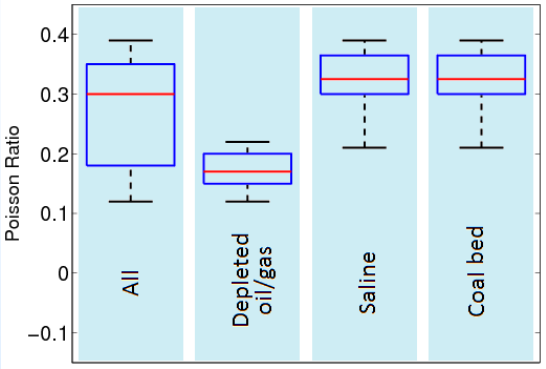


Uncertainty Due to Formation Properties

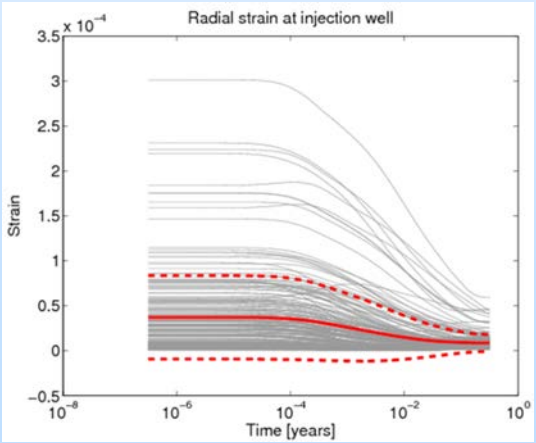
Parameter Distributions for Types of Storage Reservoirs

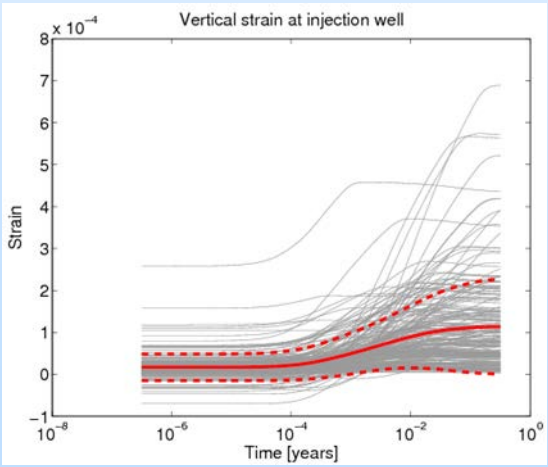


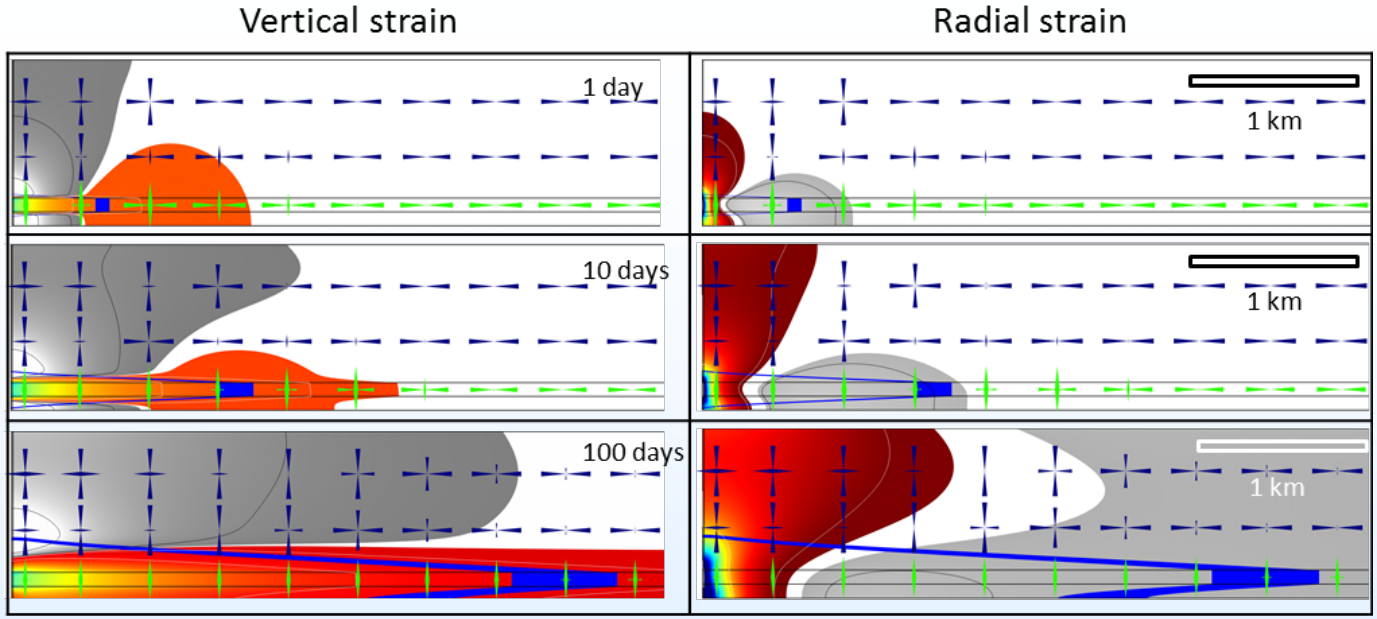


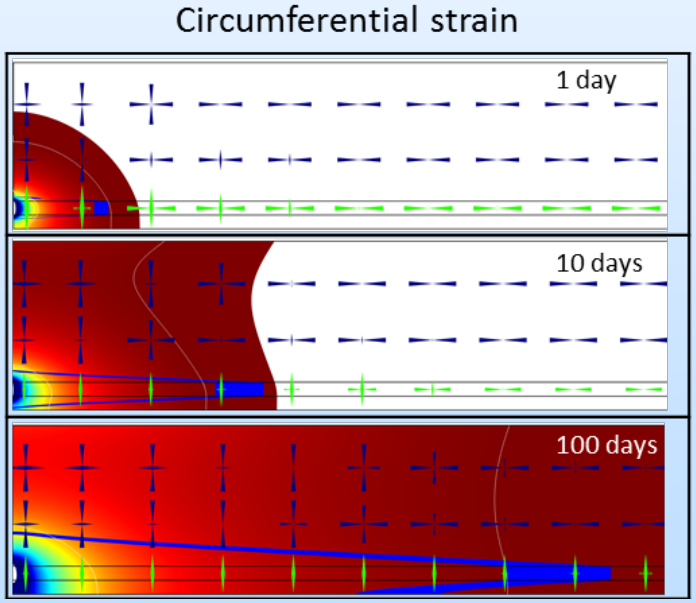


Monte Carlo analyses to estimate strain/displacement probabilities









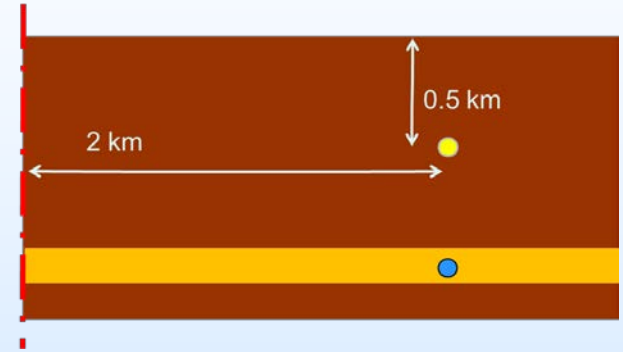
Strain distribution

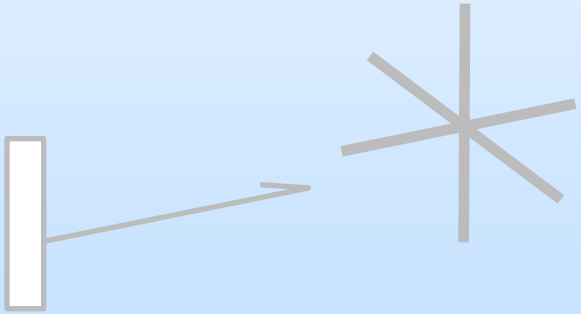
x-section as function of time

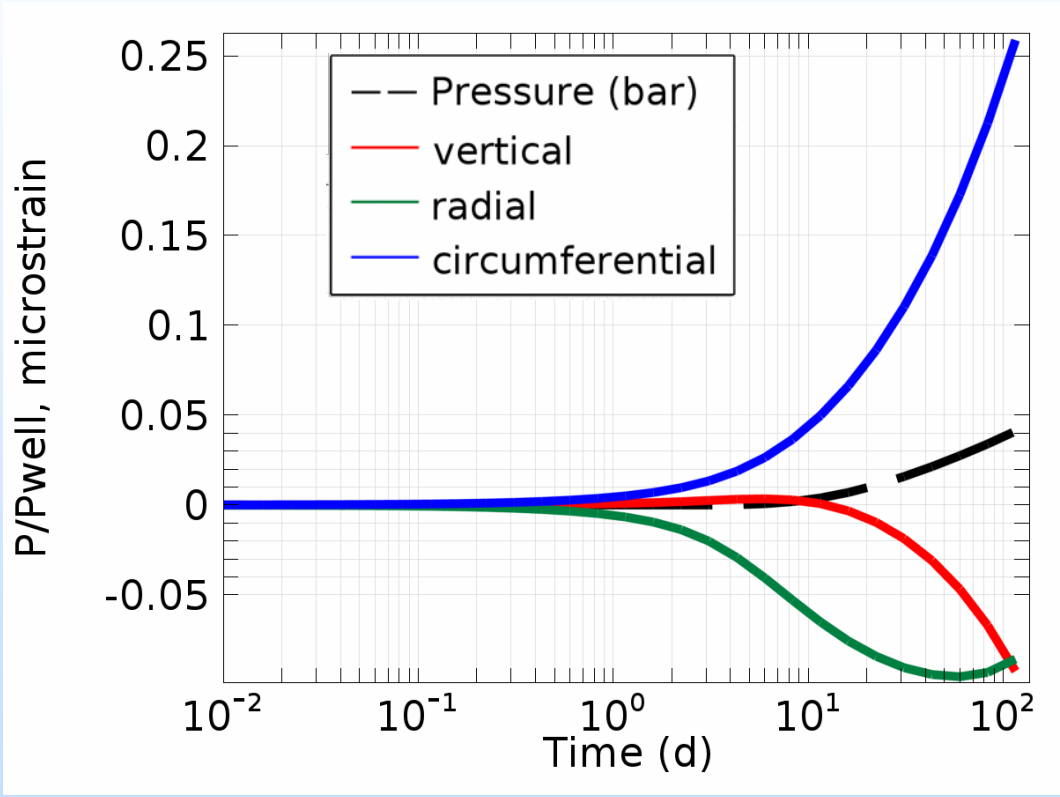
Color = positive (tensile) strain
Grey = negative (compressive) strain
Color cutoff: +/-0.05 με
Blue band = pressurized

Monitoring Well

Remote detection of ΔP in formation







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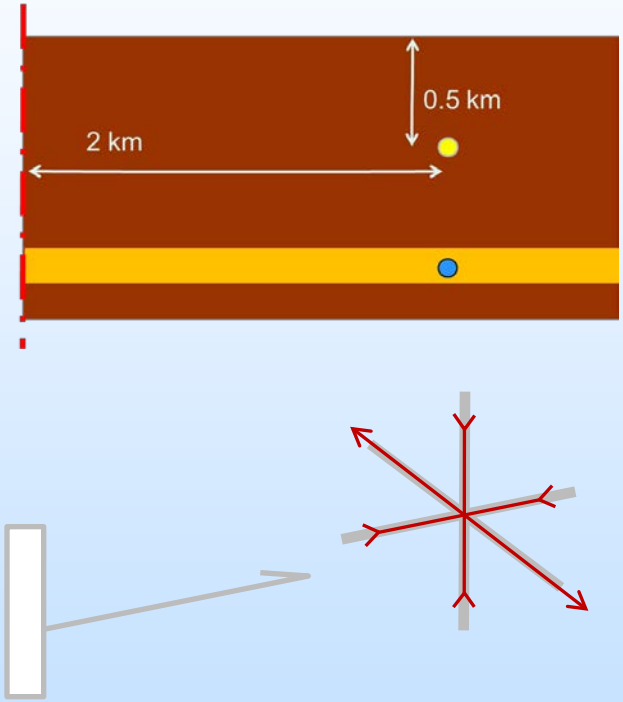
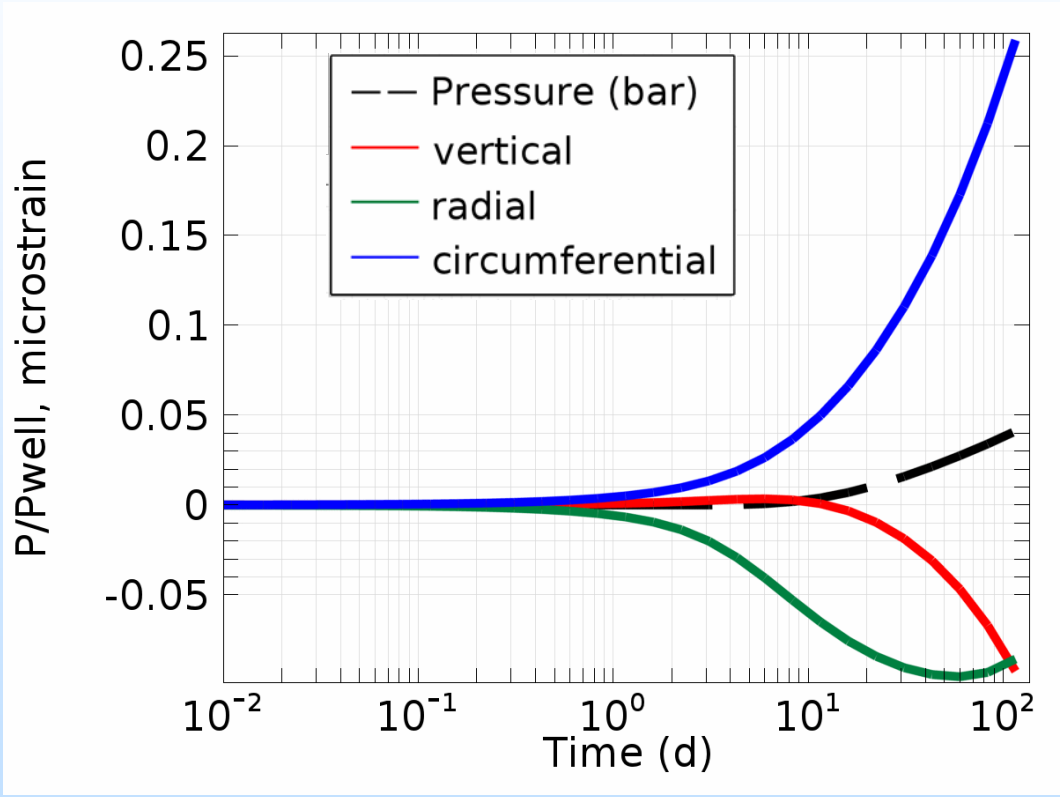
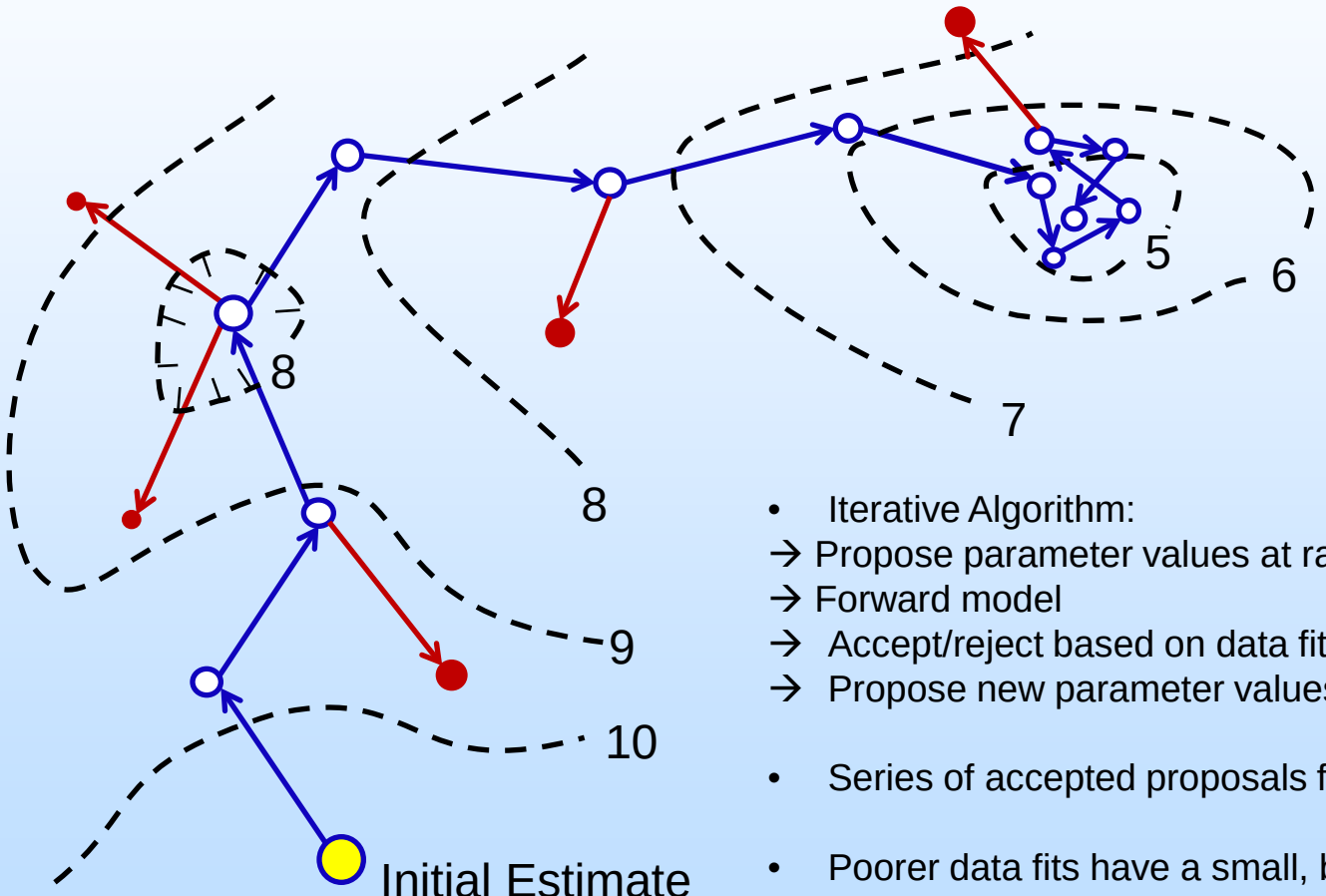




Can Measurements Be Interpreted?
Task 3

Parameter Estimation using Markov-Chain Monte-Carlo Inversion



- Iterative Algorithm:

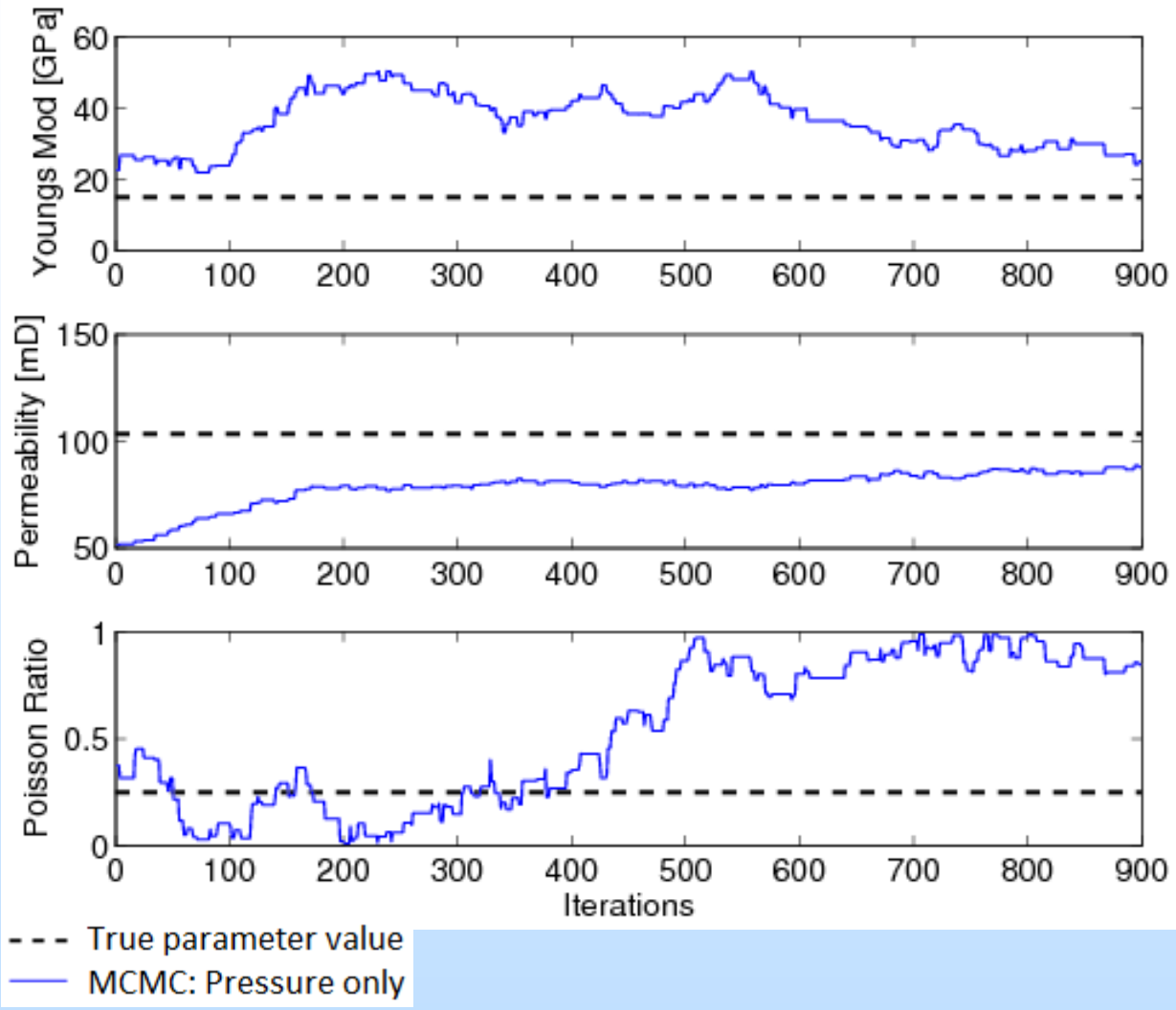
→ Propose parameter values at random
→ Forward model
→ Accept/reject based on data fit + probability
→ Propose new parameter values

- Series of accepted proposals forms a 'chain'

- Poorer data fits have a small, but meaningful chance of being accepted. This allows a chain to potentially escape a local minimum.

MCMC Results

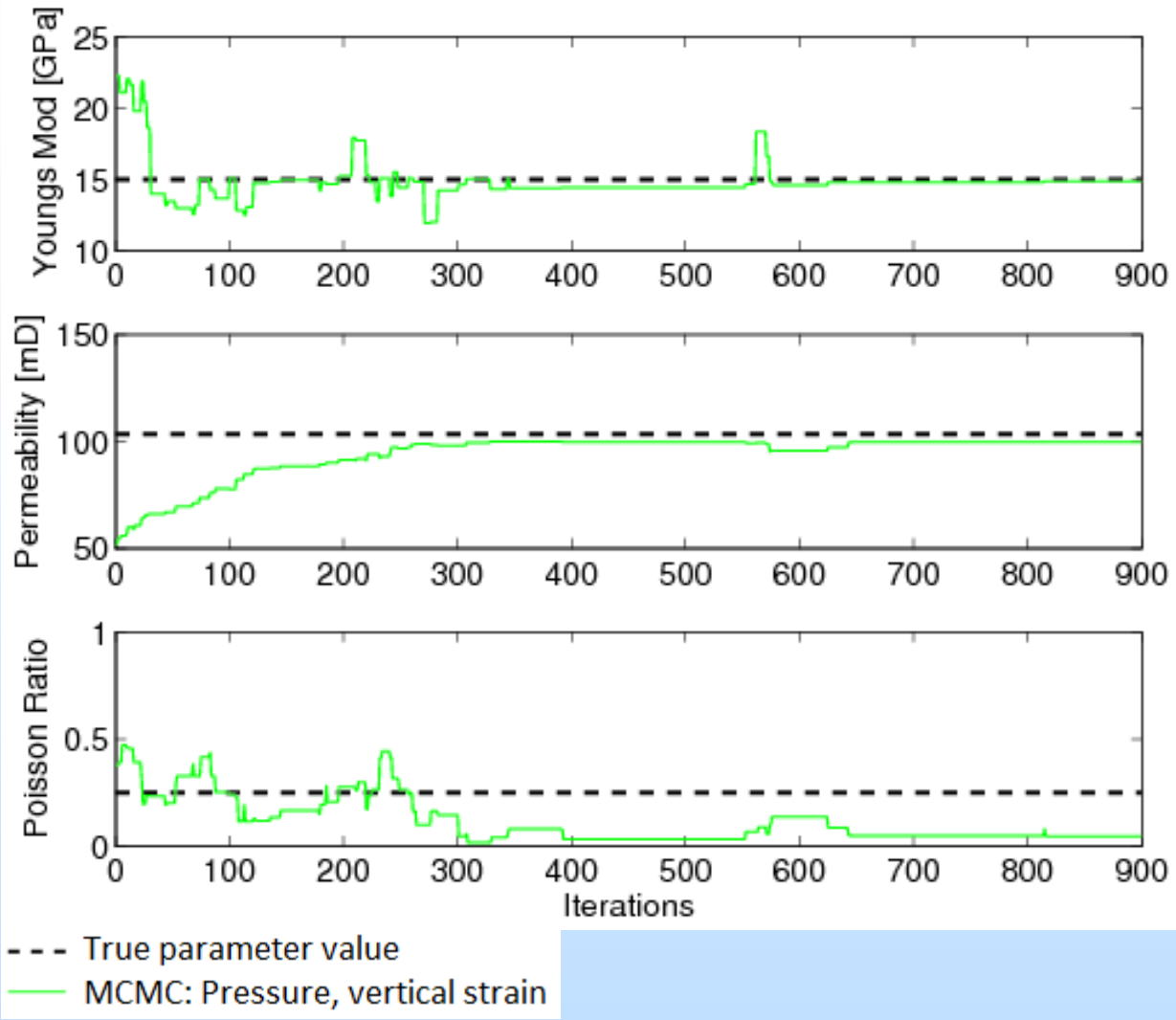
Pressure measurements only



- Pressure measurements from observation well
- Slow convergence on permeability
- No convergence on other two parameters

MCMC Results

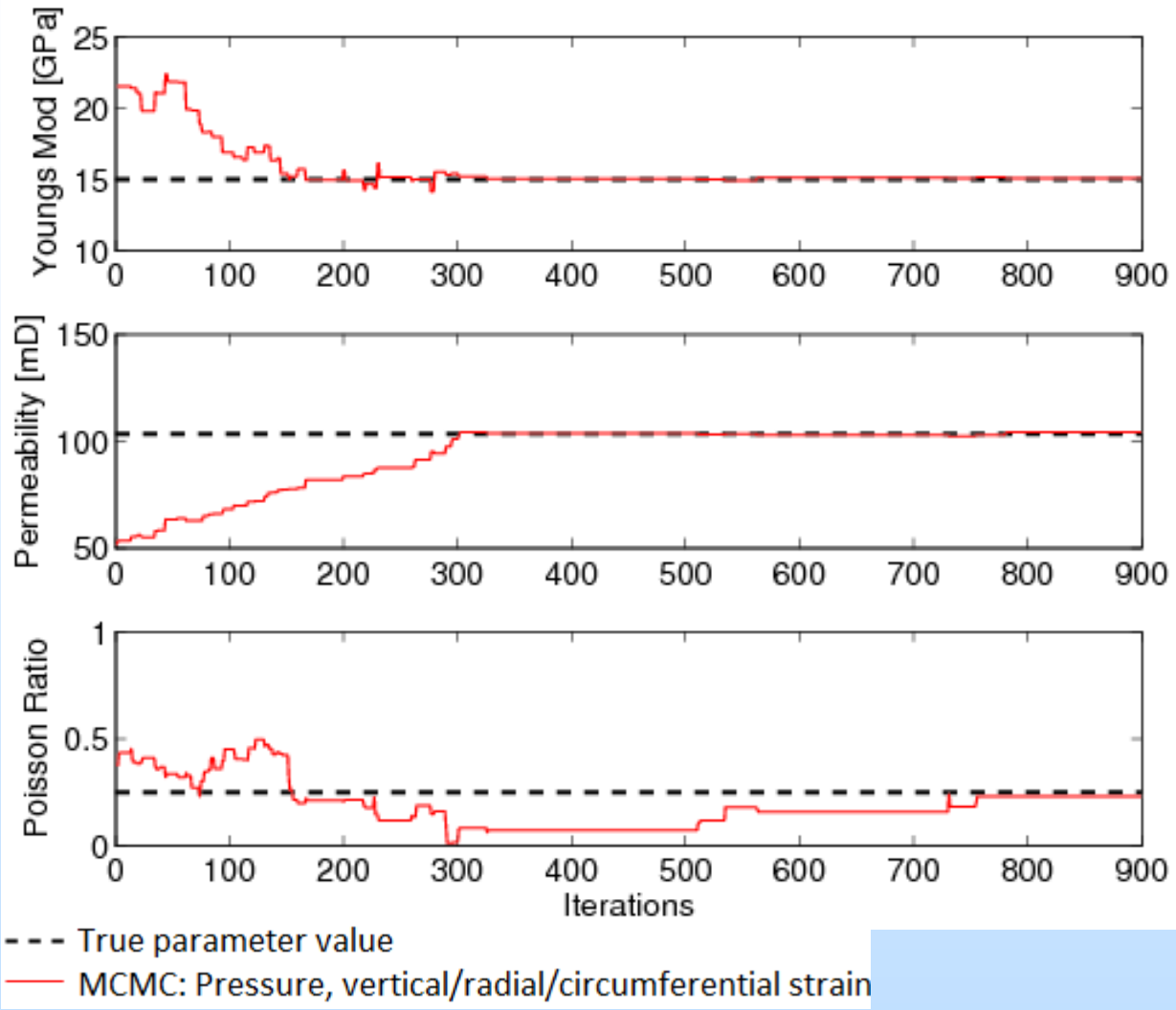
Pressure + vertical strain



- Pressure measurements, vertical strain from observation well
- Young's modulus and permeability adequately constrained
- Poisson ratio not constrained

MCMC Results

Pressure + 3 strains



- Pressure measurements, vertical, radial and circumferential strain from observation well
- Young's modulus and permeability well constrained
- Poisson ratio subjected to local minima, eventually finds correct solution

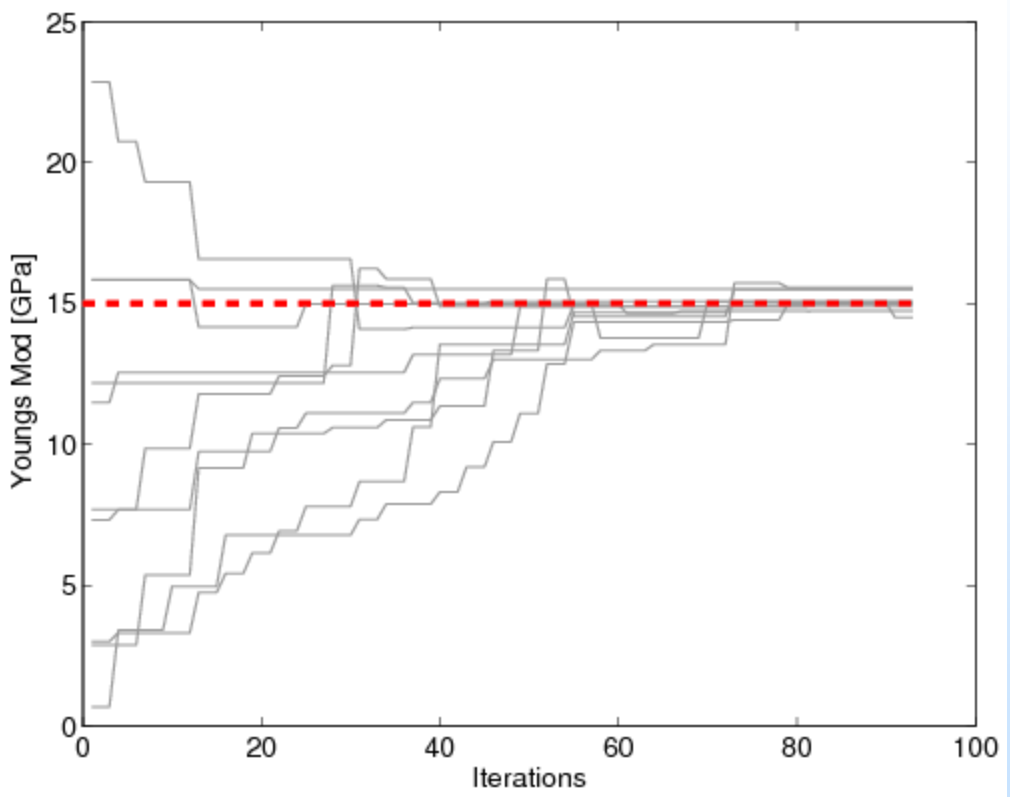
MCMC
Improving Performance with HPC

Use distributed computing to:

- Run multiple chains simultaneously
- Aggregate and share information between chains (i.e., genetic algorithm techniques)

Improvements:

- Sampling of parameter space, parameter uncertainty
- Computation time



Accomplishments to Date

- Measurement
  - Instruments to measure axial, radial, 3D
  - Resolution: ~0.01 μm, ~0.01 με
  - Demonstrated in the field
- Analyses
  - Benchmarks, Verification
  - Patterns of deformation; axial, radial, circumf, tilt;
  - Magnitudes: ~ 1μm, strain: ~1με
  - Include formation properties, Monte Carlo uncertainty
- Interpretation
  - MCMC 1 chain, Analytical and numerical
  - Demonstrate importance of deformation in parameter uncertainty
  - MCMC multi-chain, HPC

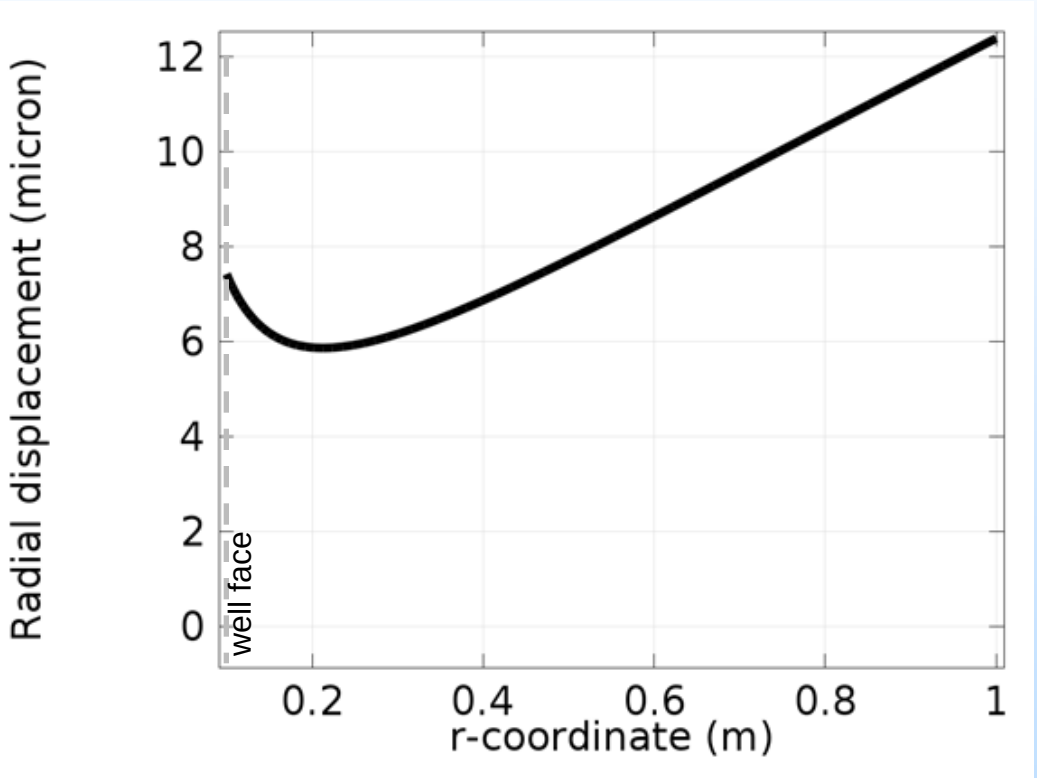
Summary

- Key Findings
  - Expect μm/με-scale displacements
  - Possible to measure 0.01 μm/με-scale
  - Interpretation appears feasible
    - Remote sensing of change in pressure
    - Formation properties, geomechanics
    - Leakage, casing integrity
- Future Plans
  - Forward analyses; reservoir structure, casing-cement-formation
  - Instrument evaluation; multi-axis horizontal strain, hardening
  - MCMC; HPC, assess uncertainties, real field data

Radial Displacement

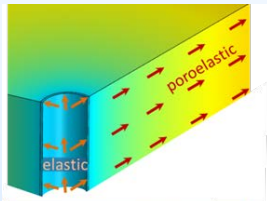
During Constant P injection, *t*=100 days

Open Hole

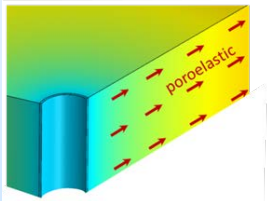


Radial Displacement

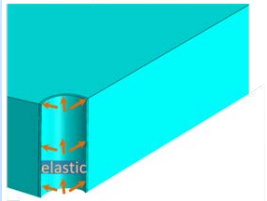
Open Hole



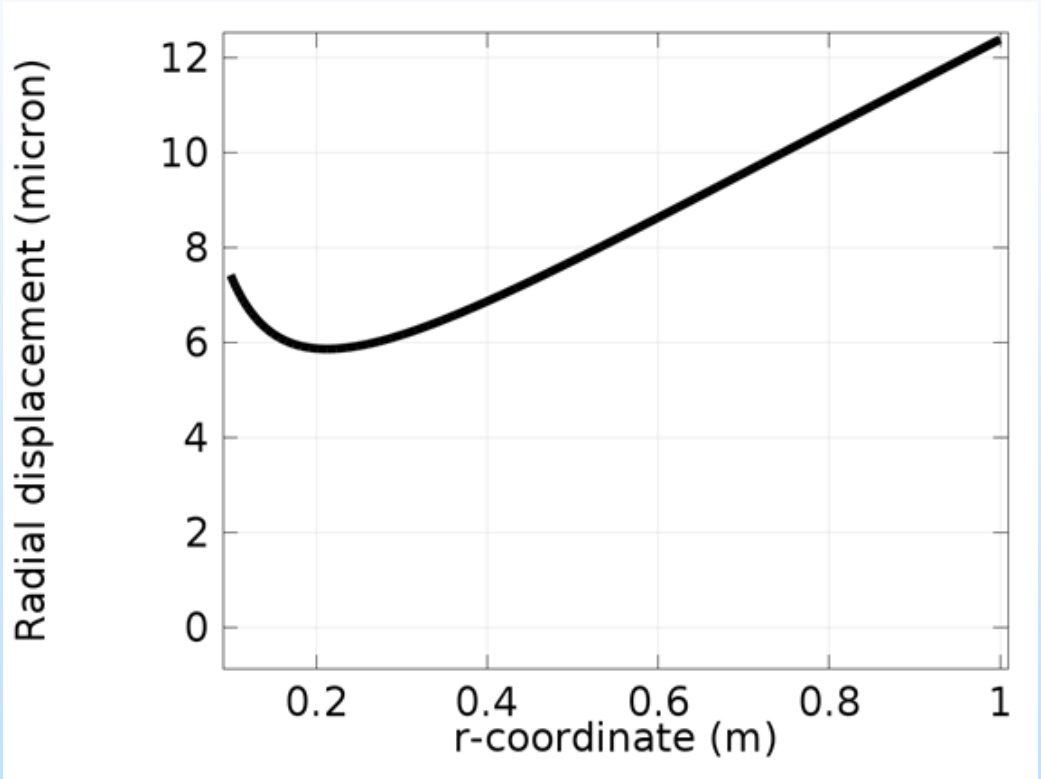
TOTAL
- P in casing, elastic load
- P in frm, poroelastic load



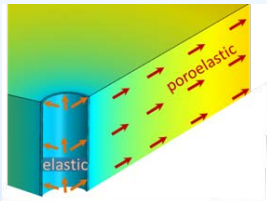
Poroelastic only
- No Pressure in Casing



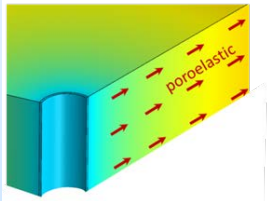
Elastic only
- No pressure in formation



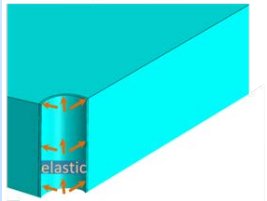
Radial Displacement



TOTAL
- P in casing, elastic load
- P in frm, poroelastic load

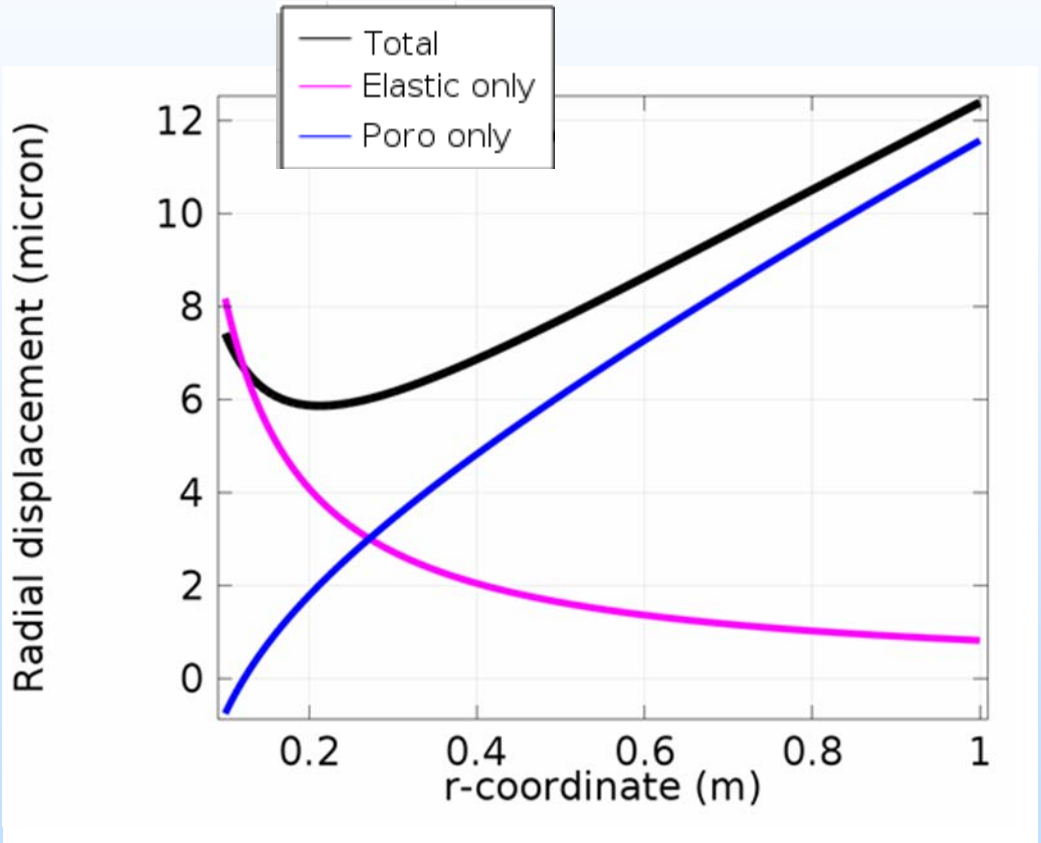


Poroelastic only
- No Pressure in Casing

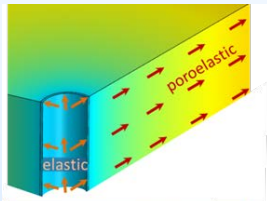


Elastic only
- No pressure in formation

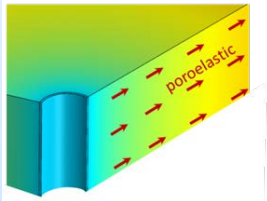
Open Hole



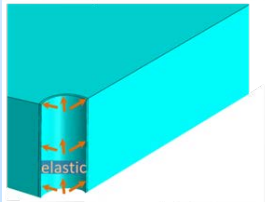
Radial Displacement



TOTAL
- P in casing, elastic load
- P in frm, poroelastic load

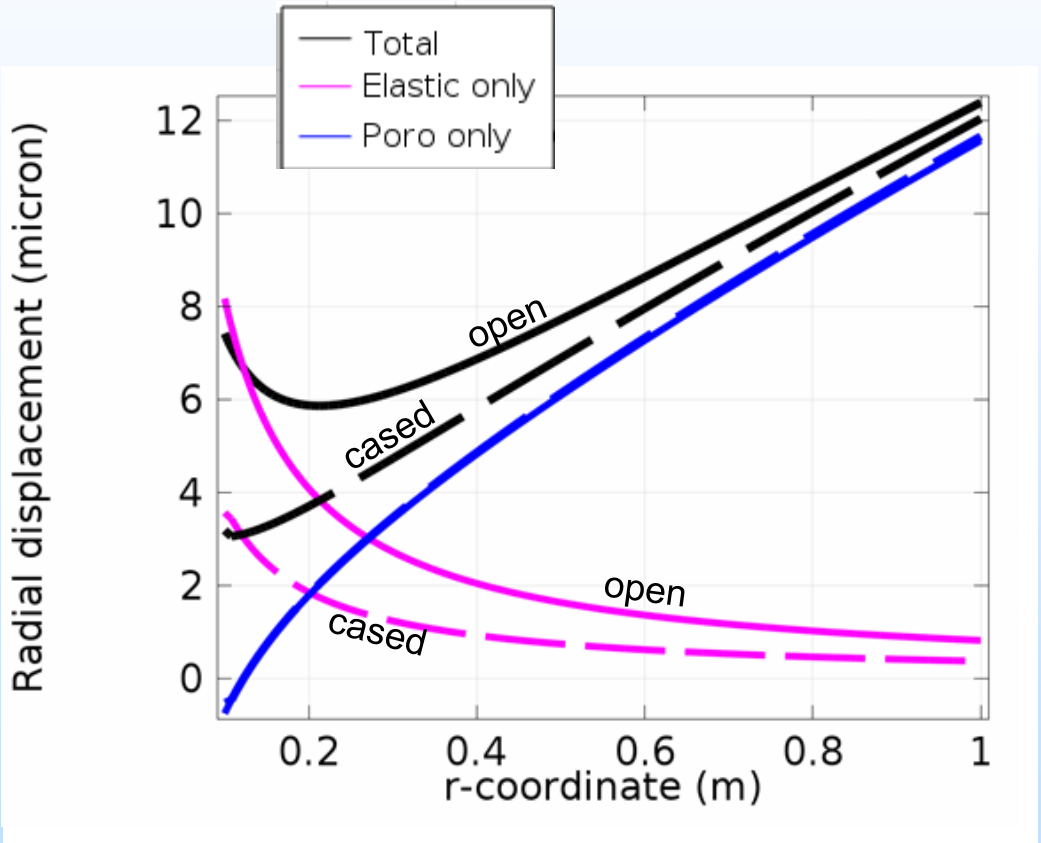


Poroelastic only
- No Pressure in Casing



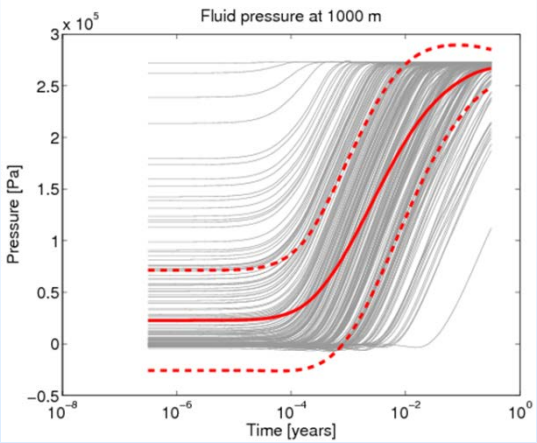
Elastic only
- No pressure in formation

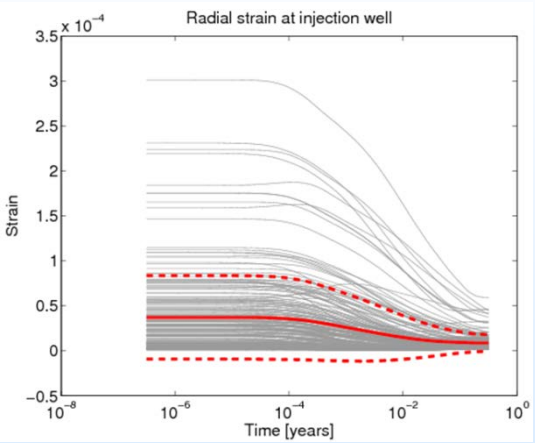
Open Hole and Cased Hole

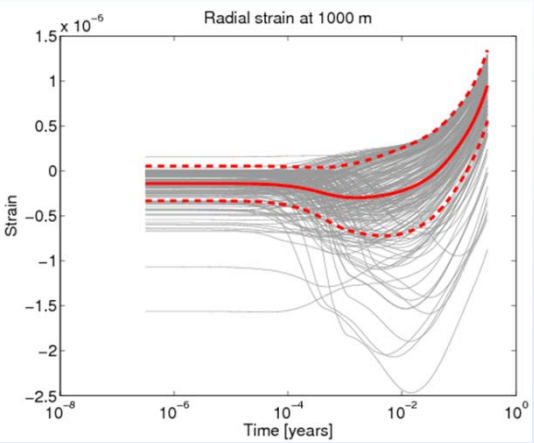


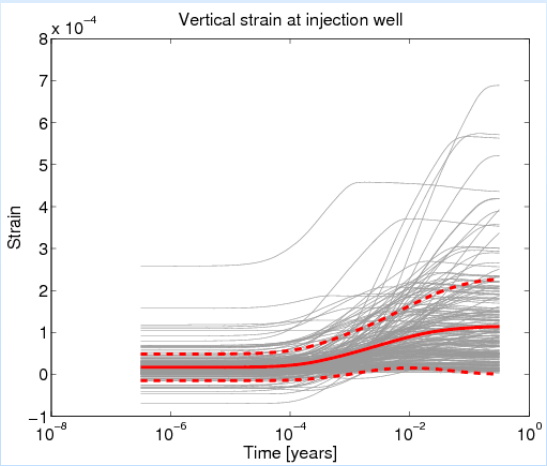
Monte Carlo Analysis

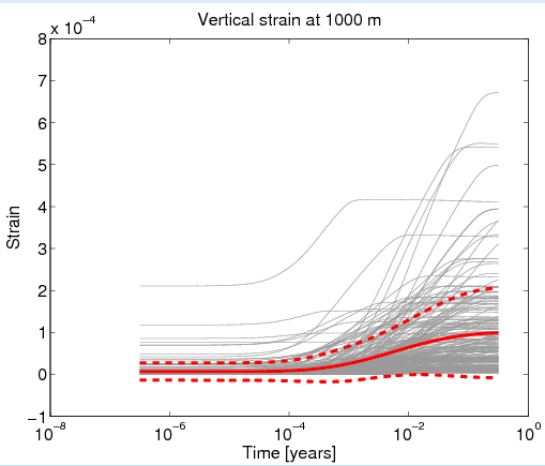
Using Distributions of Published Parameters









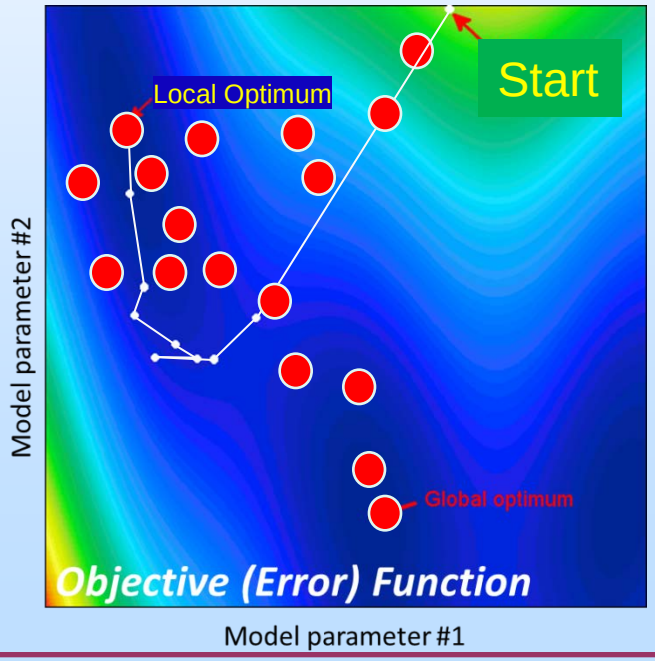


How can measurements be interpreted? Task 3:

Goals: a.) Quantify ability of data to constrain model parameters, b.) assess how uncertainty in parameters translates into risks; c.) optimize methods for efficient large-scale reservoir characterization

Gradient-Based Optimization
Objective: Find model parameters that provide minimum data misfit

- Provides local assessment of parameter uncertainty and correlation
- Efficient search of parameter space (i.e., few model runs = *fast*)
- Finds **local** minimum



Markov Chain Monte Carlo (MCMC)
Objective: Find probability distribution of model parameters consistent with observed data and uncertainties

- Allows assessment of full joint probability model for parameters (i.e., needed for *prediction uncertainty*)
- Random search of parameter space (i.e., many model runs = *slow*)
- Finds **global** minimum

Example: Effect of Data on Estimation Uncertainty

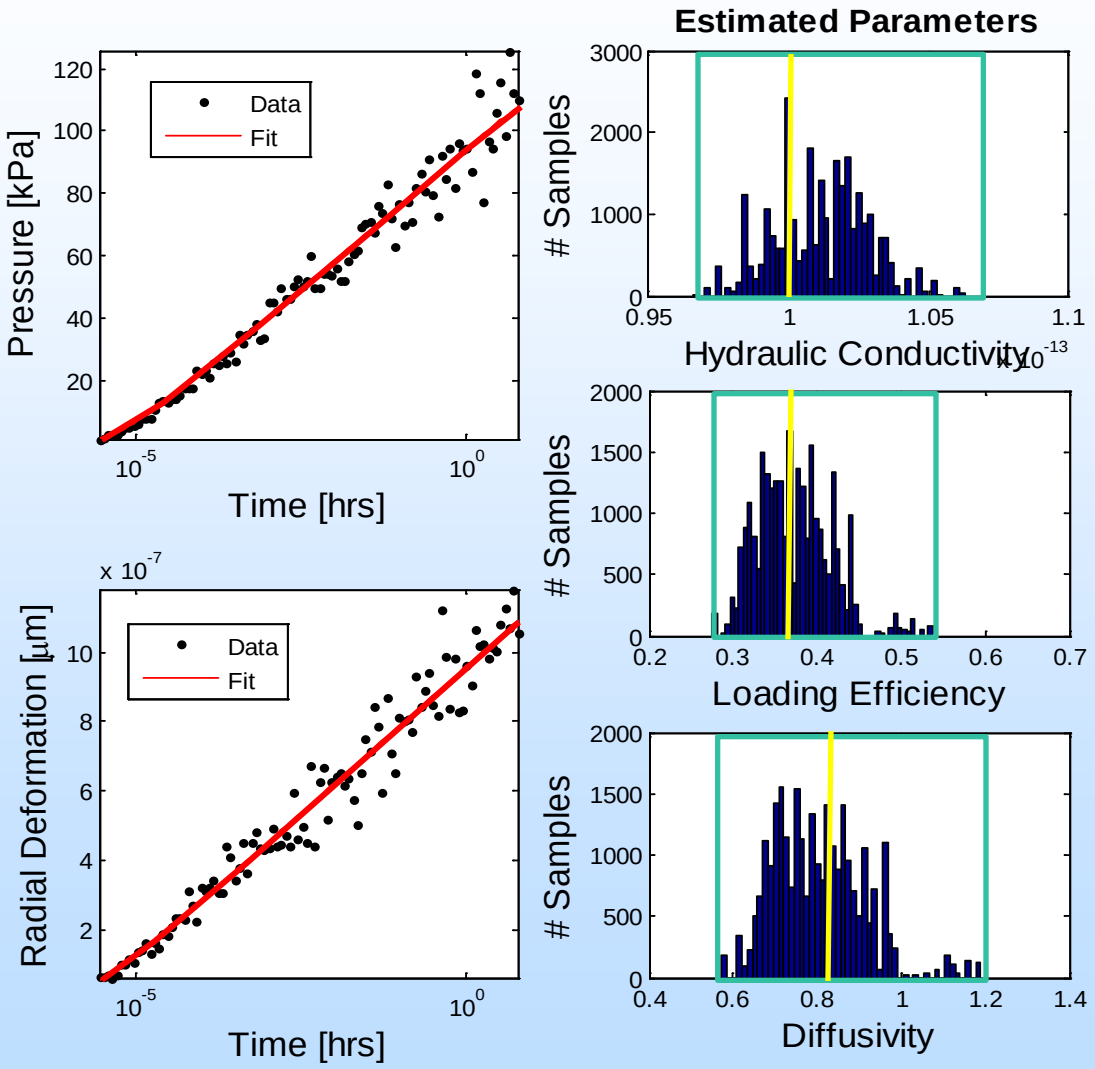
Pressure + Displacement Data (10% noise)

Constant rate injection using line source.

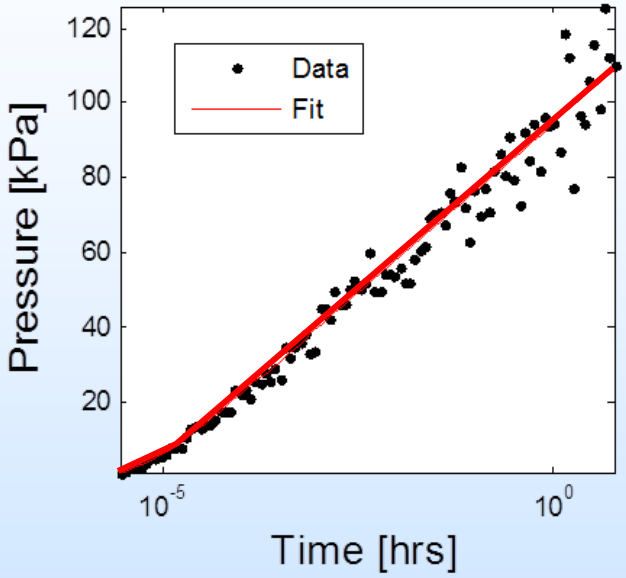
Pressure and displacement from poroelastic analytical solution. *Wang* [2000, eq. 8.105, 8.106]

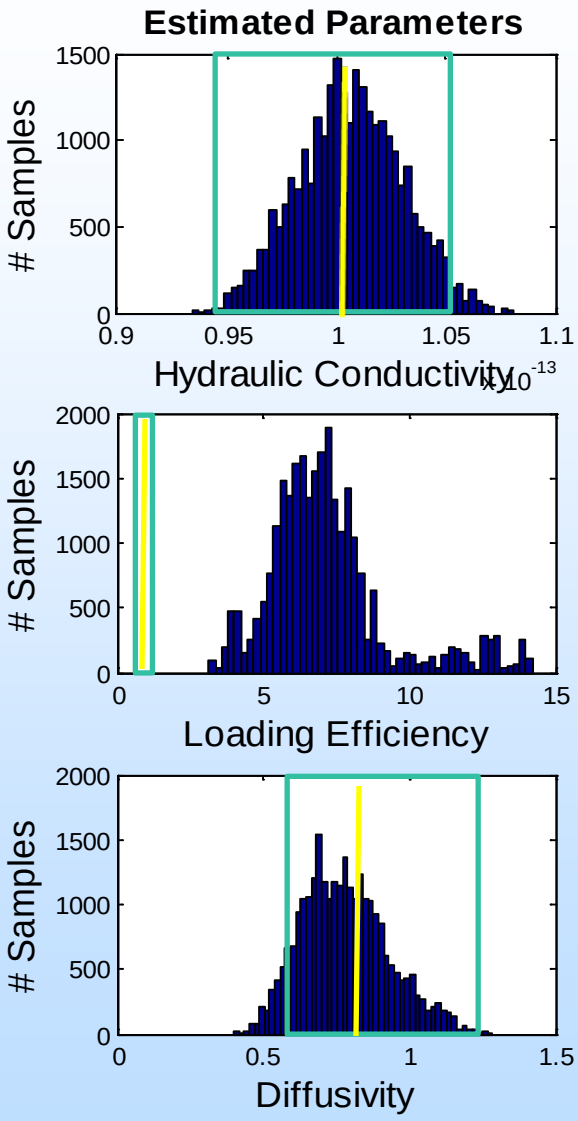
<u>Parameters:</u>

- Hydraulic Conductivity
- Hydraulic Diffusivity
- Loading Efficiency



Typical Well Test
Pressure Data Only (10% noise)



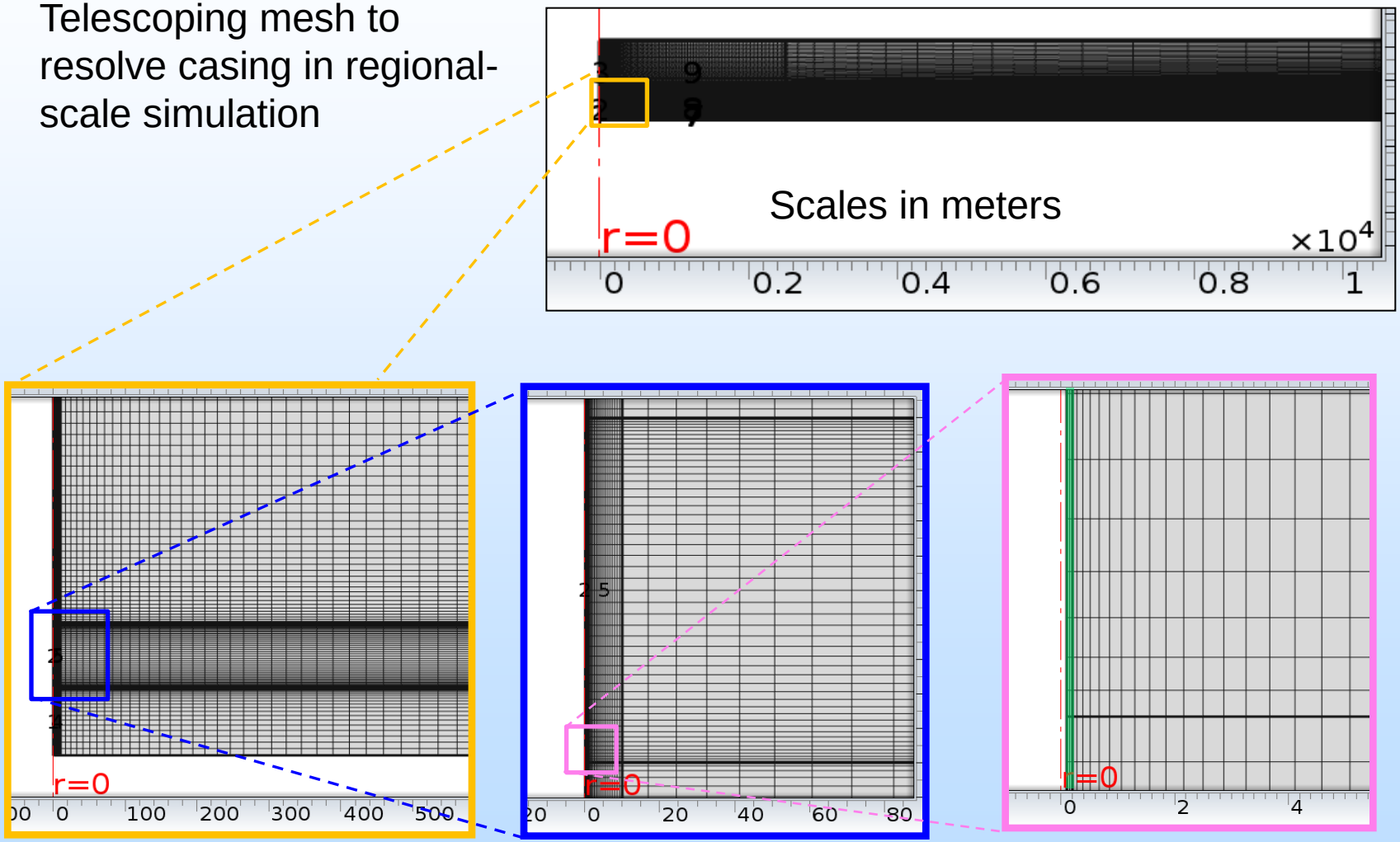


- Pressure data fit as well as for fully constrained case
- Similar constraint of hydraulic conductivity and diffusivity as fully constrained case
- Poor constraint of the loading efficiency

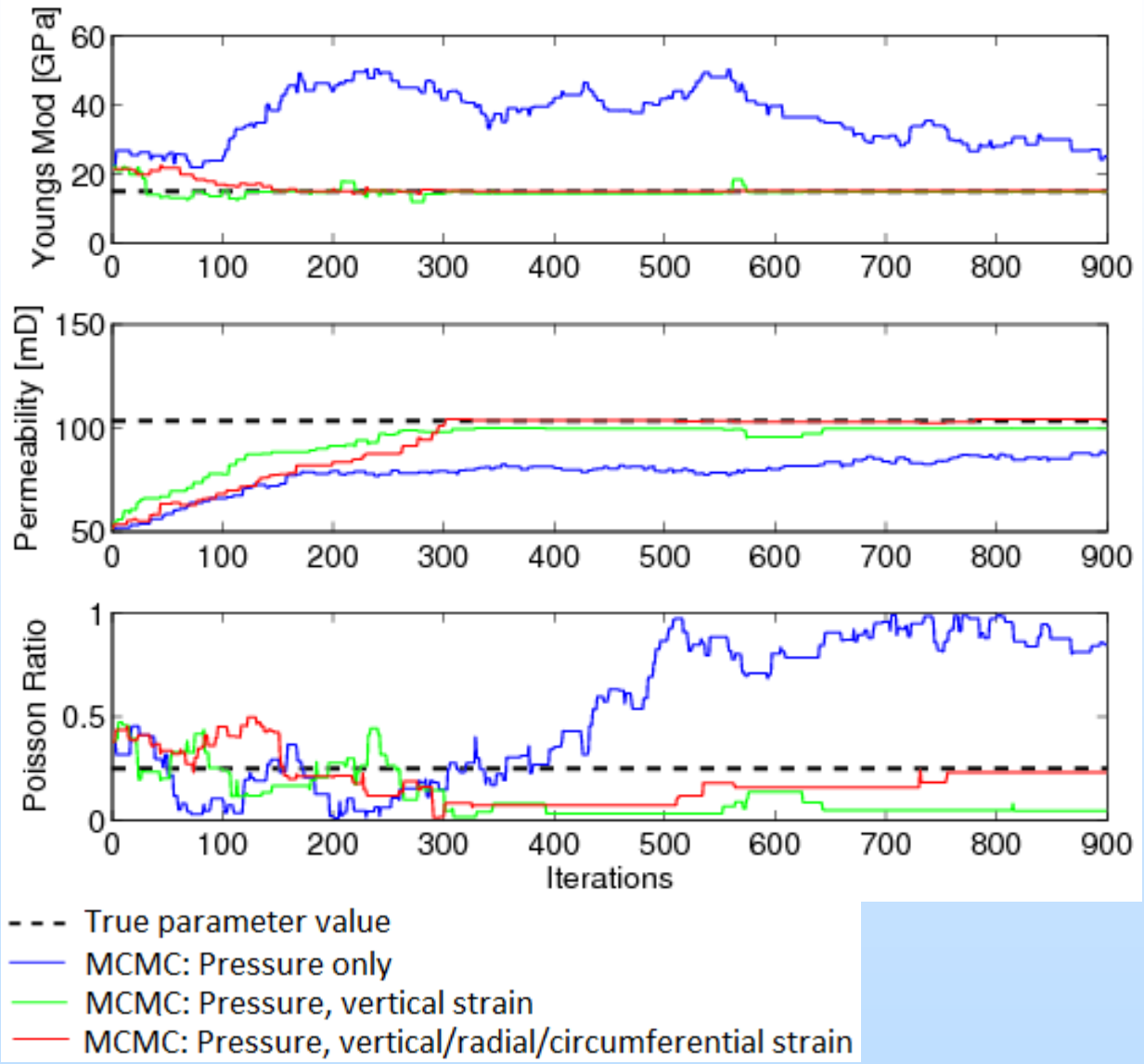
Regional-to-Wellbore-Scale Simulation

Discretization

Telescoping mesh to resolve casing in regional-scale simulation



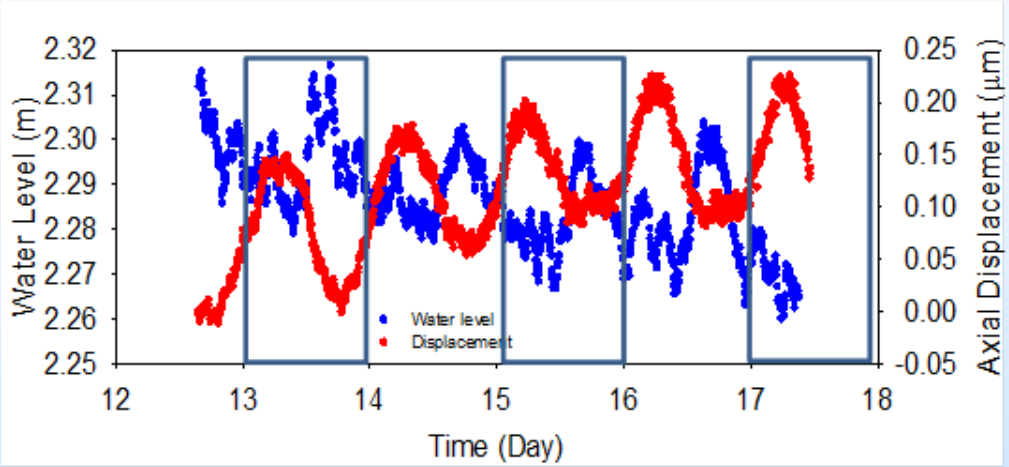
MCMC Results



Use pressure + strain during well tests to determine geomechanics parameters in situ.

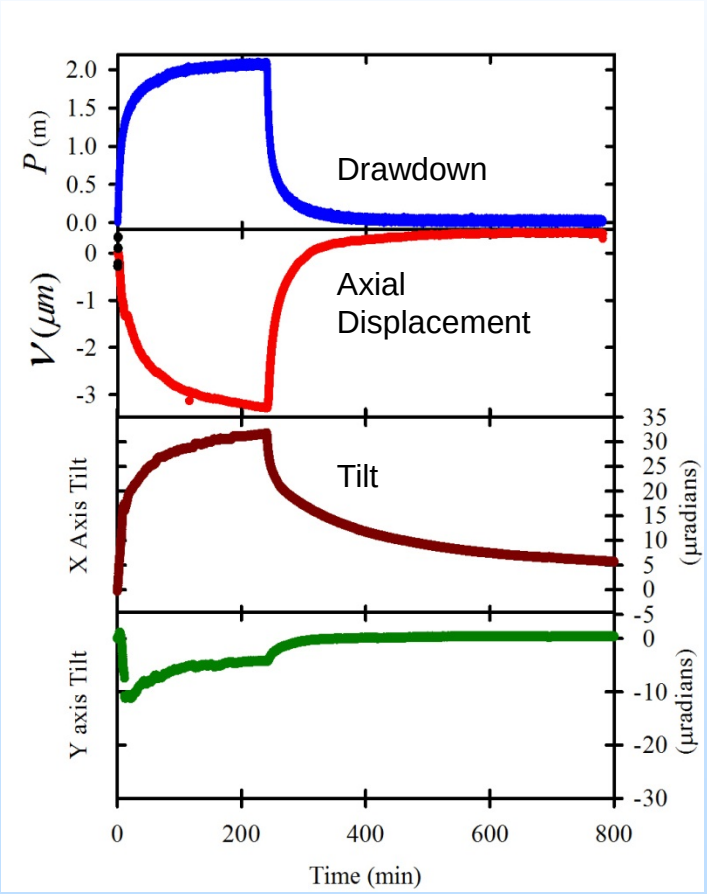
Field Testing

Ambient Response w/ FBG



Strain rate: ~10^{-7}/12hrs = $2x10^{-12}$ s^{-1}

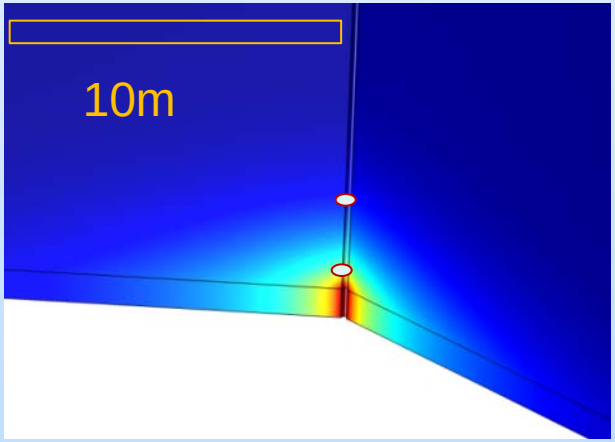
Pumping test w/DVRT and tiltmeter

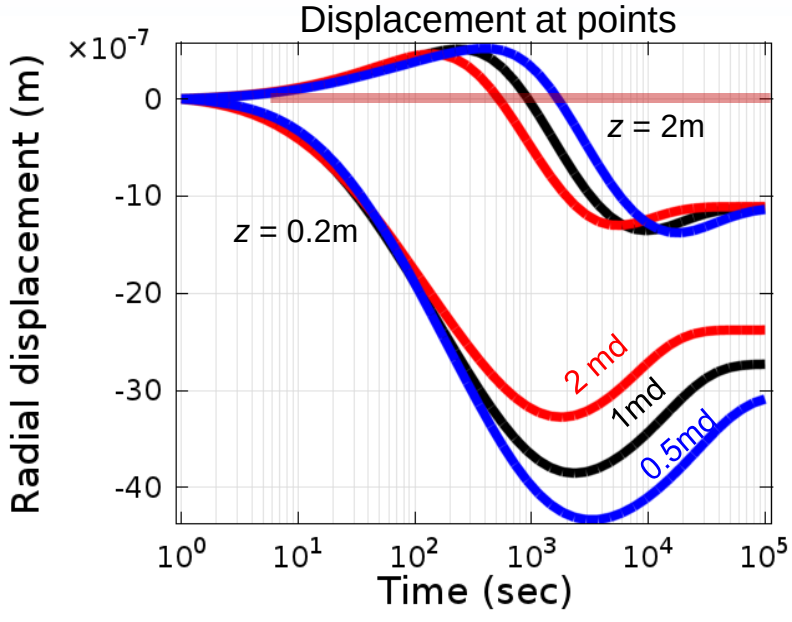


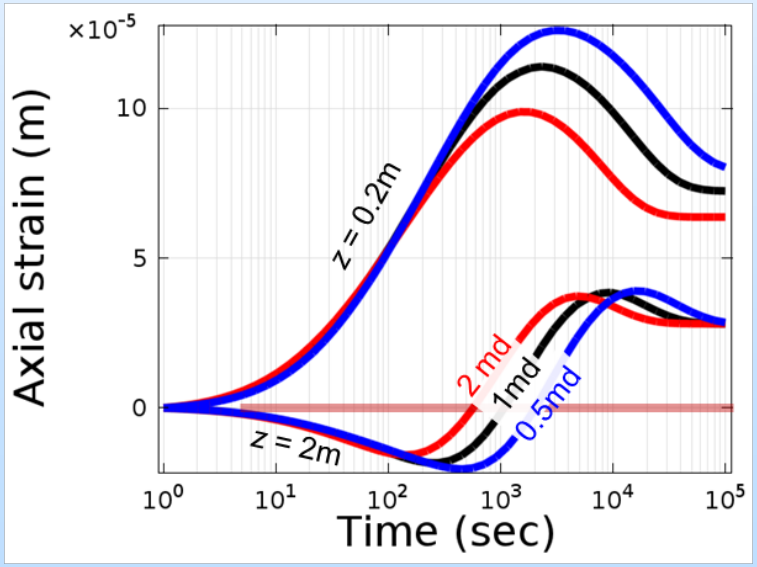
Effect of Confining Unit Permeability

Radial displacement

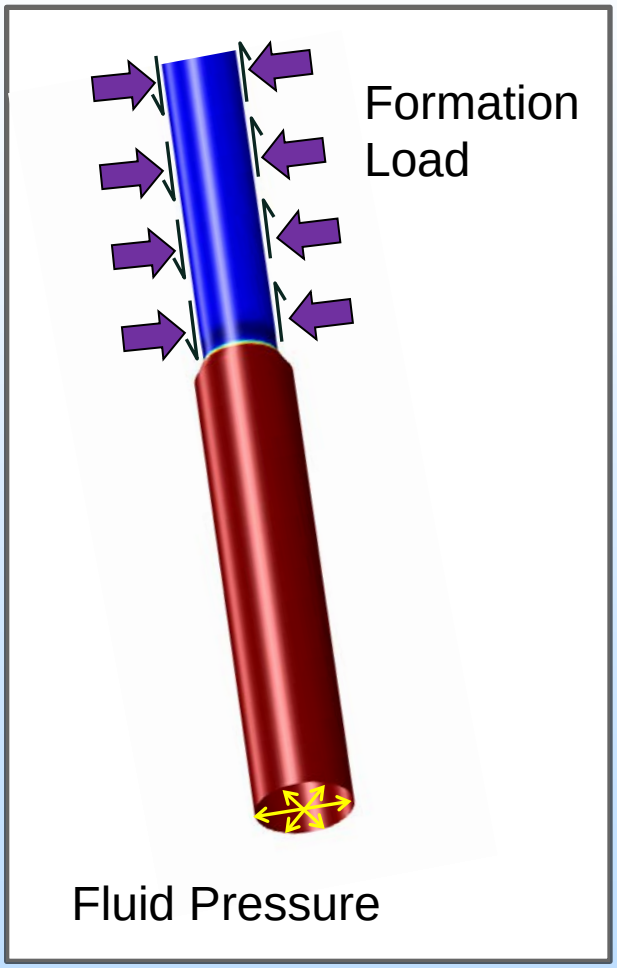
Constant *P* injection, 1 MPa
Aquifer: *k*: 0.1d, *b*: 1m, *E*: 1GPa
Confining : *k*: *1md*, *2md*, *0.5 md*
b: 10 m; *E*: 1GPa
Casing: *k*: 1nd; 8-inch, 8mm wall, *E*: 200GPa
Screen: *k*: 0.1d; 8-inch, 8mm wall, *E*: 200GPa
Measurement: 0.2 and 2 m above contact

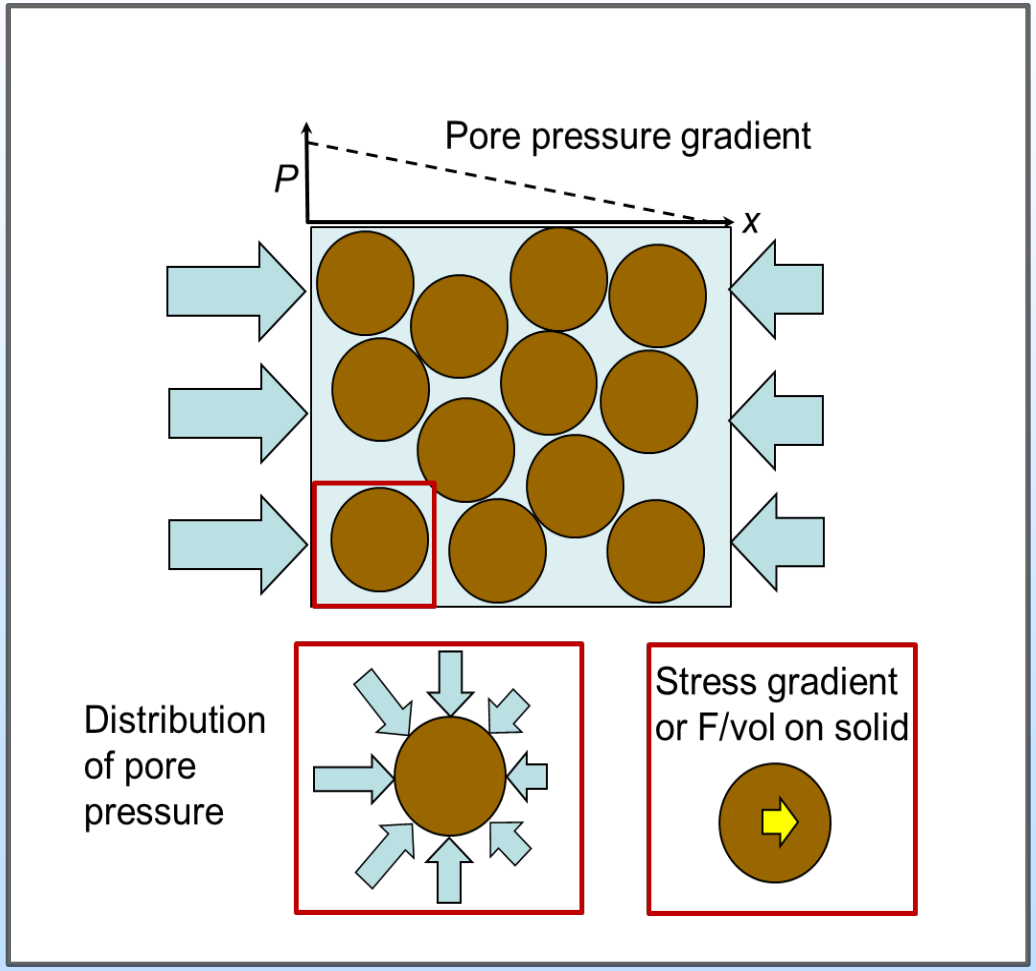






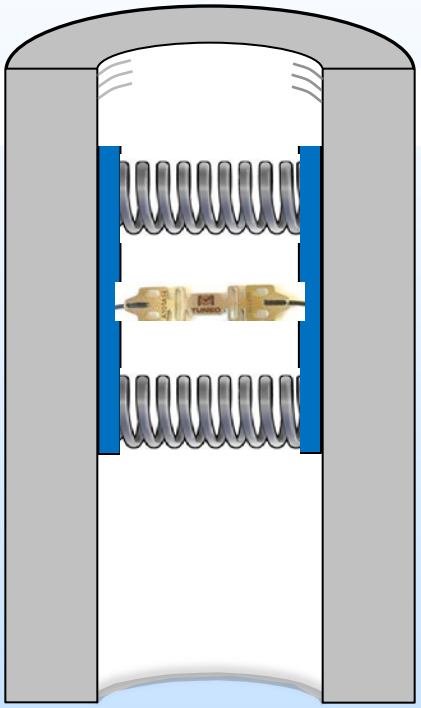
Basic Principles





Radial Displacement

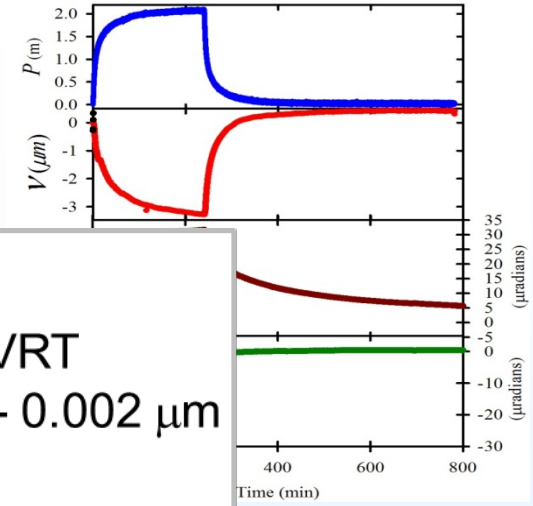
Newest Development

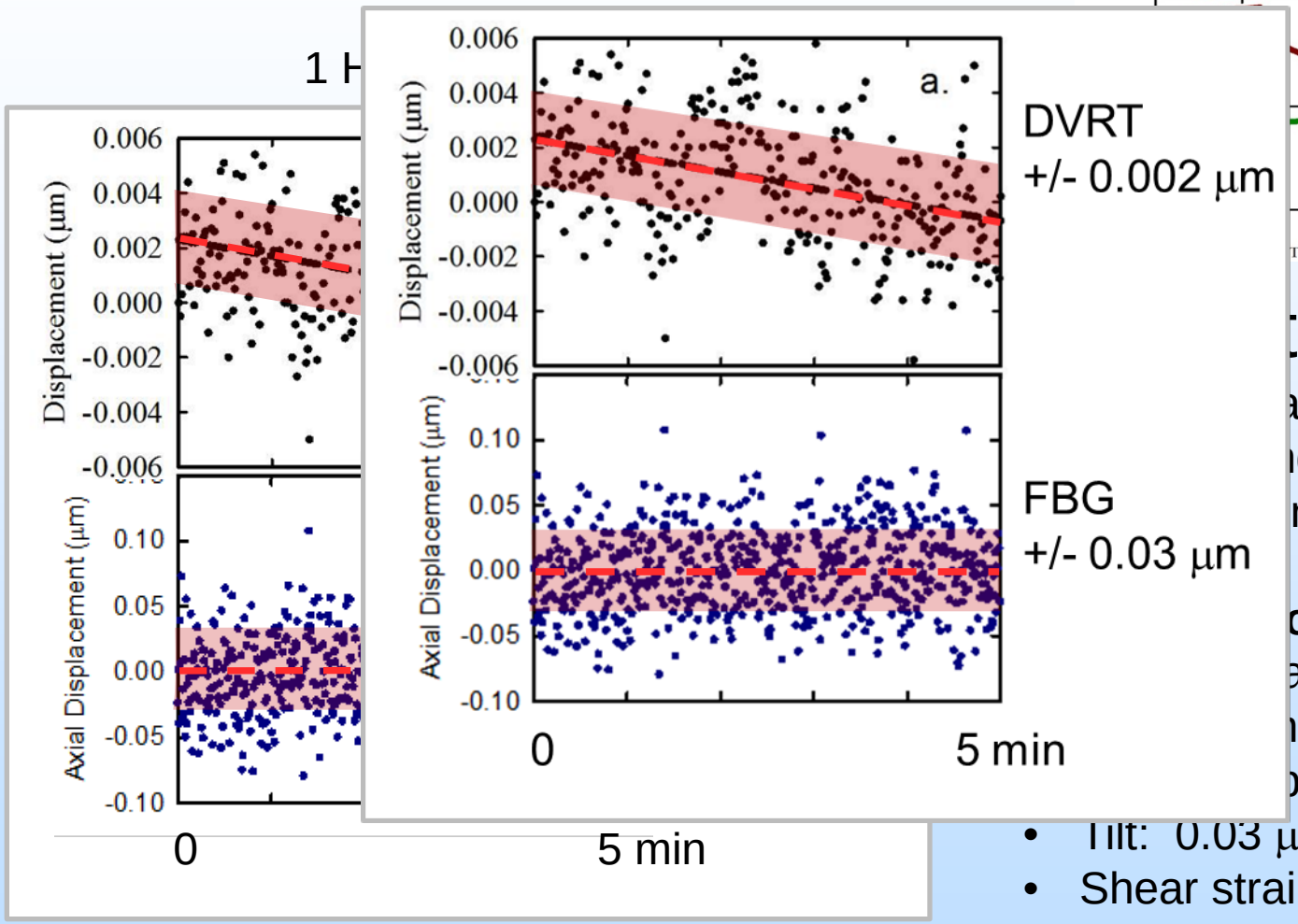


+ EM or optical gauges
+ Simpler than axial
+ More compact than axial
- Only 1 component of deformation

Prototype testing

Field Results





tus

al, 3D

g at shallow depths

n

olution

acement: 0.01 μm

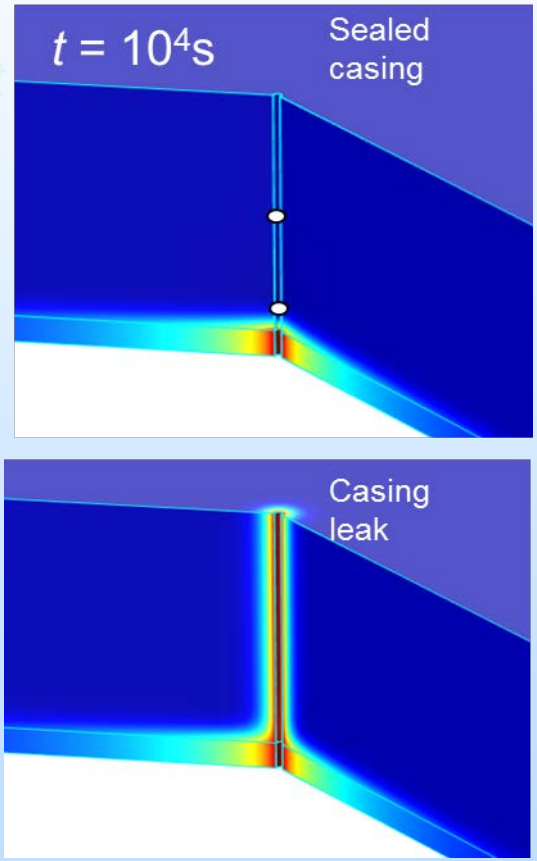
: 0.01 με

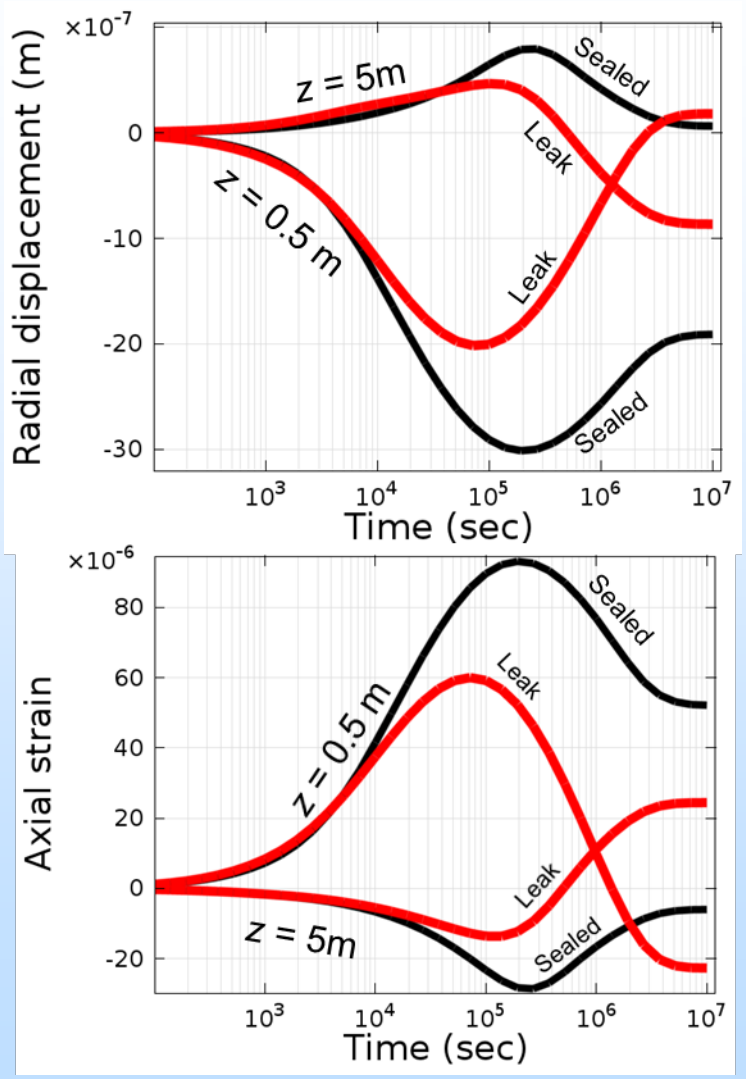
lacement: <0.1 μm

- Tilt: 0.03 μrad
- Shear strain: 0.2 με
- Strain Rate: $<10^{-12}$ s^{-1}

Effects of Annular Leakage

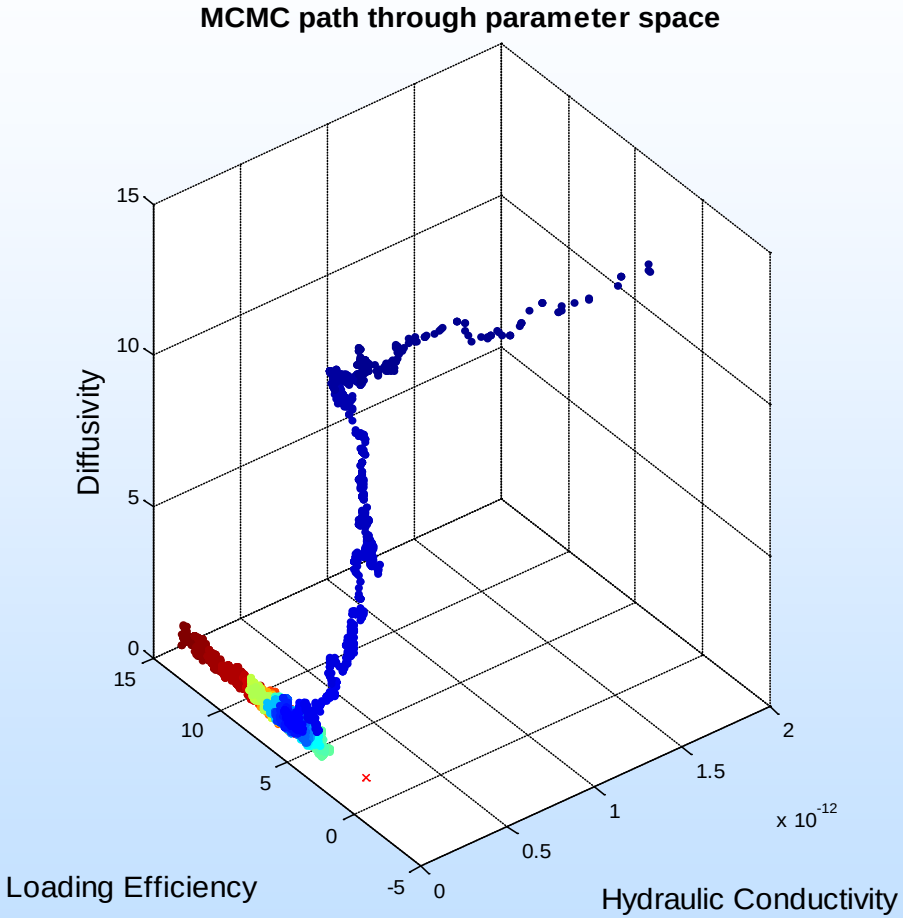
Constant *P* injection, 1MPa
Confining: *k*: 10μD

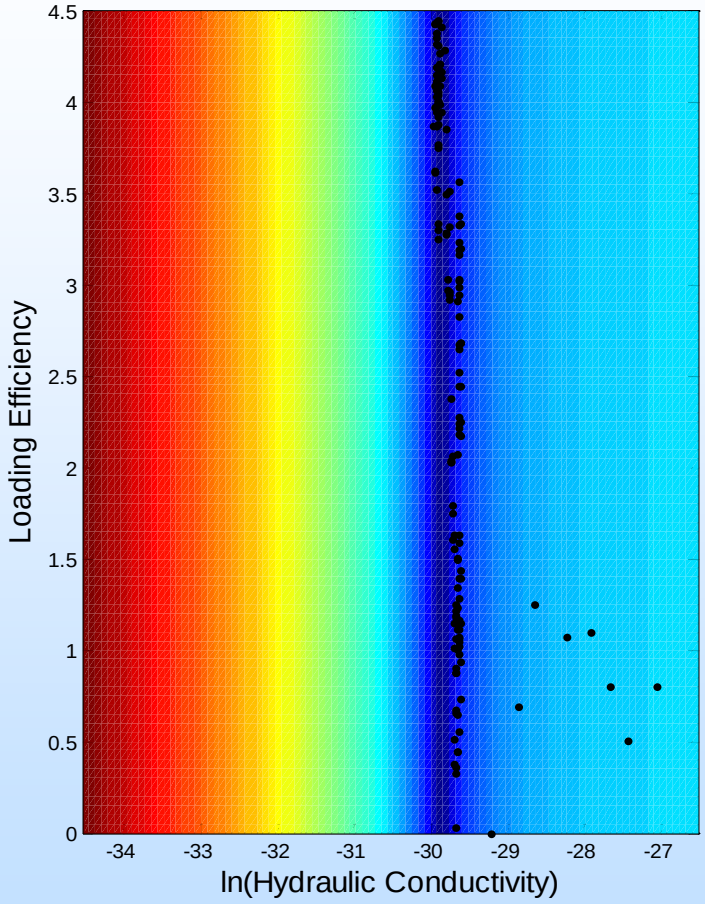




Pressure Data Only (10% noise)

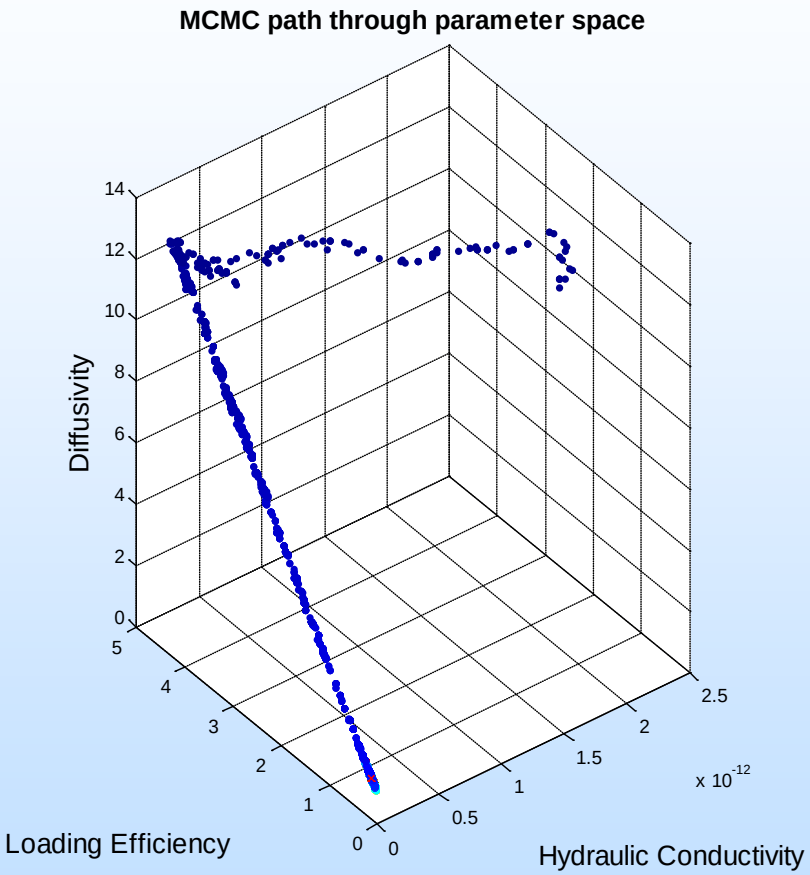
Color scale shows objective function,
Points show accepted models



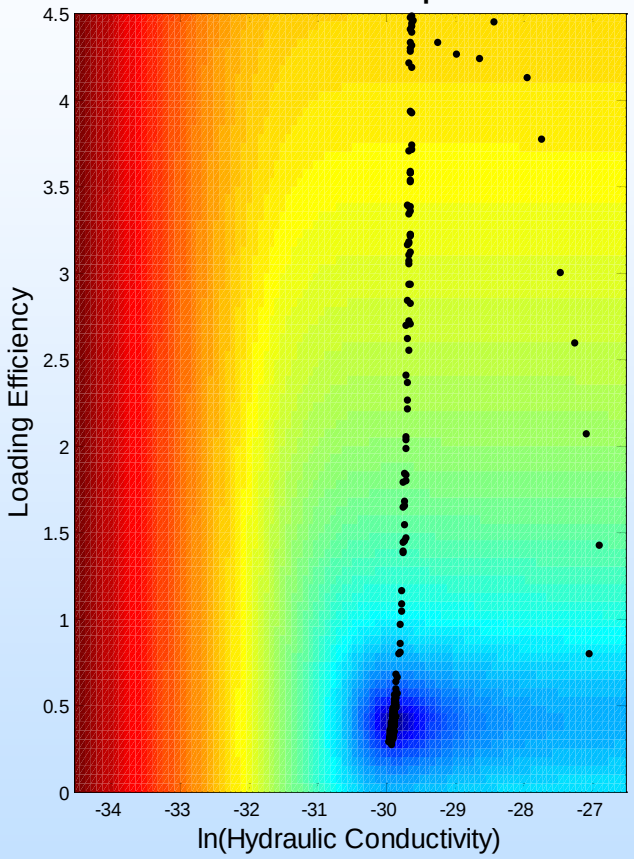


Loading efficiency cannot be constrained.

Pressure + Displacement Data (10% noise)

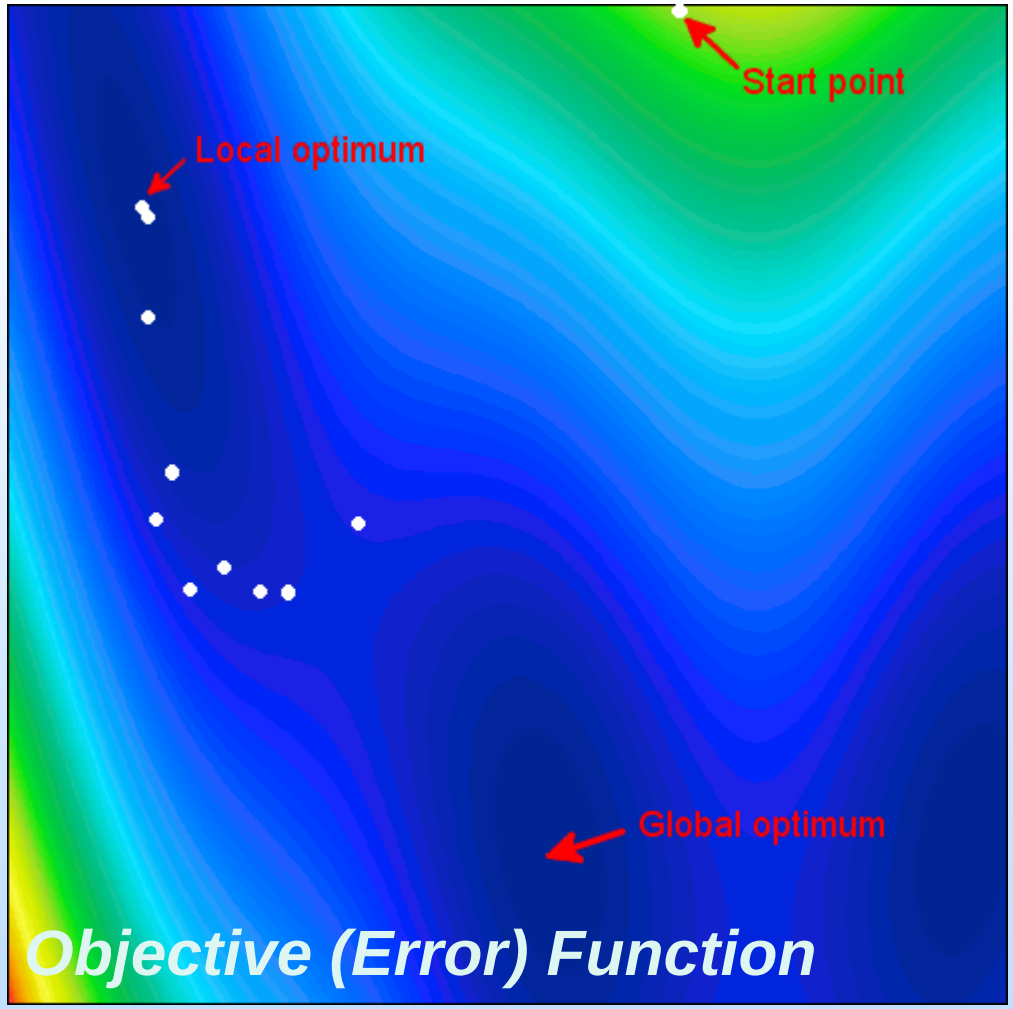


Color scale shows objective function,
Points show accepted models



Well defined minimum in objective function.

Gradient Descent:

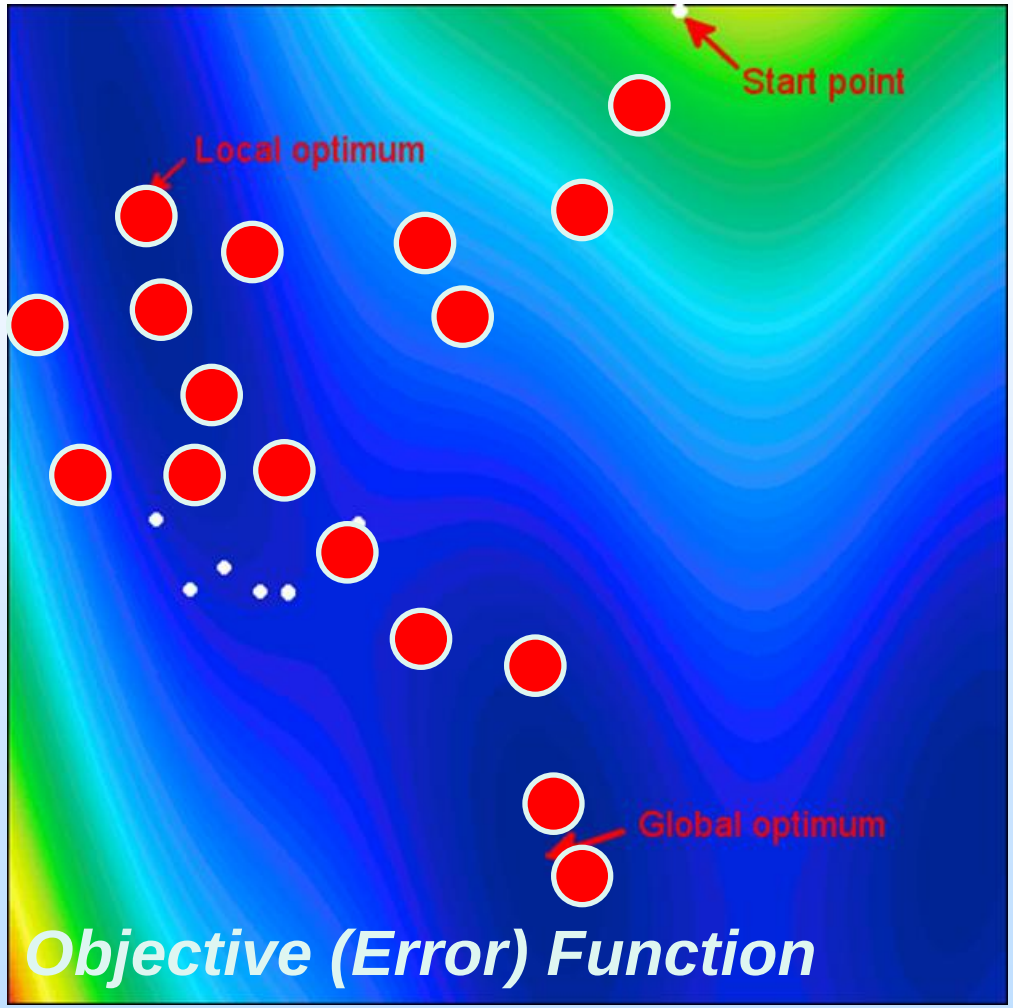


Take successive steps in gradient descent direction.

Choose steps so that error always decreases in moves toward the minimum.

Problematic when local minima occur or problem is poorly conditioned.

MCMC:



Propose step based on current position (e.g. random walk).

Accept step if error decreases.

Repeat.

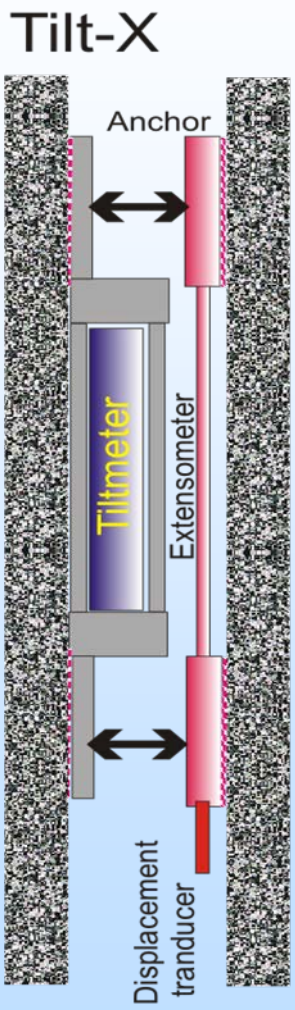
If error increases in a step, accept/reject with a probability related to the increase in error.

➔ Allows steps to move "uphill" out of local minima.

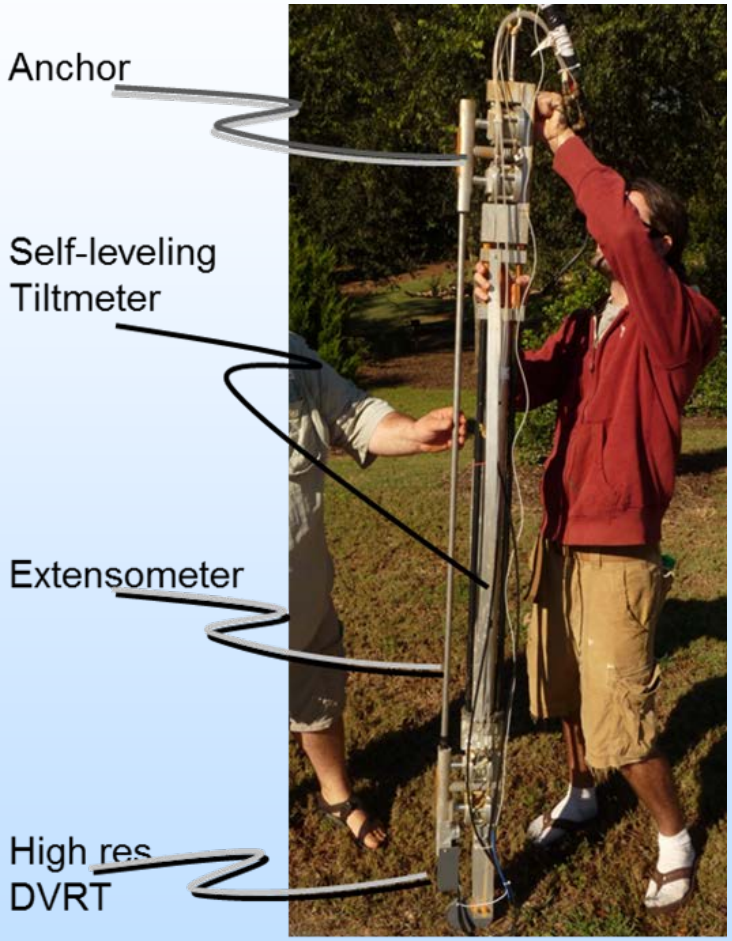
➔ After running chain, the samples can be used to infer joint statistics for parameters.

3D Borehole Displacements

Electrical Sensors



+ Proven technology
  - Electrolytic tilt
  - EM displacement
+ High resolution
- Downhole electronics
- Vulnerable to EM interference



Appendix

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

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 that work completed to date.

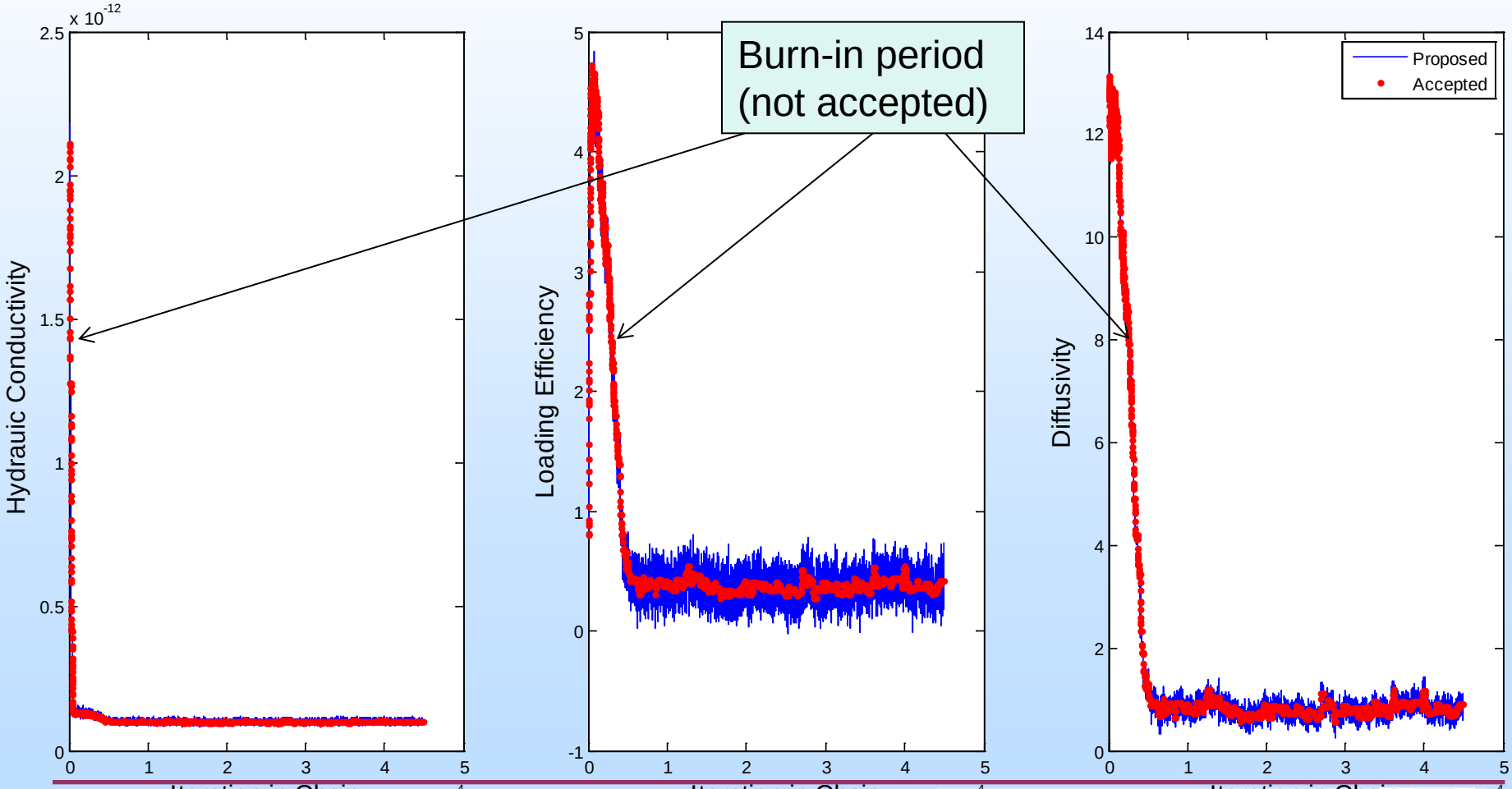
Bibliography

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

- Journal, one author:
  - Gaus, I., 2010, Role and impact of CO2-rock interactions during CO2 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.

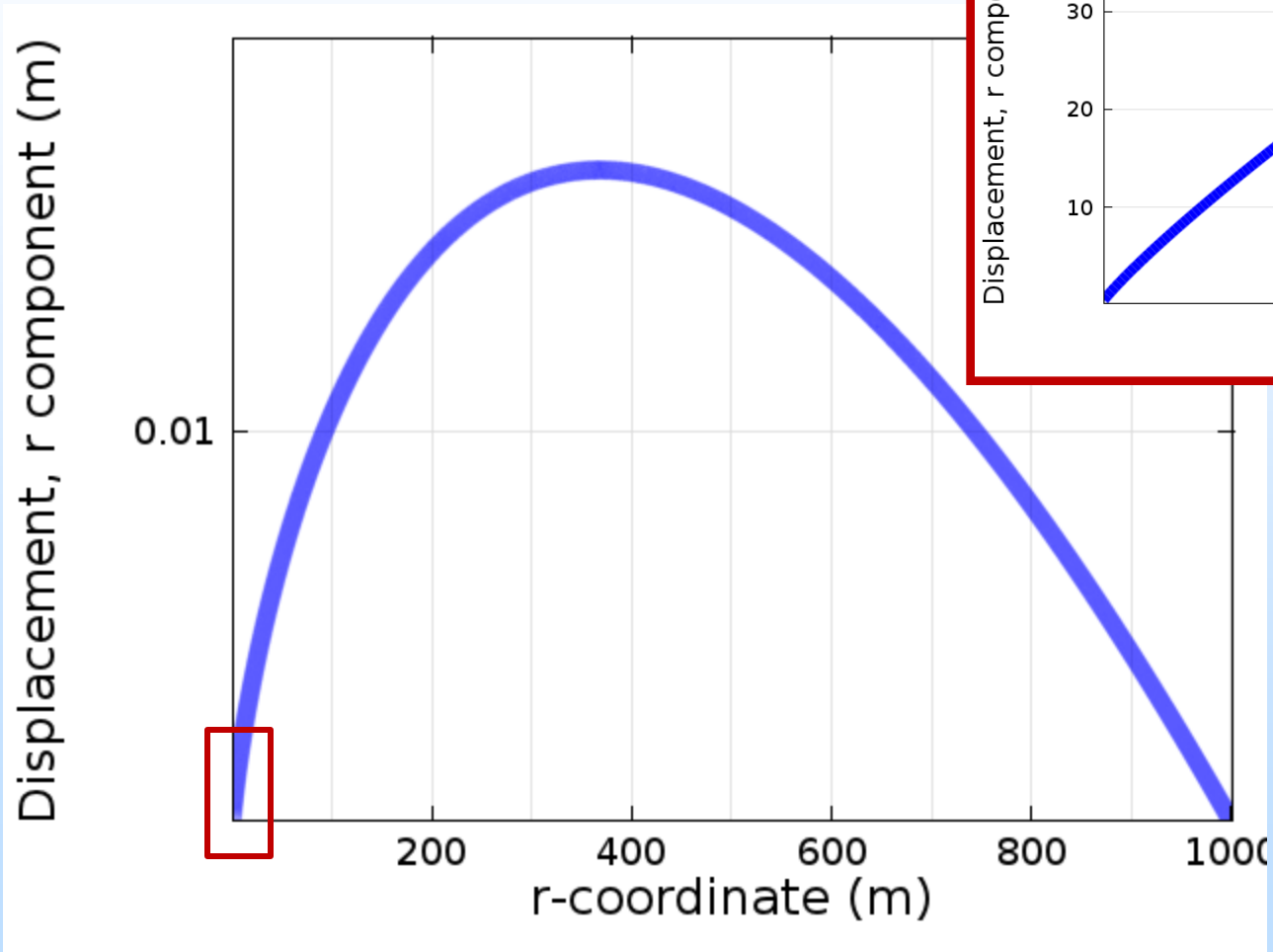
Pressure + Displacement Data (10% noise)

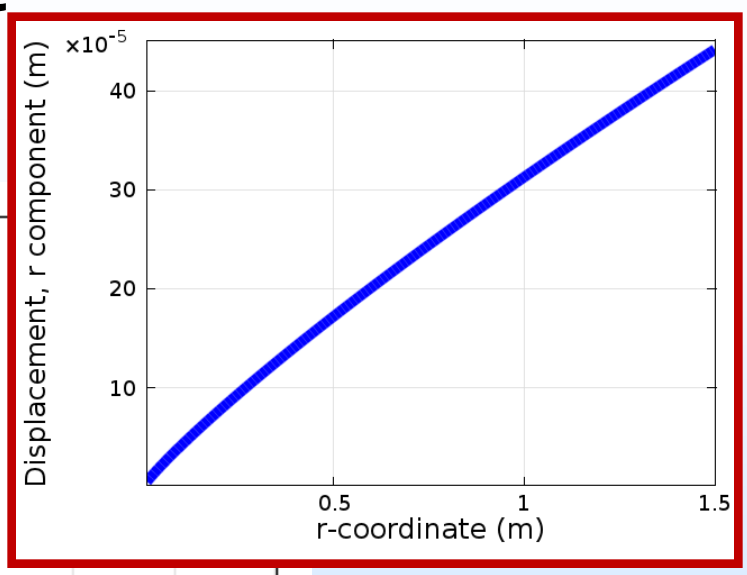
Convergence of chain achieved for all three model parameters



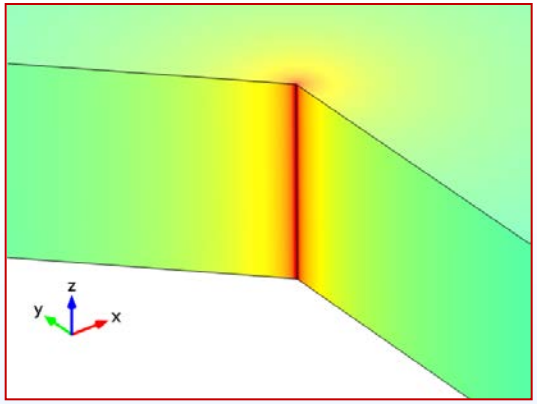
Radial displacement

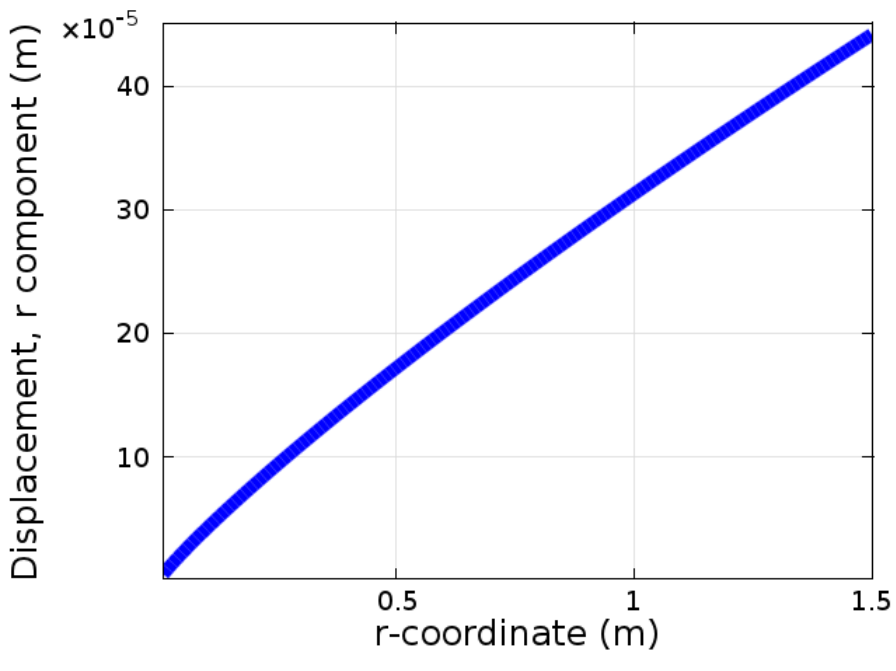
steady line source

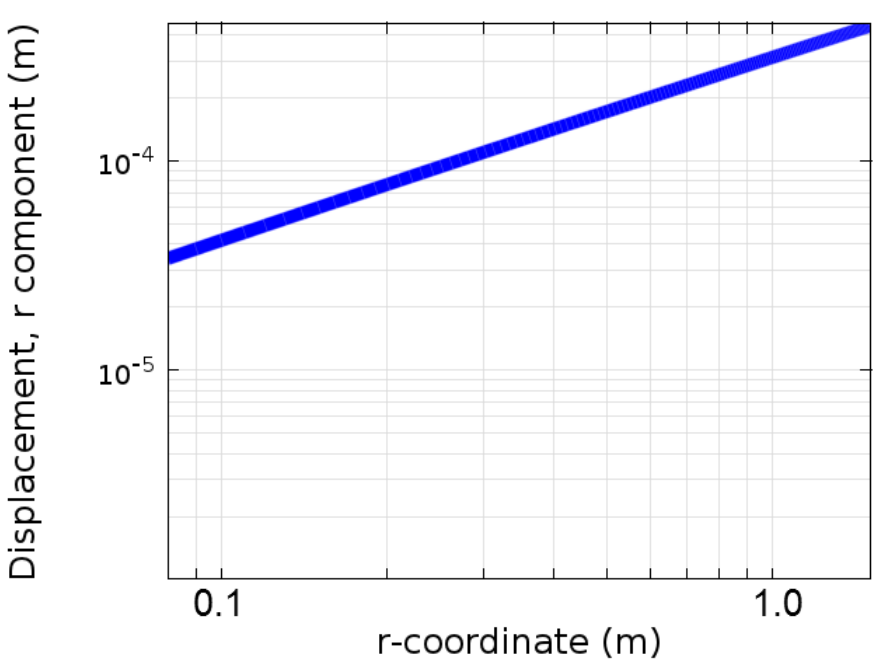




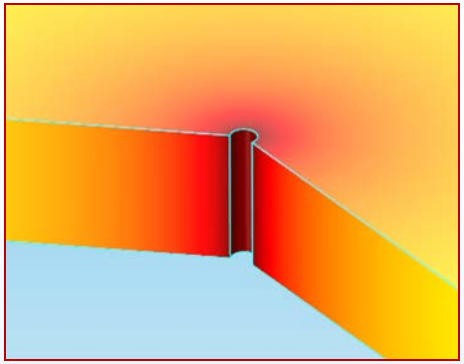
Near-well radial displacement
Line Source

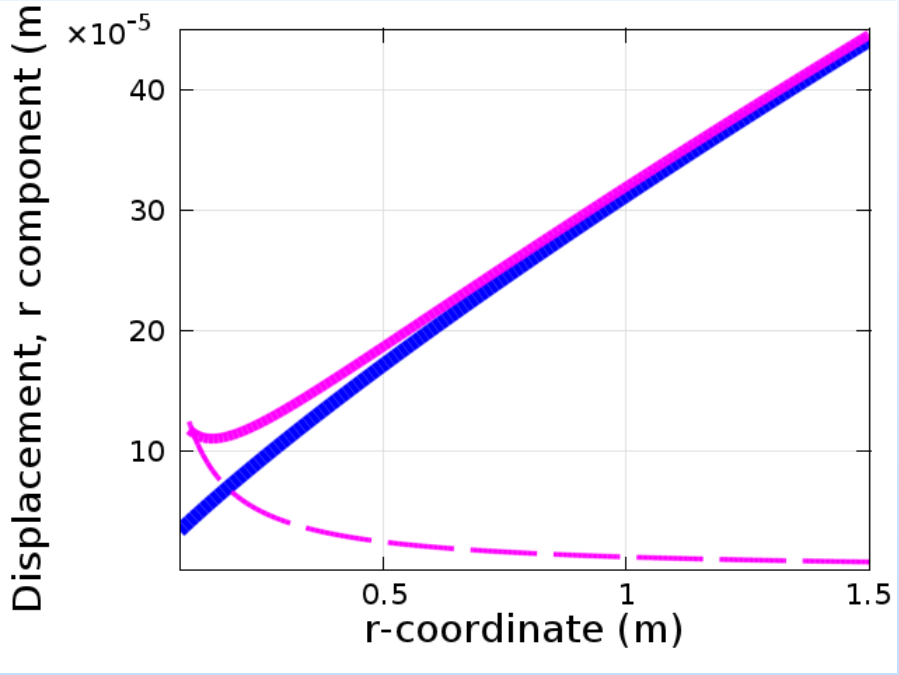


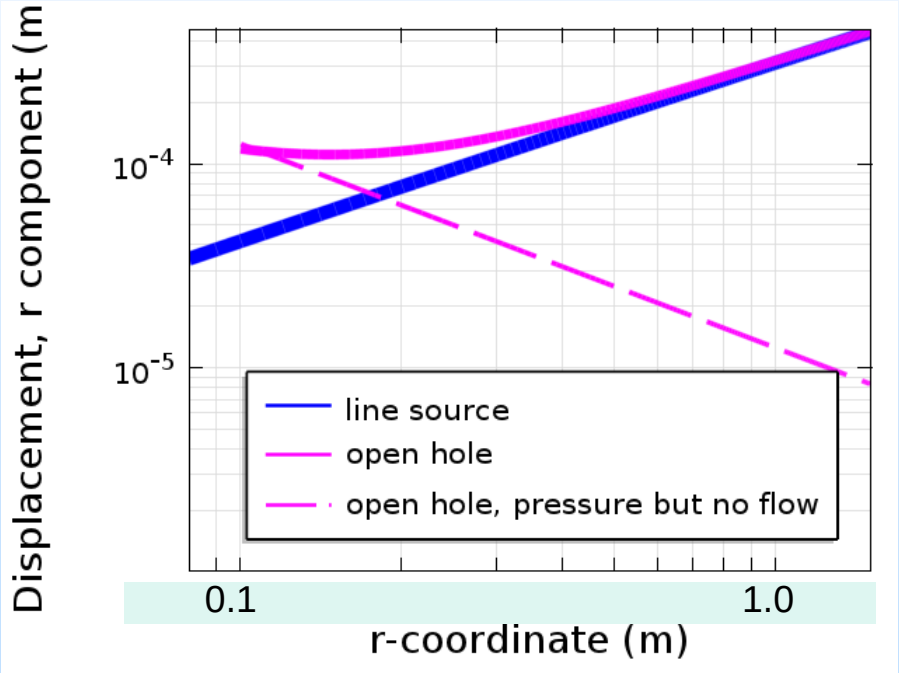




Near-well radial displacement
Open Hole

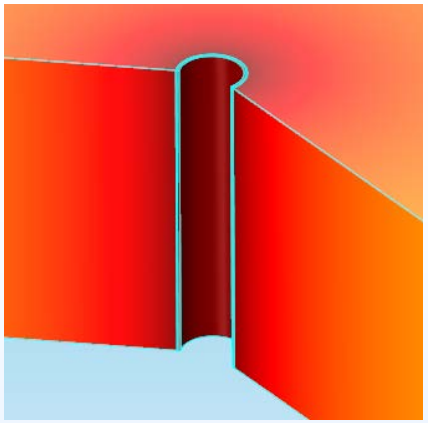


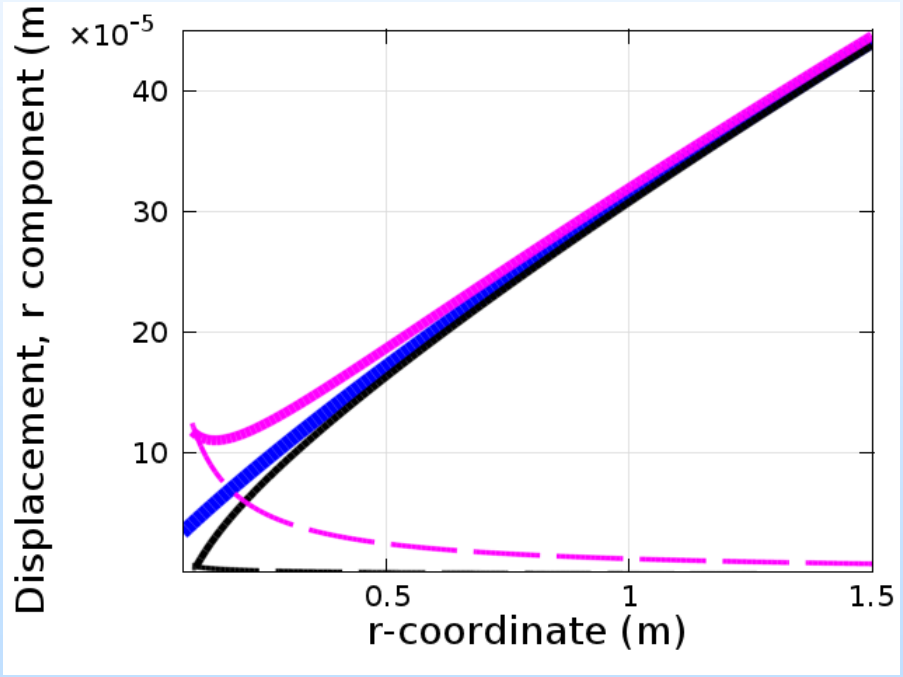


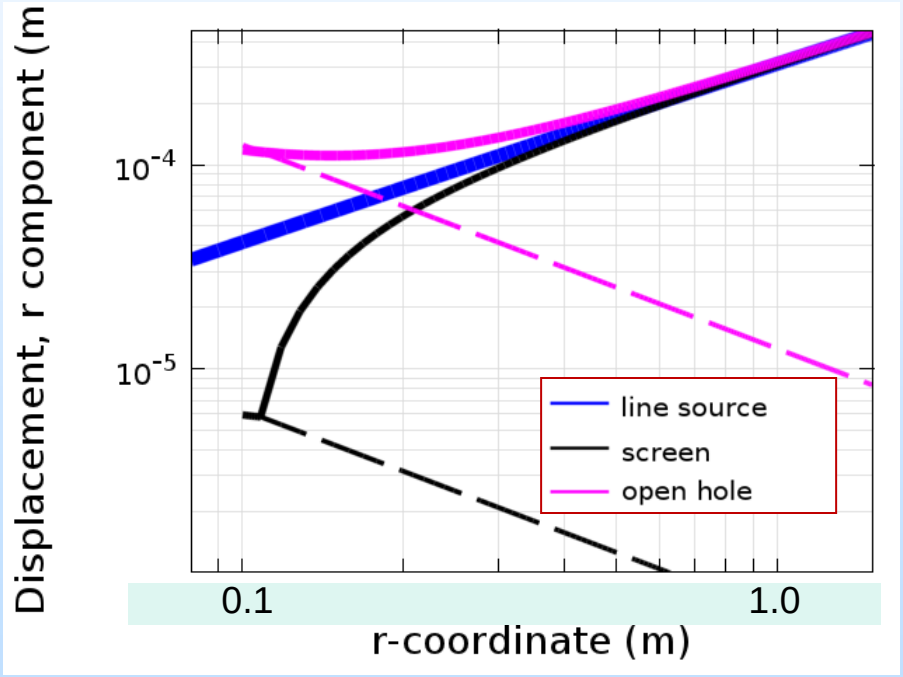


Near-well radial displacement

Screened hole, bonded to formation

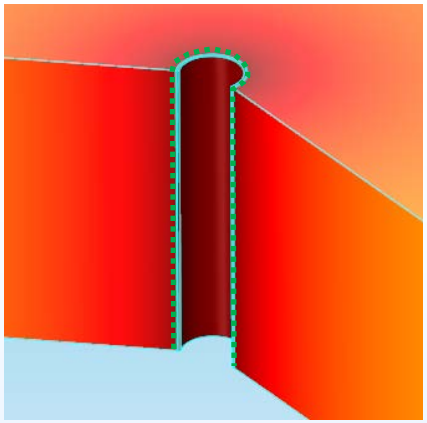


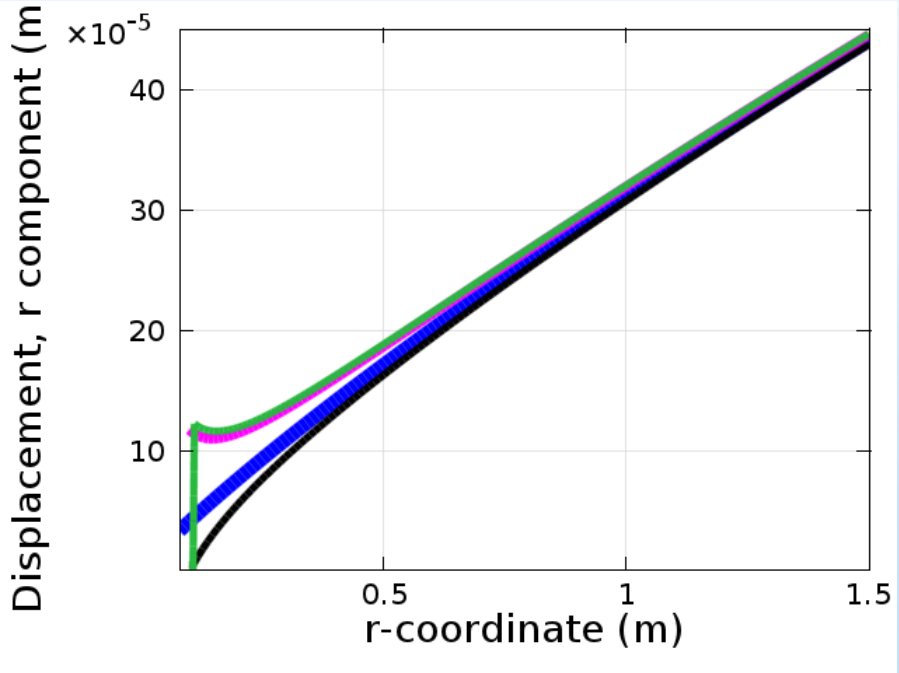


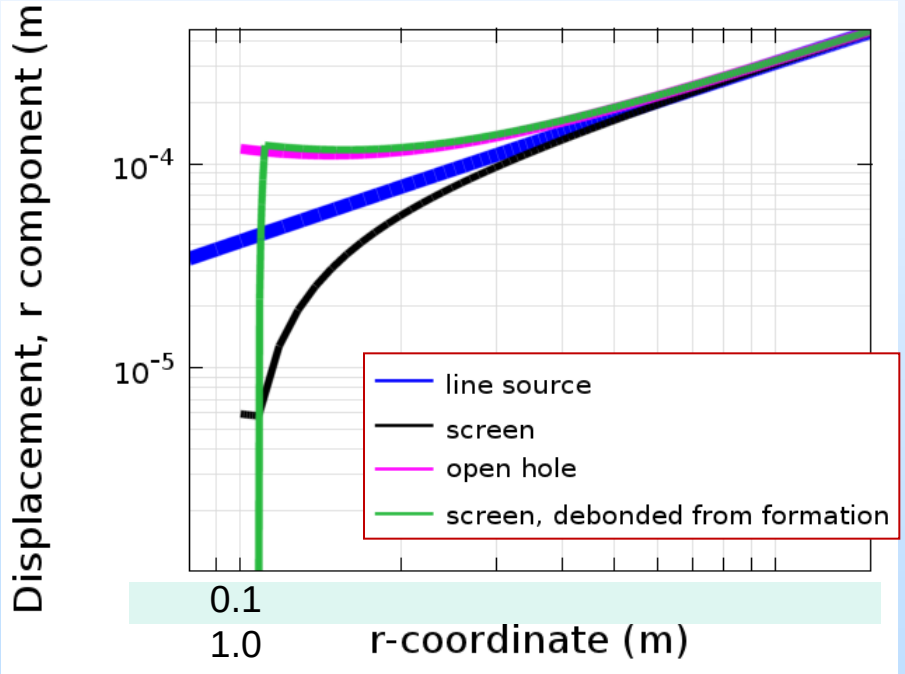


Near-well radial displacement

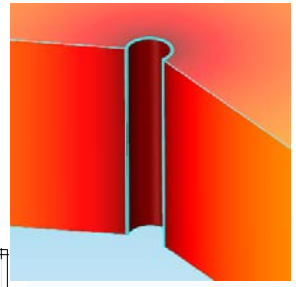
Screened hole, soft layer, no pre-stress





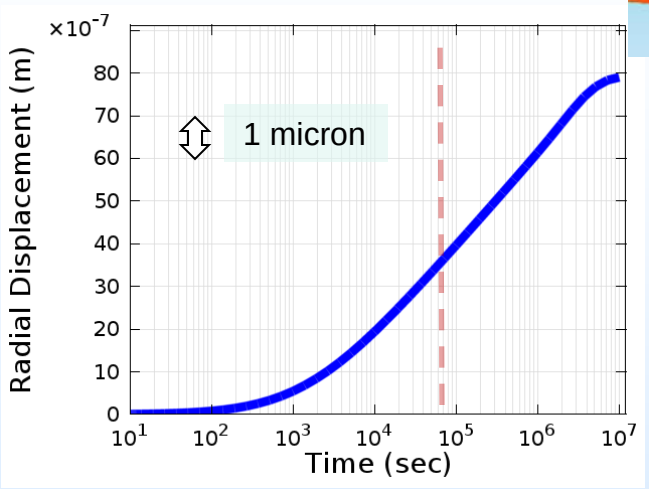


Transient injection test

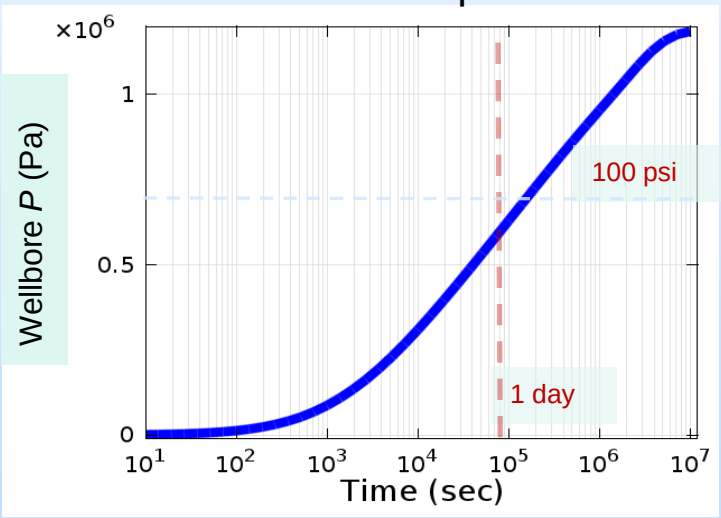


Constant Q=3x10^{-4} m^3/s
Screened
Confining stress: 10MPa
Casing compressed 10MPa
during completion

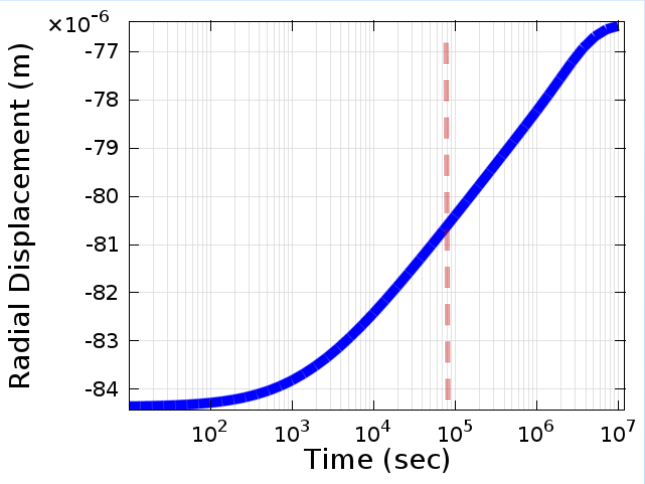
Since start of injection

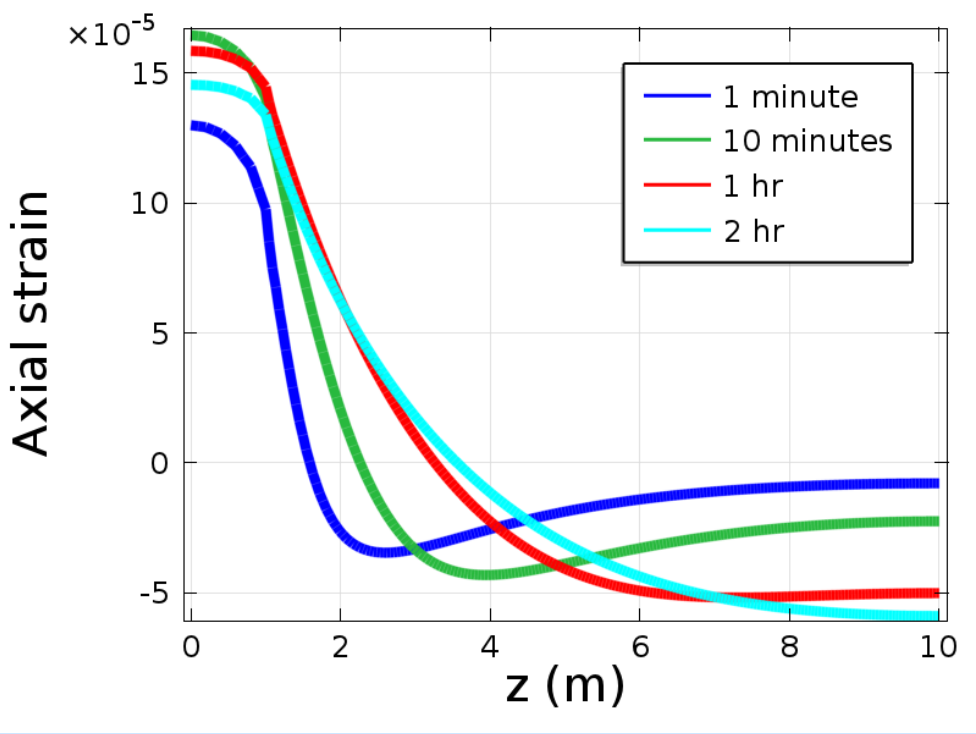


Pressure response



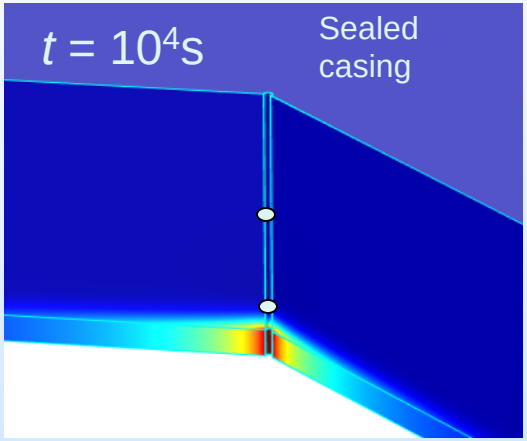
Relative to unloaded radius

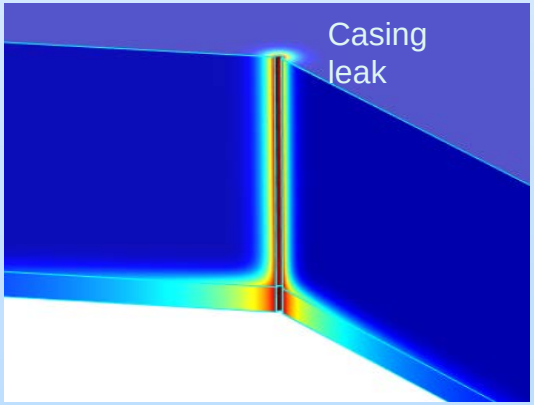


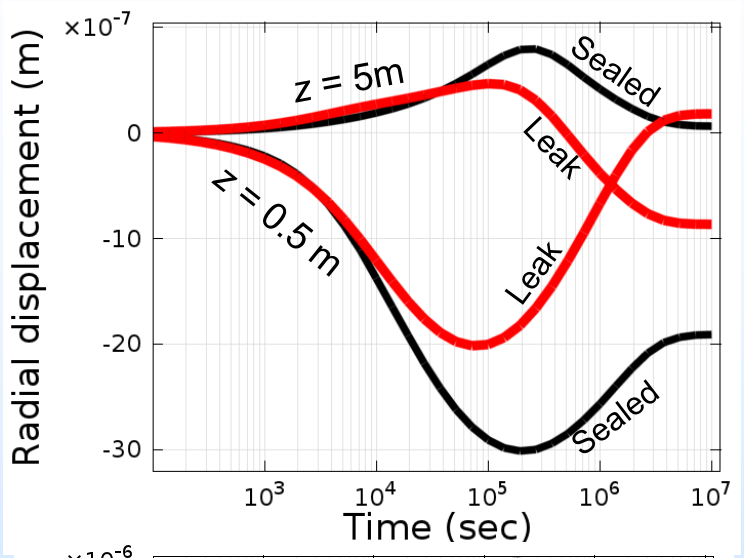

×10^-5
15
10
5
0
-5
Axial strain
0
2
4
6
8
10
z (m)
1 minute
10 minutes
1 hr
2 hr

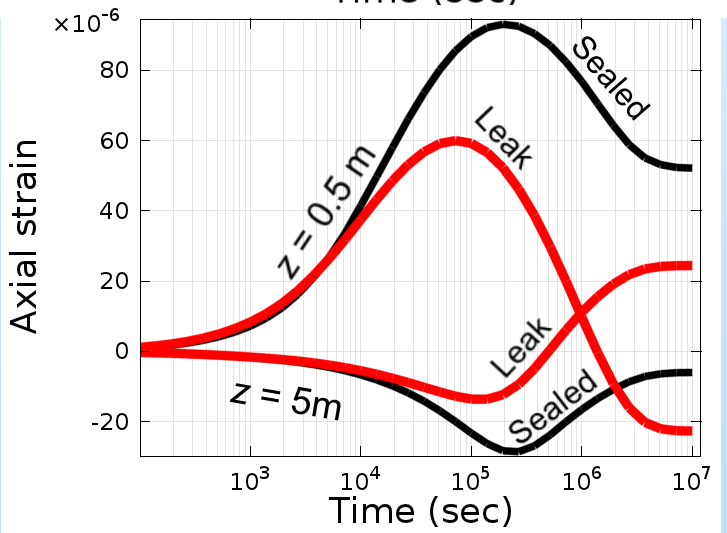
Effects of Annular Leakage

Constant *P* injection, 1MPa
Confining: *k*: 10μD







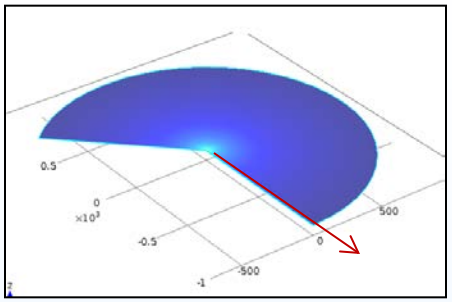


Technical Status

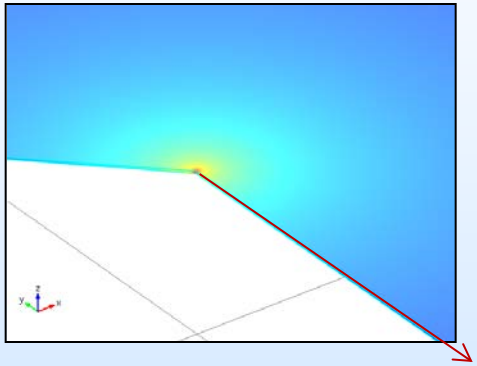
- Focus the remaining slides, logically walking through the project. Focus on telling the story of your project and highlighting the key points as described in the Presentation Guidelines
- When providing graphs or a table of results from testing or systems analyses, also indicate the baseline or targets that need to be met in order to achieve the project and program goals.

Steady injection into well

- Axial symmetry, 1-D radial
- CH boundary at *r*=1000m
- Plane strain
- Properties, sand and water

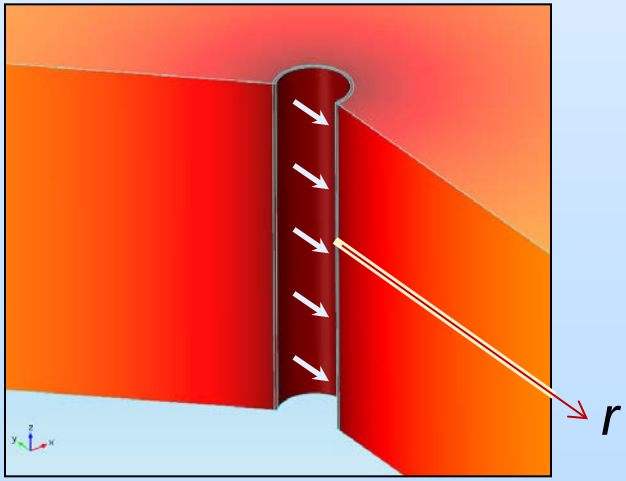


k: 100mD, *b*=1m, *E*=1GPa, α=1; ν=0.25
β=4.4x10^{-10} Pa-1, μ: 0.001 Pa s



Cases

1. Line source
2. Open hole
   - *r*: 0.1m
   - Pressurized, w/ flow
   - Pressurized, no flow
3. Casing/Screen
   - *r:* 0.1m; *w*: 8mm; *E*: 200GPa
   - Pressurized, w/ flow (screen)
   - Pressurized, no flow (casing)



What can be measured?