Area of Interest 1: Geomechanical Research

Development of Geomechanical Screening Tools to Identify Risk: An Experimental and Modeling Approach for Secure CO_2 Storage

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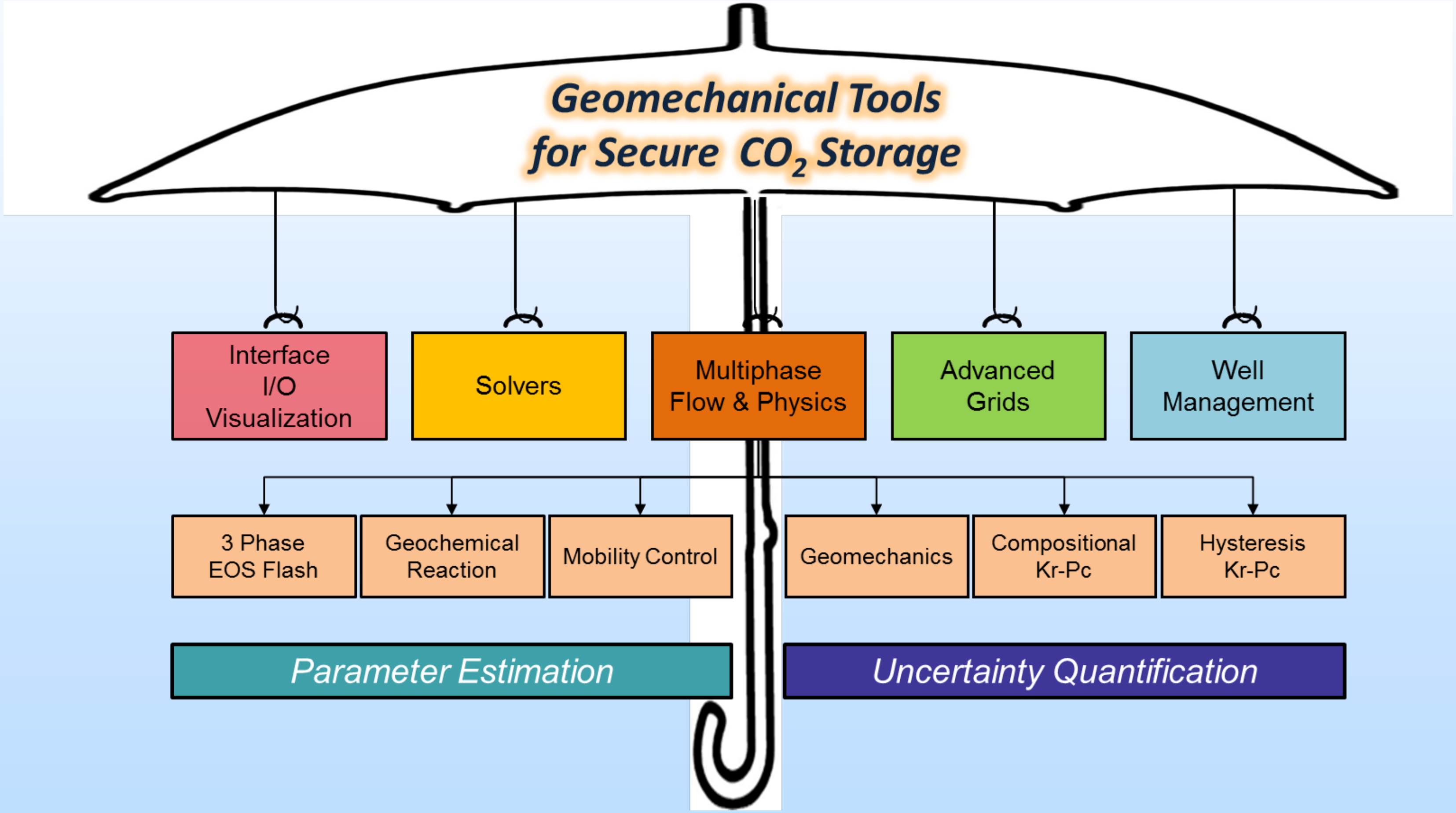
Presentation Outline

1. Benefit to the Program
2. Goals and Objectives
3. Technical Status from Tasks 2 to 6
4. Accomplishments to Date
5. Synergy Opportunities
6. Summary

Benefit to the Program

- ☐ Develop a **Geomechanical Screening Tool** to Identify Risk
  - ✓ *Experimental & Modeling Approach for Secure CO_2 Storage*



Project Overview: Goals and Objectives

- **Develop a screening tool** for improved understanding of geomechanical effects associated with CO_2 injection
- Derive a workflow **from experimental and computational** studies conducted for specific CO_2 sites, e.g. Frio, Cranfield

Task 1 Project **management** **(M.F.W.–lead)**

Task 2 Conduct **laboratory experiments** for hydro-mechanical rock properties **(N.E.–lead)**

Task 3 **Upscale** to bridge from laboratory to field scales **(M.F.W.–lead)**

Task 4 Extend **simulator** capability to model CO_2 storage field scale studies **(M.D. and M.F.W.-lead)**

Task 5 Perform **parameter estimation** & **uncertainty quantification** **(M.F.W.–lead, S.S.–consultant)**

Task 6 Integrate results to generate **geomechanical screening tool** / workflow **(M.F.W.–lead, S.S.–consultant)**

Technical Status

Task 2.

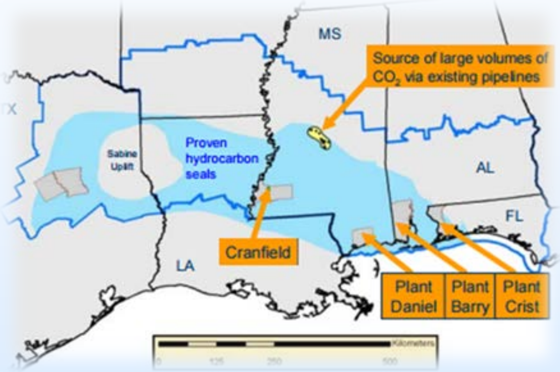
Conduct Laboratory Experiments for Petrophysical & Hydro-mechanical Rock Properties

(N. Espinoza–lead)

Task 2: Laboratory Experiments

Objectives	Complete modeling, perform reservoir simulations, and analyze geological uncertainty for two CO_2 storage field studies (Frio, TX & Cranfield, MS)

- Measure mechanical properties
- Collect other existing data (seismic, well logs, etc.)
- Measure other reservoir rock properties and corroborate with field data



Site 1: Cranfield, Mississippi

(Source: DOE Cranfield Fact Sheet)

Site 2: Frio pilot study, Texas

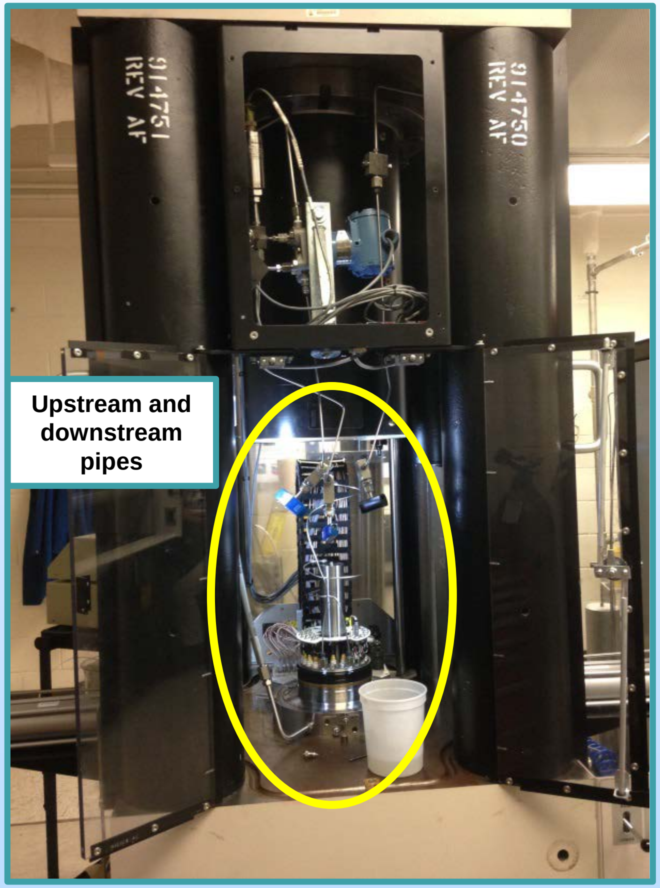
Large Axisymmetric Triaxial Frame Connected to ISCO Pumps for Fluid Injection

- Experimental setup

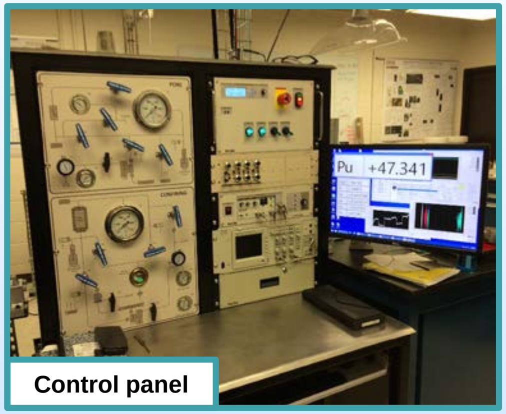
1 Sample mounted on the loading frame

2 Data acquisition

3 Cylinders & pumps for flow system connected to the triaxial cell

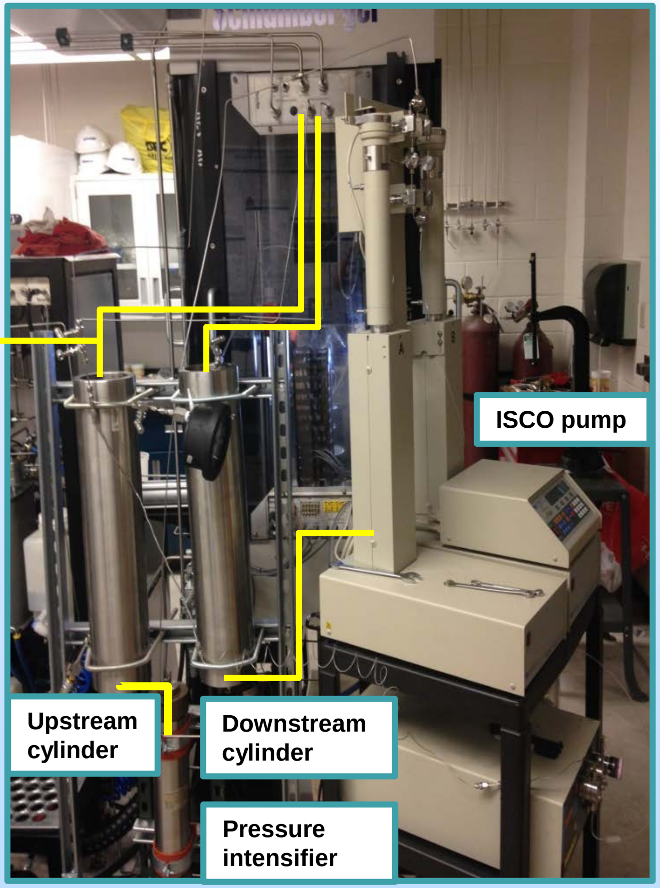


Upstream and downstream pipes



Control panel

Pressure booster



ISCO pump

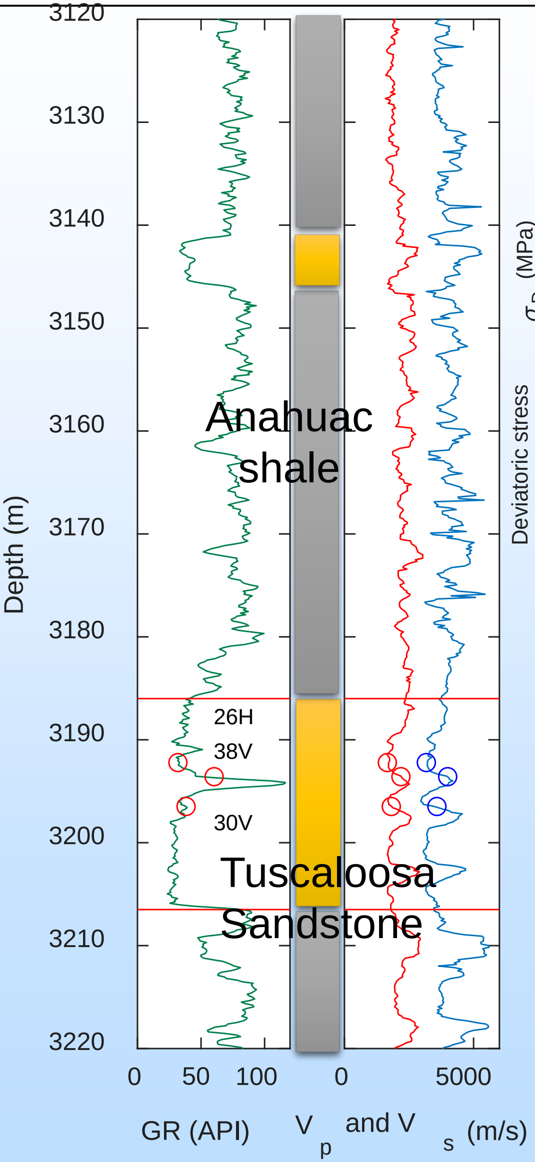
Upstream cylinder

Downstream cylinder

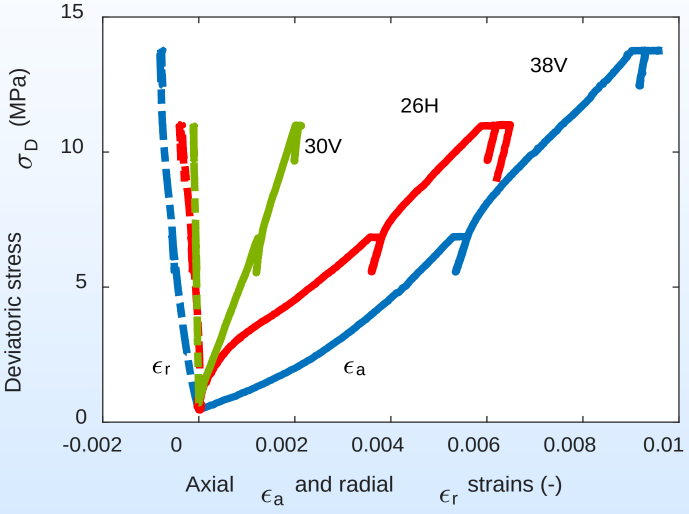
Pressure intensifier

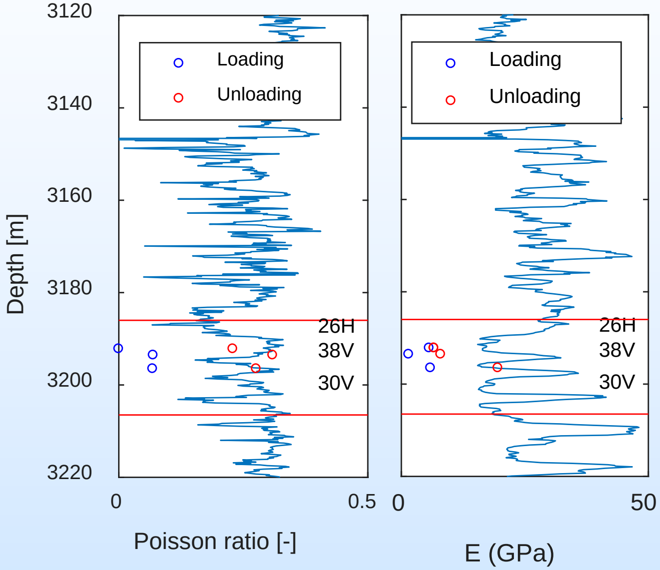
Task 2

Mechanical properties of Cranfield Tuscaloosa sandstones



From monitoring well 31F-3: 2 vertical (38V and 30V), 1 horizontal (26H), and caprock samples





	38V	30V	26H
Depth [m]	3189.9	3192.9	3188.6
$E_{loading}$ [GPa]	1.59	6.01	5.74
$E_{unloading}$ [GPa]	8.07	22.04	6.70
Poisson's ratio	0.31	0.28	0.23

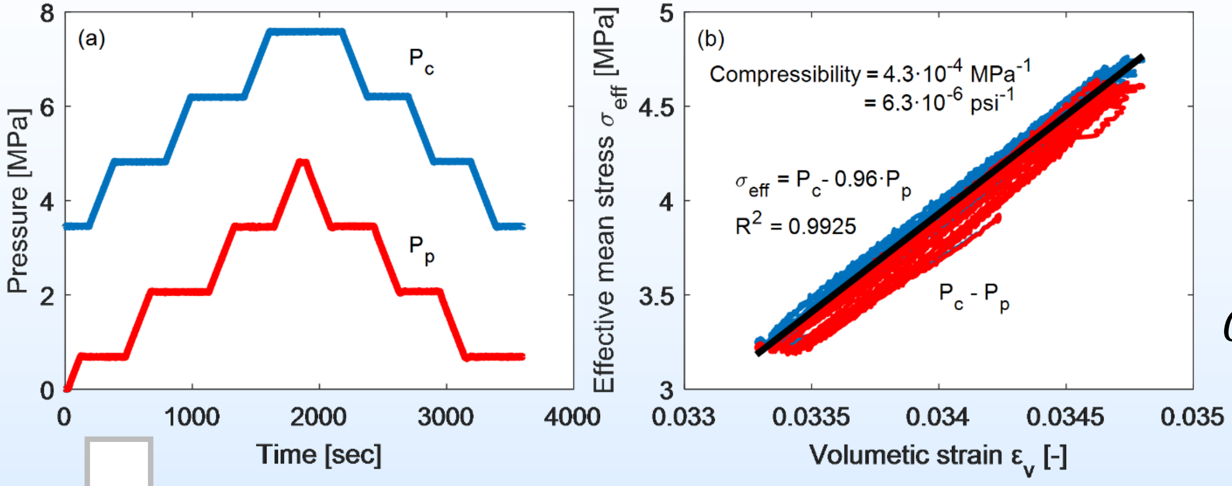
Ratio between Static/Dynamic: 0.24 (loading) and 0.56 (unloading)

$$S_{hmin} = \frac{\nu}{1-\nu} S_{vert} + \alpha_p \frac{(1-2\nu)}{(1-\nu)} P_p - \frac{E}{1-\nu^2} \varepsilon_{co_2}$$

Biot coefficient < 1

Induced from CO_2 chemo-mechanical alteration

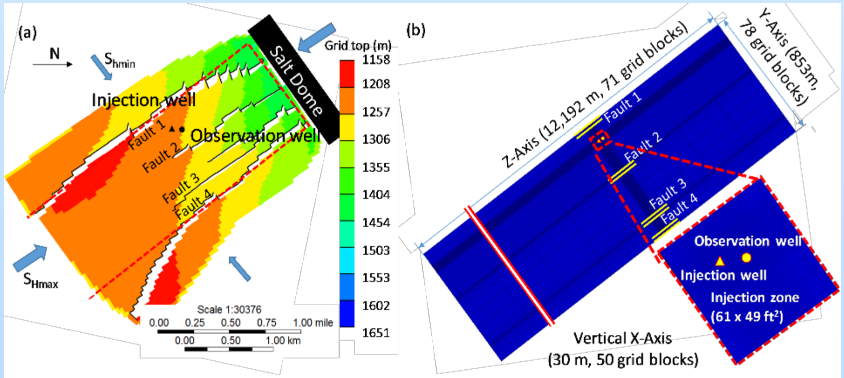
History match of Frio Pilot test using laboratory geomechanical properties in IPARS



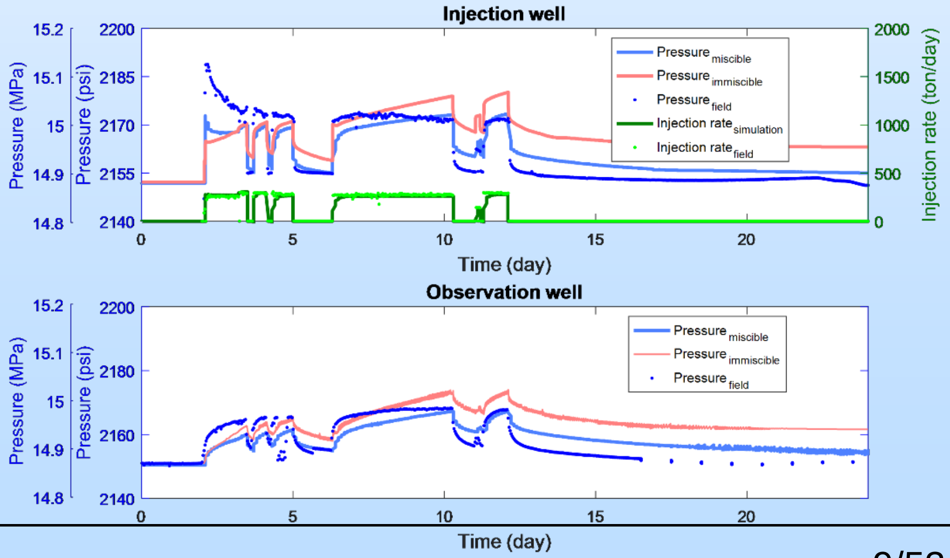
Accurate measurements of rock compressibility by laboratory experiment under in-situ condition

$$C_p = \frac{1}{V_p}\frac{\Delta V_p}{\Delta P_p} = \frac{\Delta\varepsilon_{vol}}{\Delta P_p} = 6.3\cdot 10^{-6}\ \text{psi}^{-1}$$

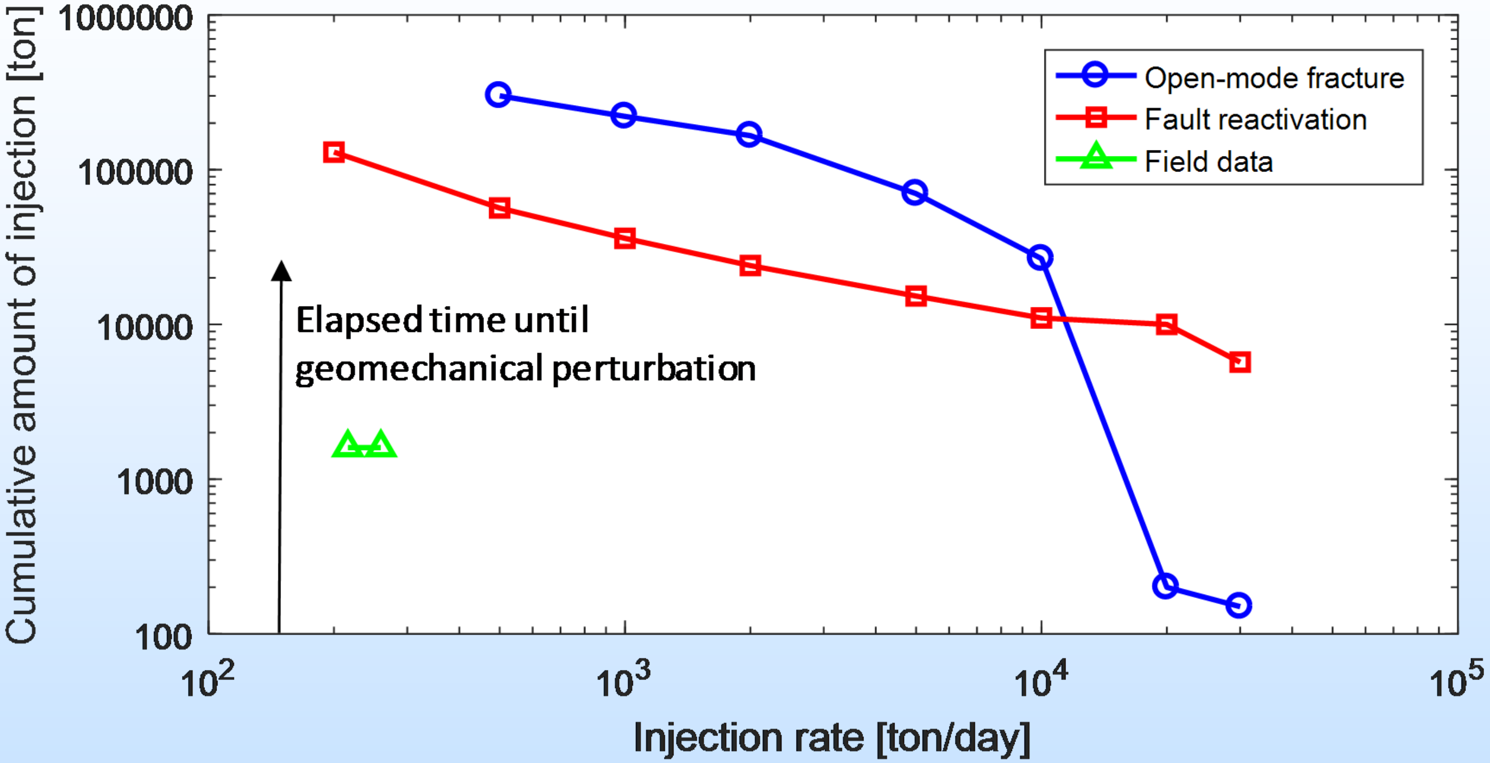
Reservoir properties and geomechanical properties assimilated into reservoir model



History match results



Storage capacity without causing geomechanical events



Cumulative amount of CO_2 injection without causing fault reactivation (red line) or hydraulic fracture at the injector (blue line) as a function of injection rate assuming closed reservoir compartments. Green triangles show actual cumulative CO_2 injection volume and injection rates attained in the field during the first Frio pilot test.

Technical Status

Task 3.

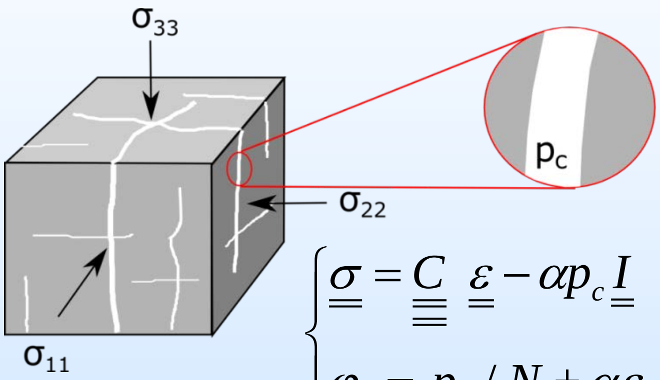
Upscale by Completing Bridge from Laboratory to Field Scales

(M.F. Wheeler–lead)

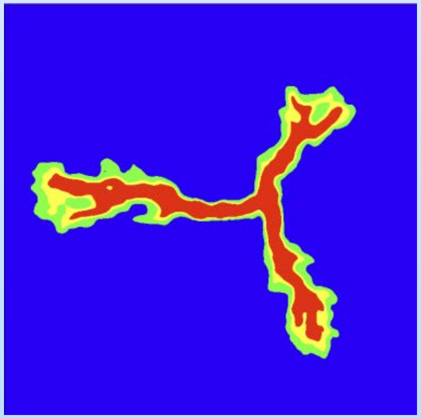
Task 3: Bridge from Laboratory to Field

Objectives Upscale measured rock properties (fluid flow & geomechanics) to scale relevant to field processes

- Development of **homogenization** schemes combining numerical and analytical approaches
- Particular emphasis will be put on including **natural fractures** in effective properties and localization effects
- Obtain field scale constitutive parameters to perform **coupled fluid flow and geomechanical** numerical simulation



$$\begin{cases} \underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{C}}}}\;\underline{\underline{\varepsilon}} - \alpha p_c \underline{\underline{I}} \\ \varphi = p_c / N + \alpha \varepsilon_V \end{cases}$$

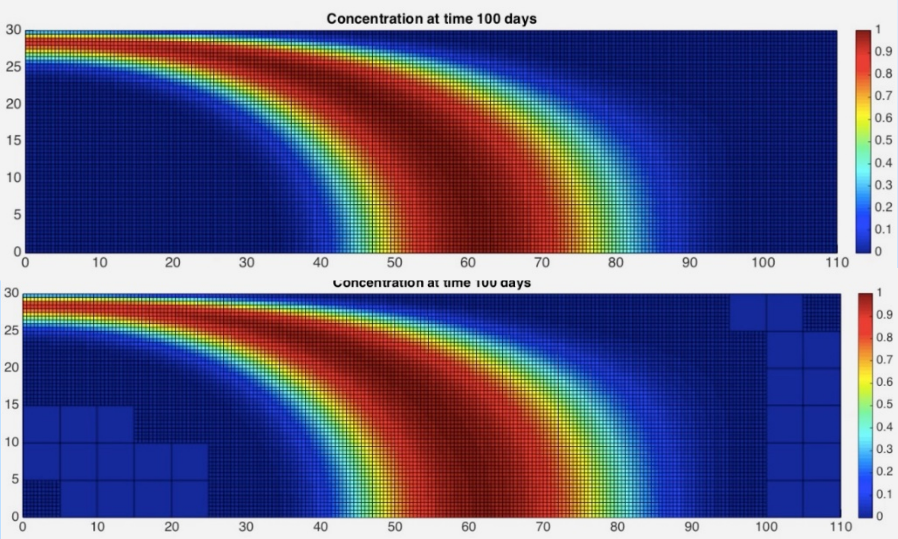


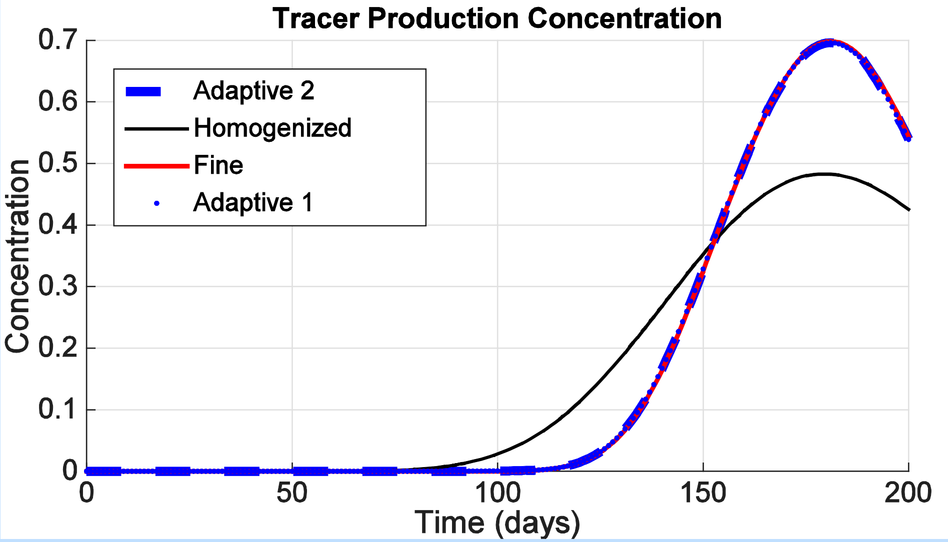
Adaptive Homogenization for Upscaling

- Problems Statement
  - Computationally prohibitive to incorporate multiscale property data from well-logs, geological models and parameter estimation
- Objective
  - A computationally efficient general upscaling framework
  - Extension to general non-linear multicomponent, multiphase flow problems
- Strategy
  - Adaptive mesh refinement for accuracy with local upscaling for computational efficiency
- Novelty
  - Preserves accuracy at the saturation/concentration front
  - Can incorporate more complex fluid flow and phase behavior descriptions with relative ease

Benchmark Homogeneous Case

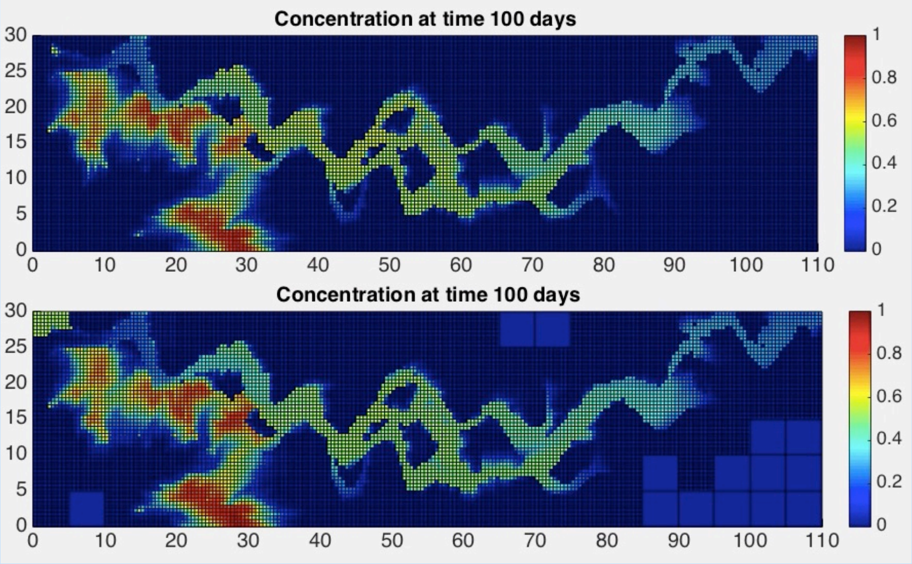
- Tracer slug injection and transport in a homogeneous medium
- Verify adaptive mesh refinement
- Three comparison
  - Fine scale
  - Coarse or homogenized
  - Adaptive with fine and coarse
- Space (Adaptive 2) and time gradient (Adaptive 2) as adaptivity criteria

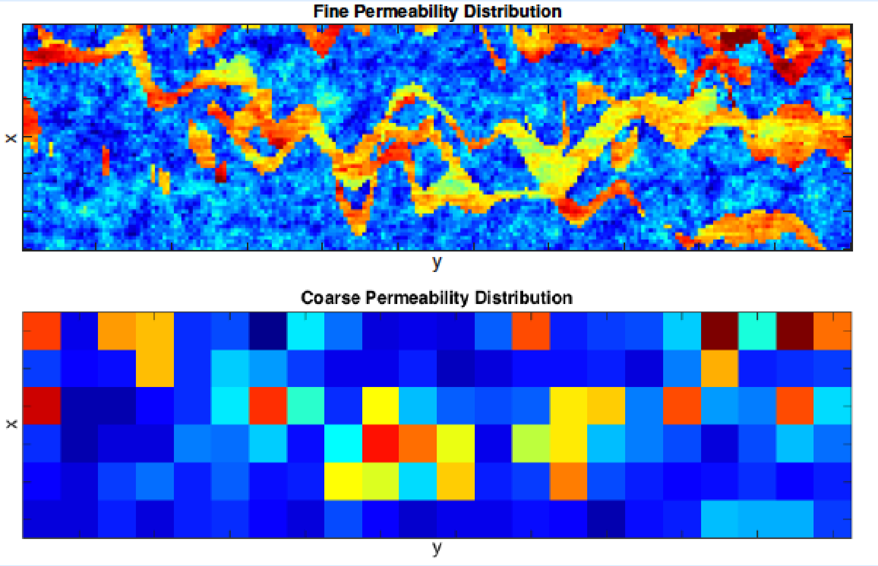




Tracer Transport: Heterogeneous Porous Media

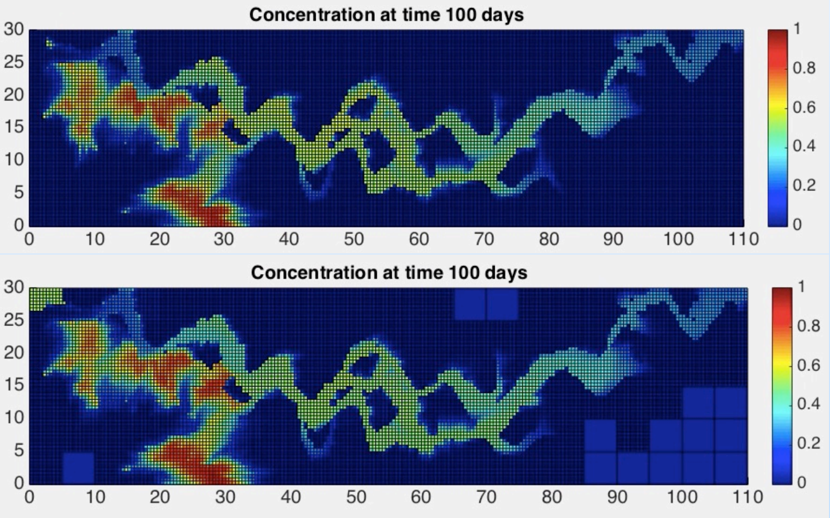
- SPE10 comparative project dataset: layer 37
  - Highly channelized permeability distribution
- Tracer slug injection and transport in a heterogeneous medium
- Computational speedup: 4X with adaptive homogenization
- Comparison
  - Concentration profiles
  - Tracer concentration production history

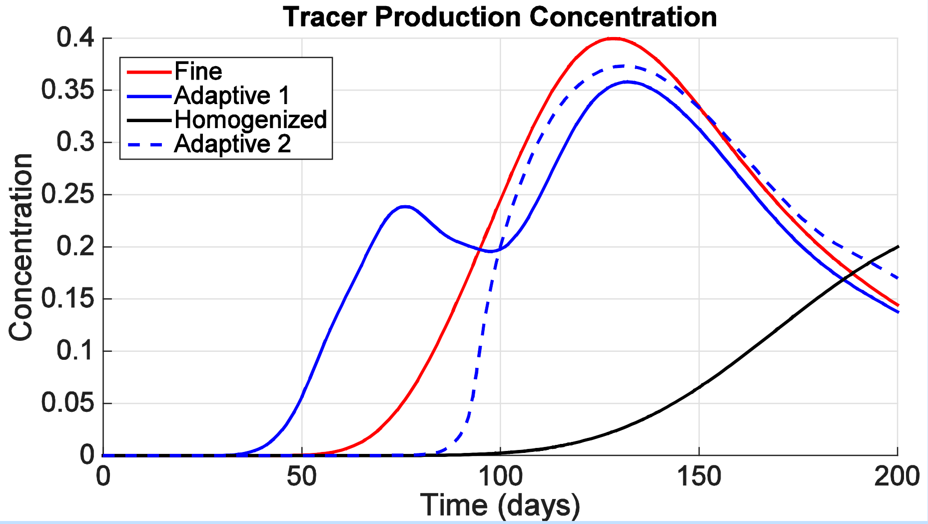




Tracer Transport: Heterogeneous Porous Media

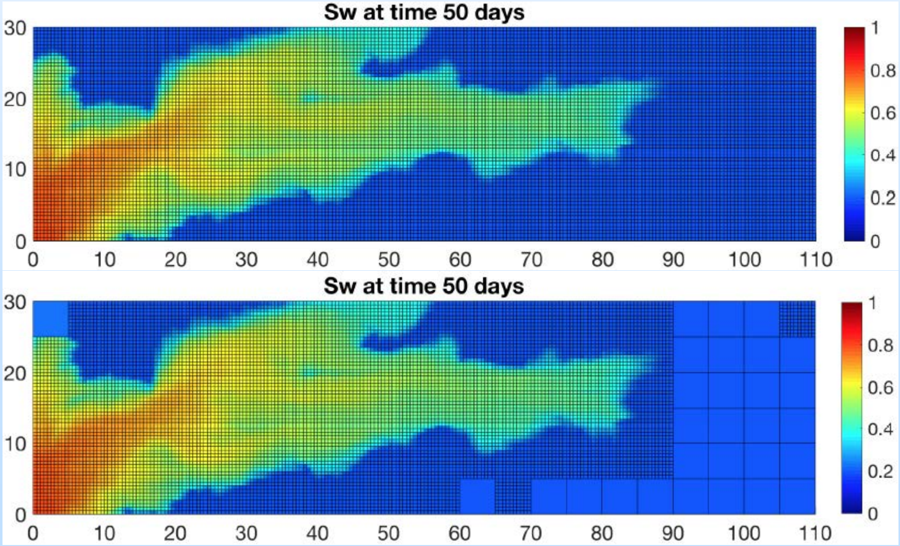
- Adaptivity criteria
  - Space gradient based criteria performs better
- Comparison
  - Concentration profiles do not show substantial differences
  - Tracer concentration production history shows the differences

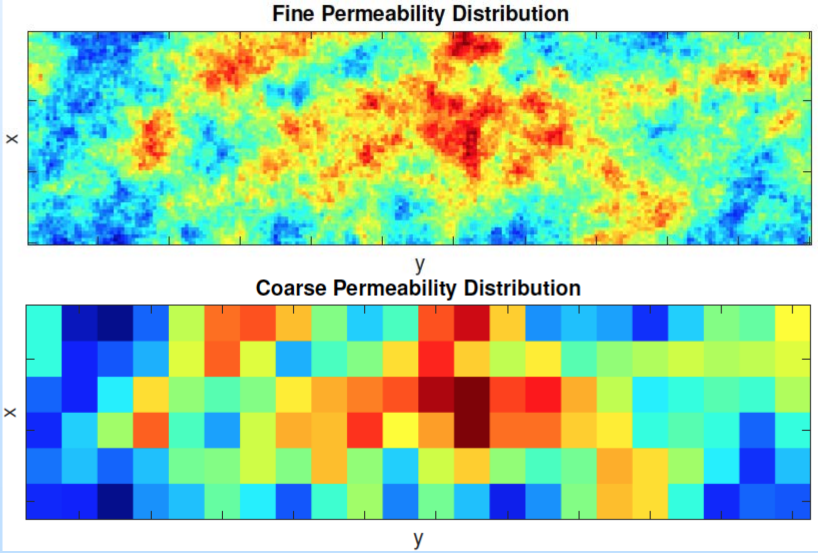




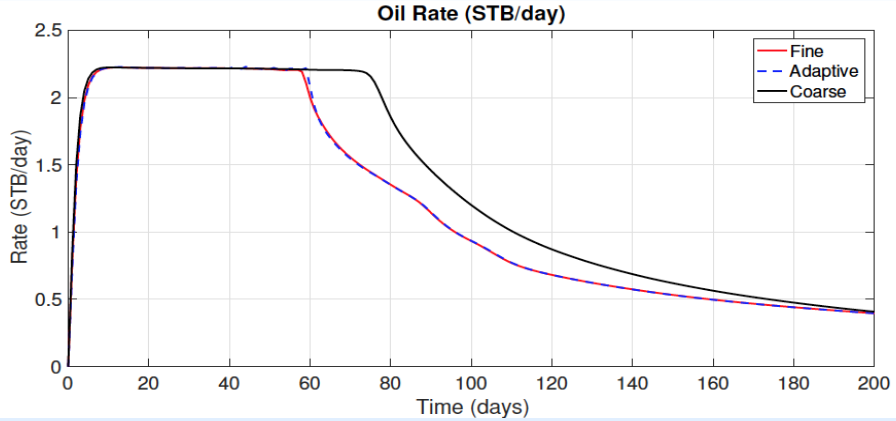
Multiphase Flow: Heterogeneous Porous Media

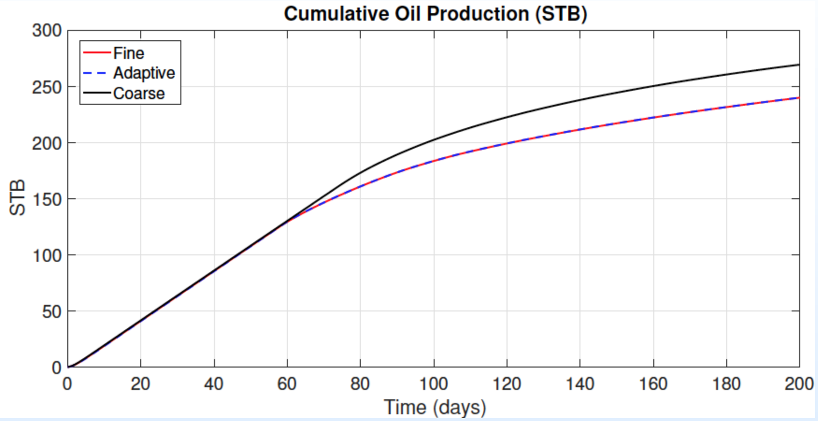
- Multiphase flow
  - Two-phase oil/water, air/water
  - Three-phase black oil
- Computational speedup: 3.5X with adaptive homogenization
- SPE10 comparative project dataset: layer 20
  - Gaussian permeability distribution

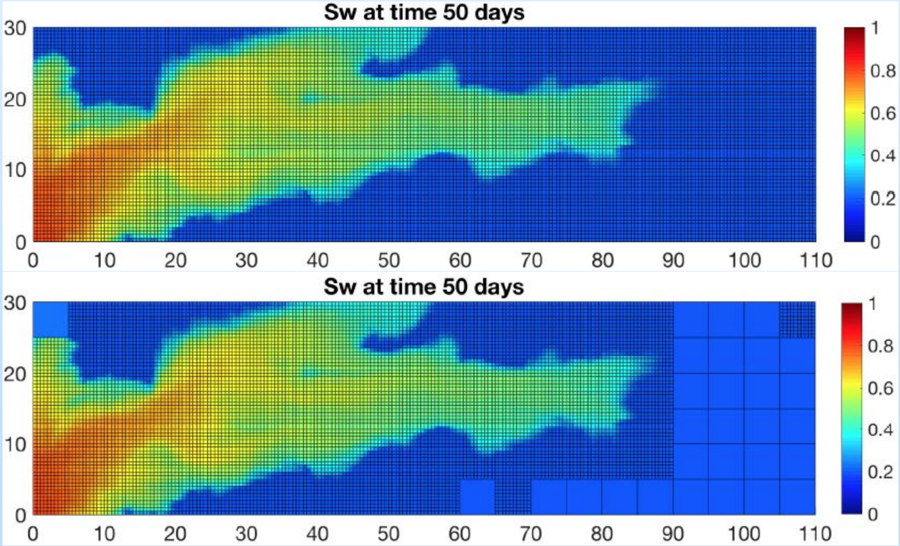




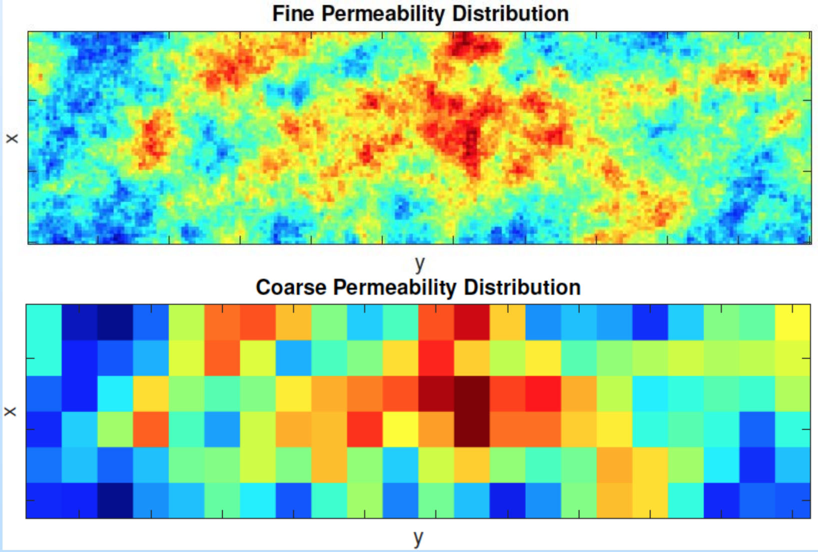
Multiphase Flow: Heterogeneous Porous Media


Oil Rate (STB/day)


Cumulative Oil Production (STB)


Sw at time 50 days

Sw at time 50 days


Fine Permeability Distribution

Coarse Permeability Distribution

Technical Status

Task 4.

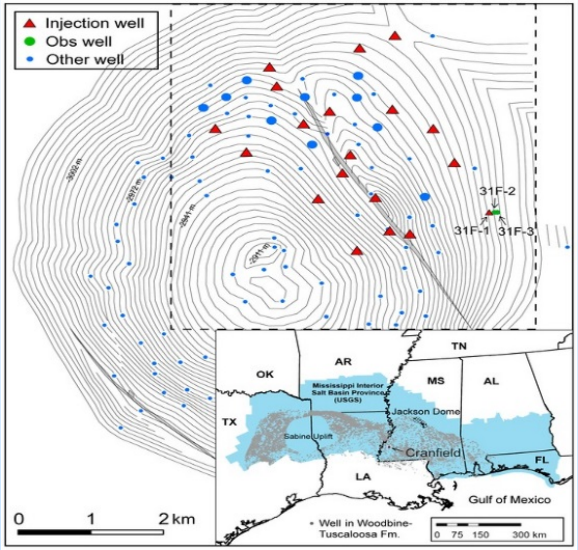
Simulator Development and Modeling CO_2 Storage Field Scale Studies

(M. Wheeler–lead)

Task 4: Simulator Development

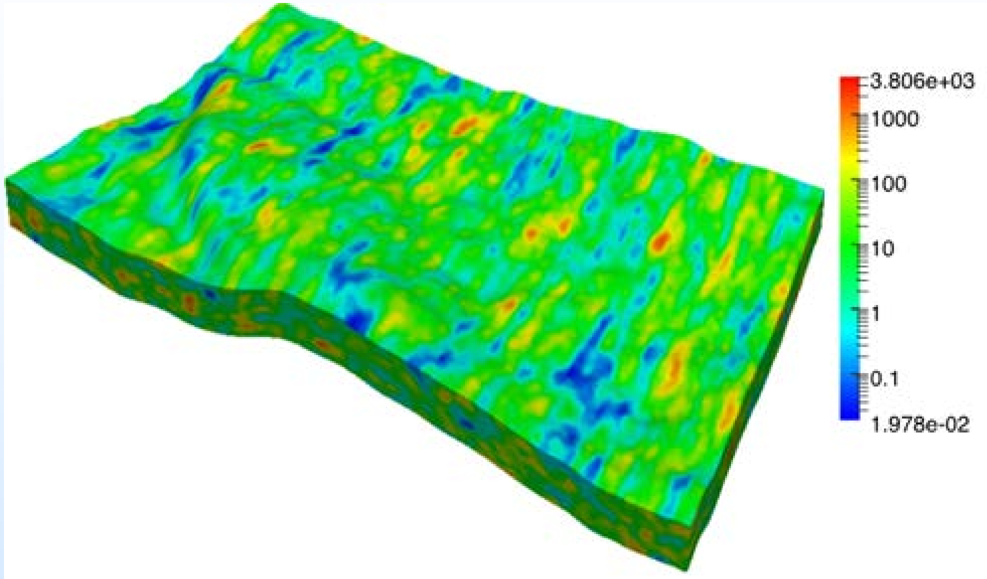
Objectives Complete simulator development with numerical schemes for coupled processes

- Develop computational methods for coupled processes based on multiscale discretization for **flow, geomechanics & hysteresis**
- Development of efficient **solvers & pre-conditioners**
- **Model CO_2 storage field sites** and perform simulations

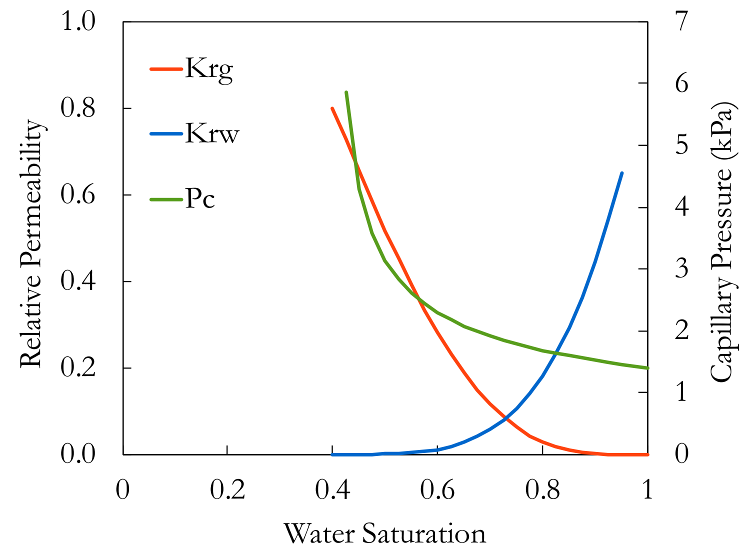


Cranfiled Numerical Model

X-Permeability



Relative Permeability- Capillary Pressure (Delshad et al, 2013)

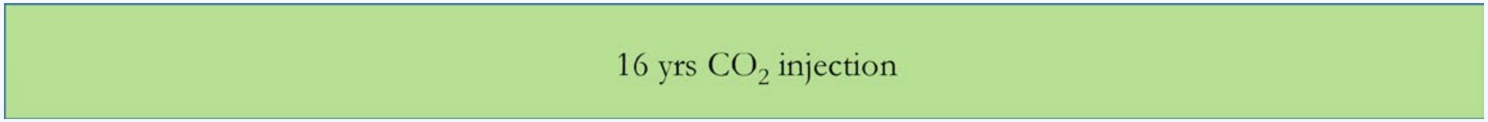


Numerical Model of Cranfield field test	
Model Type	Compositional model
Reservoir size	9400×8800×80 (ft)
Number of grid blocks	188×176×20
Initial water saturation	1.0
Initial pressure	4650 (psi)
Initial temperature	257 (°F)
Salinity	150,000 (ppm)

PVT data		
	CO_2	Brine
Critical temperature (°R)	547.56	1120.23
Critical pressure (psia)	1070.4	3540.9
Compressibility factor	0.255	0.2
Acentric factor	0.224	0.244
Molecular weight (g/g mol)	44.01	18.01
Volume-shift	-0.19	0.065
Binary interaction coefficients	0.09	0.09

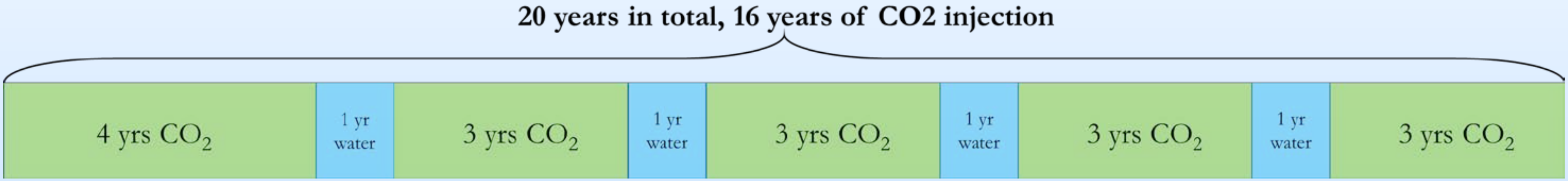
Injection Scenarios

- Continuous CO_2 injection



16 yrs CO_2 injection

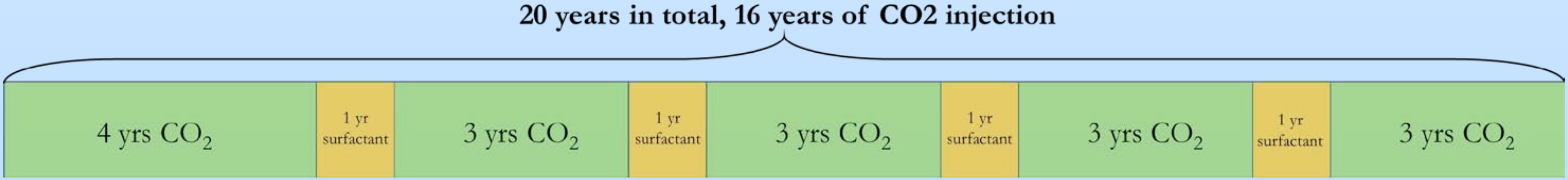
- Water Alternating Gas (WAG)



20 years in total, 16 years of CO2 injection

4 yrs CO_2 | 1 yr water | 3 yrs CO_2 | 1 yr water | 3 yrs CO_2 | 1 yr water | 3 yrs CO_2 | 1 yr water | 3 yrs CO_2

- Surfactant Alternating Gas (SAG-foam)

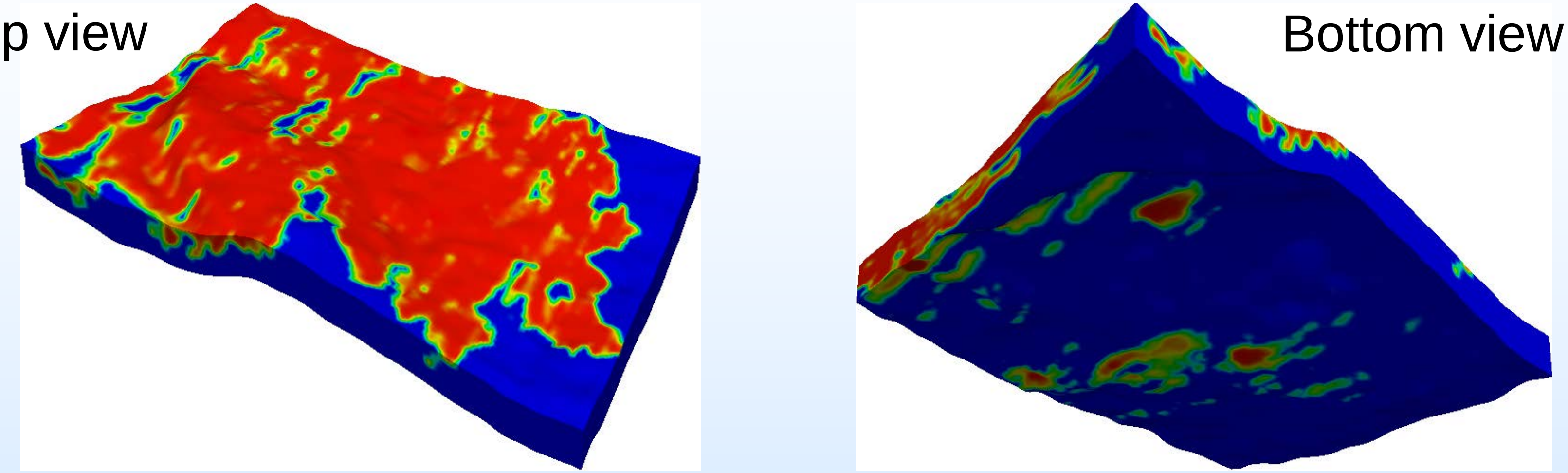


20 years in total, 16 years of CO2 injection

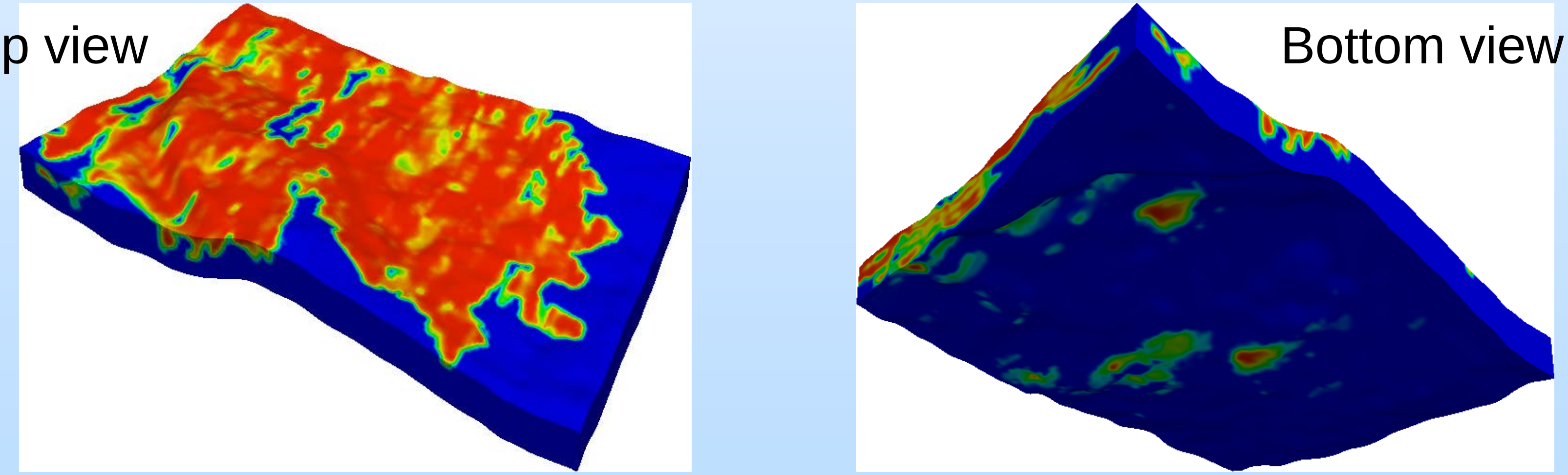
4 yrs CO_2 | 1 yr surfactant | 3 yrs CO_2 | 1 yr surfactant | 3 yrs CO_2 | 1 yr surfactant | 3 yrs CO_2 | 1 yr surfactant | 3 yrs CO_2

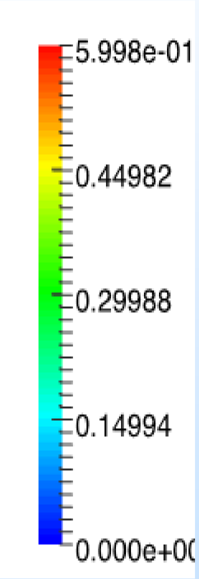
Simulation Results (CO_2 Saturation)

Continuous CO_2 Injection



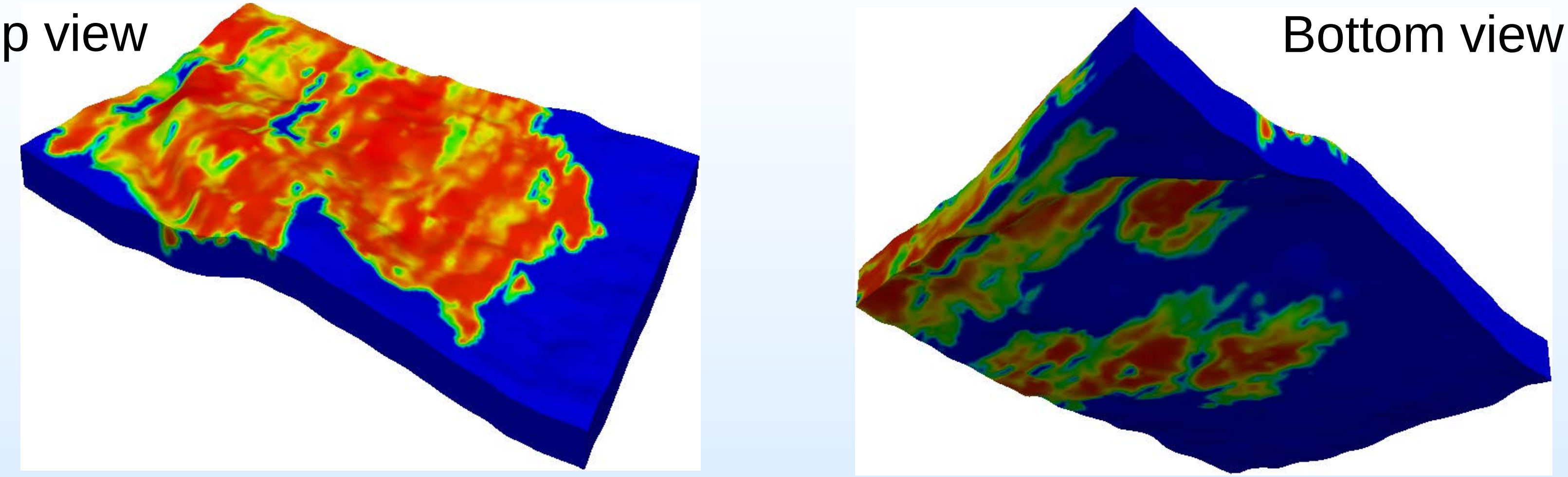
Water Alternating Gas (WAG) – without Hysteresis Modeling



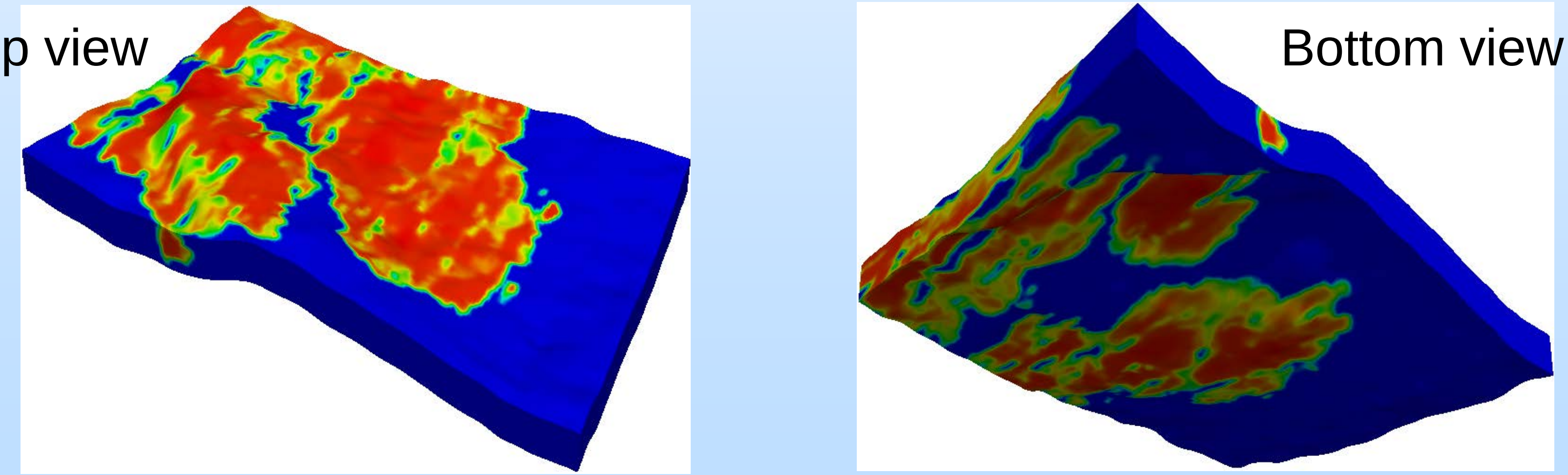


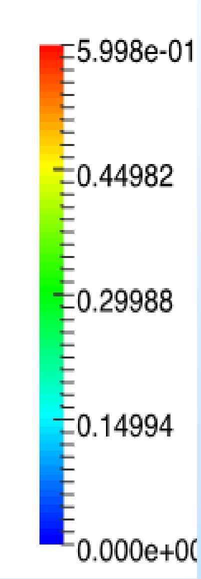
Simulation Results (CO_2 Saturation)-Cont'd

Water Alternating Gas (WAG) – with Hysteresis Modeling

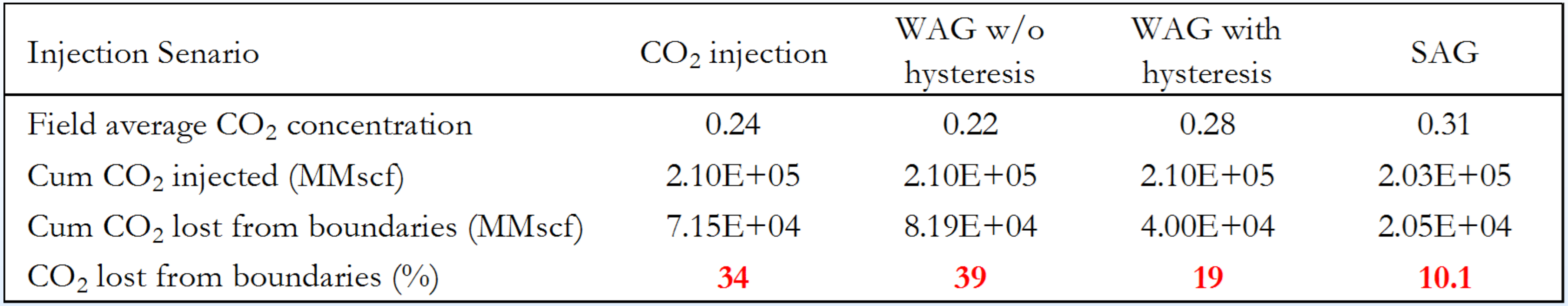


Surfactant Alternating Gas (SAG) – Foam





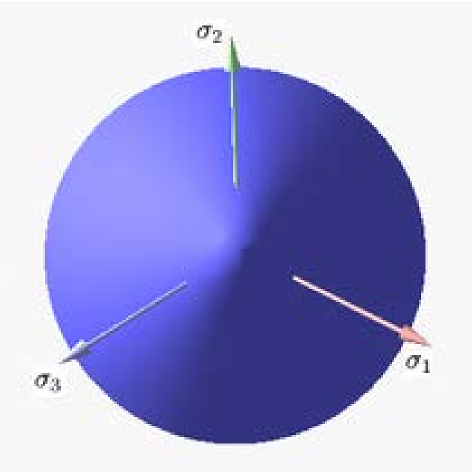
Summary of Results (Field Statistics)



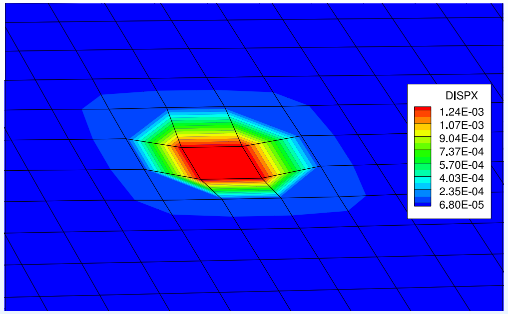
Injection Senario	CO_2 injection	WAG w/o hysteresis	WAG with hysteresis	SAG
Field average CO_2 concentration	0.24	0.22	0.28	0.31
Cum CO_2 injected (MMscf)	2.10E+05	2.10E+05	2.10E+05	2.03E+05
Cum CO_2 lost from boundaries (MMscf)	7.15E+04	8.19E+04	4.00E+04	2.05E+04
CO_2 lost from boundaries (%)	**34**	**39**	**19**	**10.1**

- In continuous CO_2 injection, 34% of the total injected CO_2 does NOT store inside the selected sector model and is produced through the boundaries.
- CO_2 lost from reservoir boundaries decreases from 34% to 19% and 10.1% using WAG and SAG processes, respectively.

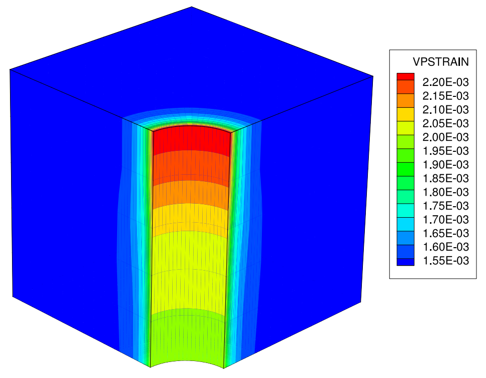
Geomechanical Effects of CO$_2$ Injection with a Poro-plasticity Model

<table>
<tr><td>Fluid Flow</td><td colspan="2">$\frac{\partial(\rho(\phi_0 + \alpha\varepsilon_v + \frac{1}{M}(p - p_0)))}{\partial t} + \nabla \cdot \left(\rho\frac{K}{\mu}(\nabla p - \rho g \nabla h)\right) - q = 0$</td></tr>
<tr><td>Stress Equilibrium</td><td colspan="2">$\nabla \cdot (\sigma'' + \sigma_o - \alpha(p - p_0)I) + f = 0$</td></tr>
<tr><td>Hooke's law</td><td>$\sigma'' = D^e : (\varepsilon - \varepsilon^p)$</td><td>Druker-Prager Yield Surface</td></tr>
<tr><td>Strain-Displacement Relation</td><td>$\varepsilon = \frac{1}{2}(\nabla u + \nabla^T u)$</td><td rowspan="3"> </td></tr>
<tr><td>Plastic Strain Evolution</td><td>$\dot{\varepsilon}^p = \lambda\frac{\partial F(\sigma'')}{\partial \sigma''}$, at $Y(\sigma'') = 0$
$\dot{\varepsilon}^p = 0$, at $Y(\sigma'') < 0$</td></tr>
<tr><td>Yield and Flow Functions</td><td>$Y = q + \theta\sigma_m - \tau_0$
$F = q + \gamma\sigma_m - \tau_0$</td></tr>
</table>

Poroelastoplastic Deformation at Cranfield

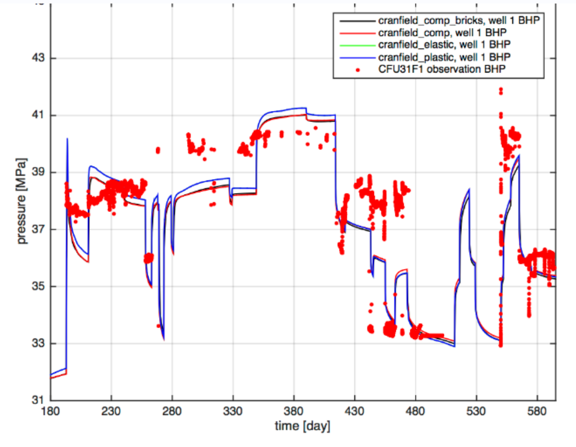


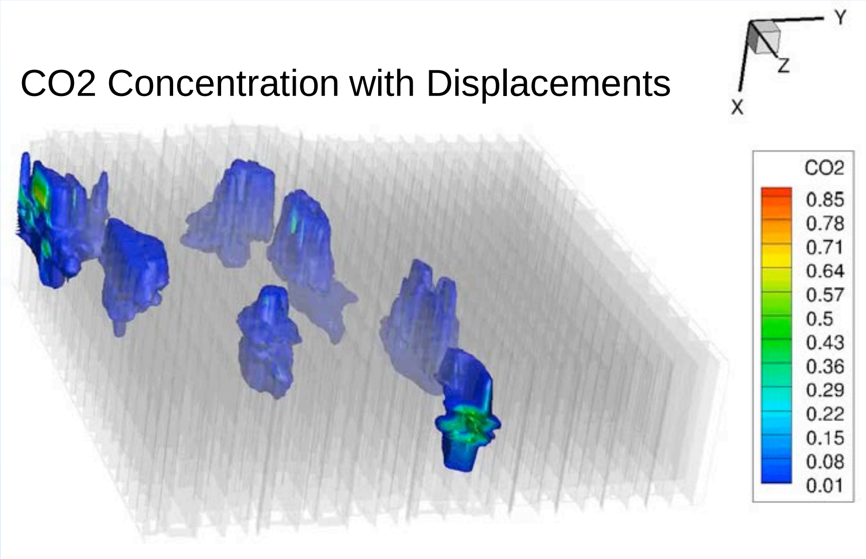
With plasticity, we have observed permanent deformations after loading/unloading.

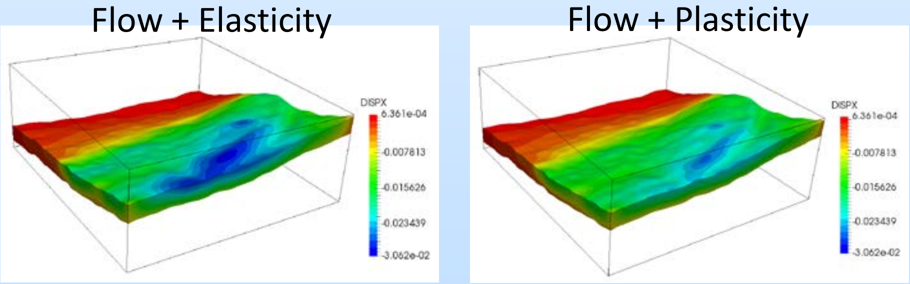


Compared discretely meshed-in well versus Peaceman.

History Matching Results using various physical models.




CO2 Concentration with Displacements


Flow + Elasticity

Flow + Plasticity

Ran Cranfield simulations to compare results with compositional flow, linear elasticity, and plasticity models.

Technical Status

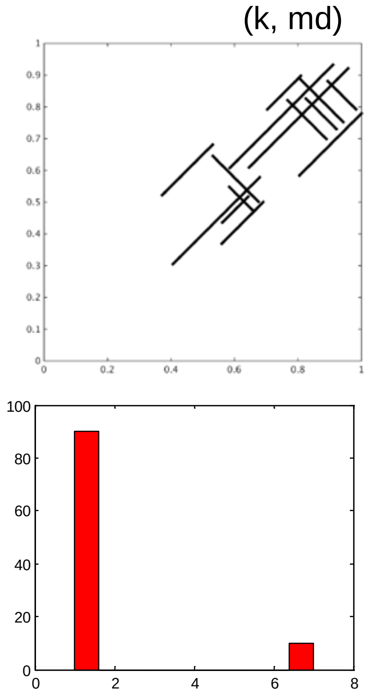
Task 5.

Parameter Estimation &
Uncertainty Quantification
(M.F.W.–lead, S. Srinivasan–consultant)

Task 5: Uncertainty Quantification

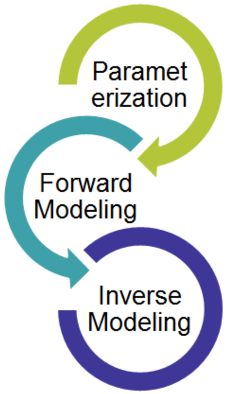
Objectives	Update input parameters for numerical models, e.g. simulated responses match observations

A Priori Model



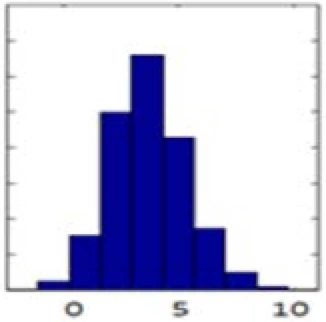
Multi-modal histogram of permeability

History Matching


Parameterization

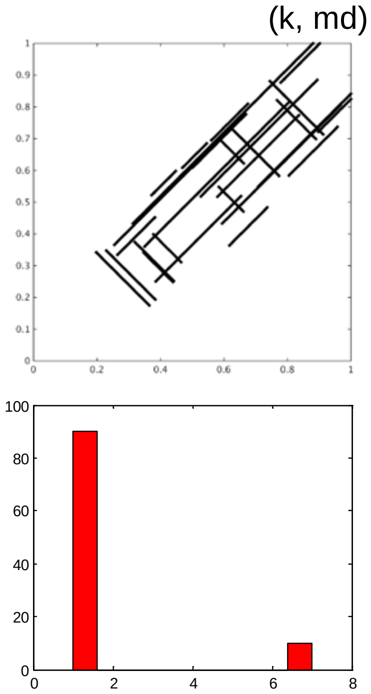
Forward Modeling

Inverse Modeling



Gaussian histogram of Level-set parameters

A Posteriori Model

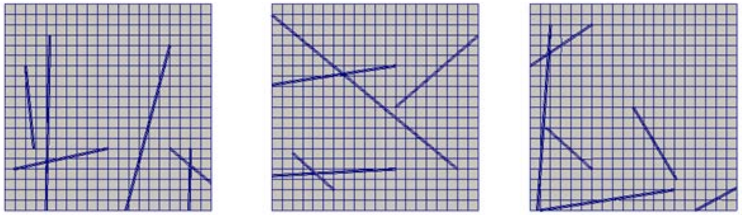


Multi-modal histogram of permeability

History Matching Coupled with Level-Set Parameterization, MFDFrac, and EnKF

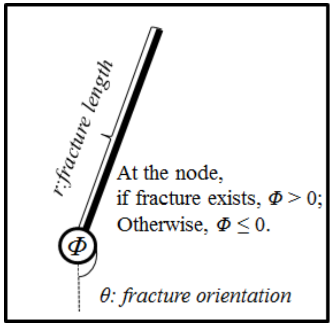
1 Initialization

- Generate initial fractured realizations


Realization #1 … Realization #100

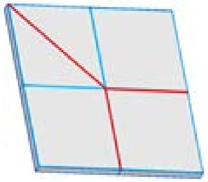
2 Level-Set Parameterization

- Convert non-Gaussian to Gaussian parameters
- Φ: level set at the node
- r: fracture length
- θ: fracture orientation

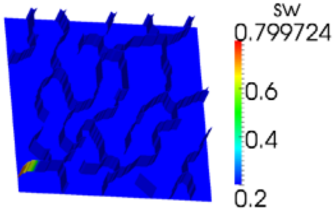


3 Simulation using MFDFrac

- Mimetic Difference Approach


Internal Fracture Boundaries

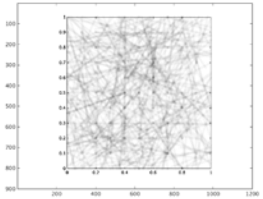

Intersecting Fractures

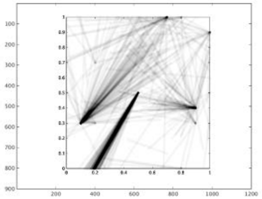


Flow

4 Inverse Modeling using EnKF

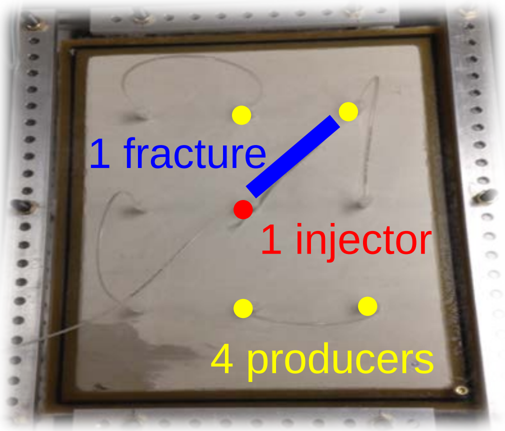
- EnKF for updating Gaussian parameters


Ensemble mean of initial fracture realizations

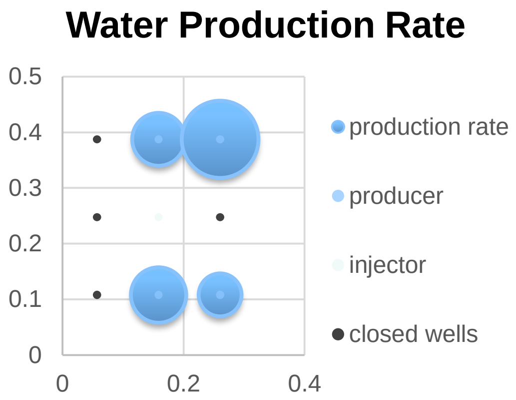

Ensemble mean of final fracture realizations

History Matching Coupled with Level-Set Parameterization, MFDFrac, and EnKF

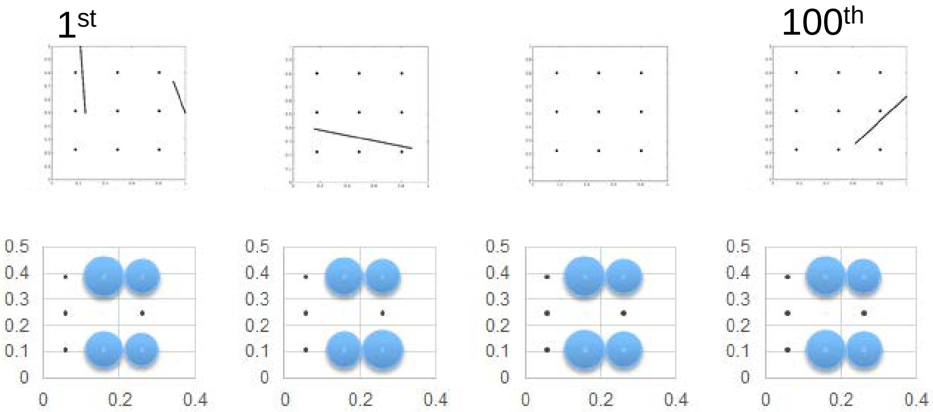
1 Lab-scale Sandpack



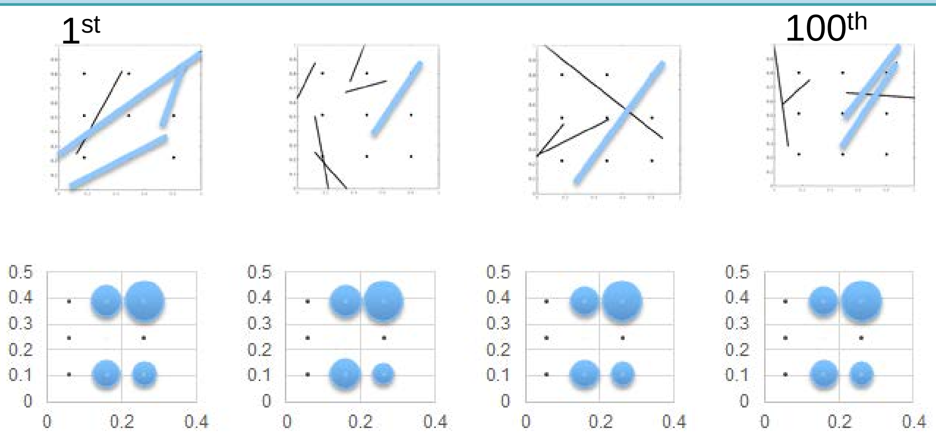
2 Observed Lab Data



3 Prior Models

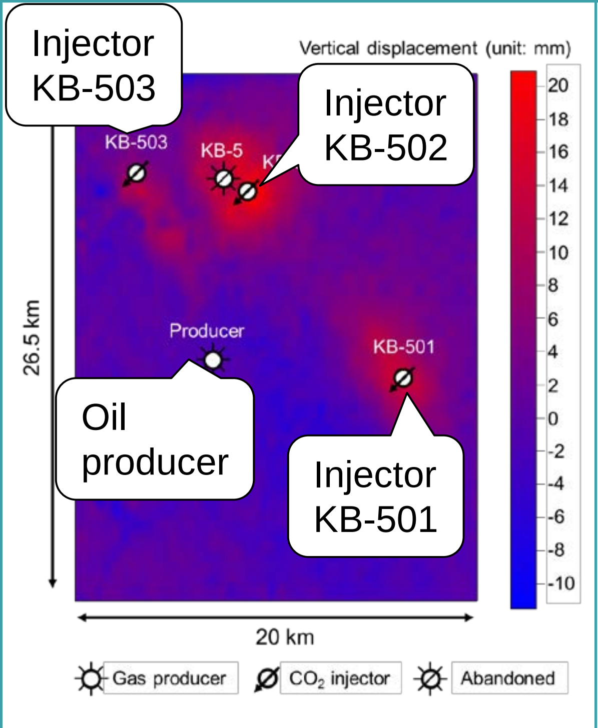
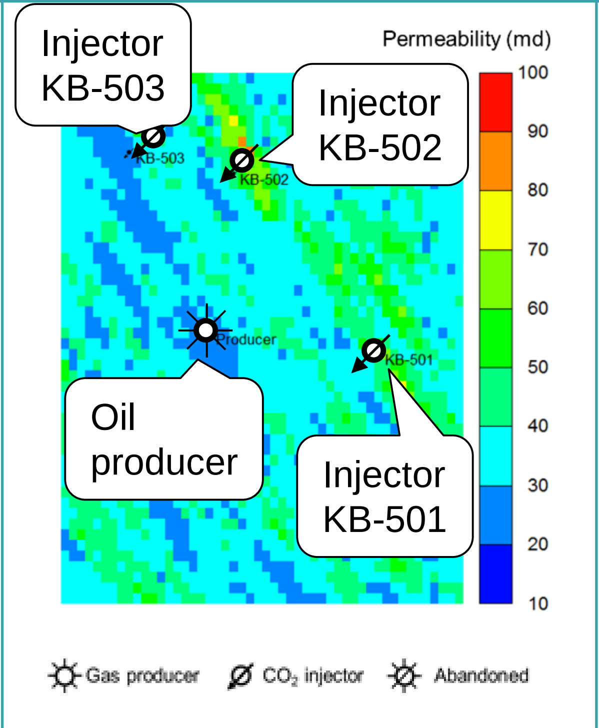
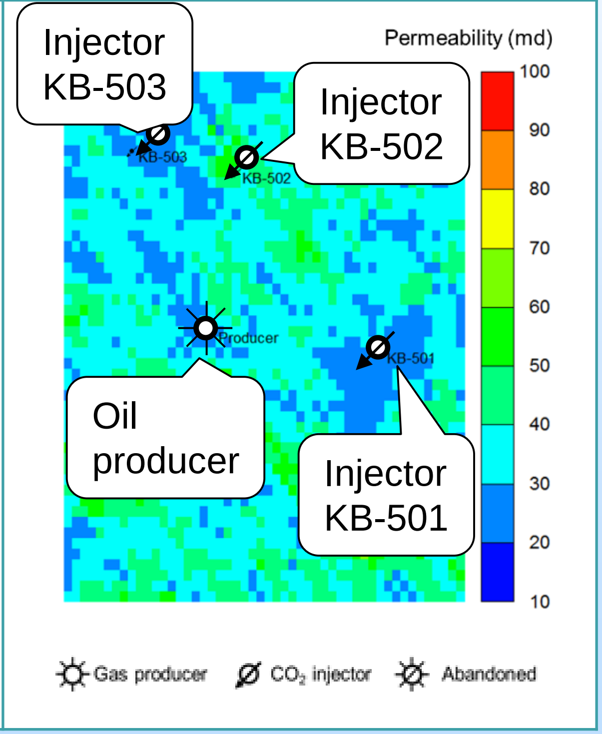


4 Posterior Models (History-matched)



(Jing et al., 2016)

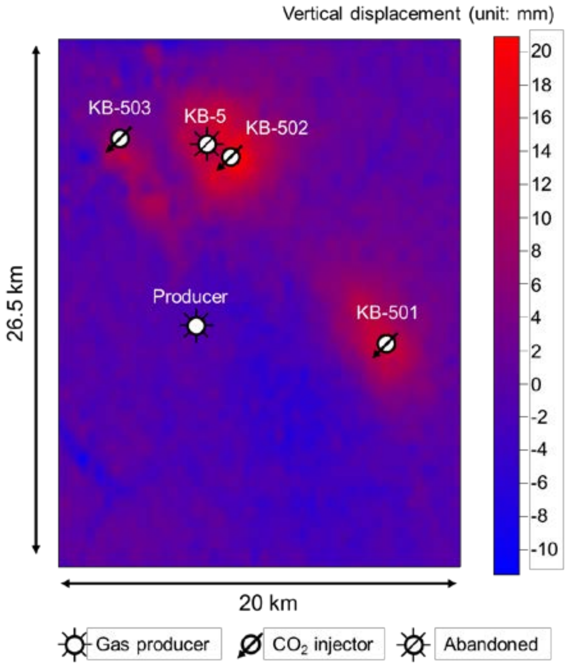
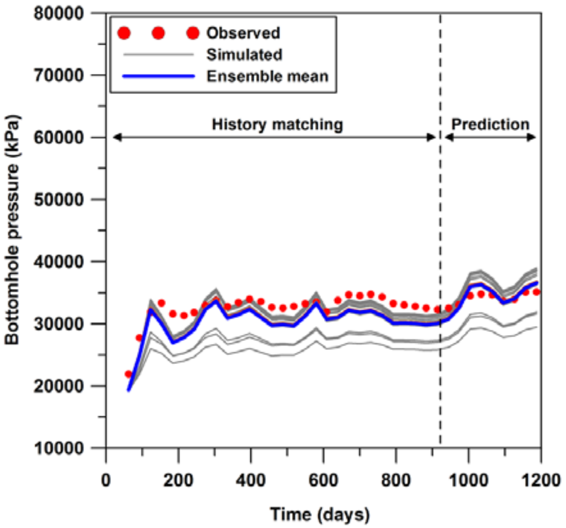
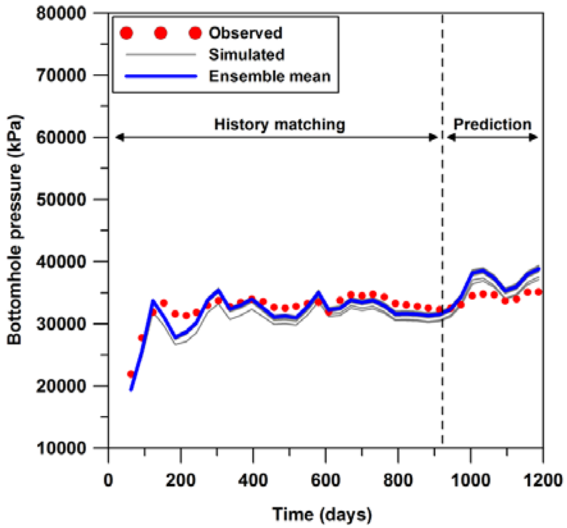
History Matching of a Fractured Reservoir : at the Well KB-503 in the In Salah CCS Field

Vertical Displacement	Global-Objective Optimization	Multi-Objective Optimization
- Observed data = InSAR (vertical displacement resulting from CO_2 injection) - Simulator: CMG-GEM	- After history matching, high permeability regions were obtained near all three CO_2 injection wells.	- After 4-objective history matching, permeability values were lowered near KB-501 and KB-503 wells .
		

(Nwachukwu et al., 2016; Min et al., 2016)

Task 5

History Matching of a Fractured Reservoir
: at the Well KB-503 in the In Salah CCS Field

Vertical Displacement	Global-Objective Optimization	Multi-Objective Optimization
- InSAR: satellite measured vertical displacement resulting from CO_2 injection - Simulator: CMG-GEM	- High permeability near the KB-503 well yielded underestimated BHP compared to observed BHP.	- Low permeability near the KB-503 well improved the matching quality of BHP.
		

(Nwachukwu et al., 2016; Min et al., 2016)

Technical Status

Task 6.

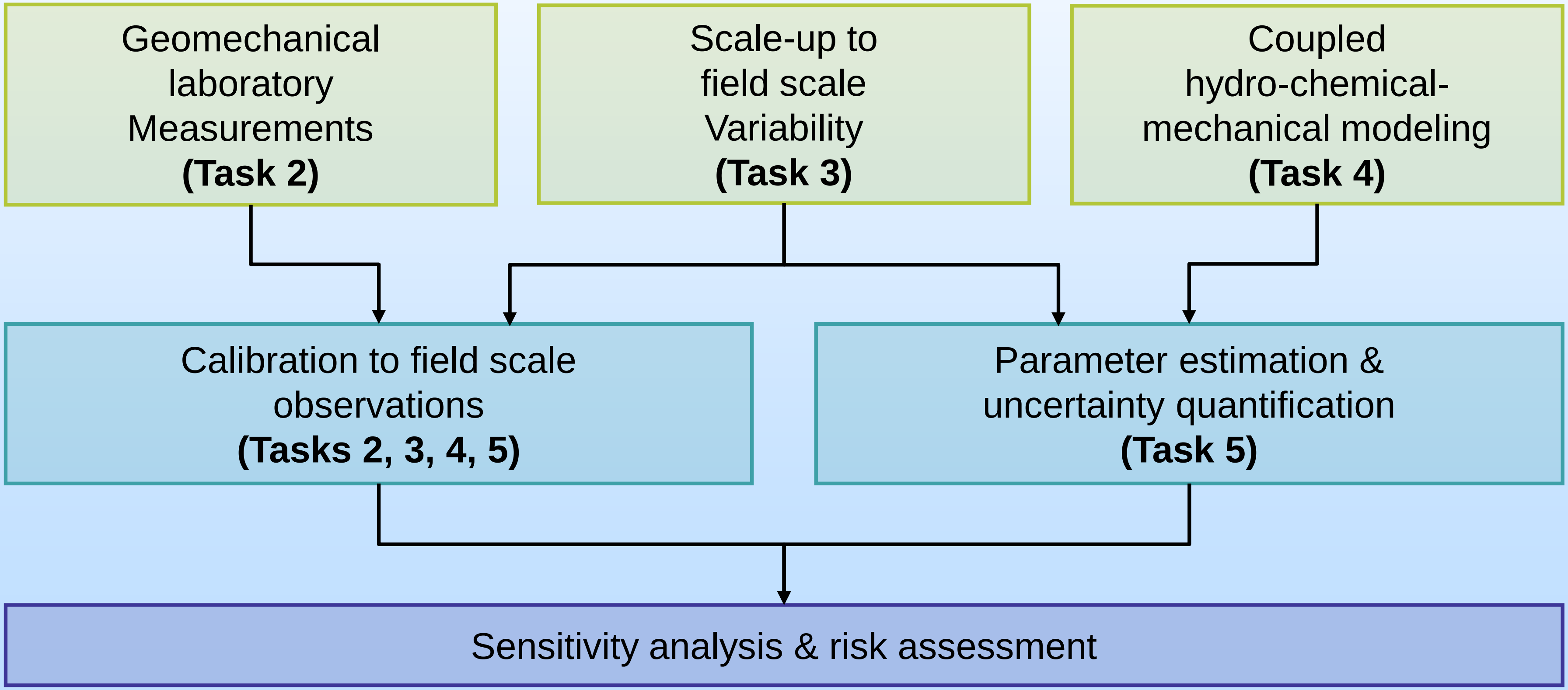
Integrate Results to Generate Geomechanical Screening Tool/Workflow

(M.F.W.–lead)

Task 6: Geomechanical Screening Tool

Objectives

Derive a workflow based on project tasks performed - experimental and numerical investigation of geomechanical processes, effects, & conditions related to CO_2 storage and analysis of two CO_2 storage field case studies



Geomechanical laboratory Measurements **(Task 2)**

Scale-up to field scale Variability **(Task 3)**

Coupled hydro-chemical-mechanical modeling **(Task 4)**

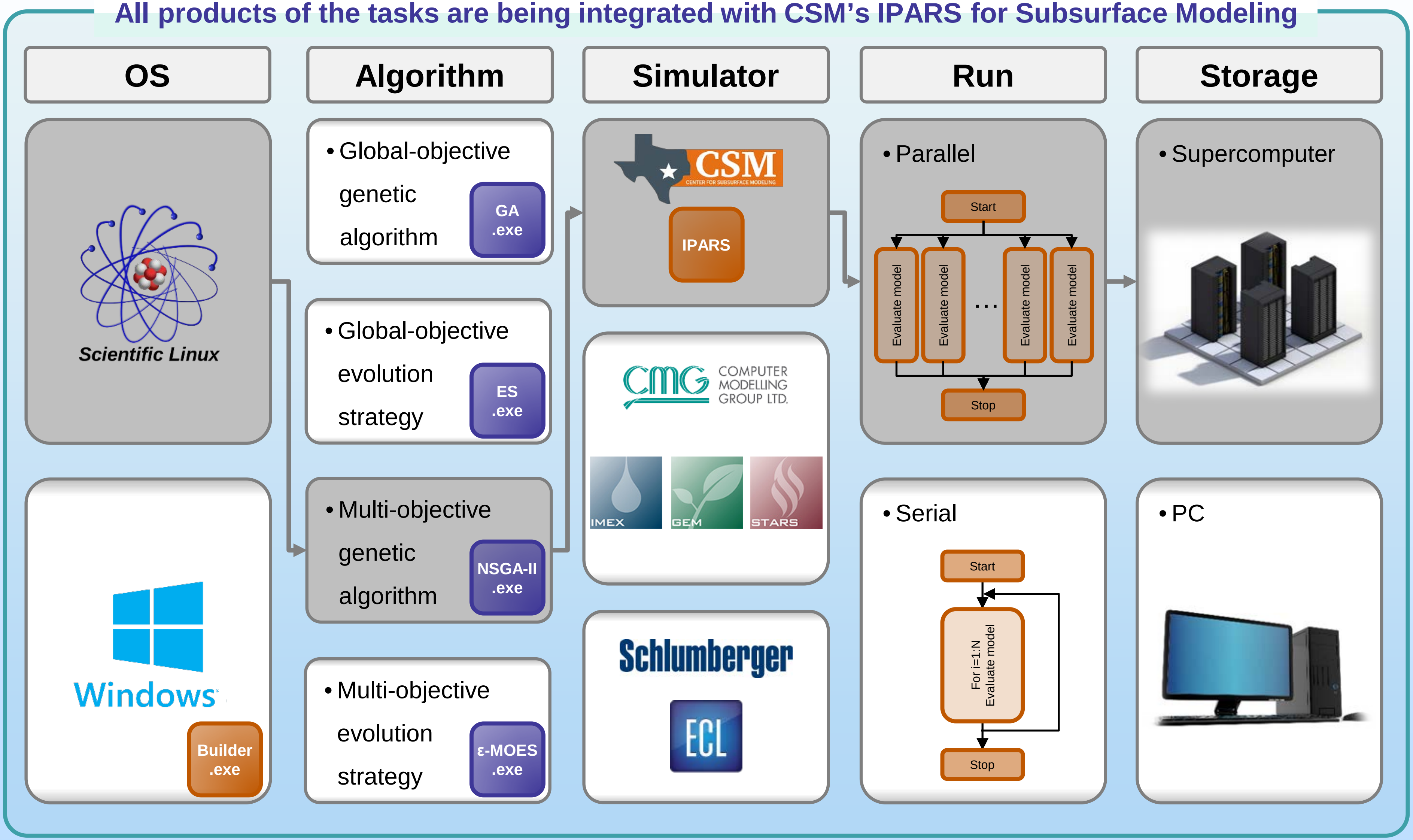
Calibration to field scale observations **(Tasks 2, 3, 4, 5)**

Parameter estimation & uncertainty quantification **(Task 5)**

Sensitivity analysis & risk assessment

Development of a Multiple Model Optimizer
: IRMS (Integrated Reservoir Management S/W)

All products of the tasks are being integrated with CSM's IPARS for Subsurface Modeling



OS

Algorithm

- Global-objective genetic algorithm
- Global-objective evolution strategy
- Multi-objective genetic algorithm
- Multi-objective evolution strategy

Simulator

Run

- Parallel
- Serial

Storage

- Supercomputer
- PC

Road Ahead

- CO_2 storage volume increased by 15% and 24% of total CO_2 injection volume during WAG and SAG processes, respectively.
- It is essential to model relative permeability hysteresis during cyclic processes (WAG, SAG here) to capture the physics of the problem more accurately.
- During SAG process, foam is created at the high permeability streaks and upper layers with higher CO_2 flow rates and diverts the CO_2 flow into low permeability regions and bottom layers leading to more efficient areal and vertical sweep efficiencies.
- Optimization of WAG and SAG processes using advanced optimization toolbox
  - Genetic Algorithm (GA)
  - Evolutionary Strategy (ES)
  - Ensemble Kalman Filter (EnKF)

Accomplishments to Date

- Task 2
  - Hydro-mechanical rock properties for Frio and Cranfield rocks
  - History matching for Frio field combining laboratory experiments and field data
- Task 3
  - Handle multiscale data: well-logs, geological models, and laboratory experiments
  - General upscaling framework using adaptive homogenization
- Task 4
  - Multiphase hysteretic relative permeability model for capillary trapping
  - Poroelastoplastic model for reservoir deformation
  - CO2 foam injection for high storage capacity
- Task 5
  - History matching for Cranfield
  - General multi-objective optimization framework

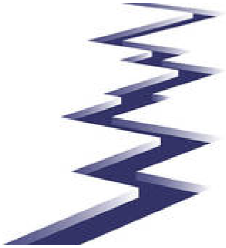
Synergy Opportunities

Assistance in Decision Making

- Assist in selection of suitable sites for safe CO_2 storage using generalized S/Ws based on a posteriori knowledge

Interdisciplinary Collaboration

- Enhance understanding of the effects of CO_2 migration on open and closed faults and fractures



Training & Education

- Support training and education of students who will take part in an interdisciplinary work, e.g. IPARS tutorial

Contribution to Identifying Geological Risk for Secure CO_2 Storage!

Acknowledgements

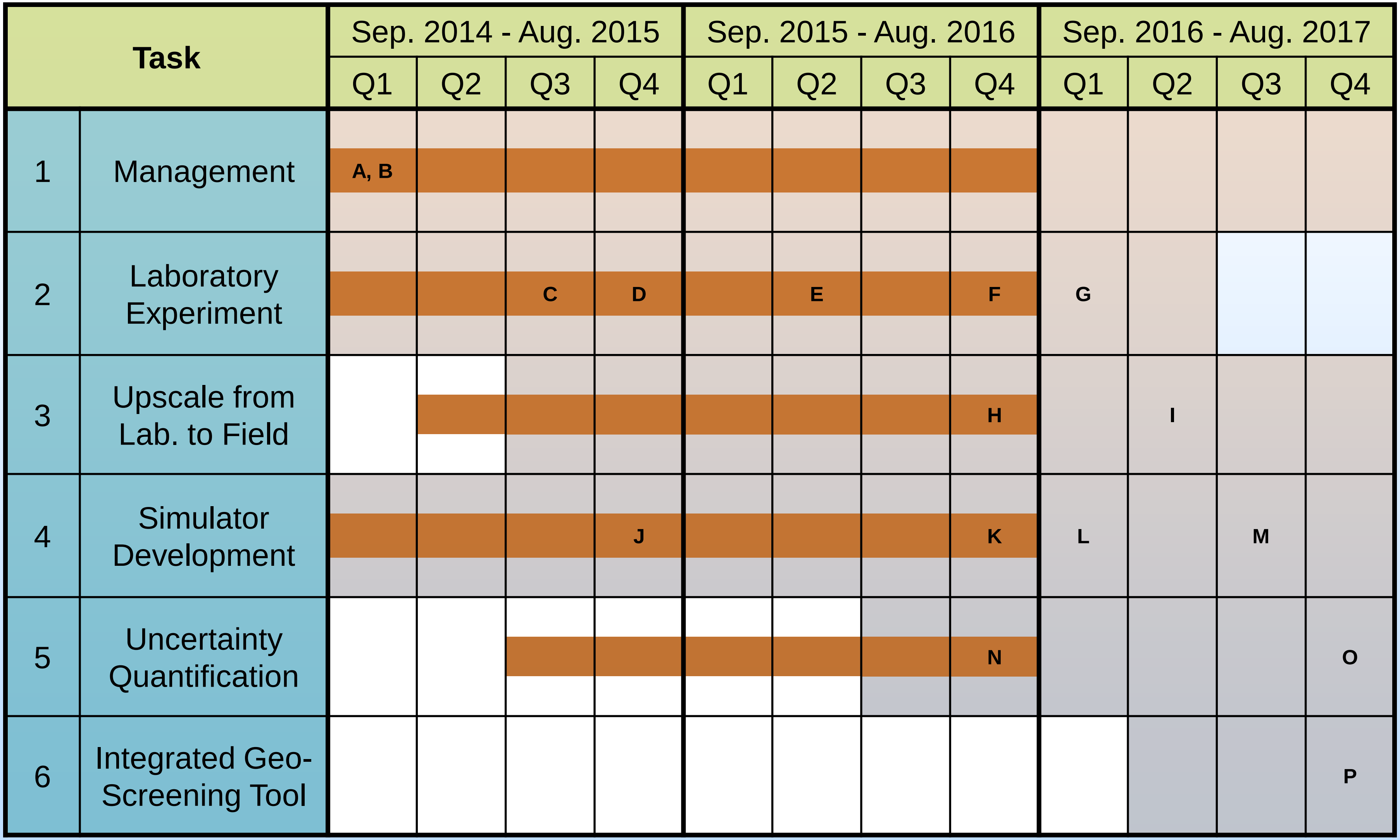
Thank you for your attention

Contact: mfw@ices.utexas.edu

Organization Chart

Project Director **M.F. Wheeler**					
Task 1 Management	**Task 2** Laboratory Program	**Task 3** Bridging between Laboratory and Field Scales	**Task 4** Modeling and Field Studies	**Task 5** Uncertainty Quantification and Parameter Estimation	**Task 6** Integrate Results to Generate Geomechanical Screening Tool / Workflow
Task Leader M.F. Wheeler	**Task Leader** N. Espinoza	**Task Leader** M.F. Wheeler	**Task Leader** M. Delshad	**Task Leader** M.F. Wheeler	**Task Leader** M.F. Wheeler
Key Personnel M. Delshad S. Srinivasan N. Espinoza	**Key Personnel** M.F. Wheeler M. Delshad ½ Postdoc 1 Student (Y 1&2)	**Key Personnel** S. Srinivasan N. Espinoza ½ Postdoc 1 Student	**Key Personnel** M.F. Wheeler N. Espinoza ½ Postdoc 1 Student (Y 3)	**Key Personnel** M. Delshad M.F. Wheeler 1 Student S. Srinivasan (Consultant)	**Key Personnel** M. Delshad S. Srinivasan N. Espinoza Postdoc Student

Gantt Chart



Task		Sep. 2014 - Aug. 2015				Sep. 2015 - Aug. 2016				Sep. 2016 - Aug. 2017			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	Management	🟧 A, B	🟧	🟧	🟧	🟧	🟧	🟧	🟧	▨	▨	▨	▨
2	Laboratory Experiment	🟧	🟧	🟧 C	🟧 D	🟧	🟧 E	🟧	🟧 F	▨ G	▨		
3	Upscale from Lab. to Field		🟧	🟧	🟧	🟧	🟧	🟧	🟧 H	▨	▨ I	▨	▨
4	Simulator Development	🟧	🟧	🟧	🟧 J	🟧	🟧	🟧	🟧 K	▨ L	▨	▨ M	▨
5	Uncertainty Quantification			🟧	🟧	🟧	🟧	🟧	🟧 N	▨	▨	▨	▨ O
6	Integrated Geo-Screening Tool										▨	▨	▨ P

A to P : Milestones ▨ Scheduled 🟧 Accomplished

Bibliography

- Publication:

  - Amanbek, Y., Singh, G., and Wheeler, M.F. Adaptive numerical homogenization for upscaling single phase flow and transport, Advances in Water Resources- Under Review.
  - Jung, H., Singh, G., Espinoza, D. N., and Wheeler, M. F., Quantification of a Maximum Injection Volume of CO2 without Geomechanical, Advances in Water Resources – Under Review.
  - Min, B., Nwachukwu, A., Srinivasan, S., and Wheeler, M.F. 2016, Selection of geologic models based on Pareto-optimality using surface deformation and CO_2 injection data for the In Salah gas sequestration project. SPE Journal (submitted). Nwachukwu, A., Min, B., and Srinivasan, S. 2016, Model selection for CO_2 sequestration using surface deformation and injection data. International Journal of Greenhouse Gas Control (submitted).
  - Liu, R., Ganis, B., White, D., and Wheeler, M.F. Implementation of a Drucker-Prager plasticity model in a reservoir simulator using a fixed-stress iterative coupling scheme. (In preparation).
  - White, D., Ganis, B., Liu, R., and Wheeler, M.F. Simulation of the Cranfield CO_2 injection site with a Drucker-Prager plasticity model. (In preparation).

Bibliography

- Publication:
  - White, D., Ganis, B., Liu, R., and Wheeler, M.F. A near-wellbore study with a Drucker-Prager plasticity model coupled with a parallel compositional Reservoir simulator. (In preparation).
  - Dewers, T. et al. 2016, Control of process for subsurface science and engineering: examples from geologic carbon storage. (Submitted).

Bibliography

- Conference:
  - Singh, G., Amanbek, Y., and Wheeler, M.F. 2017. Adaptive homogenization for upscaling heterogeneous porous media, SPE Annual Technical Conference, San Antonio, Texas, 9-11 October.
  - Jung, H. and Espinoza, D. N., 2017, Chemo-Poromechanical Properties of Tuscaloosa Sandstone: Implications on CO_2 Geological Storage, American Rock Mechanics Association Conference, San Francisco, 25-28 June, ARMA 17-303.
  - Jung, H., Singh, G., Espinoza, N., and Wheeler, M.F. 2017. An integrated case study of the Frio CO_2 sequestration pilot test for safe and effective carbon storage including compositional flow and geomechanics. SPE Reservoir Simulation Conference, Montgomery, Texas, 20–22 Feb. (accepted).
  - Min, B., Srinivasan, S., Wheeler, M.F, and Nwachukwu, A. 2016. Selection of geologic models based on Pareto-optimality using surface deformation and CO_2 injection data at the In Salah gas project, Central Algeria. SPE Annual Technical Conference and Exhibition, Dubai, Arab Emirates, 26–28 Sep. (accepted).
  - Min, B., Wheeler, M.F, Sun. A. 2016. Multi-objective optimization of pulse testing results using parallel compositional simulations for reservoir characterization of a CO_2-EOR field in Mississippi. AGU Fall Meeting, San Francisco, California, 12–16 Dec. (submitted).

Bibliography

- Conference:
  - Min, B., Wheeler, M.F, and Sun. A. 2017. Parallel multiobjective optimization for the coupled compositional/geomechanical modeling of pulse testing. SPE Reservoir Simulation Conference, Montgomery, Texas, 20–22 Feb. (accepted).
  - Ping, J., Al-Hinai, O., Srinivasan, S. and Wheeler, M.F., 2016, History matching for fractured reservoirs using mimetic finite differences and ensemble Kalman filter. AGU Fall Meeting, San Francisco, California, 12–16 Dec. (submitted).
  - Wheeler, M.F., Amanbek, Y., and Singh, G. 2016. Upscaling reservoir properties using single well tracer test, Computational Method in Water Resources, Toronto, Canada, 21–24 Jun.
  - Beygi, M.R., Varavei, A., Lotfollahi, M., and Delshad, M. 2015. Low-tension gas modeling in surfactant alternating gas and surfactant/gas coinjection processes. SPE Asia Pacific Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia, 11-13 Aug.