Area of Interest 1: Geomechanical Research

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

DE-FE0023314

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The University of Texas at Austin

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Transforming Technology through Integration and Collaboration
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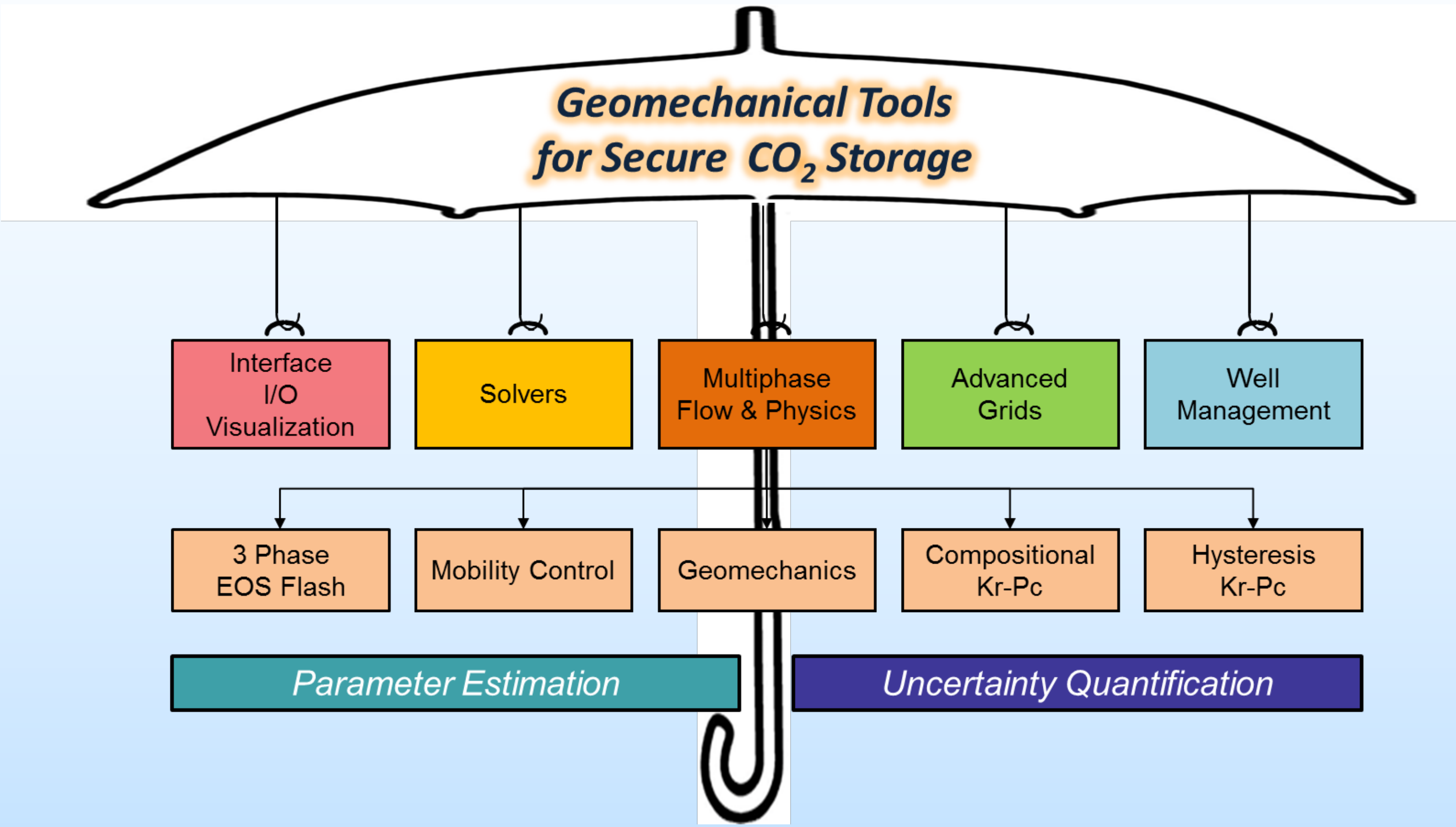
Outline

Benefit to the Program

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



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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. Wheeler–lead)**

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

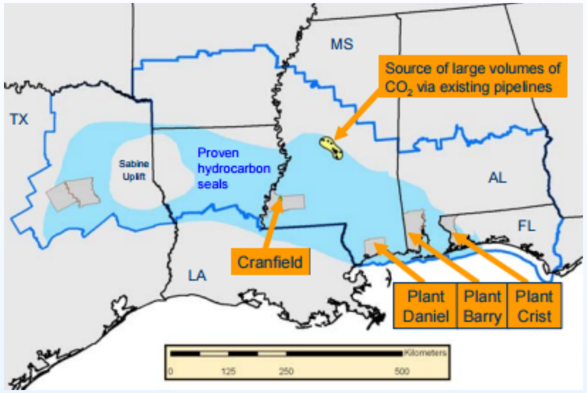
Task 5 Perform **parameter estimation** & **uncertainty quantification** **(M.F.W.–lead, S. Srinivasan–consultant)**

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

Model Field Sites

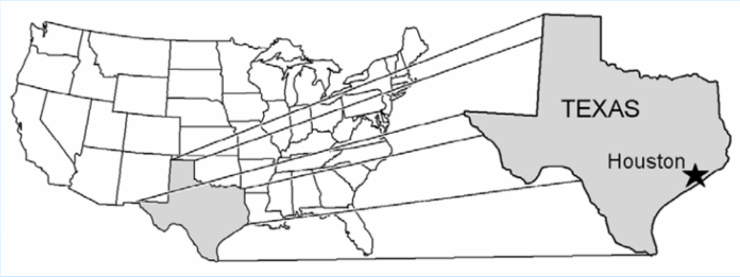
Objectives: Complete modeling, perform reservoir simulations, and analyze geological uncertainty for two CO_2 storage field studies (Frio, TX & Cranfield, MS)

- Measure mechanical property from Task 2
- Collect other existing data (seismic, well logs, etc.)
- Measure impact of geochemical alteration on mechanical properties
- Study rock dissolution and its effect on weakening the rocks and creating leakage pathways
- Enhanced simulation for studying and quantifying parameters, e.g. reservoir over pressure, chemical and thermal loading



Site 1: Cranfield, Mississippi

(Source: DOE Cranfield Fact Sheet)



Site 2: Frio pilot study, Texas

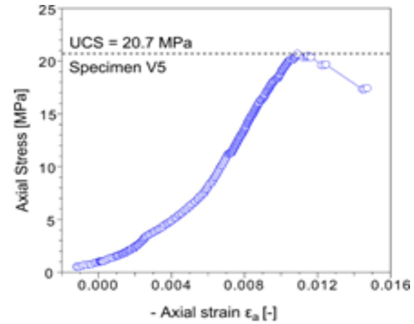
Task 2: Laboratory Experiments

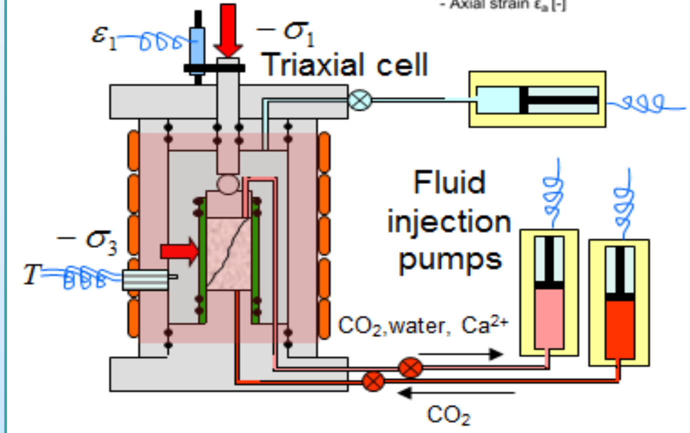
Objectives

Acquisition of representative rock samples from two CO_2 storage sites (N. Espinoza–lead)

- Consider lithology, geologic age, and natural fractures among other characteristics
- Design, fabrication and calibration of an experimental device
- Measure petrophysical and geomechanical properties of reservoir rocks: chemical, thermal, hydraulic, and mechanical loadings

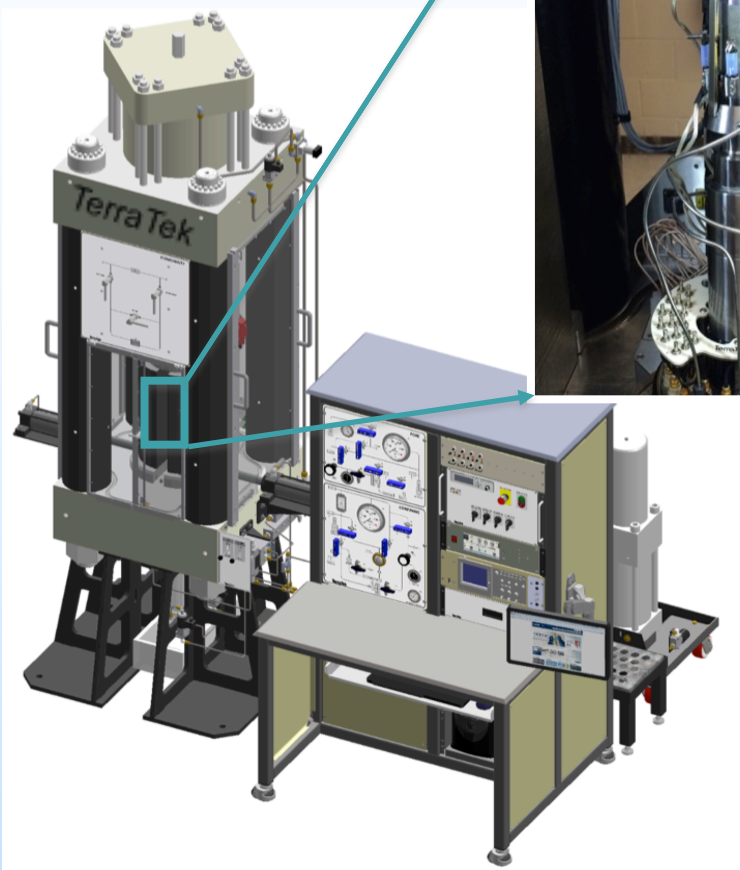
Cylindrical Triaxial Frame

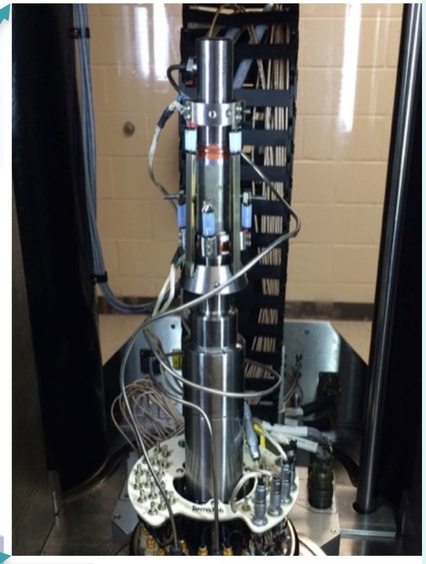




Task 2: Laboratory Experiments

- Large Axisymmetric Triaxial Frame





ø 4 in

ø 2, 1.5, 1 in

- 140 MPa (20 ksi) confining/pore pressure
- Ultrasonic monitoring
- Local strain measurement
- Strain/pressure control
- Temperature up to 150˚C (300˚F)
- Connected to CO_2 ISCO pumps

Task 2: Laboratory Experiments

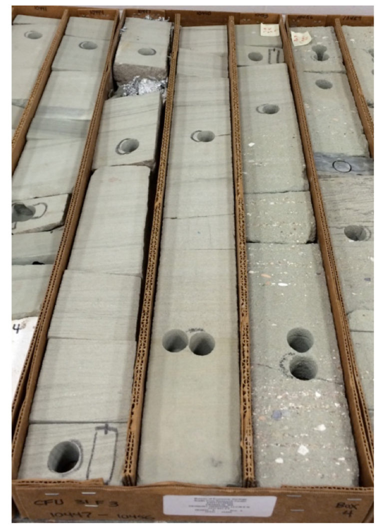
- Rock Samples

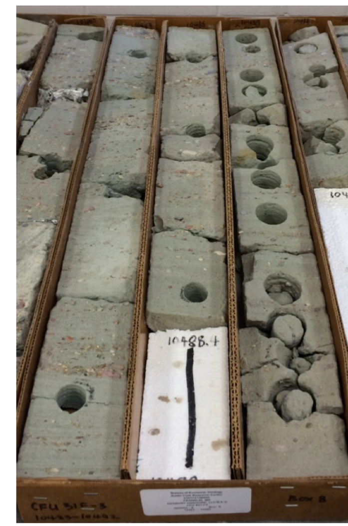
CO_2 Storage Sites

C-sand – Frio, Texas

Fluvial Oligocene, poorly consolidated
Courtesy S. Hovorka (DE-AC26-98FT40417)

Tuscaloosa SS – Cranfield, Mississippi





Cretaceous, chlorite/quartz cemented
BEG-UT Austin Core Research Center

Outcrop : Castlegate Sandstone

- Cretaceous Mesaverde group, cemented by calcite. This sandstone is attractive for testing because it can serve as an end-member due to weak cementing bonds presumably susceptible to CO_2 alteration. Available in several sizes from commercial vendors.

Task 2: Laboratory Experiments

- Planned Tests

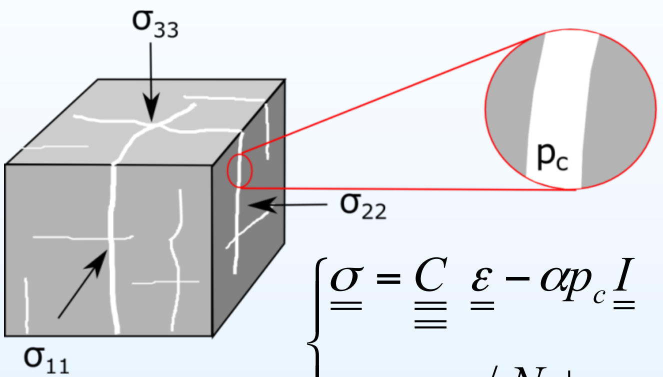
Basic Rock Properties	
Dry conditions	Saturated with water
• Mineralogy (XRF) • Drained mechanical moduli • Elastic nonlinearity • Mechanical anisotropy • Shear and tensile strength • Fracture toughness • Creep	• Porosity • Absolute permeability • Biot's coefficient • Thermal expansion coefficient • Thermal conductivity • Specific heat

Advanced Rock Properties	
Fluid flow properties with a CO_2 phase	Mechanical
• Capillary pressure	• Transition brittle to ductile
• Relative permeability	• Strain localization
Chemo-mechanical coupling	• Scale effects
• Porosity change with chemical dissolution	Thermo-mechanical coupling
• Permeability change with chemical dissolution	• Thermal induced stress
• Chemically enhanced creep	Poro-mechanical coupling
• Stress relaxation with chemical dissolution	• Stress sensitivity of permeability

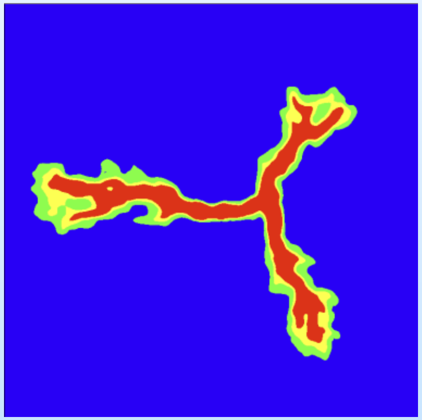
Task 3: Bridge from Laboratory to Field

Objectives | Upscale measured rock properties (fluid flow & geomechanics) to scale relevant to field processes (M.F. Wheeler–lead)

- Development of **homogenization** schemes combining numerical and analytical approaches, e.g. multiscale mortar method
- 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



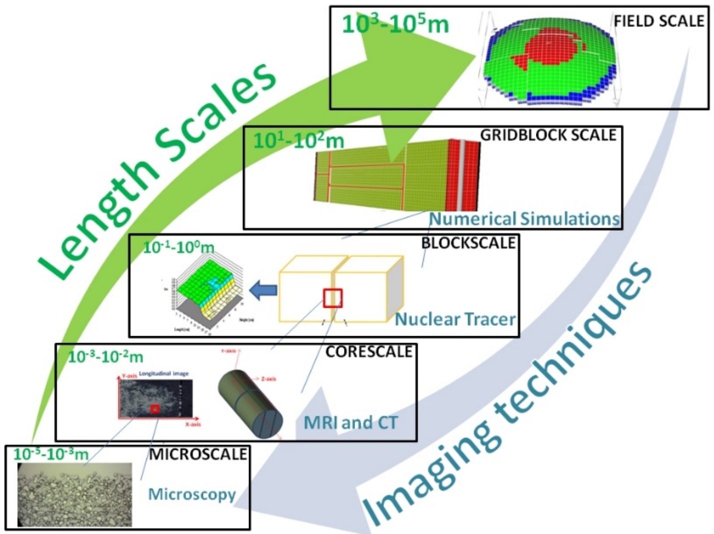
$$\begin{cases} \underline{\underline{\sigma}} = \underline{\underline{\underline{\underline{C}}}}\ \underline{\underline{\varepsilon}} - \alpha p_c \underline{\underline{I}} \\ \varphi = p_c / N + \alpha \varepsilon_V \end{cases}$$

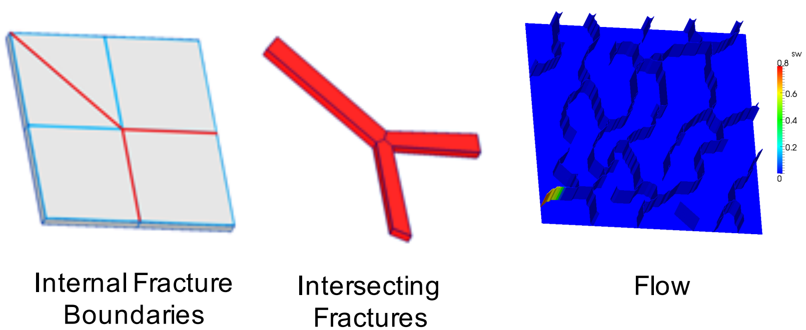


Task 3: Bridge from Laboratory to Field

- Task 3.0: Upscale to Bridge Laboratory to Field Scales

Homogenization	Simulator Development
• Homogenization of coupled flow, adsorption, and mechanics from pore to core and field. • Manuscript on theory being written and implementation underway	• **MFDFrac**: developed using mimetic finite differences • Sample fracture realizations from parameterized space • Generate unstructured polyhedral meshes based on fracture geometries



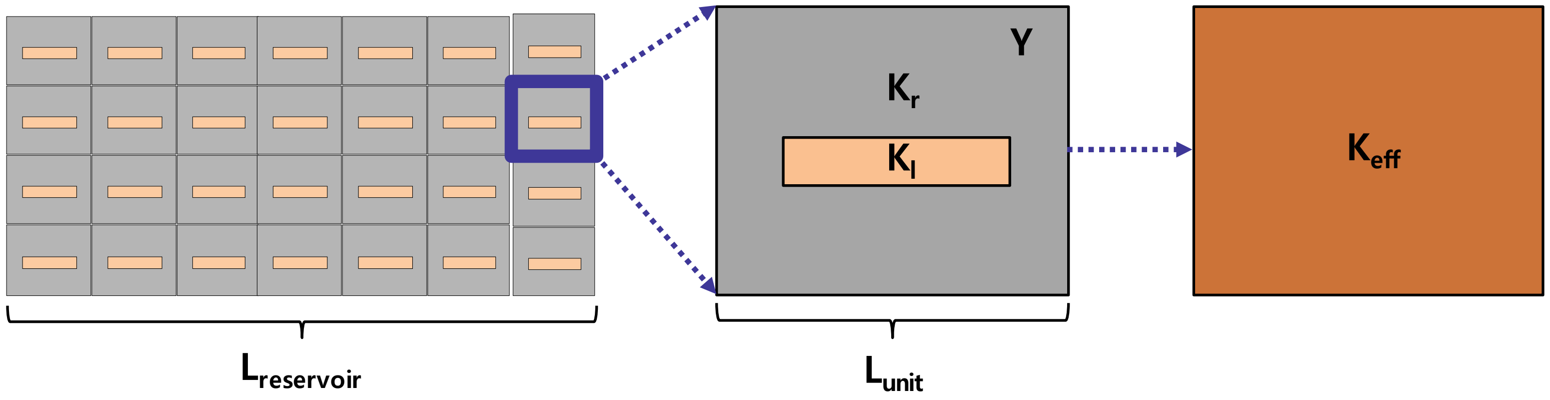


Task 3: Bridge from Laboratory to Field

- Homogenization for Upscaling: Methodology

Choice of Unit Cell Model

- Darcy's law for unit cell (mesoscale) and field (macroscale) problems
- Characteristic length scales: $L_{unit}/L_{reservoir} = \varepsilon \ll 1$
- Solve an auxiliary unit cell problem to obtain effective permeability
- Use different unit cell models in different domains (sands A, B, C, etc.) for characterizing reservoir heterogeneity



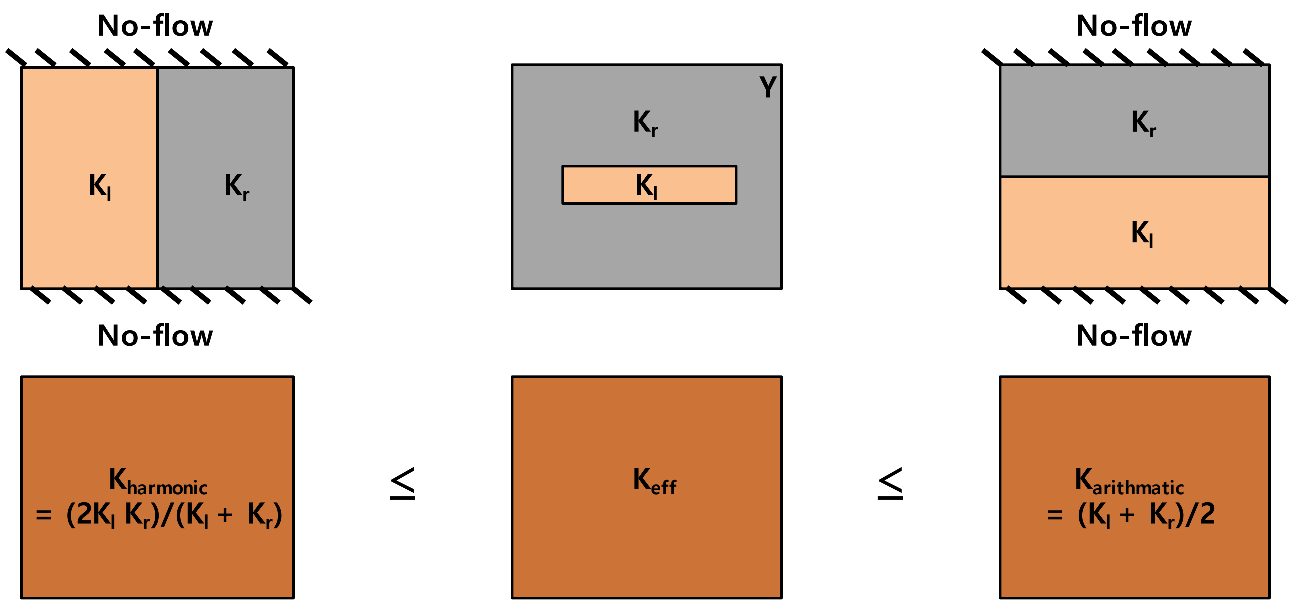
Task 3: Bridge from Laboratory to Field

- Homogenization for Upscaling: Methodology

Choice of Unit Cell Model

- Auxiliary Unit Cell Problem
$$-\nabla \cdot \left[K(y)\left(\nabla w_j + \vec{\mathbf{e}}_j\right)\right] = 0 \quad \text{in} \quad Y$$
$$w_j = 0 \quad \text{on} \quad \partial Y$$

- Effective Permeability
$$K_{eff} = \frac{1}{|Y|}\int_Y K(y)\left[\nabla w_i + \vec{\mathbf{e}}_i\right]\cdot\left[\nabla w_j + \vec{\mathbf{e}}_j\right]dy$$

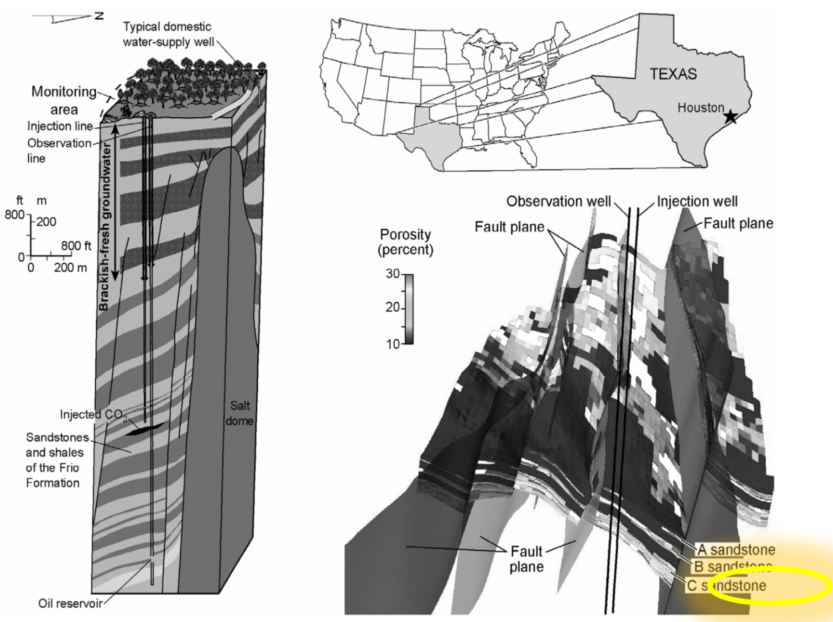


Task 3: Bridge from Laboratory to Field

- Homogenization for Upscaling: Application to Frio Field, TX

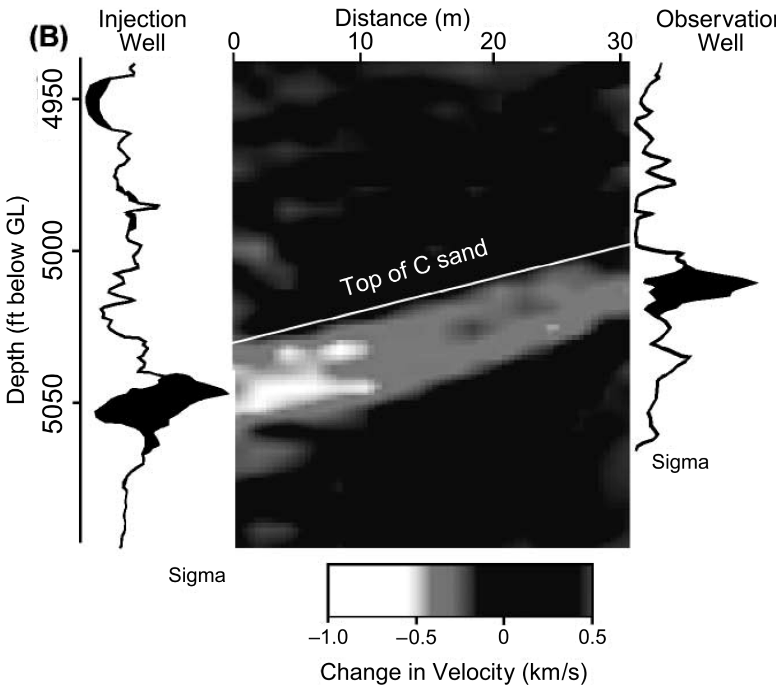
Frio Field

- 1 injector and 1 producer 30 m apart
- Well logs for near well bore (k & Φ)



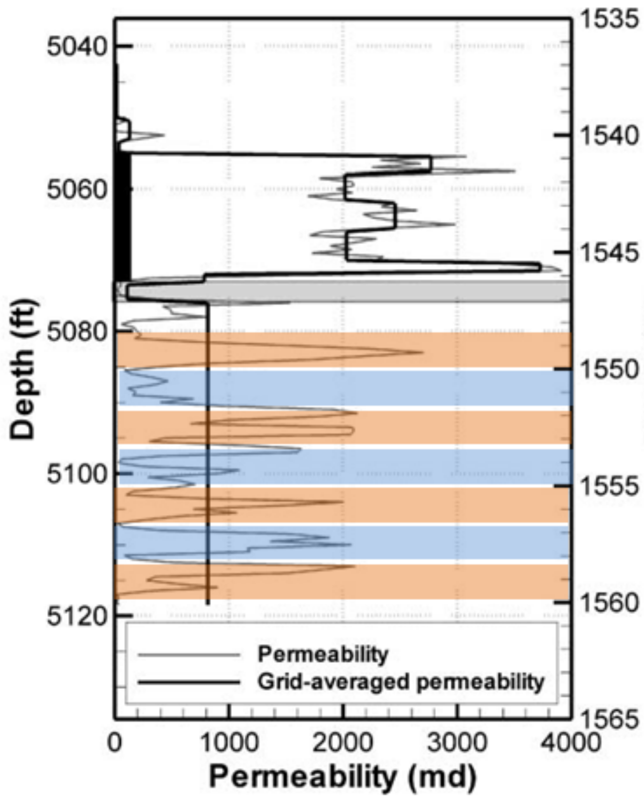
C Sandstone Formation

- Top of C sand: nearly impermeable shale



Task 3: Bridge from Laboratory to Field

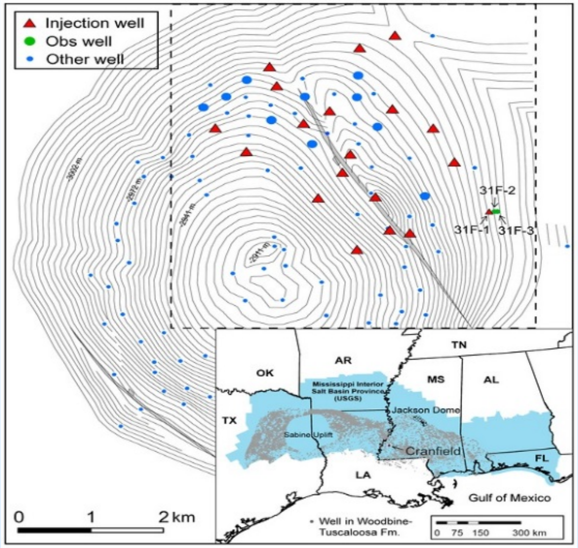
- Homogenization for Upscaling: Application to Frio Field, TX

Reservoir Characteristics	Permeability in C Sandstone
• Sandstone reservoirs ✓ Periodic deposition due to flooding of river beds ✓ Shale layer marks the end of one deposition cycle • Idealize as a periodic porous medium • Identify meso-scale periodicity from well log data • Characterize period ✓ High permeability & Low permeability • Solve local period problem to estimate up-scaled field scale permeability	

Task 4: Simulator Development

Objectives	Complete simulator development with numerical schemes for coupled processes (M. Delshad–lead)

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

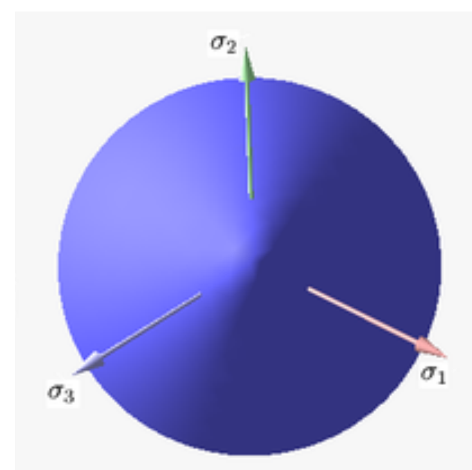


Task 4: Simulator Development

- Geomechanical Effects of CO_2 Injection with a Poro-plasticity Model

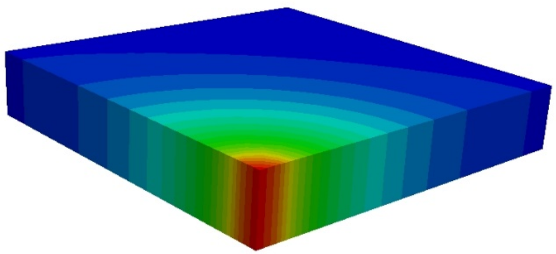
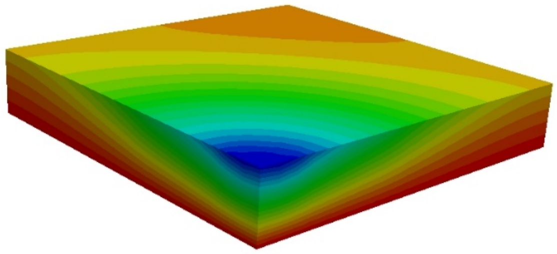
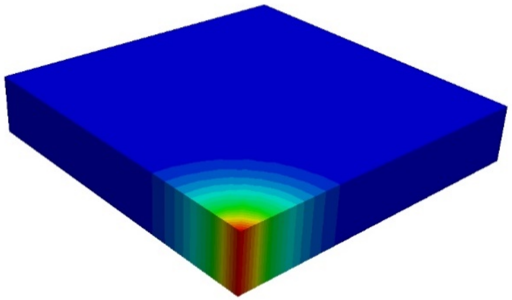
Fluid Flow	$\frac{\partial(\rho(\phi_0 + \alpha\varepsilon_v + \frac{1}{M}(p - p_0)))}{\partial t} + \nabla \cdot \left(\rho\frac{K}{\mu}(\nabla p - \rho g \nabla h)\right) - q = 0$
Stress Equilibrium	$\nabla \cdot (\sigma'' + \sigma_o - \alpha(p - p_0)I) + f = 0$
Hooke's law	$\sigma'' = D^e : (\varepsilon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

Druker-Prager Yield Surface



Task 4: Simulator Development

- Preliminary Poro-plasticity Results with Application to Cranfield, MS

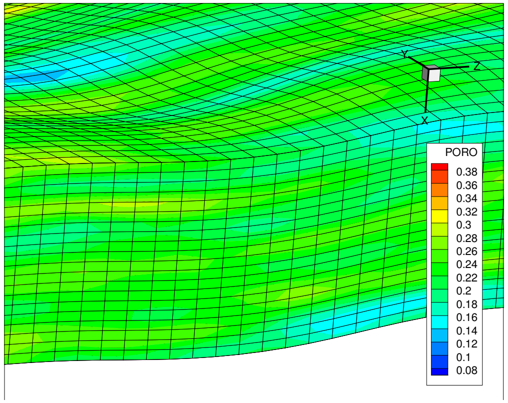
Pore Pressure	Vertical Displacement	Volumetric Plastic Strain
		

Mechanical Properties

E	**375,581 psi**
v	**0.25**
α	**1.0**
$1/M$	**1e-6 / psi**
τ_0	**1,600 psi**
θ	**0.6**

Next Steps: Geometry and Heterogeneity

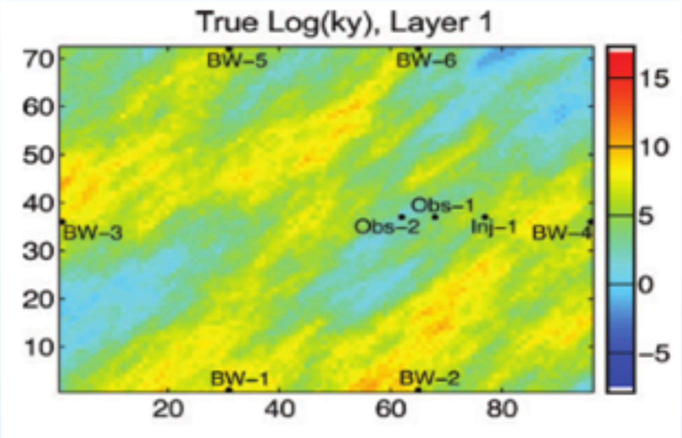
- Our findings show that at normal CO_2 pressure injection range rock formation may yield.



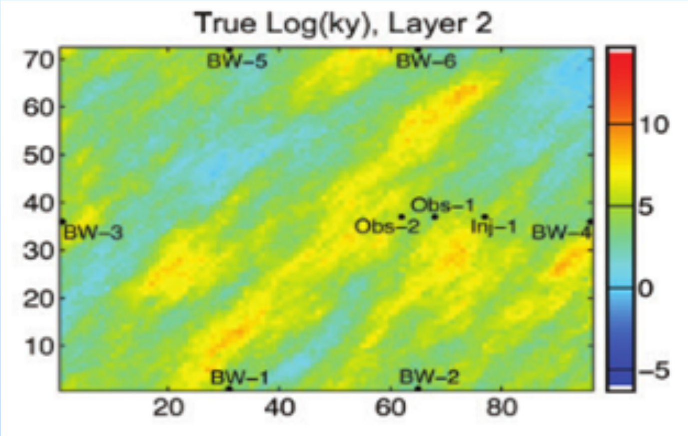
Task 5: Uncertainty Quantification

Objectives	Update input parameters for numerical models, e.g. simulated responses match observations (M.F. Wheeler–lead, S. Srinivasan–consultant)

Complex relationship between the multi-physics attributes is honored



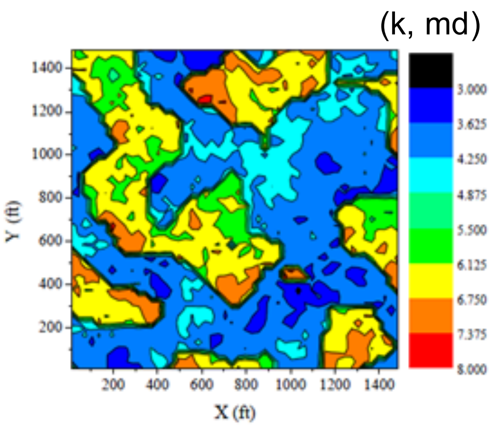
Residual uncertainty in predicting future migration of the CO_2 is faithfully represented

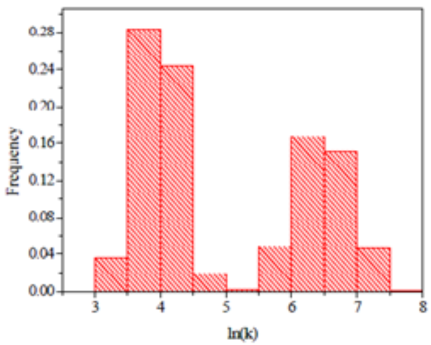


Task 5: Uncertainty Quantification

- Process of History Matching: Combination of Tasks 2 to 5

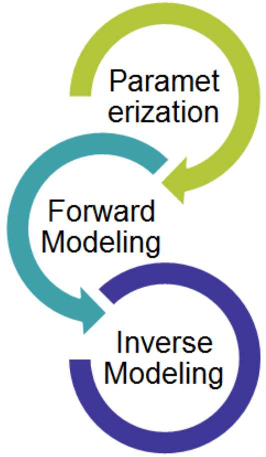
A Priori Model

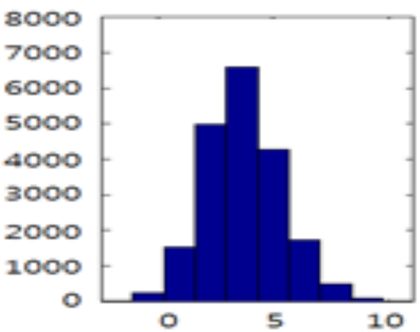




Multi-modal

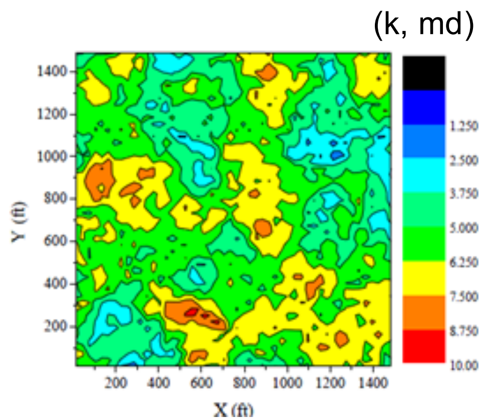
History Matching

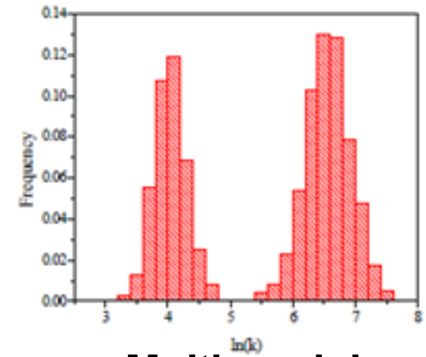




Gaussian

A Posteriori Model





Multi-modal

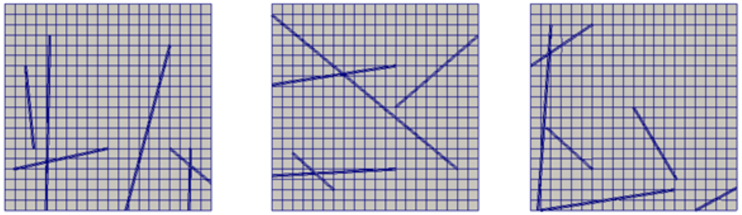
Task 5: Uncertainty Quantification

- History Matching Coupled w/ Level-Set, MFDFrac, and EnKF

1 Initialization

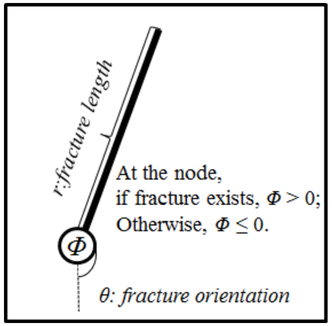
- Generate initial fractured realizations

Realization #1 … Realization #100



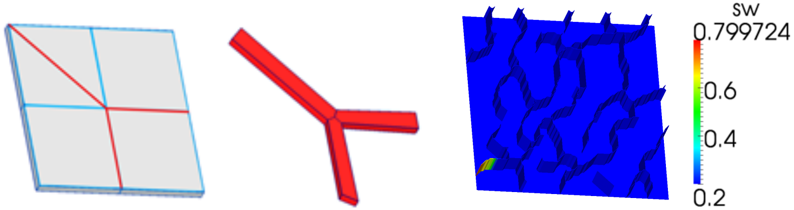
2 Level-Set Parameterization

- 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



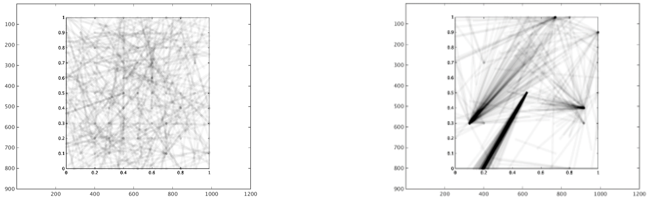
Internal Fracture Boundaries

Intersecting Fractures

Flow

4 Inverse Modeling using EnKF

- EnKF for updating Gaussian parameters

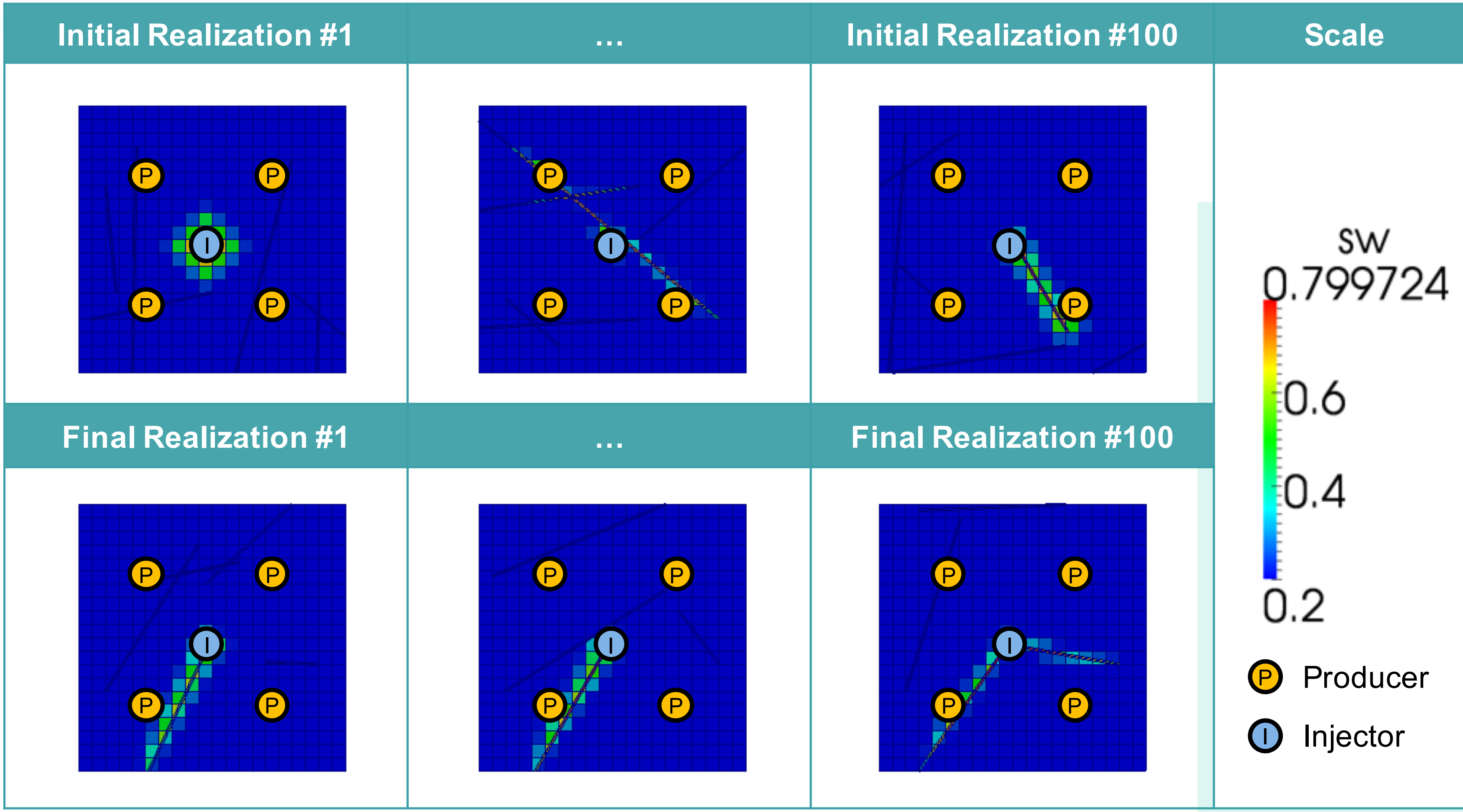


Ensemble mean of initial fracture realizations

Ensemble mean of final fracture realizations

Task 5: Uncertainty Quantification

- Matching Results: Water Saturation for Initial & Final Realizations

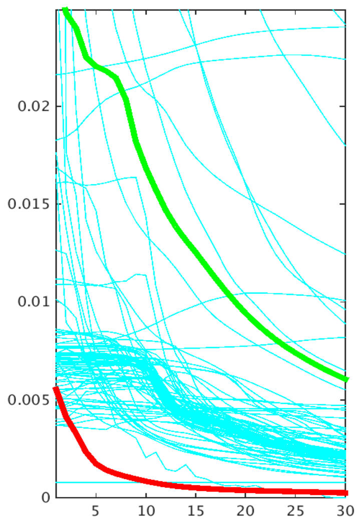


Task 5: Uncertainty Quantification

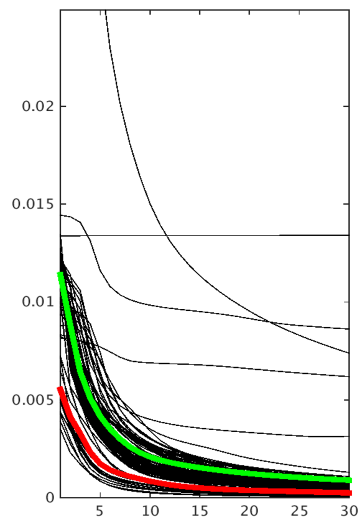
- Matching Results: Observed and Predicted Production Profiles

Oil Production at the Well #1

Before Matching

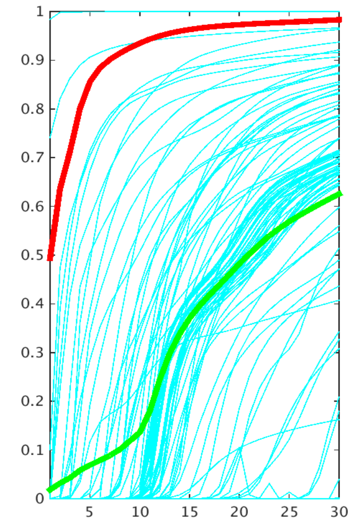


After Matching

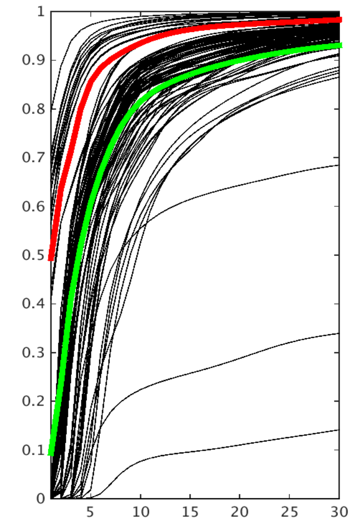


Water Cut at the Well #1

Before Matching



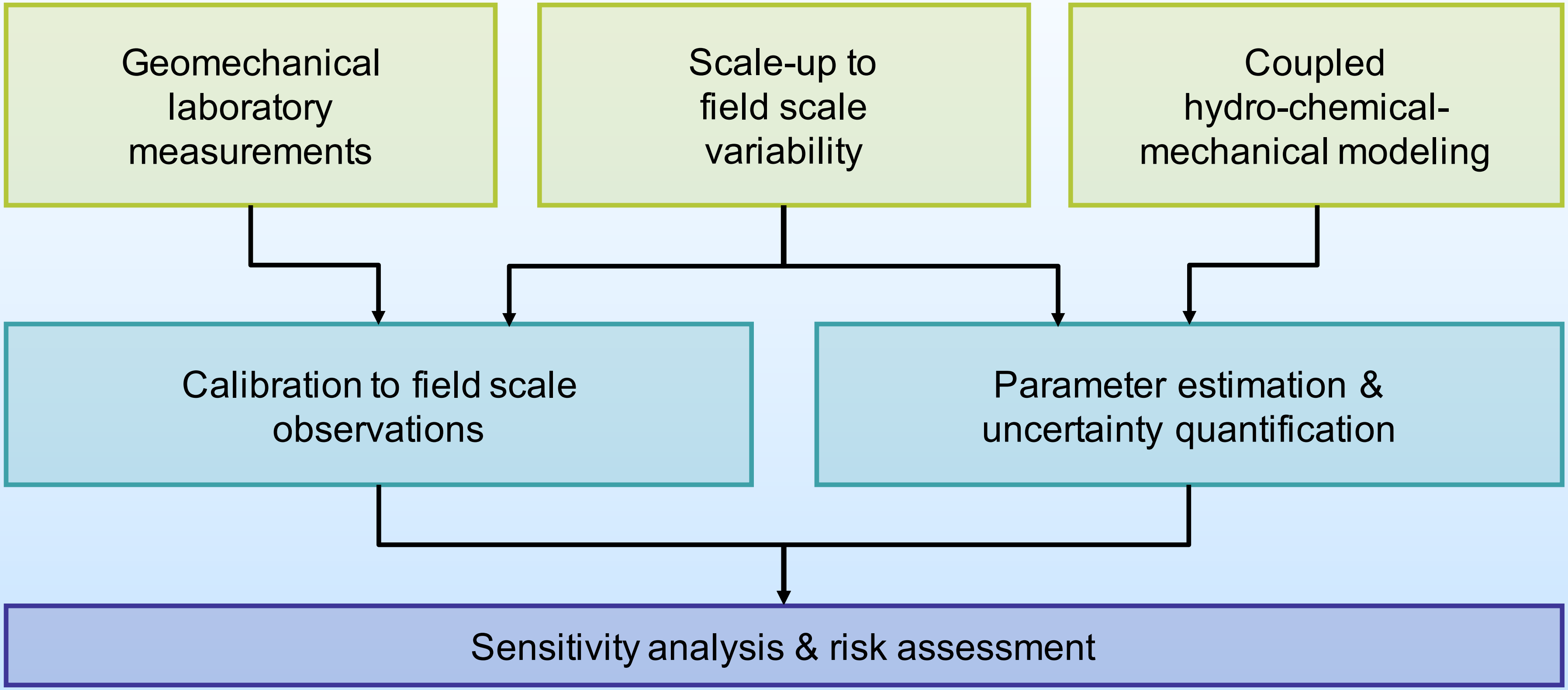
After Matching



— Observed data from the reference field
— 100 realizations before updating
— 100 realizations after updating
— Average of 100 realizations

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 (M.F. Wheeler–lead, S. Srinivasan–consultant)



Task 6: Geomechanical Screening Tool

- Quarter Wellbore Model: Flow & Geomechanics Equation

Assumption

- Assume a linear, elastic, homogenous, and isotropic porous medium
- The reservoir is saturated with a slightly compressible viscous fluid
- Quasi-static Biot model to obtain mechanical displacements

Geomechanics Equations

Balance of Linear Momentum: $-\operatorname{div} \boldsymbol{\sigma}^{\text{por}}(\boldsymbol{u}, p) = \boldsymbol{f} \quad \text{in}\, \Omega \setminus \mathrm{C}$

Cauchy Stress Tensor: $\boldsymbol{\sigma}^{\text{por}}(\boldsymbol{u}, p) = \boldsymbol{\sigma}(\boldsymbol{u}) - \alpha\, p\, \boldsymbol{I}$

Effective Linear Elastic Stress Tensor: $\boldsymbol{\sigma}(\boldsymbol{u}) = \lambda(\nabla \cdot \boldsymbol{u})\boldsymbol{I} + 2\, G\varepsilon(\boldsymbol{u})$

- $\boldsymbol{I}$ is the identity tensor , $\boldsymbol{u}$ is the solid's displacement , p is the fluid pressure
- $\alpha > 0$ is the Biot coefficient , $\lambda > 0$ and $G > 0$ are the Lamé constants
- $\boldsymbol{f}$ is a body force (gravity loading term)

Task 6: Geomechanical Screening Tool

- Quarter Wellbore Model: Flow & Geomechanics Equation

Assumption

- Assume a linear, elastic, homogenous, and isotropic porous medium
- The reservoir is saturated with a slightly compressible viscous fluid
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Geomechanics Equations

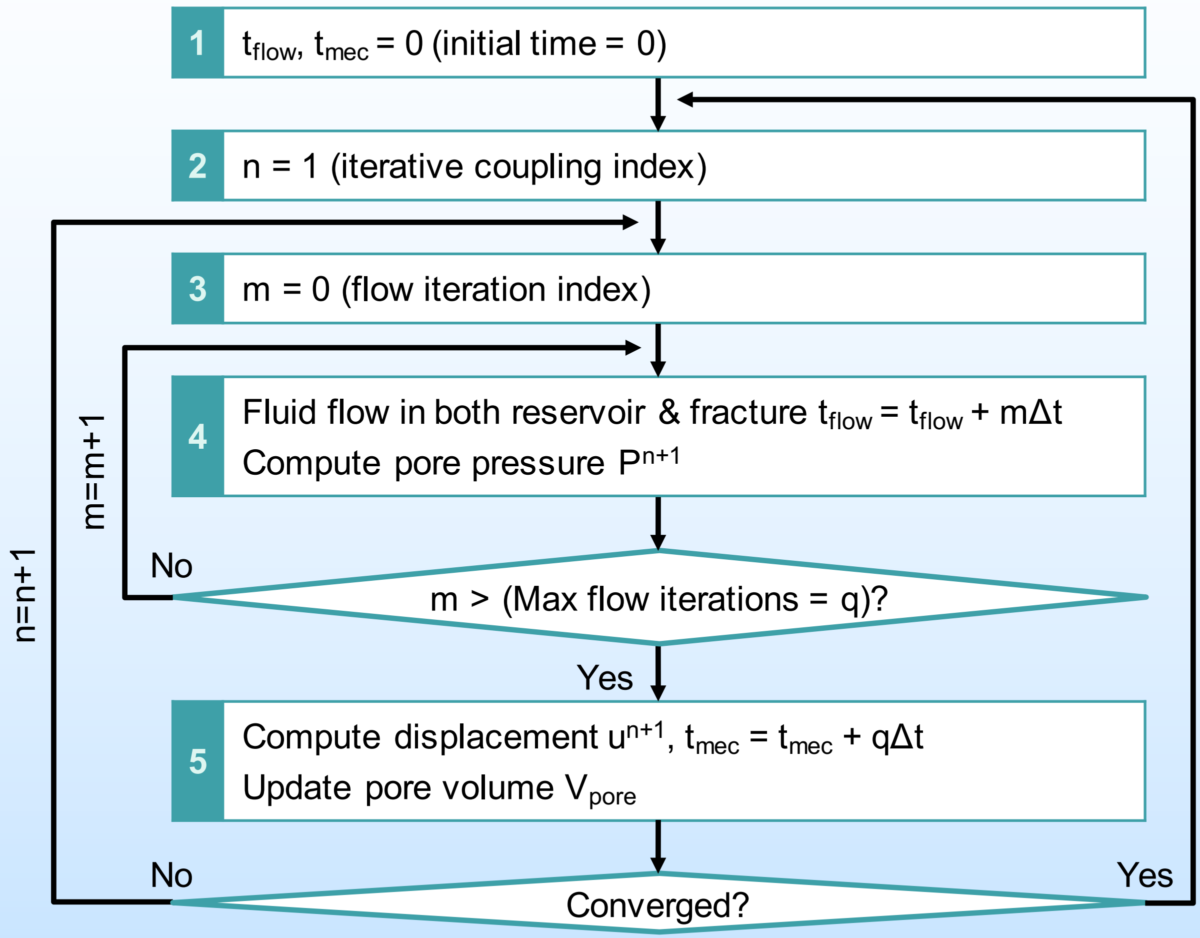
$$\frac{\partial}{\partial t}\Big(\big(\frac{1}{M} + c_f\varphi_0\big)p + \alpha\nabla\cdot\boldsymbol{u}\Big) + \nabla\cdot\boldsymbol{z} = \tilde{q} \text{ in } \Omega\setminus\mathrm{C},$$

$$\boldsymbol{z} = -\frac{1}{\mu_f}\boldsymbol{K}\big(\nabla p - \rho_{f,r}g\nabla\eta\big) \text{ in } \Omega\setminus\mathrm{C},$$

- p and $\boldsymbol{z}$ represents the pressure and flux unknowns
- $\mu_f > 0$ represents the constant fluid viscosity
- $\rho_{f,r} > 0$ is a constant reference density (relative to the reference pressure p_r)
- φ_0 is the initial porosity , $\alpha \Rightarrow$ (coupling term)
- M is the Biot constant , $\tilde{q} = \frac{q}{\rho_{f,r}}$ where q is a mass source or sink term

Task 6: Geomechanical Screening Tool

- Quarter Wellbore Model: Iterative Algorithm using Multi-rate Time Step



Task 6: Geomechanical Screening Tool

- Quarter Wellbore Model: Accumulated Number of Mechanics

Simulation Time vs. Iterations

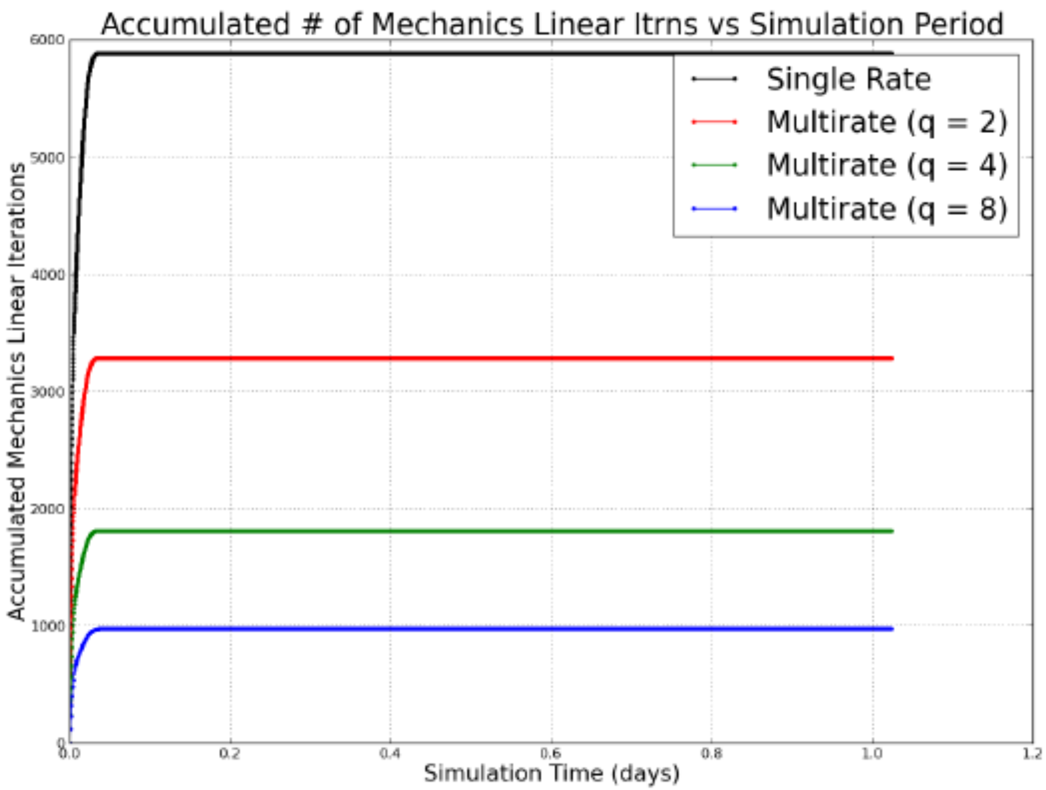
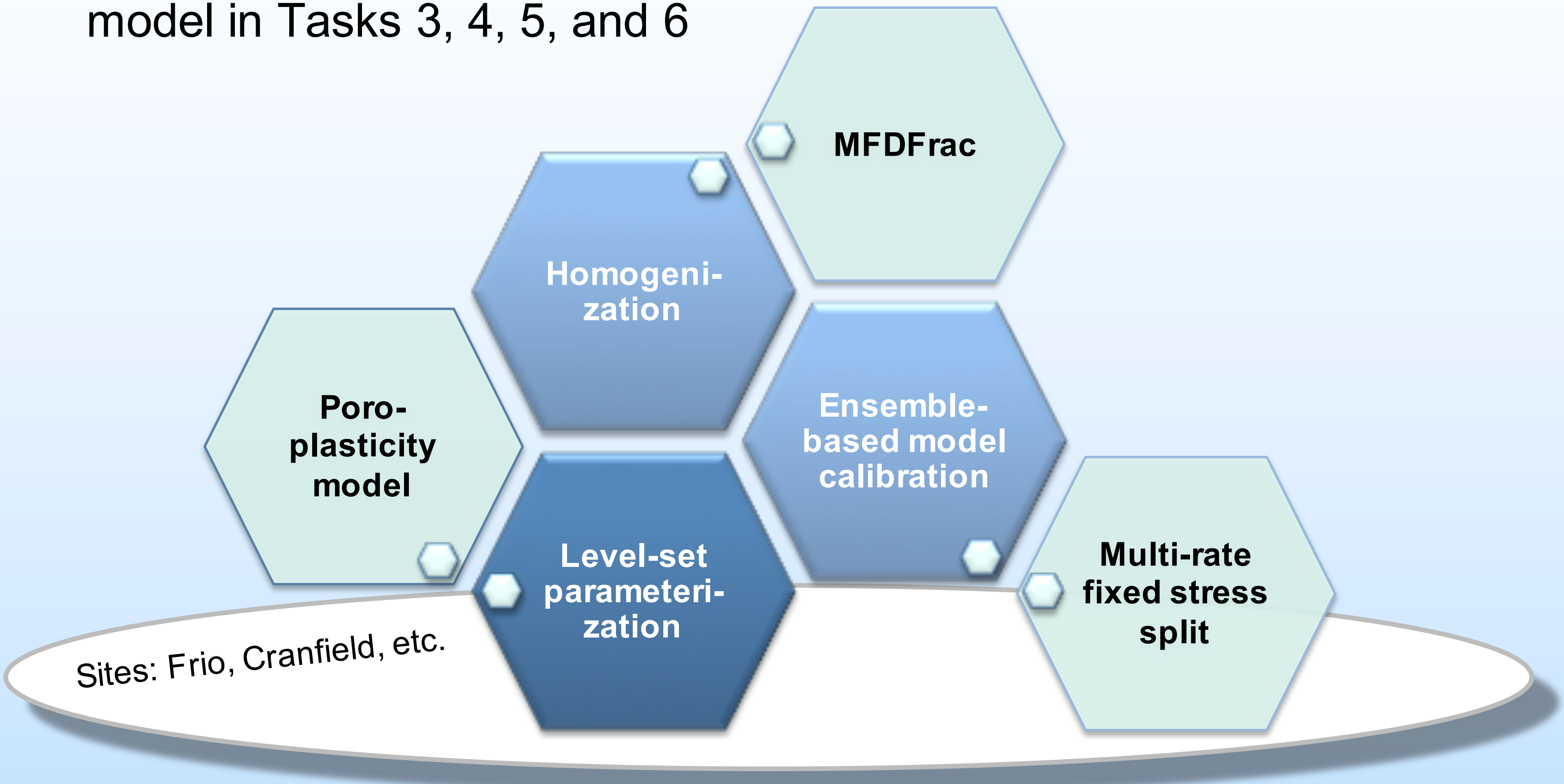


Figure: Multirate coupling with two flow finer time steps (q = 2), within one coarser mechanics time step results in **44.2%** reduction ↓ in total number of **mechanics** linear iterations. Multirate couplings (q = 4), (q = 8) results in **69.2%**, **83.5%** reduction ↓ in total number of **mechanics** linear iterations respectively.

Accomplishments to Date

- Set up of experimental studies on homogenization in Tasks 2 and 3
- Site characterization initiated in Tasks 2, 3, and 4
- Preliminary results from the advanced flow and geomechanics model in Tasks 3, 4, 5, and 6



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!

Summary

- Developing a generalized geomechanical screening tool
- Preliminary outcomes from interdisciplinary collaboration
- Homogenization / Poro-plasticity / Level-set / MFDFrac / Ensemble-based calibration / Multi-rate fixed stress split
- Achievement ahead of milestone

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

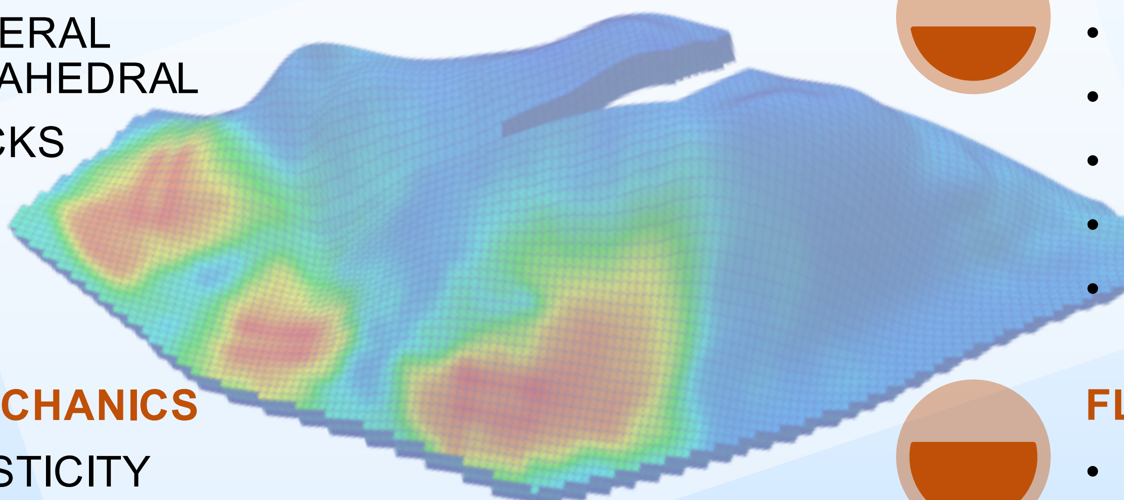
Gantt Chart

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
T1	Management		A, B										
T2	Laboratory Experiment			C	D		E		F	G			
T3	Upscale from Lab. to Field								H		I		
T4	Simulator Development				J				K	L		M	
T5	Uncertainty Quantification								N				O
T6	Integrated Geo-Screening Tool												P

A to P : Milestones — Schedule — Accomplishment

IPARS

- **Integrated Parallel Accurate Reservoir Simulator (IPARS)**
  - ➢ Workhorse for multiphysics, parallel, field scale simulations
  - ➢ Coupled geomechanics, flow, reactive transport and thermal models
  - ➢ Fractured reservoirs: hydraulic and natural fracture treatment
  - ➢ Advanced well models: horizontal and deviated wells



GEOMETRIES

- GENERAL HEXAHEDRAL
- BRICKS

SOLVERS

- SAMG
- GMRES
- BCGS
- TRILINOS
- HYPRE

GEOMECHANICS

- ELASTICITY
- PLASTICITY

REACTIVE TRANSPORT

- TRCHEM
- ASP FLOODING

FLOW MODELS

- COMPOSITIONAL
- BLACK OIL
- SINGLE & TWO PHASE