Center for Subsurface Modeling (CSM)
Project Highlights for 2017-2018

(1) **Big Data Analytics Project**
Multiphysics Code-Coupling
UQ, Data Assimilation, and Optimization

(2) **Advanced Numerical Solution Schemes**
Dynamic Mesh Refinement
Space-Time Domain Decomposition

(3) **Novel Upscaling Techniques**
Adaptive Numerical Homogenization
Generalized Multiscale Basis Functions

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Approximate Jacobian Non-linear Solver
Non-linear Preconditioners

(5) **Coupled Flow and Geomechanics**
Poro-Elasto-Plasticity
Multiscale Geomechanical Modeling
Novel Multi-phase Biot Model
Energized Fluid Fracturing
Ultra-dry Foam Fracturing

(6) **Advances in Novel Recovery and Production Enhancement Technologies**
CO_2 Foam for CCUS
Matrix Acidization

(1) Big Data Analytics

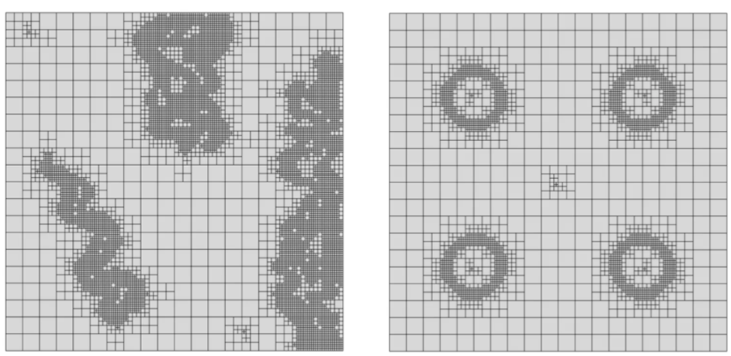
A major new effort combines Big Data Analytics with High Performance Computing for Subsurface Modeling Applications. This is a collaborative project with Professor Sanjay Srinivasan at Pennsylvania State University, Professor Manish Parashar at Rutgers University, and Professor Mrinal Sen at The University of Texas at Austin. This project addresses the following key BIG data and computer science challenges: (1) Computation of seismic wave propagation in fractured media; (2) BIG data analytics for inferring fracture characteristics; (3) High Performance Computation of flow and transport in fractured media and; (4) Integration of data from disparate sources for risk assessment and decision-making.

Multiphysics Code-Coupling: In order to couple its complex physical models with other codes, a library interface has been developed for the Integrated Parallel Accurate Reservoir Simulator (IPARS) reservoir simulator. A project is currently underway to couple multi-phase flow with mixed finite element methods to phase-field fracture propagation with mechanics in deal.II. A data staging library called Data-Spaces has also been used for this multi-physics coupling which enables in suit/in transit workflows for Big Data.

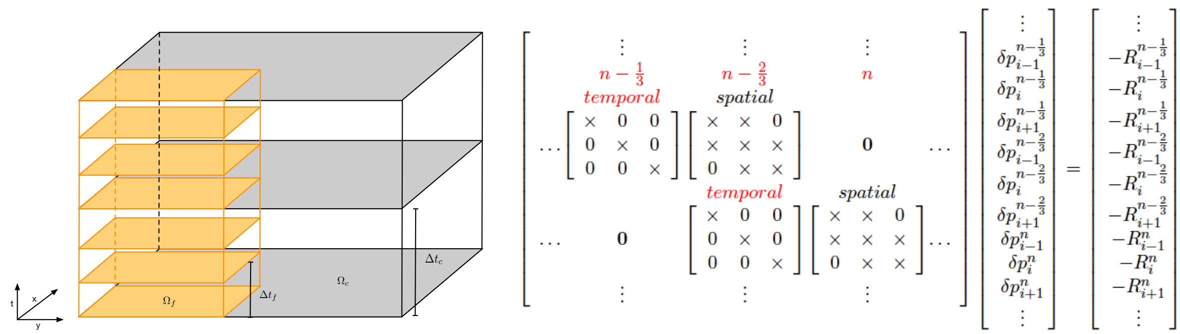
UQ, Data Assimilation, and Optimization: This project includes a genetic algorithm based optimization toolkit, ensemble smoothers for history matching, and uncertainty quantification. The UT-OPT optimization framework coupled with our in-house reservoir simulator IPARS and our fracture propagation simulator, IPACS, has been used in a number of field studies for conformance control with foam injection, diagnostics using pulse testing, and optimizing fracture spacing.

(2) Advanced Numerical Solution Schemes

Dynamic Mesh Refinement: We have extended the enhanced velocity mixed finite element method (EVMFEM) to track physical features such as saturation and concentration fronts and locally refine in the region of interest for higher solution accuracy. A new semi-structured grid is implemented in IPARS for computational efficiency. This development addresses several non-linear, multi-phase flow and reactive transport problems of interest, including equation of state compositional flow.

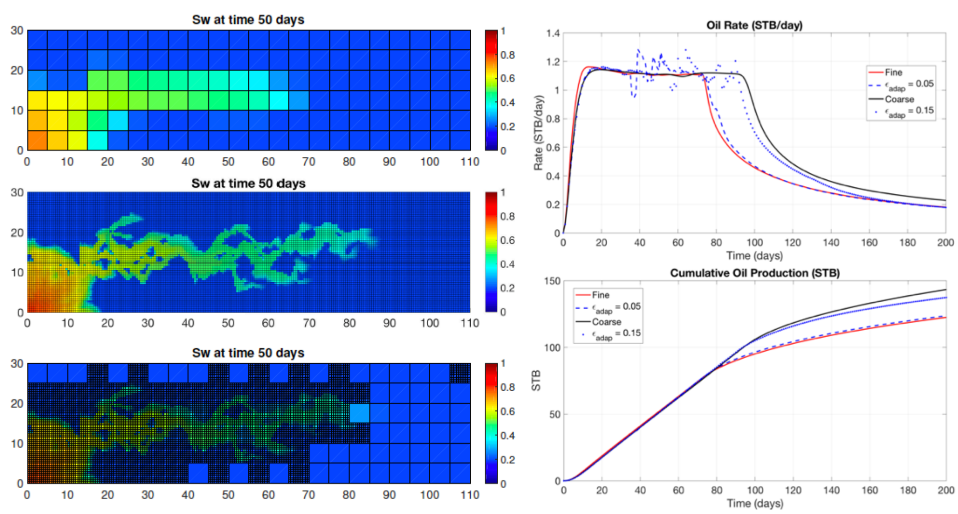


Space-Time Domain Decomposition: In order to accurately resolve physical features in multi-phase flow and reactive transport, it is necessary that fine spatial and temporal scales be required in subdomains. This poses a serious computational restriction necessitating small time-step sizes for the entire domain, substantially increasing the computational overheads. A space-time domain decomposition approach has been developed as a natural extension of the enhanced velocity mixed finite element method to circumvent this issue. A novel spatio-temporal monolithic solver was also developed for the fully-implicit system that is currently being implemented in IPARS.

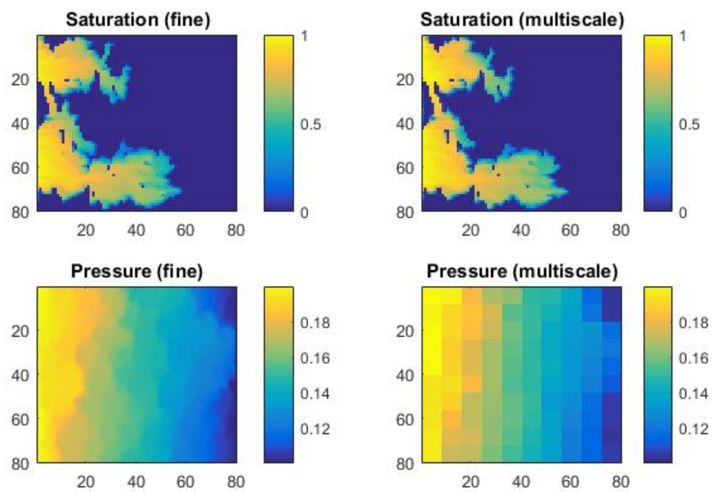


(3) <u>Novel Upscaling Techniques</u>

Adaptive Numerical Homogenization: A novel upscaling approach was recently presented at the 2017 Annual Technical Conference and Exhibition (ATCE) in San Antonio, Texas. A combination of local numerical homogenization and adaptive mesh refinement (using EVMFEM) is used to reduce computational cost while maintaining solution accuracy compared to the fine scale solution. This upscaling approach has been extended for non-linear multi-phase flow problems such as oil-water, air-water, and black oil type systems.



Generalized Multiscale Basis Functions: The multiscale basis functions approach for model order reduction that was earlier restricted to incompressible or slightly compressible type flow systems, was recently combined with extended mixed finite element method to handle air-water, and black-oil type systems. An iterative numerical solution algorithm was also developed for computational efficiency and solution accuracy compared to the fine scale solution.



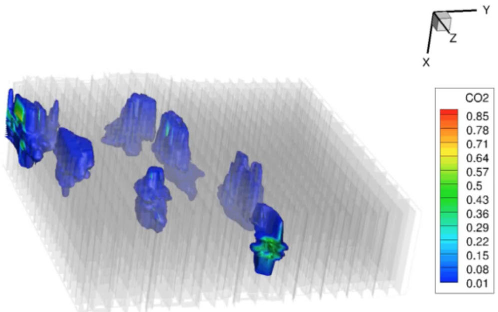
(4) <u>Solvers and Preconditioners</u>

Approximate Jacobian Non-linear Solver: A novel solver for non-linear, multi-phase flow and transport problems was developed that outperforms Compressed Pressure Residual (CPR) or two stage preconditioners. The solver relies upon an approximation in the non-linear, fully-discrete, variational formulation to decouple pressure and saturation prior to the construction of a linear, monolithic system. A wide range of numerical experiments considering heterogeneous rock properties such as permeability, porosity, capillary pressure, and relative permeability consistently indicate computational speedups ranging from 1.32 to 4 times in comparison to the existing solvers and preconditioners.

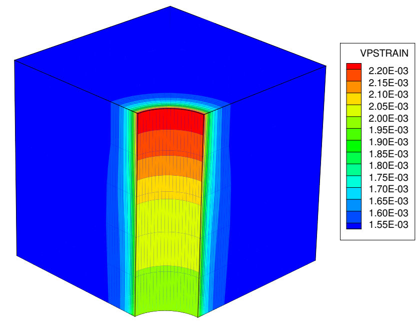
Non-linear Preconditioners: Non-linear solvers such as Newton-Raphson method are often marred by small time-step sizes. An increase in time-step size often results in an increase in non-linear iterations or convergence issues depending upon the nature of the non-linear flow and transport problem. This is further exacerbated by mesh refinement (local or global) and consequently increased computational costs. We recently developed physics based non-linear preconditioners to overcome this issue with time-step sizes relevant to the subsurface flow and transport problems. These preconditioners were used extensively with our adaptive numerical homogenization for upscaling where local mesh refinement is used to achieve higher solution accuracy.

(5) <u>Coupled Flow and Geomechanics</u>

Poro-Elasto-Plasticity: A poro-elasto-plasticity model has been coupled with single-phase, two-phase, and compositional fluid flow models using an iterative fixed-stress regime and parallelized for efficiency. Applications have included near-wellbore problems as well as carbon sequestration, utilizing data from the Cranfield site based in Mississippi, to showcase the need for capturing permanent deformations through plasticity. The work on poro-elasto-plasticity modeling is continuing through verification testing, implementation of a new splitting scheme, and possible extensions to chemo-mechanical coupling.

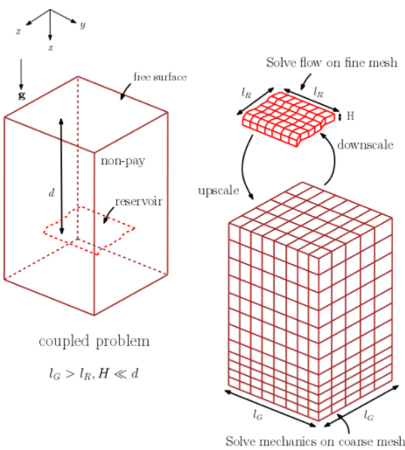


CO2 concentration from simulation of the Cranfield CO2 sequestration site using injection well schedule and mechanical parameter data



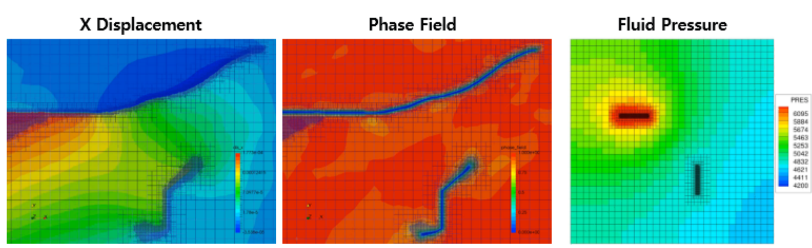
Volumetric plastic strain on a wellbore surface

Multiscale Geomechanical Modeling: In order to address the multiscale nature of coupled flow and mechanics in the payzone and non-payzone, we augment the fixed-stress split iterative scheme with upscaling and downscaling operators to enable modeling flow and mechanics on overlapping nonmatching hexahedral grids. Flow is solved on a finer mesh using a multipoint flux mixed finite element method and mechanics is solved on a coarse mesh using a conforming Galerkin method. The multiscale operators are constructed using a procedure that involves singular value decompositions, a surface intersections algorithm, and Delaunay triangulations. We numerically demonstrate the convergence of the augmented scheme using the classical Mandel's problem solution.



Novel Multi-phase Biot Model: A major theoretical development has been analyzed which formulates Biot's model for poroelasticity in the setting of multi-phase flow, including defining pore pressure. First known analysis for multi-phase Biot.

Energized Fluid Fracturing: Aqueous based fracturing fluids get trapped inside the reservoir and cause significant formation damage. This leads to exponential decrease in the production of hydrocarbons in the fracture network. A computational framework has been developed to model the effect of using energized fluids on the fracture propagation, geometry, and the overall reservoir productivity. The new framework couples phase field fracture propagation model with a compositional reservoir simulator (IPARS) to perform efficient multi-physics simulation of flow, geomechanics, and fracture propagation

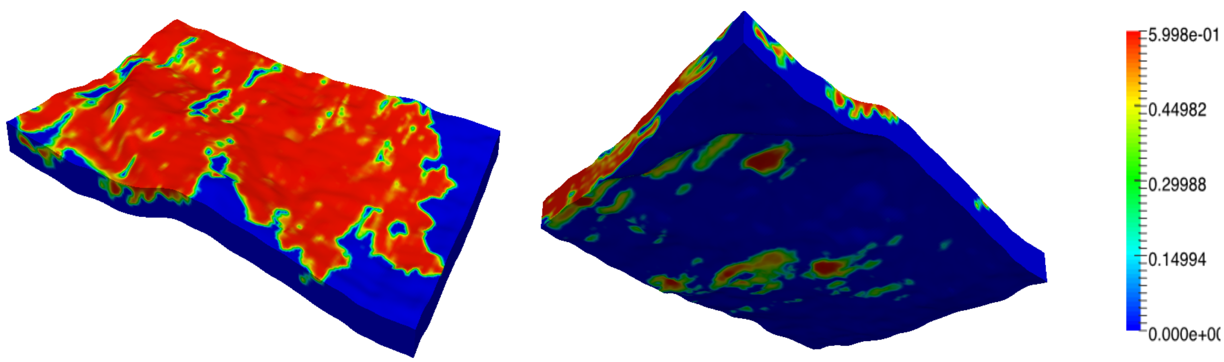


Ultra-dry Foam Fracturing: The phase field fracture propagation model developed earlier assumes slick water (water with chemical additives) as the carrier fluid for proppant. This project will extend these previous developments to replace slightly compressible water phase with ultra-dry CO_2 foam. Hydraulic fracturing using slick water injection in tight shale gas and oil formations is known to encounter liquid loading and proppant flow back issues. We are developing mathematically consistent models and robust numerical solution schemes in order to assist commercial field operations. We are also extending our previous developments on proppant transport to model CO_2 foam as the carrier fluid.

(6) Advances in Novel Recovery and Production Enhancement Technologies

***CO_2 Foam for CCUS**:* Foam injection has been proven to be effective for flood conformance during enhanced oil recovery processes. In situ generation of foam serves to block gas migration along high permeability pathways and that technology is especially attractive due to its low water and chemical additives requirements. An advanced foam module with hysteresis in development has shown that Surfactant Alternating Gas (SAG-foam) injection has the potential to store larger amounts of CO_2 by improving aerial and vertical sweep efficiency and increasing CO2 capillary entrapment. An optimized foam injection scenario, designed by UT optimization toolbox (UT-OPT), led to achieving 56% more CO_2 storage compared to continuous CO_2 flooding.

(a) Continuous CO_2 Injection



(b) Surfactant Alternating Gas (SAG) – Foam Injection

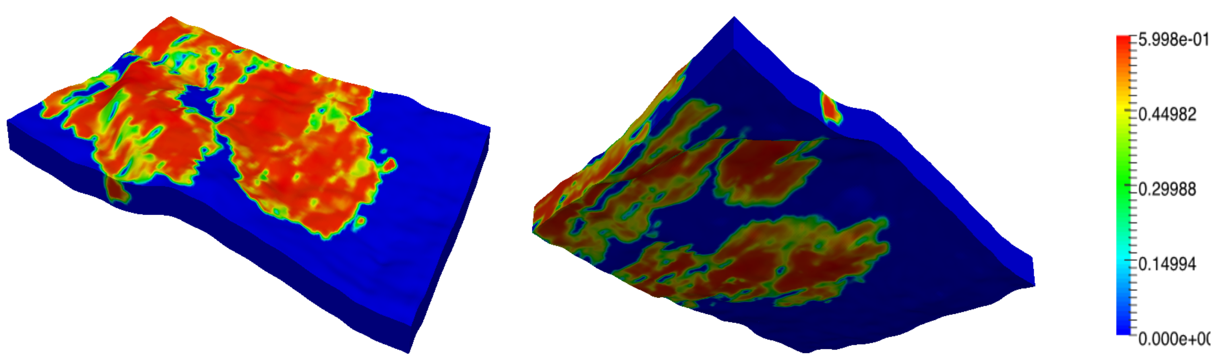
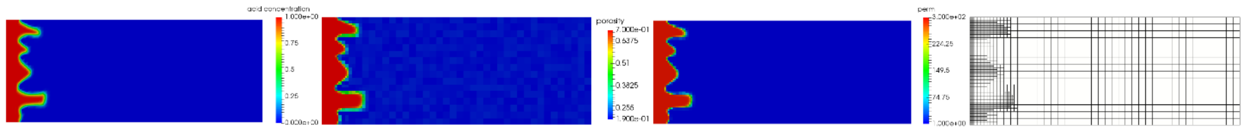
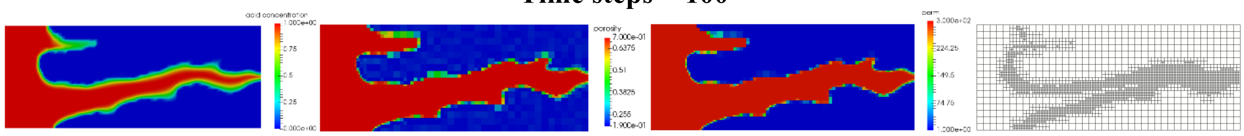


Figure: Top and bottom view of CO_2 saturation at the end of injection in (a) continuous CO_2 flooding, (b) SAG-foam injection.

Matrix Acidization: Due to reservoir heterogeneity and coupling of chemical reactions, the performance of carbonate matrix acidizing is difficult to predict. Accurate modeling of wormholes, however, requires very fine mesh to capture the physics at the vicinity of wormhole interfaces. This research uses an adaptive Enriched Galerkin (EG) method for solving flow and acid transport in the acidizing process. EG has less effects of grid orientation and numerical dispersion than the standard finite difference or finite volume method. Different dissolution regimes in core-flooding experiments have been reproduced from simulation results. The simulator can resolve sharp acid fronts with dynamic adaptive mesh around wormhole interfaces.



Time steps = 100



Time steps = 500