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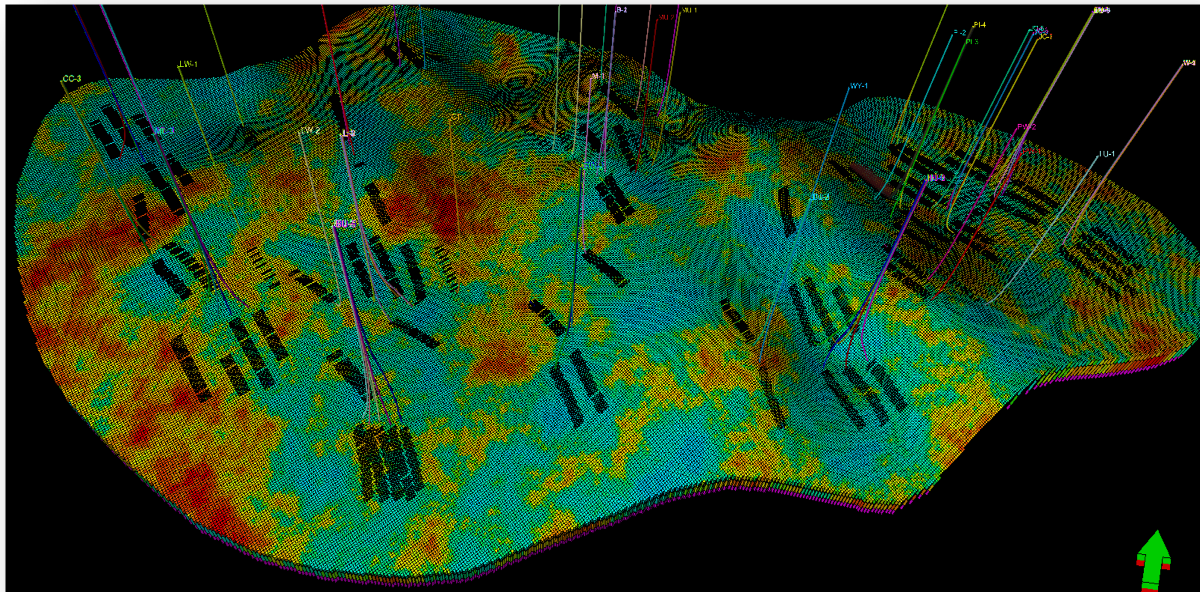


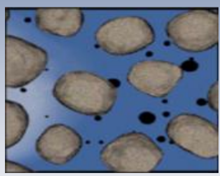
Advanced Simulation Tools for Reservoir Performance

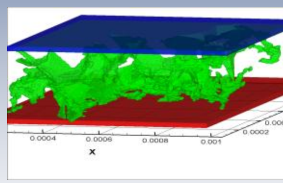
Grant S. Bromhal, NETL ORD, Geosciences Division

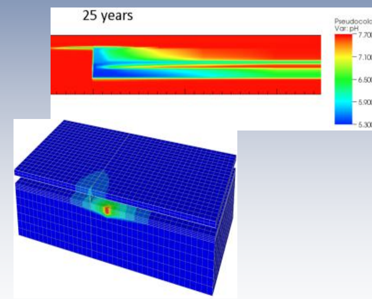
NETL-RUA Fall Meeting
Canonsburg, PA
November, 28, 2012

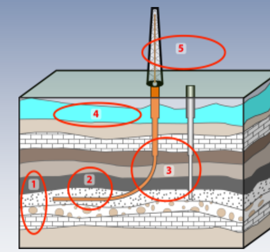
NETL leads the National Risk Assessment Partnership

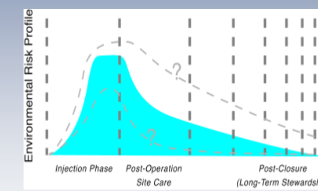
Elucidate key fundamental physics/chemistry → Predict behavior of critical components → Predict system behavior (reservoir to receptor) over space and time → Quantify risk and safety relationships











NRAP Technical Team

NETL-RUA Regional University Alliance

Carnegie Mellon

URS

Berkeley Lab

Los Alamos National Laboratory EST. 1943

Pacific Northwest National Laboratory

The University of Utah

NRAP Stakeholder Group

AEP American Electric Power

Blue Source

bp

CONSOL Energy America's Energy Starts Here.

ExxonMobil Taking on the world's toughest energy challenges.

ieaghg

IEc

MIT

NRDC Natural Resources Defense Council The Earth's Best Defense

Schlumberger

Southern States Energy Board

Stanford University

The University of Utah

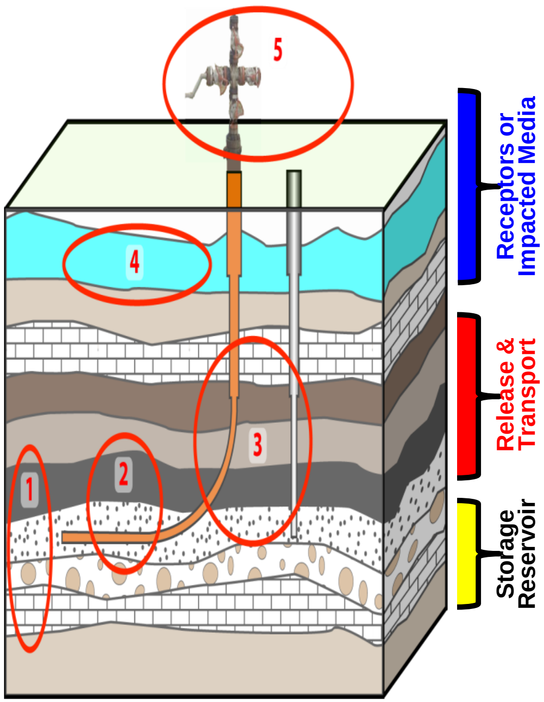
Wade, LLC

Zurich Because change happenz

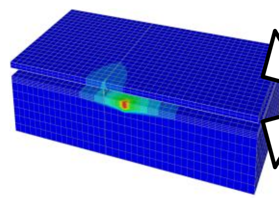
NRAP is a multilab effort to develop simulation tools needed to provide confidence in CO_2 storage safety and security.

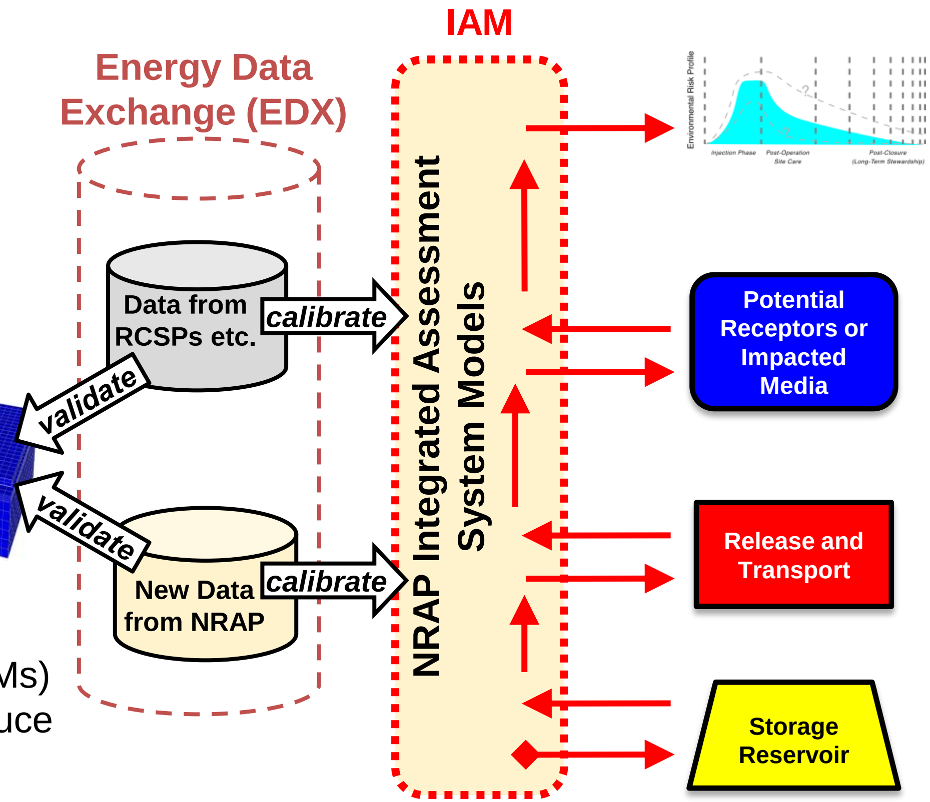
Integrated assessment models (IAMs) allow us to break the system into manageable components.

A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data





C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

Integrated assessment models (IAMs) allow us to break the system into manageable components.

- Applications to:
  - Risk assessment for oil and gas sites (e.g., permitting, site selection)
  - Risk management for oil and gas sites (e.g., operations for risk reduction, decreasing monitoring costs)
  - Operational management and decision making
  - Systems-level analysis of individual sites

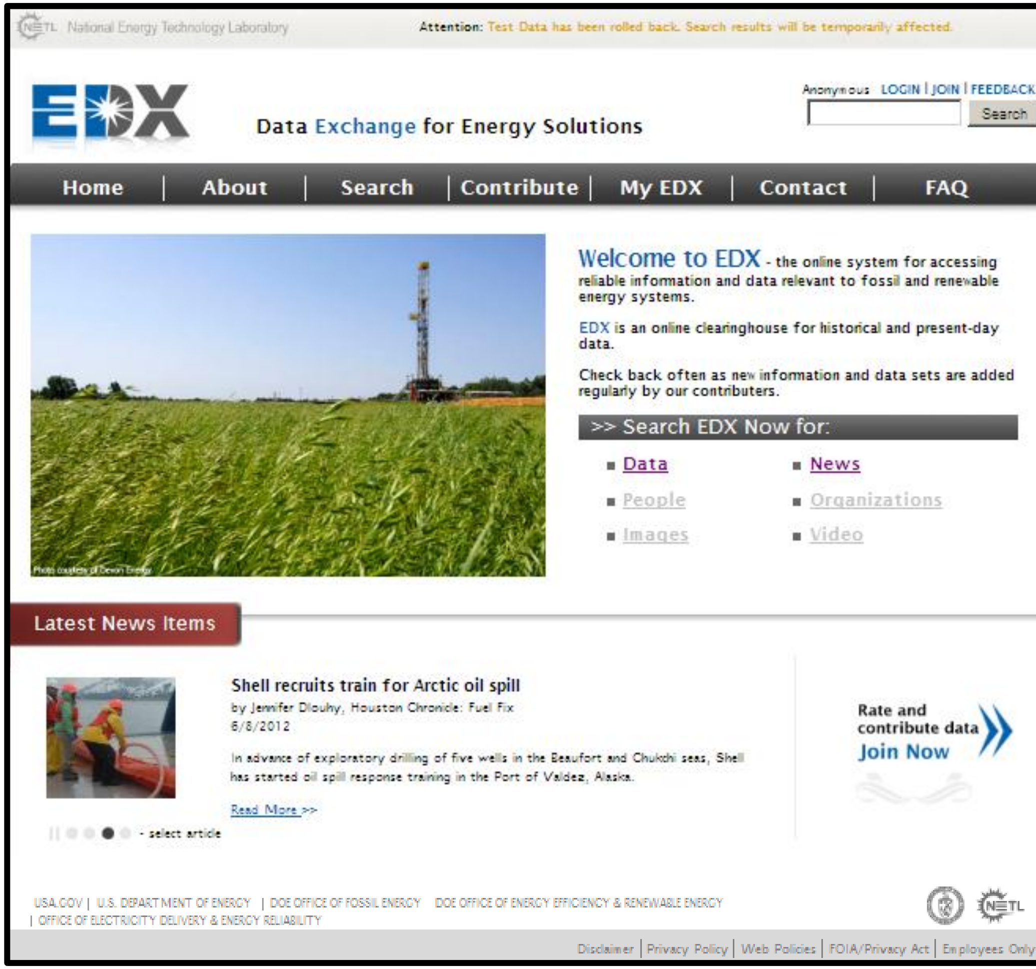
- Future areas for growth:
  - Integration with monitoring operations for efficient operation
  - Development of systems to handle high resolution real-time data
  - Systems-level analysis of entire basins

EDX
Energy Data eXchange

- *R&D coordination & collaboration tool*
- *Share information across networks*
- *Rapid access through one site*
- *Online access for historical data*
- *Venue for newly released datasets*
- *Security, database design, and structure leverage DHS system*
- *Built to accommodate both open access and restricted access data*
- *Role-based security allows for groups or "communities" within the system*
- *Future FY13 roll outs will incorporate spatial/mapping tools, displays and other opportunities*

More information on EDX:
http://www.netl.doe.gov/publications/factsheets/rd/R%26D184%20.pdf

Data Exchange for Energy Solutions



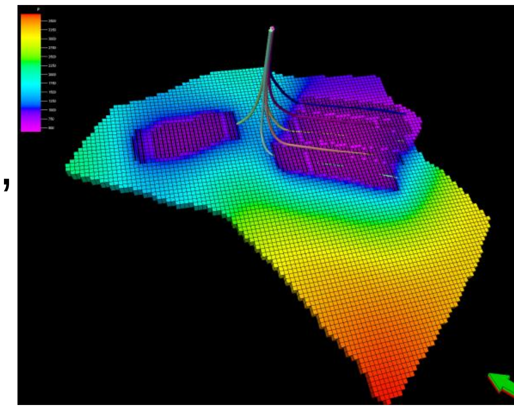
Designed for:

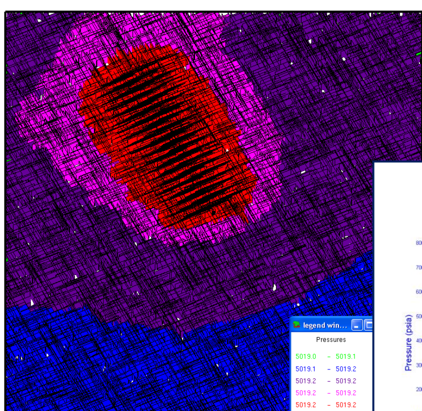
- *Fossil & renewable energy researchers*
- *Policy makers*
- *General public*

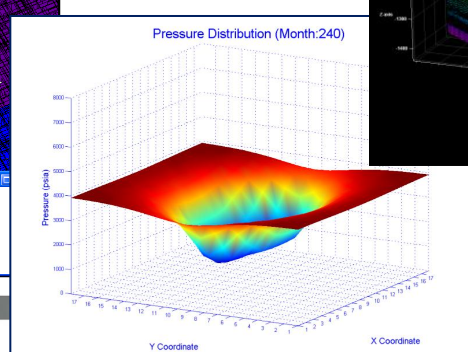
Now available at: https://edx.netl.doe.gov

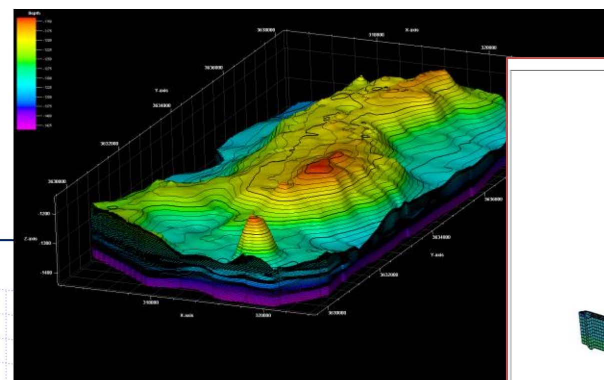
Several types of modeling techniques are being used to study hydrocarbon reservoirs.

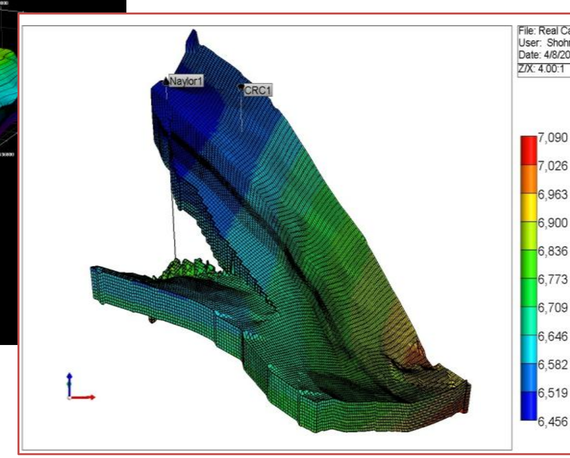
- Commercial software (IMACS, GEM, Eclipse)
- Lab developed codes (TOUGH2, FEHM)
- NETL and RUA developed codes:
  - Modified dual porosity, multiphase, compositional, multidimensional flow model
  - NFFLOW discrete fracture network and flow modeling
  - Reduced order and surrogate models for stochastic analysis





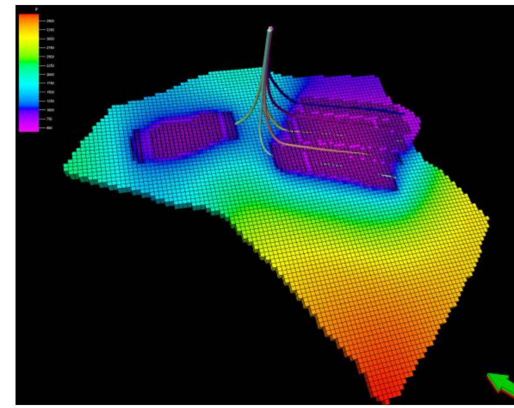


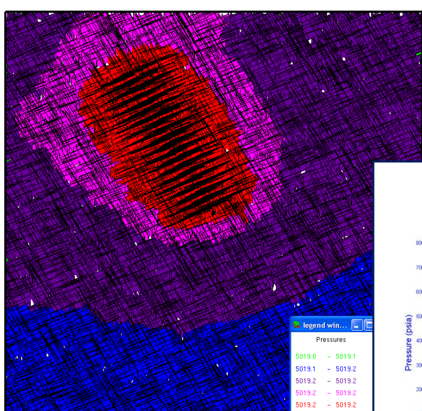


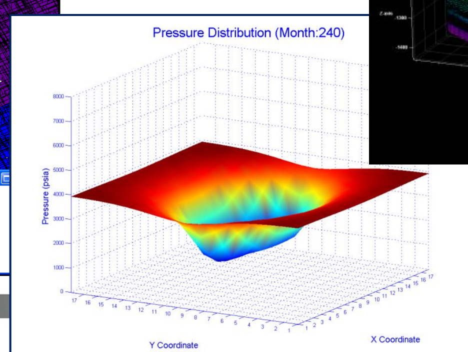


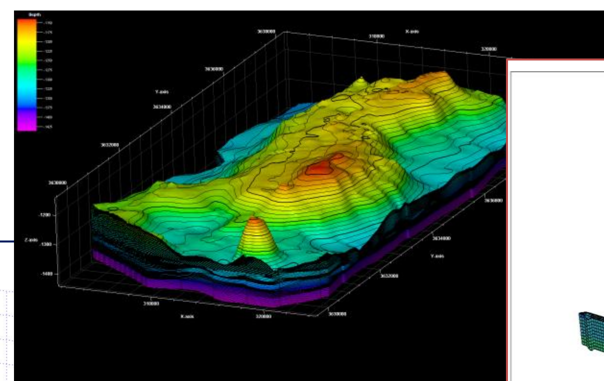
Several types of modeling techniques are being used to study hydrocarbon reservoirs.

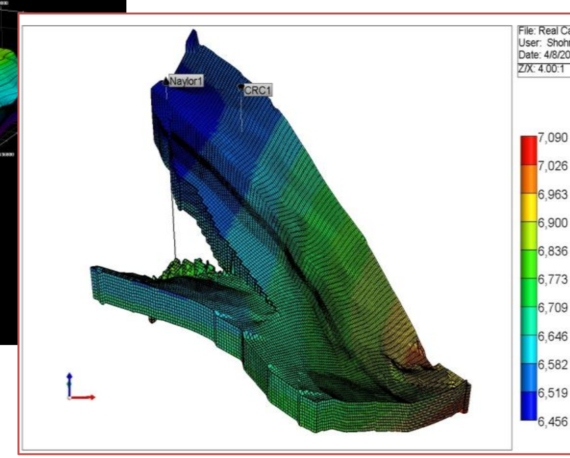
- **Applications to:**
  - Enhanced oil recovery
  - Unconventional oil and gas recovery
  - Methane hydrates
  - Geothermal systems
- **Understanding mechanisms for shale gas recovery is of particular interest**





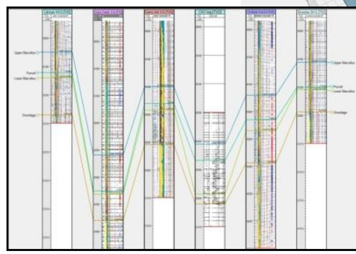


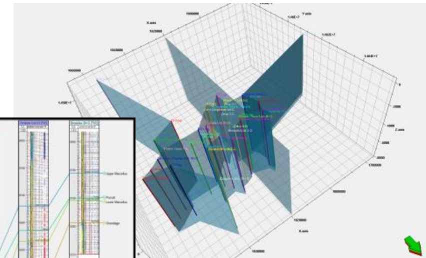




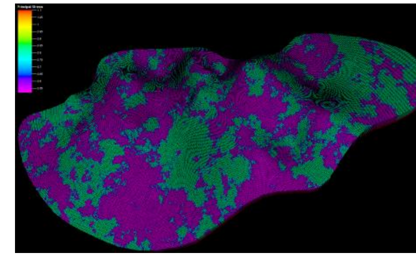
We have developed multiple workflows for simulation of shale gas production.

Structural Modeling

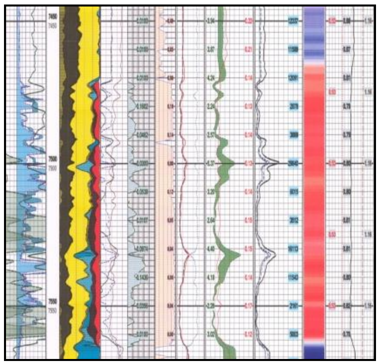




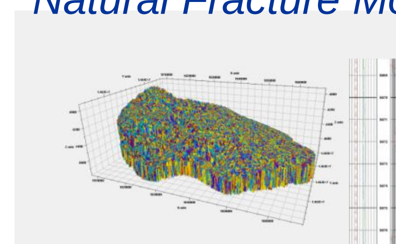
Property Modeling

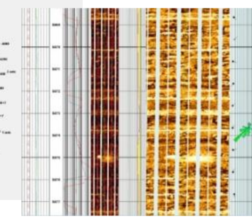


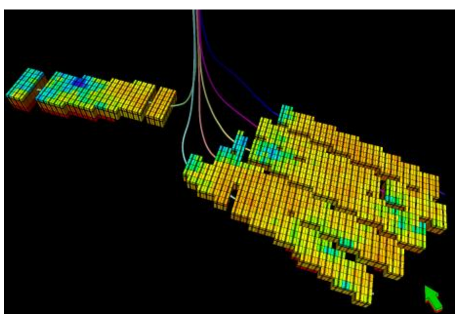
Well Logs



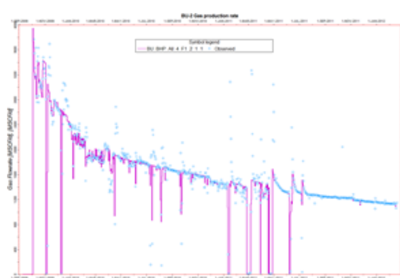
Natural Fracture Modeling

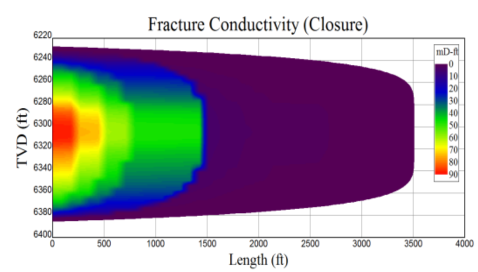






Hydraulic Fracture -LGR





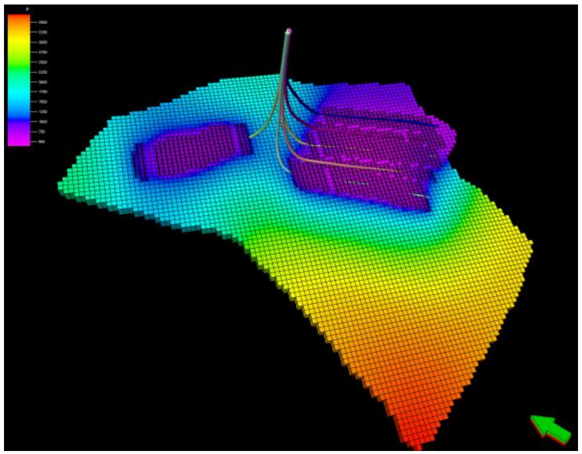
HF treatment modeling

But there is still a great amount of uncertainty in our models.

History matching

Reduced Order Models (ROMs) allow us to generate

Numerical Reservoir Simulation

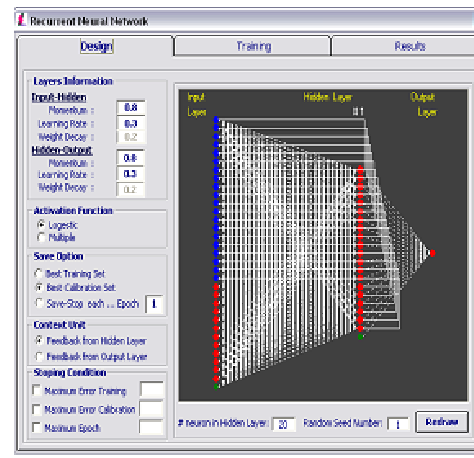


Database of 10-20 Simulation Runs

SRM Training

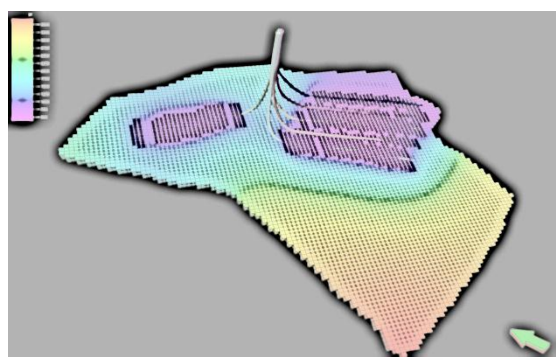
Pattern Recognition

(fuzzy set theory and Artificial Neural Networks)



SRM validation

SRM Mimics Behavior of Numerical Simulation



Multiple ROM Techniques

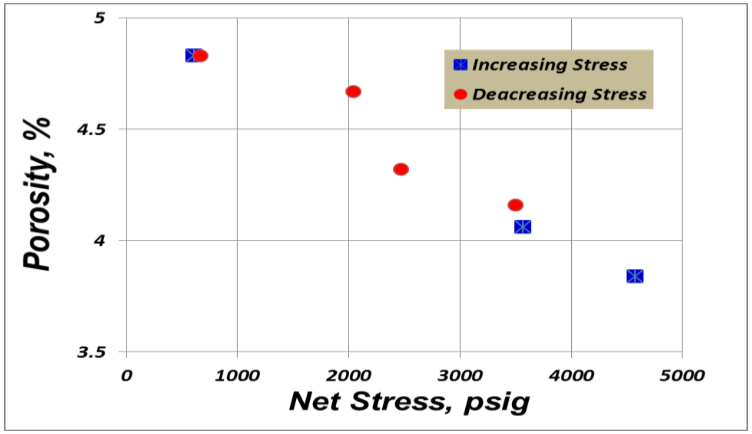
(Surrogate Reservoir Modeling, Polynomial Chaos Expansion)

Explore Reservoir Behavior

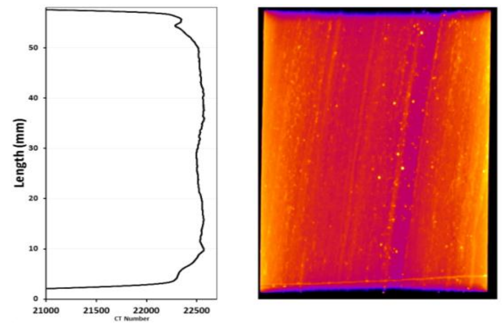
(Sensitivity and Uncertainty Analyses, and Scenario Evaluation)

Shale Experimental Characterization
Model Validation and Grounding

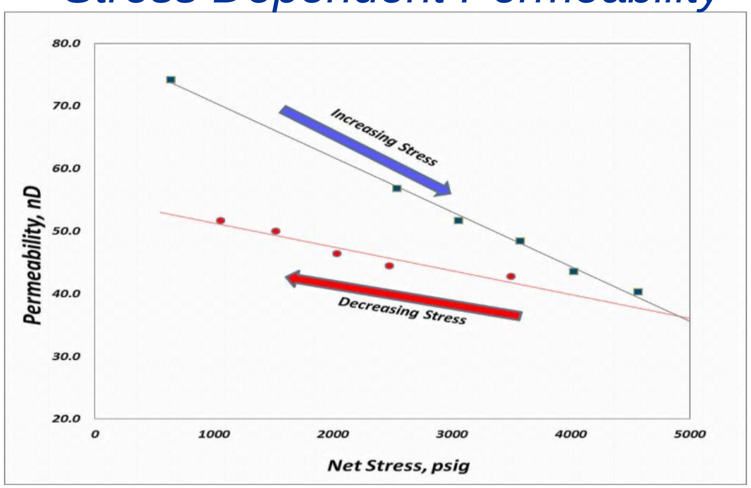
Stress Dependent Effective porosity



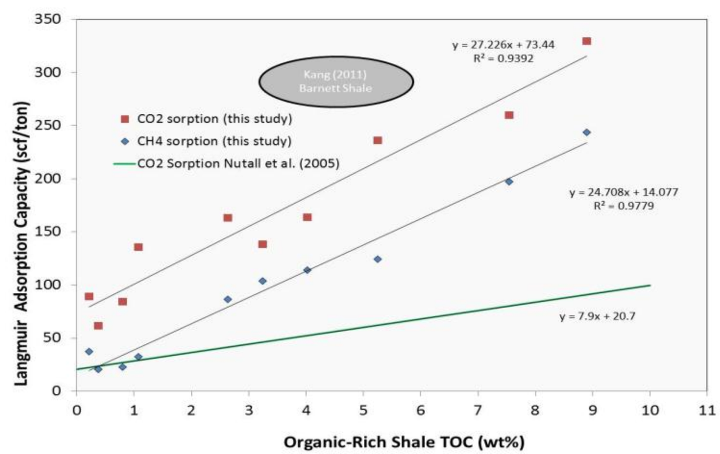
Imaging shale matrix heterogeneity



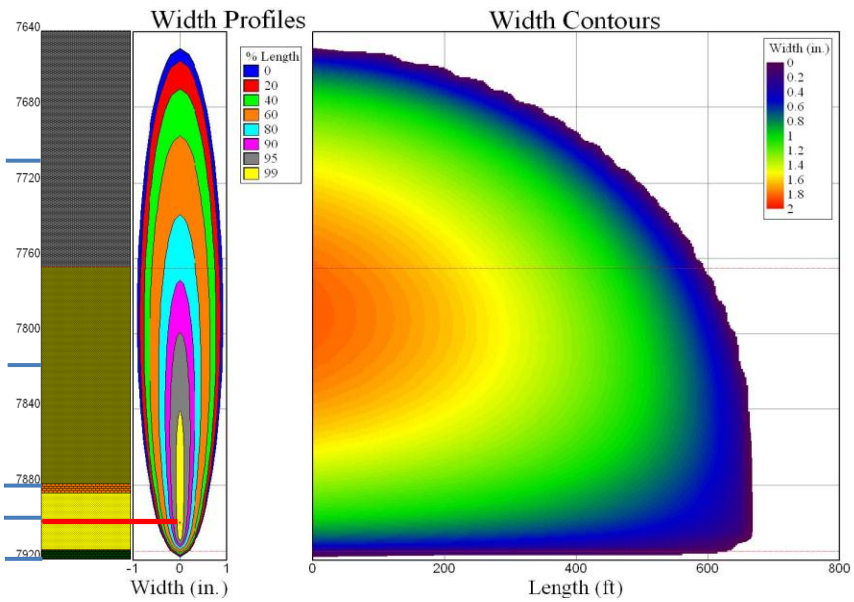
Stress Dependent Permeability

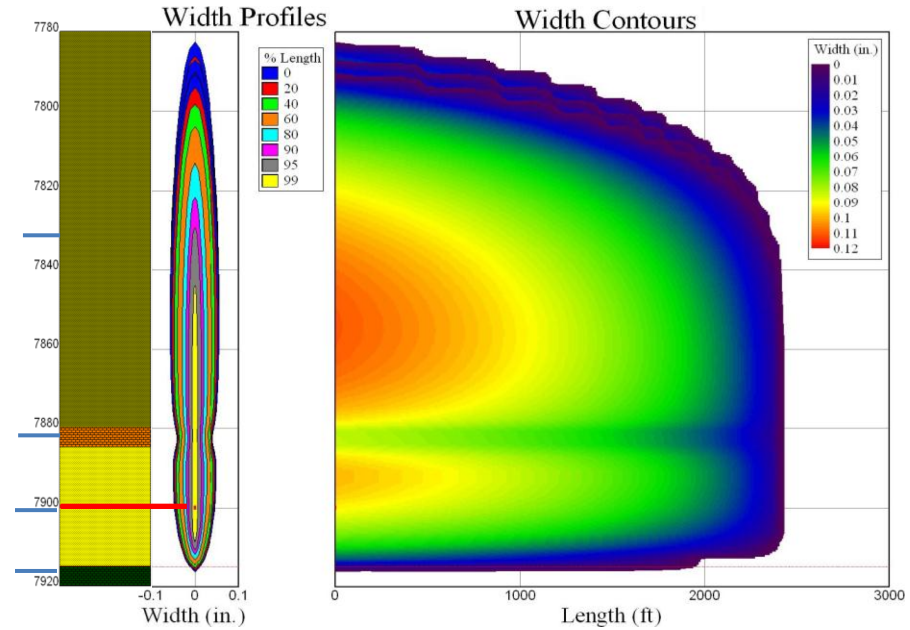


CO_2 and CH_4 Sorption Capacity



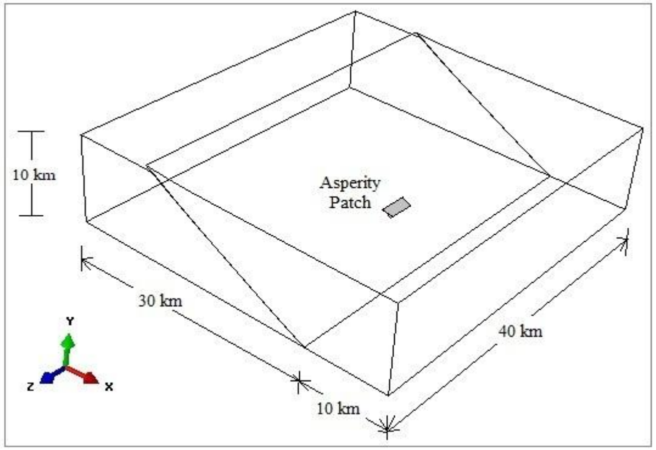
Flow and mechanical models predict fracture growth.

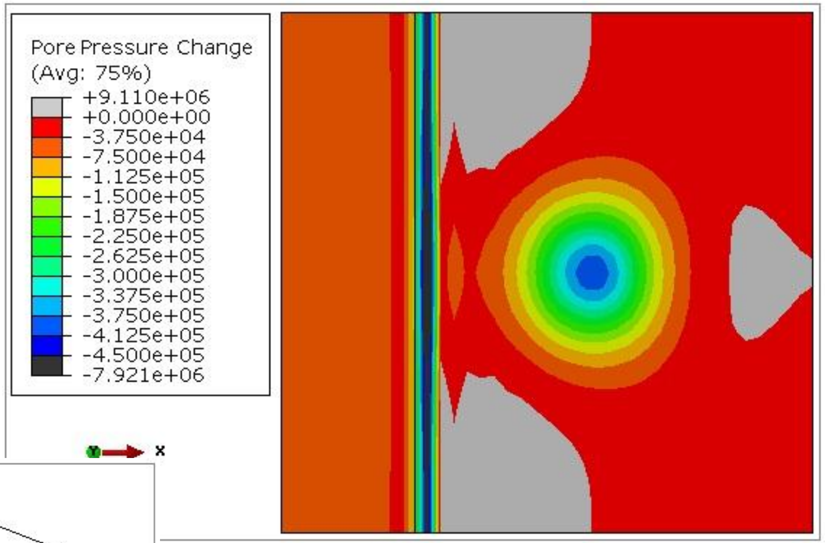




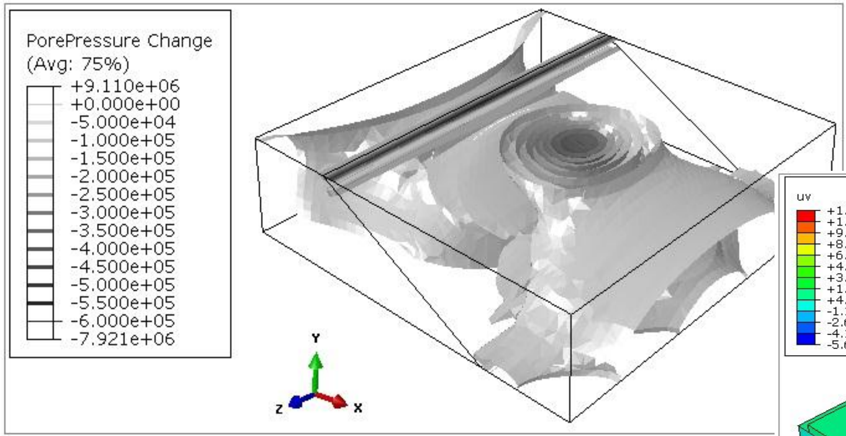
- **Allows the study of several operational and subsurface parameters:**
  - Rock strength
  - Type of frac fluid (CO_2, slickwater)
  - Amount and type of proppant
  - Injection rates and pressures

Also can predict pressure changes and ground deformations due to natural and injection activity.

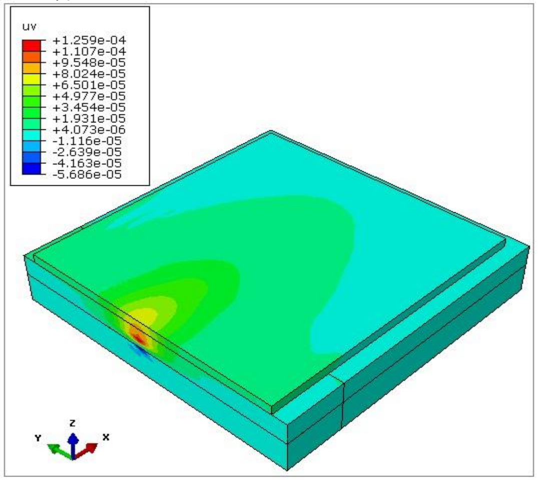




Pore pressure change on the model surface after sudden fault slip

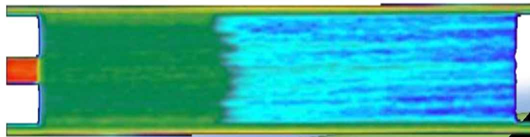


Pore pressure decrease region with 50,000 Pa cutoff



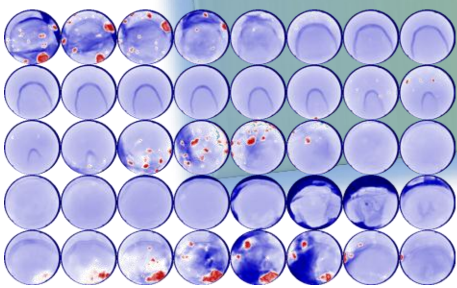
Ground deformation due to pressure changes cause by injection in the presence of a fault

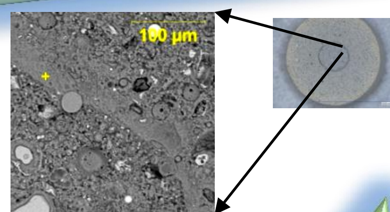
Modeling reservoir behavior involves processes from the pore to field scale.

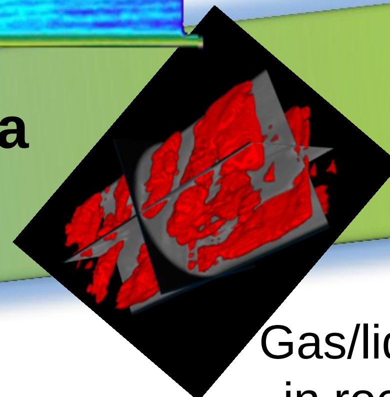


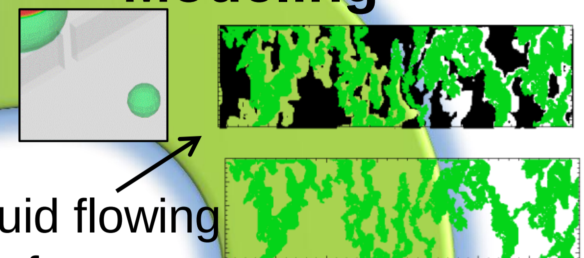
Data Conversion, CFD, and Pore Level Modeling

Micro-Scale Data Collection (CT, SEM, etc)

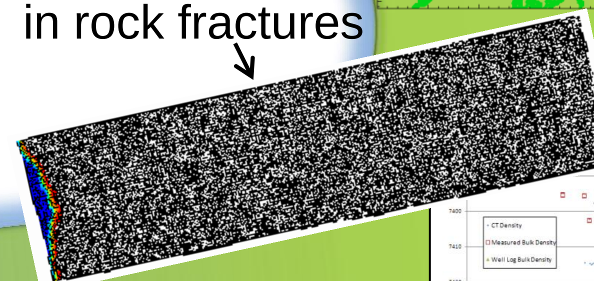




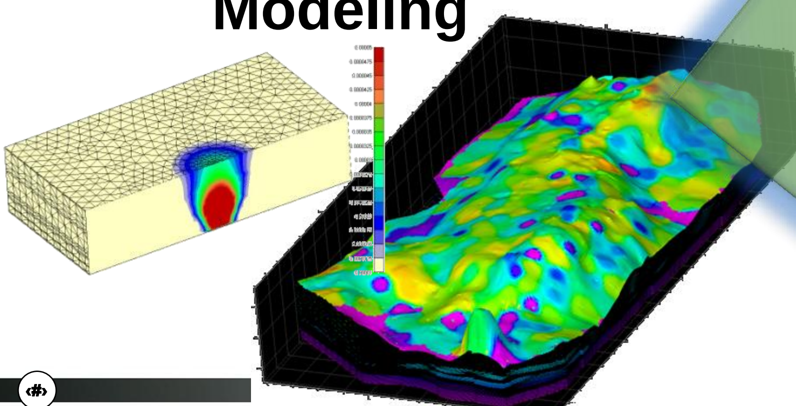




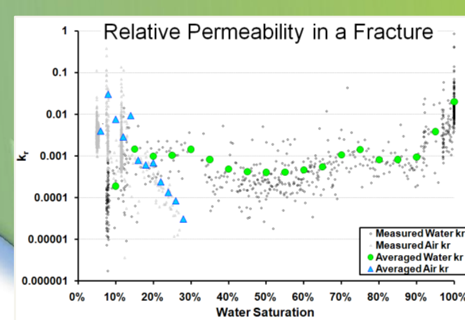
Gas/liquid flowing in rock fractures

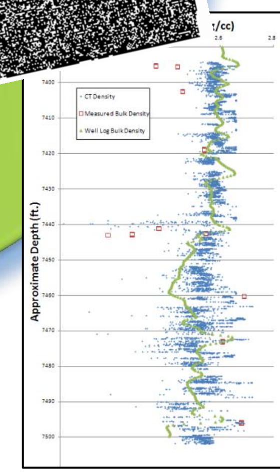


Reservoir-Scale Modeling



Multiscale Data Analysis

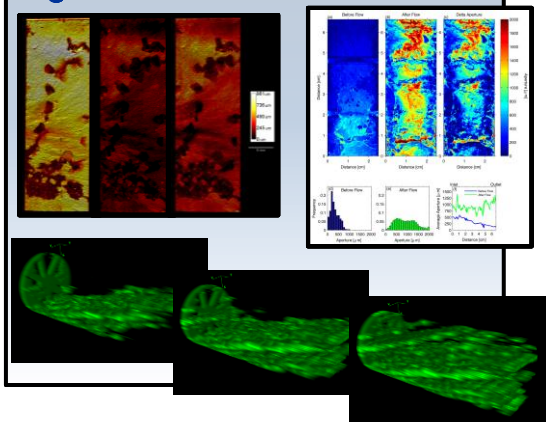




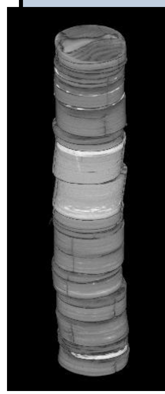
Comparison of Shale Density from CT Scans and Well Logs

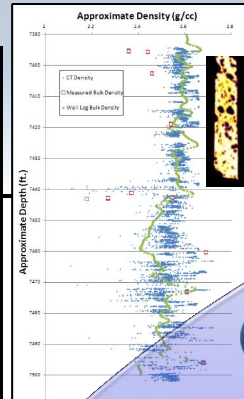
Flow through and imaging tools help validate models, understand behavior.

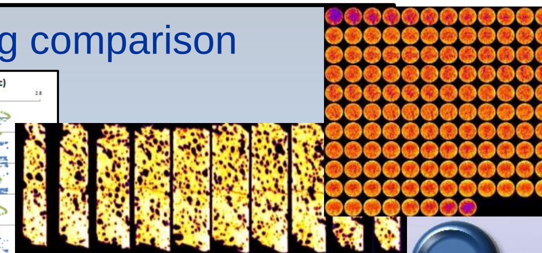
Measuring flow at *in situ* P, T, stress, and geochemical conditions



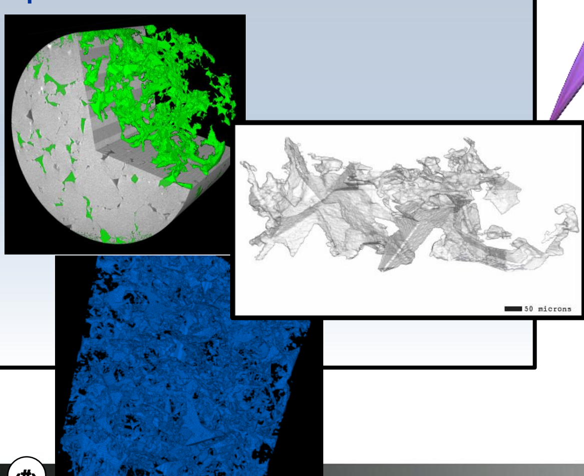
CT/well log comparison





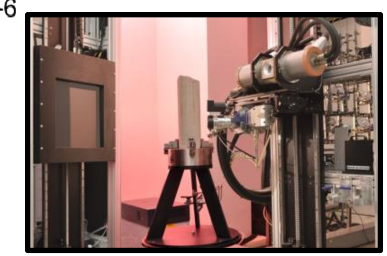


Simulating flow through pore and fracture networks

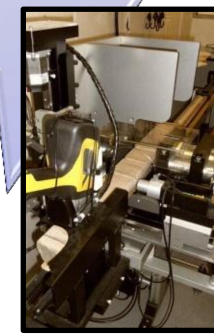


Micro CT Scanner
- Resolution 10^{-6} to 10^{-5} m
- Pore scale

Industrial CT Scanner
-10^{-6} to 10^{-3}m
- Pore & core scale
- Pressure & flow controls



Medical CT Scanner
-10^{-4} to 10^{-2}m
- Core scale
- Pressure, temperature, and flow controls



MSCL for geophysical logging

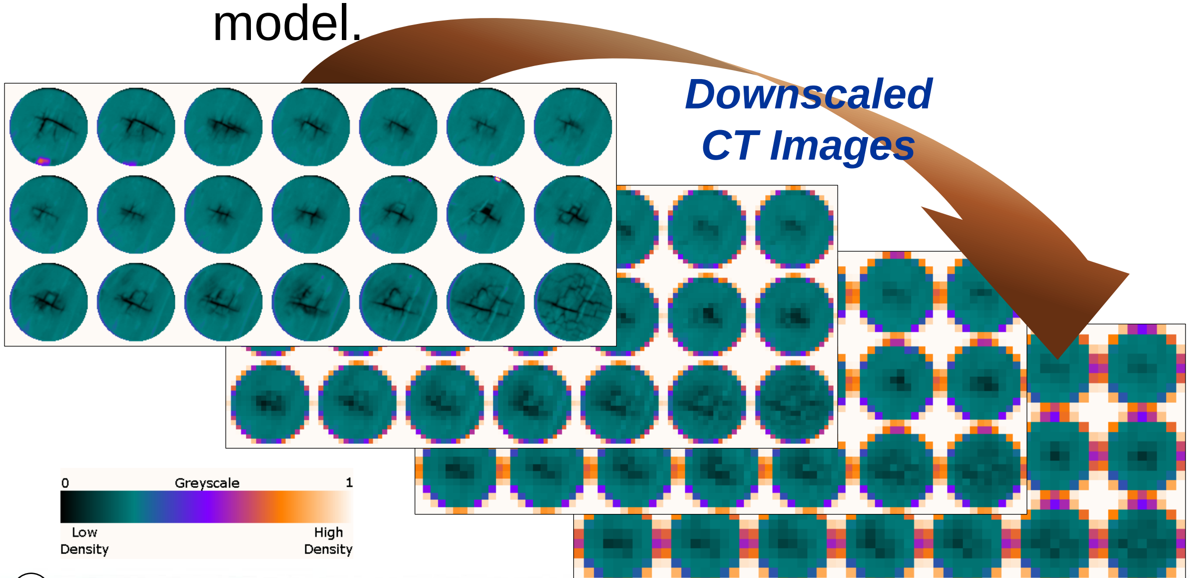
Current Collaborations

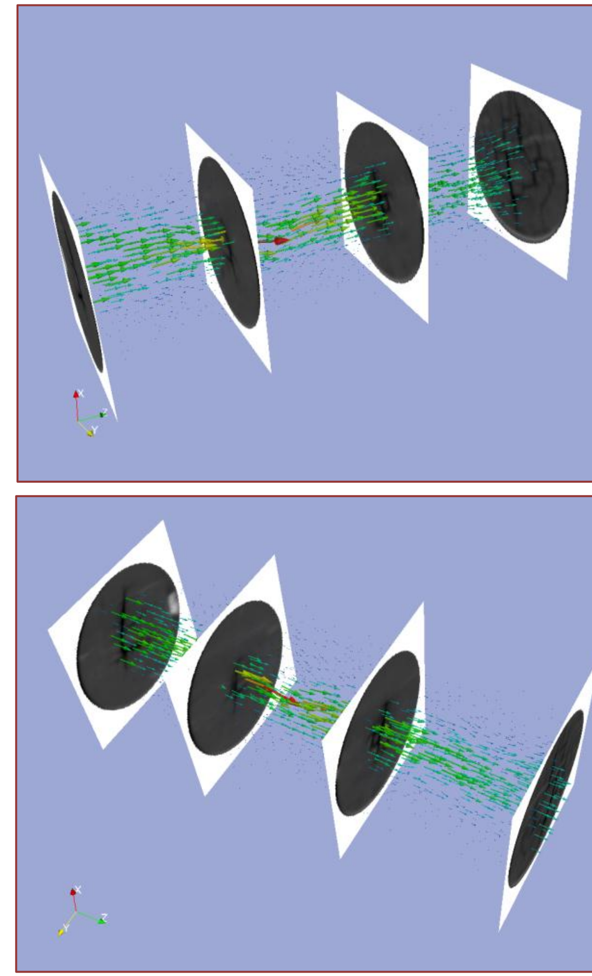
Los Alamos National Laboratory
Petrobras
Glori Energy
Pacific Northwest National Laboratory
Princeton University
NETL-RUA Regional University Alliance
The University of Texas at Austin
Chinese Academy of Sciences
Ormat
URS
Schlumberger
Lawrence Livermore National Laboratory

NATIONAL ENERGY TECHNOLOGY LABORATORY

Data from CT scans can be used to develop CFD models.

- **Computed tomography scans can be converted to computational fluid dynamics (CFD) simulations that solve the full Navier-Stokes equations of fluid conservation**
  - Systematic downscaling of high-resolution CT data required.
  - Automated conversion codes to generate permeable media representation in CFD model.

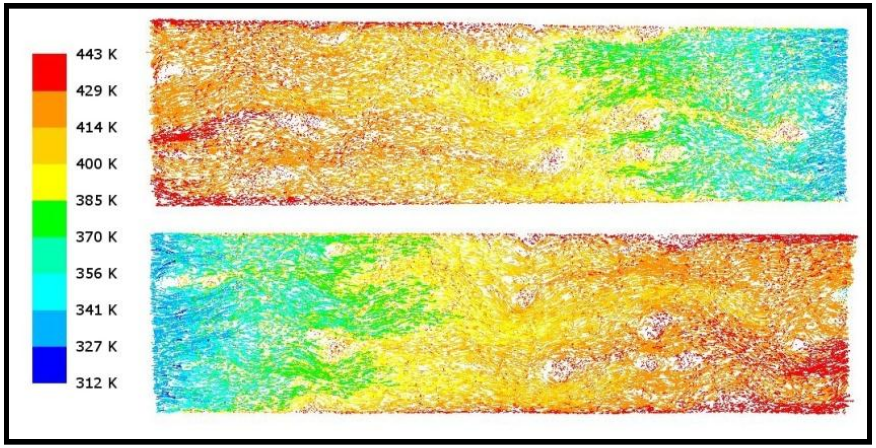




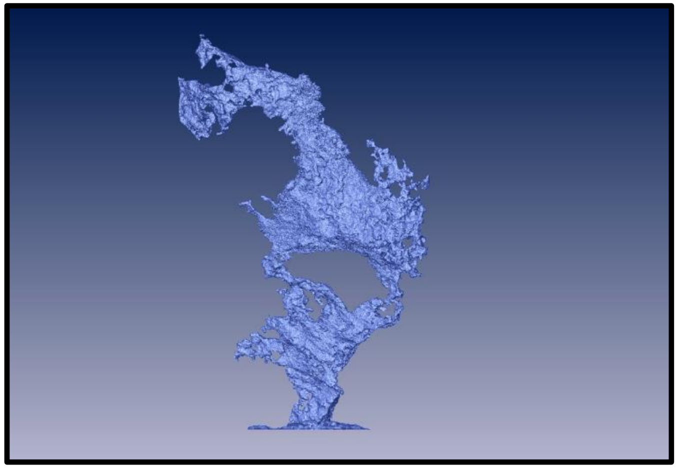
Simulated velocity vectors through fractured coal core

Modeling allows us to develop scaling relationships, study other processes.

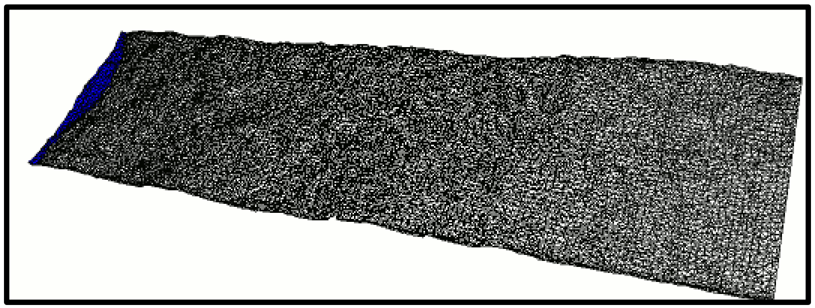
- **Applications to:**
  - Shale interactions with frac fluid
  - Long term production from shale
  - Geothermal reservoir management
  - Enhanced oil recovery techniques
  - …

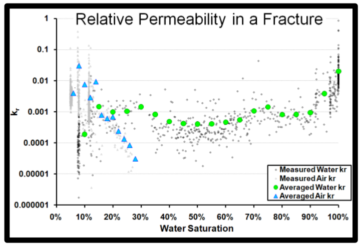


Simulated thermal transport from rock walls to geothermal fluids



High-resolution CT scan of a tortuous fracture in granitic rhyolite



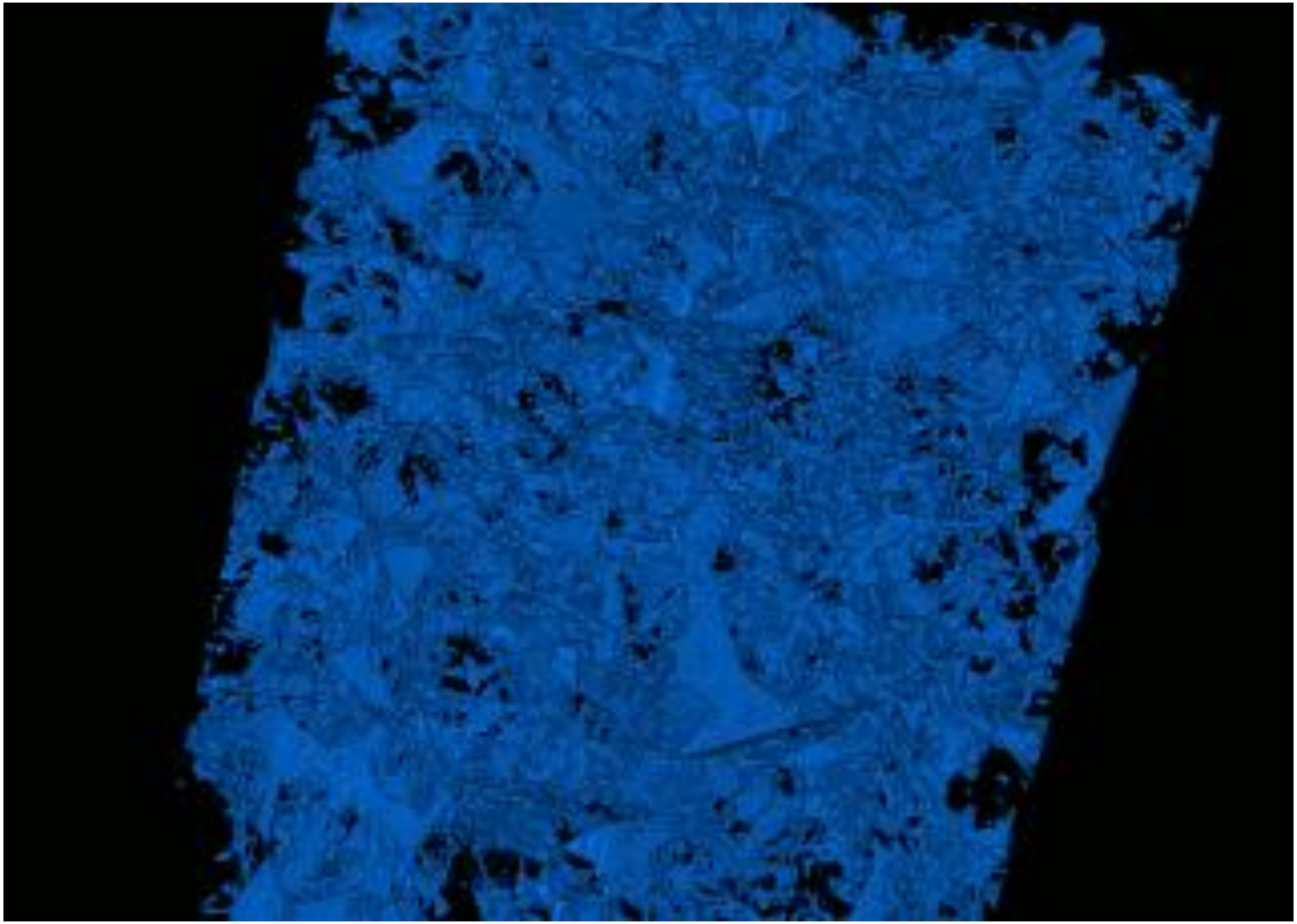


Air displacement of water from an open fracture in sandstone used to develop a relative permeability curve

Specific Focus: CO_2 as a Frac Fluid

- **Detection of gas/liquid phase (and sorption) fronts in sandstone, coal, shale**
  - CO_2 vs. brine vs. oil vs. gas
  - Detect saturation of different phases in different parts of the core
- **Simulation of production from shale given known saturations/sorption**
  - Discrete fracture flow simulator
  - Pore-scale modeling to determine k_r, etc.

Thank You



Chemical reactions change flow pathways in reservoirs and seals.

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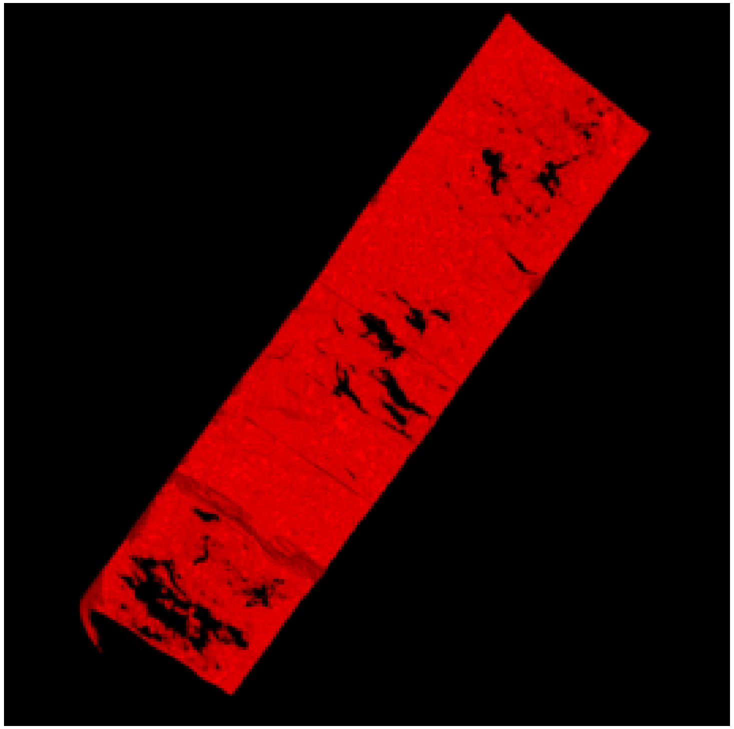
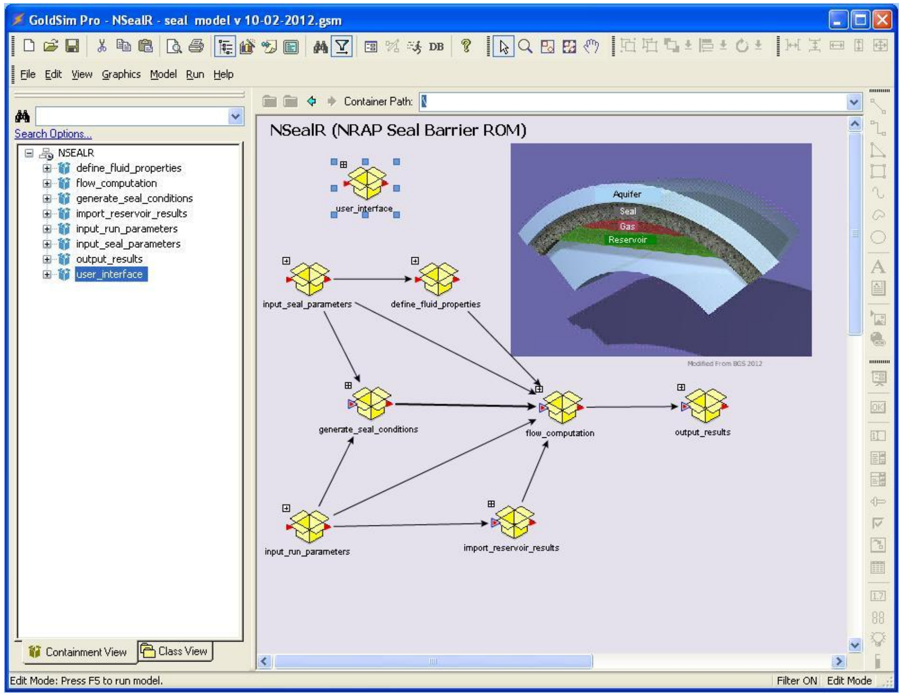
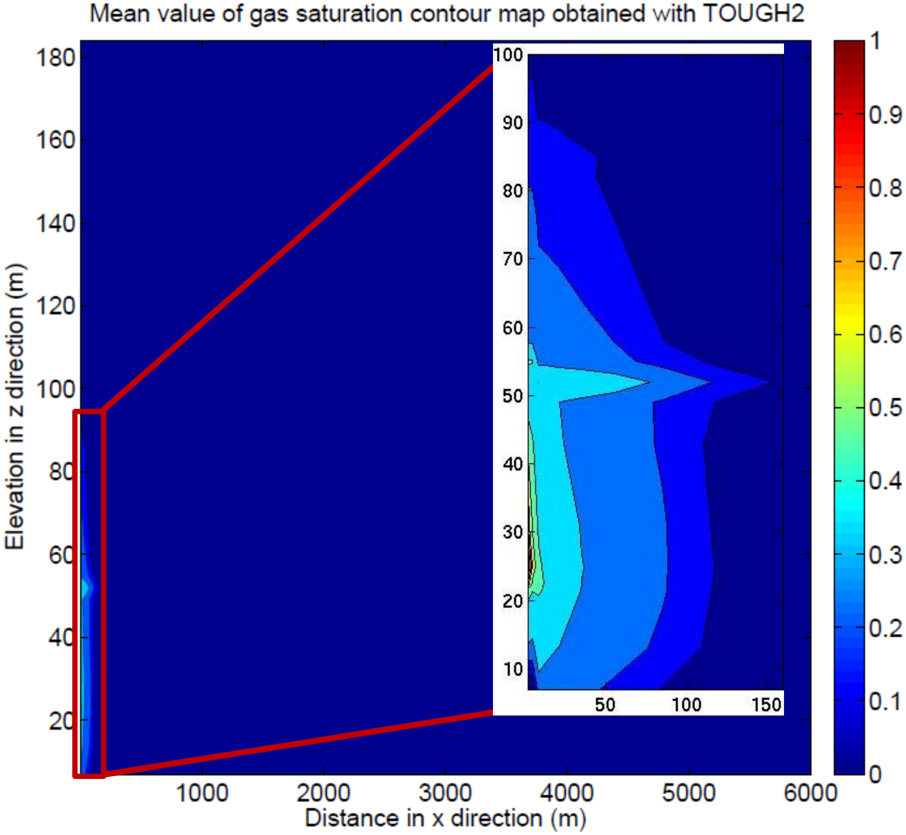
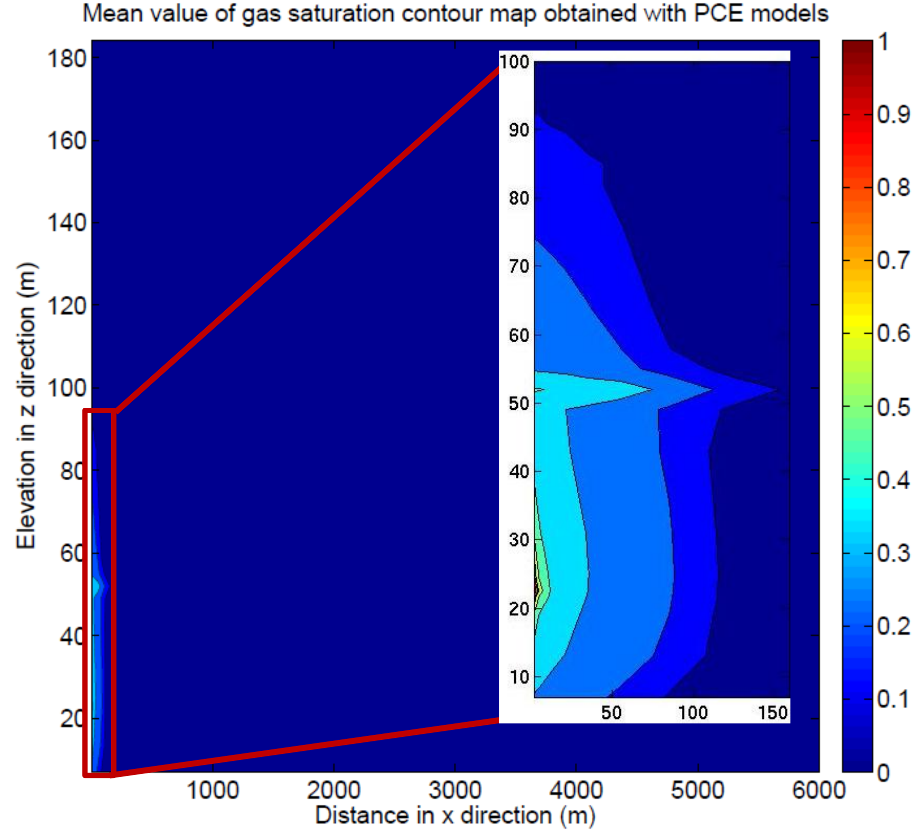
- Altered flow pathway within fractured cement obtained from flow through tests in the industrial CT scanner
- Link between geometric alteration and permeability
- Applicable to shales, wells, seals, reservoirs

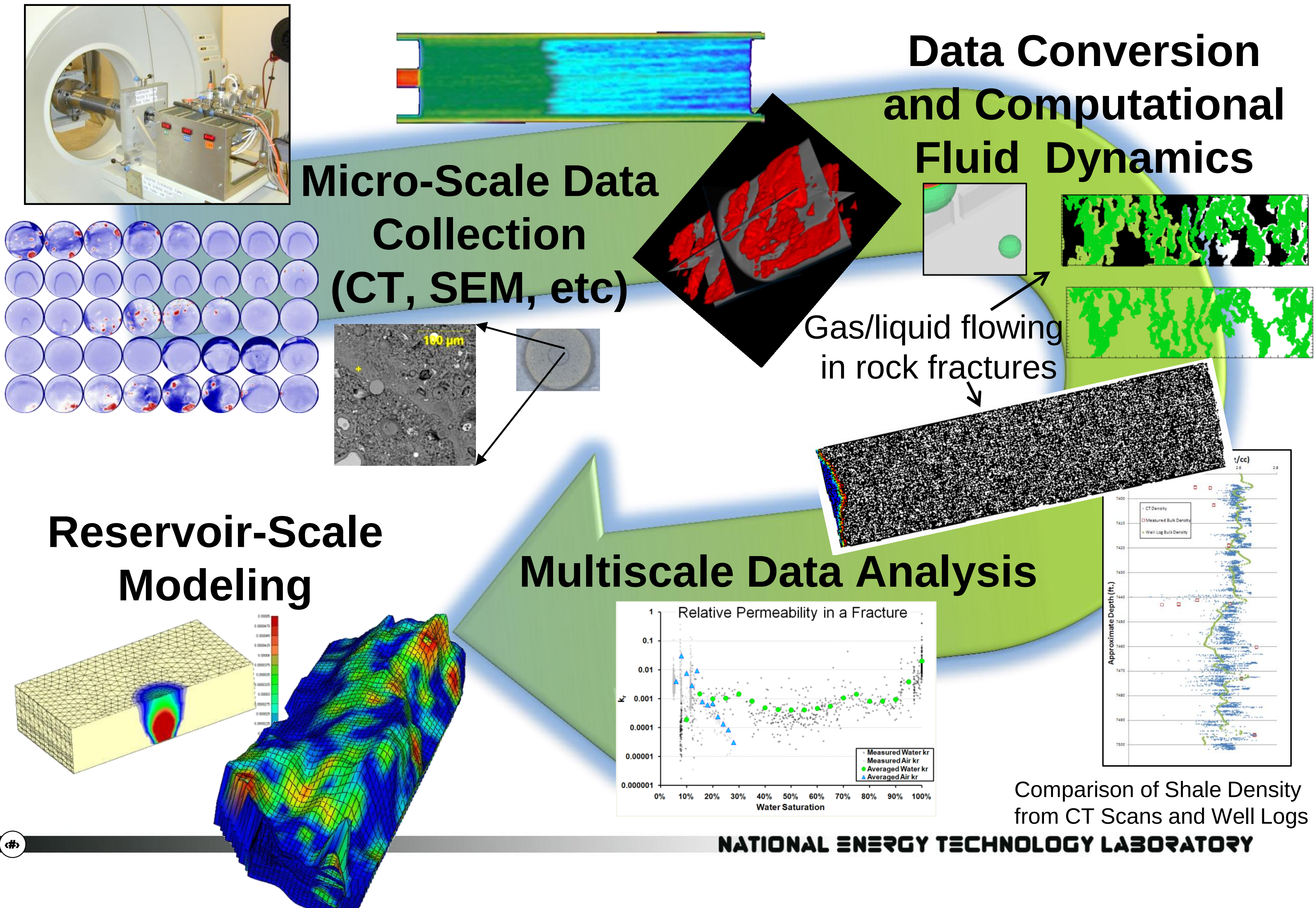



GoldSim Pro - NSealR - seal_model v 10-02-2012.gsm
File Edit View Graphics Model Run Help
Search Options...
Container Path:
NSealR (NRAP Seal Barrier ROM)
NSEALR
define_fluid_properties
flow_computation
generate_seal_conditions
import_reservoir_results
input_run_parameters
input_seal_parameters
output_results
user_interface
Aquifer
Seal
Gas
Reservoir
input_seal_parameters
define_fluid_properties
generate_seal_conditions
flow_computation
output_results
input_run_parameters
import_reservoir_results
Containment View
Class View
Edit Mode: Press F5 to run model.
Filter ON
Edit Mode


Mean value of gas saturation contour map obtained with TOUGH2
Elevation in z direction (m)
Distance in x direction (m)

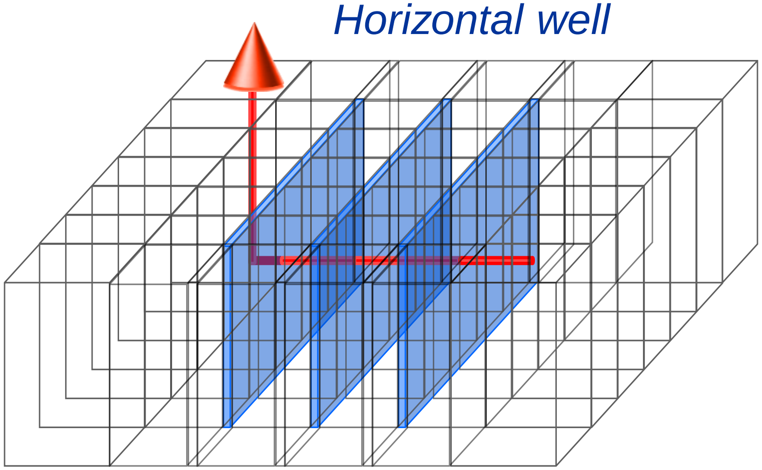

Mean value of gas saturation contour map obtained with PCE models
Elevation in z direction (m)
Distance in x direction (m)

Multiscale and Multiphase Flow



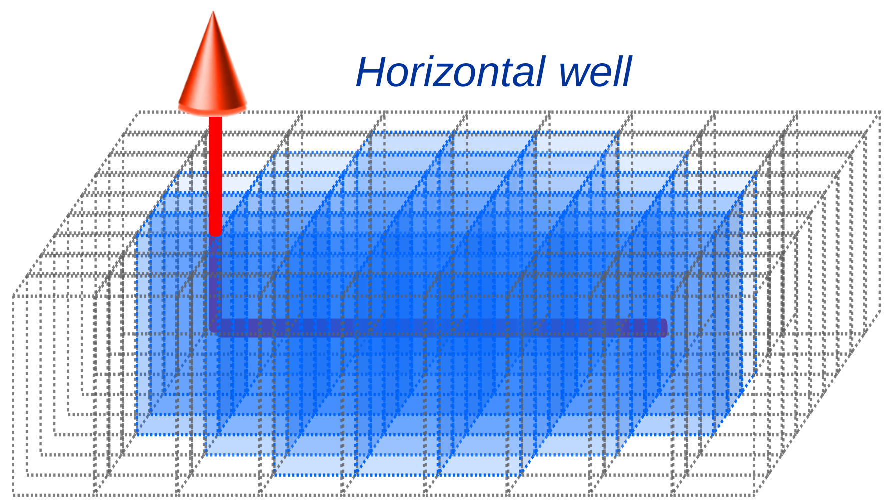
PSU-SHALECOMP model (Ertekin, PSU)

- *Define a "crushed zone" with same gas production performance) as an equivalent discrete fracture network model*
- *Apply this fracture zone representation in simulations using dual porosity, dual permeability compositional model of fractured low perm reservoirs*
- *Validate "crushed zone" model using available production data*
- *Use the validated "crushed zone" model to predict CO_2 storage potential*



Discrete transverse fracture representation

?
=

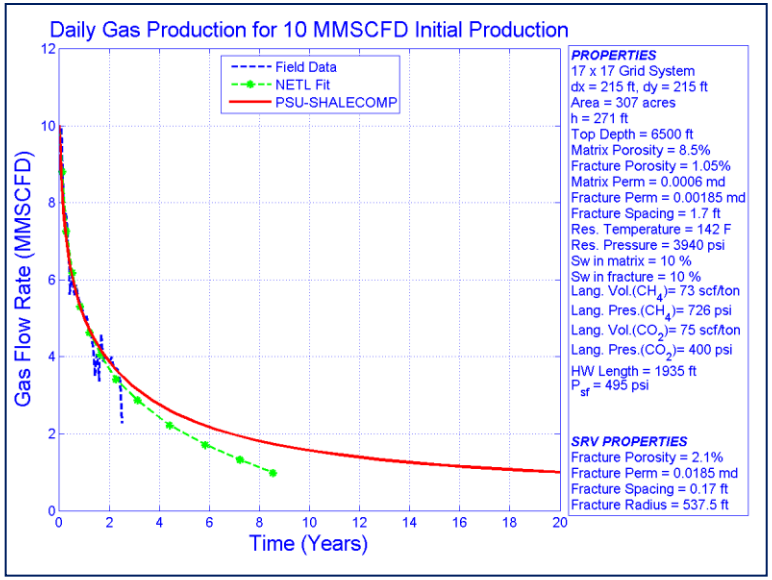


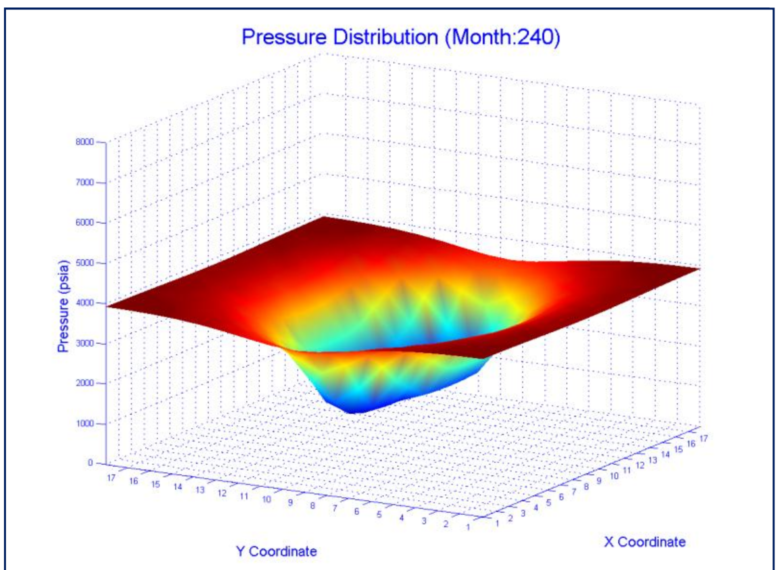
Crushed zone representation

Content Contributed by: *Turgay Ertekin, Penn State University Department of Energy and Mineral Engineering*

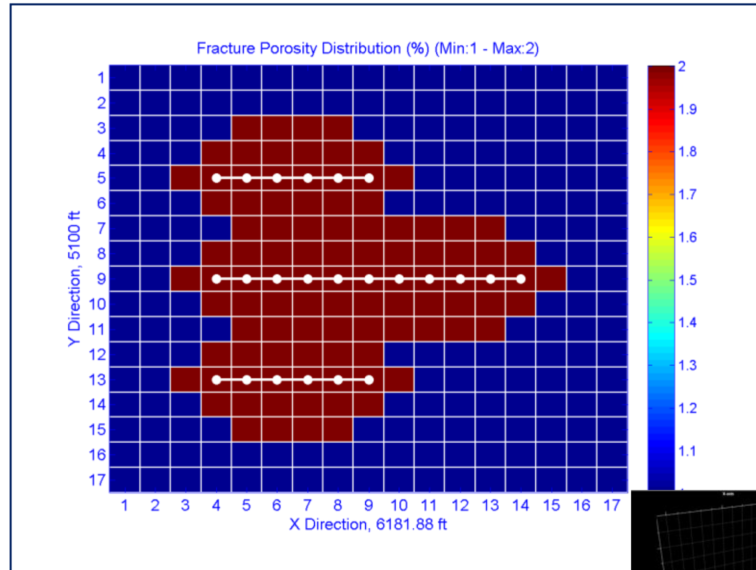
PSU-SHALECOMP

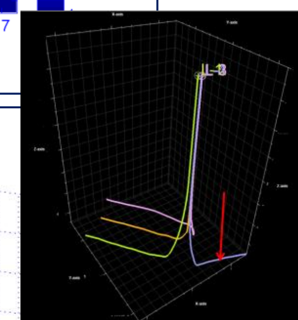
Single lateral

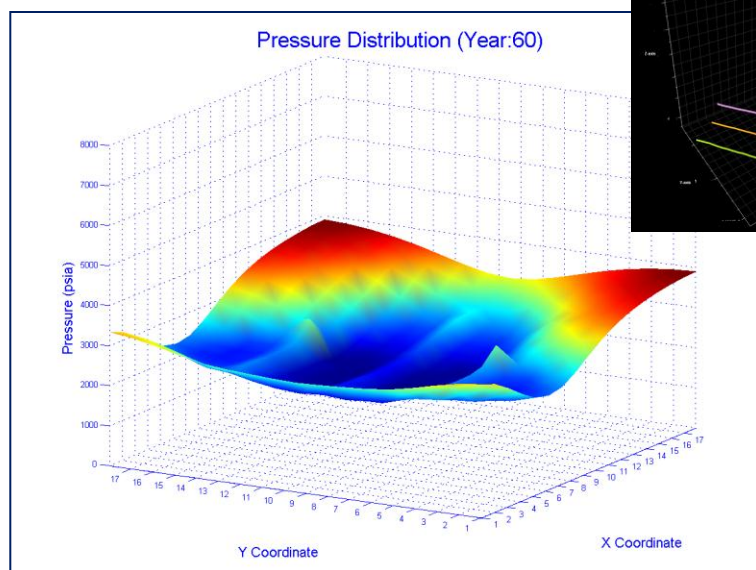




Multi-lateral Well Pad





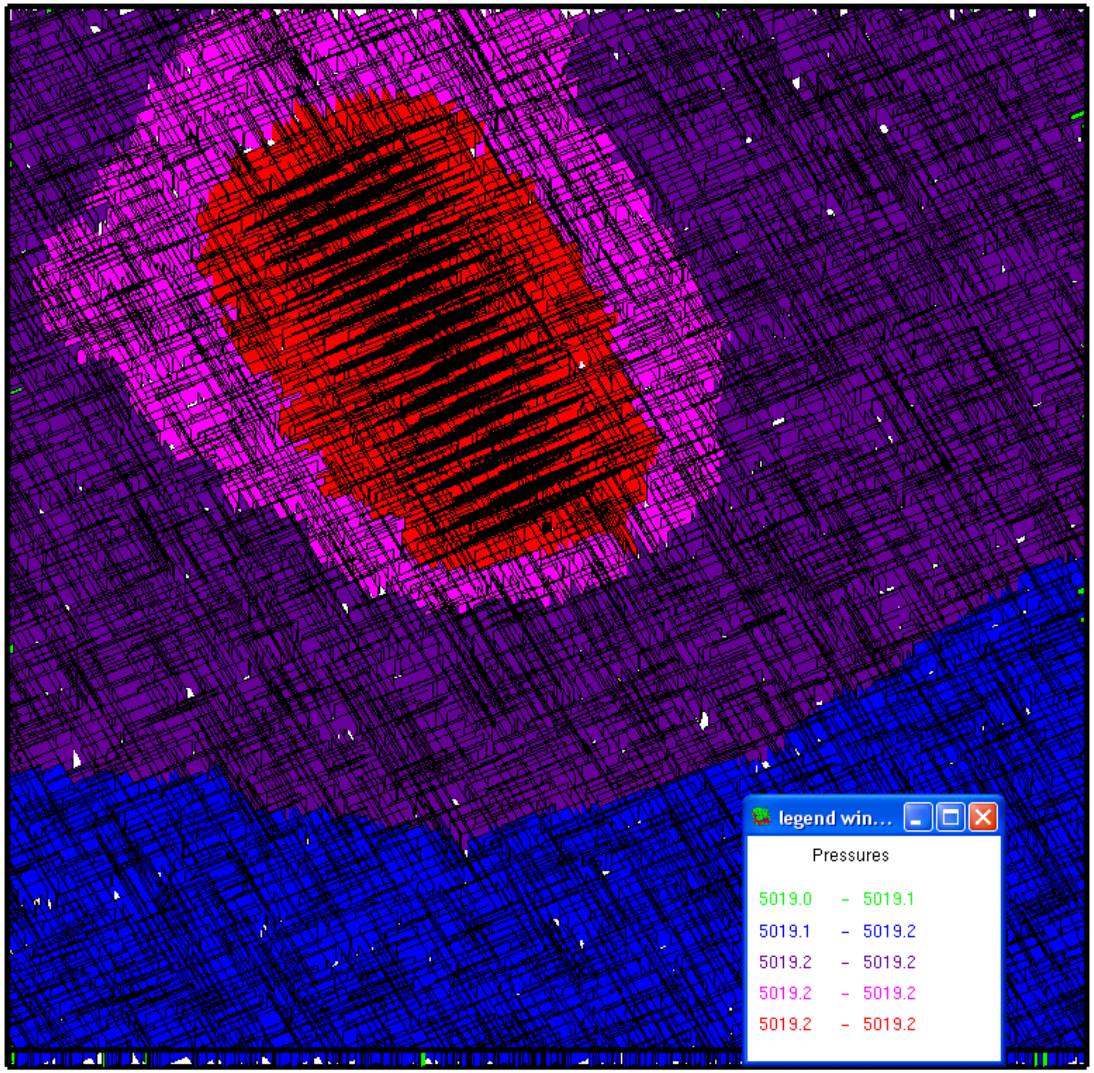


Content Contributed by: *Turgay Ertekin, Penn State University Department of Energy and Mineral Engineering*

Initiated Development of Fracture Network-Based Simulation of CO_2 Storage in Shale

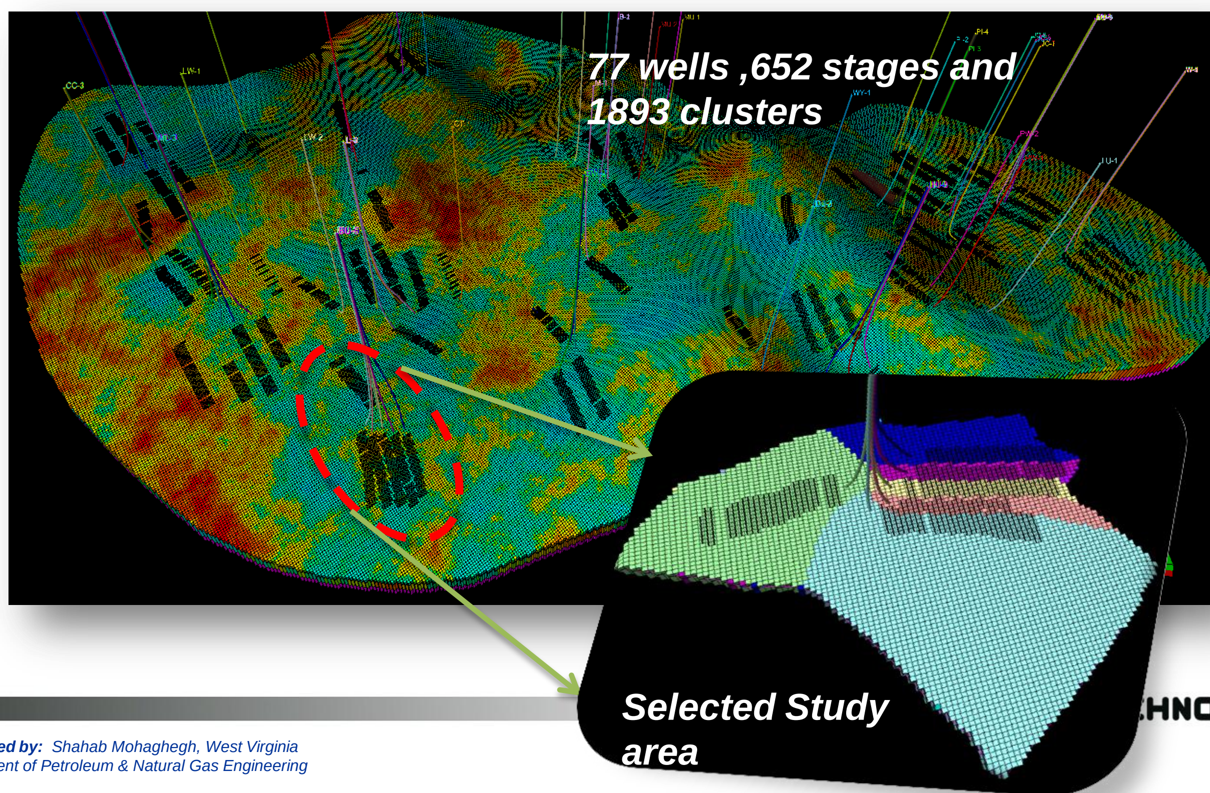
2D view of FracGen/NFFlow realization for Marsellus shale.

Engineered hydraulic fractures (in this case a single lateral with 20 fractured stages) are introduced into a network of pre-existing natural fractures.



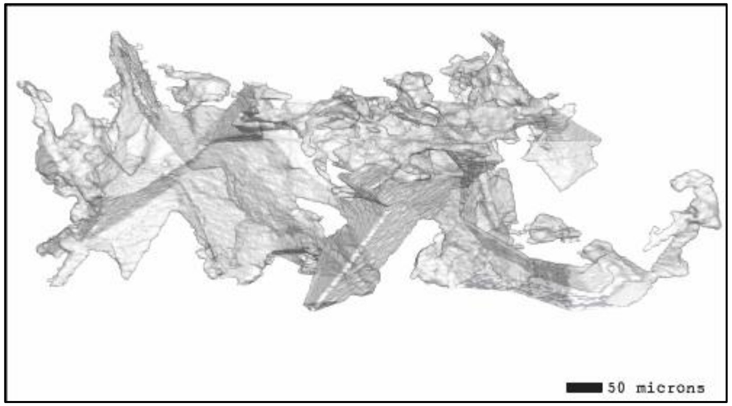
Conventional Simulation & AI-based modeling
(Mohaghegh et al.)

- Acquire real data on gas production from a set of shale gas wells
- Use that set of data to develop population statistics
- Develop a history-matched model of shale gas production (29 month production history) using a conventional reservoir model
- Project forward to economic limit before initiating CO_2 injection
- Develop a surrogate reservoir model based on the history matched model to predict wellpad performance under CO_2 loading

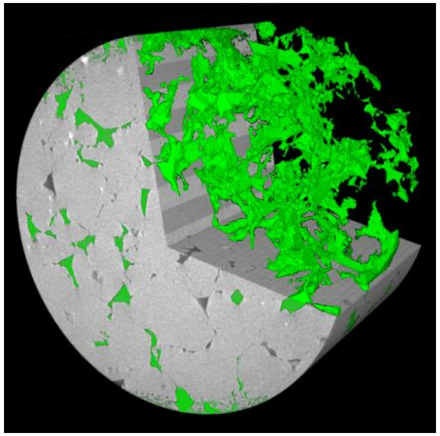


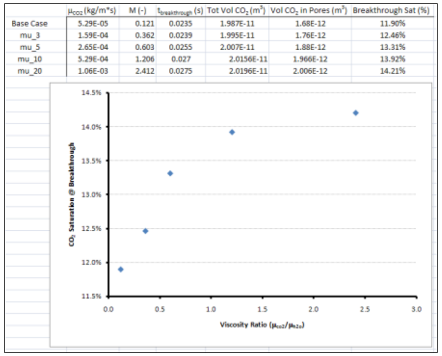
CT Scans to CFD Simulations: Pore Level Models

- **Mt Simon sandstone pores**
  - 1 x 1 x 3.5 mm domain. CO_2 & brine properties @ depth approximate of 5800 ft
  - Series of variations to complement flow through tests in the medical CT scanner performed with a university partner looking at bulk transport

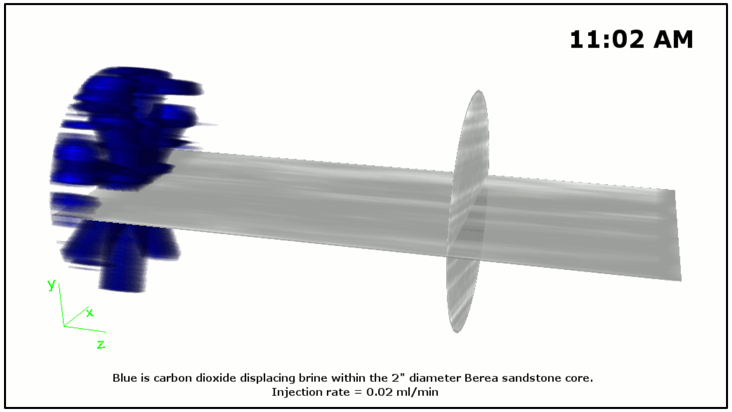


Simulated CO_2 transport within individual sandstone pores



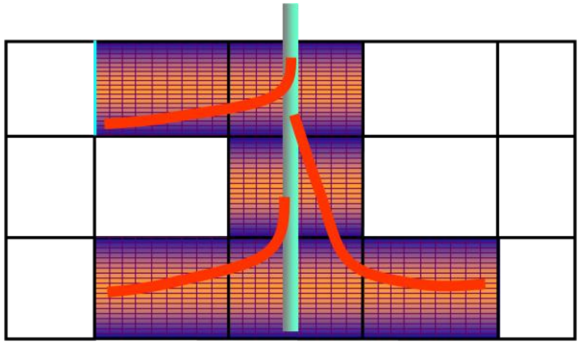


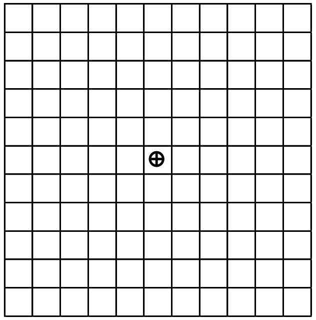
	μ_{CO2} (kg/m*s)	M (-)	$t_{breakthrough}$ (s)	Tot Vol CO_2 (m^3)	Vol CO_2 in Pores (m^3)	Breakthrough Sat (%)
Base Case	5.29E-05	0.121	0.0235	1.987E-11	1.68E-12	11.90%
mu_3	1.59E-04	0.362	0.0239	1.995E-11	1.76E-12	12.46%
mu_5	2.65E-04	0.603	0.0255	2.007E-11	1.88E-12	13.31%
mu_10	5.29E-04	1.206	0.027	2.0156E-11	1.966E-12	13.92%
mu_20	1.06E-03	2.412	0.0275	2.0196E-11	2.006E-12	14.21%



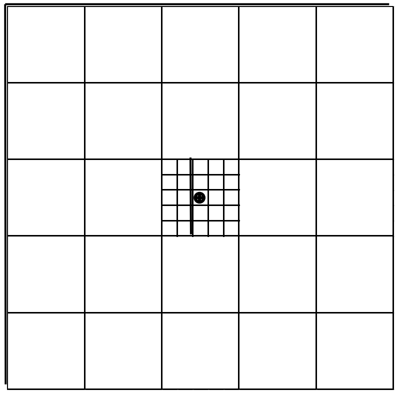
Experimental CO_2 transport within a sandstone core

Advanced numerical techniques are being applied to enhance simulation efficiency.





Global Grid Refinement



Local Grid Refinement

	Time Consumed on each Newton-Raphson Iteration (seconds)		
Number of Unknowns	Direct solver	GMRES	Parallel and Preconditioned GMRES
100	0.001	0.003	0.079
900	0.047	0.090	0.095
9000	3.950	0.137	0.145
40000	84.620	0.610	0.342