Mechanistic Approach to Analyzing and Improving Unconventional Hydrocarbon Production

Project #FE-954-18-FY18

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U.S. Department of Energy

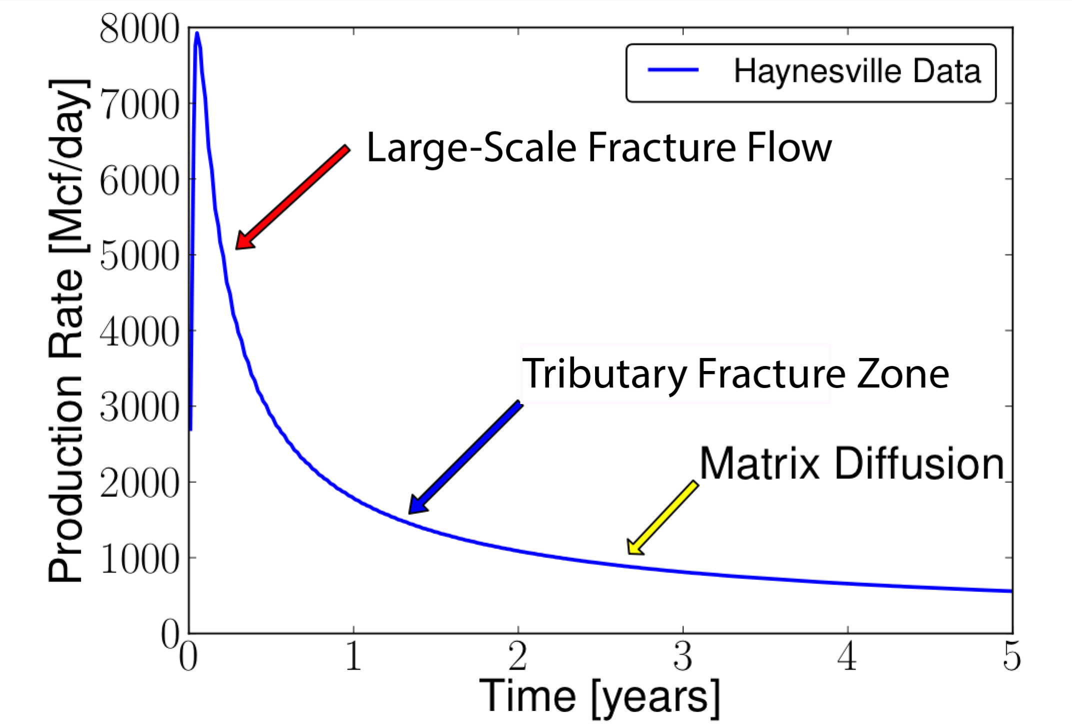
National Energy Technology Laboratory

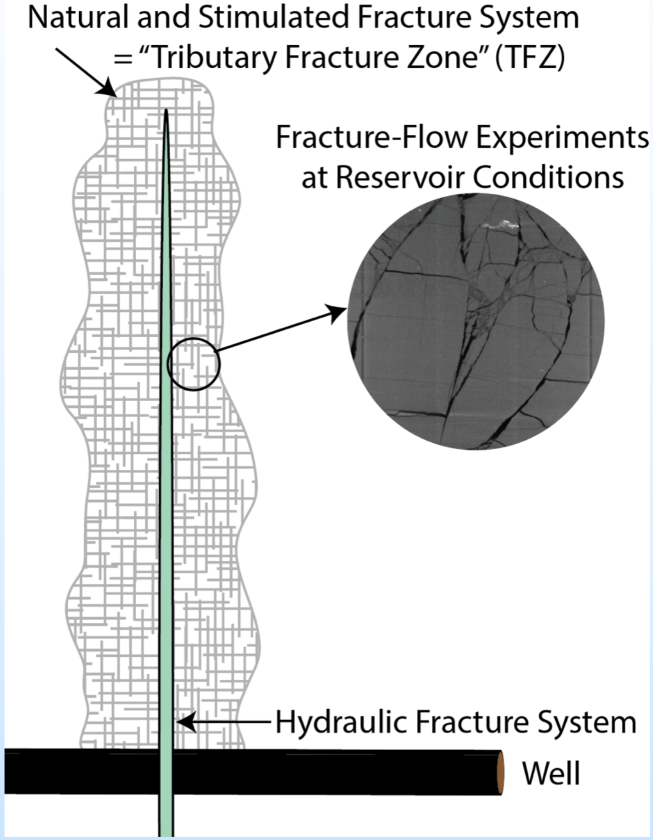
Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

Benefit to Program

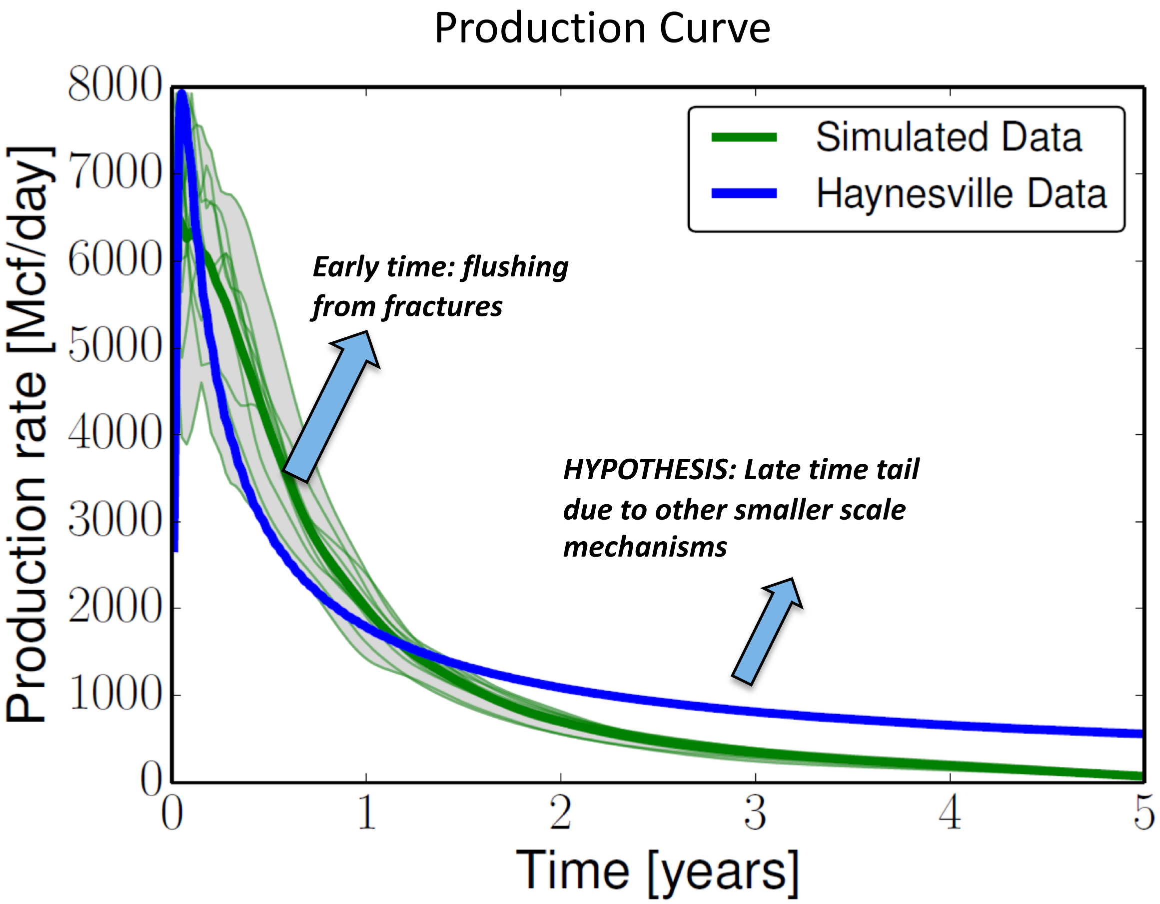
- Our approach to doubling recovery efficiency is to identify and enhance key production mechanisms operating at multiple scales (10 year scope)
- We aim to develop software tools and new reservoir management strategies to transform industrial practices (5 year scope)





Hypothesis: Production curves reflect physical and chemical phenomena that change with time

Our previous results show multiscale processes are important for mid- & long-term production


Production Curve

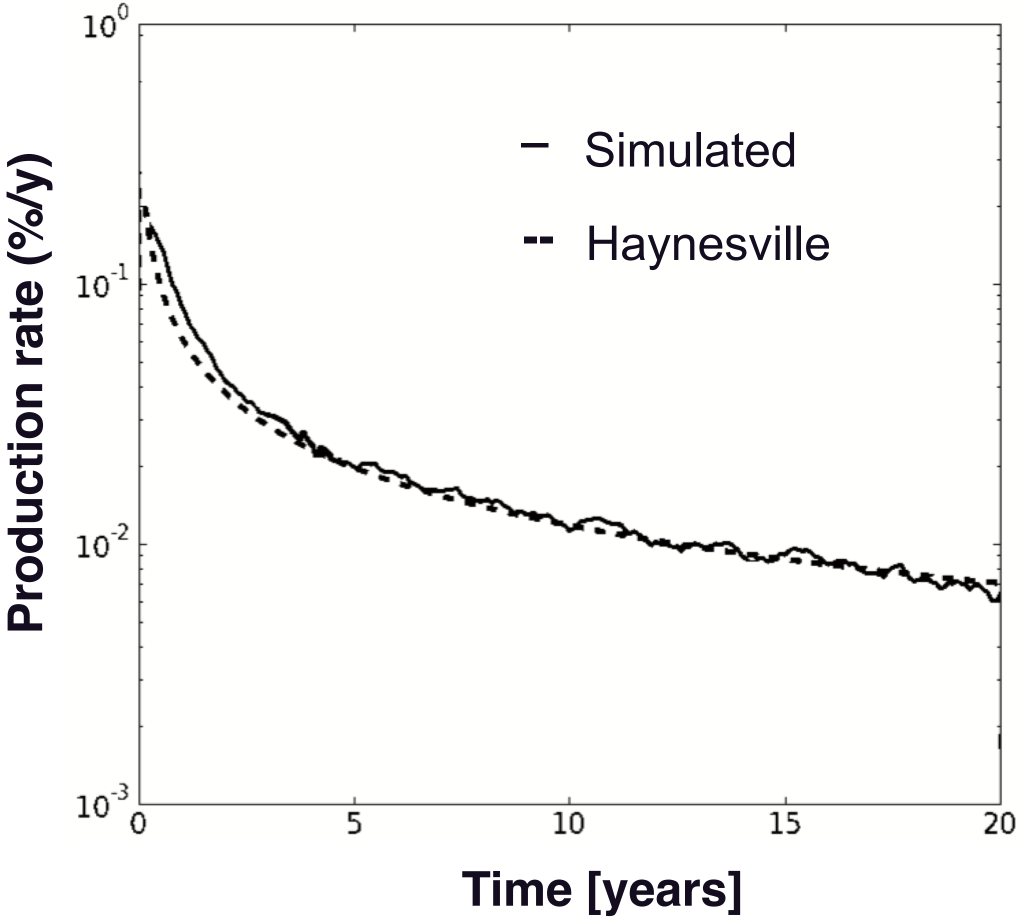
Early time: flushing from fractures

HYPOTHESIS: Late time tail due to other smaller scale mechanisms

Discrete Fracture Network simulations reveal:

- Initial peak and early (< 1 year) production arises from drainage of large hydraulic and natural fractures
- Connection of HF to an extended large-scale natural fracture allows continued but declining production
- Observed later time (> 2 years) production of 80% of hydrocarbon resource requires engagement of smaller-scale features: tributary fracture zone and ultimately the matrix

Simulations after adding matrix diffusion and transport in tributary zone fractures

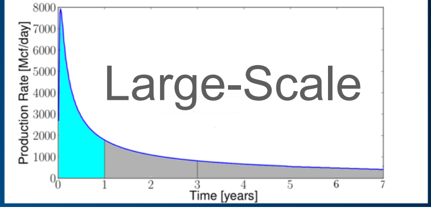


Lovell, A.E et al., 2018. Extracting hydrocarbon from shale: An investigation of the factors that influence the decline and the tail of the production curve. *Water Resources Research*, *54*(5), pp.3748-3757.

The Los Alamos effort is focusing on pressure-management impacts on production

- **Focus: Pressure Management**
- **Reservoir: Gas-dominated shale (Marcellus Shale)**
  - Samples of Marcellus shale outcrop (via D. Crandall)
  - Samples of MSEEL-1 (via D. Crandall)
- **Reservoir-Scale Analysis of Pressure Management—PI Karra**
  - Discrete Fracture Network Modeling—Physics-Based Prediction of Production
  - Graph Theory and Machine Learning—Real Time Simulation
  - *Leveraging: LDRD on Machine Learning and Fracture Systems*
- **Fracture Response to Pressure—PI Carey**
  - Experimental fracture-permeability studies—Basic data
  - Formulation of fracture-stress response—output to reservoir scale study
  - *Leveraging: Basic Energy Sciences study of fundamental fracture behavior*
- **Matrix Response to Pressure—PI Xu**
  - Experimental nanopore-hydrocarbon behavior—Basic data
  - Simulation of matrix transport processes—Basic data
  - Formulation of matrix-stress response—output to reservoir study
  - *Leveraging: LDRD on impact of nano-confinement*

Discrete Fracture Network (DFN) Modeling of Pressure Management



Science Question:

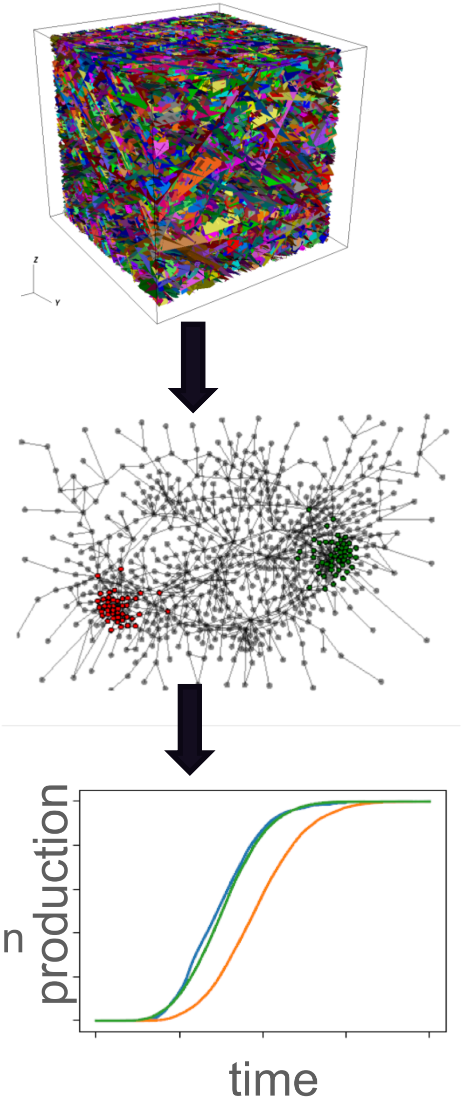
How can experiments and field data be developed into an effective predictive tool?

Motivation

- Uncovering critical mechanisms requires modeling at multiple scales in a physics-based framework
- Mechanism-interactions combined with evolving pressure and chemistry create significant challenges
- A tool facilitating real-time decision making is needed

Objectives

- Develop DFN models with multi-scale, physical processes derived from field and experimental data
- Use graph theory and machine learning to allow rapid simulation and decision making

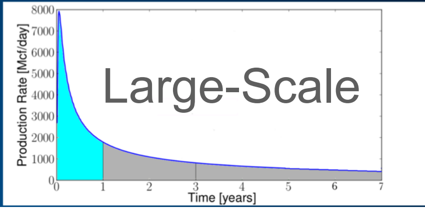


High fidelity DFN

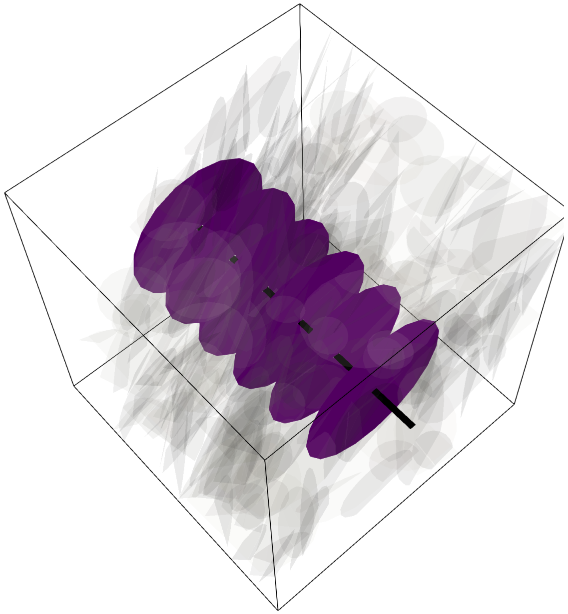
Graph theory

Rapid Simulation

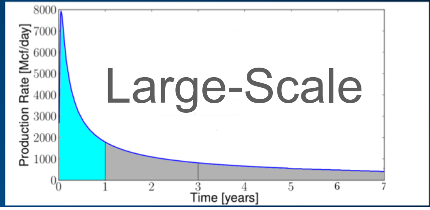
Real-Time Decision Making Using Graph-Based Representations of Discrete Fracture Networks



- Discrete fracture networks allow physics-based simulation of fracture-matrix transport
- However DFNs are computationally expensive
- Thousands of realizations are needed to quantify uncertainty
- Speed is needed to permit real-time decision making
- Graph theory excels in capturing behavior of structured systems
- Machine learning is used to enhance fidelity of the graph-based representation
- Speed-up of 3-4 orders of magnitude achieved



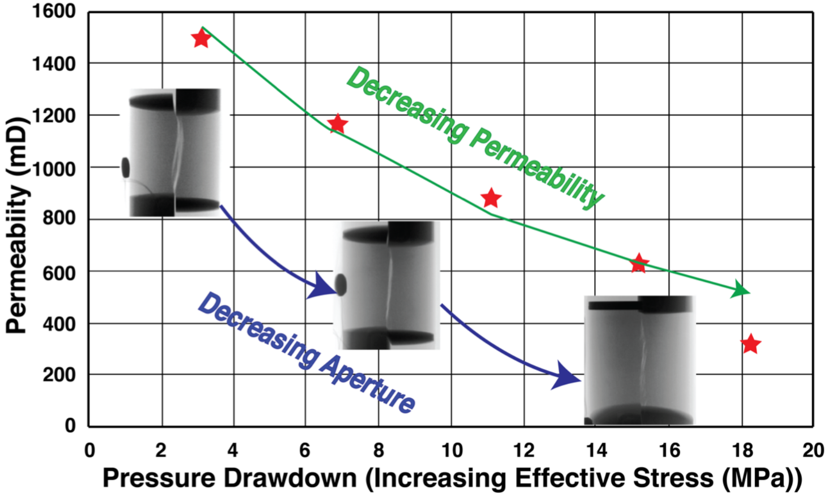
Impact of Pressure Drawdown on Production: Incorporation in Discrete Fracture Networks



- As pore-pressure falls, effective stress increases
  - Potential for loss of fracture permeability and production
- Integrate Bandis et al. (1983) model into physics-based modeling approach (PFLOTRAN)

$$b = b_{\max} + A\sigma_n' + Bb\sigma_n'$$

where b is fracture aperture, $b_{\max}$ is maximum aperture,
$b_{\min}$ is minimum aperture,
σ_n' is the effective normal stress
A and B are fit parameters

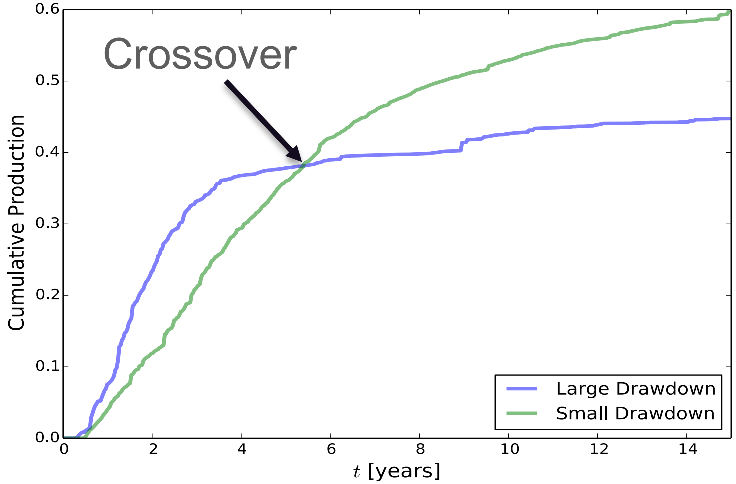


- Instead of estimating A and B, we make direct experimental
- Observations
- Hydraulic aperture:

$$A = 5.794 * 10^{-5}; B = 0.0136; b_{\max} = 0.00342$$

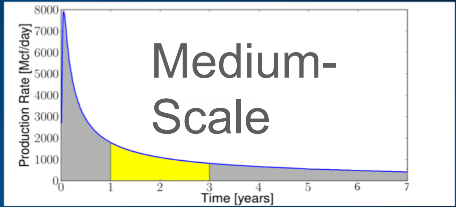
- Dilatant aperture:

$$A = 6.312 * 10^{-3}; B = 0.03223; b_{\max} = 0.1958$$



- **By including accurate, experimental-based geomechanics we avoid heuristic parameter fitting and provide a robust modeling framework from which to build graph-based models**

Fracture Properties of Marcellus Shale: Barton-Bandis Parameters—PI B. Carey



Science Question:

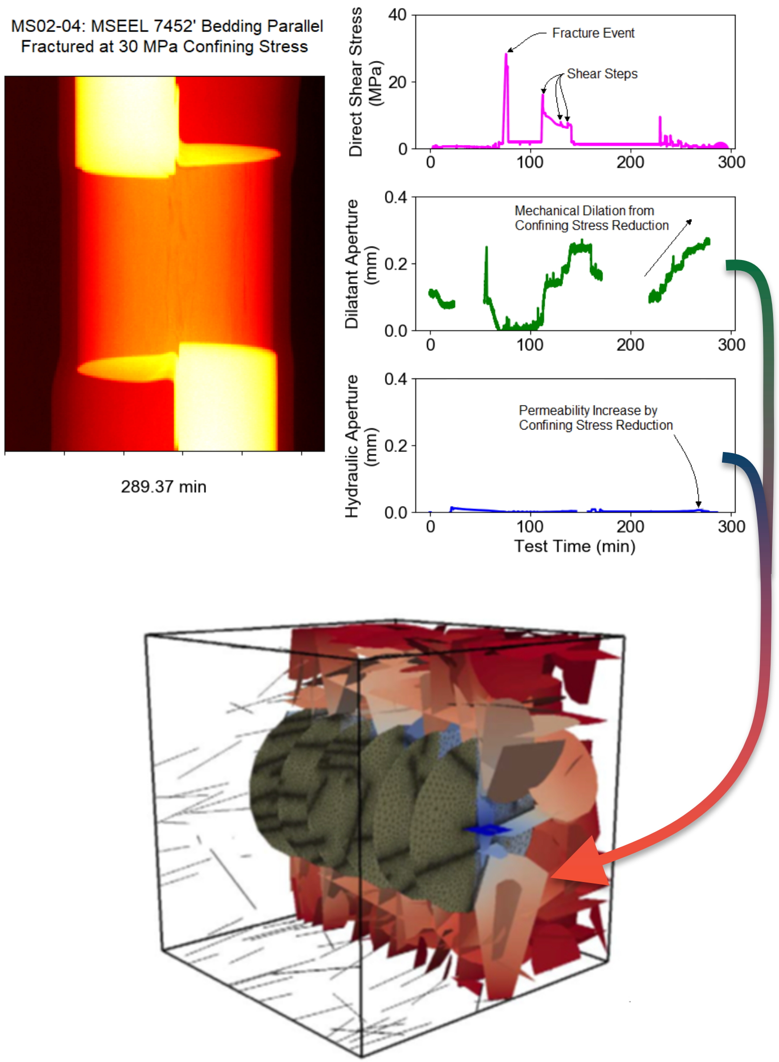
How can fractures be optimized to enhance ultimate oil and gas recovery?

Motivation

- Unconventional oil and gas production is made possible by rock fractures.
- Fracture *storativity* and *permeability* can strongly affect recovery efficiency.
- Laboratory experiments provide data needed for predictive and diagnostic modelling of unconventional plays.

Objectives

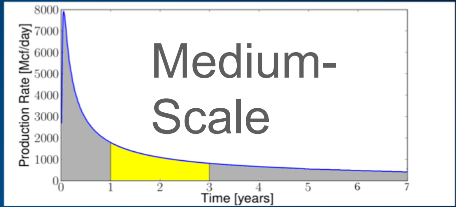
- Complete triaxial direct-shear testing on Marcellus shale, characterizing fracture aperture at reservoir conditions.
- Formulate Barton-Bandis relations
- Integrate measurements into a fracture network modelling workflow.



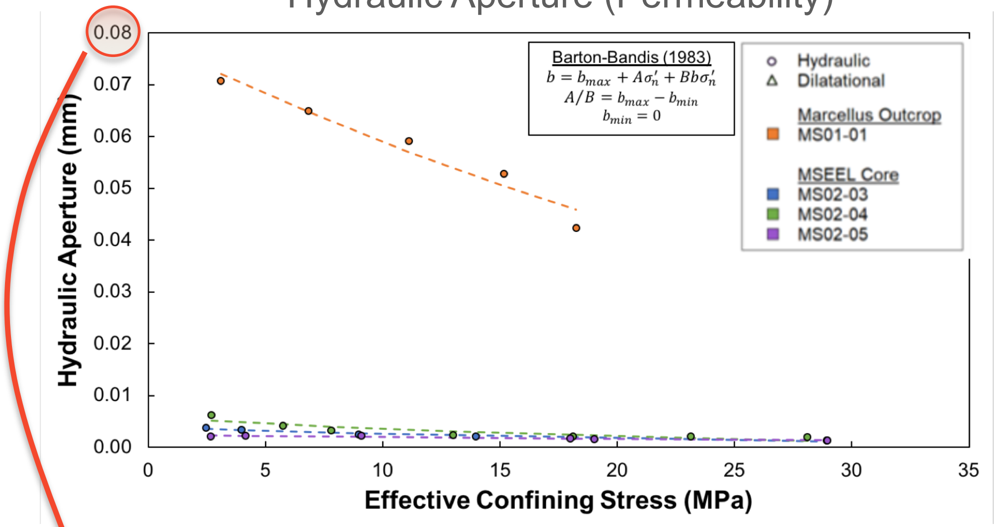
Task 4: Fracture Properties

Barton-Bandis Results:
Fracture Aperture and Drawdown Pressure

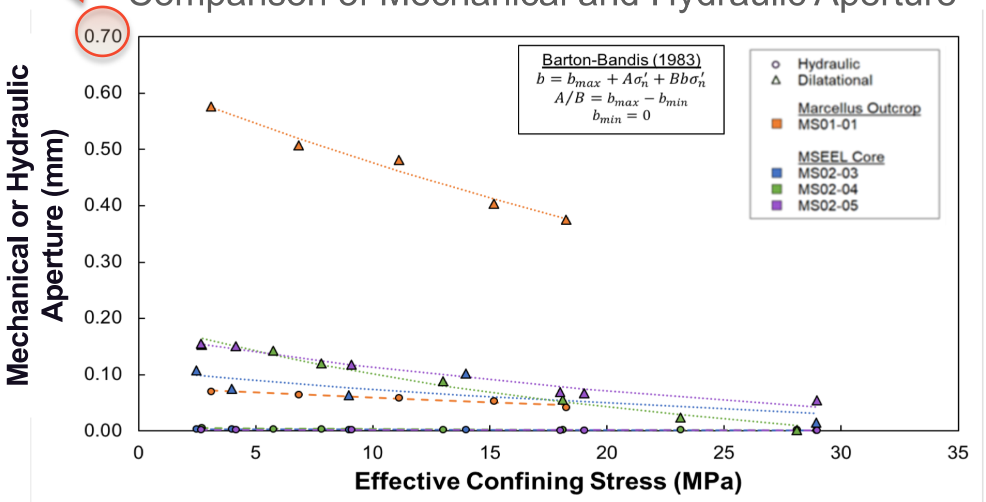
Presented at URTeC 2019 (Welch et al.)



Hydraulic Aperture (Permeability)



Comparison of Mechanical and Hydraulic Aperture



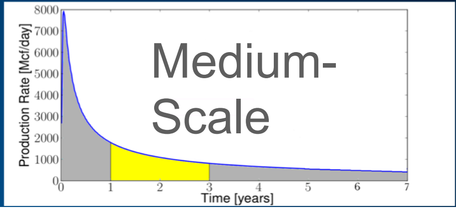
Completed Experiments

Specimen	Bedding	Confining Stress at Fracture Creation	Flowing Fluid
Outcrop MS01-01	None	3 MPa	Water
Outcrop MS01-02	None	15 MPa	Water
Outcrop MS01-03	None	30 MPa	Water
Outcrop MS01-04	None	5 MPa	Water
Outcrop MS01-05	None	10 MPa	Water
Outcrop MS01-06	None	3 MPa	KI
Outcrop MS03-01	None	10 MPa	$BaCl_2$
MSEEL Core MS02-03	45˚	3 MPa	$BaCl_2$
MSEEL Core MS02-04	0˚	30 MPa	$BaCl_2$
MSEEL Core MS02-05	45˚	10 MPa	$BaCl_2$
MSEEL Core MS02-06	0˚	20 MPa	$BaCl_2$

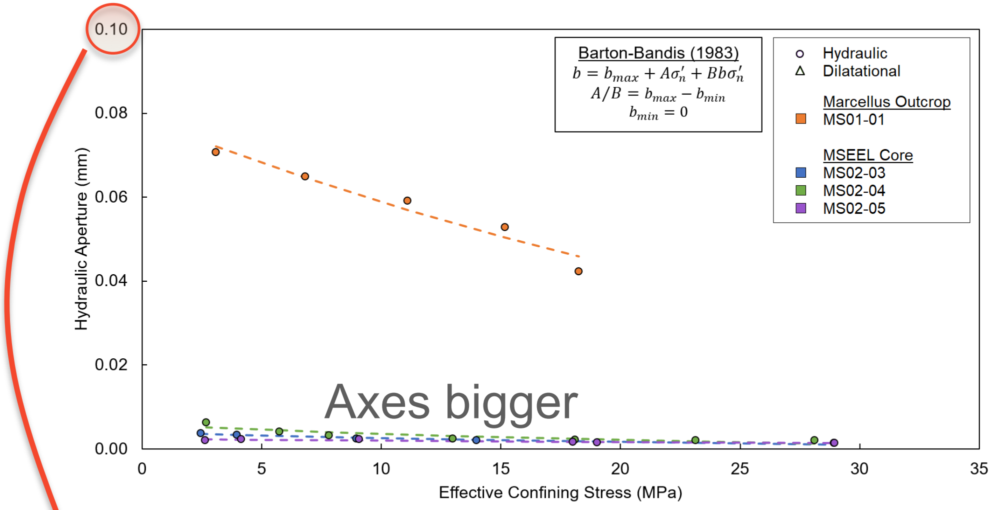
Carbonate facies are both more permeable and more sensitive to pressure drawdown

Barton-Bandis Results: Fracture Aperture and Drawdown Pressure

Presented at URTeC 2019 (Welch et al.)

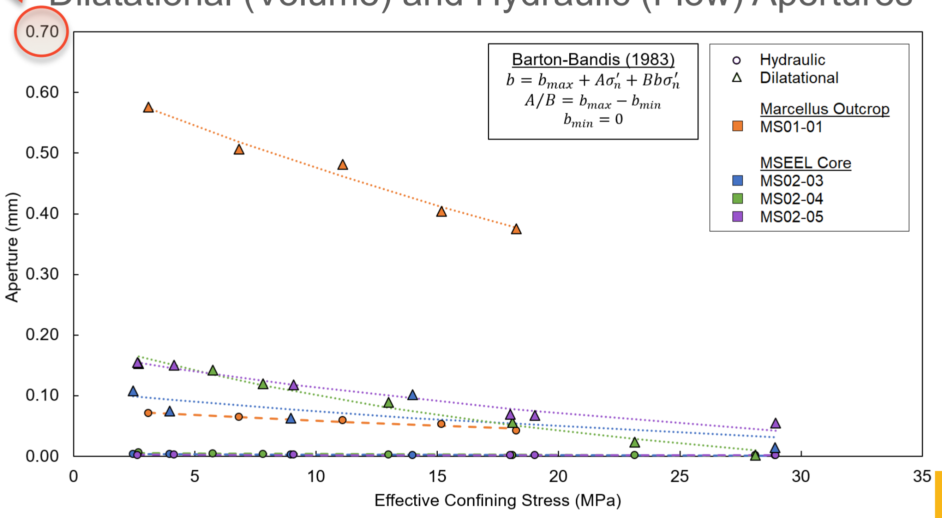


Hydraulic Aperture (Permeability)



Axes bigger

Dilatational (Volume) and Hydraulic (Flow) Apertures



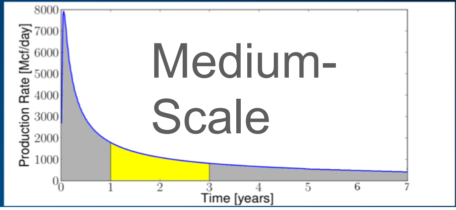
Other Related FE30 Efforts

- LBNL (Seiji Nakagawa—Controlling Sustainability of Hydraulic Fracture Permeability in Ductile Shales)
  - Response of propped fracture systems to pressure
- PSU (Derek Elsworth—Geophysical and Mineralogical Controls on the Rheology of Fracture Slip and Seal Breaching)
  - Mineralogical controls on fracture reactivation and permeability
- NETL (Dustin Crandall—Shale Fundamentals Research
  - Propped fracture behavior and shear-permeability relations
- UT-Austin (Mukul Sharma—industry-funded research)
  - Stress-fracture relations in other shale systems

Toward a complete representation of fracture-pressure controls on production

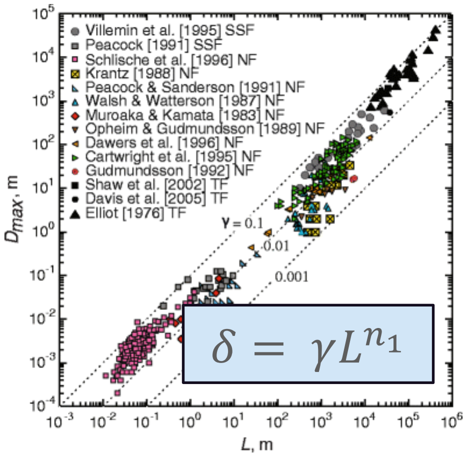
Lab-to-Field Integration: Scale Dependence

Benchmark Against Available MSEEL Data



Displacement, Length, and Aperture Scaling

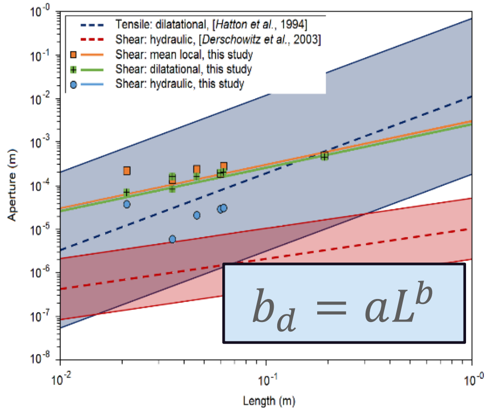
(1) Length & Displacement



$$\delta = \gamma L^{n_1}$$

Schultz et al. 2008

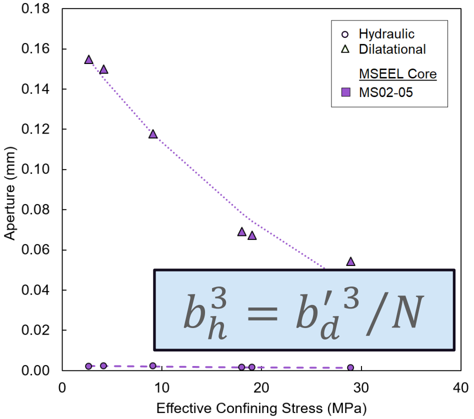
(2) Length & Dilation



$$b_d = aL^b$$

Dershowitz et al. 2008;
Frash et al. 2019

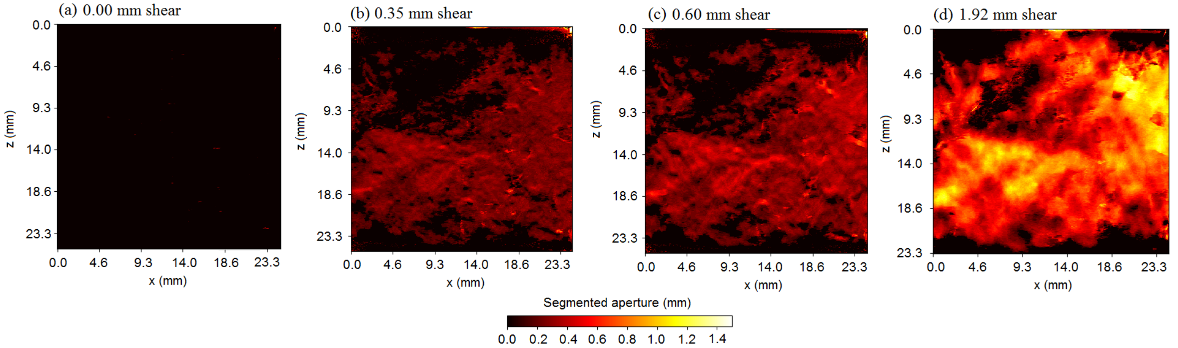
(3) Flow & Volume Aperture



$$b_h^3 = {b'_d}^3/N$$

Frash et al. *In Prep*

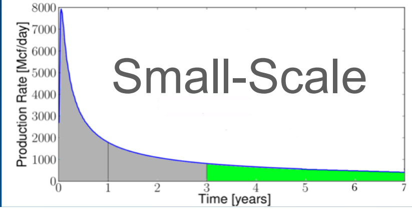
Example with Aperture Anisotropy



Shear Disp. (mm)	**N_1, meas. para. Shear**	**N_1, LBM para. shear**	**N_2, LBM perp. shear**
0.00	n/a	n/a	n/a
0.35	1.9E4	7.9	2.2
0.60	3.1E2	7.9	2.3
1.92	9.2E7	3.5	1.8

Literature studies and laboratory experiments are combined to provide scaling relationships for field applications

Pressure Management of Hydrocarbon Production from Matrix—PI H. Xu



Science Question:

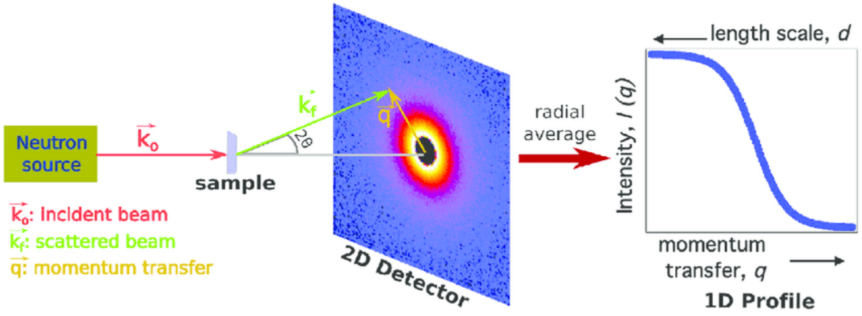
How can pressure be manipulated to optimize production from the matrix?

Motivation

- The majority of oil and gas left in the ground is trapped in the matrix.
- Laboratory experiments and simulations determine mobility and production hydrocarbon

Objectives

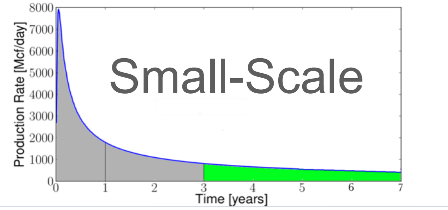
- Complete small-angle scattering neutron experiments for *in situ* measurement of hydrocarbon in nanopores
- Simulate transport processes using experimentally determined matrix geometries.
- Formulate matrix-pressure-permeability relations for DFN models

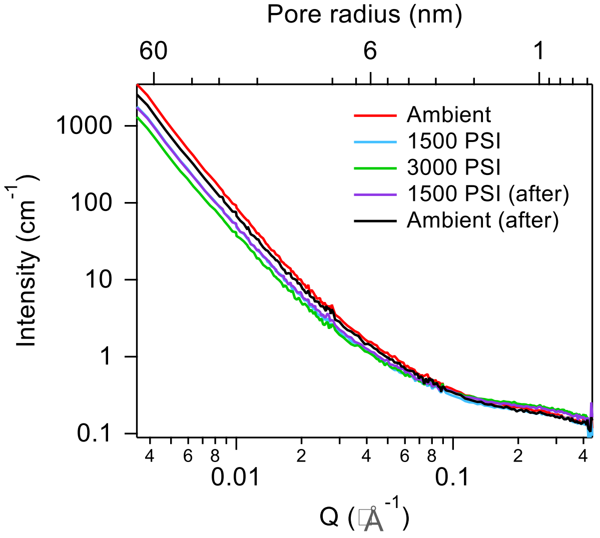


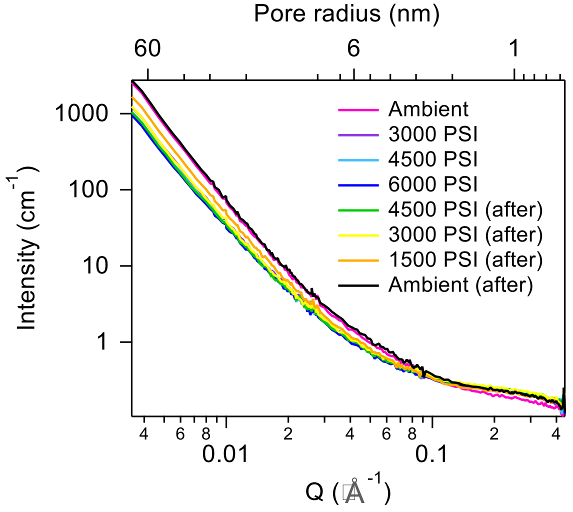
Small-angle neutron scattering schematic

from Castellanos *et al*. *Comput Struct Biotechnol J*, 15, (2017)

Drawdown Pressure Effects on Methane Retention

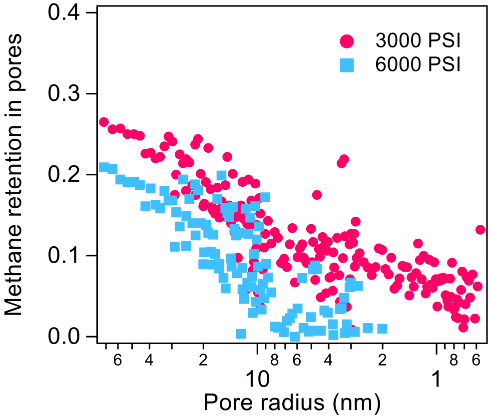






3000 PSI Peak Pressure Cycle

6000 PSI Peak Pressure Cycle

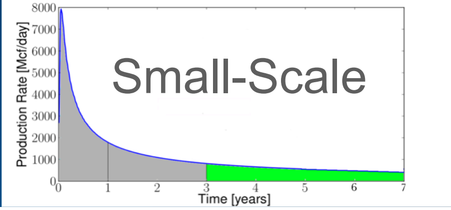


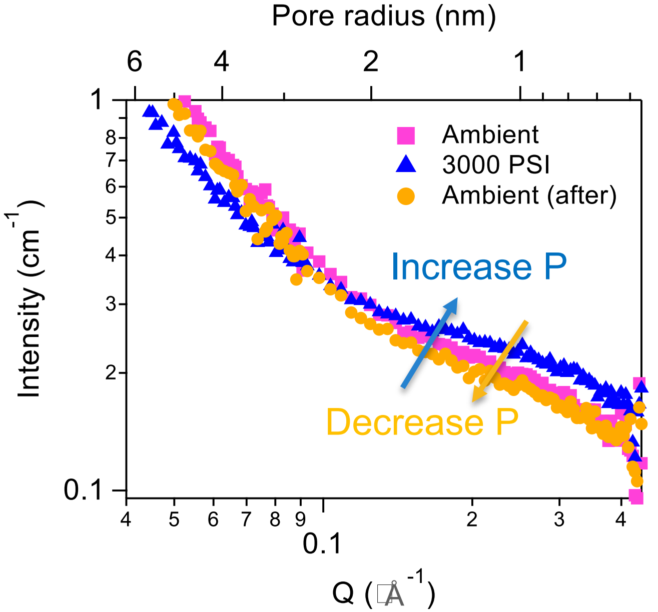
A MSEEL sample was pressurized with CD_4 twice:

1. In a low P cycle, the pressure was increased to 3000 PSI and decreased to ambient.
2. In a high P cycle, the pressure was increased to 6000 PSI and decreased to ambient.

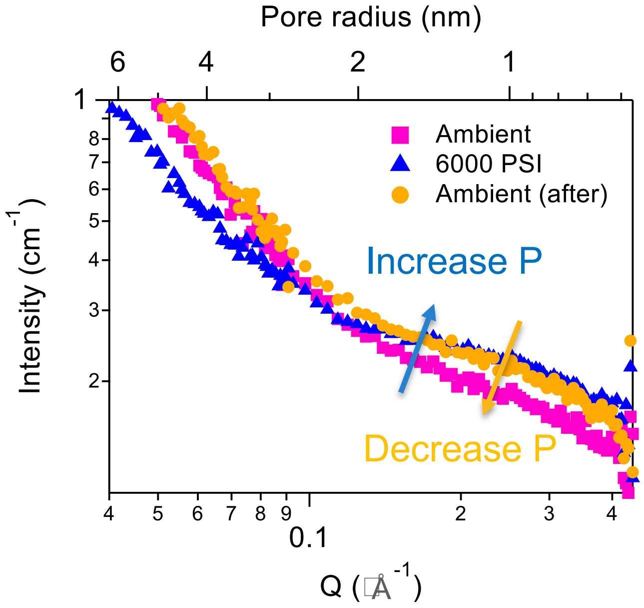
- More methane gas retention in nanopores for the lower pressure cycle (3000 PSI).

Pressure-Induced Methane Condensation in Nanopores





3000 PSI Peak Pressure Cycle

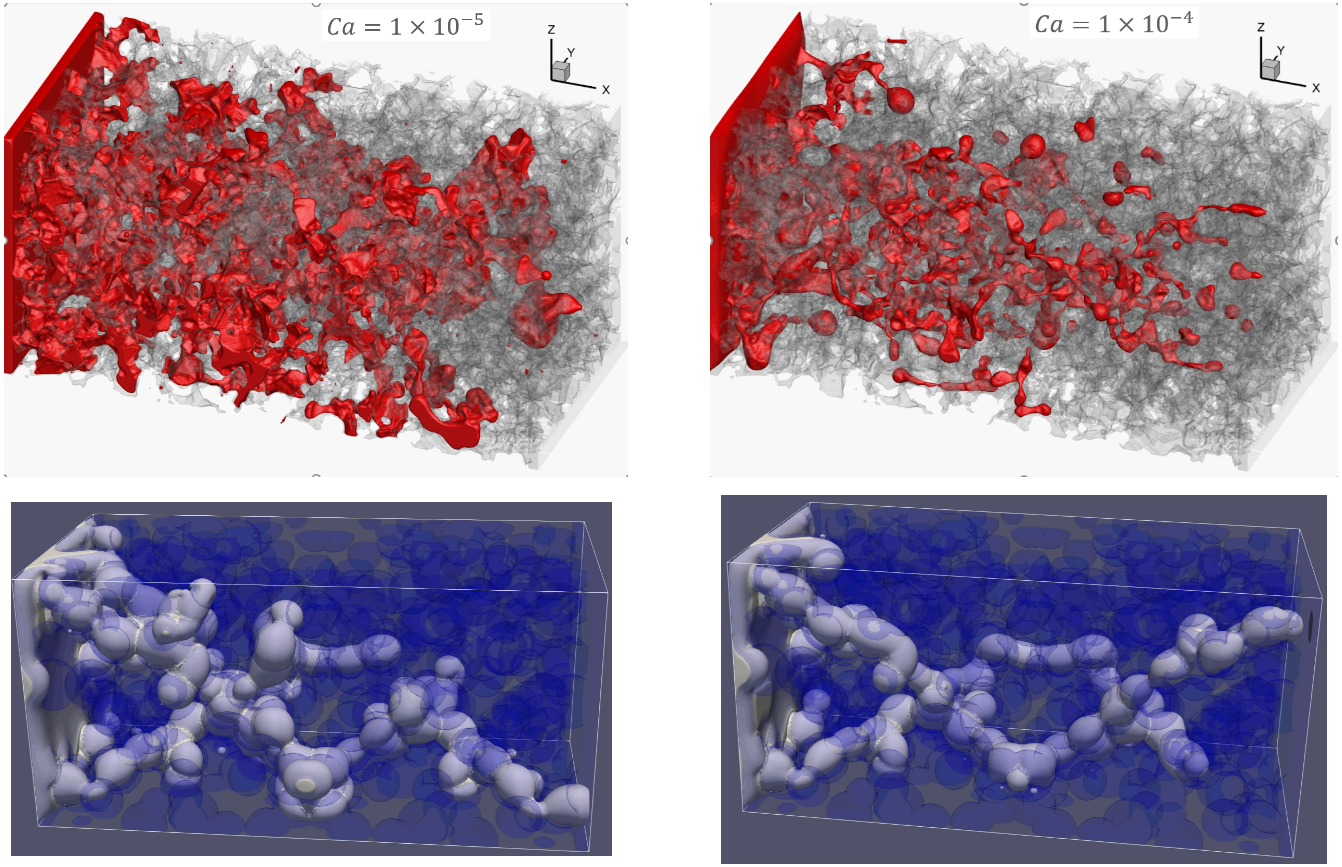


6000 PSI Peak Pressure Cycle

- At high Q values or small pore sizes, increasing pressure increases the scattering intensity due to capillary condensation of methane in nanopores.
- Decreasing pressure returned intensity to ambient values for 3000 PSI cycle, but not for 6000 PSI cycle.

- Methane condensation in small pores (< 3 nm) is reversible for lower pressure cycle, but not for higher pressure cycle.

Impact of Pressure Gradients on Matrix Gas Production: LBM Simulation of Two-Phase Flow



Sandstone

Kerogen

$Ca=1\times10^{-5}$ $Ca=1\times10^{-4}$

A lower pressure gradient (left) leads to capillary fingering and higher sweeping efficiency than the case of viscous fingering caused by a higher pressure gradient (right) at breakthrough

Accomplishments to Date

1. (Baselined dfnWorks with high resolution single continuum representation of fracture network—LANL LDRD)
2. Developed machine learning to enable rapid, graph-based models of full discrete fracture network results
3. Enabled assessment of matrix contributions to production from discrete fracture networks
4. Expanded discrete fracture network to include aperture response to changes in pressure (Barton–Bandis approach)
5. Developed "cross over" analysis approach to quantify time required for a lower production rate to exceed cumulative production from a rapid draw-down

Accomplishments to Date

6. Measured pressure–stress–aperture relationships for carbonate and clay facies in 11 samples of Marcellus shale
7. Established a framework for scaling fracture aperture and permeability relations
8. Determined using neutron experiments that pressure cycles control trapping of methane and is associated with irreversible changes of nanopores
9. Used lattice Boltzmann simulations to show that moderate pressure gradients improved sweep efficiency of hydrocarbon compared with high gradients

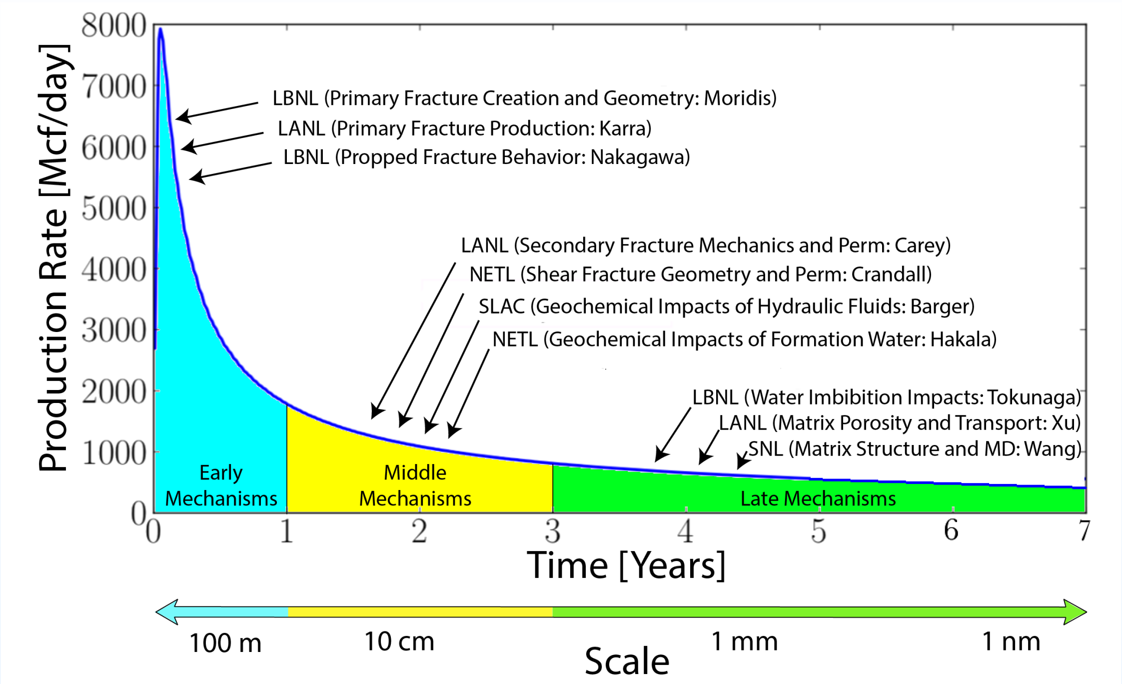
Lessons Learned

1. Accurate simulation of fracture flow requires computationally accurate meshes that capture fracture topologies
2. ML-enabled graph-theory produces accurate results with a speed-up of > 1000X
3. Most of the production (60–80% over a 20-yr period) in a gas-dominated system originates adjacent to fracture network
4. Demonstrated that tradeoffs between rapid & moderate pressure drawdown can be assessed by determining crossover time in cumulated production
5. Preliminary assessment using prototypical pressure–stress relationships suggest cross-over times will likely range from month to years

Lessons Learned

6. Different Marcellus facies have distinct aperture-stress responses, showing importance of site-specific data
7. Scaling relationships for fracture apertures can be developed from a combination of field data and experiments
8. Transport of hydrocarbon out of nanopores depends on magnitude of DP, methane condensation at higher P, and pore properties
9. Lower pressure gradients (e.g., moderate drawdown) leads to higher sweep efficiency due to shift from viscous fingering to capillary fingering

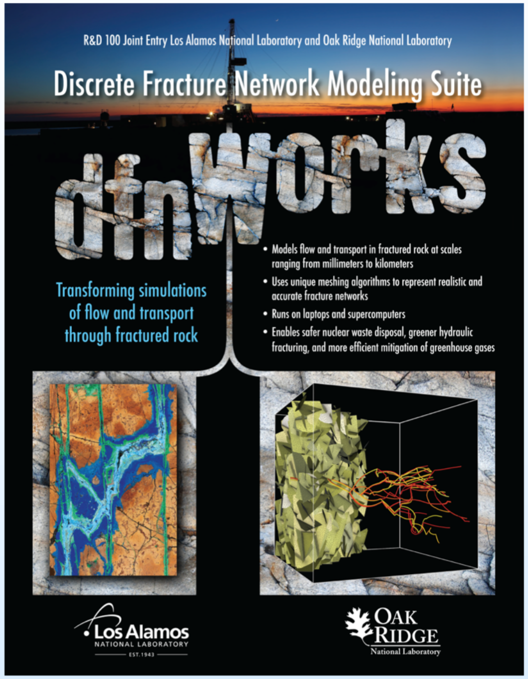
Synergistic Opportunities



- Strong synergy already exists across DOE-FE national lab portfolio in the fundamentals of shale (see figure)

- Los Alamos portfolio also heavily synergistic with internal (LANL) investments through LDRD

Synergistic Opportunities



R&D 100 Joint Entry Los Alamos National Laboratory and Oak Ridge National Laboratory

Discrete Fracture Network Modeling Suite

dfnWorks

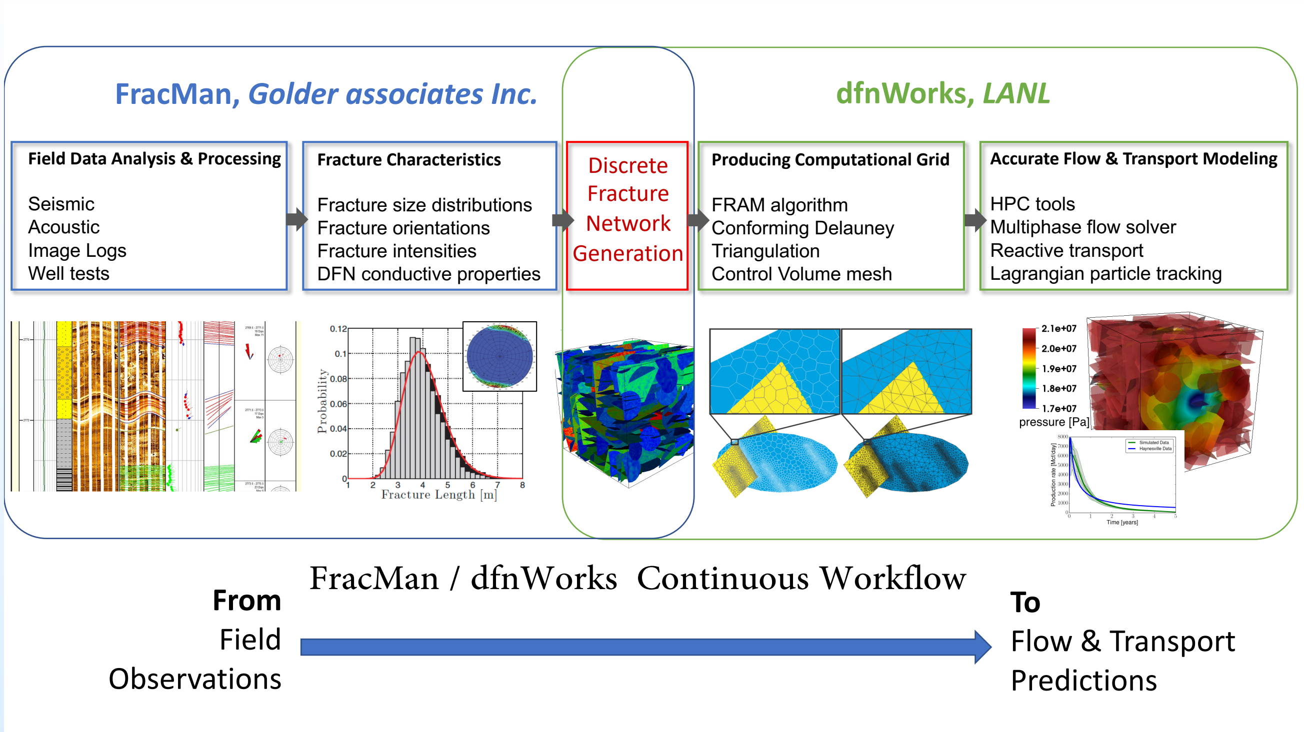
Transforming simulations of flow and transport through fractured rock

- Models flow and transport in fractured rock at scales ranging from millimeters to kilometers
- Uses unique meshing algorithms to represent realistic and accurate fracture networks
- Runs on laptops and supercomputers
- Enables safer nuclear waste disposal, greener hydraulic fracturing, and more efficient mitigation of greenhouse gases

Los Alamos NATIONAL LABORATORY EST. 1943

OAK RIDGE National Laboratory

R&D 100 Winner



FracMan, *Golder associates Inc.*

dfnWorks, *LANL*

Field Data Analysis & Processing
Seismic
Acoustic
Image Logs
Well tests

Fracture Characteristics
Fracture size distributions
Fracture orientations
Fracture intensities
DFN conductive properties

Discrete Fracture Network Generation

Producing Computational Grid
FRAM algorithm
Conforming Delauney
Triangulation
Control Volume mesh

Accurate Flow & Transport Modeling
HPC tools
Multiphase flow solver
Reactive transport
Lagrangian particle tracking

FracMan / dfnWorks Continuous Workflow

From
Field
Observations

To
Flow & Transport
Predictions

DOE Investments in Fractured Systems

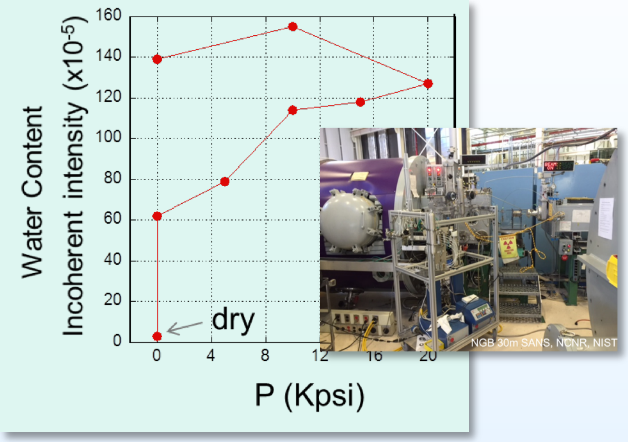
New TCF Commercialization Project linking FracMan fracture (FE-20) Characterization to meshing, flow and transport algorithms of dfnWorks

Appendix

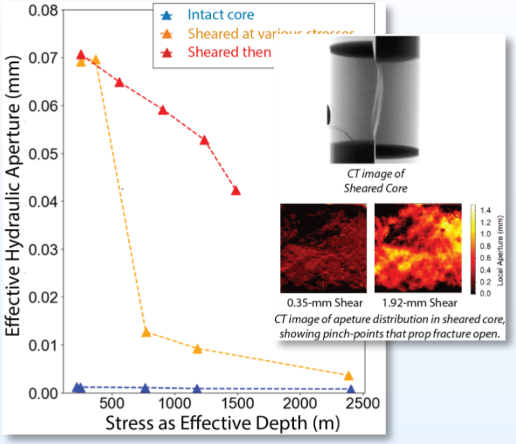
Project Organization

Los Alamos Shale Project (#FE-954-18-FY18)

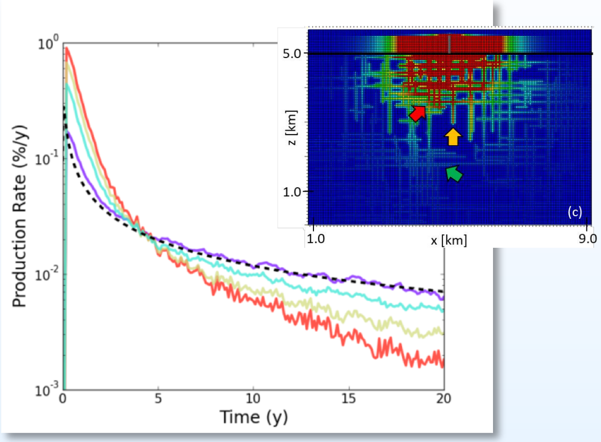
Pore-Scale



Fracture-Scale



Reservoir-Scale



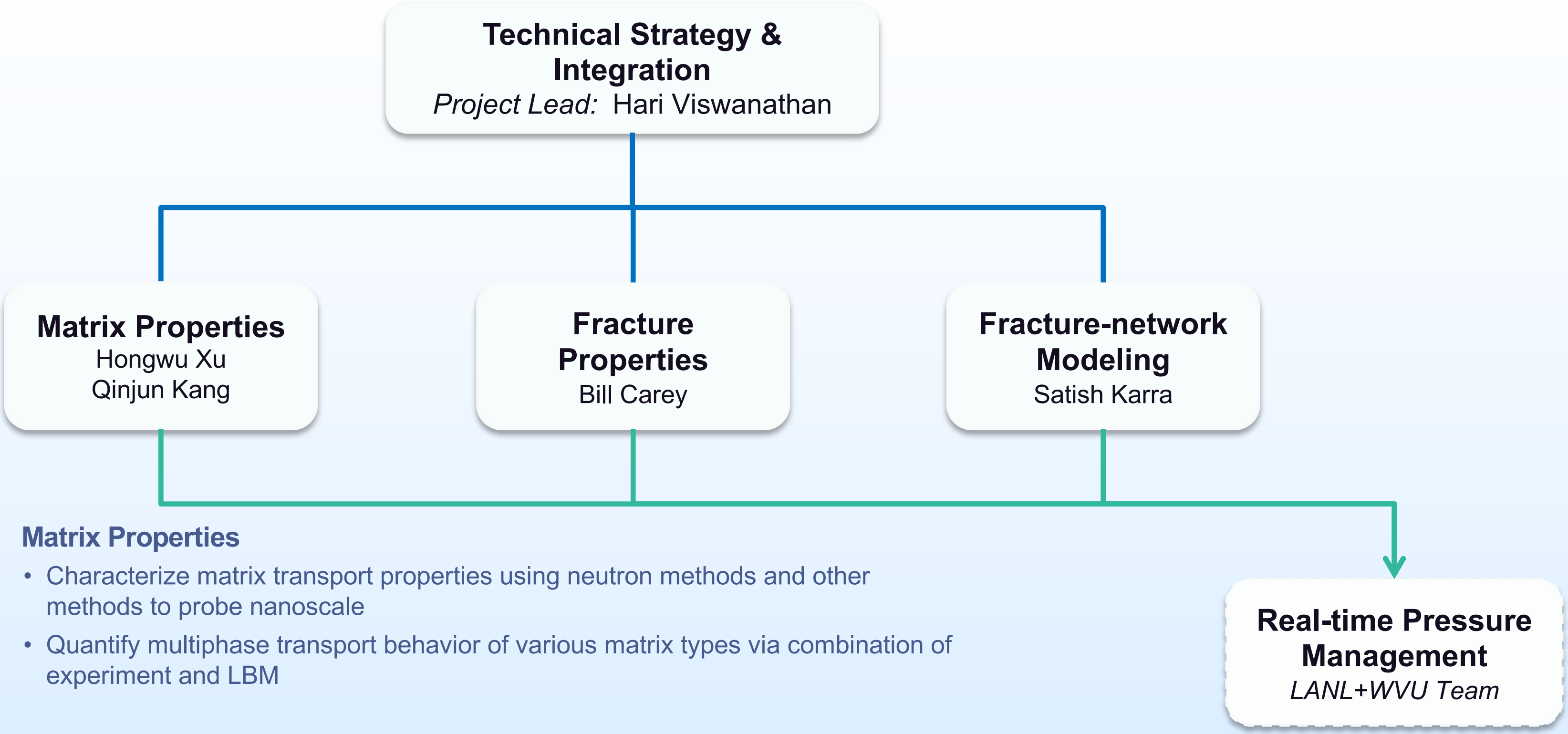
Hari Viswanathan (project leader)

Project Team

Bill Carey, Luke Frash, George Guthrie, Qinjun Kang, Satish Karra, Nataliia Makedonska, Chelsea Neil, Phong Nguyen, Dan O’Malley, Matt Sweeney, Hari Viswanathan (project leader), Nathan Welch, Hongwu Xu

Organization Chart

Los Alamos Shale Project (#FE-954-18-FY18)



Technical Strategy & Integration
Project Lead: Hari Viswanathan

Matrix Properties
Hongwu Xu
Qinjun Kang

Fracture Properties
Bill Carey

Fracture-network Modeling
Satish Karra

Real-time Pressure Management
LANL+WVU Team

Matrix Properties

- Characterize matrix transport properties using neutron methods and other methods to probe nanoscale
- Quantify multiphase transport behavior of various matrix types via combination of experiment and LBM

Fracture Properties

- Characterize fracture behavior for various shale properties and fracturing conditions
- Quantify multiphase transport behavior of various fracture types via combination of experiment, theory, and simulation

Fracture-Network

- Develop platform for capturing the critical physical (and chemical) processes that control hydrocarbon production based on a system of discrete fractures and shale-matrix

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