A New Framework for Microscopic to Reservoir-Scale Simulation of Hydraulic Fracturing and Production: Testing with Comprehensive Data from HFTS

Jens Birkholzer & Joe Morris and all other HFTS Team Members from LBNL, LLNL, SLAC, NETL

Annual Review Meeting, October, 2020

BERKELEY LAB

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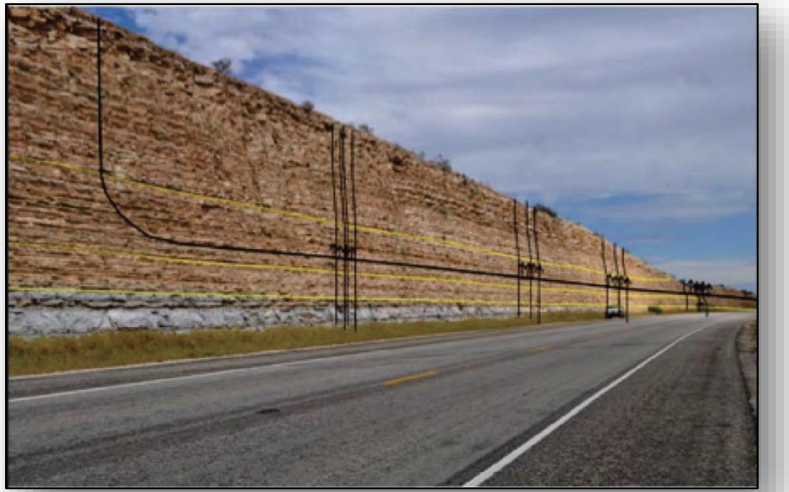
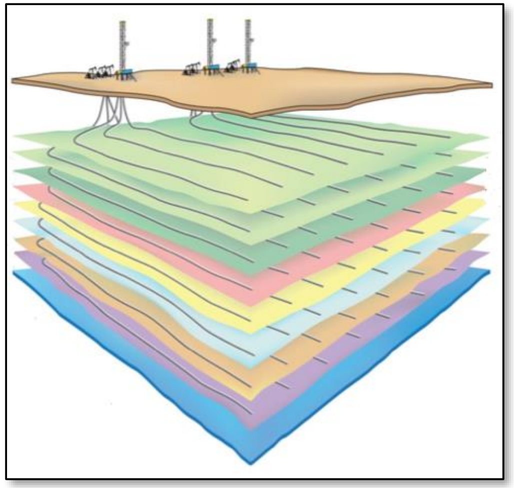
Typical Process in Unconventionals Today





Characterize geology core/logs/seismic/etc. → **Design and execute stimulation** → **Monitor stimulation** → **Produce from well**

Try and refine

Barriers to Production: Multiple Gaps in Understanding Prevent Predictive Design

What is really going on inside proppant packs during production?

How does characterized geochem/geomech influence frac growth?

What do geophysical observations really tell us?

How does micro-scale geochem/geomech influence production of hydrocarbon and waters?

Characterize geology core/logs/seismic/etc. → Design and execute stimulation → Monitor stimulation → Produce from well

Predictive Simulation Framework to Enable Adaptive Subsurface Management

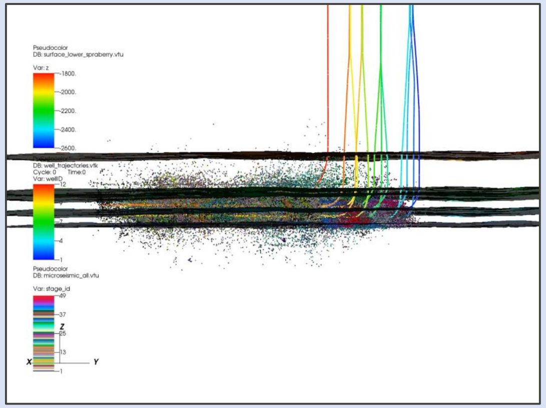
What are implications of *fracture swarms* for frac growth?

How does well-to-well interaction affect performance?

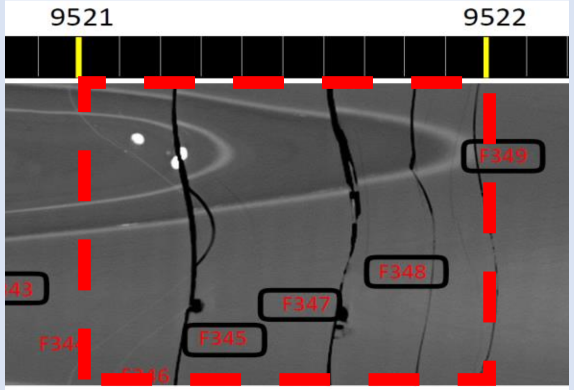
What are implications of fracture swarms for production?

A Multi-Scale Multi-Physics Multi-Lab Project

HFTS Field Data and Core



Extensive reservoir scale data



4 hydraulic fractures within 1 foot!

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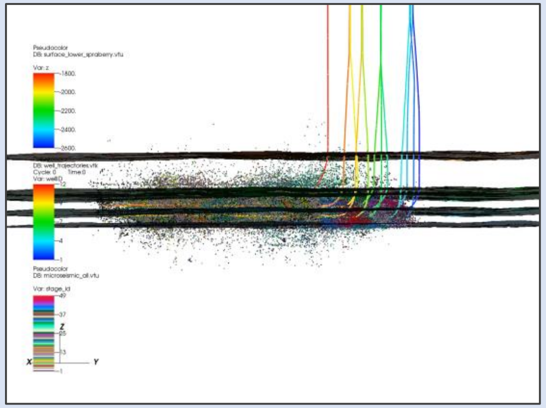

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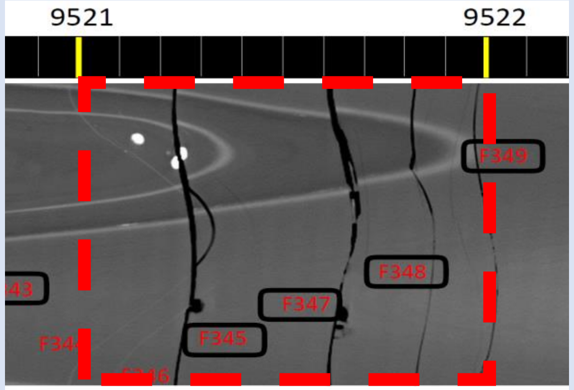

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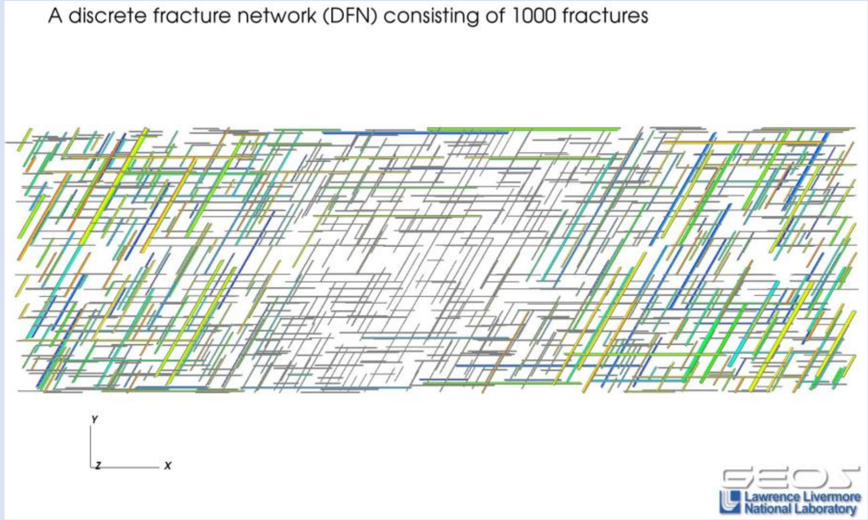
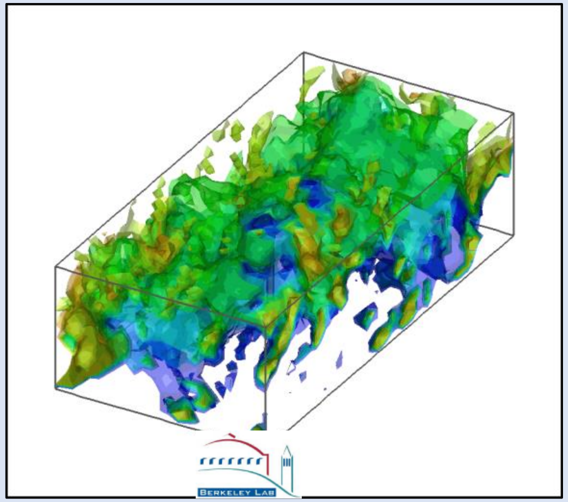
Linked Two Powerful Simulators to Answer Complex Questions at the Reservoir Scale: GEOS for Stimulation Behavior, TOUGH for Production

GEOS ⟺ **TOUGH**





GEOS Stimulation:

- Fracture network evolution, proppant placement, permeability enhancement, zonal isolation, etc.
- Simulate geophysical observables – seismicity, fiber optics, etc.

TOUGH Reservoir production

- Fully compositional simulator
- Fully non-isothermal
- Multi-well production, or production-injection
- Extensible: Can accommodate microscale relations

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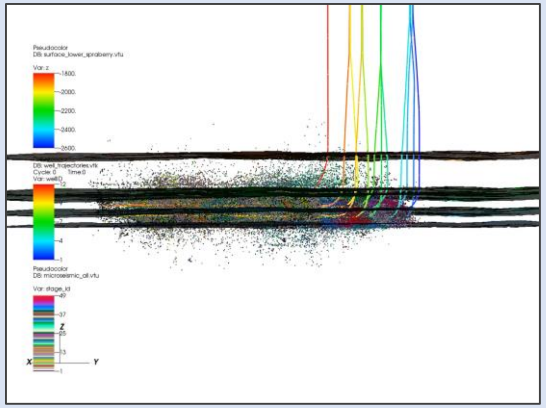

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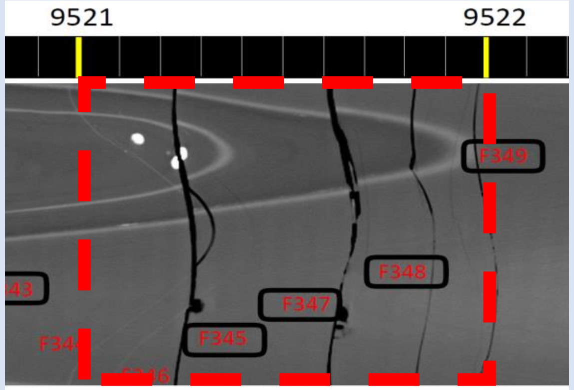

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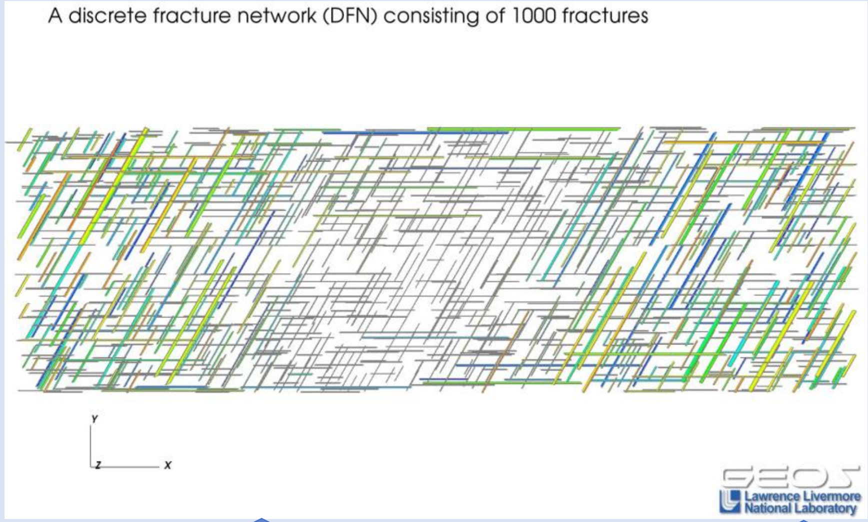
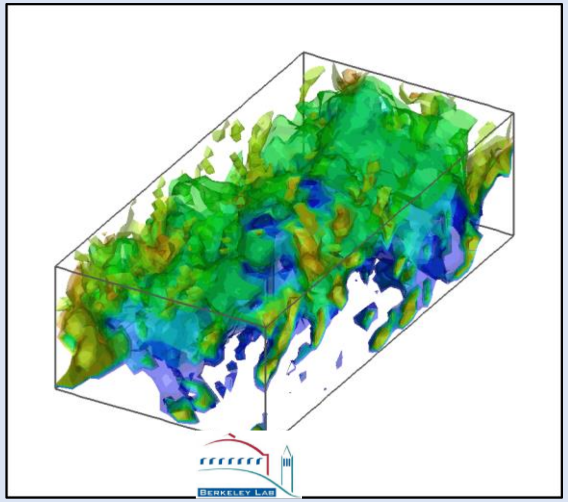
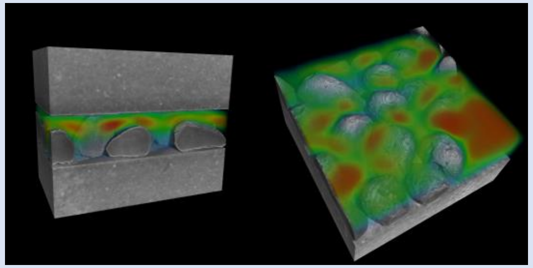
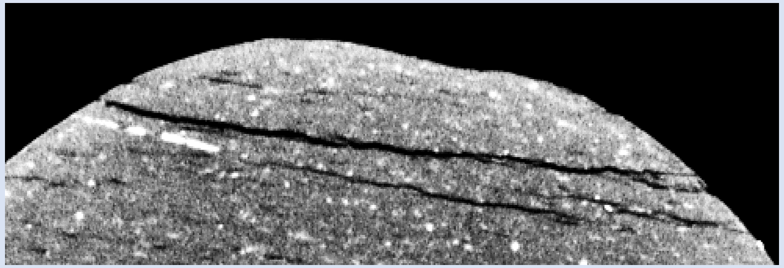
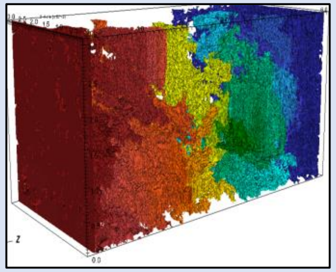




New Constitutive Models for Shale Property Evolution from Geomechanics and Reactions Based on Micro/core-scale Experiments/Simulations (Fundamental Shale Synergies)







Our Multiscale/Multilab Collaboration Confronts Challenges Enabling *Predictive* Optimization

Multiscale: LLNL-LBNL
What is really going on inside proppant packs during production?

Multiscale: ALL
How does characterized geochem/geomech influence frac growth?

Field-scale: LLNL
What do geophysical observations really tell us?

Multiscale: SLAC-LBNL-NETL
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Multiscale: LLNL

How does well-to-well interaction affect performance?
Field-scale: LLNL-LBNL

What are implications of fracture swarms for production?
Multiscale: LLNL-LBNL

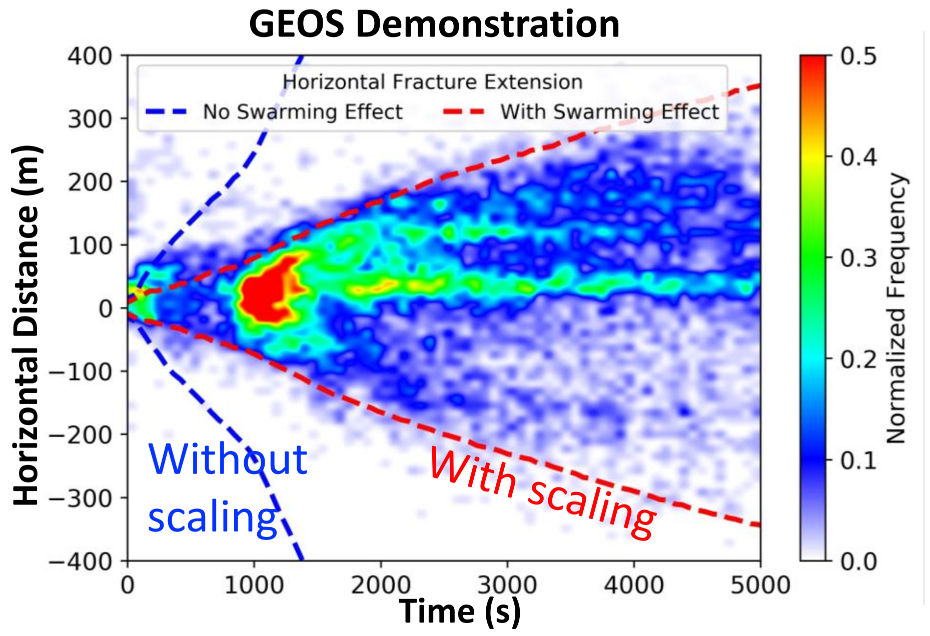
Field-scale Highlights: Fracturing and Reservoir Modeling

Upscaled Swarm Treatment

Cannot afford to resolve fracture swarms explicitly

→ Developed upscaled approach (Fu et al. SPE-199689-MS)

- Viscosity: $\mu_0 = N^2\mu$
- Toughness: $K_{IC0} = \sqrt{N} K_{IC}$
- Leak-off: $C_{L0} = NC_L$
- Proppant: $D_0 = ND$



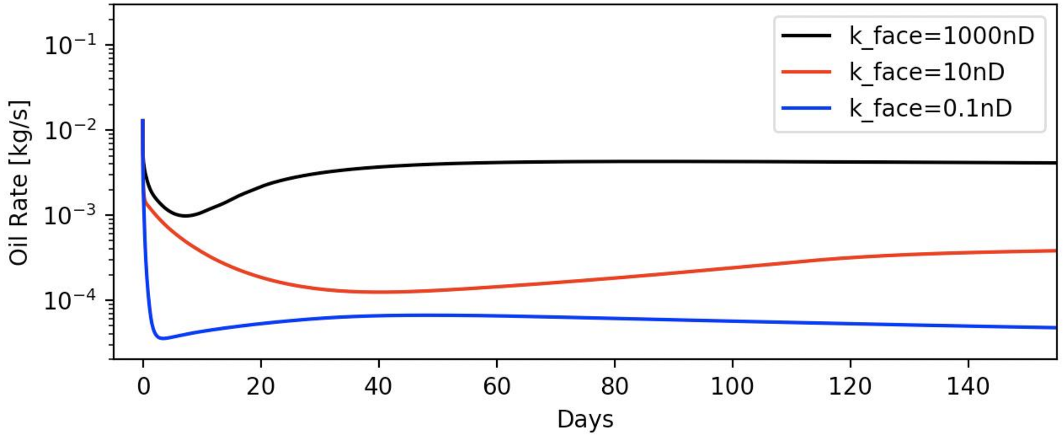
Readily implemented into existing simulators

RESFRAC

Influence of Fracture Skin

Microscale Lab data indicate frac-fluid reactions with shale induce low-perm zones on hydraulic fracture surface (skin)

4SU ***GEOS*** stimulation + ***TOUGH*** production + low perm skin:



Low face permeability impedes production

Future Work

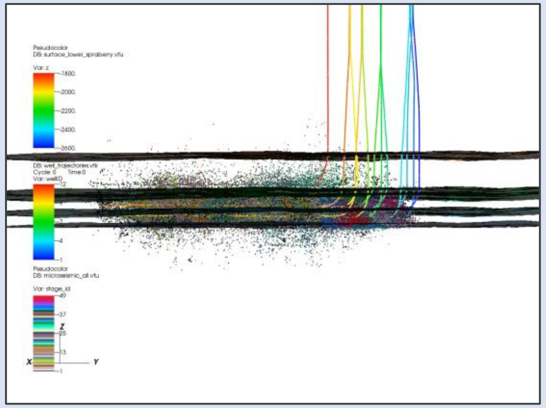
Additional parametric studies

Reproduce observed trends for different wells and stages

Incorporate incoming results from ***micro-scale*** studies (stress-dependent fracture perm, micro-reaction impacts)

A Multi-Scale Multi-Physics Multi-Lab Project

HFTS Field Data and Core



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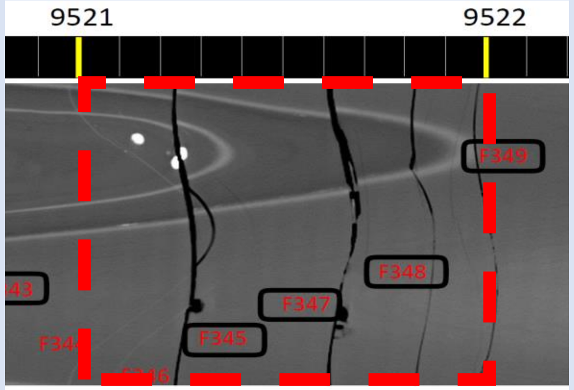

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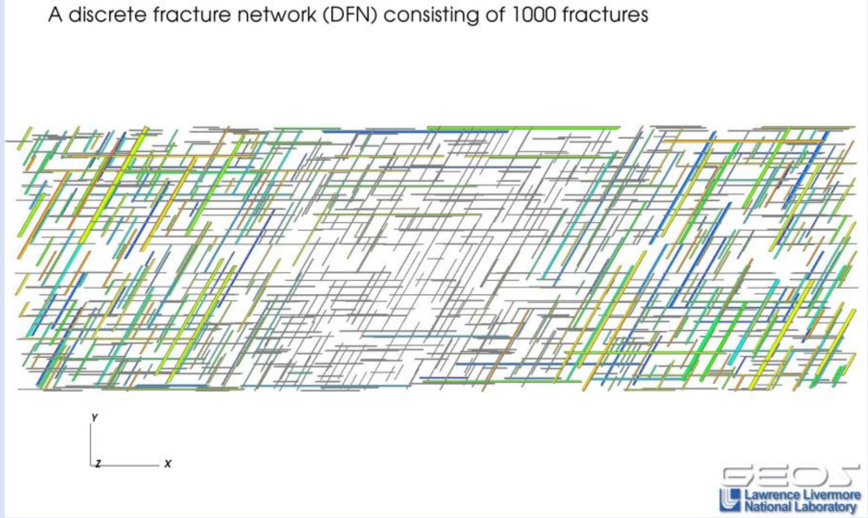

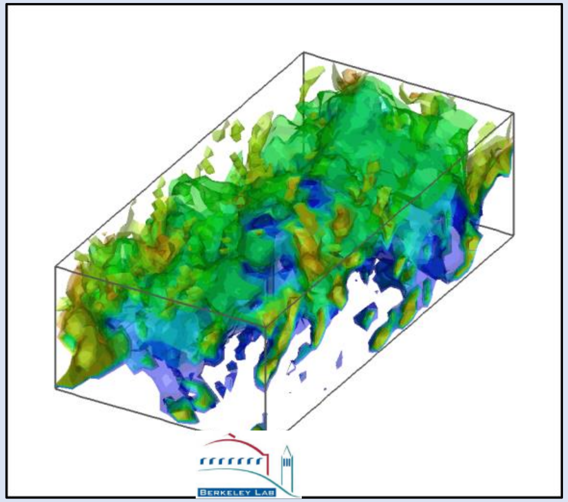

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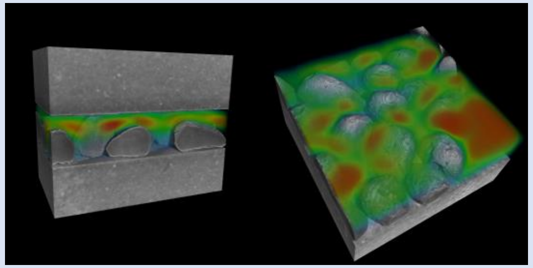

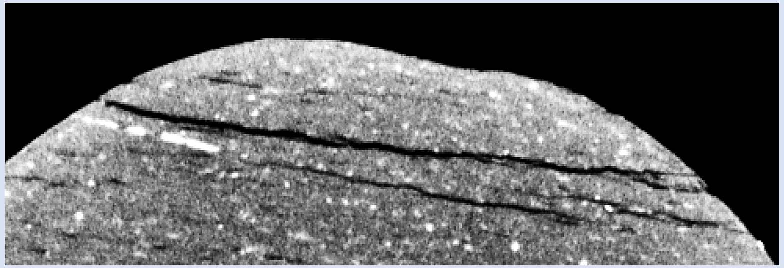

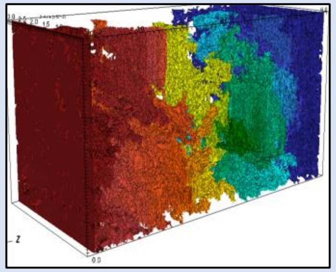

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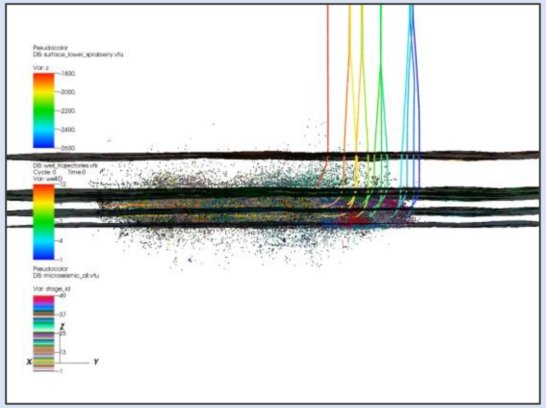

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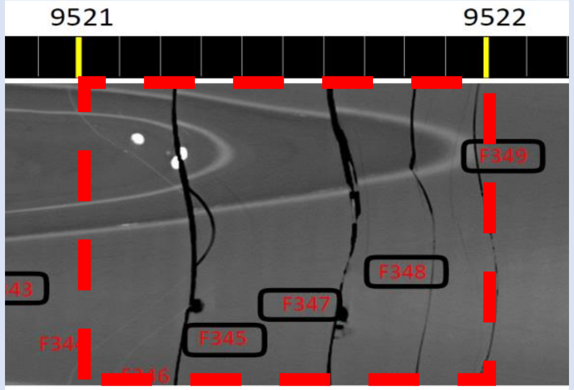
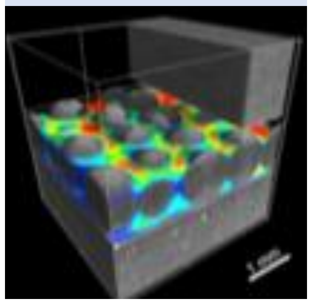
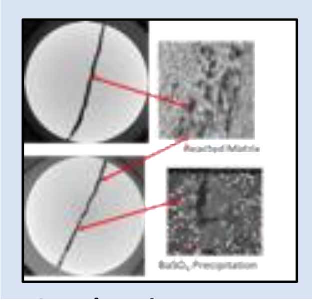


4 hydraulic fractures within 1 foot!

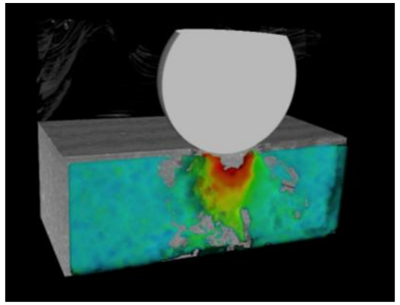
Impact of proppant/shale mechanical interactions on fracture permeability



Impact of micro-scale reactions on fracture and shale permeability



Impact of reactive weakening of fracture faces on mechanical behavior



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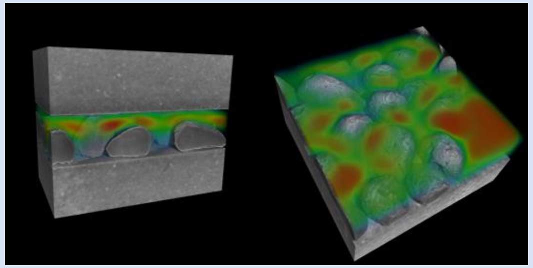
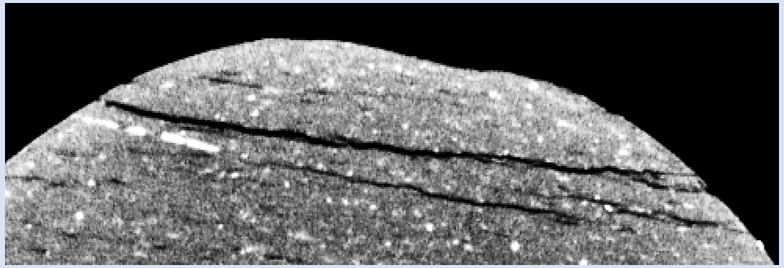
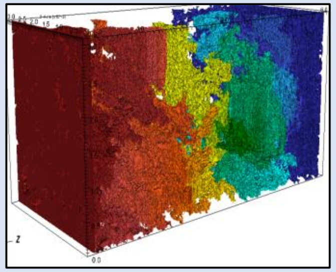


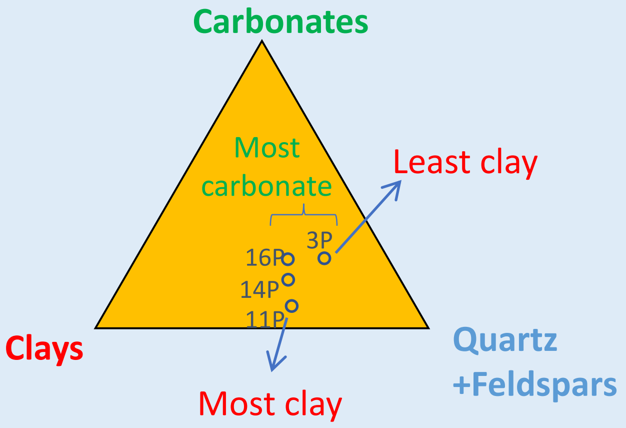




Micro- and Meso-scale Observations of Propped Fracture Behavior

Micro- and meso-mechanical behavior **<u>at reservoir conditions</u>** is translated into understanding propped fracture behavior over time

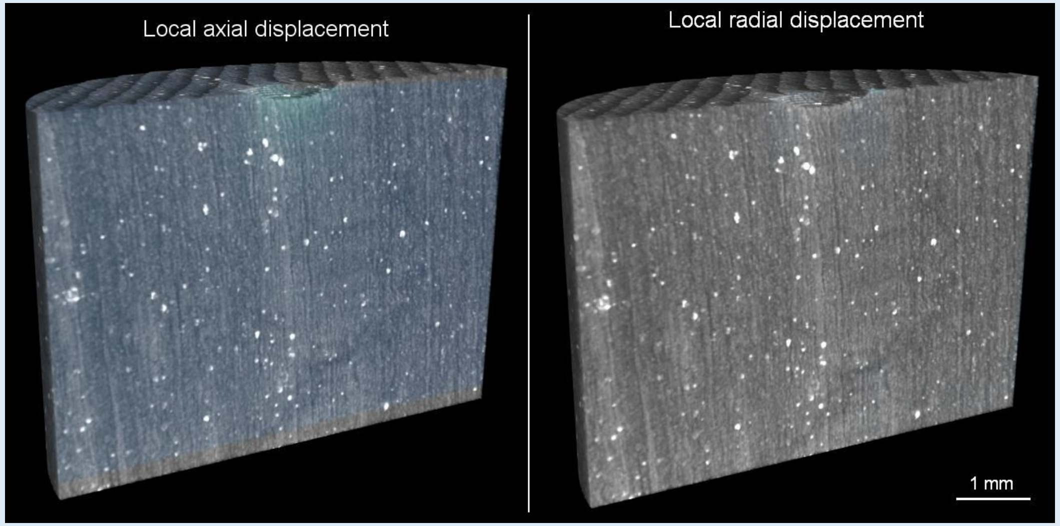
Wolfcamp Sample Analysis/Selection



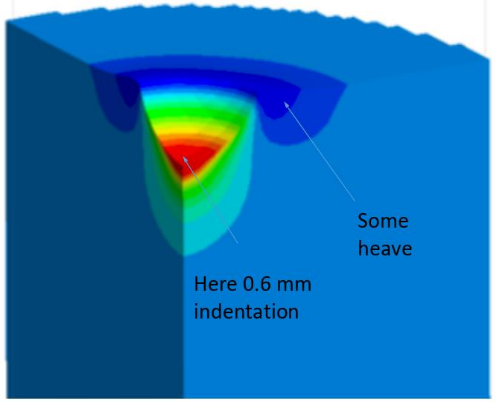
Wolfcamp samples in preparation vary in composition

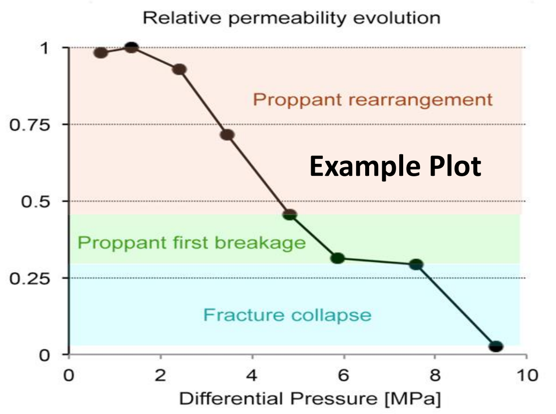
Micro-scale (Wolfcamp)

Quantitative 4D analysis of shale deformation



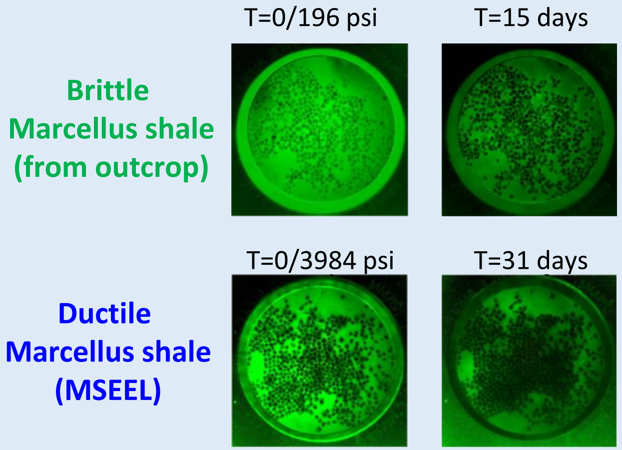
Simulation of the displacement fields & permeability changes



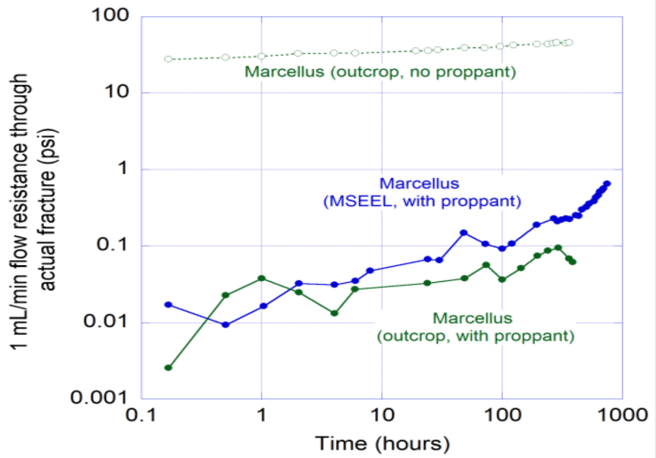


Meso-scale (Marcellus)

Meso-mechanical (permeability/displacement) tests

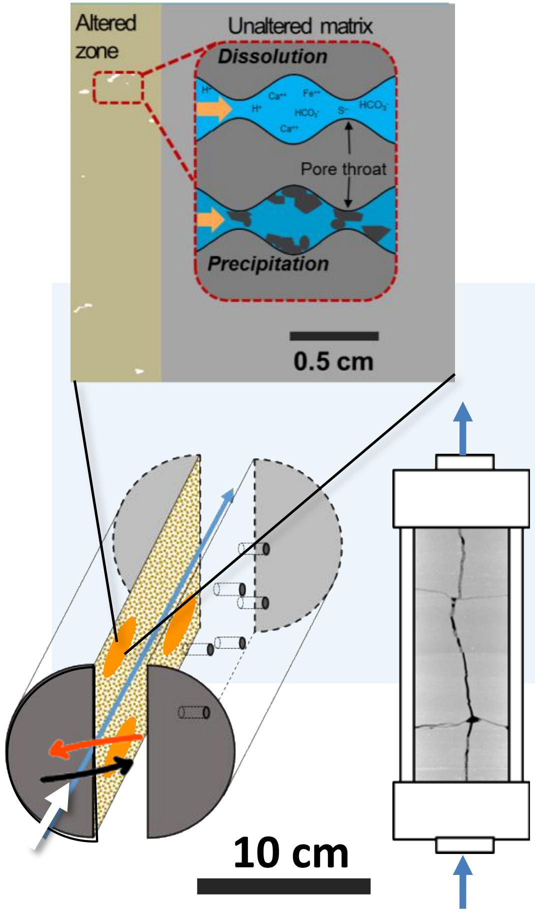


~1/permeability data



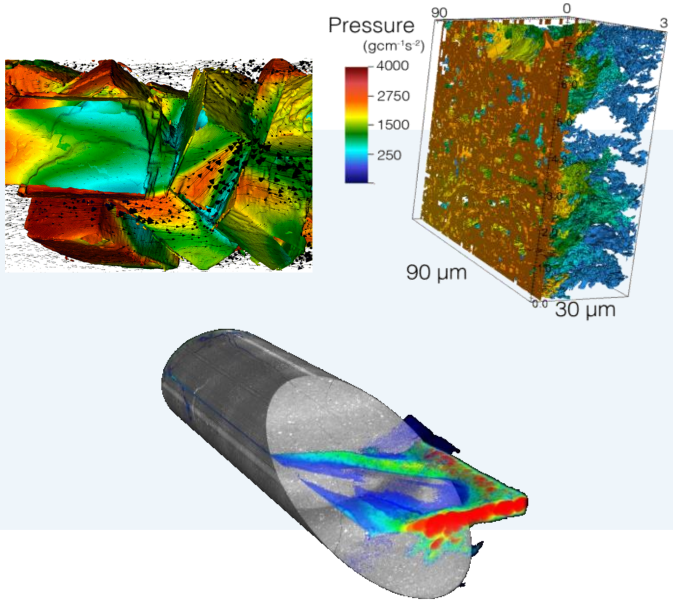
Impact of Micro-scale Reactions on Fracture and Shale Permeability

SLAC: Characterization of shale matrix pre- and post- injection

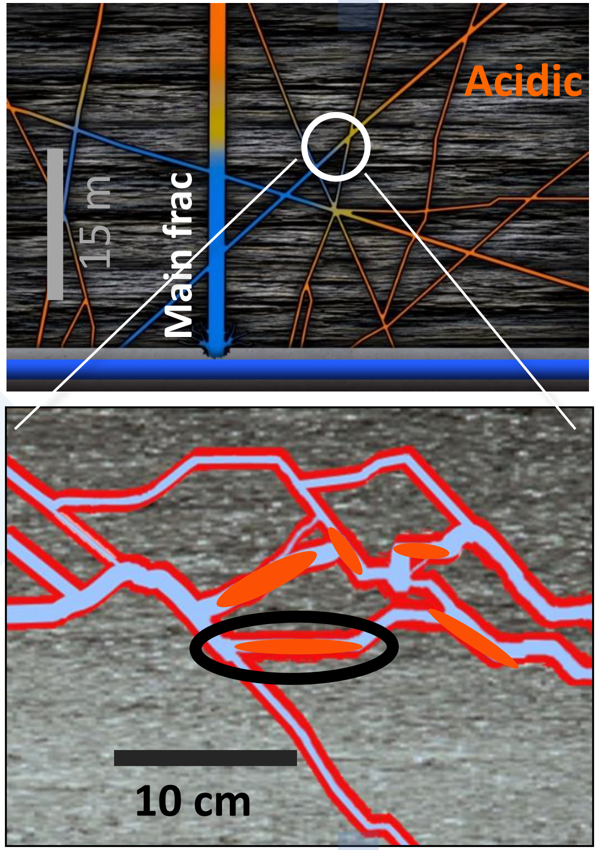


NETL: Fracture flow experiments

LBNL: pore- and continuum- scale reactive-transport modeling



Develop constitutive laws that describe permeability and diffusivity evolution due to coupled physical-chemical alteration

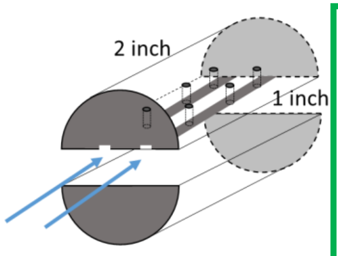


Experimental conditions relevant to the field practice (e.g., pH and salinity across the stimulated rock volume), and samples from the HFTS site

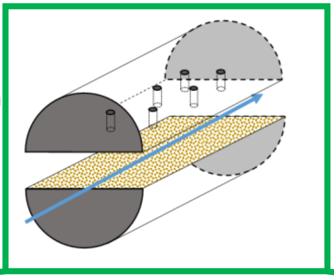
Chemical Reactions in Fractures: Impact on Flow Properties and Controlling Factors

Chemical Reactions in Realistic Fractures

Channel Flow

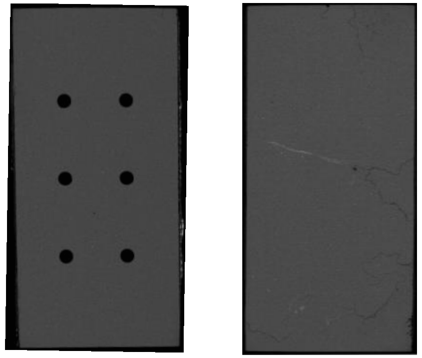


Propped Flow

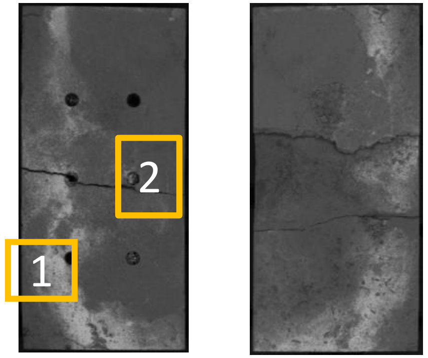


Results from Marcellus Shale test case

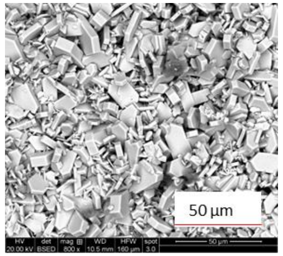
Pre-reaction



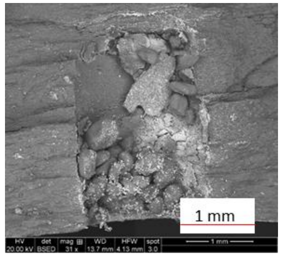
Post-reaction



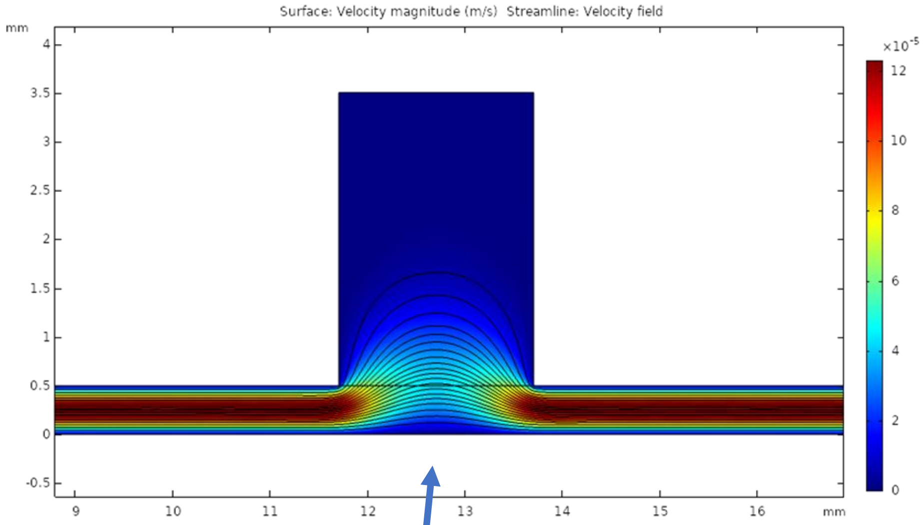
1. Euhedral barite along surface

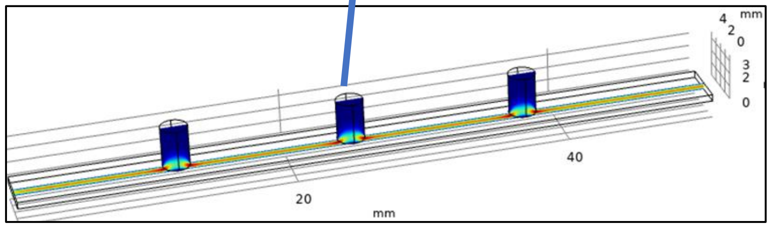


2. Proppant cemented by barite in “dead end”



CFD simulations with experimental inputs show slower flow around “dead end” zone – leading to enhanced precipitation



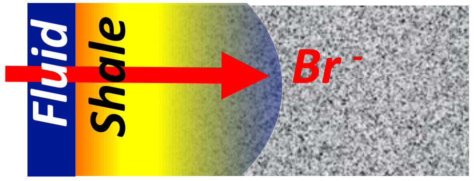


Chemical Reactions on Fracture Walls and in Shale Altered Zone: Image Fluid Penetration to Understand Skin Effects

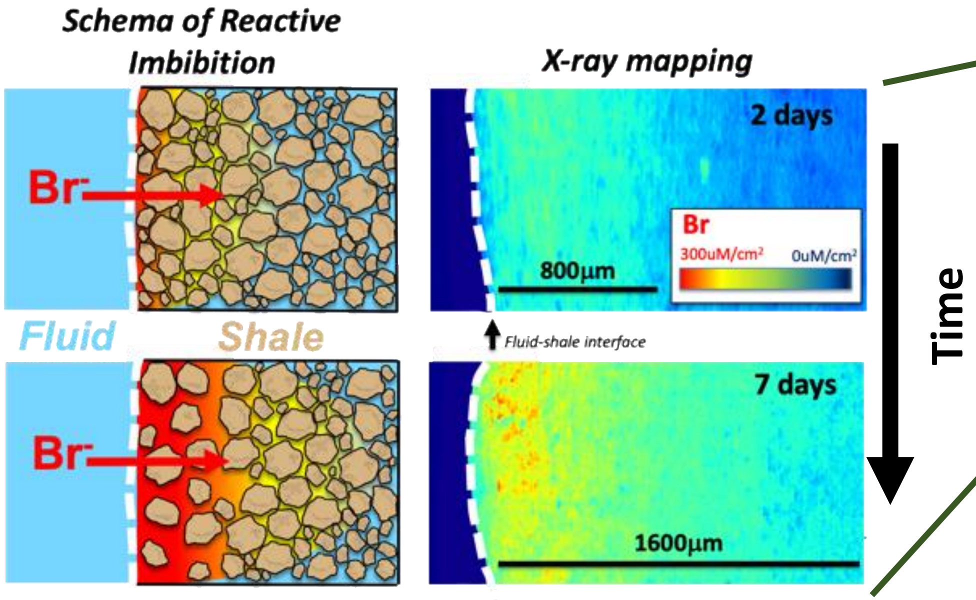
Use chemistry to image fluid movement and manipulate porosity/permeability

X-ray microprobe imaging

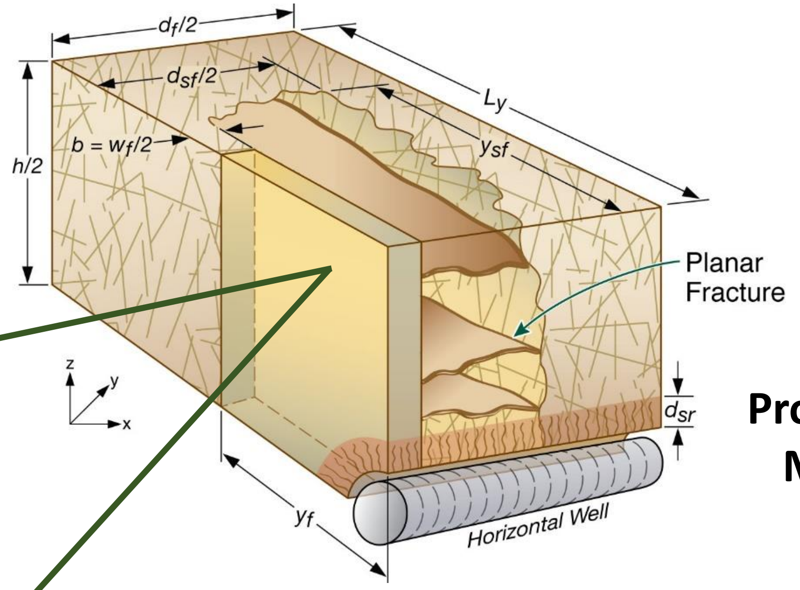
Br$^-$ tracer



Fluid penetration (Br tracer)



V. Noël et al., In prep.



Production Models

X-ray microprobe: Fluid penetration (diffusion tests ongoing) → Fracture skin model

A Multi-Scale Multi-Physics Multi-Lab Project: Progress To Date

Reservoir Stimulation

- New understanding of fracture “swarms”, a paradigm shift
- Developed new upscaling techniques now adopted by industry

GEOS-TOUGH Interface

- Fully automated procedure for TOUGH reservoir simulations based on GEOS outputs

Reservoir Production

- Investigated impact of fracture/well interference and other sensitivities
- Demonstrated impact of near-fracture skin effects

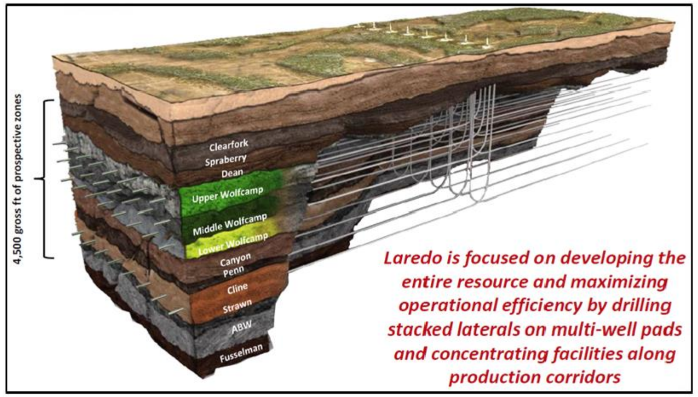
Micro-Mechanical Studies

- Demonstrated micro- and meso-scale testing procedure and hand-over to GEOS/TOUGH
- Conducted first experiments on proppant behavior in HFTS core

Micro-Reaction Studies

- Developed new testing methods for shale alterations due to interaction with fracturing fluids
- Initiated reactive transport models and development of upscaling methods

Using the HFTS Opportunity to…



- Validate DOE's high-performance computational capabilities for fracturing and production against a unique high-quality field and lab data set
- Develop and test a framework for reservoir simulations informed by micro-scale processes for adaptive subsurface management
- Utilize tested framework for other field test sites and industry collaborations

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Publications and Conference Contributions

- Fu, W., Morris, J., Fu, P., Huang, J., Sherman, C., Settgast, R., Wu, H., Ryerson, R., “Multiscale Simulations of Swarming Hydraulic Fractures Observed at the Hydraulic Fracturing Test Site (HFTS)”, AGU 2019 Fall Meeting, T31F-0328.
- Fu, W., Morris, J., Fu, P., Huang, J., Sherman, C., Settgast, R., Wu, H., Ryerson, R., Developing Upscaling Approach for Swarming Hydraulic Fractures Observed at Hydraulic Fracturing Test Site Through Multiscale Simulations”, SPE-199689-MS (presented at 2020 SPE Hydraulic Fracturing Technology Conference and Exhibition).
- Huang, J., Fu, P., Morris, J.P., Settgast, R.R., Sherman, C. S., Hao, Y., Ryerson F.J., “Numerical Modeling of Well Interference Across Formations at the Hydraulic Fracturing Test Site,” ARMA 19–1995.
- Moridis, G.J., Reagan, M.T., Queiruga, A.F., “High-Definition Analysis and Evaluation of Gas Displacement EOR Processes in Fractured Shale Oil Formations,” IPTC-19276, Proc. Int. Petroleum Technology Conference, Beijing, China, 26-28 March 2019.
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- Noël, V., Fan, W., Bargar, J.R., Druhan, J., Jew, A.D., Li, Q., Brown, Jr., G.E. (2019) Synchrotron X-ray Imaging of Reactive Transport in Unconventional Shales. AGU Fall Meeting, symposium H44B: Porous Media Across Scales: From Interfacial Properties to Subsurface Processes. Dec 12, 2019, San Francisco, CA, USA [contributed talk].
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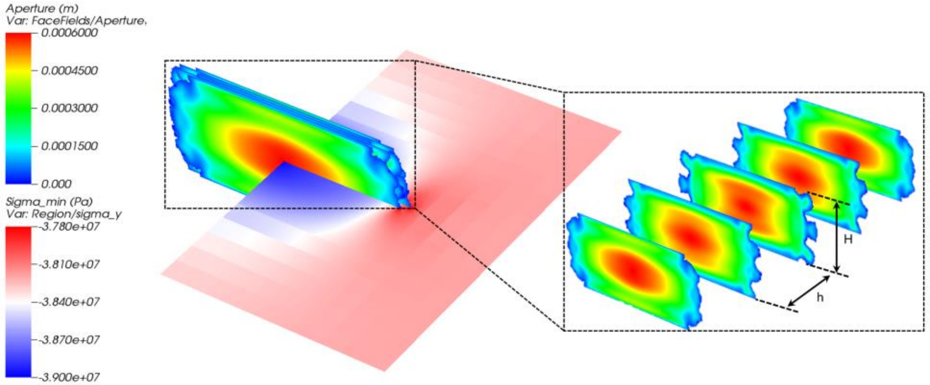
Backup

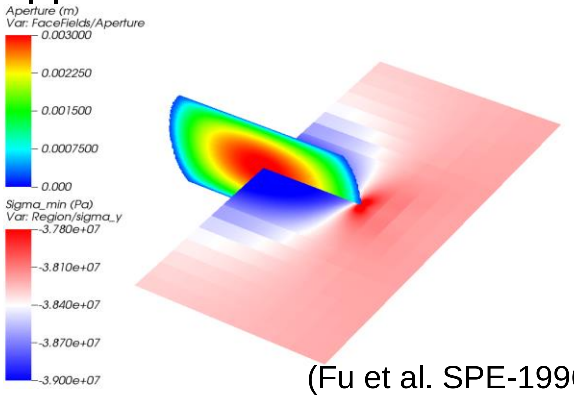
An Upscaled Approximation for Swarms

Resolve individual fractures:



Upscaled fast-running, monolithic approximation:

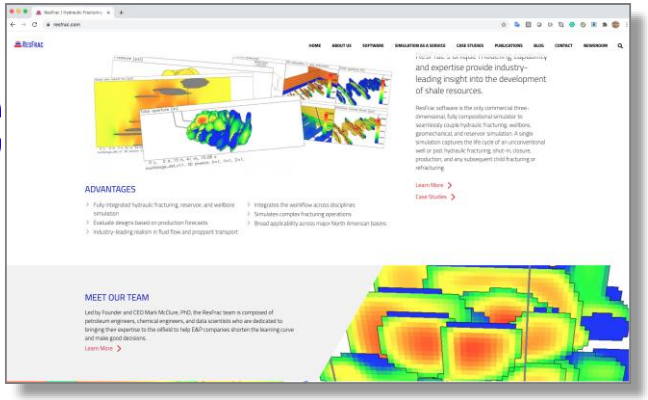
- ✓ Viscosity: $\mu_0 = N^2\mu$
- ✓ Toughness: $K_{IC0} = \sqrt{N}K_{IC}$
- ✓ Leak-off: $C_{L0} = NC_L$
- ✓ Proppant: $D_0 = ND$



(Fu et al. SPE-199689-MS)

Enables existing simulators to predict realistic fracture growth with physical parameters.

ResFrac



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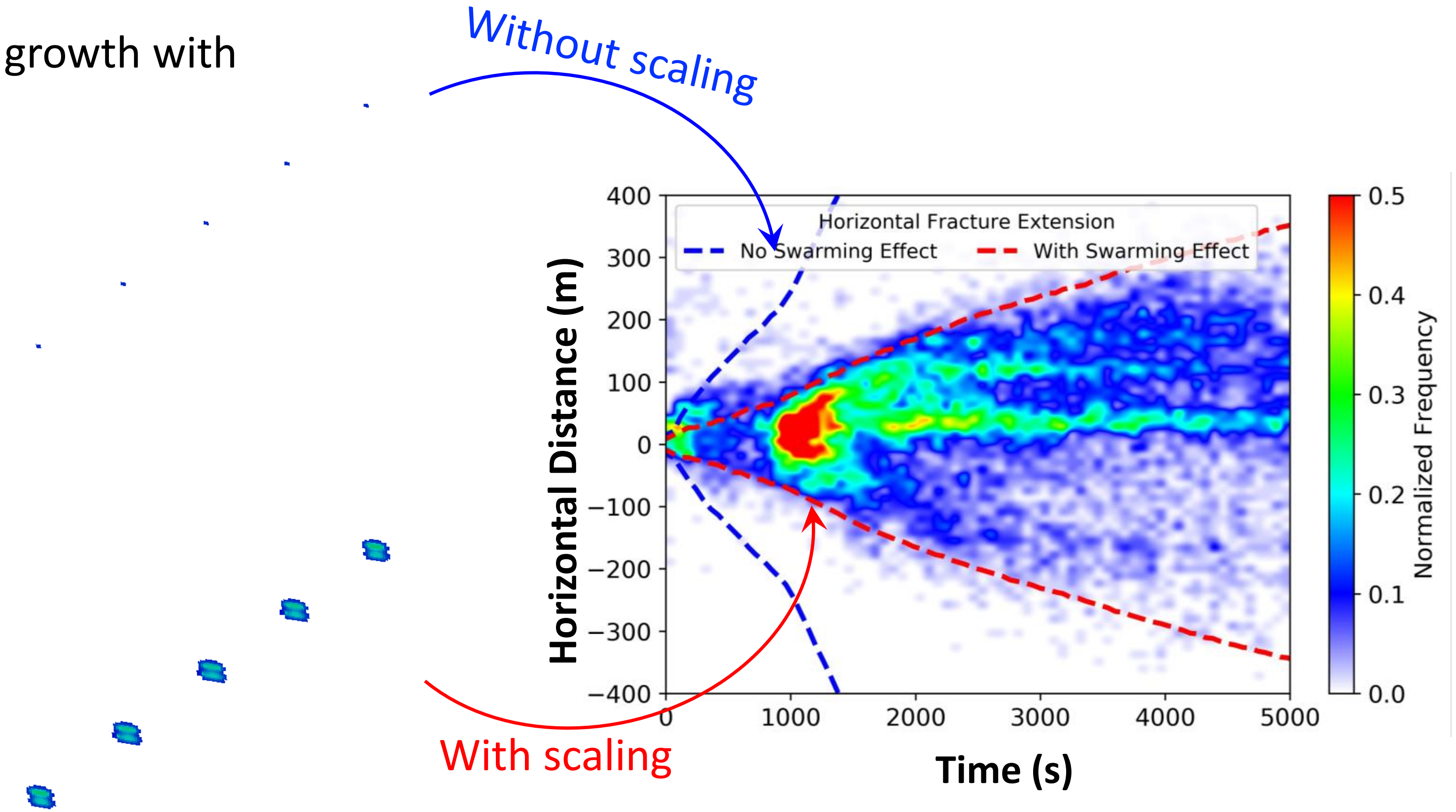


GEOS – TOUGH+ Simulation Workflow Is Complete and Automated

Developed automation for TOUGH+ simulations using GEOS outputs and production data

Leverage development of the TOUGH+ family of unconventional reservoir simulators

User-defined data

Production data

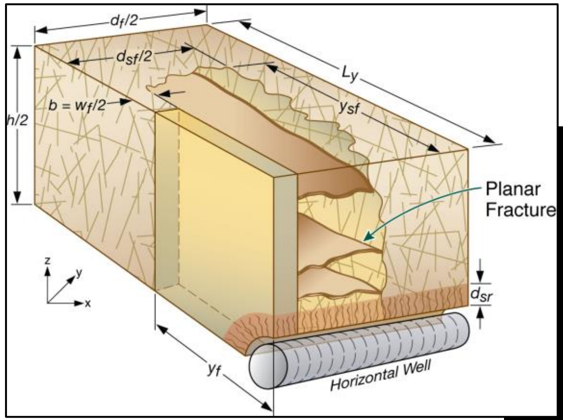
Fracture geometry & aperture from GEOS

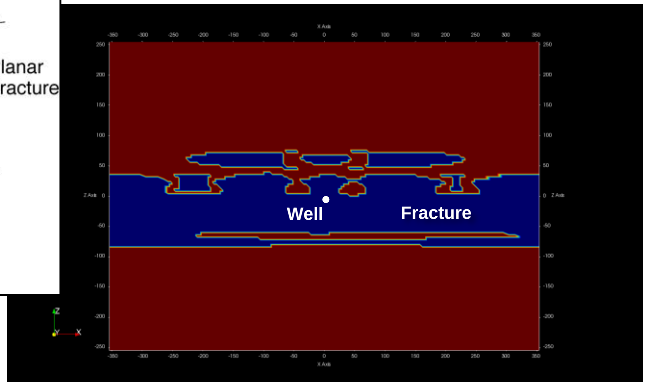
Build mesh

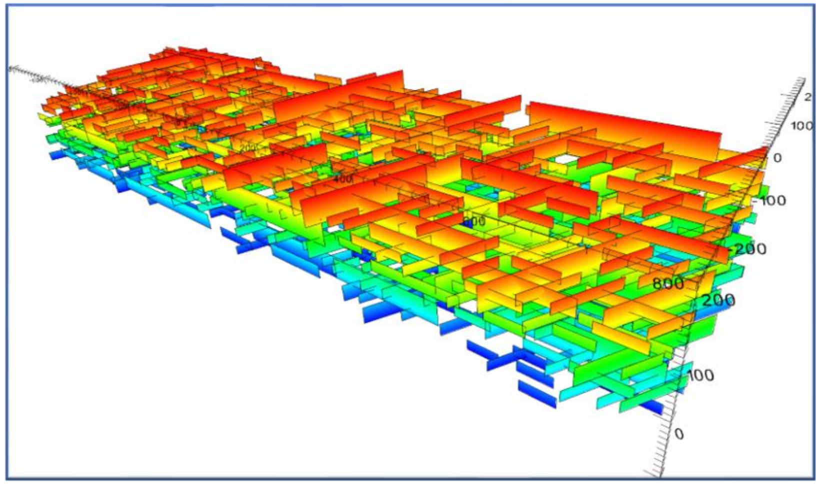
Adjust mesh to match aperture

Create boundary conditions from data

Create initial condition from GEOS



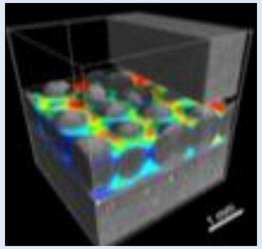


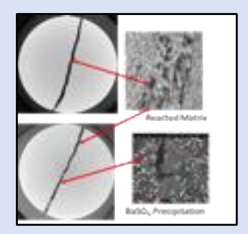


TOUGH initial conditions and inputs

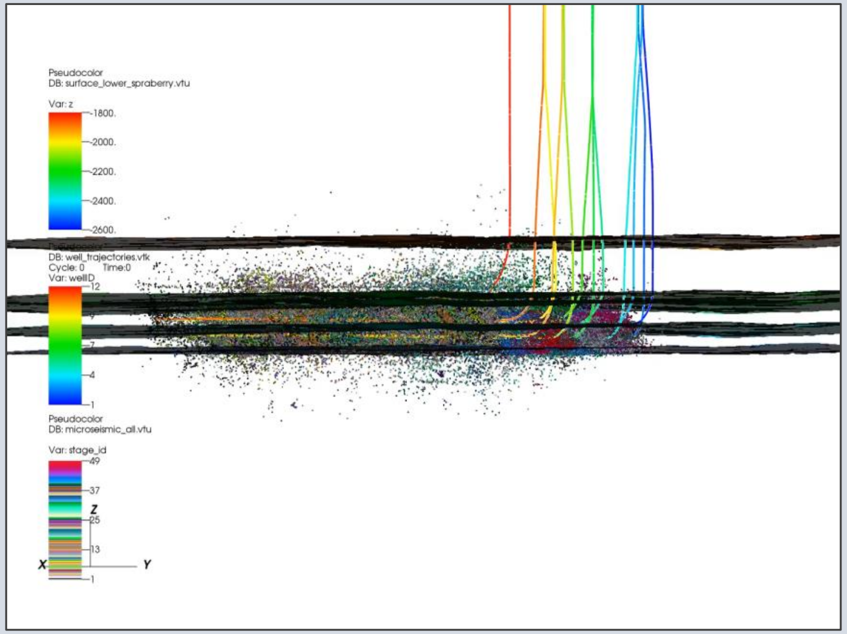
Run simulations, visualize outputs

Core- & micro-scale results and data

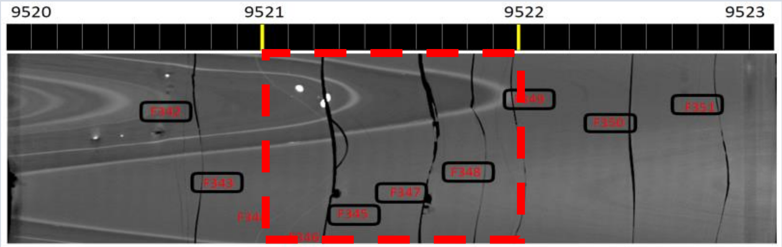




Hydraulic Fracturing Test Site (HFTS)



4 hydraulic fractures within 1 foot!



- Over 240 GB, hosted in an EDX Workspace
- Raw geophysical logs
- Fiber-based temperature data
- Extensive microseismic catalog
- Production and tracer data
- Multitude of reports and presentations
- ***Identified prevalence of "fracture swarms"***
- ***Special thanks to GTI and the rest of the HFTS consortium for facilitating access, navigating the dataset, and providing feedback to our project!***

Chemical-Mechanical Coupling: Impact of Weakening of Fracture Faces on Mechanical Behavior

React Wolfcamp shale with fracture fluid

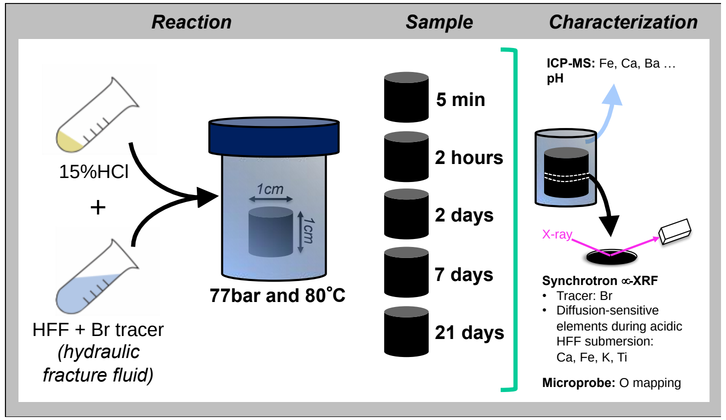
SLAC

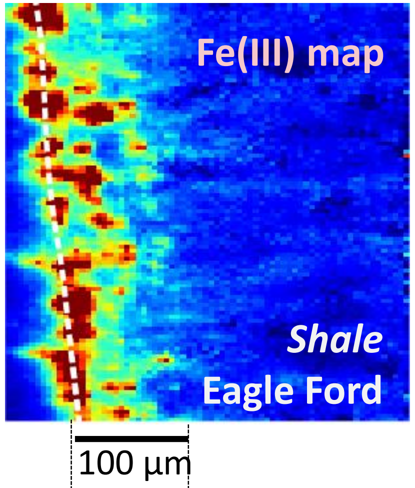
Characterize microscale chemical alteration

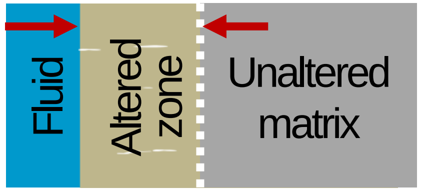
SLAC

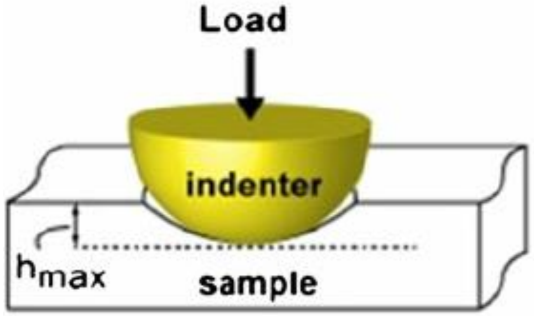
Indentation measurements

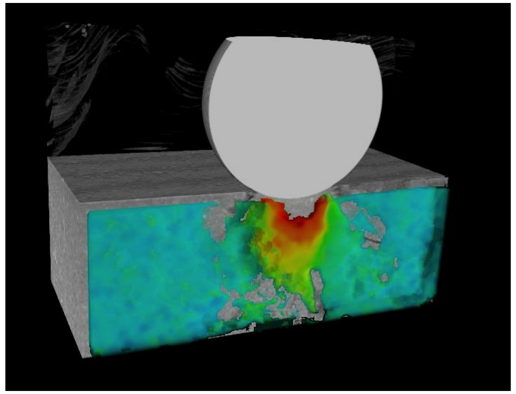
LBNL







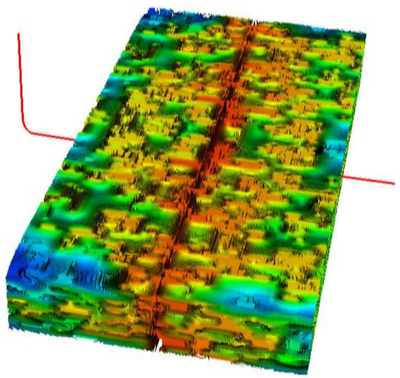


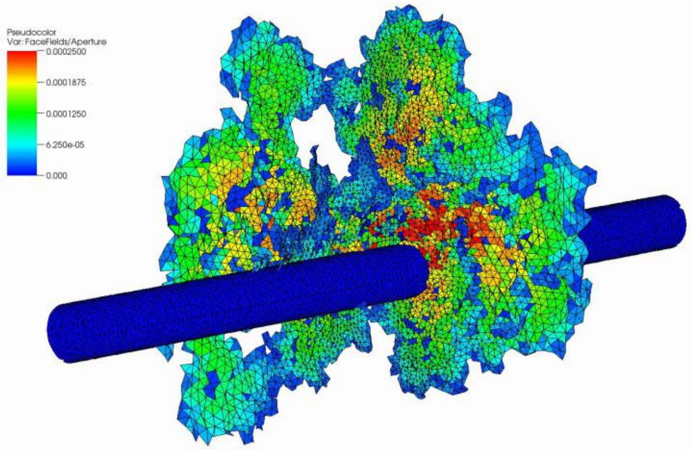


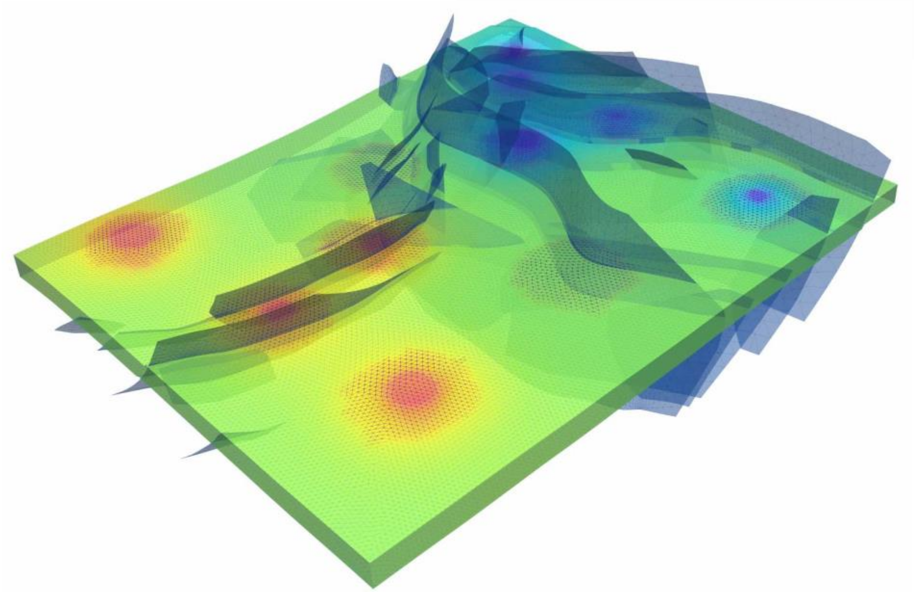
Microscale alteration of fracture face **SLAC**	→	Assess geomechanical alteration **LBNL**

GEOS: Hydraulic Fracturing Simulation Tool

- Predict the growth of fracture network, proppant placement, permeability enhancement, production forecasting, zonal isolation, etc.
- Evaluate the influence of geologic conditions ***and*** engineering controls
- Simulate geophysical observables, e.g., time-series of seismic events
- *Gain insight - unify existing data – suggest new experiments, tools and methods*
- ***Latest version (GEOSX) is open source***







GEOS is a unified code framework providing a common data structure that can be shared by various physics solvers and material models

Is "swarming" the right analogue?

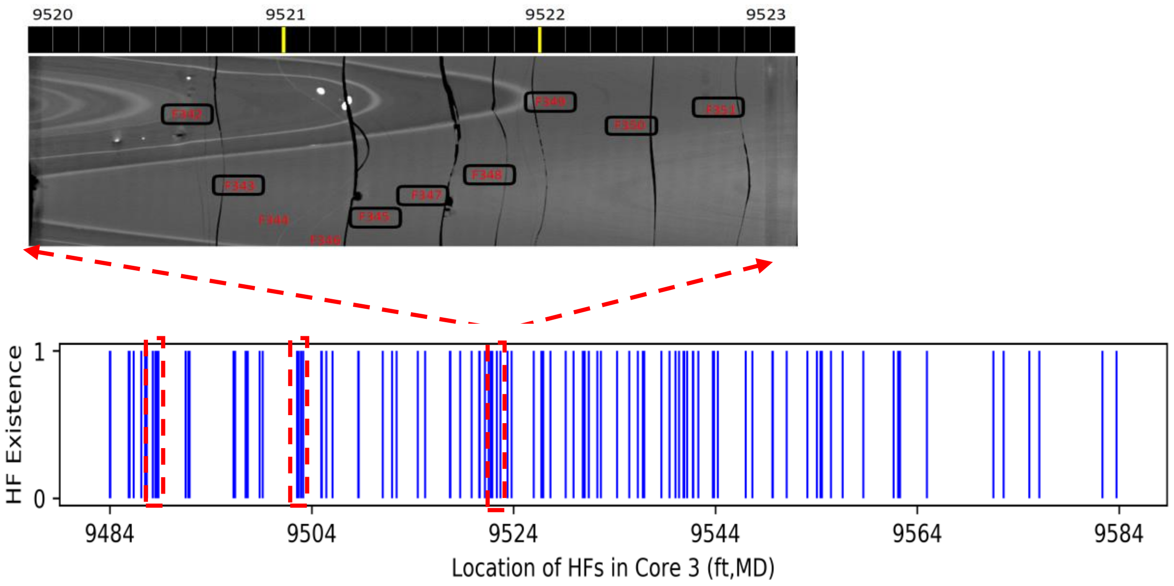
- Apparent "swarming" was the most striking feature common to HFTS and a similar experiment in Eagle Ford (Raterman et a., 2018)

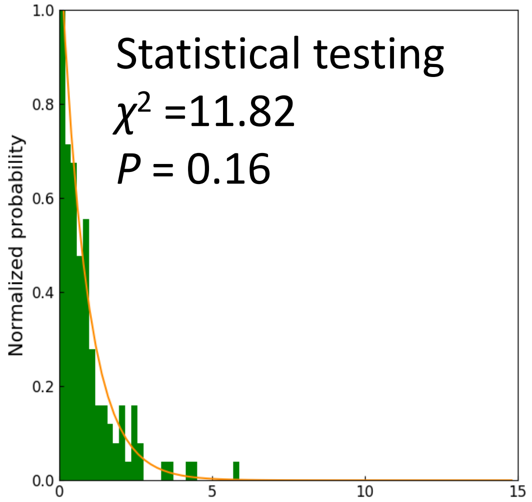
- If true swarming:
  - Has implications for the underlying mechanisms. E.g.: individual fractures in one swarm may have a common root.

- If apparent swarming is a *Poisson process*:
  - Individual fractures within apparent swarm may not be "related"
  - Mechanism might be more chaotic?

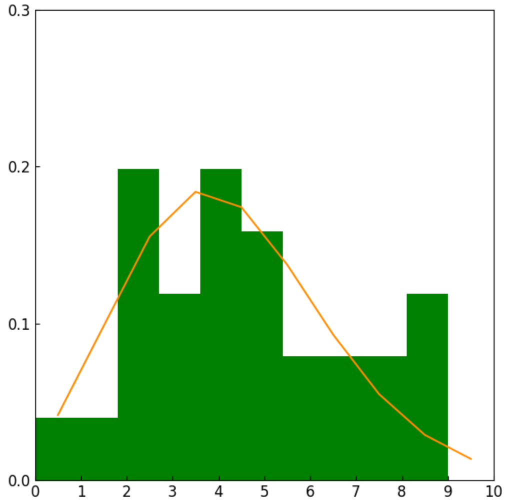
What are implications of fracture swarms for production?

8 HFs in a 3-ft core





Spacing between HFs



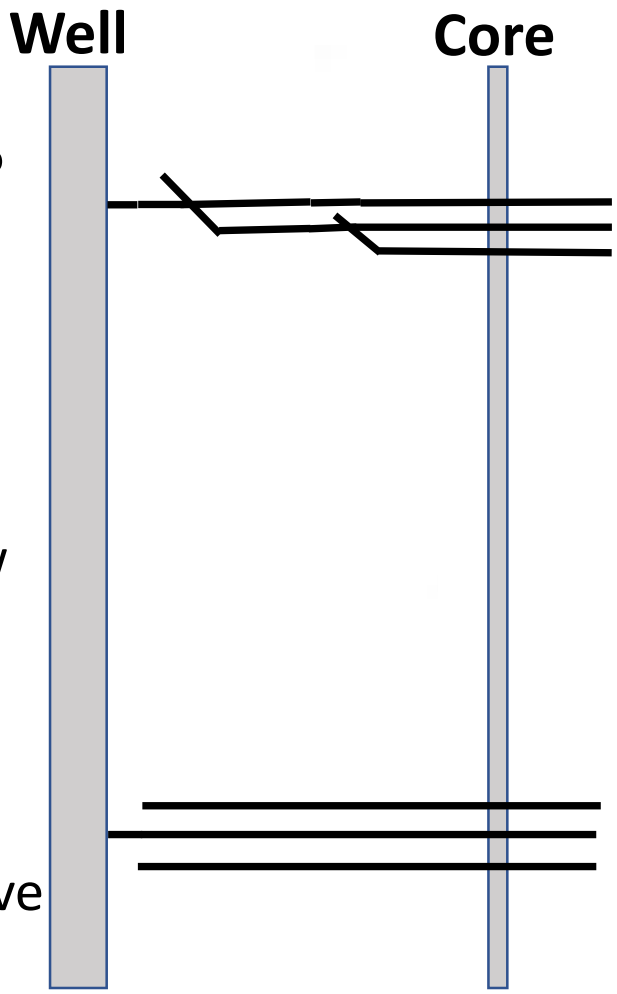
Count per 4 ft

GEOS is the Perfect Tool for Exploring Hypotheses

Ideas from HFTS Consortium and others have profound ***production*** implications!

The branching hypothesis:

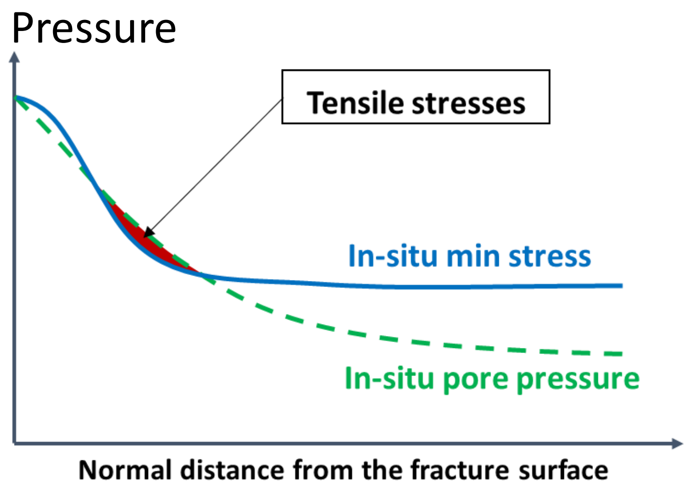
- Can natural fracture cause branching?
- Can branches survive?
- ***All fractures connect to well***



GEOS model indicates branches tend to die off

The poroelastic hypothesis:

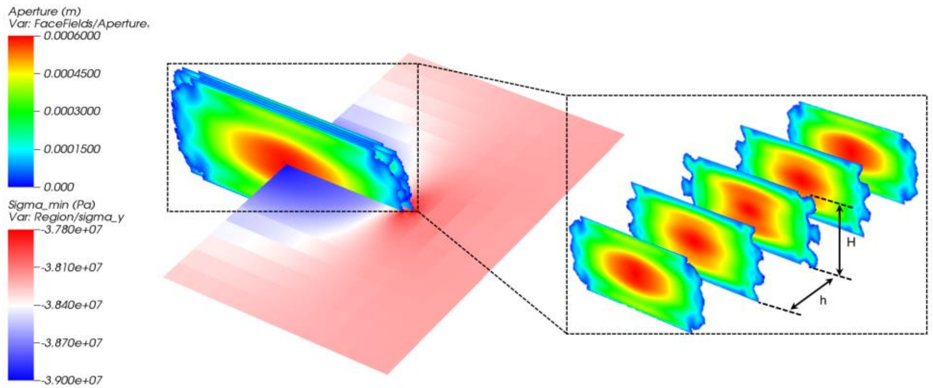
- Can the mismatch between stress shadow and pressure shadow cause tensile crack?
- ***Most fractures NOT connected to well!***
- Shell has a simple conceptual model
- We are collaborating to develop a definitive understanding using GEOS



Less “arm waving” and more objective, rigorous analysis!

An Upscaled Approximation for Swarms

Resolve individual fractures:



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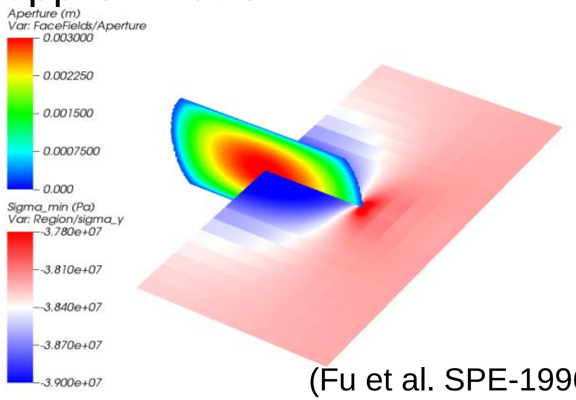

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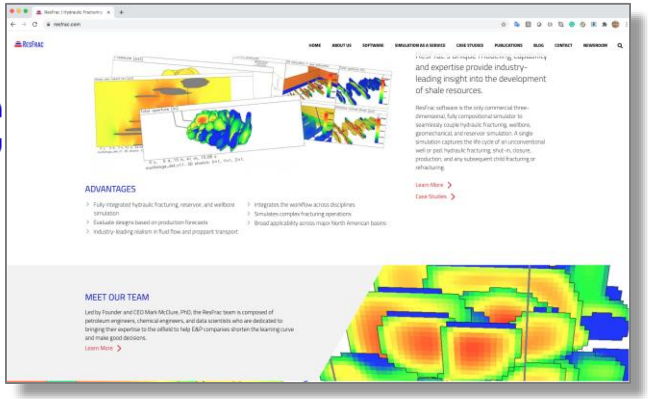

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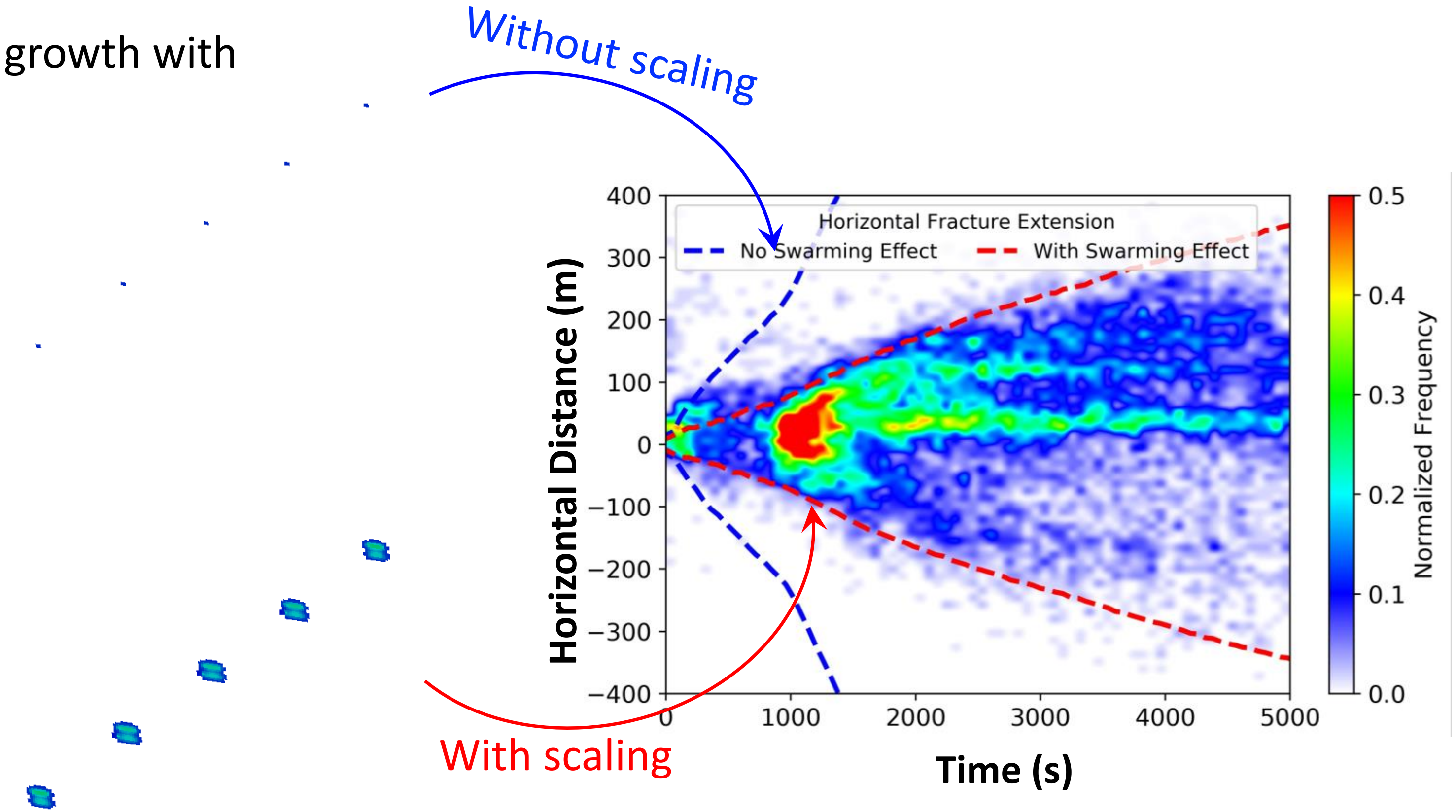
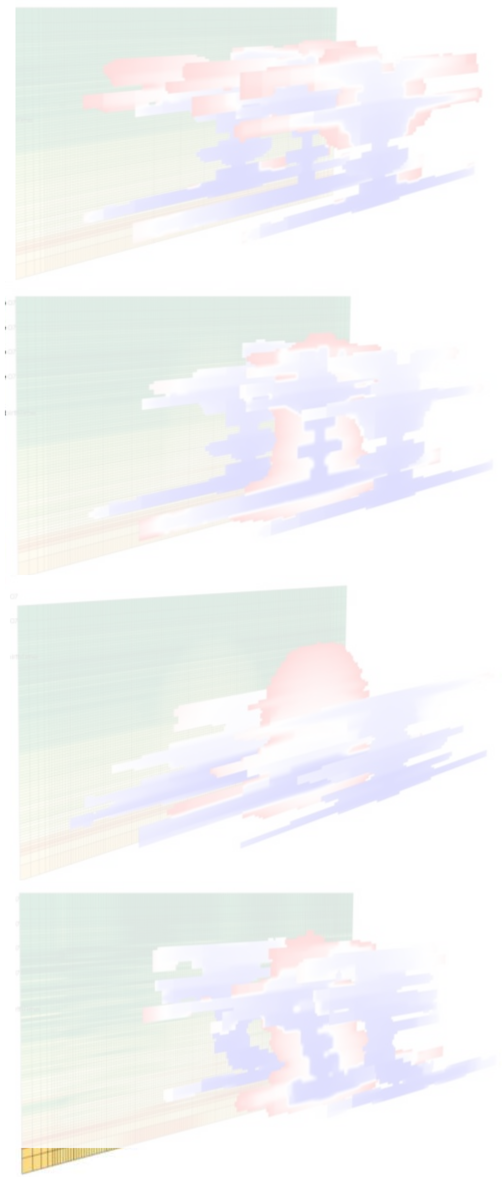


Investigating Factors Controlling Connection to Reservoir

Landing depths

Stress heterogeneity



Complex proppant-wellbore-fracture interaction

TOUGH Family of Codes: A Massively Parallel Reservoir Simulator for Porous and Fractured Media

TOUGH2

multi-dimensional	0D, 1D, 2D, 3D
multi-phase	liquid, gas, NAPL, solid
multi-component	water, NCG, VOC, RN, …
non-isothermal	heat
flow and transport	multi-phase Darcy law
fractured-porous	dual-f, dual-k, MINC, ECM, DFN

iTOUGH2

MPiTOUGH2
iTOUGH2-PVM

parameter estimation
sensitivity analysis
uncertainty analysis
data-worth analysis

TOUGHREACT
+ reactive geochemistry

TOUGH-FLAC
TOUGH-ROCMECH
+ geomechanics

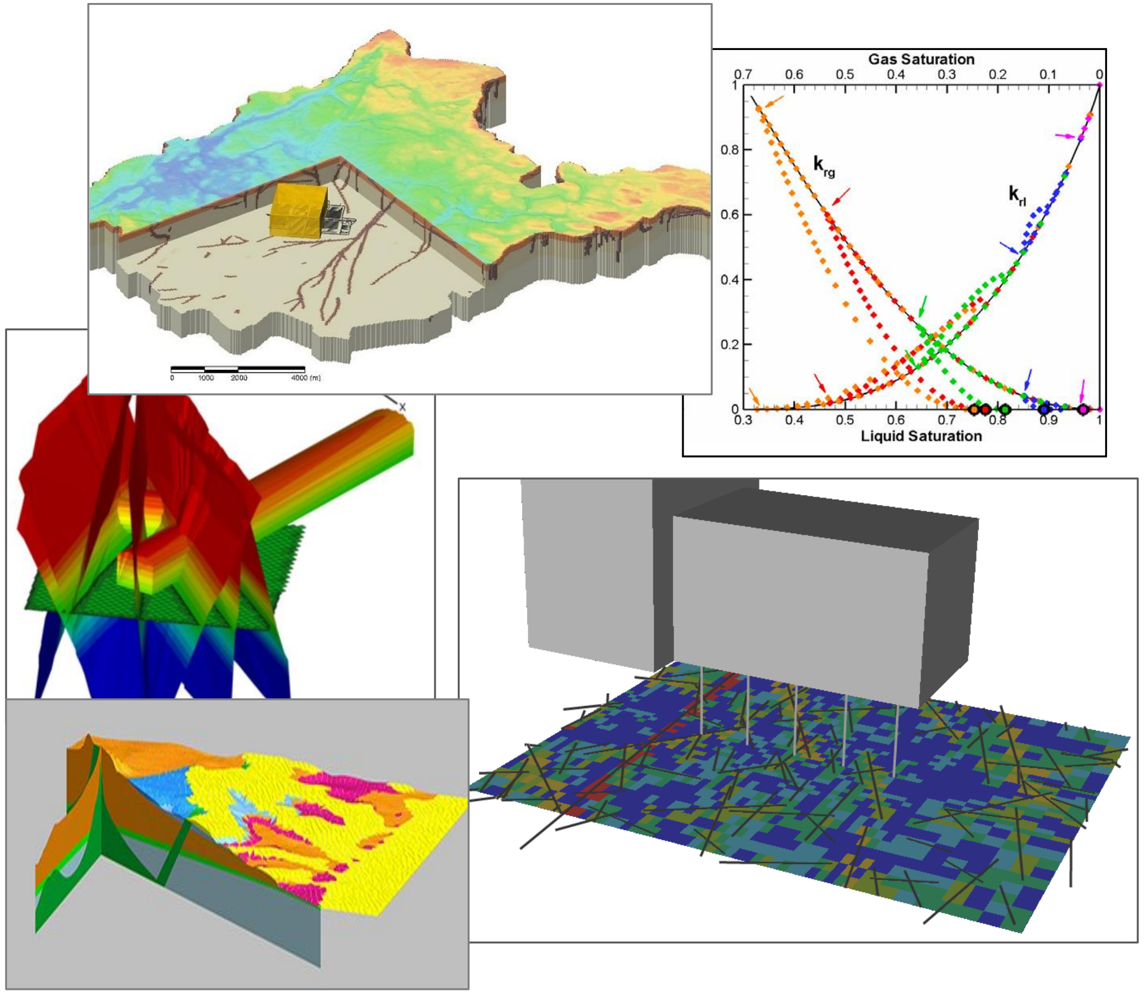
TOUGH+
+ hydrates
+ shale gas

TOUGH3
+ parallel

T2WELL
+ wellbore simulator

PEST Protocol

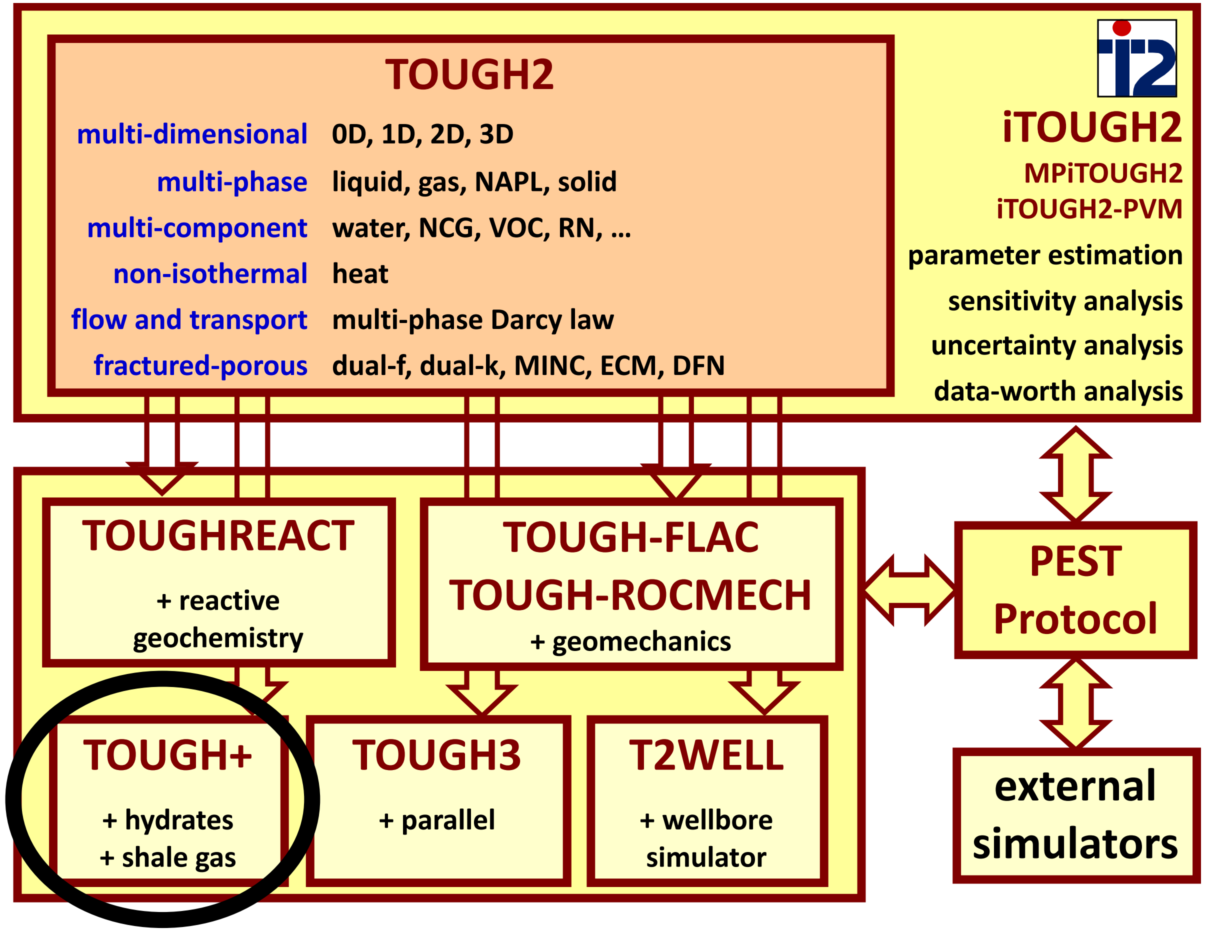
external simulators



Suite of Non-isothermal, Multiphase, Multicomponent Subsurface Flow and Transport Simulators Integrated into the iTOUGH Inversion and Optimization Framework

LBNL

TOUGH Family of Codes: A Massively Parallel Reservoir Simulator for Porous and Fractured Media



TOUGH+OilGasBrine (T+OGB):

- Conventional and tight/shale oil/gas
- Fully compositional simulator, fully non-isothermal
- Oil (live or dead), H_2O, Salt(s)
- Up to 11 gas components ($C_{1\text{-}3}$, CO_2, N_2, H_2, etc.)
- Enhanced oil physical properties relationships (viscosity, etc.)
- Parallel computing capabilities (features merged with pTOUGH+)
- Simulate stencils (irreducible reservoir sub-unit)
- One, two, or multiple wells
- Multi-well production, or production-injection

Suite of Non-isothermal, Multiphase, Multicomponent Subsurface Flow and Transport Simulators Integrated into the iTOUGH Inversion and Optimization Framework

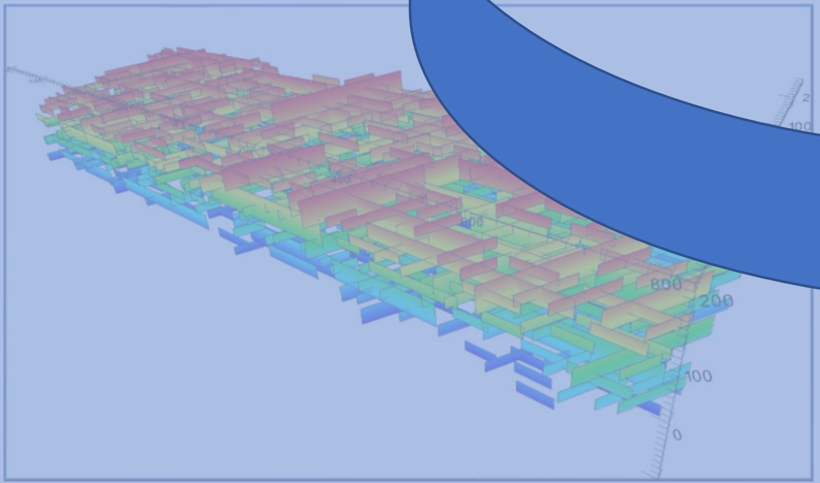
GEOS – TOUGH Simulation Workflow Is Complete and Automated

Developed automation for TOUGH+ simulations using GEOS outputs and production data

User-defined data

Production data

Fracture geomet
aperture from G S



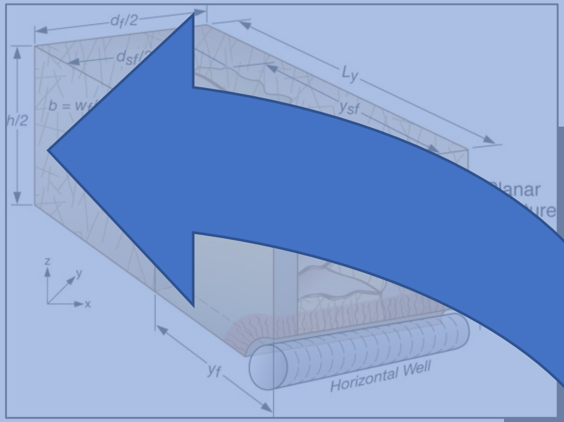
Leverage development of the TOUGH+ family of unconventional reservoir simulators

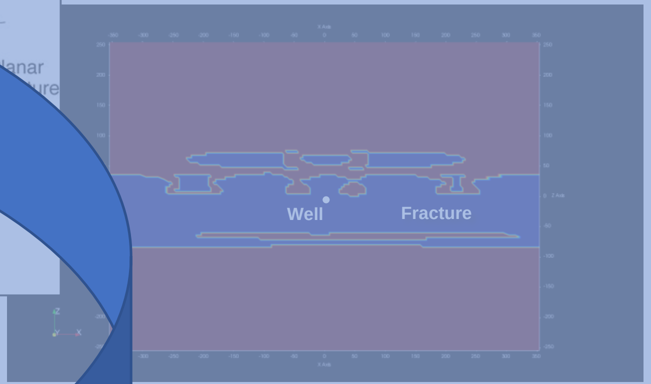
ld mesh

Adjust mesh to match aperture

Create boundary conditions from data

Create initial condition from GEOS

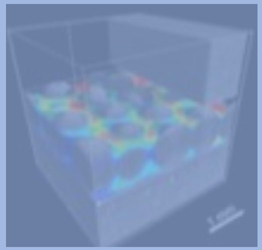


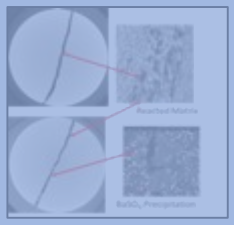


TOUGH initial conditions a

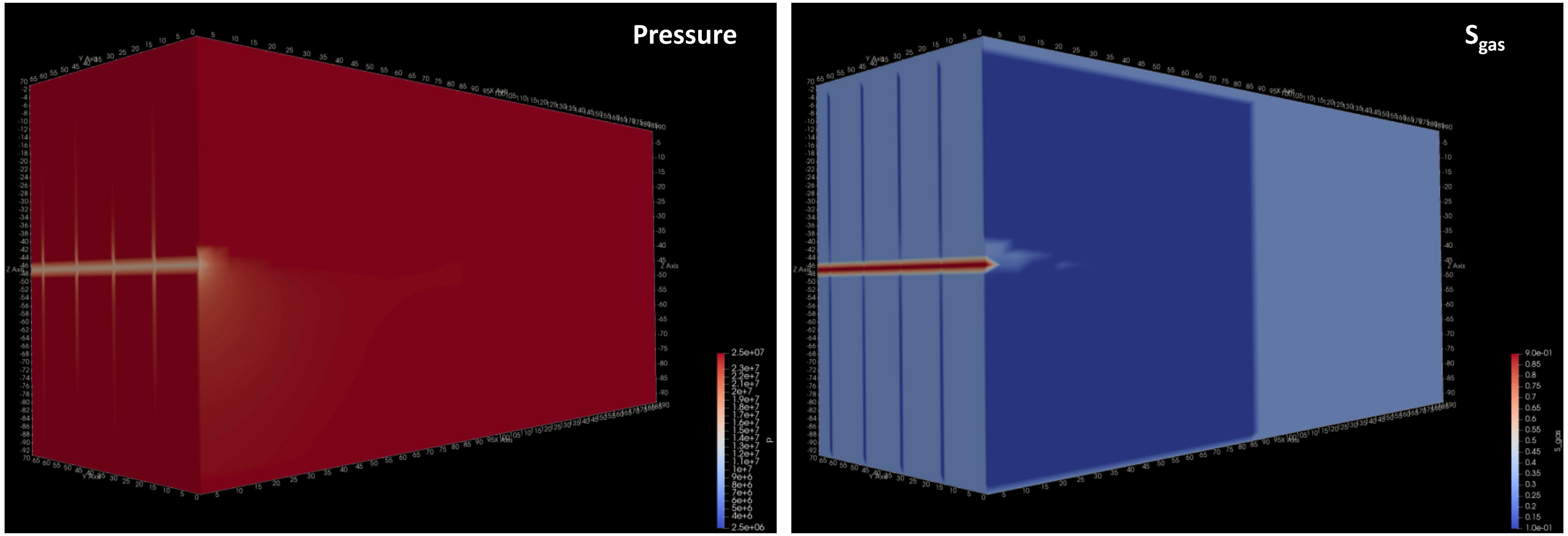
Run simulations, visualize outputs

Core- & micro-scale results and data

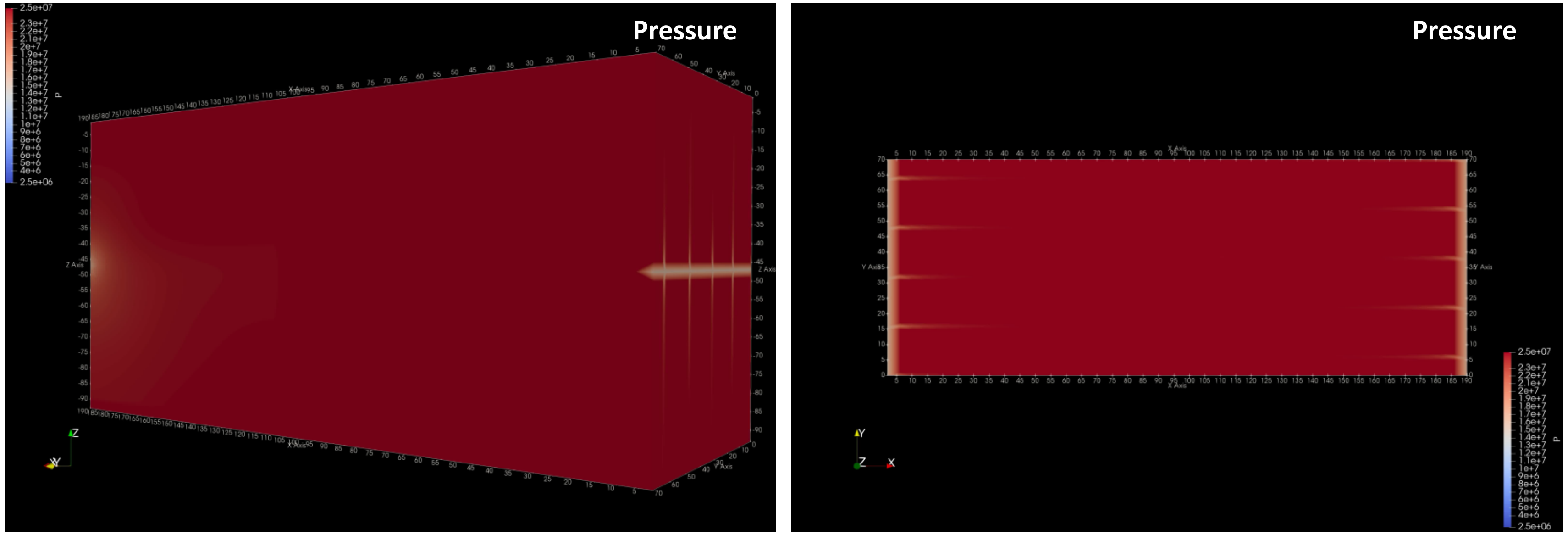




Preliminary GEOS – TOUGH Simulations for HFTS: 5-Cluster Case



One well, five fractures



Two wells, five fractures each (offset)

HFTS Simulation Case

- 5-fractures from GEOS test problem
- **One well** and **two wells** (3SU/4SU)
- Matrix and fracture properties from HFTS dataset
- Variable well BHPs from HFTS data

Processes Studied

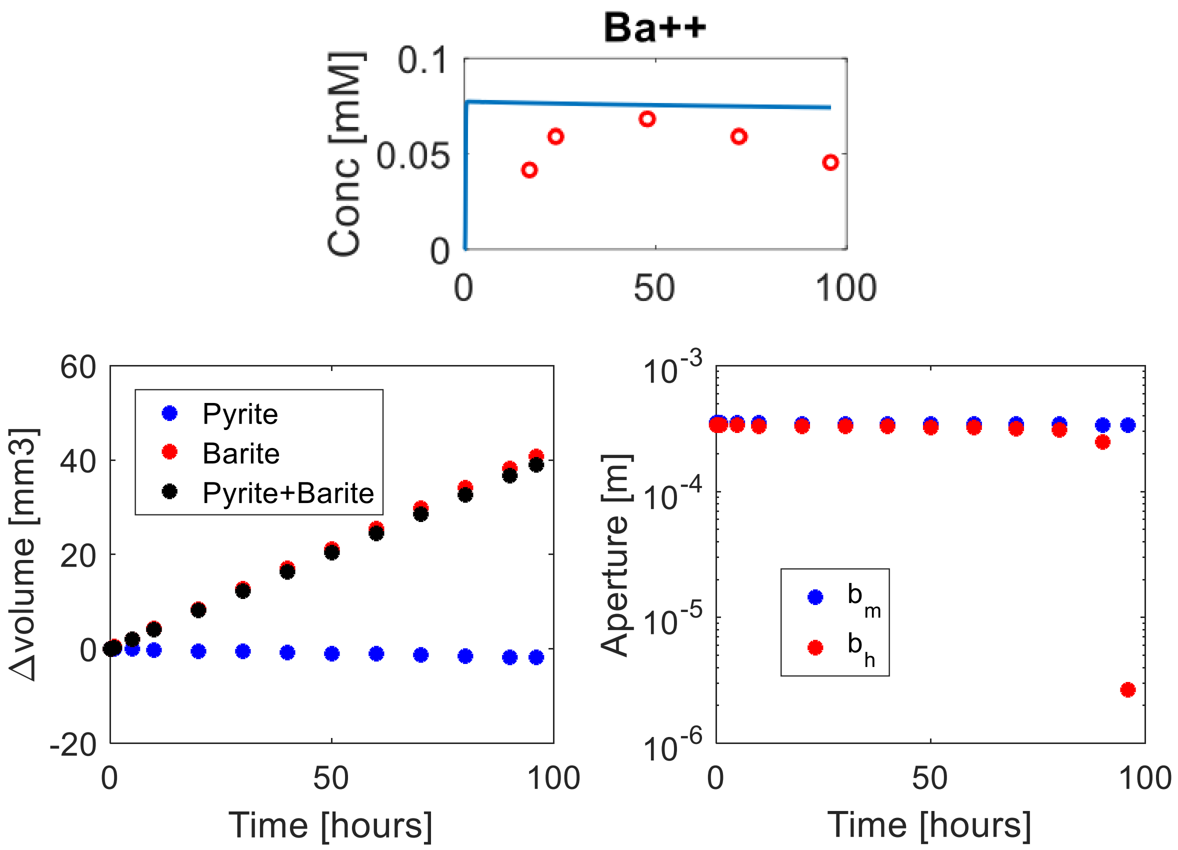
- Depressurization, fluid production, exsolution of gas
- Interference between fractures
- Interference between wells

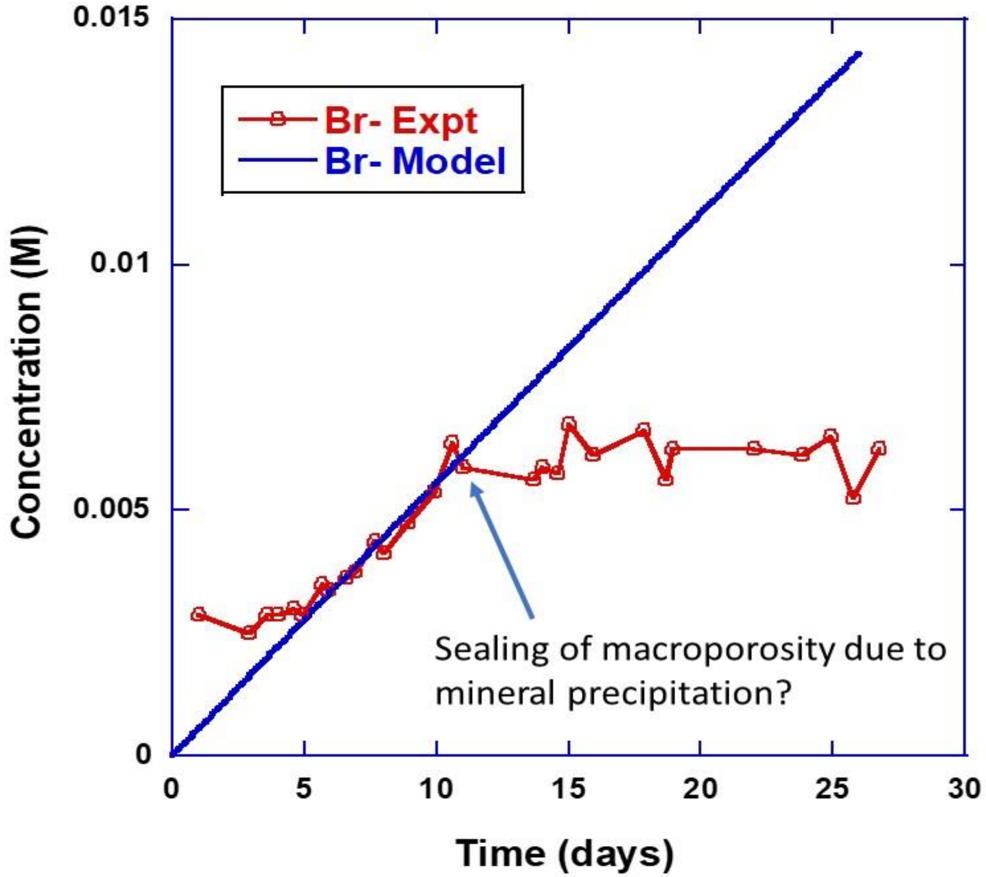
Current Focus Due to Delays in Micro-Scale Studies

- Sensitivity studies
- Numerical experiments

Preliminary Modeling of the Reaction Experiments

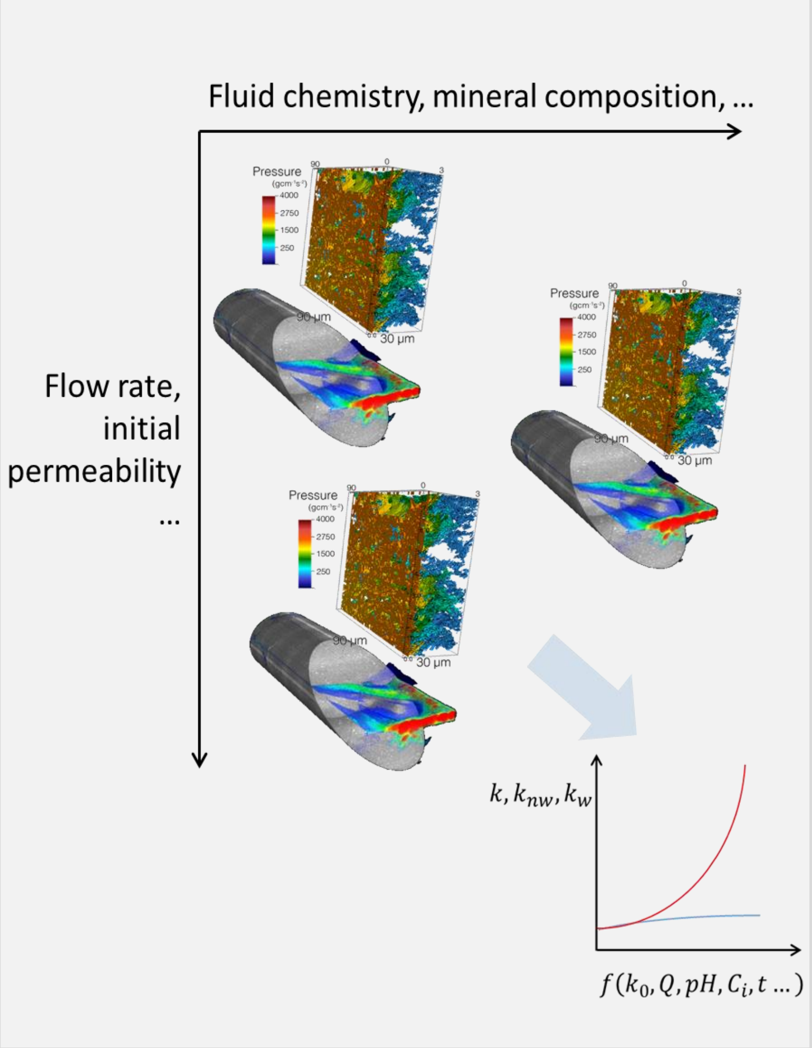
- Fracture flow experiments: captured the key features in fracture aperture change
- Batch experiments: explored different reaction networks to reproduce the measured fluid chemistry
- Diffusion experiment: evaluating the effective diffusivity across altered (skin) layer





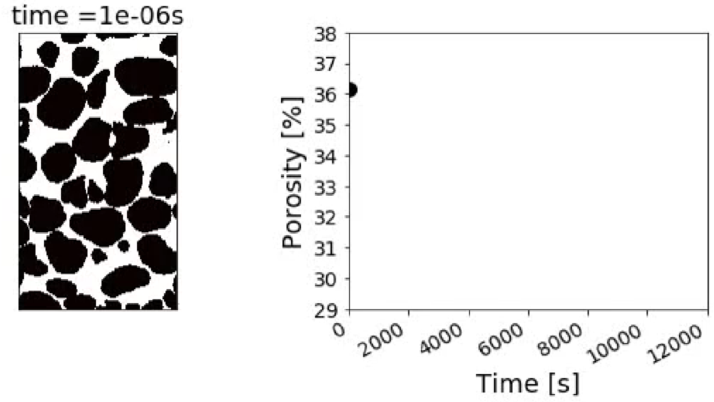
Development of Upscaling Framework

- Conduct modeling efforts with expanded parameter space of fluid chemistry, mineralogy and flow patterns
- Develop constitutive relations for (relative) permeability and diffusivity for use in reservoir-scale models

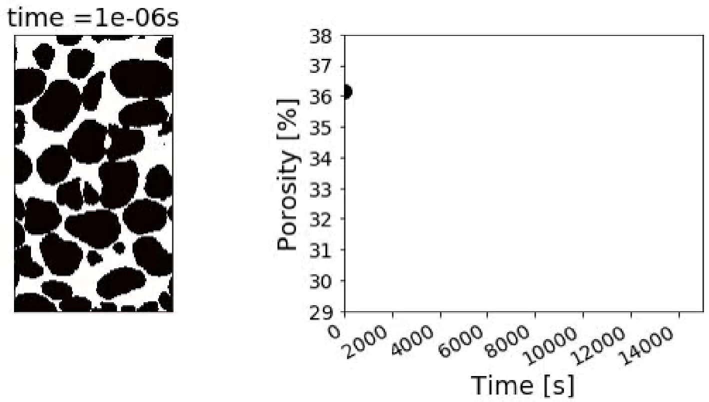


Example: Pore-scale reactive transport simulations to quantify the evolution of diffusivity/permeability of the matrix following mineral precipitation

Homogeneous Nucleation



Surface Growth



$$D_{eff} = D_{eff_c} + a(\phi - \phi_c)^n$$

$$\cancel{D_{eff} = b\phi^m}$$