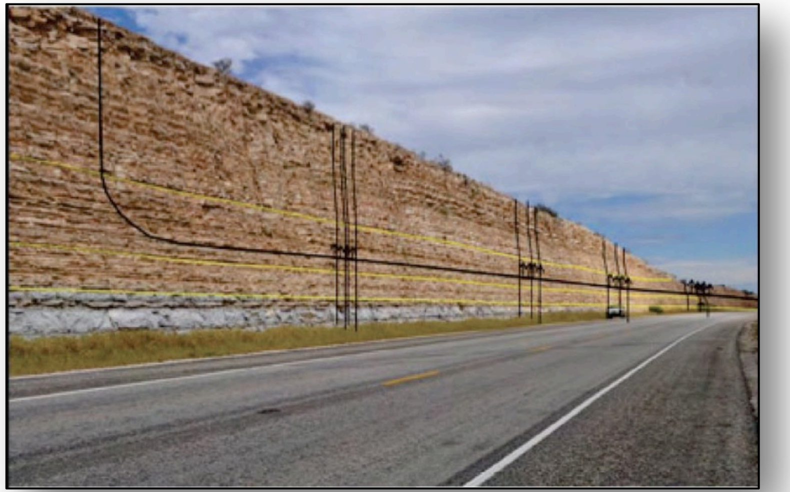
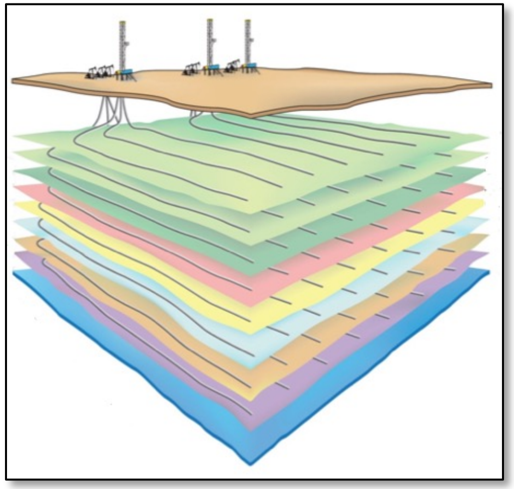
# An Integrated Multi-Scale Modeling Framework for Unconventional Stimulation and Production

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

*Annual Review Meeting, August, 2021*

# 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 Environmentally Prudent Subsurface Utilization: Multiple Gaps in Understanding Prevent Predictive Design

How does characterized geochem/geomech influence frac growth?

What do geophysical observations really tell us?

What is really going on inside proppant packs during production?

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?

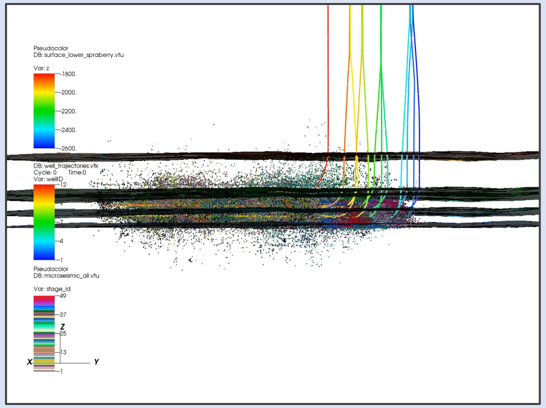
What are implications of fracture swarms for production?

***A predictive capability can be applied to new locations AND broad applications***

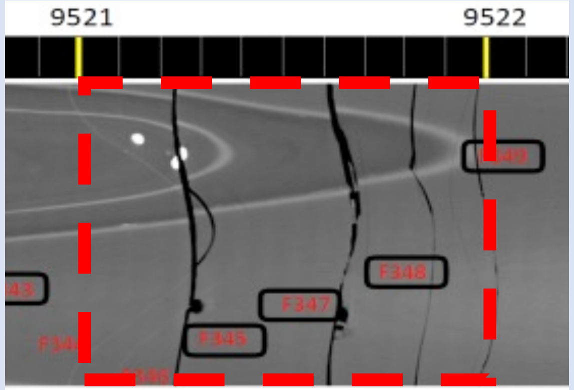
NATIONAL ENERGY TECHNOLOGY LABORATORY

# A Multi-Scale Multi-Physics Multi-Lab Project

**Hydraulic Fracturing Test Site (HFTS) Field Data and Core**



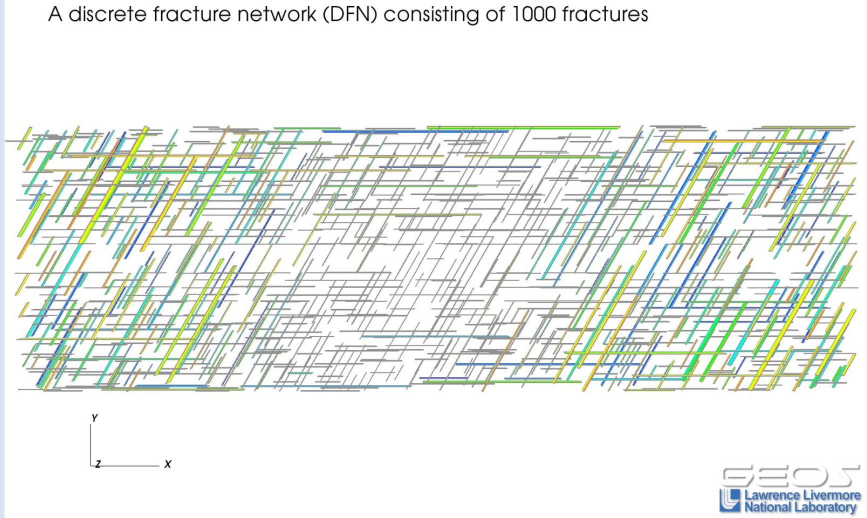
**Extensive reservoir scale data**

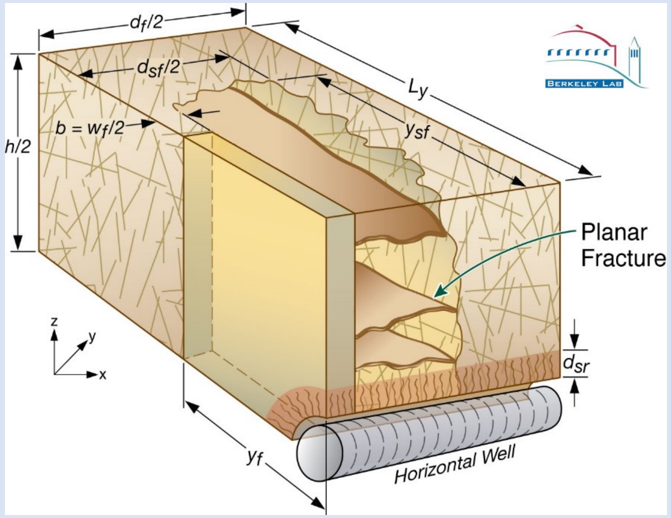



**4 hydraulic fractures within 1 foot!**

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

**GEOS** ⟷ **TOUGH**




GEOS Stimulation:

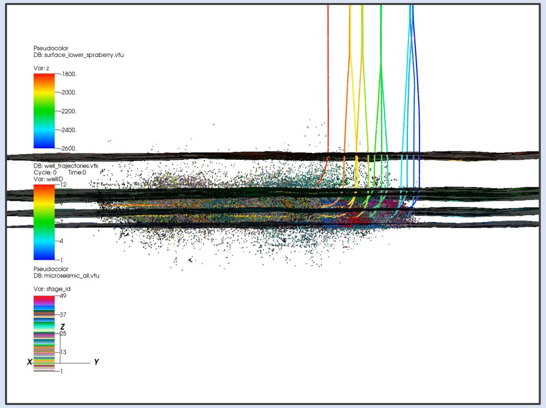
- Fracture network evolution, proppant placement, permeability enhancement, zonal isolation, etc.
- Simulate geophysical observables – seismicity, fiber optics, etc.

TOUGH Reservoir production

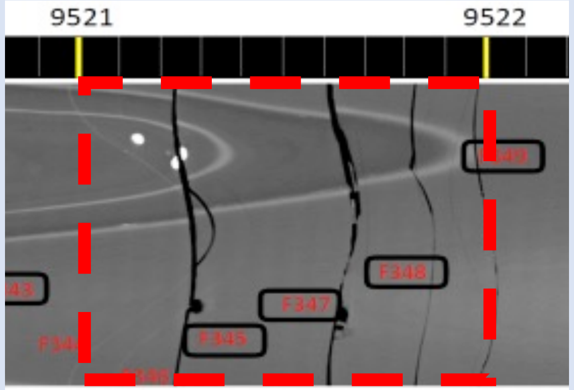
- Fully compositional simulator
- Fully non-isothermal
- Discrete and multi-continuum fracture representations
- Extensible: Can accommodate microscale relations

# A Multi-Scale Multi-Physics Multi-Lab Project

**HFTS Field Data and Core**



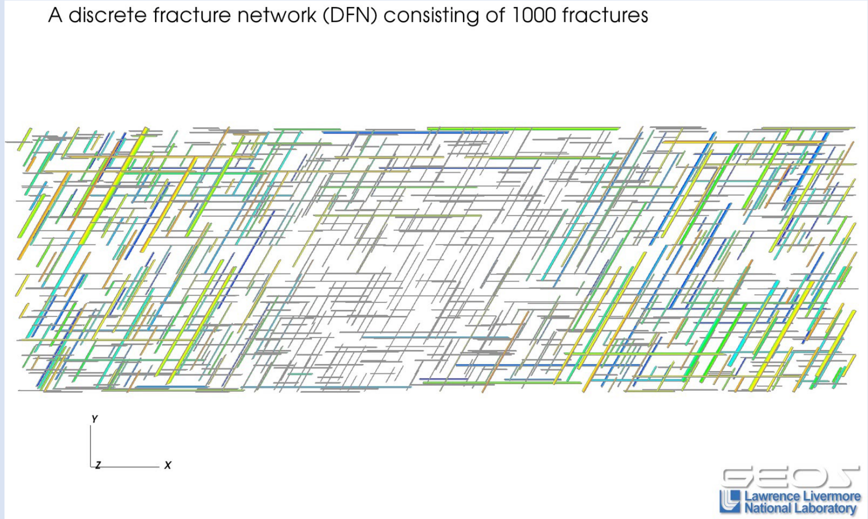
**Extensive reservoir scale data**

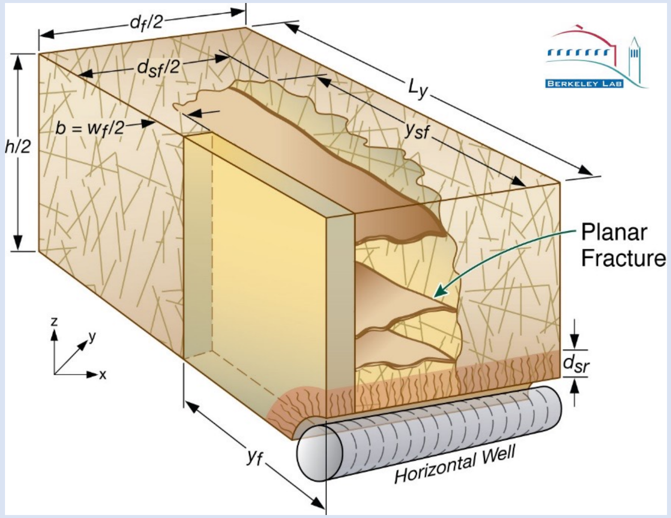



**4 hydraulic fractures within 1 foot!**

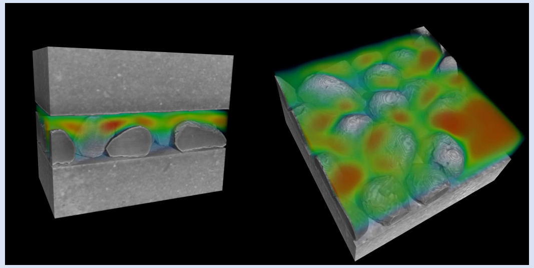
**Linked Two Powerful Simulators to Answer Complex Questions at the Reservoir Scale: GEOS for Stimulation Behavior, TOUGH for Production**

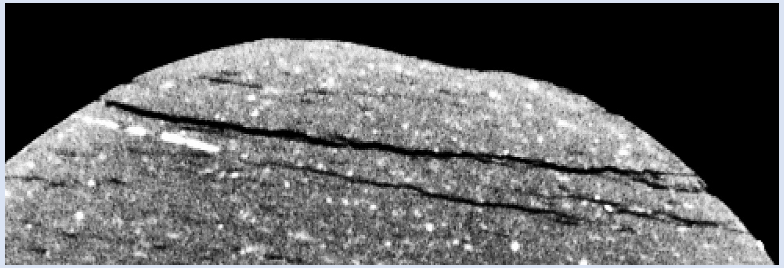
**GEOS** ⟷ **TOUGH**

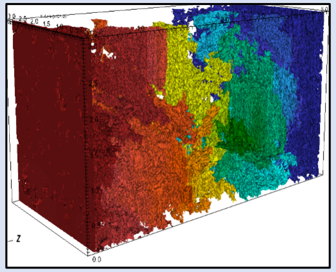



**New Constitutive Models for Shale Property Evolution from Geomechanics and Reactions Based on Micro/Core-scale Experiments/Simulations (Fundamental Shale Synergies)**







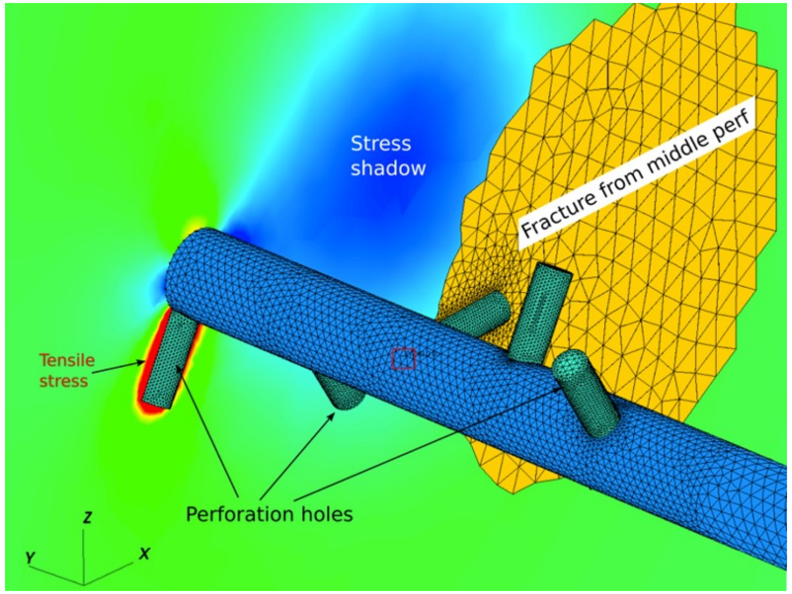
# Reservoir-Scale GEOS Stimulation Models Explore the Impact and Origins of "Swarms"

- MMP previously investigated impact of swarms and transitioned predictive capabilities to scientific community and industry

- We have turned our attention to understanding swarm ***origins***
  → Will enable ***engineering*** of surface area

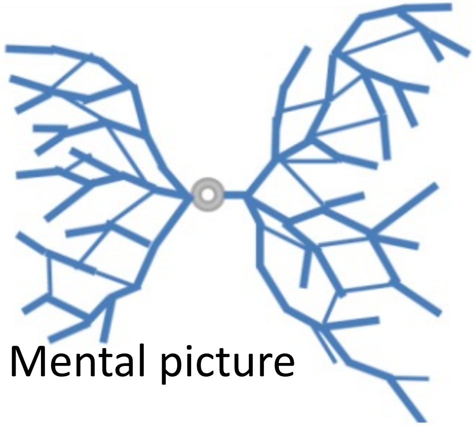
- Study is challenging many theories proposed in the literature
  - Fracture branching
  - Poromechanics

- Results will be published shortly

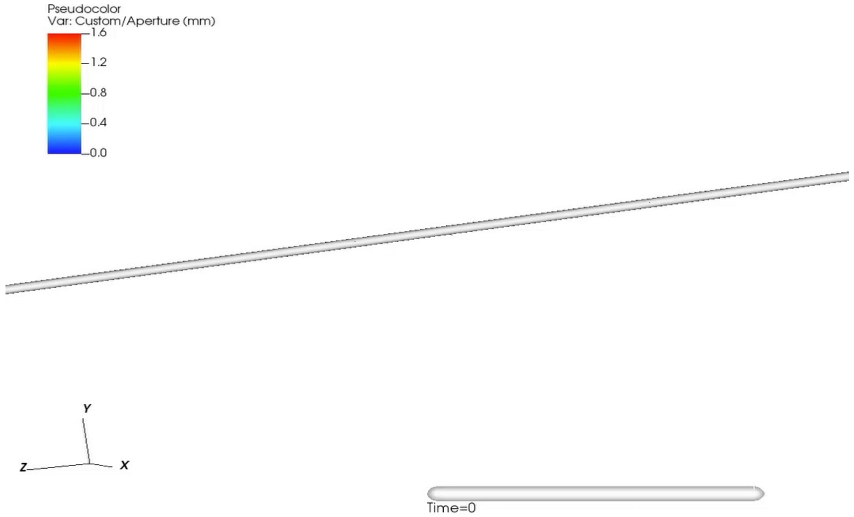



Interference among neighboring perforations in a single cluster.

Physical reality

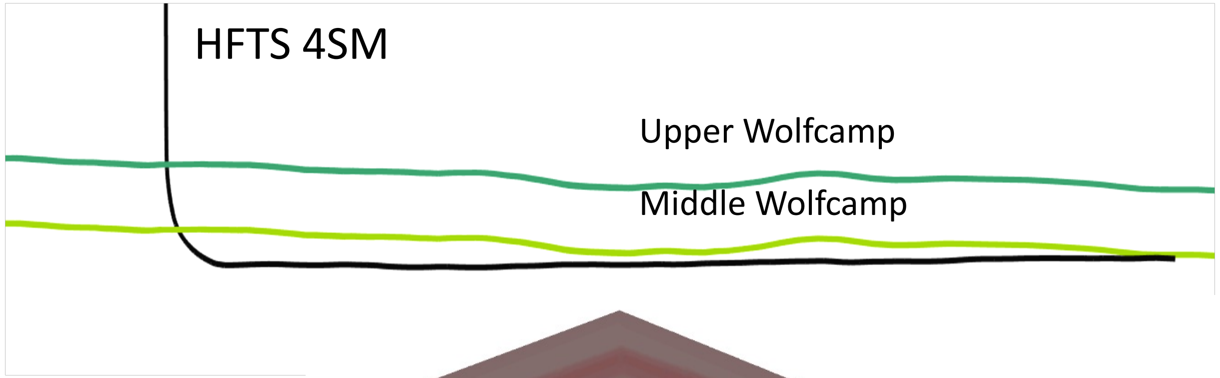


Mental picture

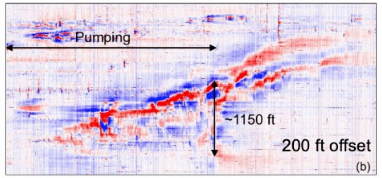


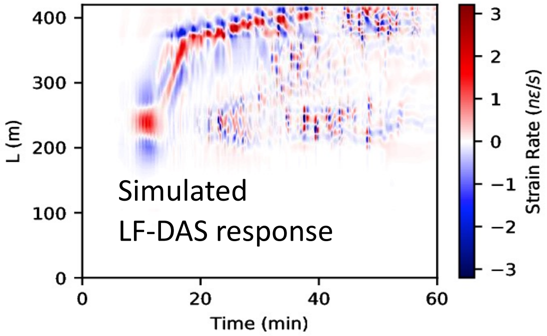
# Reservoir-Scale GEOS Stimulation Modeling Reveals Geomechanical Factors Underlying Fracture Shapes

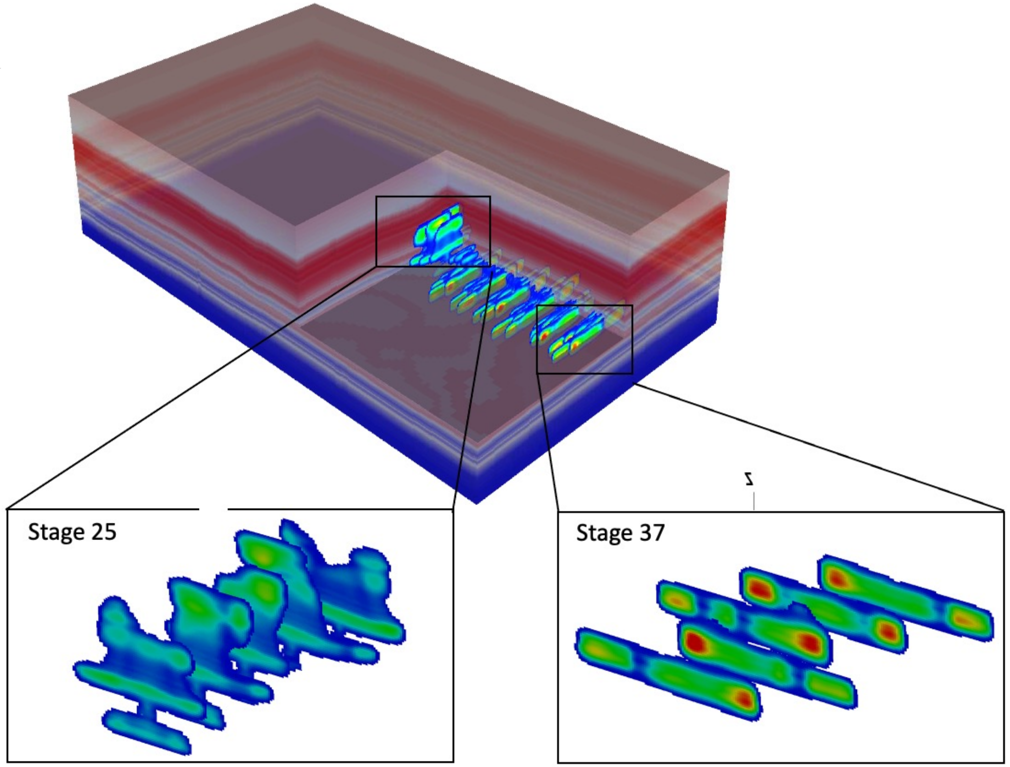
- Fracture height/length are key design targets
  - Want to stay inside target zone
  - Avoid wasted frac fluids, proppant
  - Risk of well-to-well interference
- Our modeling explains geomechanical factors dictating height growth
- HFTS wells cut through different geology along their length
  - Offering a rare validation opportunity
- This work enables stage-specific design ahead of time to reduce waste and avoid frac hits




HFTS-2 LF-DAS data




**_Geometry, proppant distributions from these were fed to production model_**

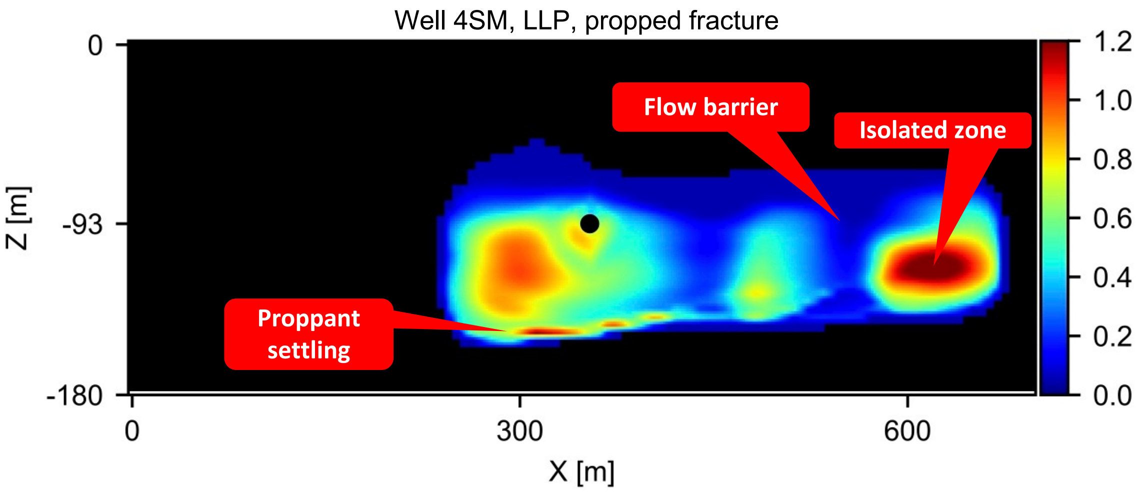
# Reservoir-Scale Production Modeling: Informed by GEOS Fracture Predictions and Micro-Scale Core Studies

## Accomplishments

- **Achieved excellent match with HFTS production data**
- **New understanding of fracture heterogeneity effects**
- **Production driven by conductivity of primary, secondary, and natural fractures, and changes due to fracture closure**

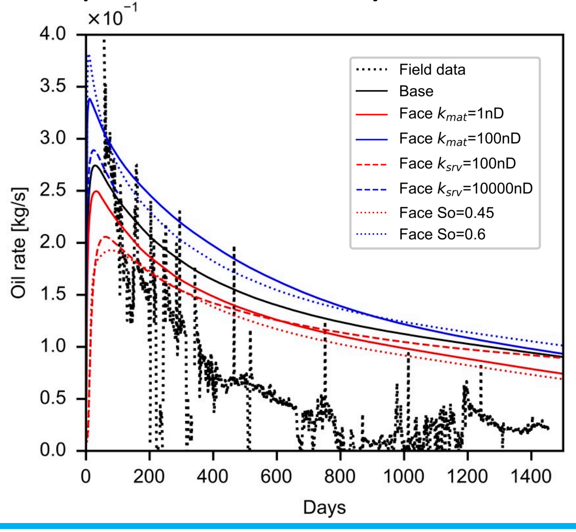
### Fracture Heterogeneity and Isolated Zones

- New methods to represent propped and unpropped fractures with heterogeneous apertures, which create low-conductivity zones
- *Exclude* isolated zones with minimal contribution to production
- Developed novel fracture conductivity relationships




### Influence of Fracture Face Permeability

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



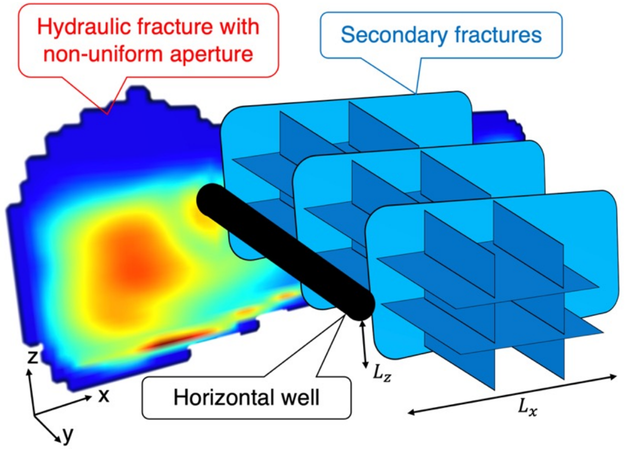

- Sensitivity studies assess impact of reactions (and other properties)
- Face (skin) permeability impedes production only at sub-nD levels

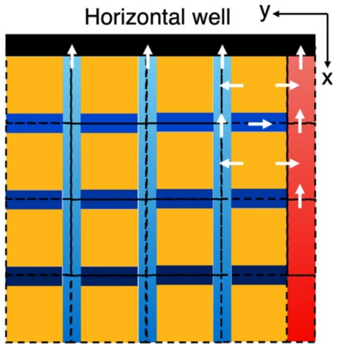
- Strong *stage-to-stage* variance (heterogeneity)
- Production controlled by *low-permeability zones*
- *Secondary and natural fractures* are essential for production from Wolfcamp
- Data match with HFTS was *not* achieved by varying: production pressure, unfractured matrix permeability, oil saturation, or gas-oil ratio (although production rate varies with properties)

# Reservoir-Scale Production Modeling: Production Driven by Complex Fracturing and Fracture Closure

## Accomplishments

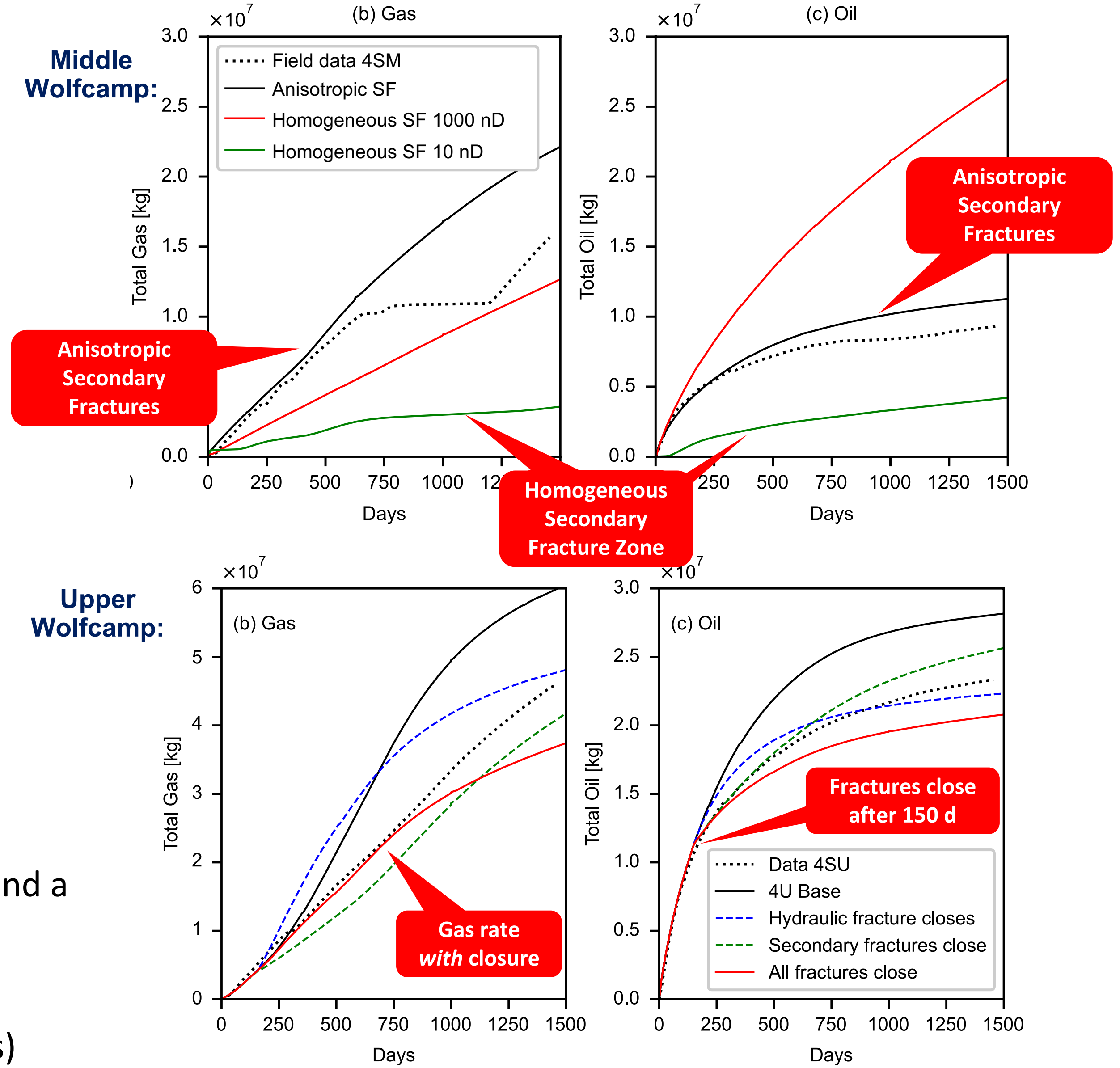
- **Achieved excellent match with HFTS production data**
- **New understanding of fracture heterogeneity effects**
- **Production driven by conductivity of primary, secondary, and natural fractures, and changes due to fracture closure**



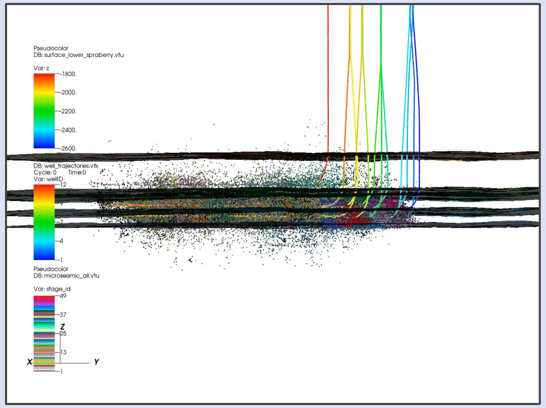

**Optimal fractured reservoir representation requires:**

- Heterogeneous representation of primary fractures
- Inclusion of secondary fractures (anisotropic, with inter-connections) and a "stimulated volume" represented by *multi-continuum* methods
- Closure of primary and secondary fractures after 150 days is key to matching long-term production behavior (based on micro-scale studies)

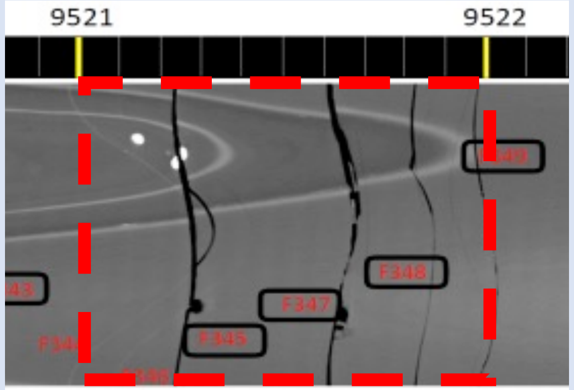


# Reservoir Models Are Informed by Micro-Scale Core Studies

HFTS Field Data
and Core

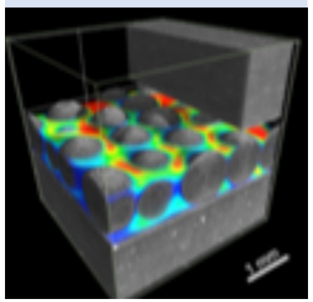


Extensive reservoir
scale data

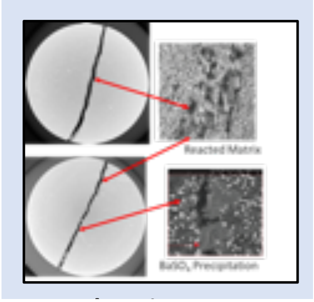



4 hydraulic fractures
within 1 foot!

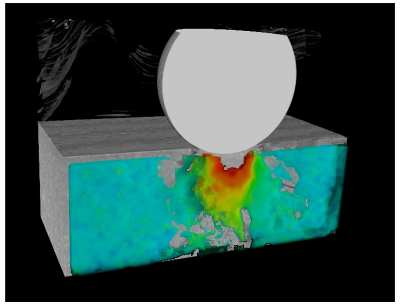
Impact of
proppant/shale
mechanical
interactions on
fracture permeability



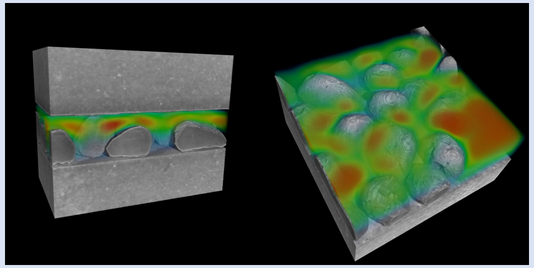
Impact of micro-
scale reactions on
fracture and shale
permeability

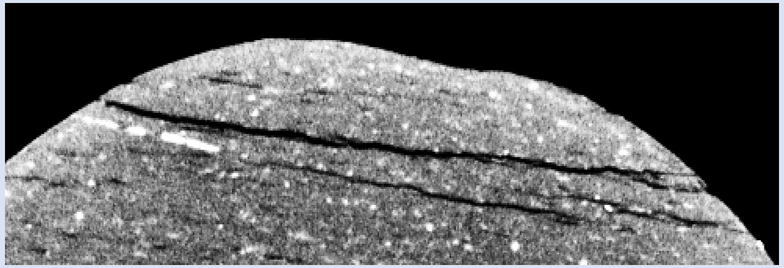


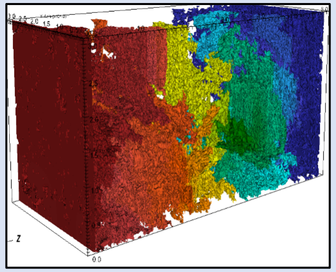
Impact of reactive
weakening of
fracture faces on
mechanical
behavior



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



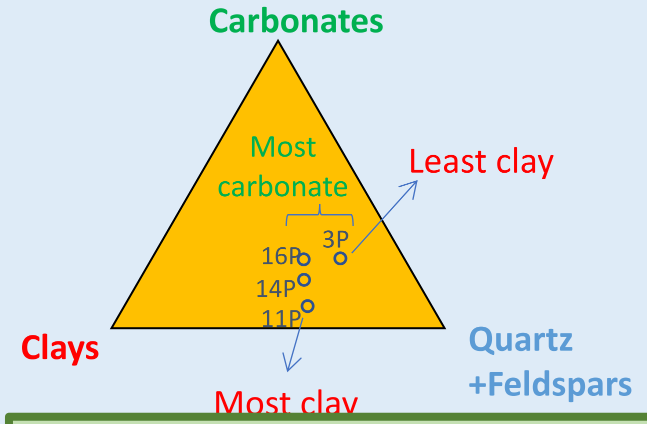




# Impact of Micro-Mechanics on Propped Fracture Behavior

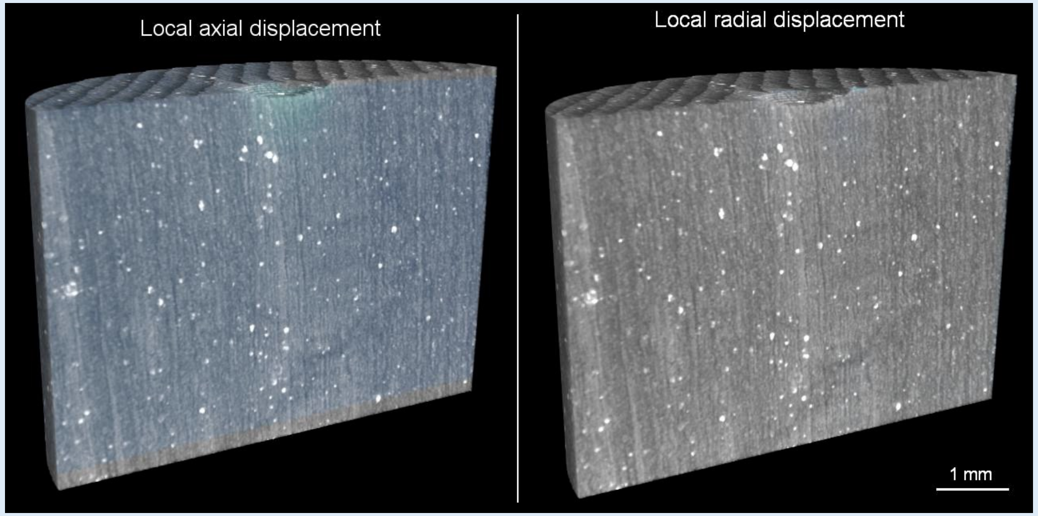
Micro- and meso-mechanical behavior **at reservoir conditions** is translated into understanding propped fracture behavior over time

## Sample Analysis/Selection

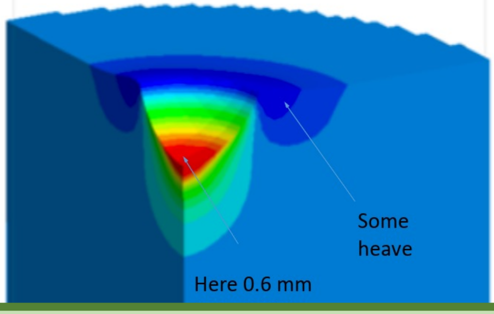



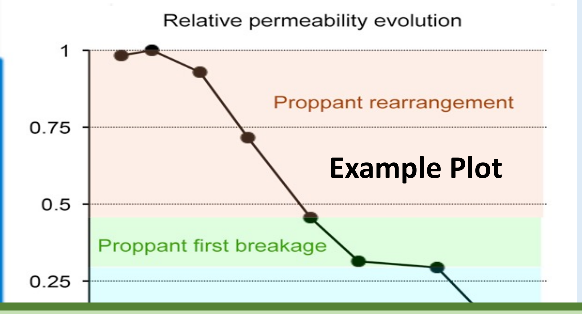

## Micro-scale

Quantitative 4D analysis of shale deformation




Simulation of the displacement fields & permeability changes

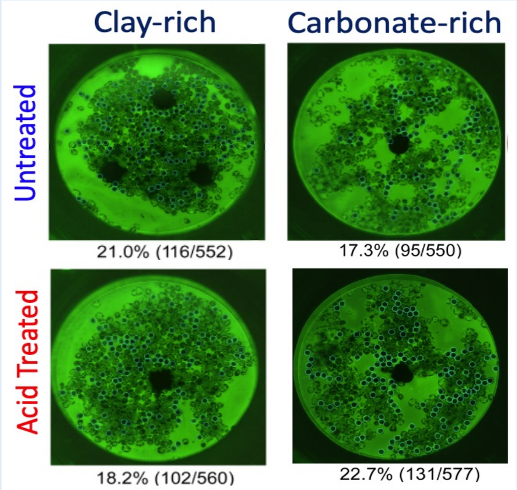


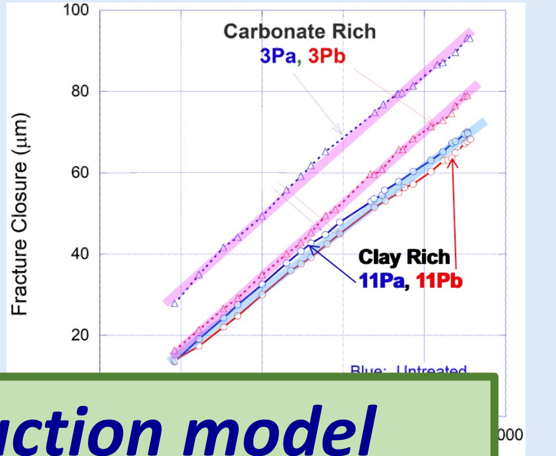

## Meso-scale

Permeability/displacement tests

Proppant survivability in Wolfcamp samples (untreated and acid-treated)



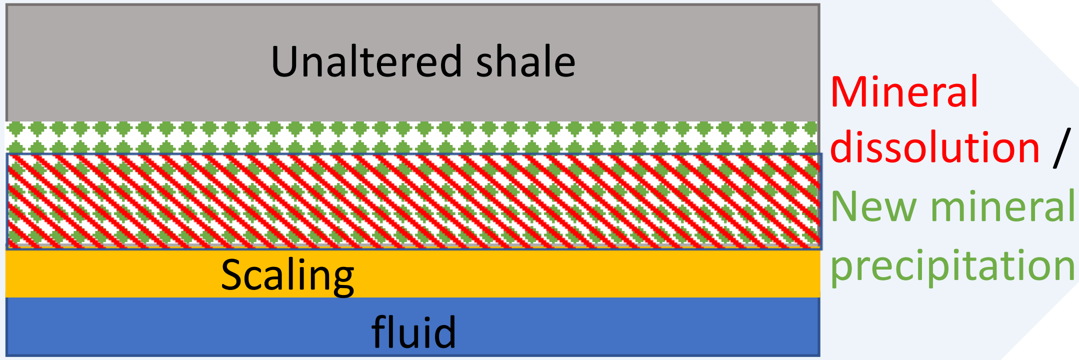

ure closure over time



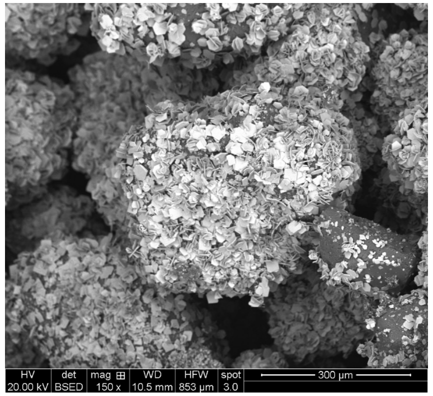

***Permeability vs stress or time relationships are fed to production model***

# Impact of Micro-scale Reactions on Fractured Shales

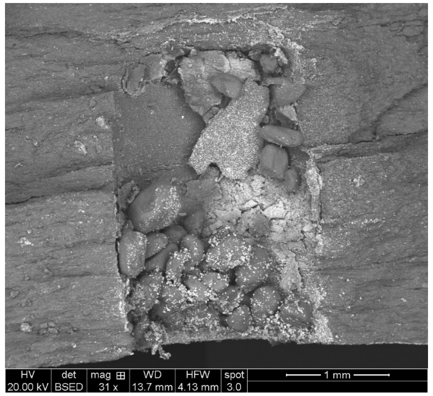
Conceptual illustration of key alterations at the fracture-matrix interface due to micro-reactions

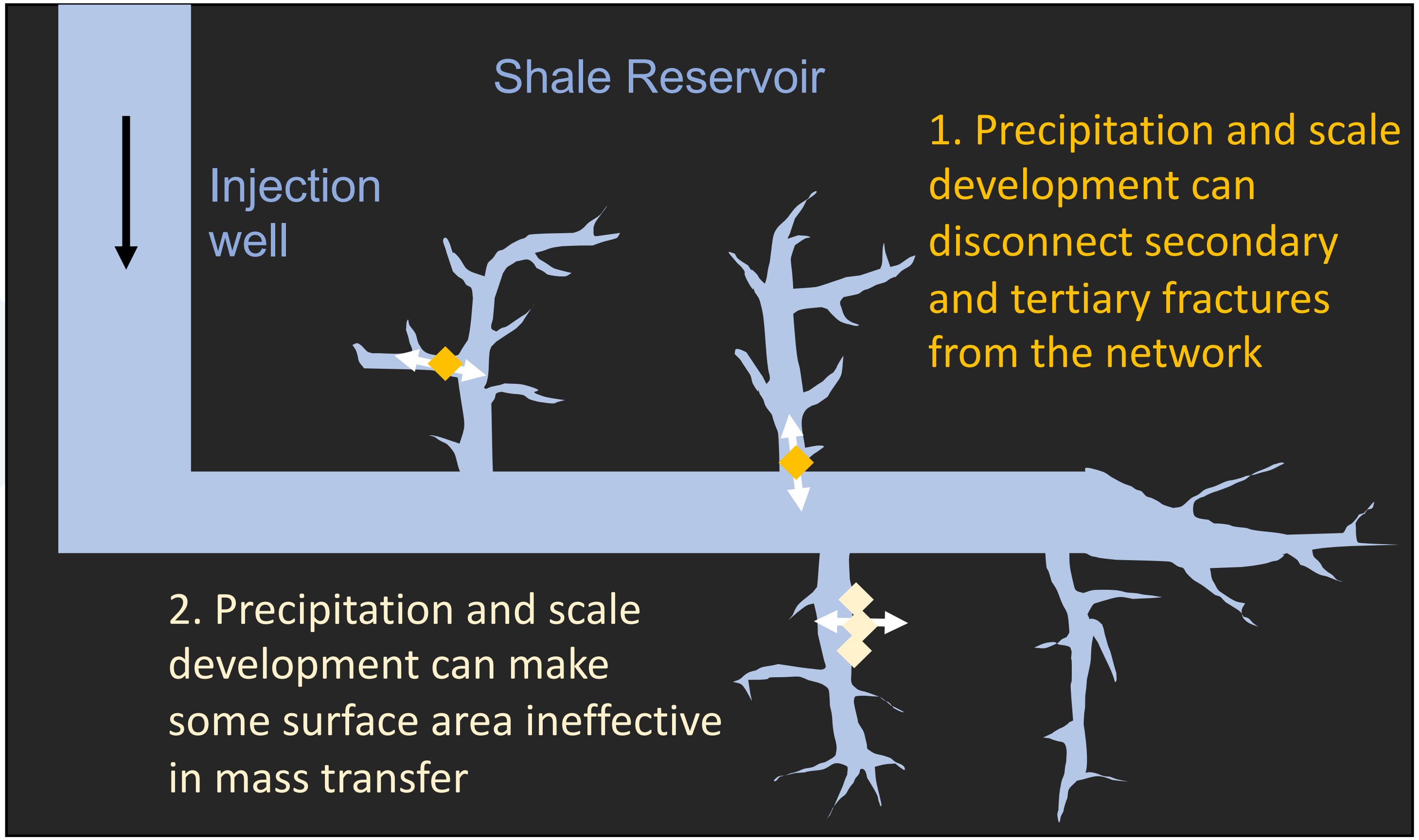



Proppant covered with barite



Proppants cemented with barite inside the dead-end hole



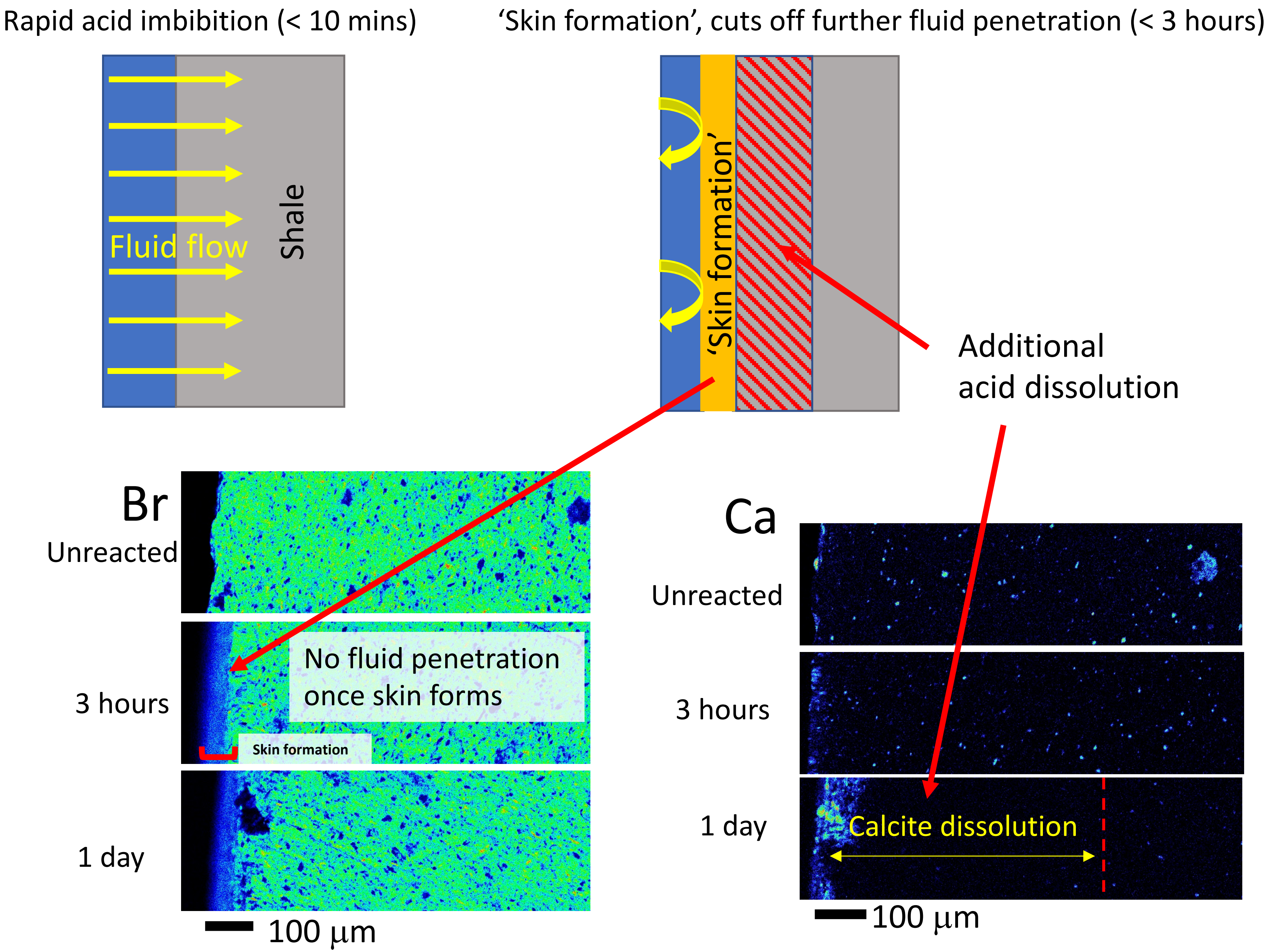



3. Alterations can also affect the interactions between proppant and fracture surface, and thus may result in fracture closure from proppant embedment and breaking during production.

# Matrix Mineral Alteration and Skin Formation

**Experimental Methods:**
- Shale samples reacted with HFF and Br tracer (batch experiments)
- Electron microprobe maps of cores reacted for various times
- Synchrotron XRF multiple energy mapping of Fe redox

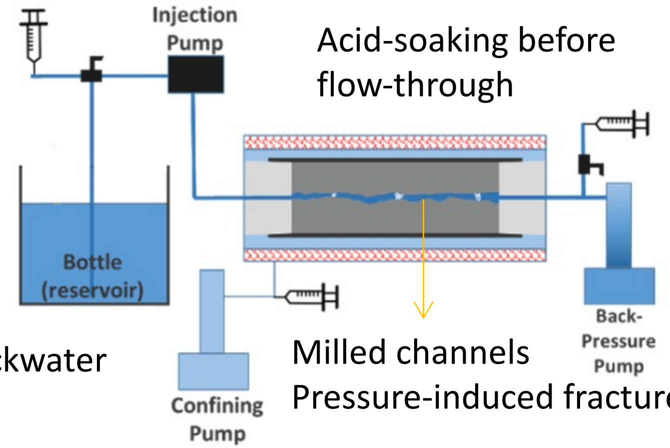
**Main results:**
- Rapid acid imbibition leads to prolonged calcite dissolution
- New 'skin' forms rapidly as a result of matrix scaling (ion precipitation)
- Skin cuts off further penetration of acid solution
- The degree of the skin formation and where it occurs in the SRV can have major implications on reservoir production



# Mineral Alteration at Fracture Faces and Permeability Change

Mineral alteration at the fracture face and into the matrix is observed along reactive flow pathways in single-fracture core flood experiments with Wolfcamp shale – primarily calcite dissolution and iron oxidation.

Acid-soaking before flow-through



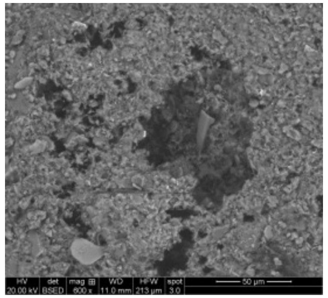

Slickwater

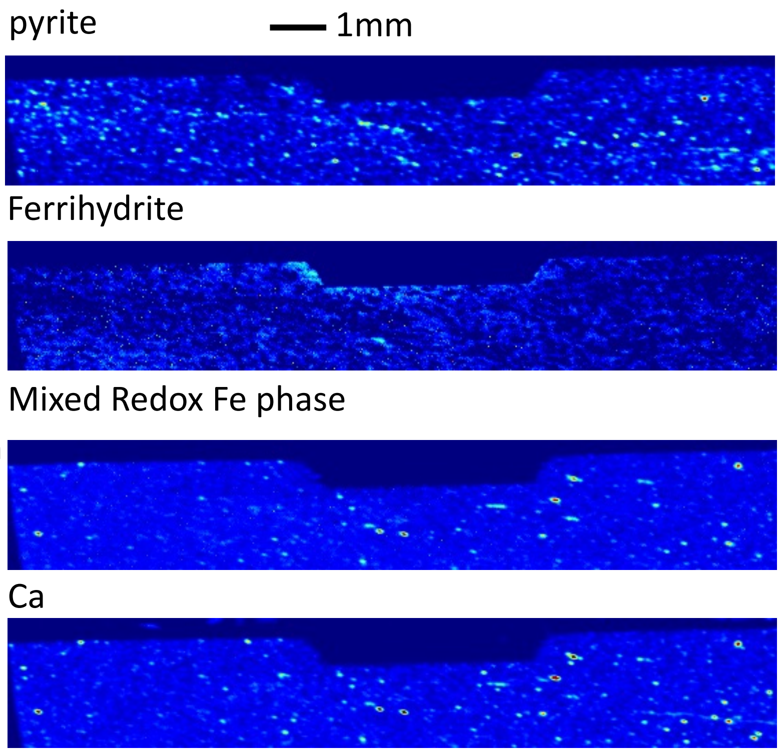
Milled channels
Pressure-induced fracture

Non-patterned channels

Post-reaction clay-rich cores

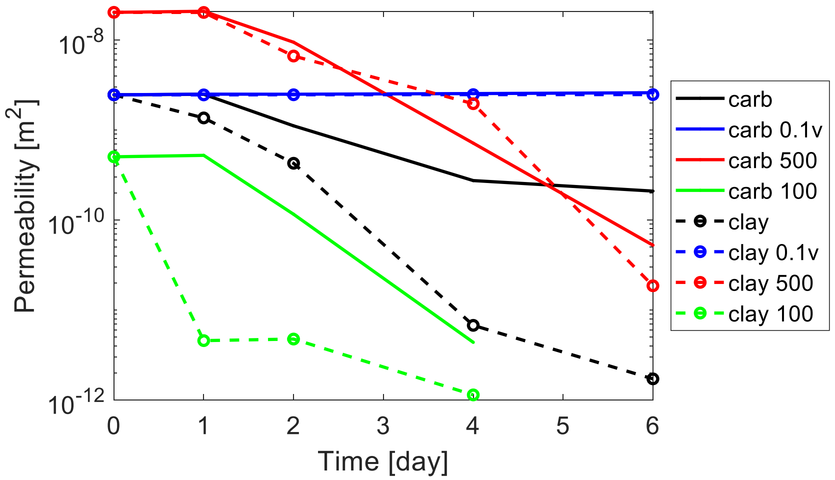
Surface mineral dissolution






Simulation showing mineral coating in a milled channel

Simulation results showing permeability decrease as a result of mineral precipitation, and highlighting faster clogging in finer fractures.




The extent of the alteration is dependent on the chemical system (e.g., fluid chemistry and mineral composition), highlighting the possibility of manipulating the system via careful design of system chemistry.

# A Multi-Scale Multi-Physics Multi-Lab Project: Key Achievements

## Reservoir Stimulation

- New understanding of fracture “swarms” and upscaling techniques now adopted by industry
- Model enables predictive optimization of individual stages along a well

## Reservoir Production

- Excellent match between production models and HFTS data
- Production is driven by conductivity of primary, secondary, and natural fractures, and transient fracture closure

## Micro-Mechanical Studies

- Demonstrated micro- and meso-scale testing procedure and hand-over to GEOS/TOUGH reservoir models
- Conducted several HFTS core tests on proppant behavior and fracture closure

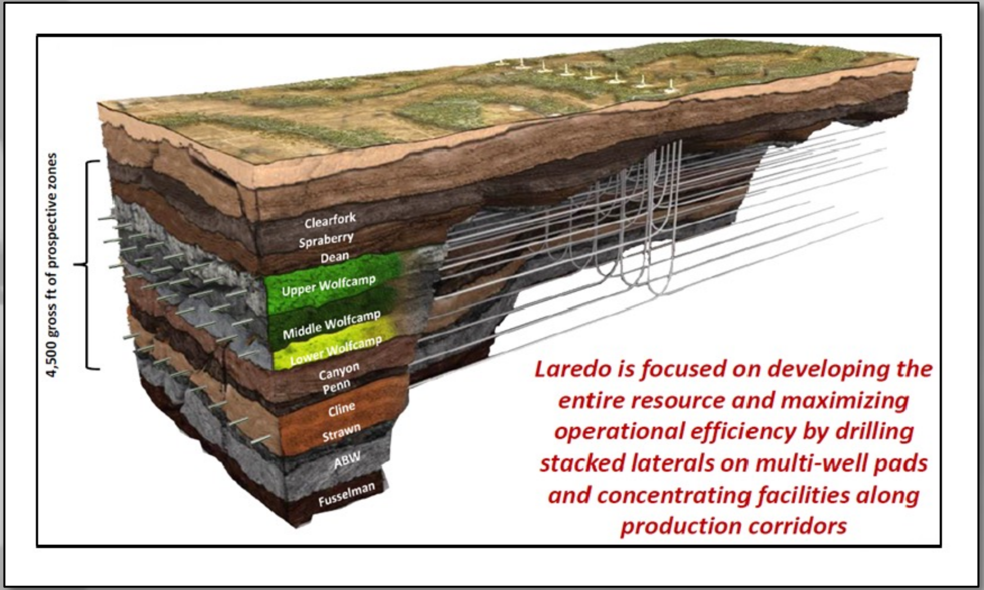
## Micro-Reaction Studies

- Developed and applied new testing methods for HFTS core shale alterations due to interaction with fracturing fluids
- Developed reactive transport models and upscaling methods

- Developed a multi-scale modeling framework for reservoir simulations informed by micro-scale processes

  → Has broad applicability across multiple subsurface applications

- Demonstrated predictive capabilities of multi-scale modeling using a unique high-quality field and lab data set




**LBNL, LLNL, SLAC and NETL appreciate the funding and valuable guidance for this project provided by the U.S. Department of Energy, Office of Fossil Energy and Carbon Management.**

BERKELEY LAB SLAC NATIONAL ENERGY TECHNOLOGY LABORATORY

# Selected Publications and Conference Contributions


- Birkholzer, J.T., Morris, J., Bargar, J.R., Brondolo, F., Cihan, A., Crandall, D., Deng, H., Fan, W., Fu, W., Fu, P., Hakala, A., Hao, Y., Huang, J., Jew, A.D., Kneafsey, T., Li, Z., Lopano, C., Moore, J., Moridis, G., Nakagawa, S., Noël, V., Reagan, M., Sherman, C.S., Settgast, R.,. Steefel, C.I., Voltolini, M., Xiong, W., Ciezobka, J. (2021): A New Modeling Framework for Multi-Scale Simulation of Hydraulic Fracturing and Production from Unconventional Reservoirs, Energies, 14(3):641.
- Wei Xiong, Hang Deng, Johnathan Moore, Dustin Crandall, J. Alexandra Hakala, Christina Lopano (2021), “Influence of Flow Pathway Geometry on Barite Scale Deposition in Marcellus Shale During Hydraulic Fracturing,” Accepted 2021, Energy & Fuels.
- Wei Xiong, Johnathan Moore, Dustin Crandall, Christina Lopano, Alexandra Hakala, (2021), “Hydraulic Fracturing Geochemical Impact on Fluid Chemistry: Comparing Wolfcamp Shale and Marcellus Shale.” Unconventional Resources Technology Conference 2021, DOI 10.15530/urtec-2021-5524.
- Deng, H., C. Tournassat, S. Molins, F. Claret, C.I. Steefel, (2021), A pore-scale investigation of mineral precipitation driven diffusivity change at the column scale , Water Resources Research, April 2021.
- Voltolini, M. (2021), In-Situ 4D Visualization And Analysis Of Temperature-Driven Creep In An Oil Shale Propped Fracture, Journal of Petroleum Science and Engineering, 200, May 2021.
- Nakagawa, S., M. Voltolini, S. E. Borglin, and A. D. Jew, (2021), Chemically Induced Reduction of Fracture Closure for Shale Fractures Containing Sub-Monolayer Proppant, Paper presented at 55th US Rock Mechanics/Geomechanics Symposium, Houston, Texas, USA, 20-23 June 2021.
- Fu, W., Morris, J.P., Fu, P., Huang, J., Sherman, C.S., Settgast, R.R., and Ryerson, F.J. (2020), An upscaling approach to model swarming hydraulic fractures observed at the Hydraulic Fracturing Test Site in field-scale simulations, The SPE Journal, SPE-199689-PA, https://doi.org/10.2118/199689-PA.
- Morris, J. P., W. Fu, C.S. Sherman, P. Fu, J. Huang, Y. Hao. R. Settgast, J. Birkholzer, M. Reagan, H. Deng, G. Moridis, C. Steefel, S. Nakagawa, M. Voltolini, T. Kneafsey, Z. Li, J. Bargar, A. Jew, V. Noël, W. Fan, A. Hakala, C. Lopano, W. Xiong, D. Crandall and J. Moore, (2020), A New Framework for Microscopic to Reservoir-Scale Simulation of Hydraulic Fracturing and Production: Testing with Comprehensive Data from the Hydraulic Fracturing Field Test in the Permian Basin, ARMA 20-1721, 54th US Rock Mechanics/Geomechanics Symposium, Golden, Colorado, USA, 28 June-1 July 2020.
- Moridis, G.J. and M.T. Reagan (2020), Evaluation of the Effectiveness of Continuous Gas Displacement for EOR in Hydraulically Fractured Shale Reservoirs, SPE Journal, 198899.
- Voltolini, M., Barnard, H., Creux, P. and Ajo-Franklin, J. (2019). A new mini-triaxial cell for combined high-pressure and high-temperature in situ synchrotron X-ray microtomography experiments up to 400° C and 24 MPa. Journal of synchrotron radiation, 26(1).