Fluid Injection in Mudstones: How do Hydraulic Fractures evolve?

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Introduction

Over the past decade there has been a significant rise in fluid injection into mudstones for the purposes of hydraulic fracturing, wastewater disposal and carbon sequestration. Upon fluid injection, a rock undergoes reduction in effective stress, known as unloading. The objective of my research is to understand the evolution of petrophysical properties in mudstones upon fluid injection:

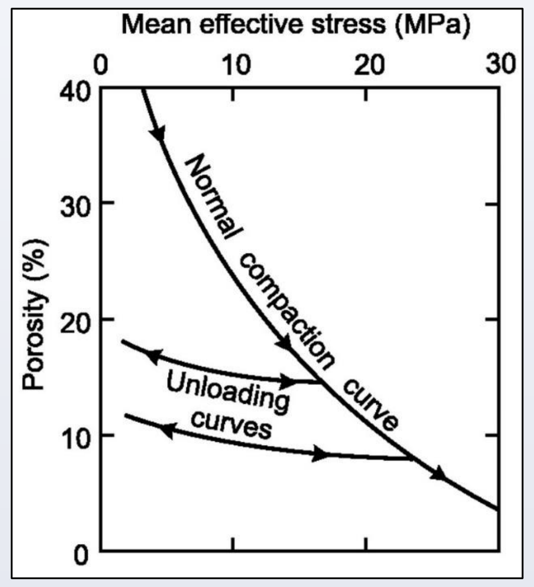
1. How do petrophysical signatures such as porosity, permeability and velocity change upon fluid injection in mudstones?
2. How do the pore structures of mudstones evolve elastically and inelastically to accommodate injected fluid?
3. Can geomechanical models of mudstone pore structure be used to understand evolution of porosity and permeability in mudstones?

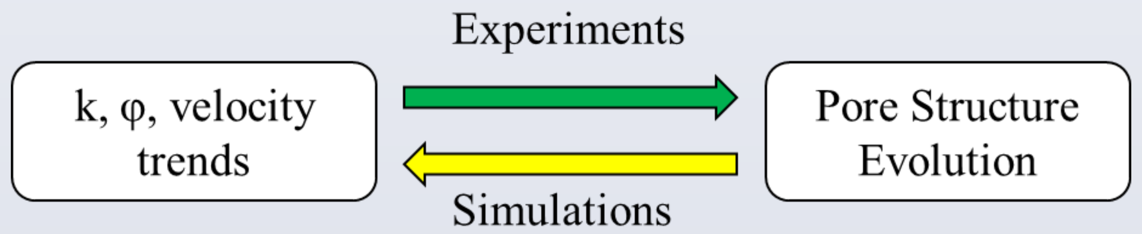
I make experimental measurements of porosity, permeability, strain and acoustic velocities to understand evolution of storage and transport properties of mudstones upon unloading induced by fluid injection. Geomechanical modeling using Lattice Boltzmann Method is conducted simultaneously to build analogs of permeability response under different mechanisms of fluid accommodation in mudstones.

Effective Stress and Pore Structure

$$\sigma_{eff} = \sigma_V - \alpha P_p$$

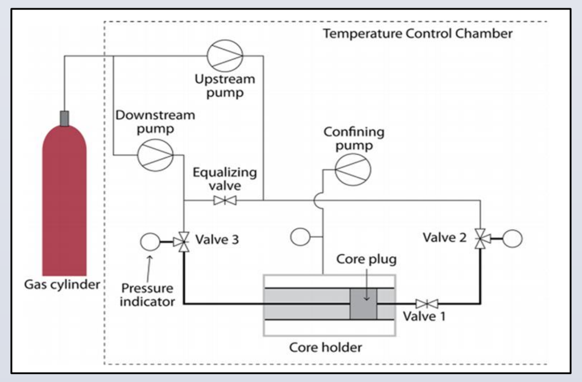
σ_{eff} : Effective Stress
σ_V :Vertical Stress
α : Pressure constant
P_p : Pore Pressure

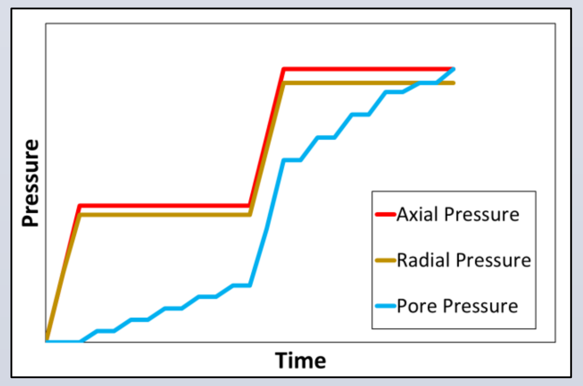




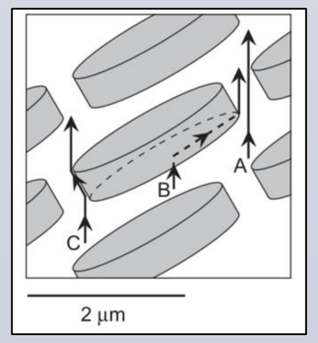
$$Q = -kA\frac{P_u - P_d}{\mu L}$$

Q = flowrate (m^3/s)
k = permeability (m^2)
P_u= Upstream Pressure (Pa)
P_d= Downstream Pressure (Pa)
µ = Viscosity (Pa.s)
L = length of sample (m)





Lattice Boltzmann simulations track the movement of simulated fluid particles through a pore geometry to calculate flow velocity

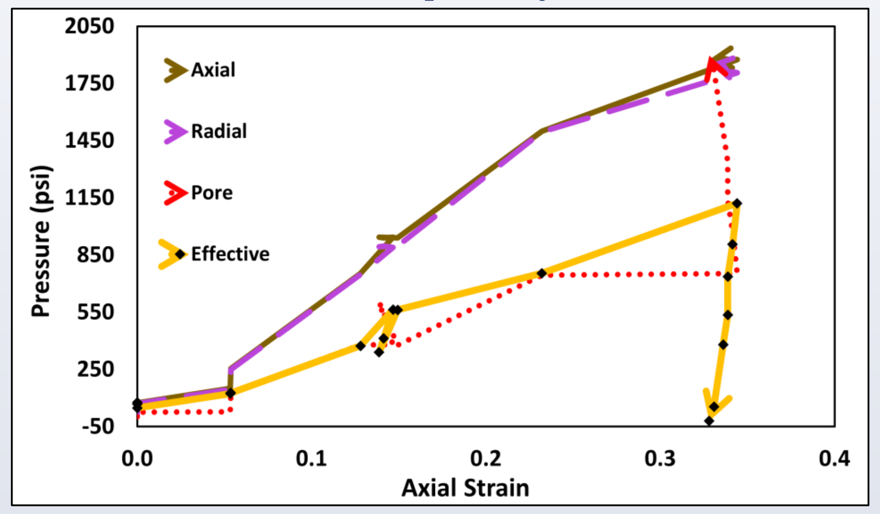


Results

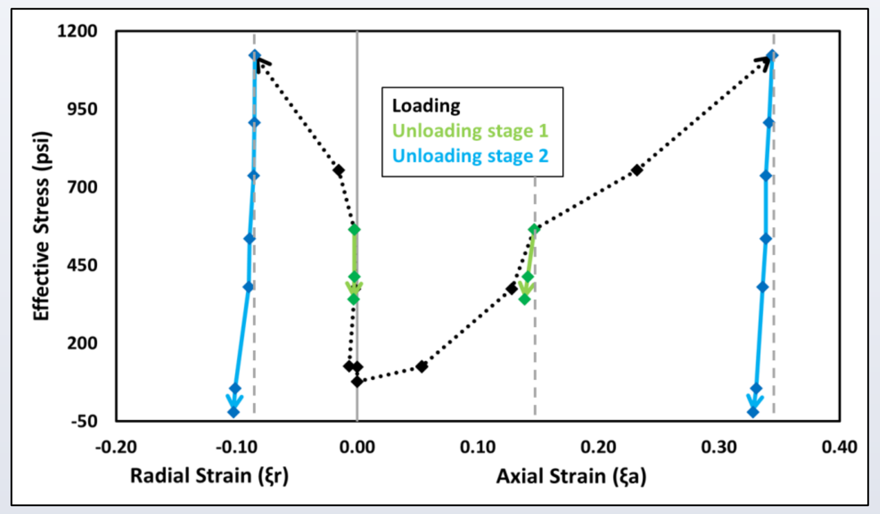
1. Dilation of pores upon fluid injection in mudstone samples is manifested by an increase in porosity and vertical permeability, a decrease in acoustic velocities (V_P and V_S) and axial and radial strain.
2. Hypothesis for evolution of pore structure of mudstones upon fluid injection:
   - At low injection pressures, fluid is accommodated by elastic dilation of inter-bed pores, corresponding to a small increase in porosity and vertical permeability.
   - At high injection pressures, fluid is accommodated by dilation of inter-bed and intra-bed pores, which possible coalesce to form a fracture, yielding larger increase in porosity and vertical permeability.
3. Lattice Boltzmann models of fluid flow through mudstones yield porosity-permeability relationships analogous to experimental datasets and support developed hypothesis of pore structure evolution in mudstones upon fluid injection.

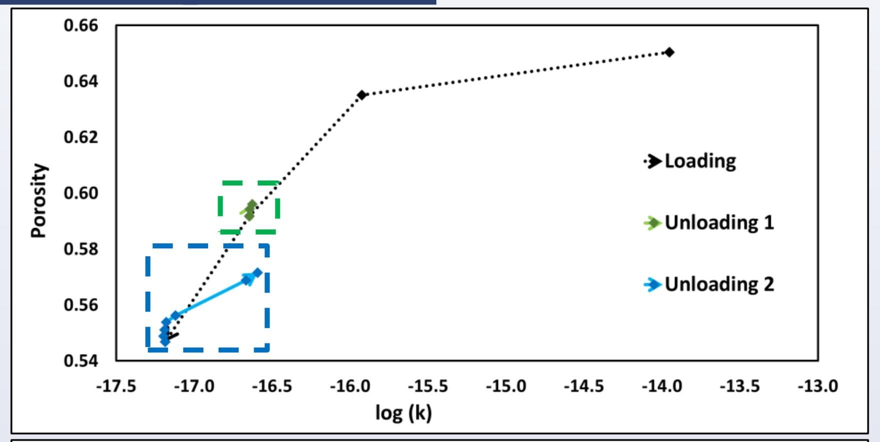
Fluid Injection Experiments

Stress pathway

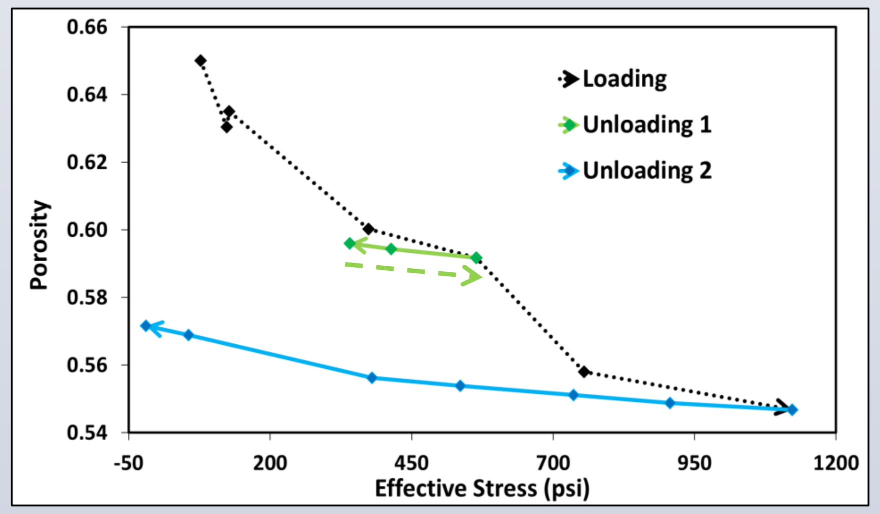


Axial and Radial Strain

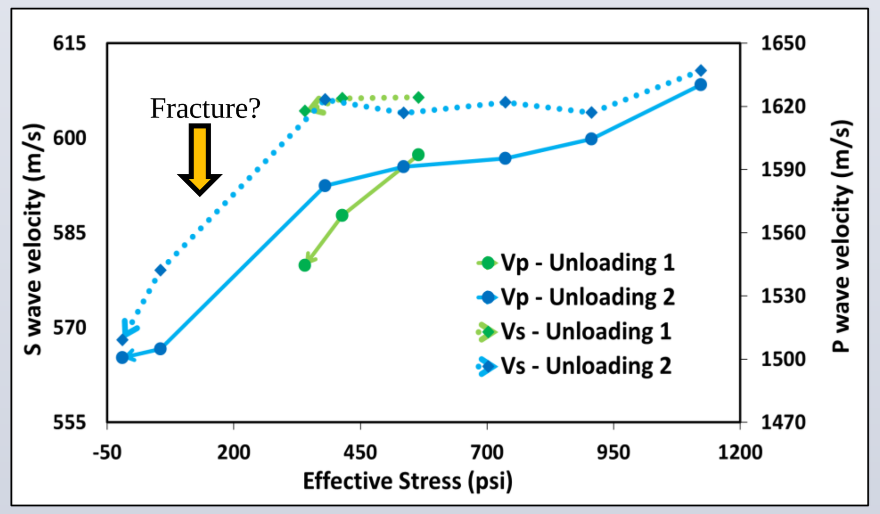


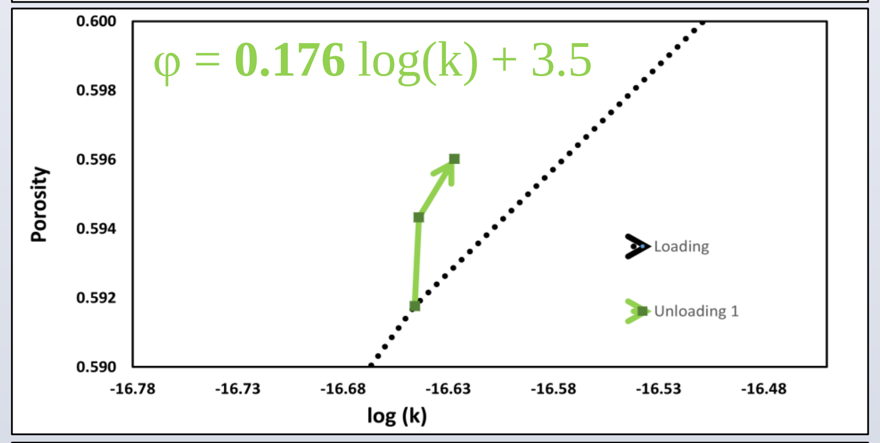


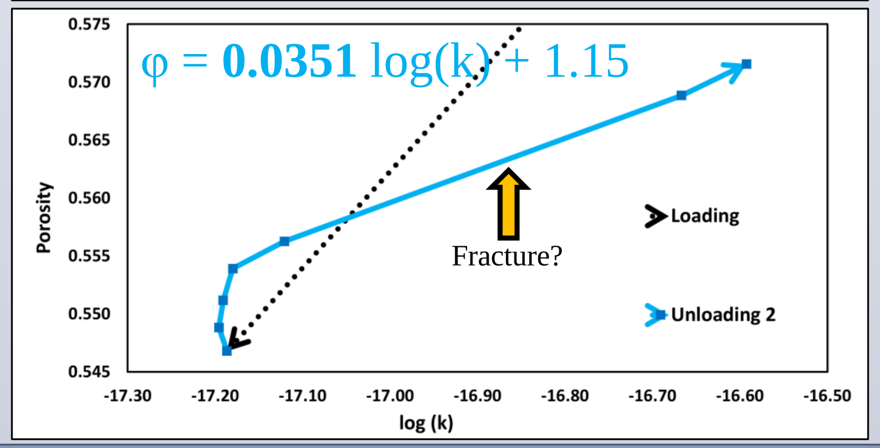
Porosity evolution



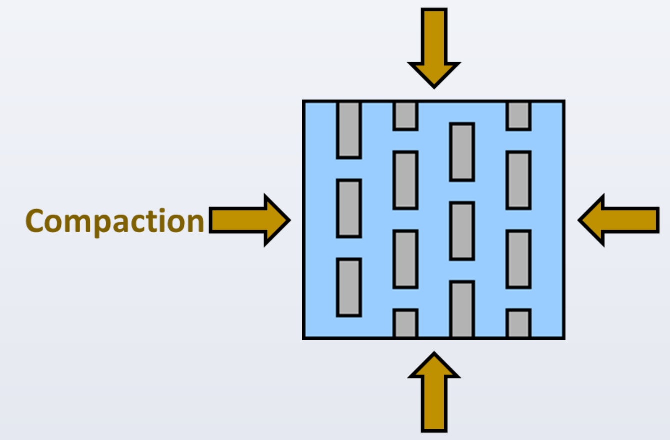
Acoustic Velocity



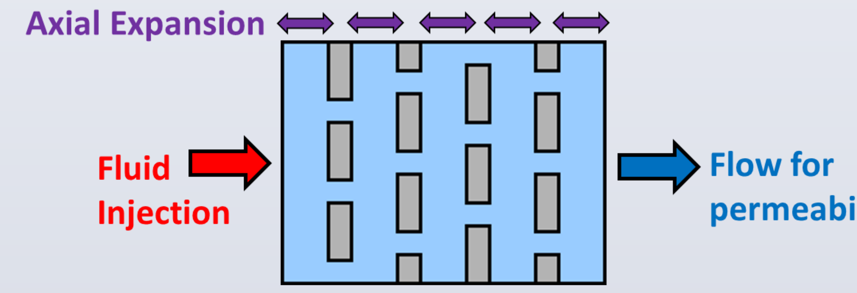




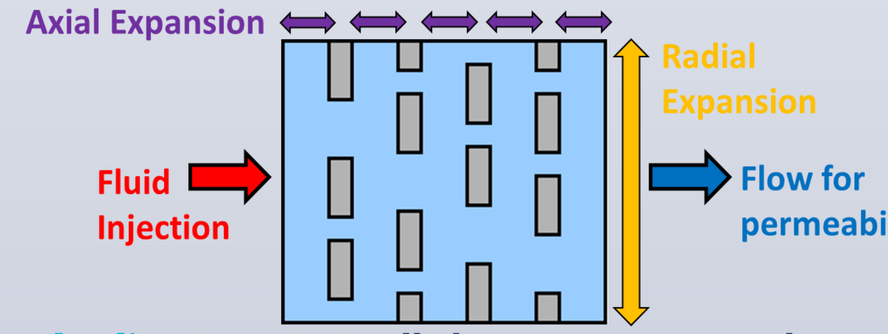
- **Unloading Stage 1:** Elastic increase in porosity, decrease in axial strain, and small decrease in V_P and V_S.
- **Unloading Stage 2:** At low effective stress states we observe significant increase in porosity, decrease in axial and radial strain, and sharp decrease in V_P and V_S.



Compaction leads to reduction in porosity and vertical permeability by reducing pore spaces

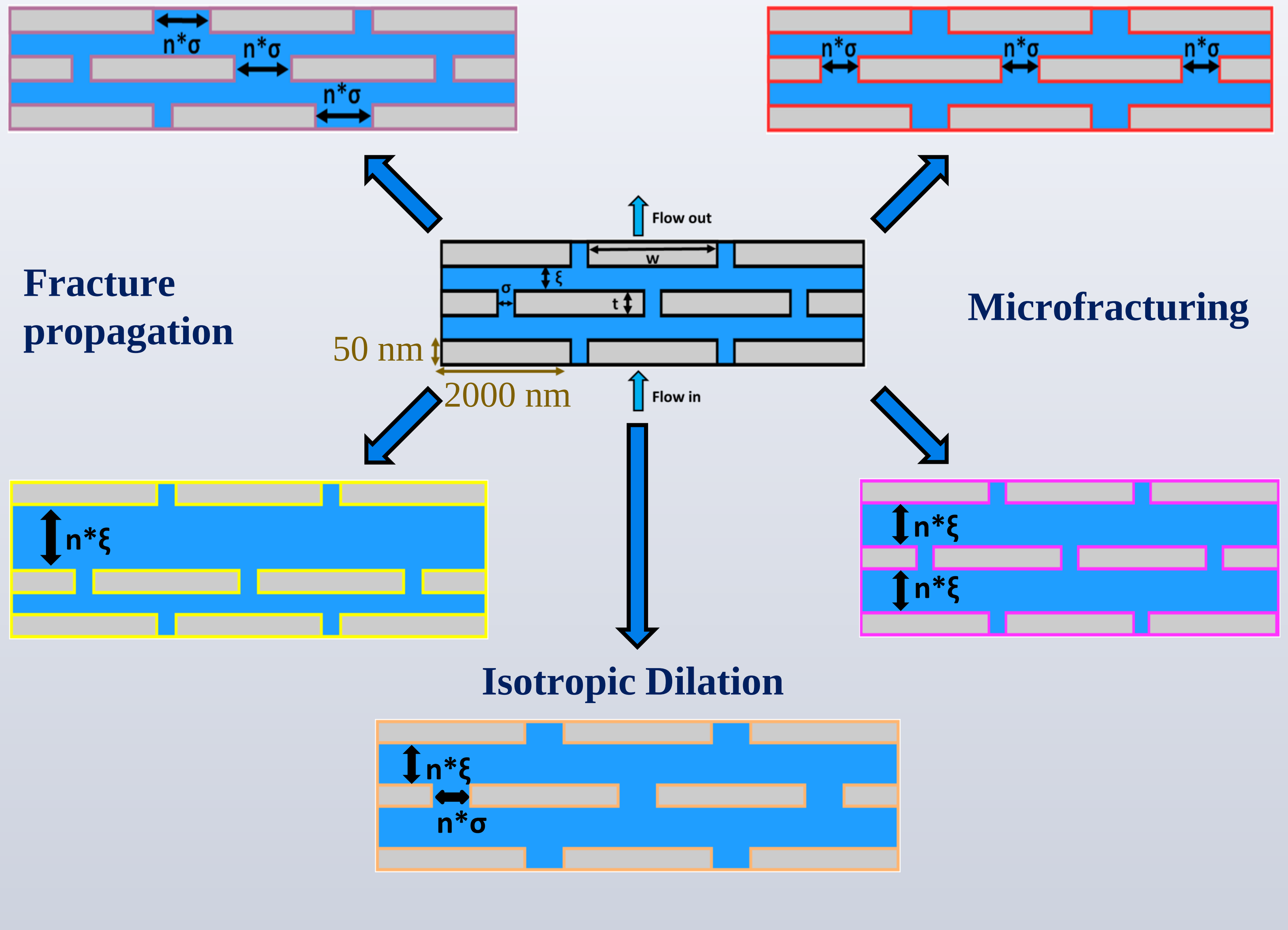


Unloading Stage 1: Small change in porosity and permeability from axial expansion of interbed pores

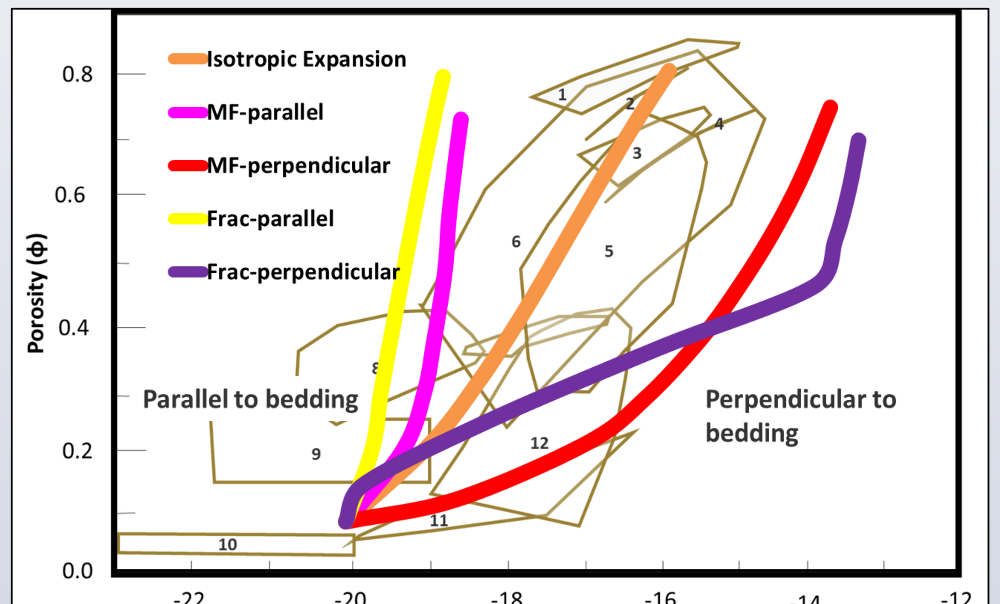


Unloading Stage 2: Small change in porosity and permeability from axial and radial expansion of pores, coalescing into a fracture

Lattice Boltzmann Modeling



- Simulated k vs. Ø trends match experimental datasets
- Fluid accommodation via dilation of interbed pores yields small increase in vertical permeability
- Fluid accommodation via dilation of intra-bed pores yields large increase in vertical permeability



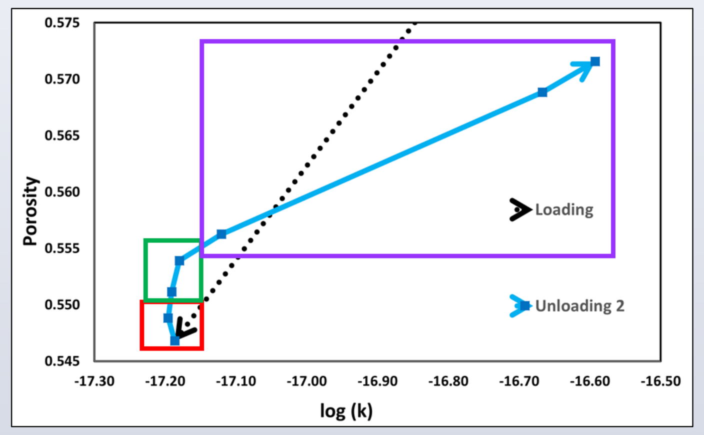
φ = **0.158** log(k) + 3.2

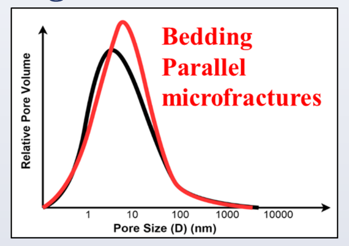
φ = **0.373** log(k) + 7.4

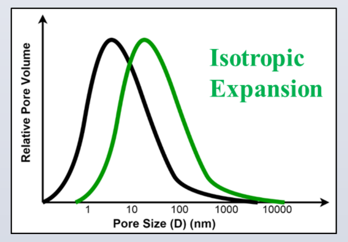
φ = **0.0479** log(k) + 1.07

Future Work

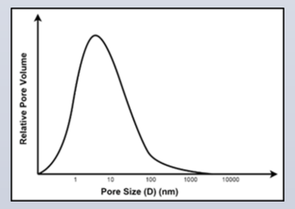
Test hypothesis of pore structure evolution pathway using NMR signatures upon fluid injection experiments

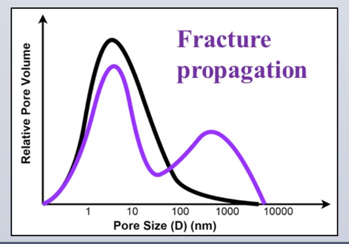






Initial NMR signature





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