EVOLUTION OF PERMEABILITY AND MICROSTRUCTURE OF MUDSTONE CARBONATES DUE TO NUMERICAL SIMULATION OF CALCITE DISSOLUTION

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EOR & CO₂ sequestration

• CO₂ can be stored in low permeability reservoirs.
• Reaction with carbonic acid and calcite changes the microstructure.
• Permeability is dynamic.
• Potential for leakage.
• Useful to monitor changes in subsurface permeability.

(Anthonsen et al., 2009)
Seismic $\rightarrow$ Porosity $\rightarrow$ Permeability

- Seismic monitoring to obtain of the rock.
- Rock physics data to convert velocity to porosity.
- Geometric model to convert porosity to permeability.

(Vanorio et al., 2015; Geol. Soc. London)

(White, 2009; The Leading Edge)
• Many rock types adhere to a unique permeability-porosity relationship:
  
• Sandstone modeled as a piece-wise power law or Kozeny-Carman equation.
Tight carbonates exhibit 3 OM spread of permeability.

$\text{CO}_2$ injection lead to porosity-independent permeability evolution.

Stiff matrix, no compaction.

Completely contrary to conventional thinking.

No major changes in the microstructure before and after injection.

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(Vanorio, 2015; Geophysics)
If not porosity, what are the attributes of the pore geometry that controls permeability evolution for tight carbonates and gives rise to porosity-independent permeability behavior exhibited by tight carbonates?
Digital rock physics (DRP)

- Image pore geometry of tight carbonate.
- Simulate fluid flow with LBM
- Erode geometry based simple dissolution rules
- Obtain permeability and pore attributes.
- Attempt to relate micro and macro.

- Porosity
- Specific surface area
- Tortuosity
- Hydraulic diameter

DIGITIZE ROCK -> PORE GEOMETRY -> MICRO-PROCESS -> ANALYSIS
Digitizing the carbonate rock

Tight micrite matrix

Pores

1 mm

2.65 mm
Simulation of laminar flow

- Simplest dissolution model we could think of.
- Erode calcite at a rate controlled by the local velocity and surface area, equivalent to solving:

\[
\rho \frac{dV_i}{dt} = -n_i \frac{v_i}{v_{\text{max}}} R_0
\]

\( R_0 \): Plummer et al. (1978)

- Compute geometric properties and permeability.
- Iterate with updated geometry.

For each boundary voxel \( i \),

\[
\rho \frac{dV_i}{dt} = -n_i \frac{v_i}{v_{\text{max}}} R_0
\]
Velocity distribution evolution

- Velocity magnitude heterogeneous over fluid path.
- Dissolution rules reinforce high-conductivity paths.
- Velocity becomes more homogenous over path.
Stage 1: Patchy Dissolution of narrow pore throats

Stage 2: Channelization Formation and dilation of channels
Permeability-porosity evolution

- Calculate permeability at every LBM computation.
- Sharp transition between Stage 1 and 2.

\[ k = k_0 \left( \frac{\phi}{\phi_0} \right)^n \]
Comparison with experiment

- Compare simulation results with CO$_2$ injection experiments.
- Normalize porosity and permeability by initial value.

\[ k = k_0 \left( \frac{\phi}{\phi_0} \right)^n \]
Connecting permeability with pore parameters
Connecting permeability with pore parameters

- Plug attributes into Kozeny-Carman equation.
- Underestimate the changes in permeability by orders-of-magnitude.
- Qualitative explanation:
  - KC good for microstructures with open pores.
  - KC sensitive to uniform changes.
- Dissolution can target critical porosity in a pore network, induce large change with minimal volumetric impact.
Effective pore geometry

- Fluid flow dominated by preferred fluid pathways.
- Try to isolate the changes in the permeability to the portion of porosity that actually contributes significantly to fluid flow.
- Keep pores whose flux is > 10% of the average flux.
Conclusions

- Dissolution seems to target the permeability-limiting narrow pores.
- Dissolution with high flow rate results in first widening of narrow pores, then formation of channels.
- Narrow pores constitute small % of total pore volume, so widening of those pores induces virtually porosity-independent permeability increase.
- Kozeny-Carman Equation does not capture the small changes in the pore geometry, induced by dissolution, that can give rise to large changes in the permeability.
- Not all of the pores contribute significantly to the permeability. There is a backbone porosity that dominates the fluid flow through the rock.
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