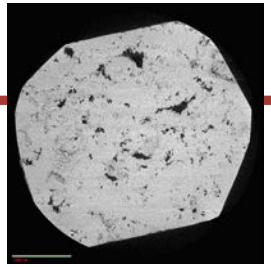
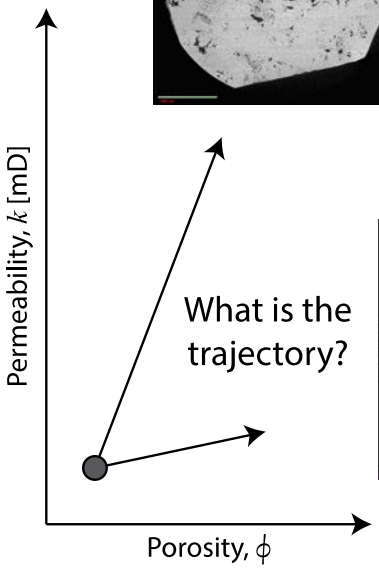
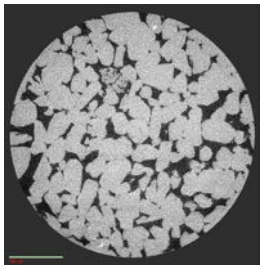
EVOLUTION OF PERMEABILITY AND MICROSTRUCTURE OF MUDSTONE CARBONATES DUE TO NUMERICAL SIMULATION OF CALCITE DISSOLUTION







SCCS Annual Affiliates Meeting 2017

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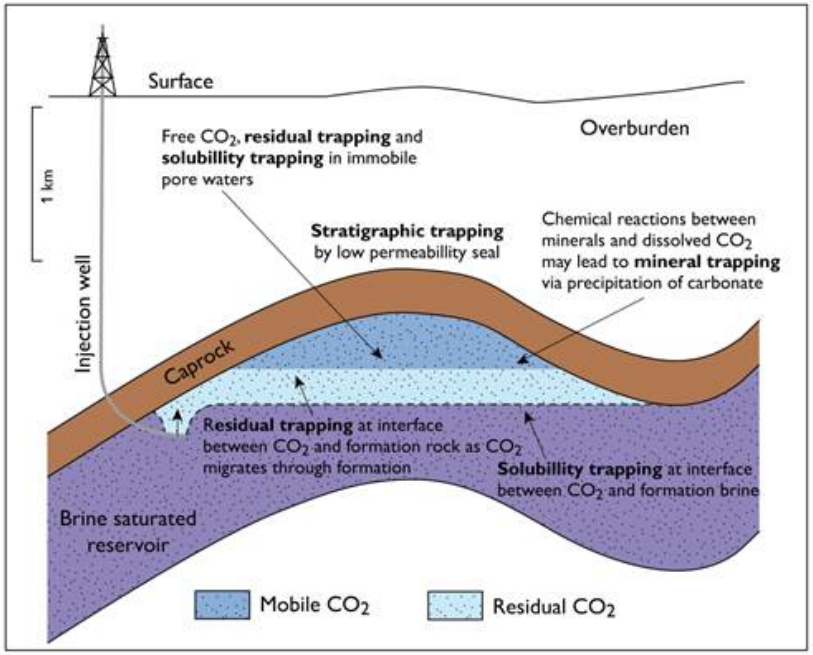
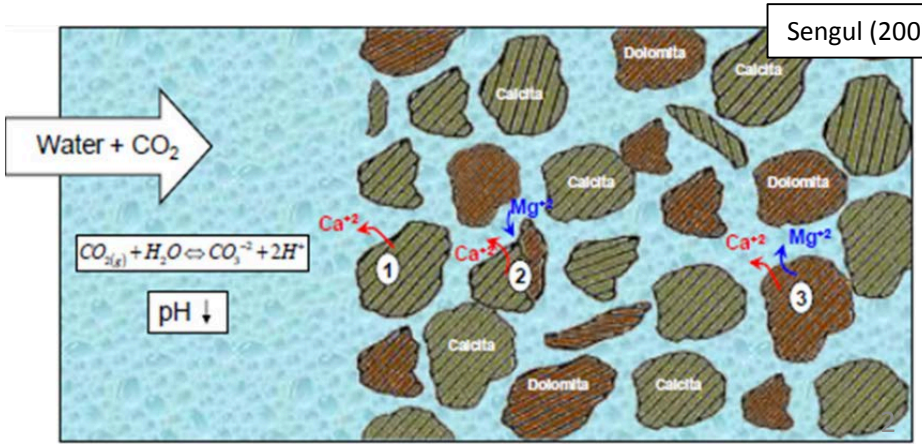
EOR & CO_2 sequestration

- 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)



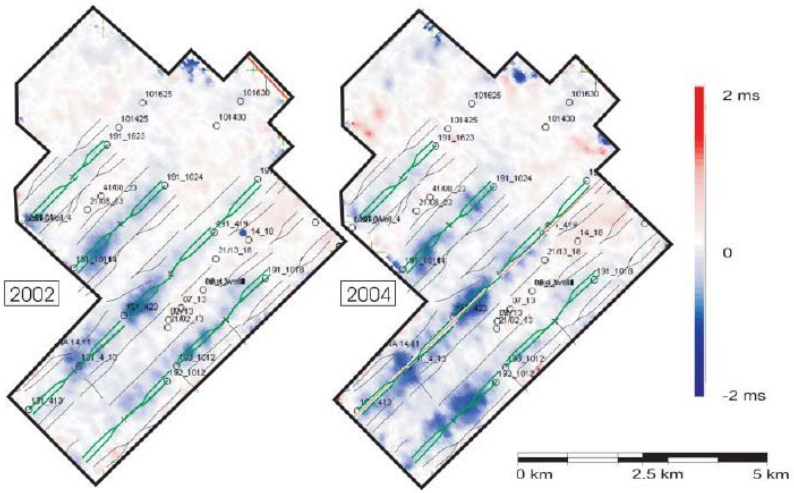
Sengul (2007)

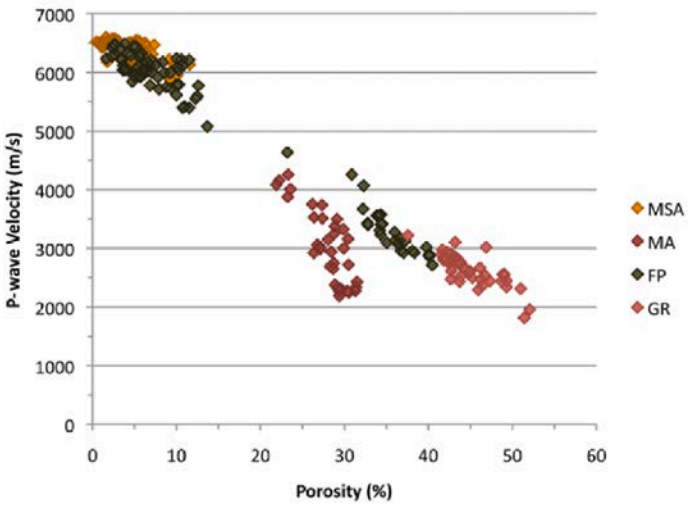


Seismic→ Porosity → Permeability

(White, 2009; The Leading Edge)

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

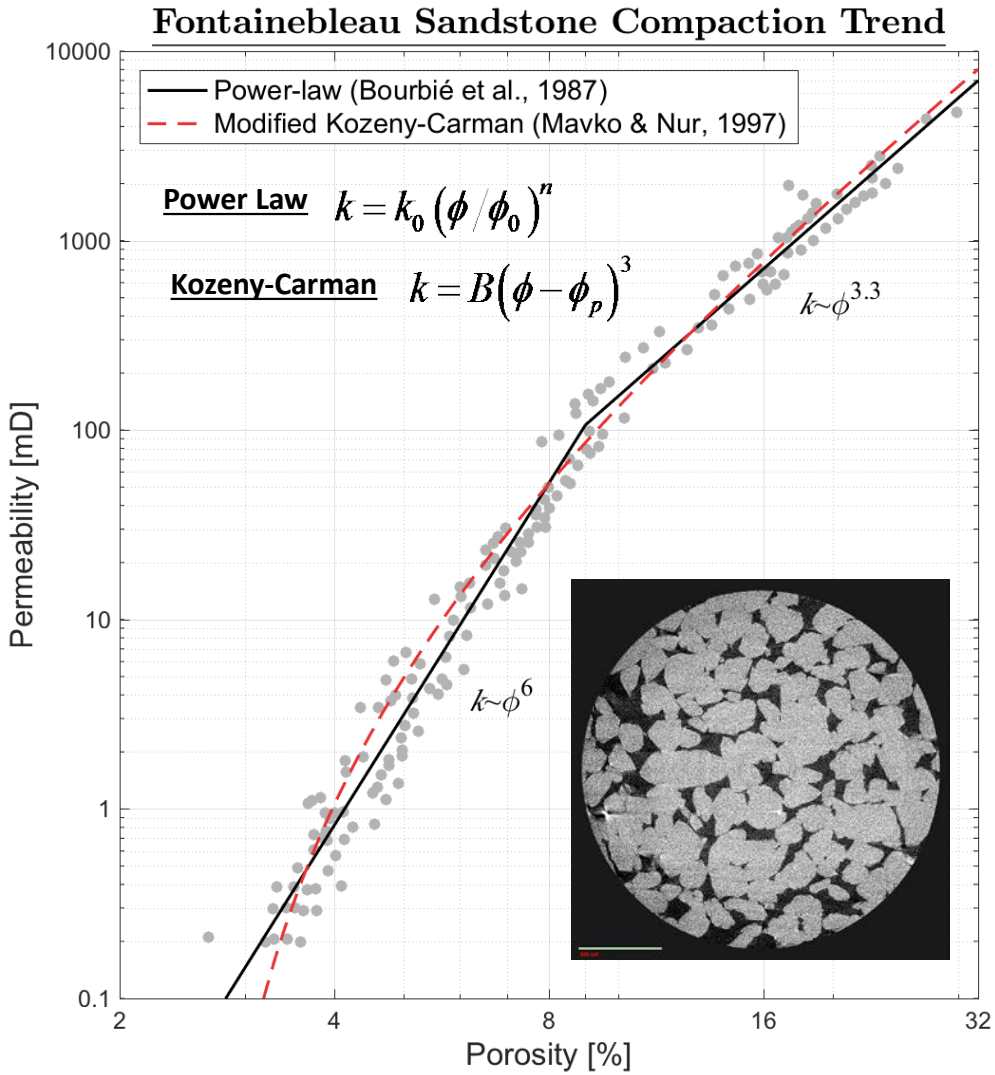




(Vanorio et al., 2015; Geol. Soc. London)

Velocity → Porosity → Permeability

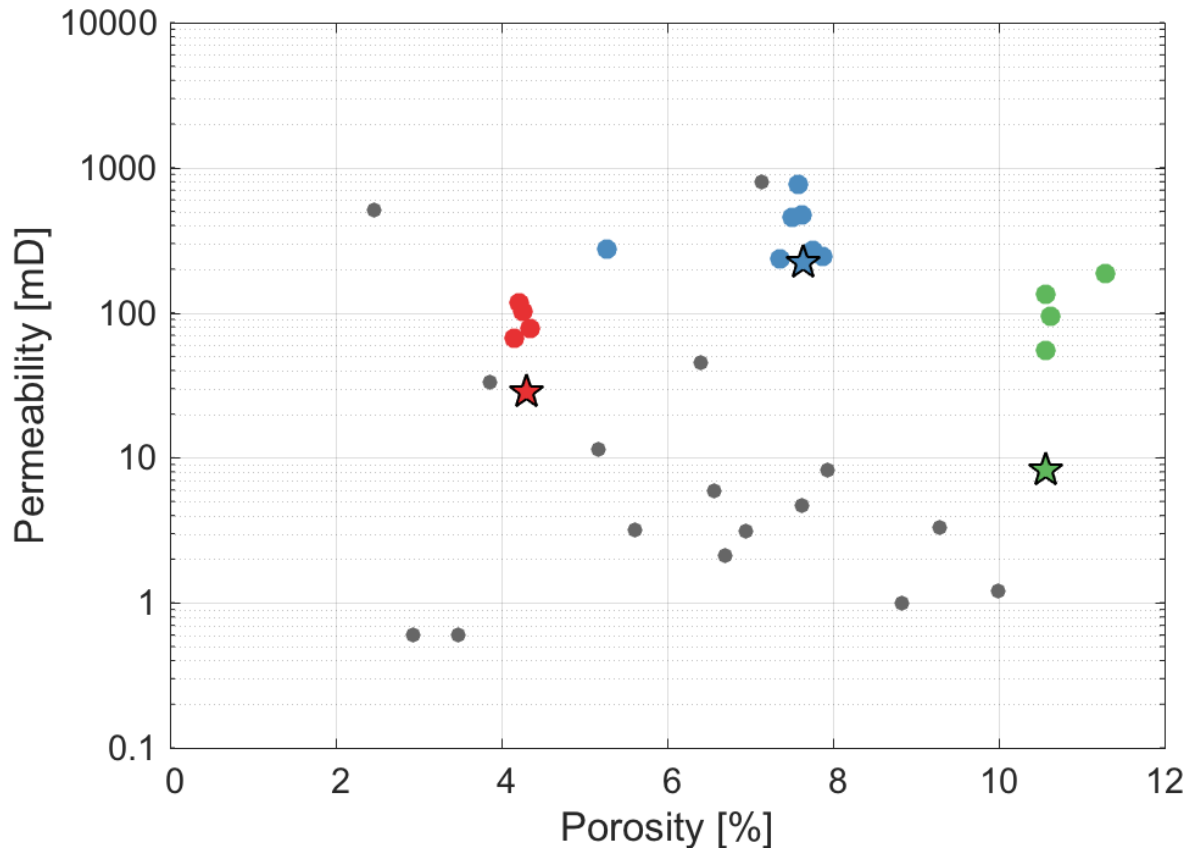
- Many rock types adhere to a unique permeability-porosity relationship:
- Sandstone modeled as a piece-wise power law or Kozeny-Carman equation.



Bourbie & Zinszner (1985)

Carbonate permeability-porosity

- Tight carbonates exhibit 3 OM spread of permeability.
- 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.



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

Carbonate permeability-porosity

(Vanorio, 2015; Geophysics)

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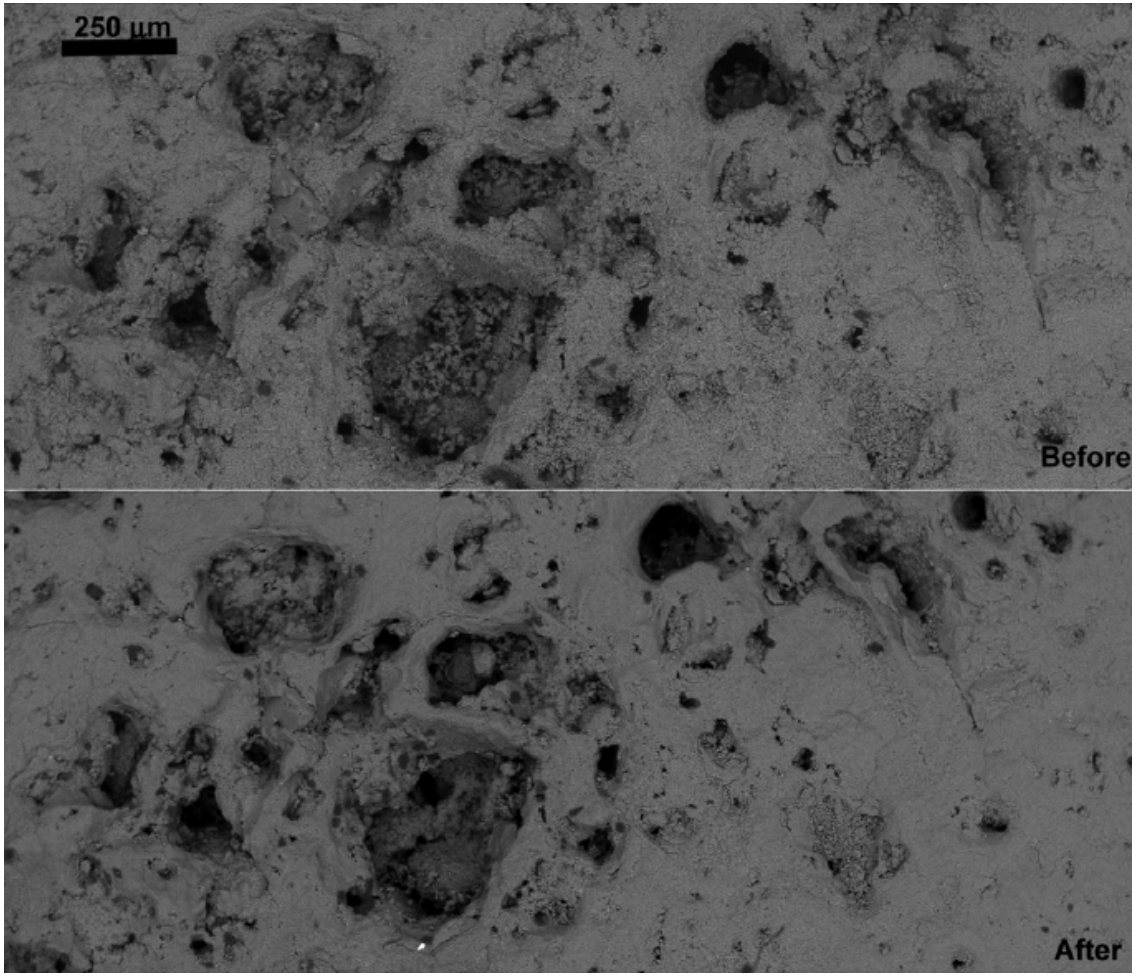


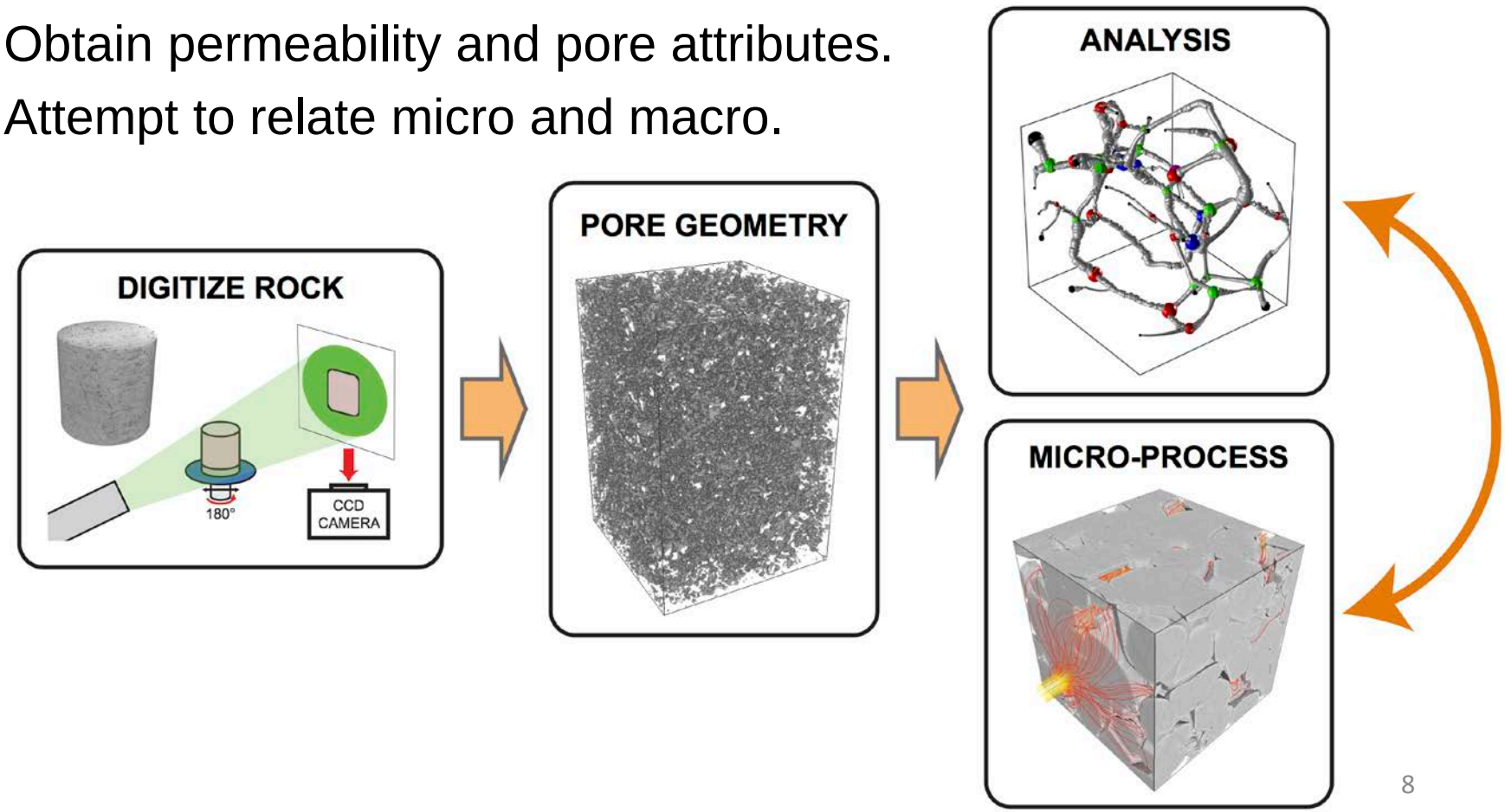
Scientific question

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?

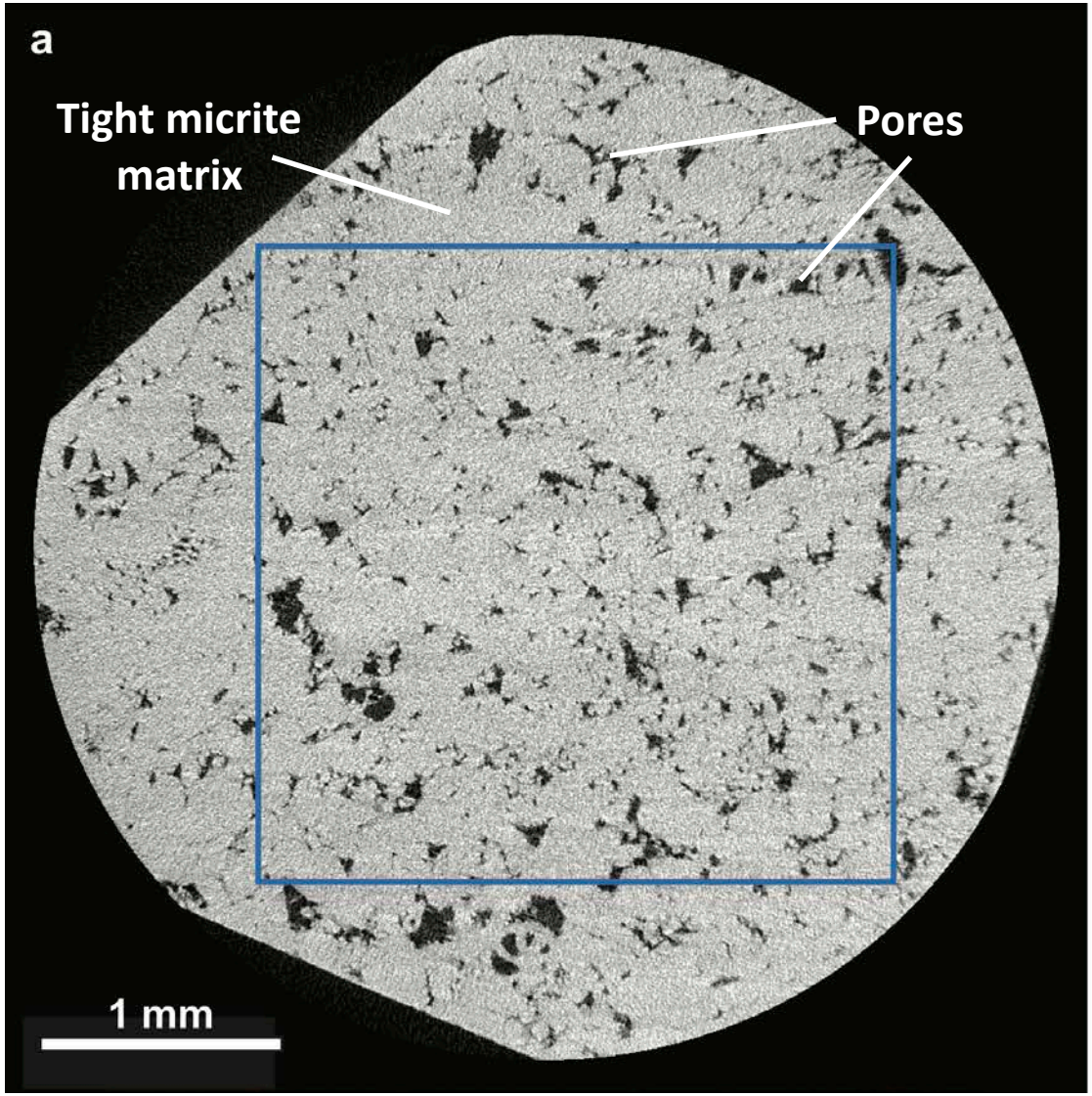
Digital rock physics (DRP)

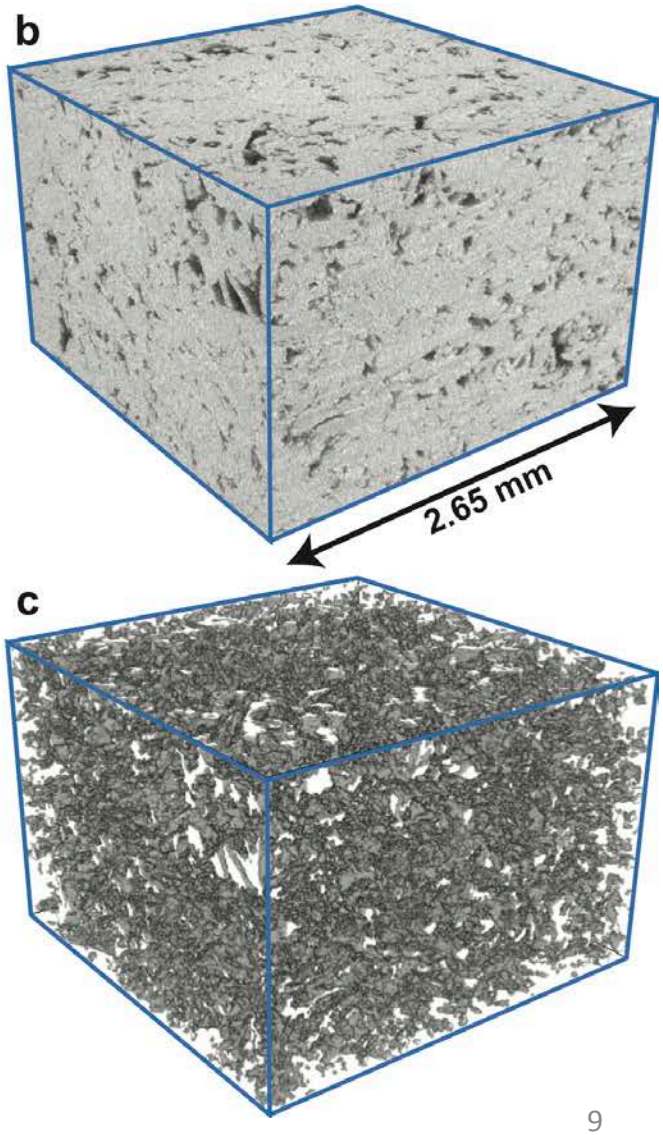
- Image pore geometry of tight carbonate.
- Simulate fluid flow with LBM
- Erode geometry based simple dissolution rules
- Obtain permeability and pore attributes.
- Attempt to relate micro and macro.

- Porosity
- Specific surface area
- Tortuosity
- Hydraulic diameter



Digitizing the carbonate rock





Simulation of laminar flow

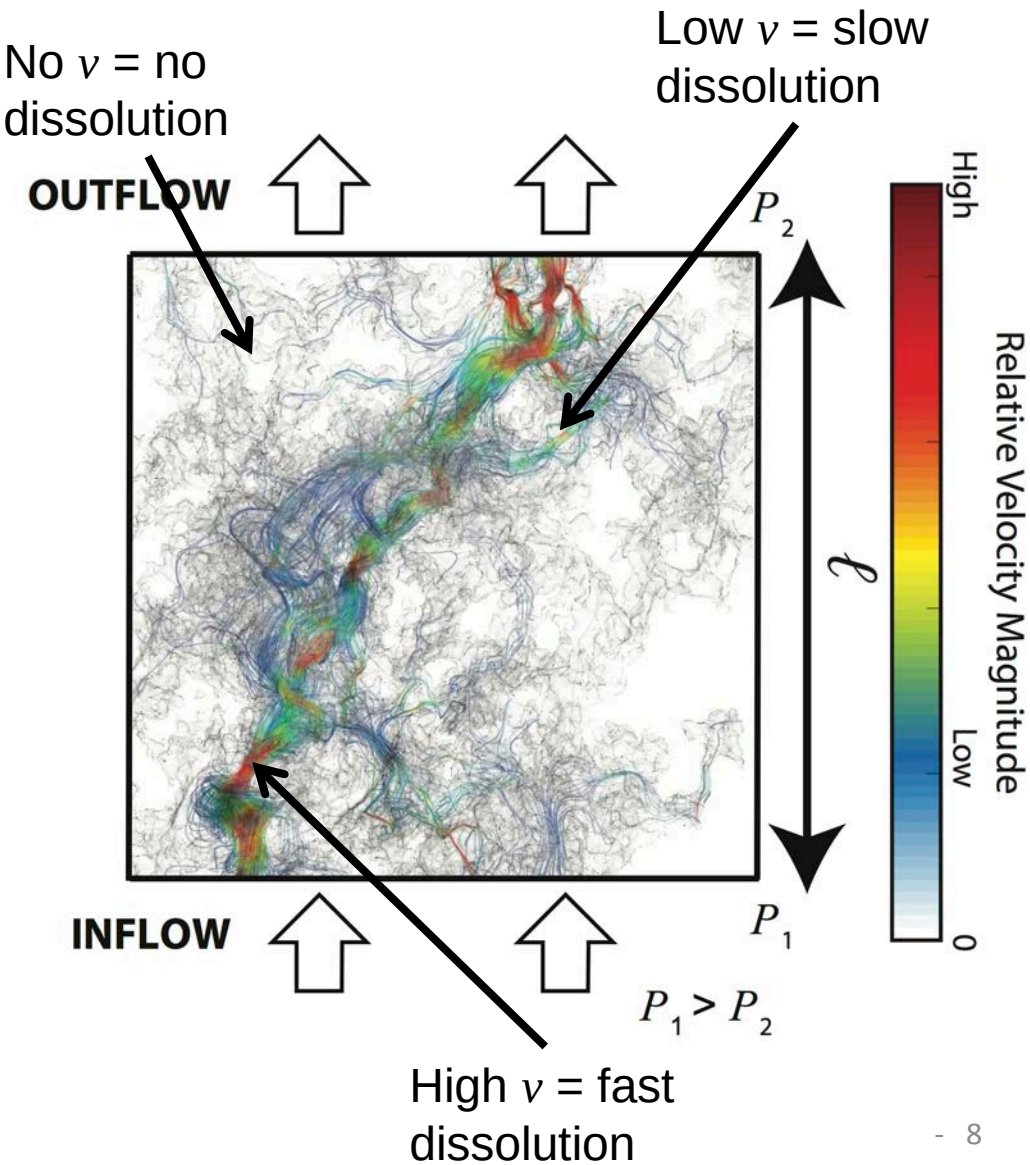
- Simplest dissolution model we could think of.
- Laminar flow simulated using Lattice-Boltzmann Method (Keehm et al. 2003).
- Erode calcite at a rate controlled by the local velocity and surface area, equivalent to solving:

For each boundary voxel i,

$$\rho \frac{dV_i}{dt} = -n_i \frac{v_i}{v_{\max}} R_0$$

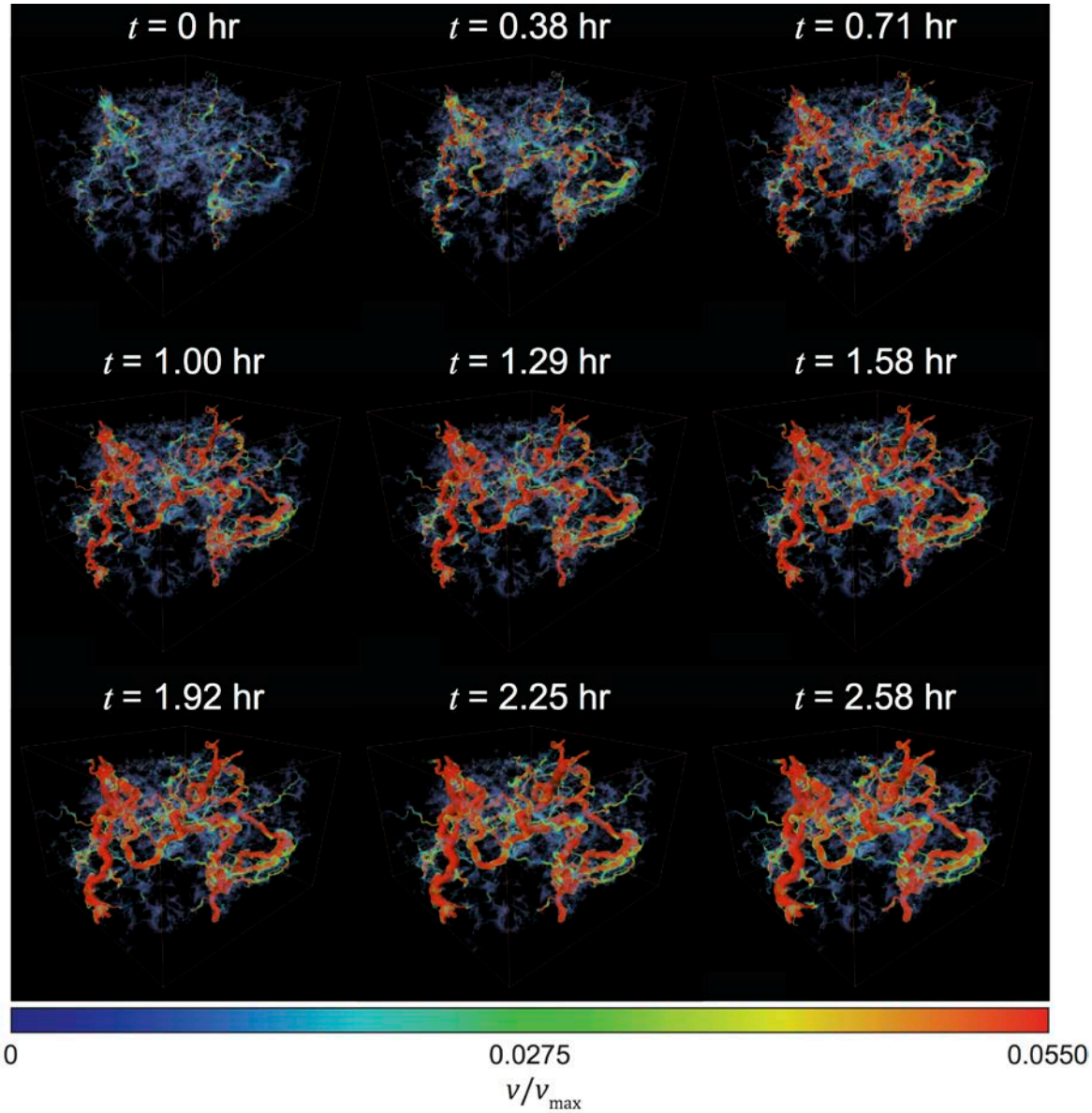
R_0 : Plummer et al. (1978)

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



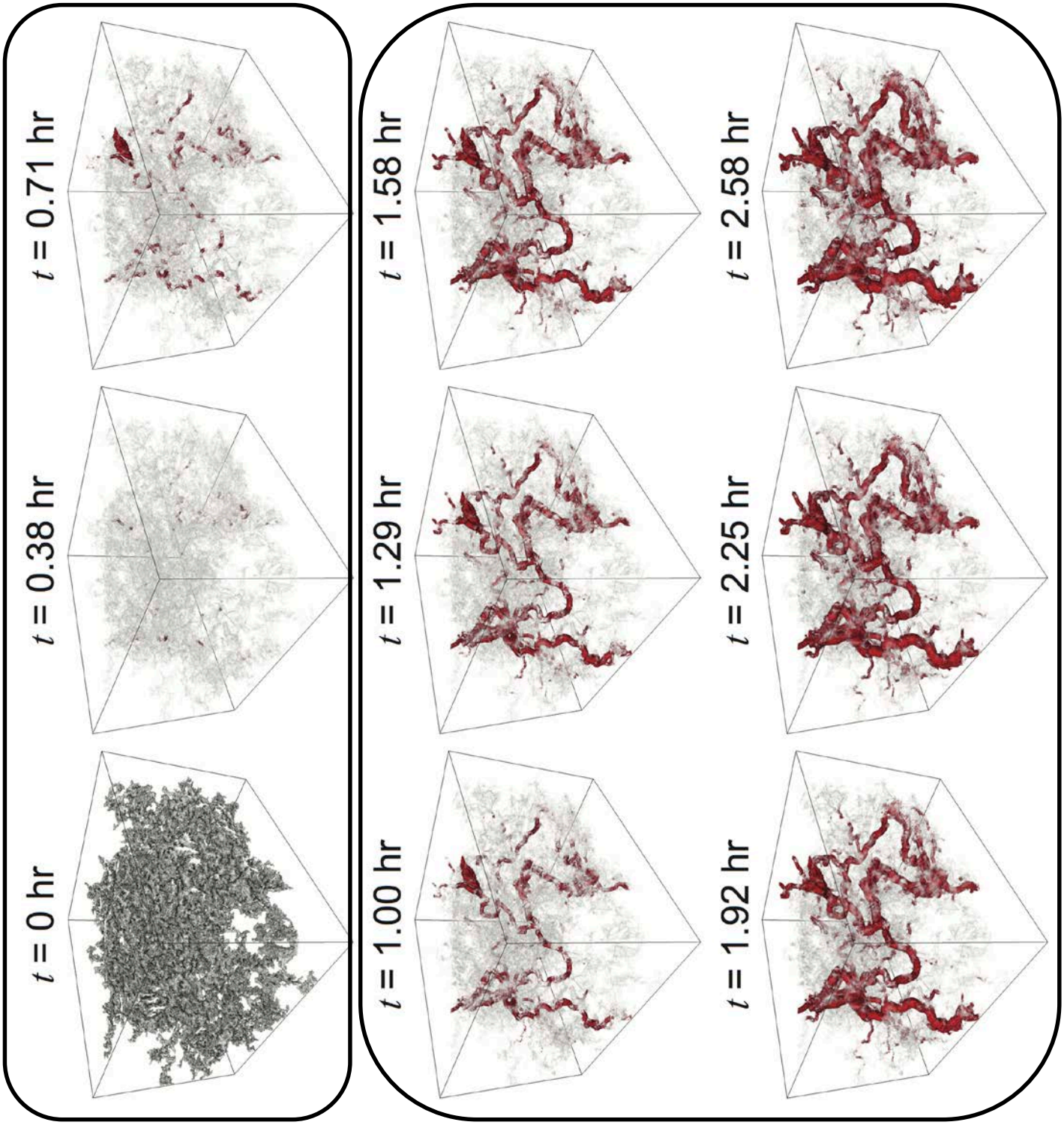
Velocity distribution evolution

- Velocity magnitude heterogeneous over fluid path.
- Dissolution rules renforce high-conductivity paths.
- Velocity becomes more homogenous over path.



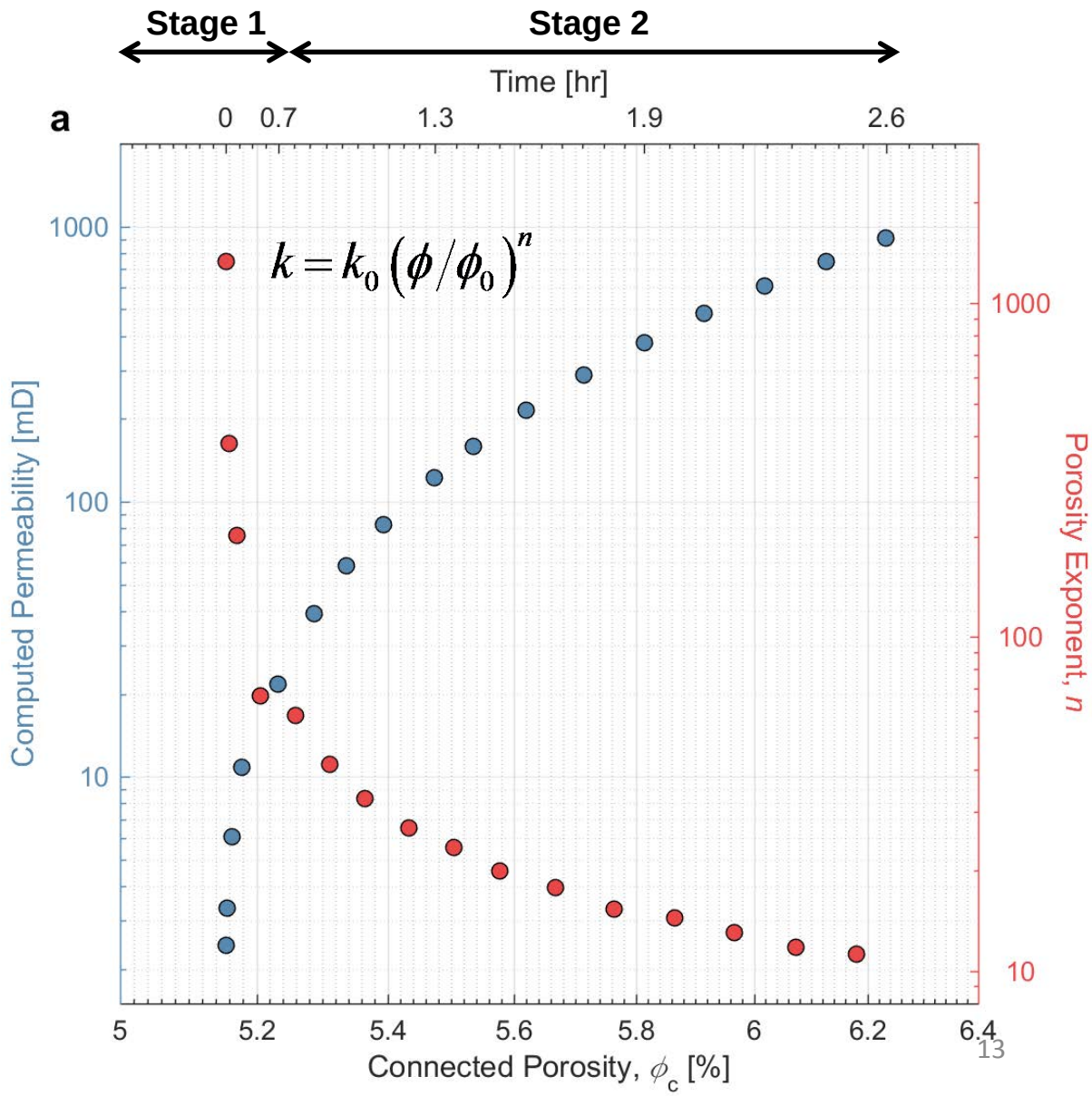
Stage 1: Patchy
Dissolution of narrow pore throats

Stage 2: Channelization
Formation and dilation of channels



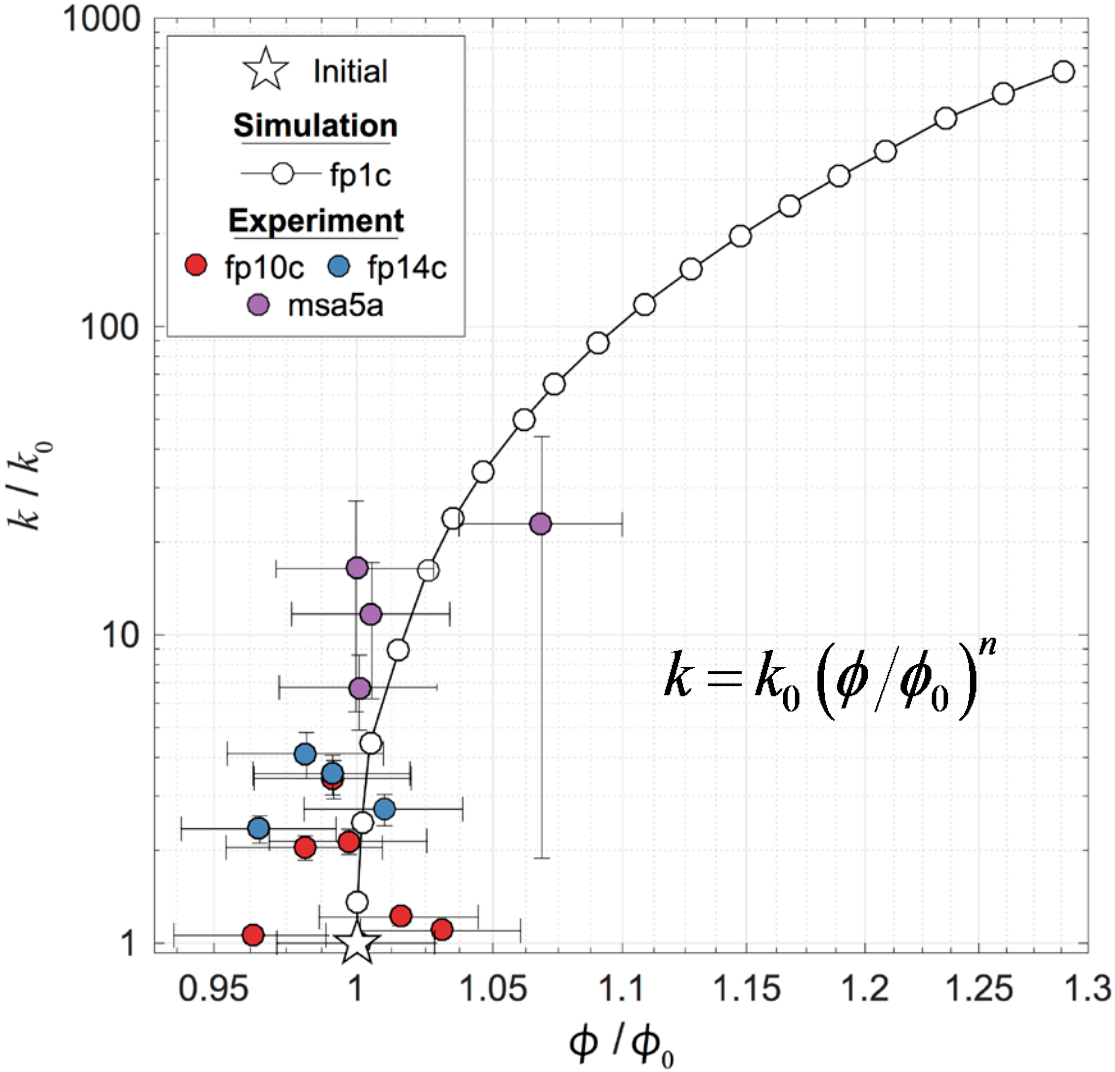
Permeability-porosity evolution

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

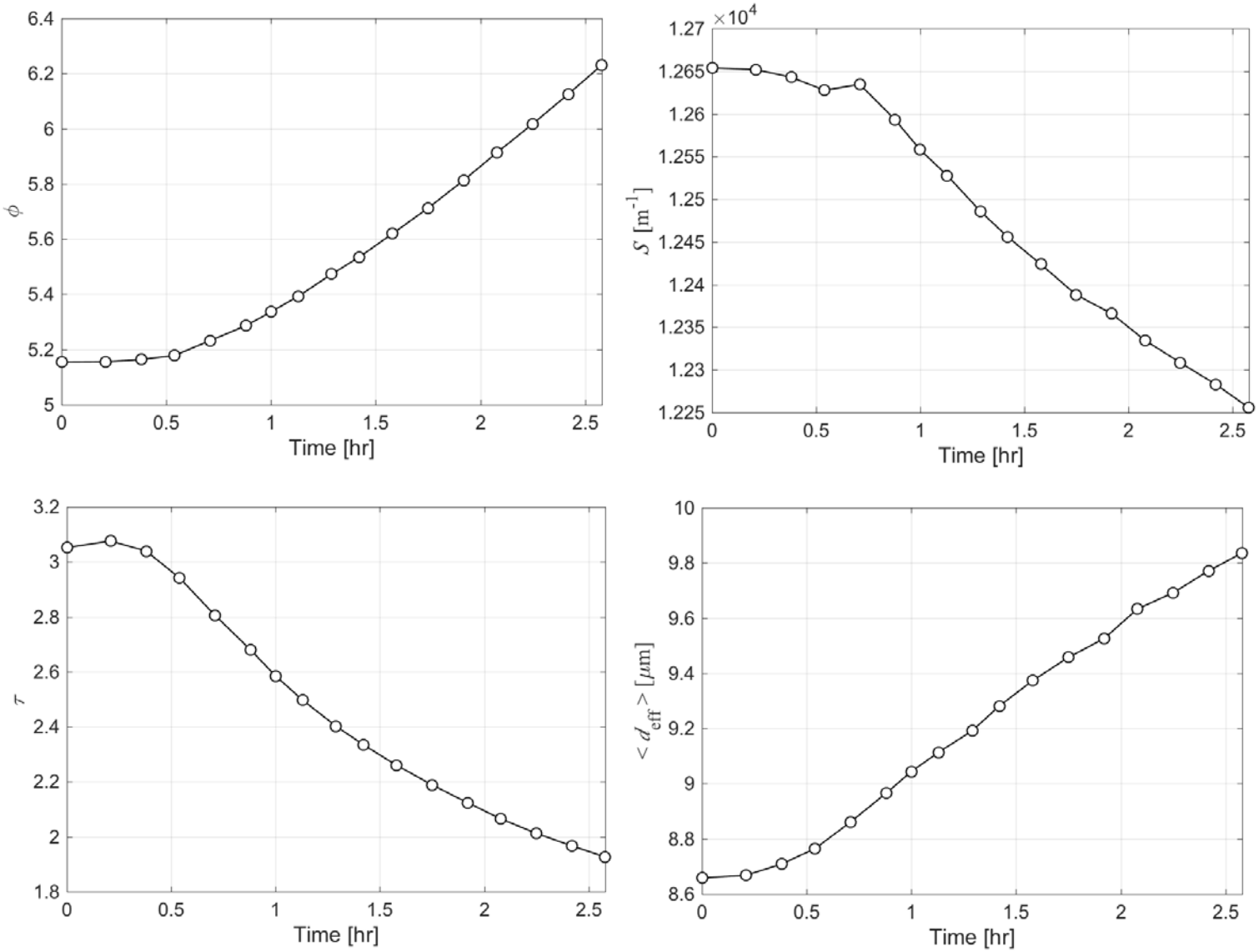


Comparison with experiment

- Compare simulation results with CO_2 injection experiments.
- Normalize porosity and permeability by initial value.



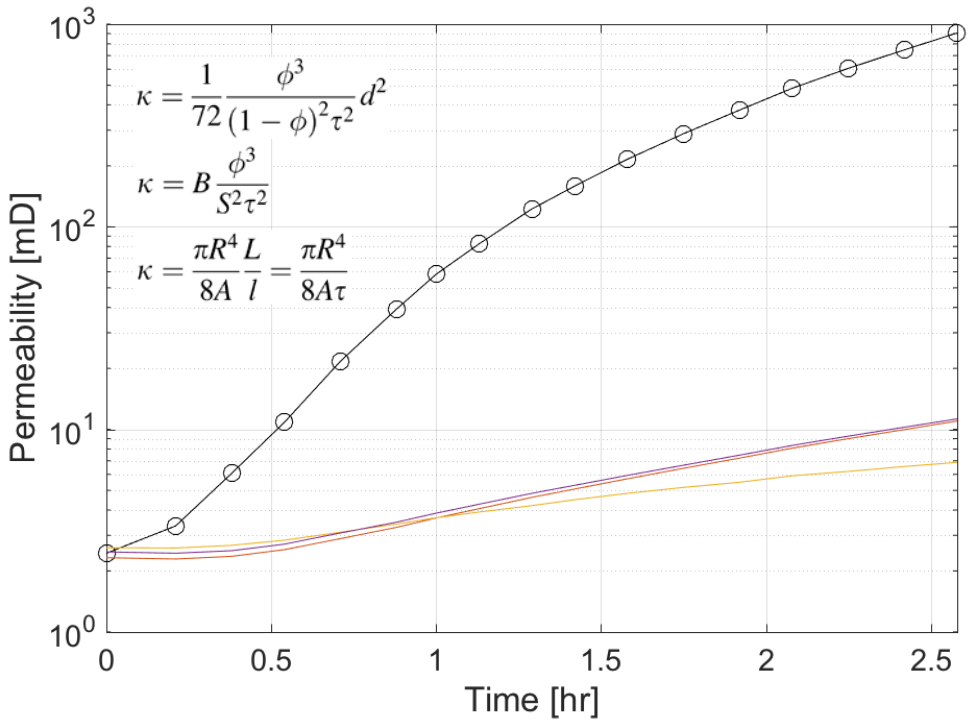
Connecting permeability with pore parameters



Connecting permeability with pore parameters

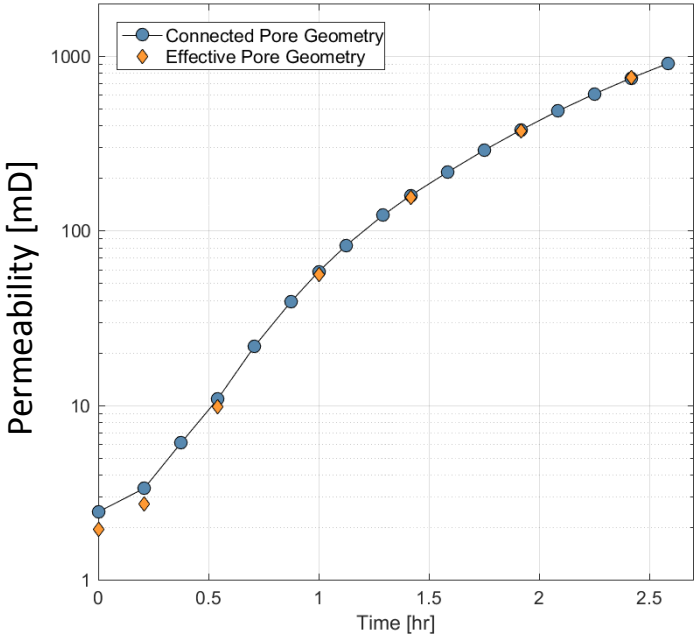
- Plug attributes into Kozeny-Carman equation.
- Underestimate the changes in permeability by orders-of-magnitude.
- Qualitative explanation:
  - KC good for microstructures with open pores.
  - KC sensitive to uniform changes.
- Dissolution can target critical porosity in a pore network, induce large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

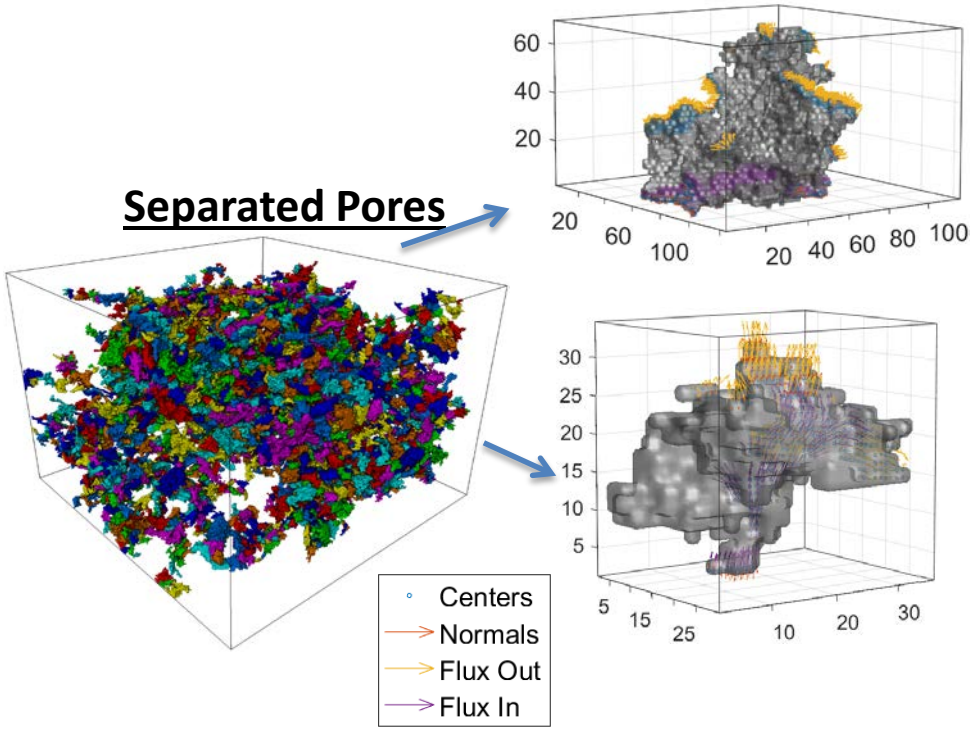
Calculated Permeability

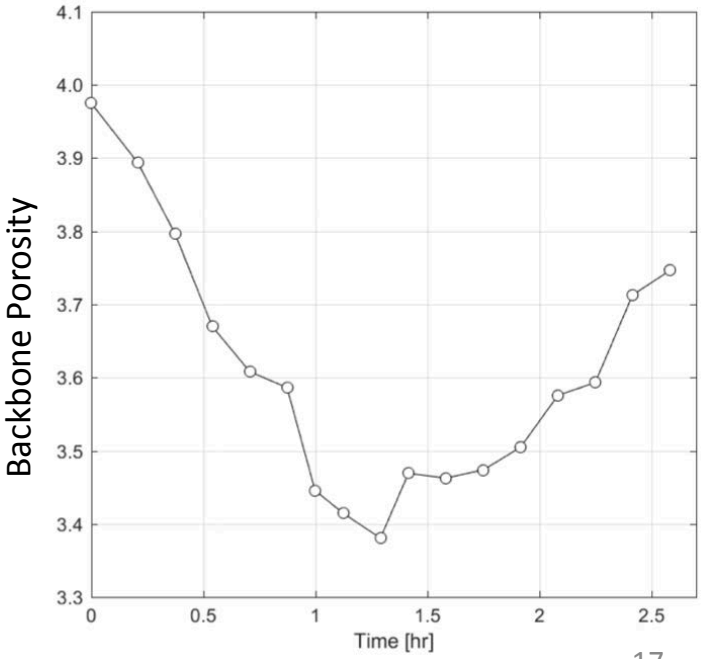


Effective pore geometry

- 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.

Acknowledgements

- Stanford Center for Carbon Storage
- NSF CAREER Award to Tiziana Vanorio