# $CO_2$ Storage in Carbonate Reservoirs


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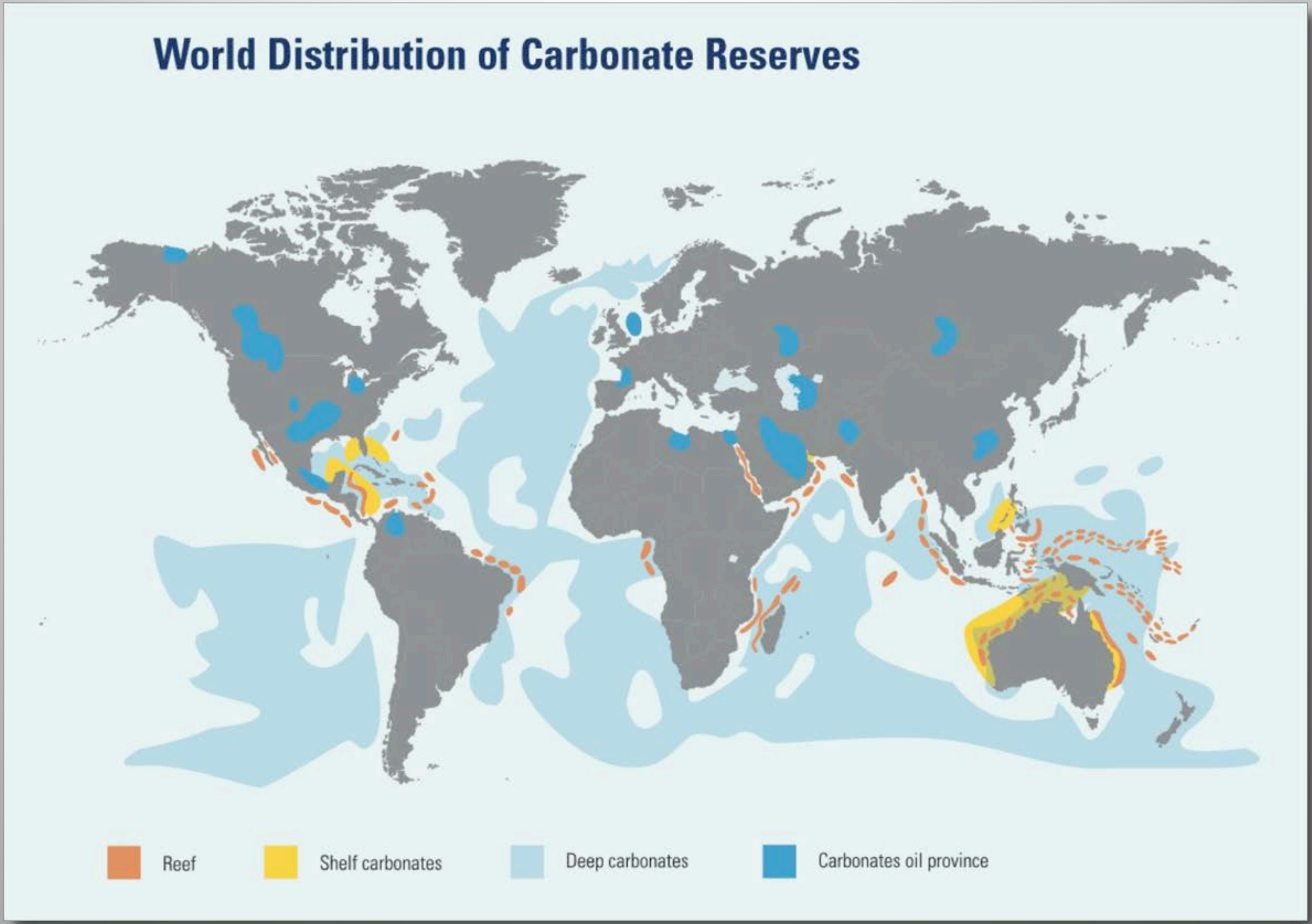
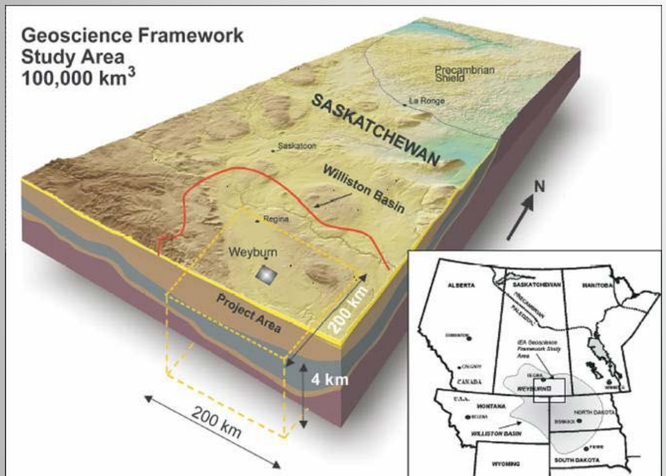


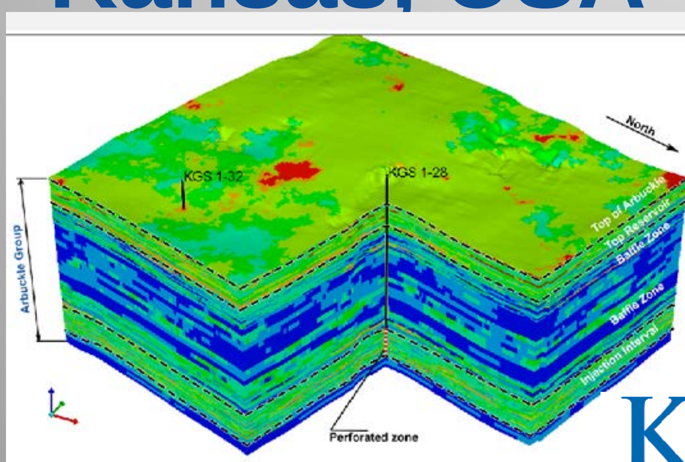

Schlumberger, “Carbonate Reservoirs,” 2007.

# Weyburn, Canada




*images: www.ptrc.ca*

# Kansas, USA

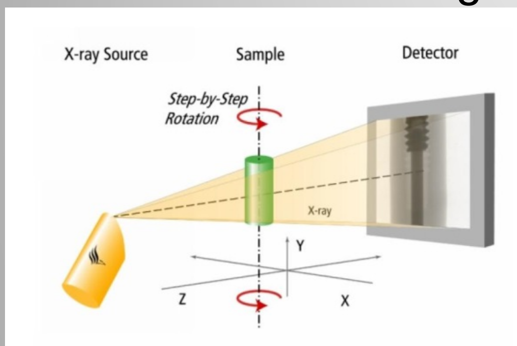



KU
KANSAS GEOLOGICAL SURVEY

We derived key reactive-transport parameters and ranges for carbonate rocks over a wide range of heterogeneity and initial permeability

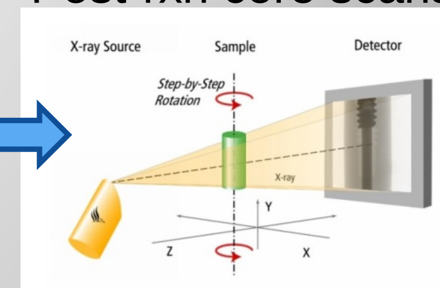
# Coupling experiments to parameter calibration and model refinement

XCMT core scanning




Constant flowrate brine/$CO_2$ core-flooding experiments


Post-rxn core scans



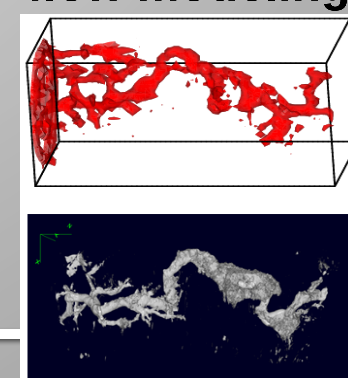

NMR scanning

NMR scanning

Fluid chemistry analyses

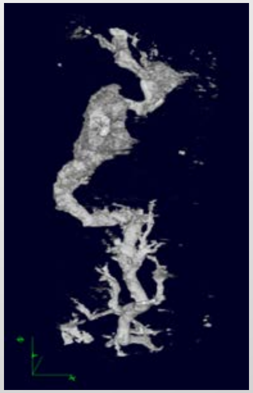
Additional core statistics (SEM)

**Reactive flow modeling**

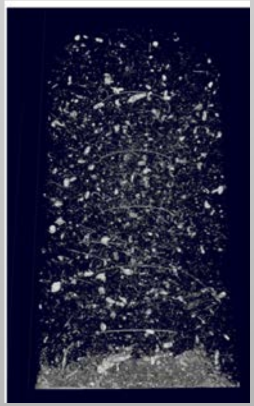


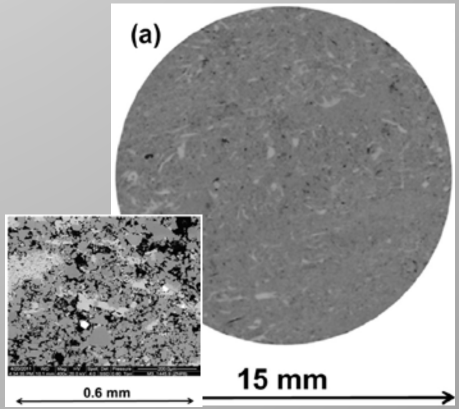
# Dissolution yields preferential flow paths in more heterogeneous carbonate rocks

Unstable Dissolution Fronts

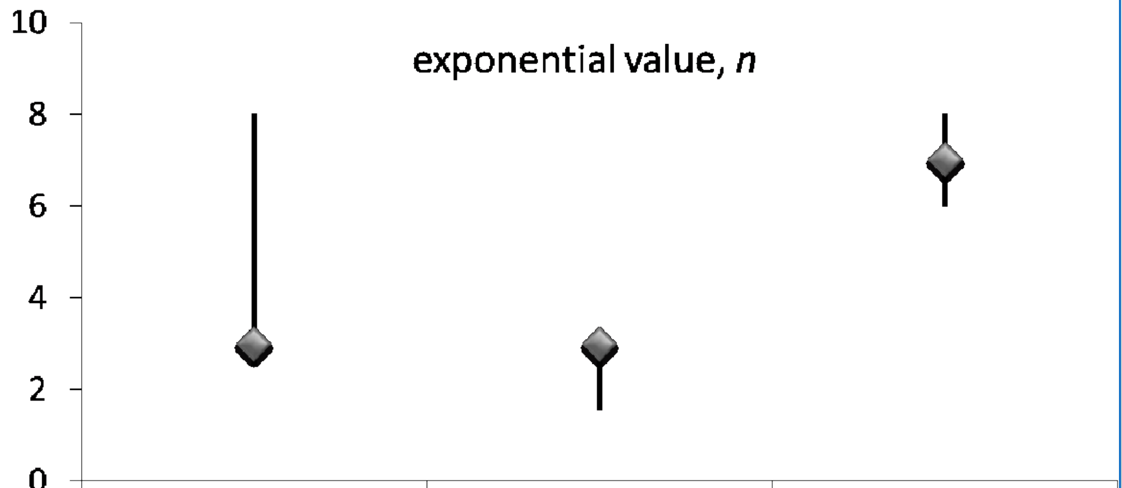


Stable Dissolution Fronts





# Evolution of permeability is tied to the heterogeneity and the mineral reactivity

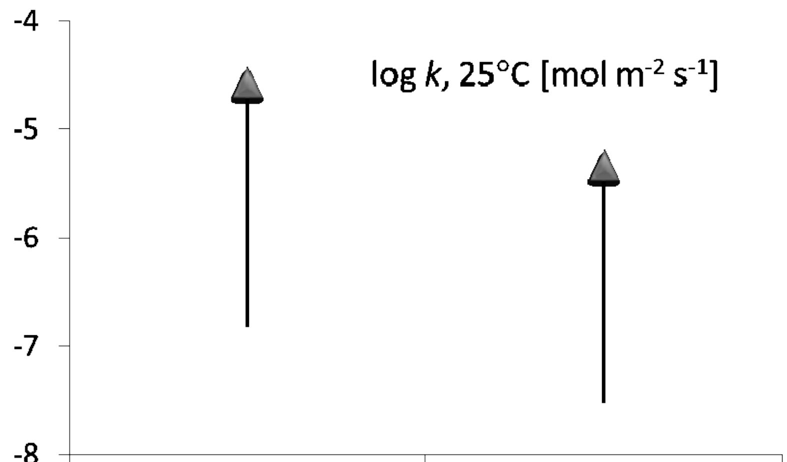



| | dolostone, homogeneous | dolostone, heterogeneous | limestone, heterogeneous |
|---|---|---|---|
| max | 8.0 | 3.3 | 8.0 |
| min | 2.5 | 1.6 | 6.0 |
| median | 3.0 | 3.0 | 7.0 |

Greater permeability change with limestone

$$K_t = K_0 \left( \frac{\phi_t}{\phi_0} \right)^n$$

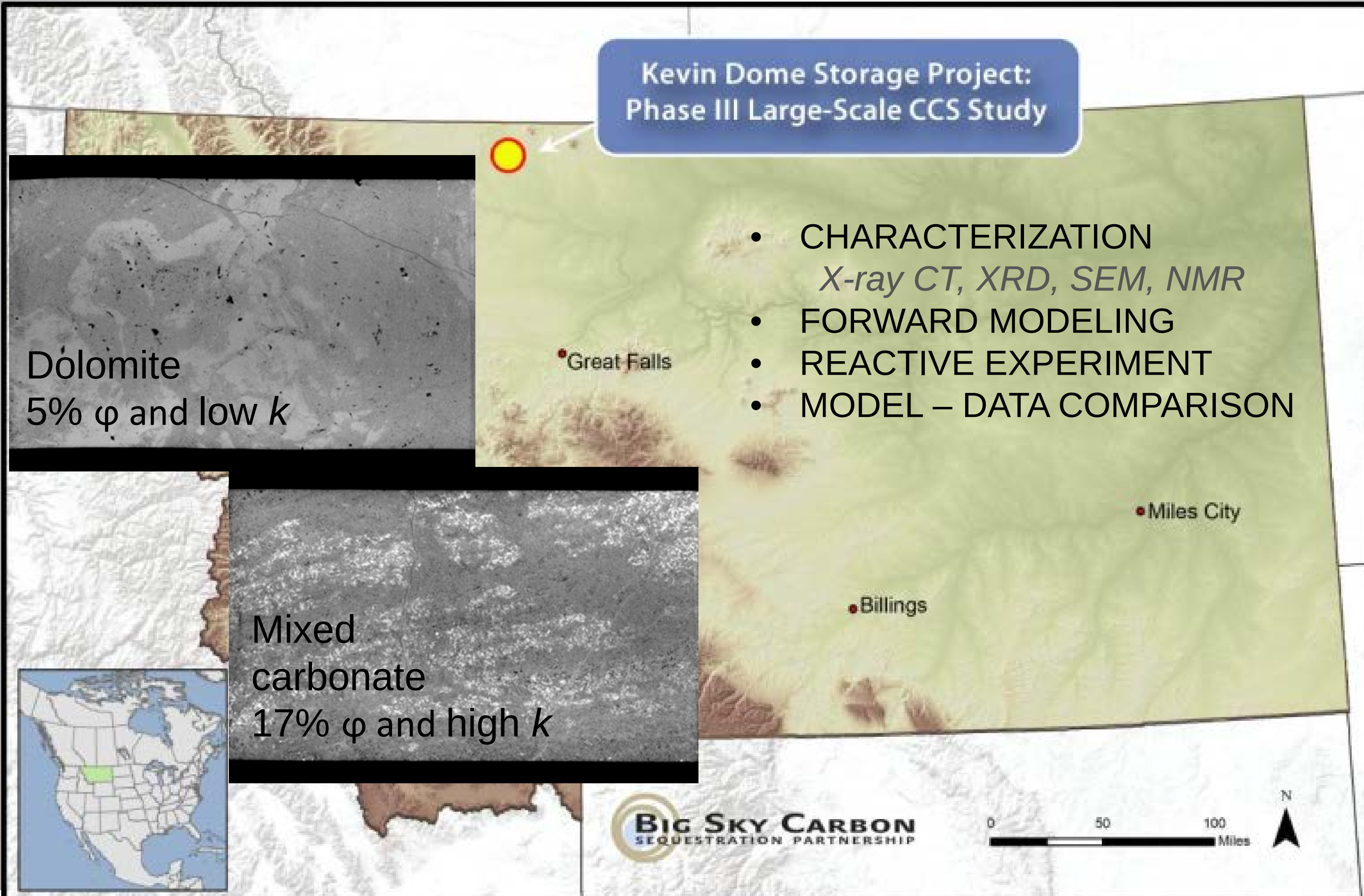
# Mineral dissolution rates vary by 100 times and may require calibration of reactive surface area




| | calcite | dolomite |
|---|---|---|
| max | -4.82 | -6.00 |
| min | -6.82 | -7.53 |
| Palandri and Kharaka | -4.57 | -5.34 |

$$\frac{dn}{dt} = -Sk_{298.15K}e^{-\frac{E}{R}\left(\frac{1}{T}-\frac{1}{298.15}\right)}\left(1-\frac{Q}{K}\right)$$

# Validation Study – Big Sky Demonstration, Duperow Formation (Lee Spangler and Stacey Fairweather)



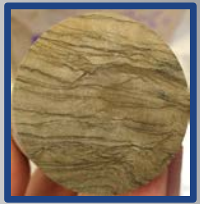

- CHARACTERIZATION
  *X-ray CT, XRD, SEM, NMR*
- FORWARD MODELING
- REACTIVE EXPERIMENT
- MODEL – DATA COMPARISON



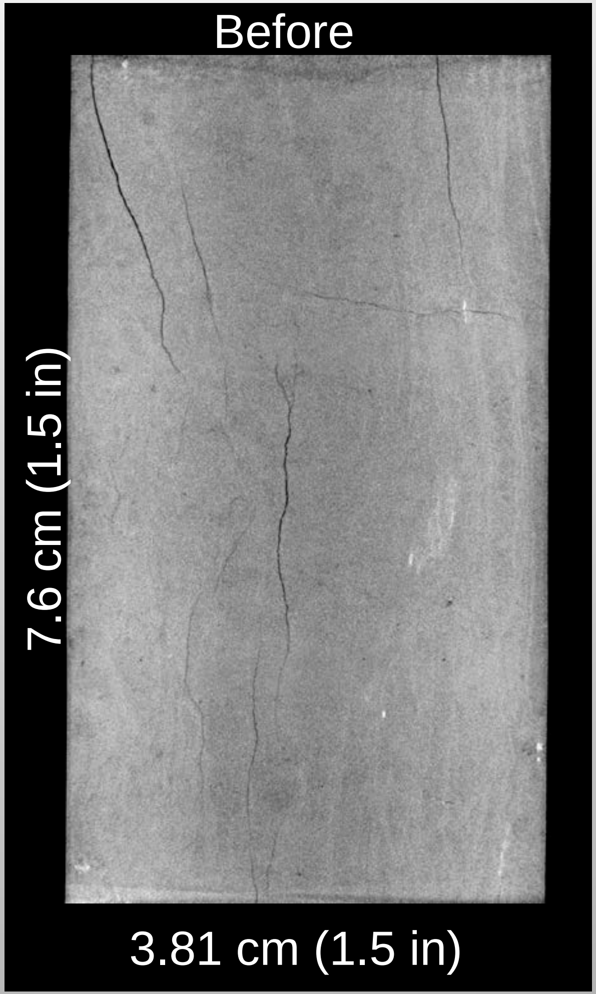
*www.bigskyco2.org/kevin_dome_site_characterization*

# Approach

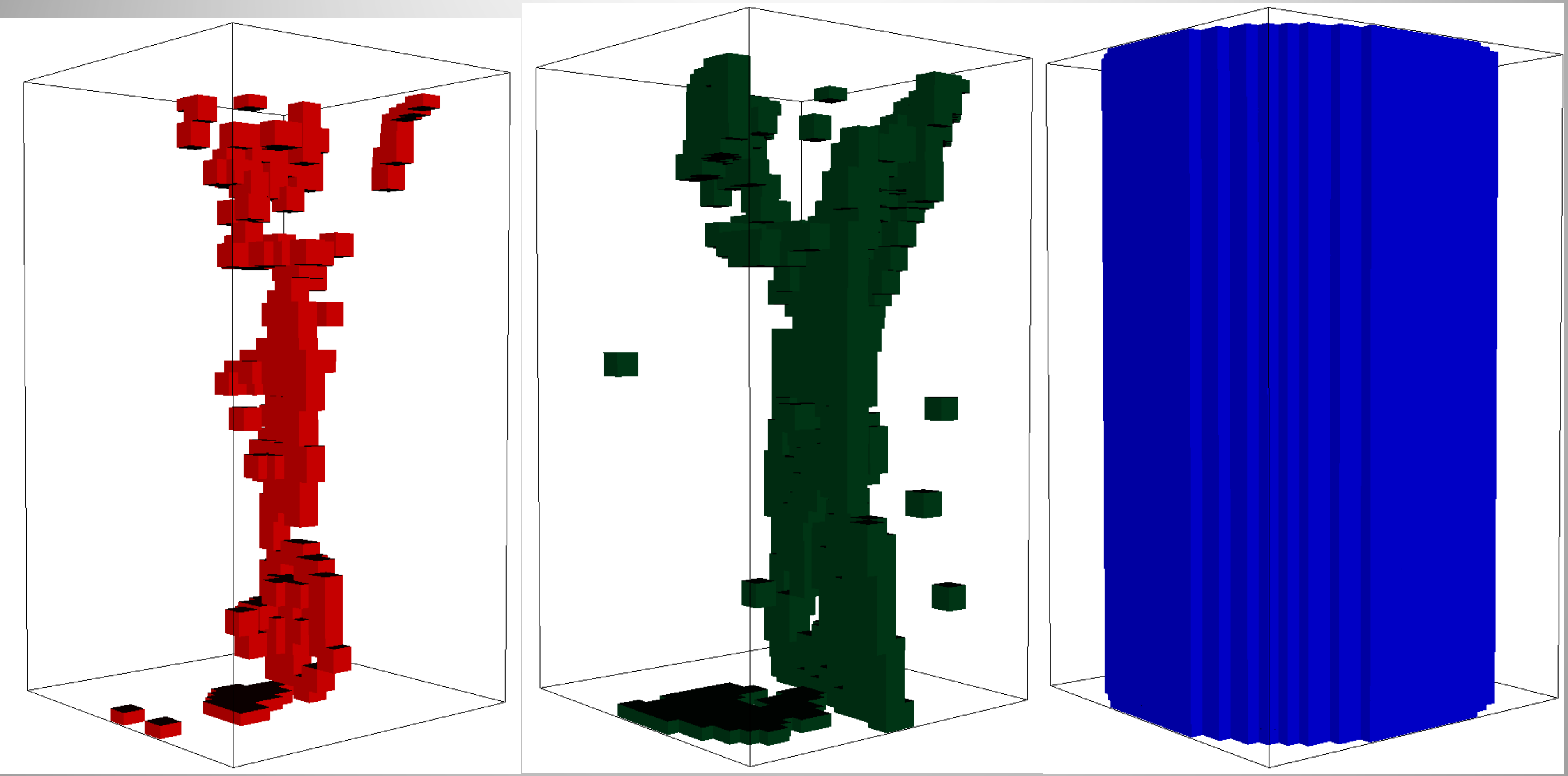
Duperow Dolostone
(1231 m)



- Calibrate the initial model permeability against the experiment.
- Run simulations spanning model parameters (n, k)
- Compare simulated and measured results

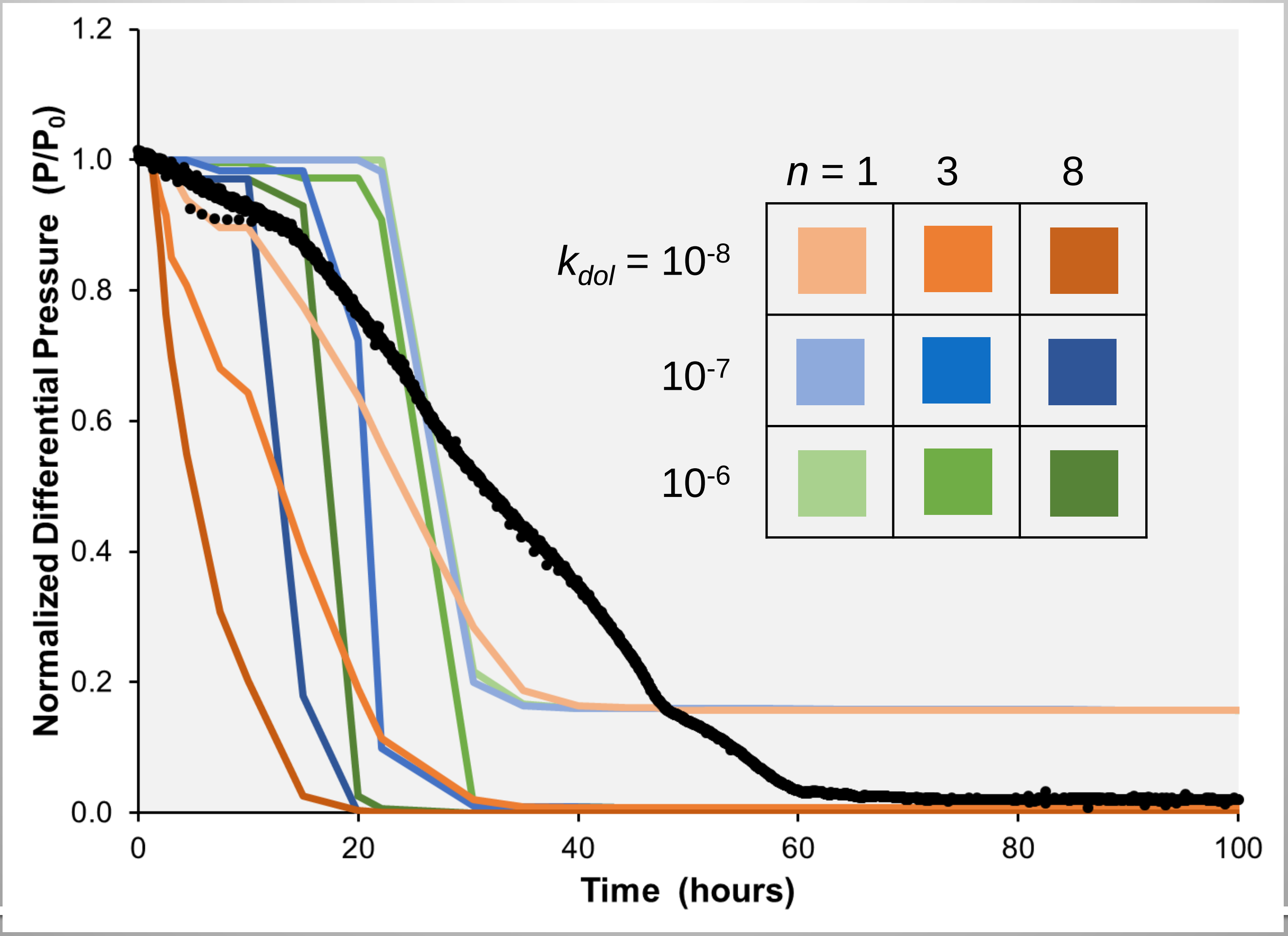



# Permeability zones fit to permeability of unreacted core (0.5 mD)



| high perm | medium perm | low perm |
|---|---|---|
| fractures | boundary walls | dense matrix |

# Comparison of model with experiment suggest that lower reaction rates may be needed to match trends in pressure



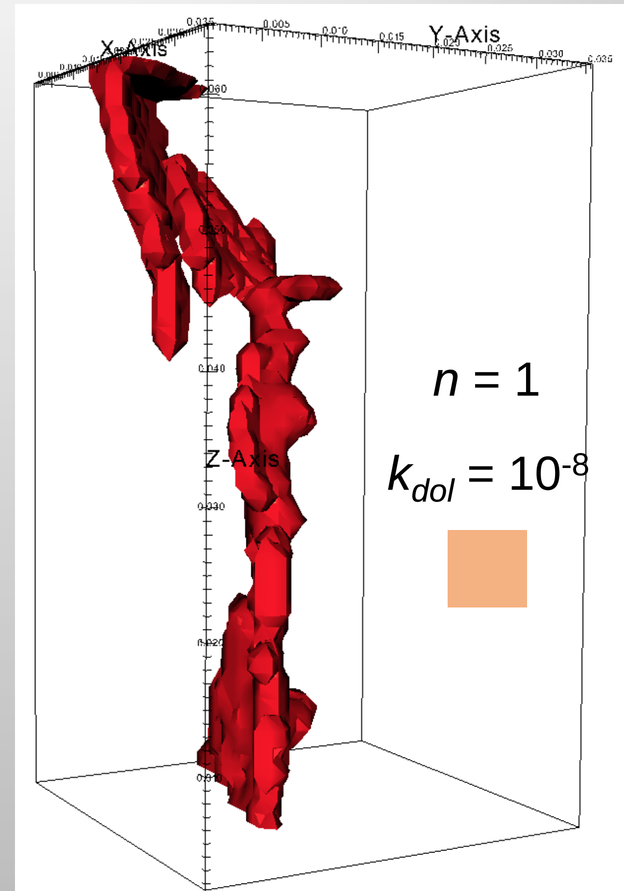
# Simulation captures measured changes in porosity

Experiment

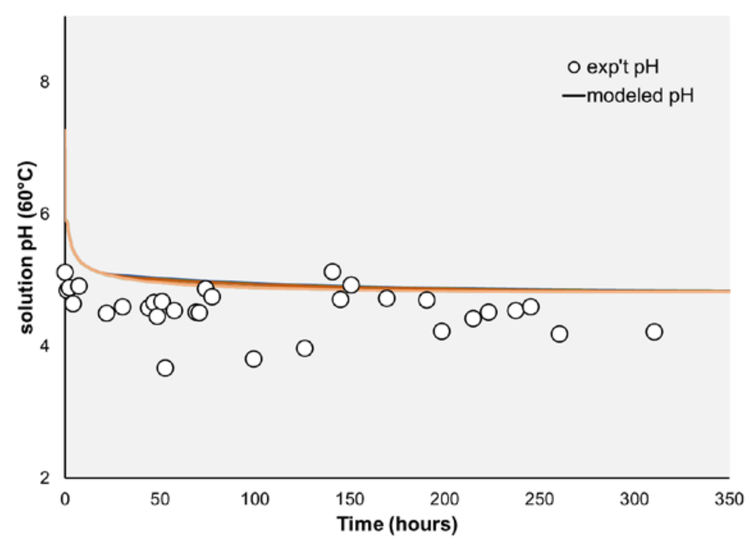
7.6 cm (1.5 in)

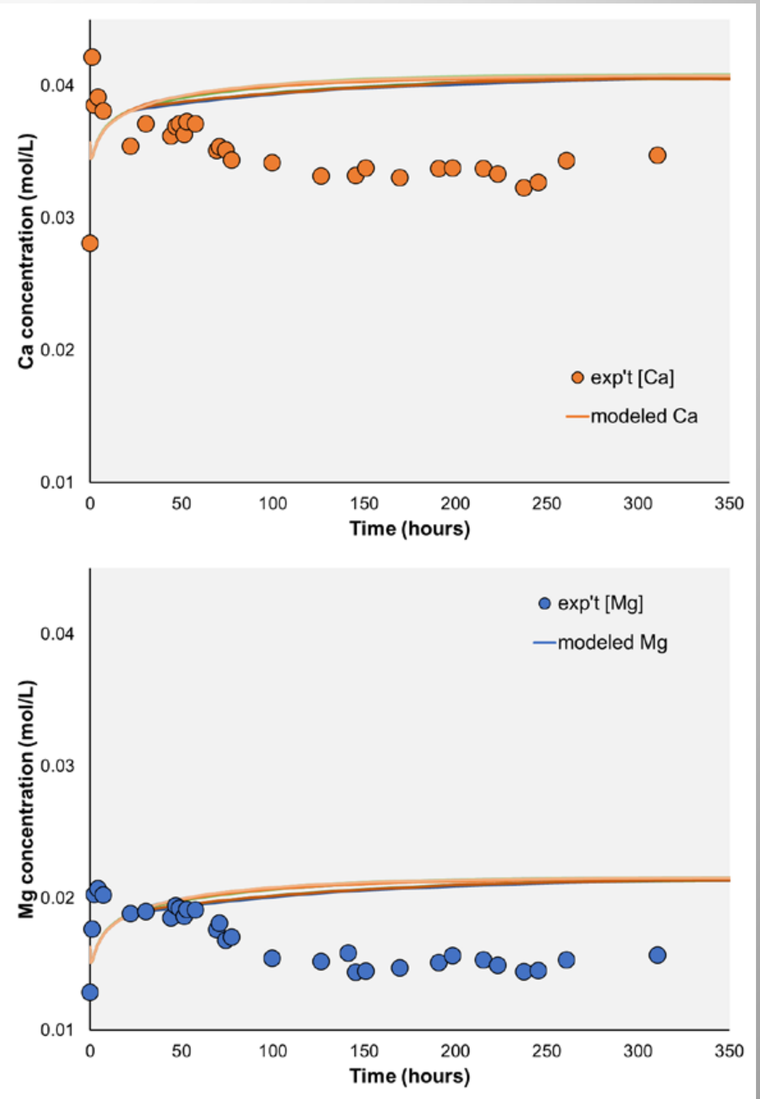
3.81 cm (1.5 in)

Simulation

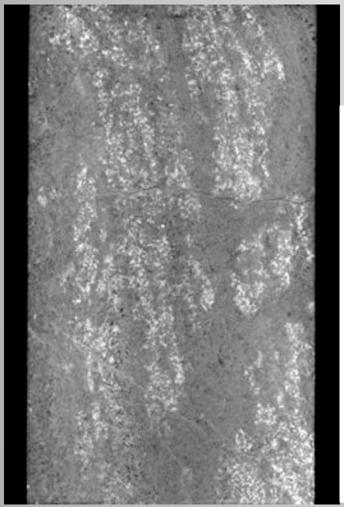


# Lower rates might also yield better match with solution data

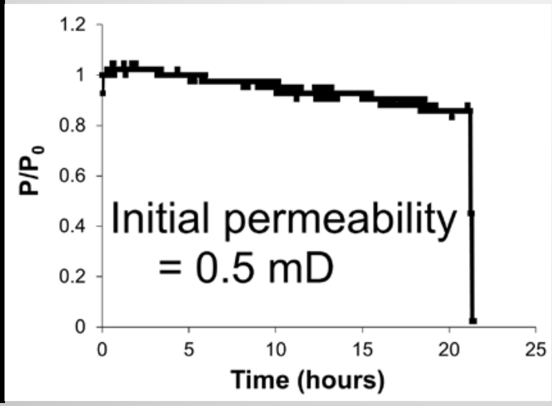


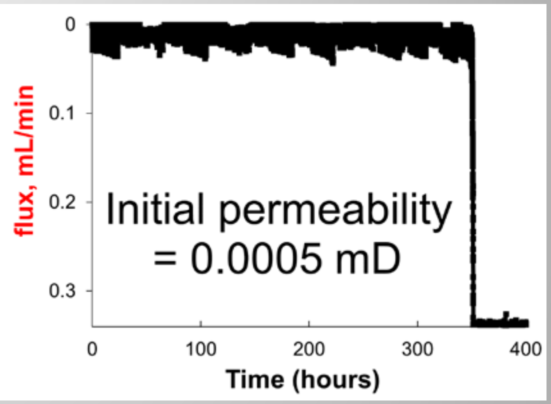
# Remaining validation experiments span three orders of magnitude in permeability

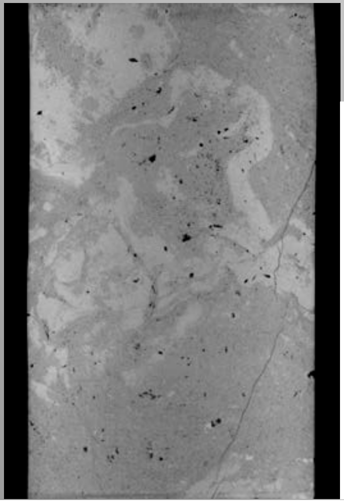


1 km – high k

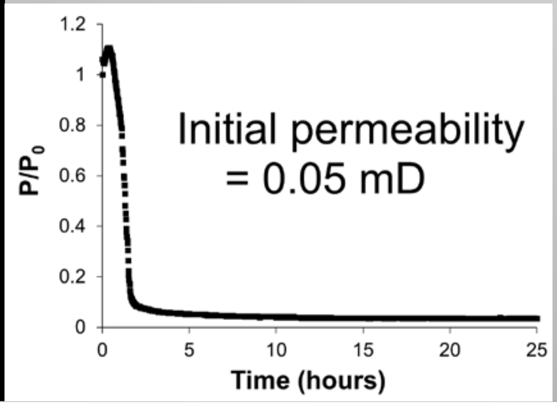


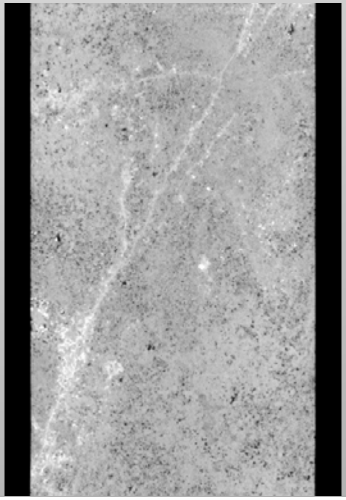

1 km – very low k



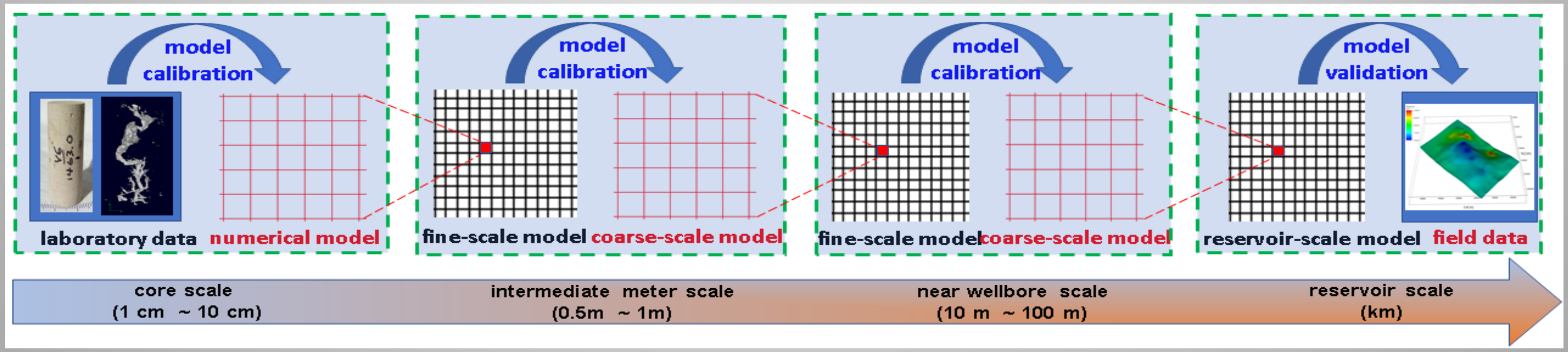
1 km – moderate k



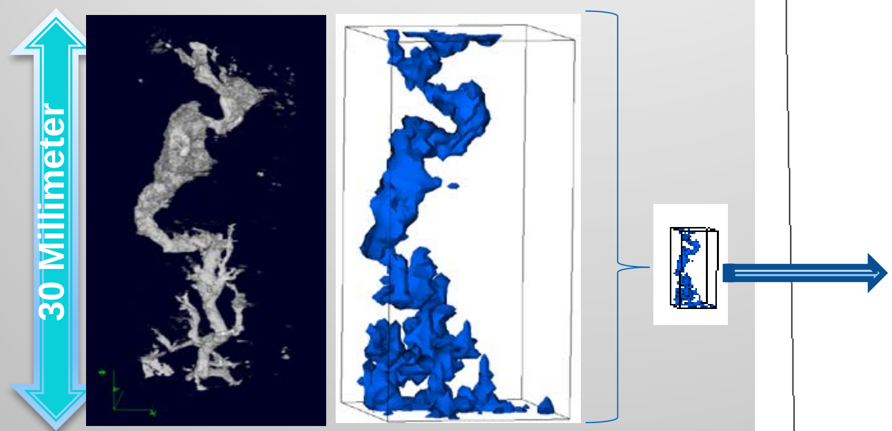
1.3 km – expected high k

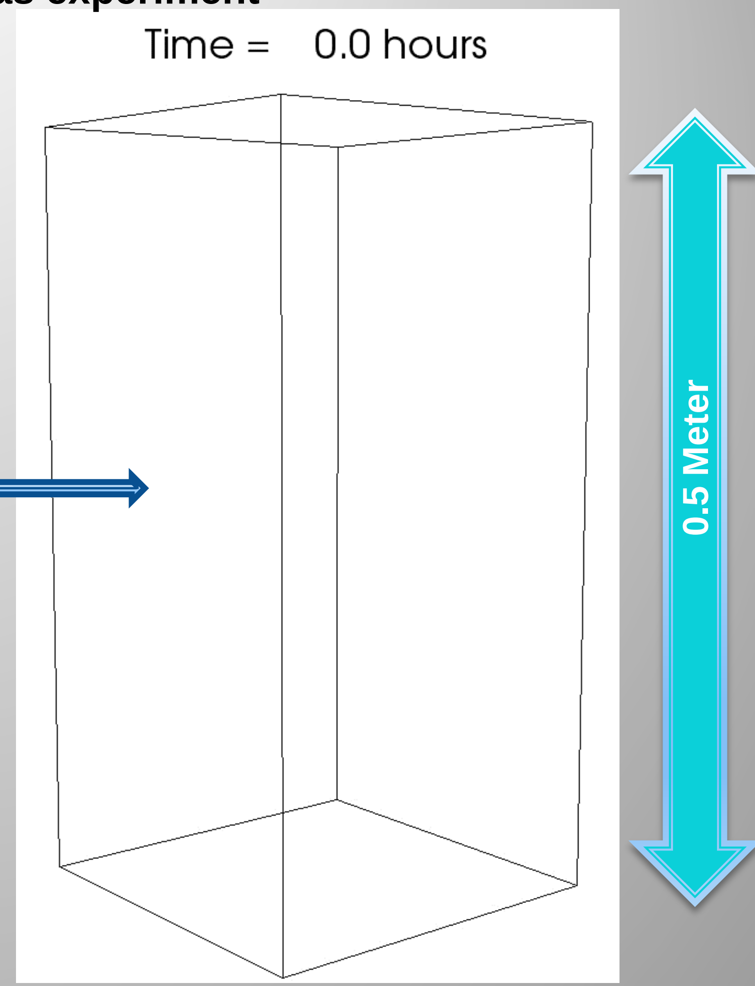
# Can we upscale the change porosity and permeability to the reservoir scale?



# We extend the calibrated core-scale model to simulate carbonate dissolution at a meter scale

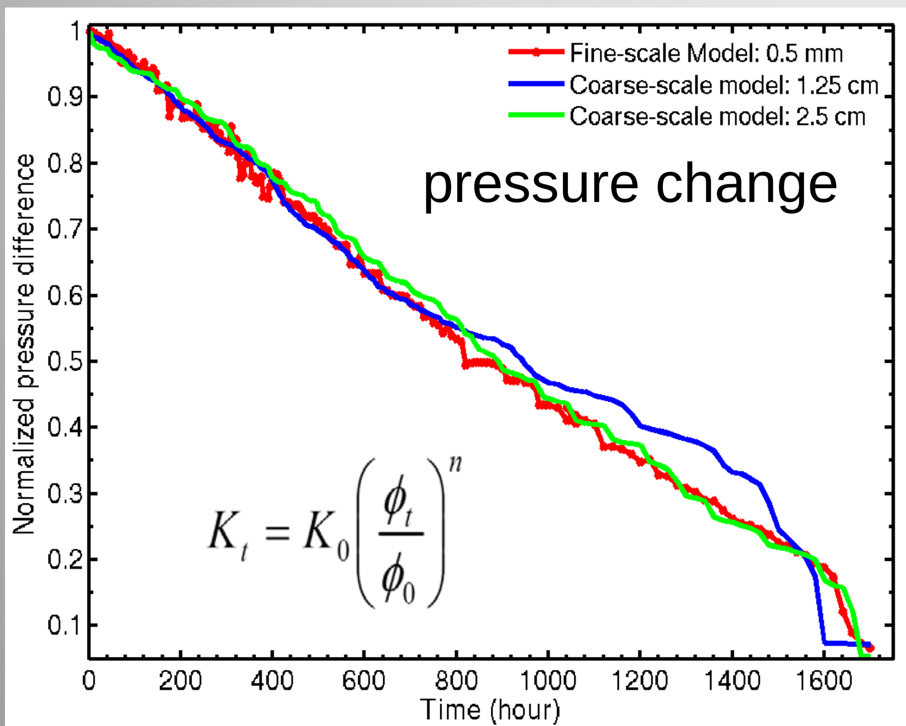
- **Model is calibrated against experiment**
- **Brute force calculation to maintain same resolution as experiment**
  - **250 million grid blocks**
  - **4096 cores**
  - **1,000 times increase in rock volume**
  - **20 times increase in reaction time**

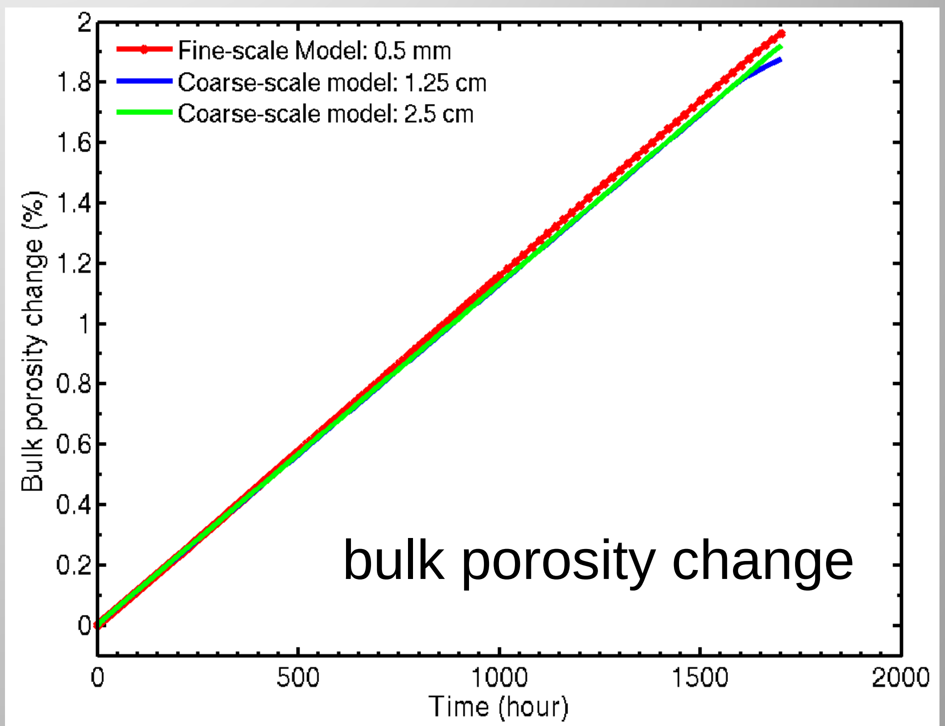



at 1700 hours after injection

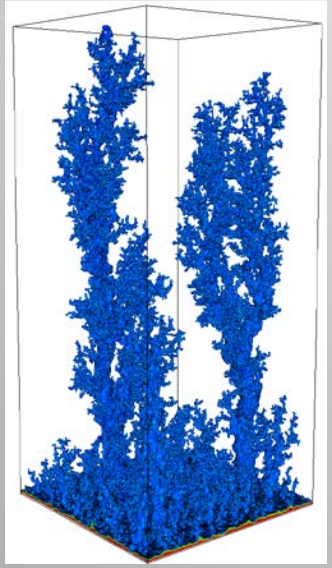
# Grid coarsening of 50X requires an increase in the permeability order “n” *to match pressure and retain channel development*

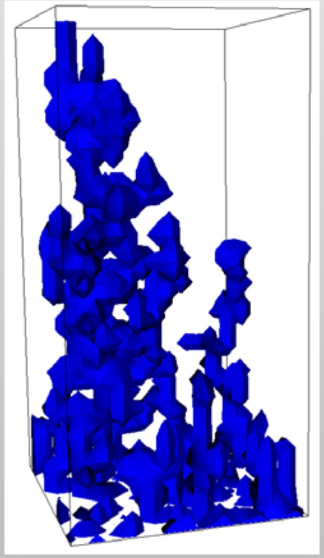


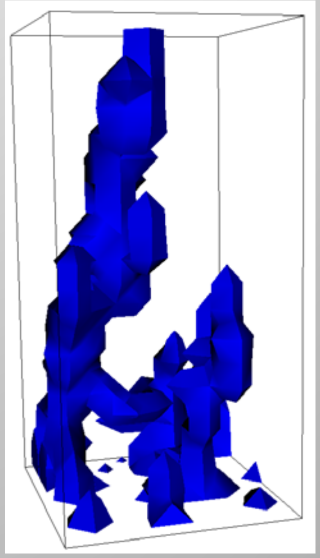



# Grid coarsening requires an increase in permeabil power "n" and a decrease available reactive surface to retain major flow paths

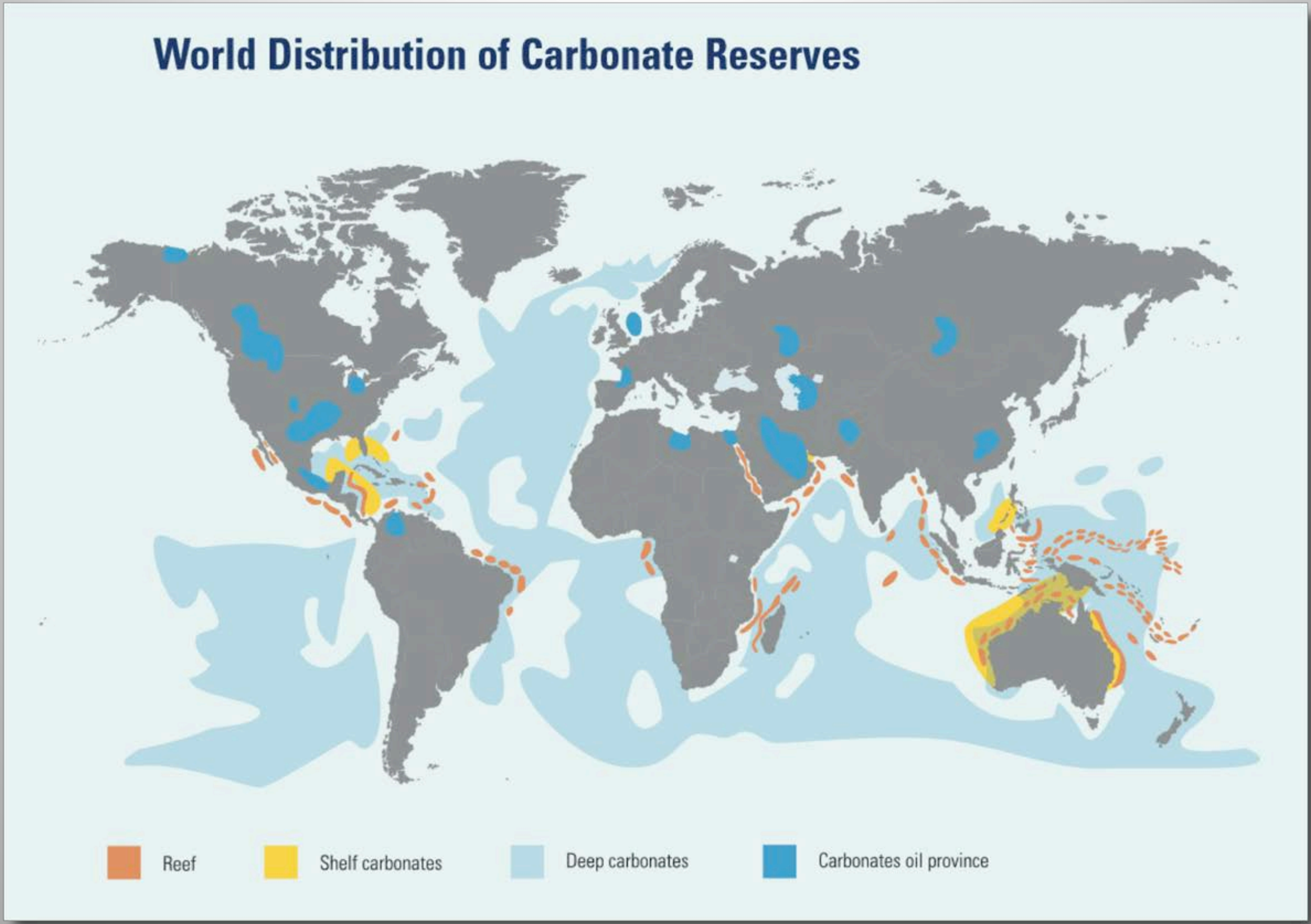
| fine-scale | 25x | 50x |
|---|---|---|
| dx = 0.5 mm | dx =12.5 mm | dx =25 nm |
| n = 8 | n = 11 | n = 12 |







1700 hours




Schlumberger, "Carbonate Reservoirs," 2007.

# Summary

- Derived key reactive-transport parameters and ranges for carbonate rocks over a wide range of heterogeneity and initial permeability
- Conducting a validation study using core from an independent $CO_2$ storage formation
- Using numerical methods to scale laboratory parameters to reservoir

# Bibliography


- Smith, M., Hao, Y., Carroll, S (2017) Development and calibration of a reactive transport model for porosity and permeability changes in carbonate reservoirs, *International Journal Greenhouse Gas Control* http://dx.doi.org/10.1016/j.ijggc.2016.12.004

- Smith, M., Sholokhova, Y., Hao Y., and Carroll, S., 2013, Evaporite caprock integrity: An experimental study of reactive mineralogy and pore – scale heterogeneity during brine – $CO_2$ exposure. *Environmental Science and Technology*, http://dx.doi.org/es3012723.

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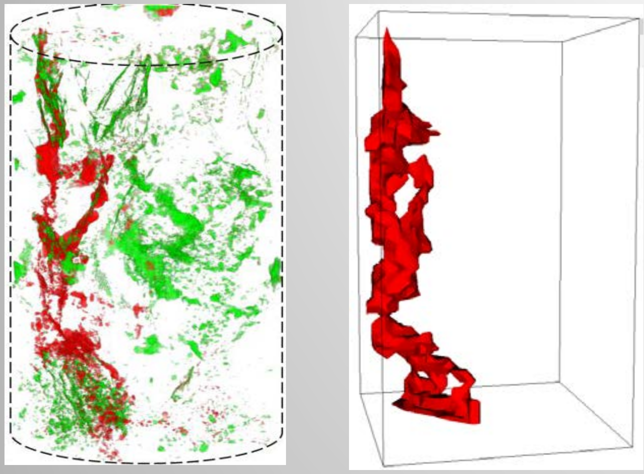
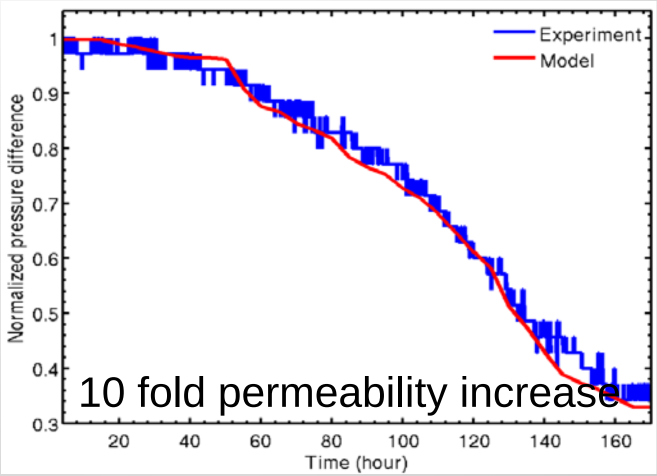
- Hao, Y., Smith, M., Sholokhova, Y., and Carroll, S. (2013) $CO_2$-induced dissolution of low permeability carbonates. Part 1: Numerical modeling of experiments, *Advances in Water Resources* http://dx.doi.org/10.1016/j.advwatres.2013.09.009

- Smith, M. Sholokhova, Y., Hao, Y., and Carroll, S. (2013) $CO_2$-induced dissolution of low permeability carbonates. Part 2: Characterization and experiments, *Advances in Water Resources* http://dx.doi.org/10.1016/j.advwatres.2013.09.008

# Permeability is enhanced through the dissolution of fracture filling carbonates

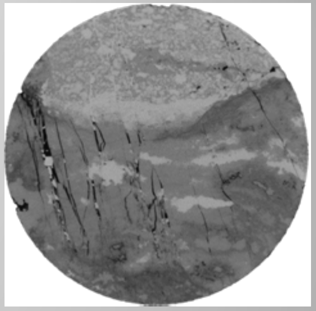


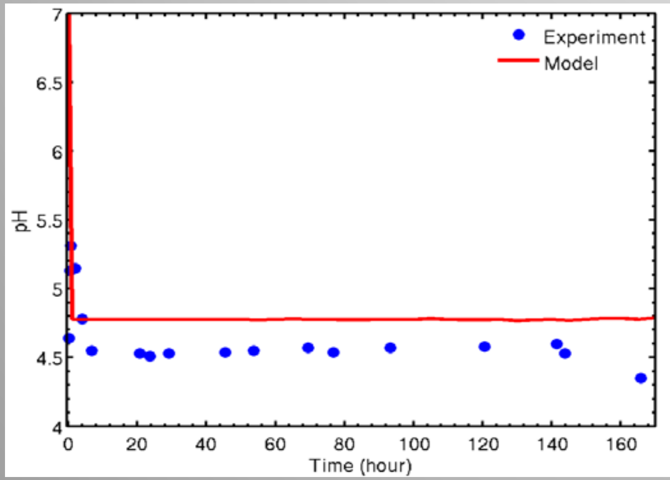
dissolution front



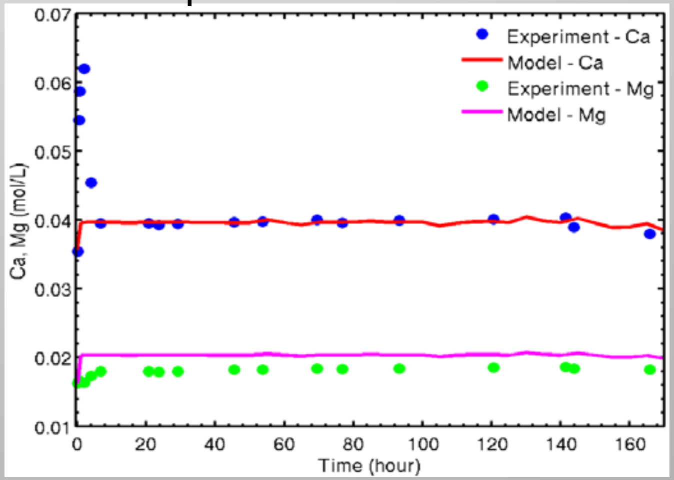

pressure difference

Injection Zone






solution chemistry (pH)




solution chemistry (Ca/Mg)