Transition of CO_2 Enhanced Oil Recovery to Carbon Storage: Experimentally Constrained Reactive Transport Model

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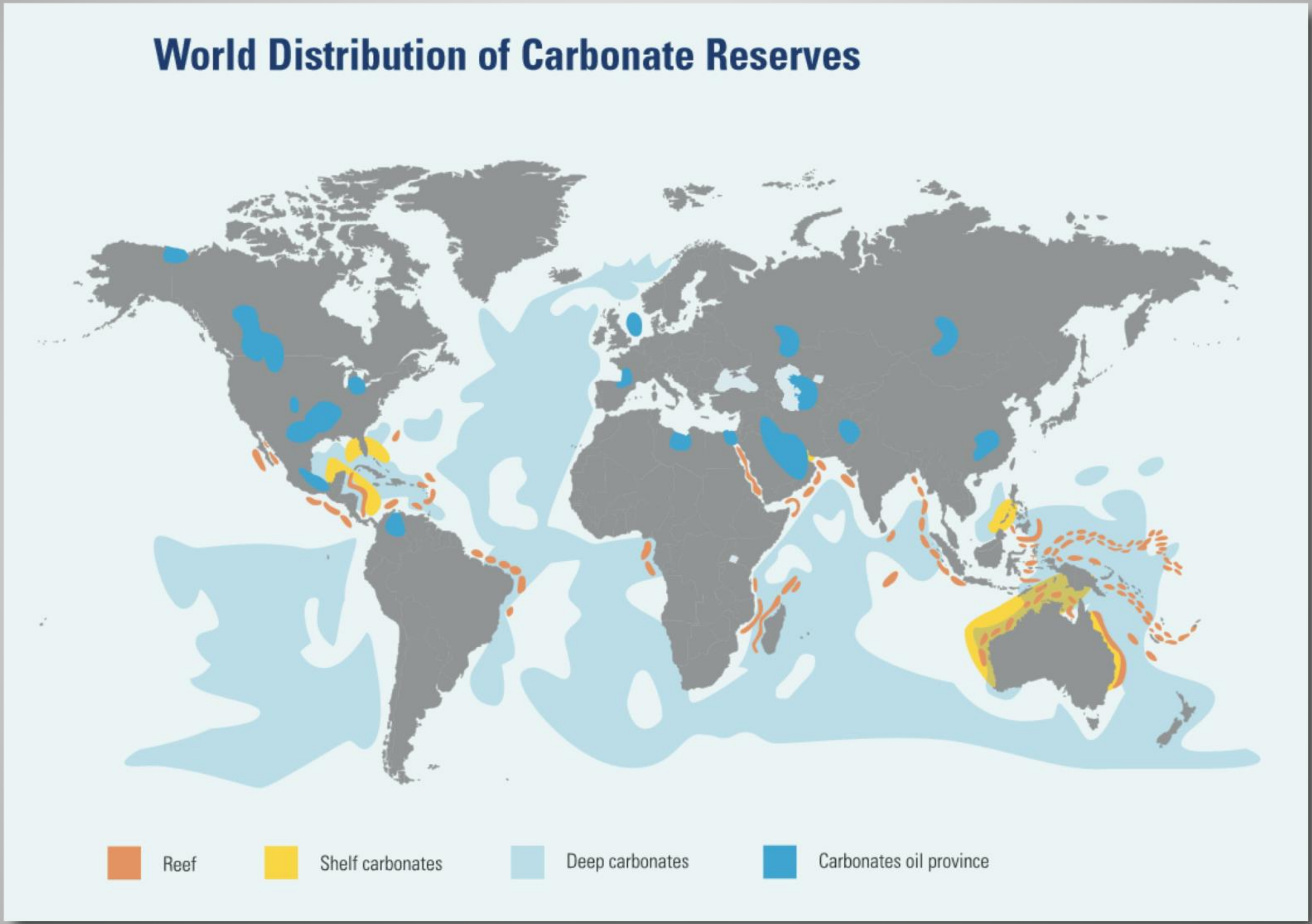
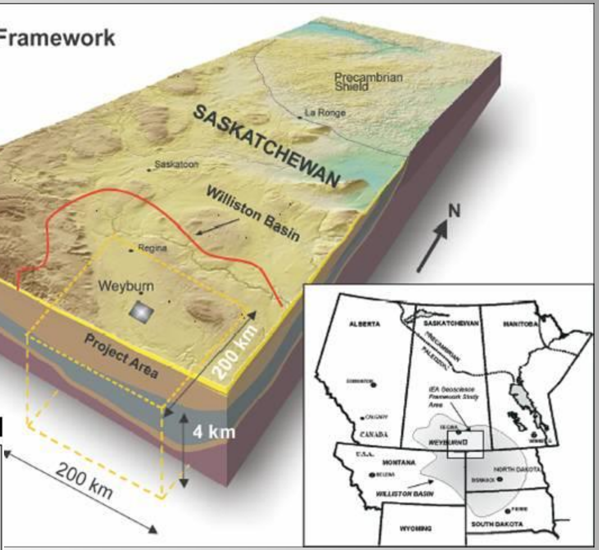


Schlumberger, “Carbonate Reservoirs,” 2007.

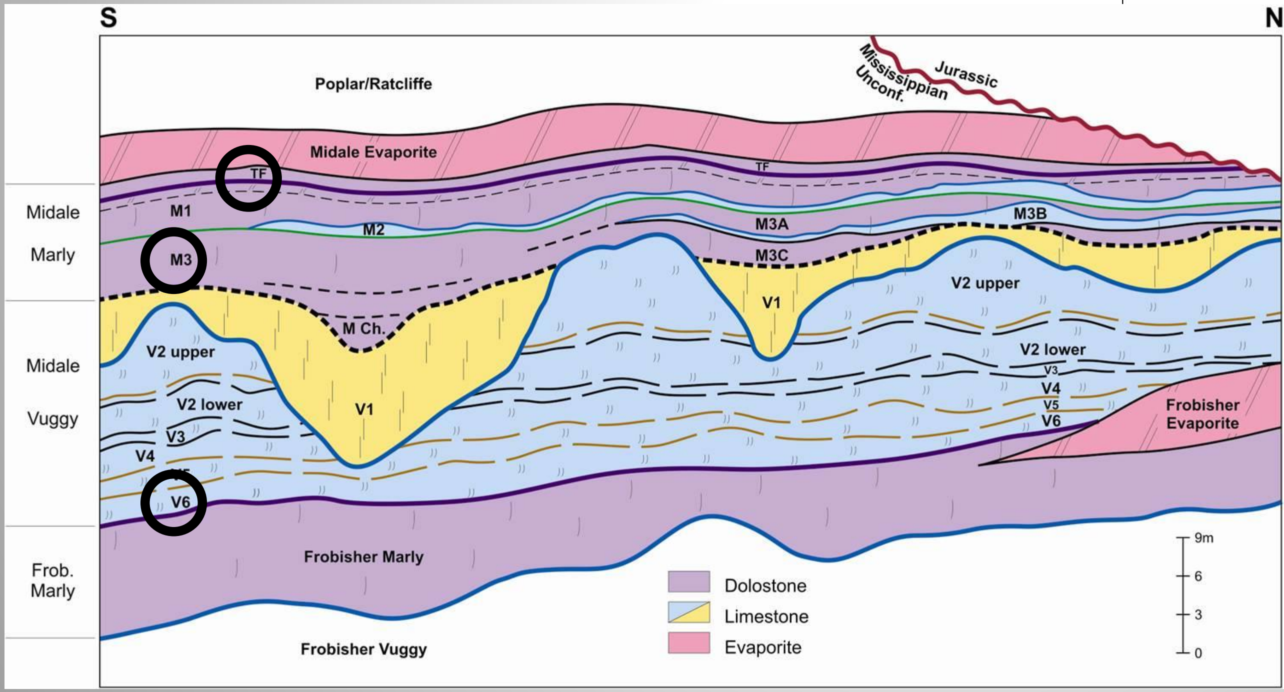
Goals and Benefits

- To quantify key relationships in reactive transport models to constrain final CO_2 storage estimates.
- To calibrate down hole logging measurement methods to estimate carbonate formation permeability.
- Our results improve prediction of changing CO_2 storage capacity in carbonate reservoirs as a consequence of enhanced oil recovery (±30%)

Weyburn Demonstration



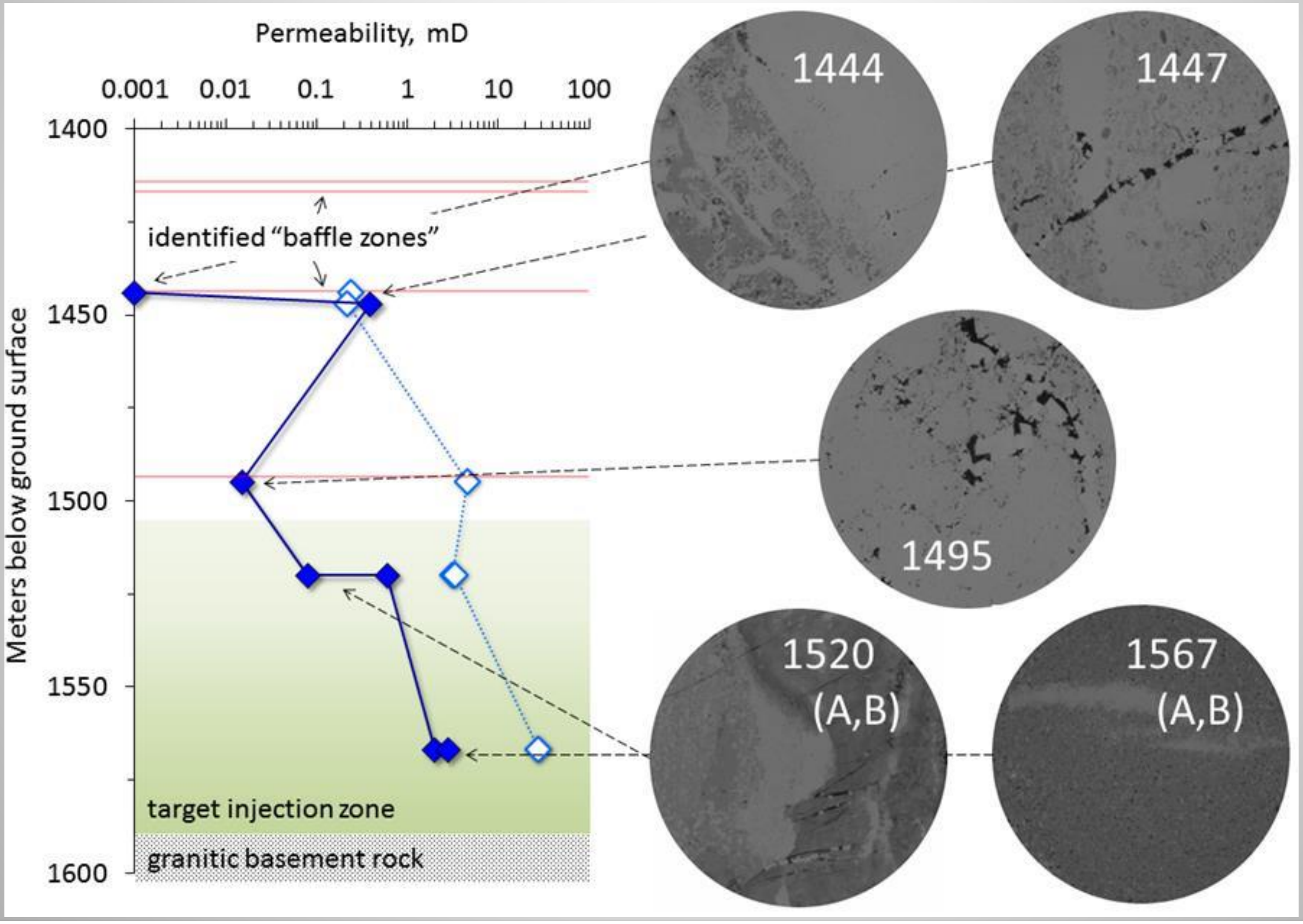
images: www.ptrc.ca



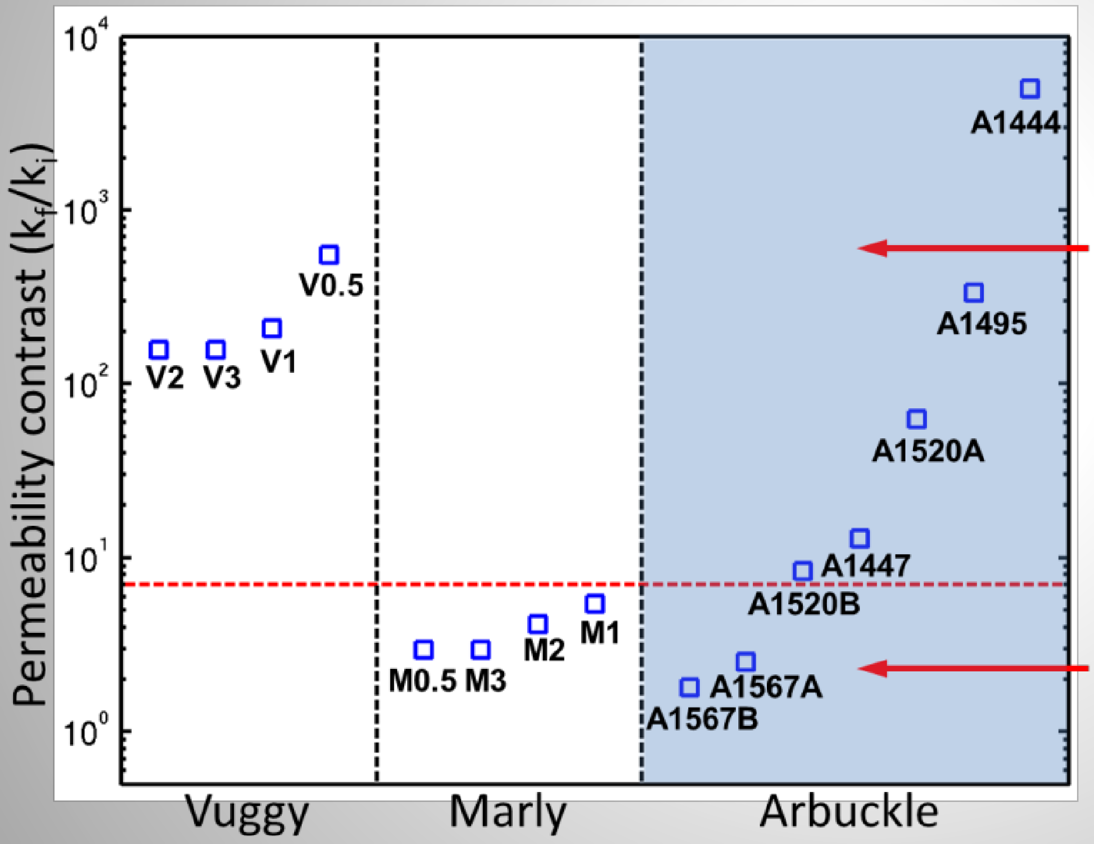
- calcite, $CaCO_3$, and
- dolomite, $(Ca,Mg)CO_3$

Wellington, Kansas Demonstration

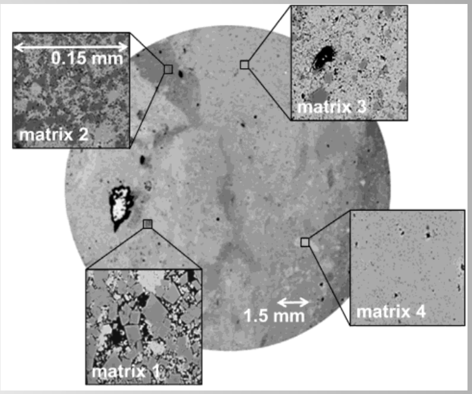
- Dolomite $(Ca,Mg)CO_3$



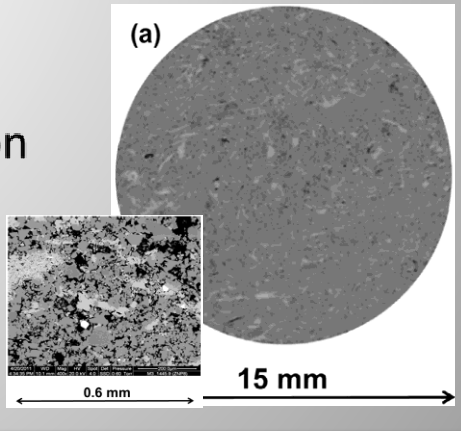
Dissolution yields preferential flow paths in more heterogeneous carbonate rocks



unstable dissolution fronts



stable dissolution fronts



Dissolution yields preferential flow paths in more heterogeneous carbonate rocks

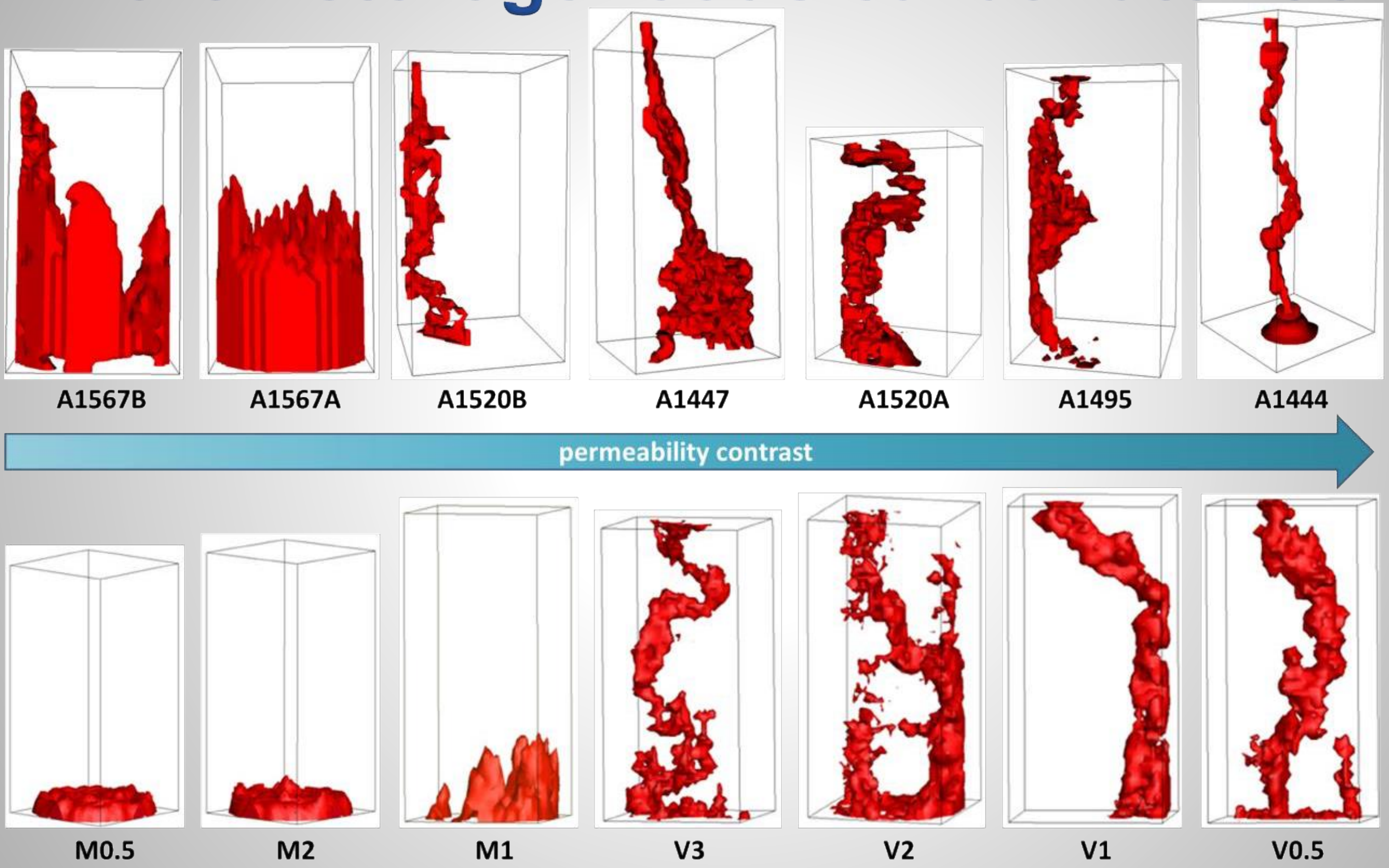
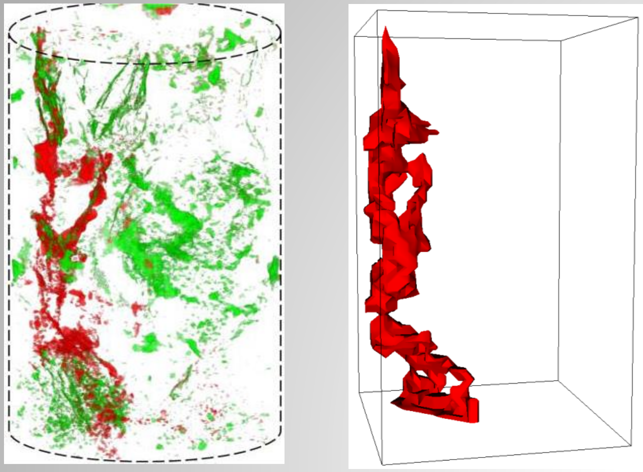
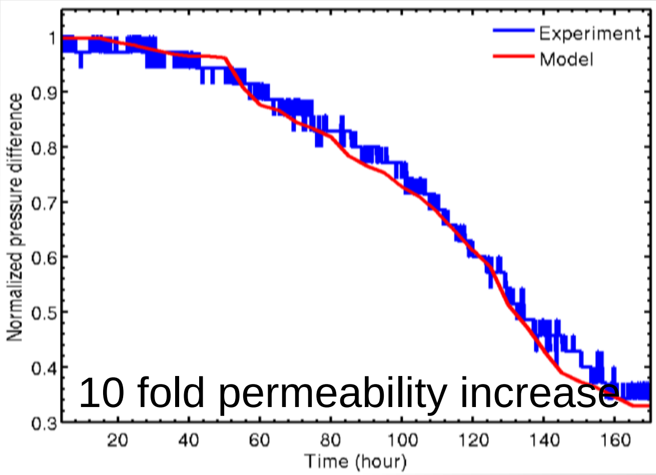


Figure 12: Qualitative correlation between permeability contrast (k_f/k_i, increasing towards the right) and evolution of dissolution patterns from stable to less stable.

Model parameters are constrained by characterization, pressure, and solution data



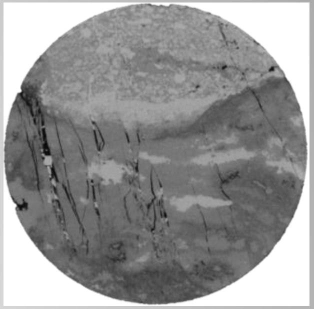
dissolution front

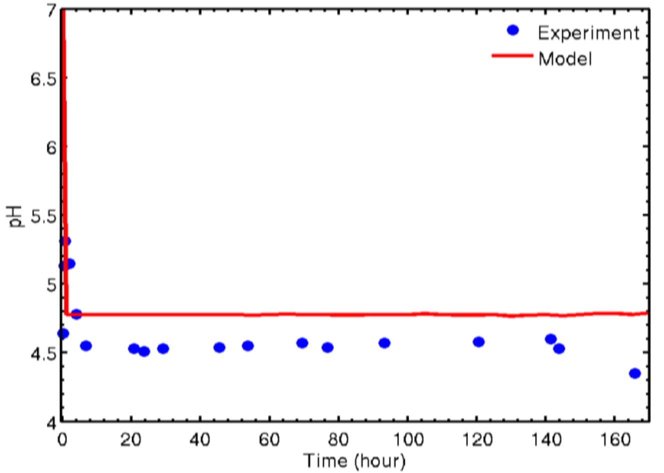


10 fold permeability increase

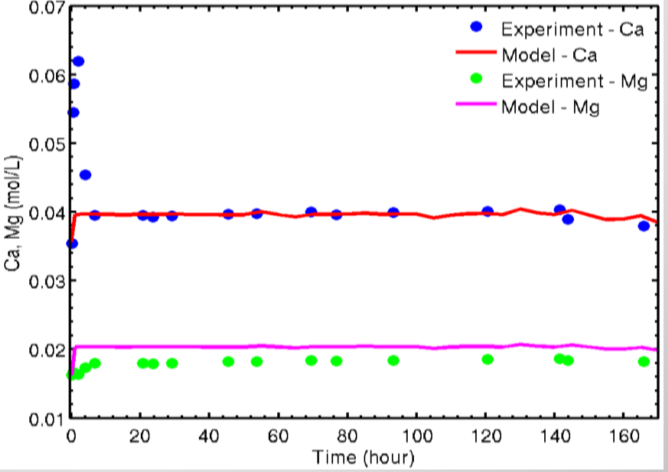
pressure difference

Injection Zone





solution chemistry (pH)



solution chemistry (Ca/Mg)

Reactive Transport Model

Reactions
calcite + H^+ = Ca^{++} + HCO_3^-
dolomite + $2H^+$ = Ca^{++} + Mg^{++} + $2HCO_3^-$
$CO_{2(aq)}$ + H_2O = H^+ + HCO_3^-
$MgHCO_3^+$ = Mg^{++} + HCO_3^-
$CaCO_{3(aq)}$ + H^+ = Ca^{++} + HCO_3^-
$CaHCO_3^+$ = Ca^{++} + HCO_3^-

Mineral Reaction Rates

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

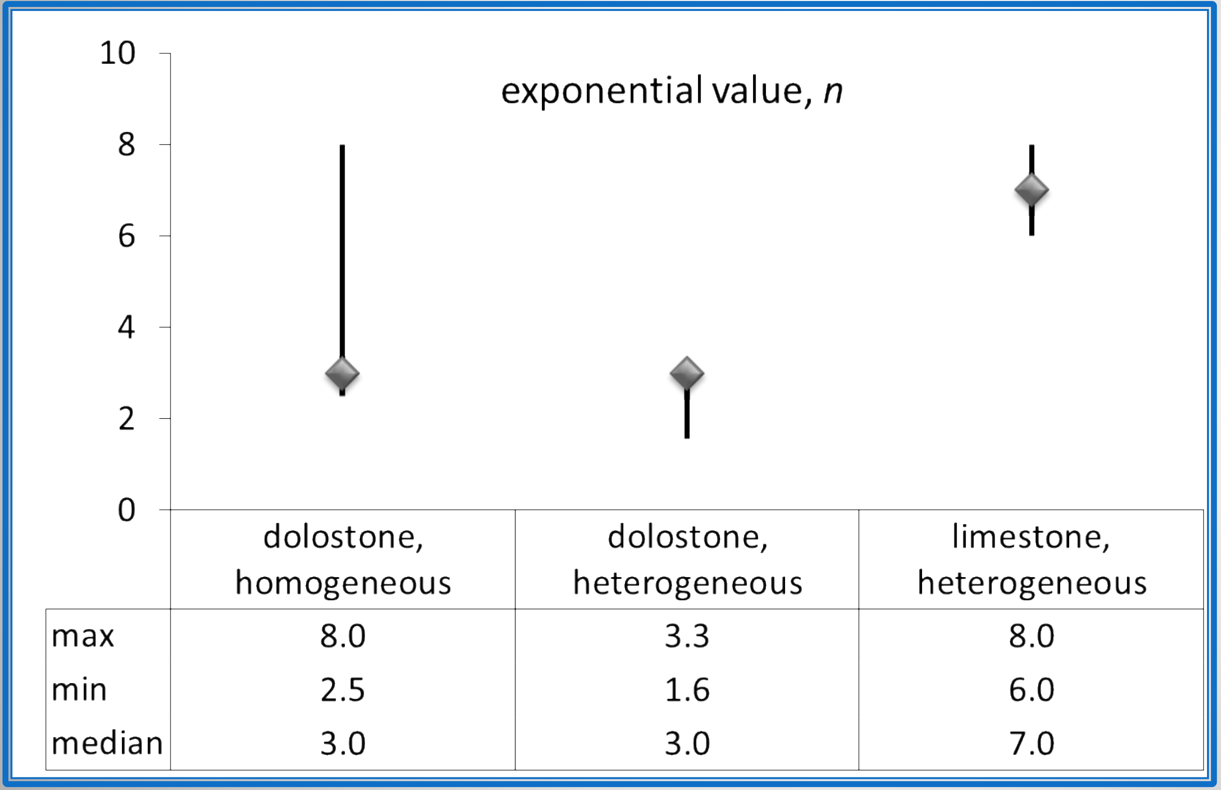
Permeability-Porosity n – best fit

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

Surface Area-Porosity m – 2/3

$$S_t = S_0\left(\frac{\theta_t}{\theta_0}\frac{\phi_t}{\phi_0}\right)^m$$

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

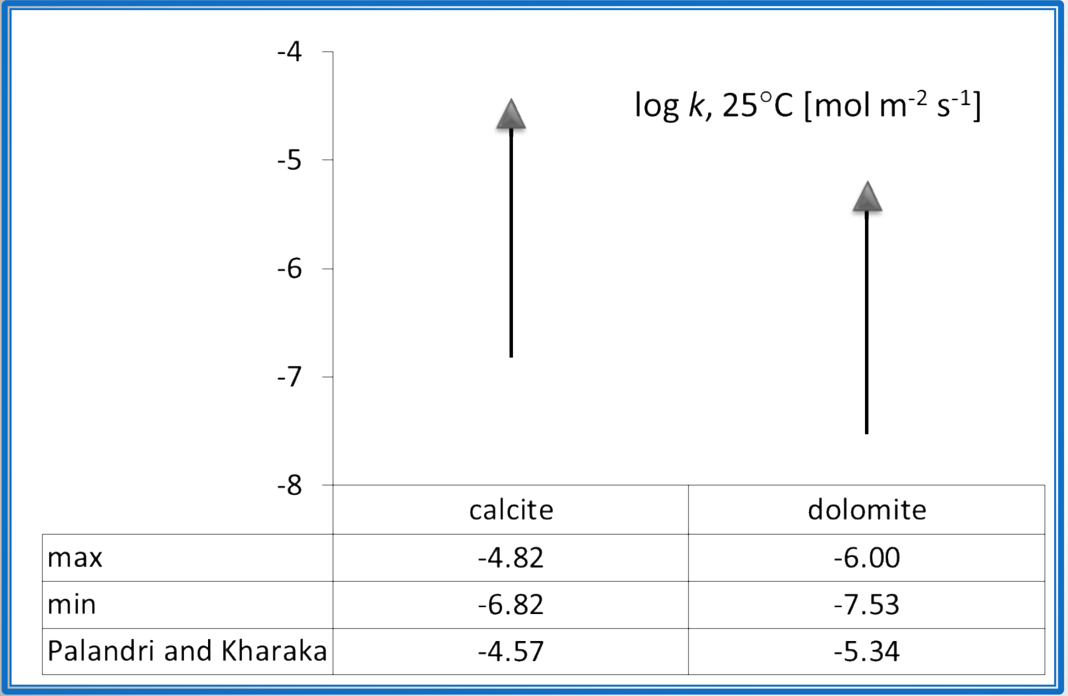


	dolostone, homogeneous	dolostone, heterogeneous	limestone, heterogeneous
max	8.0	3.3	8.0
min	2.5	1.6	6.0
median	3.0	3.0	7.0

Greater permeability change with limestone

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

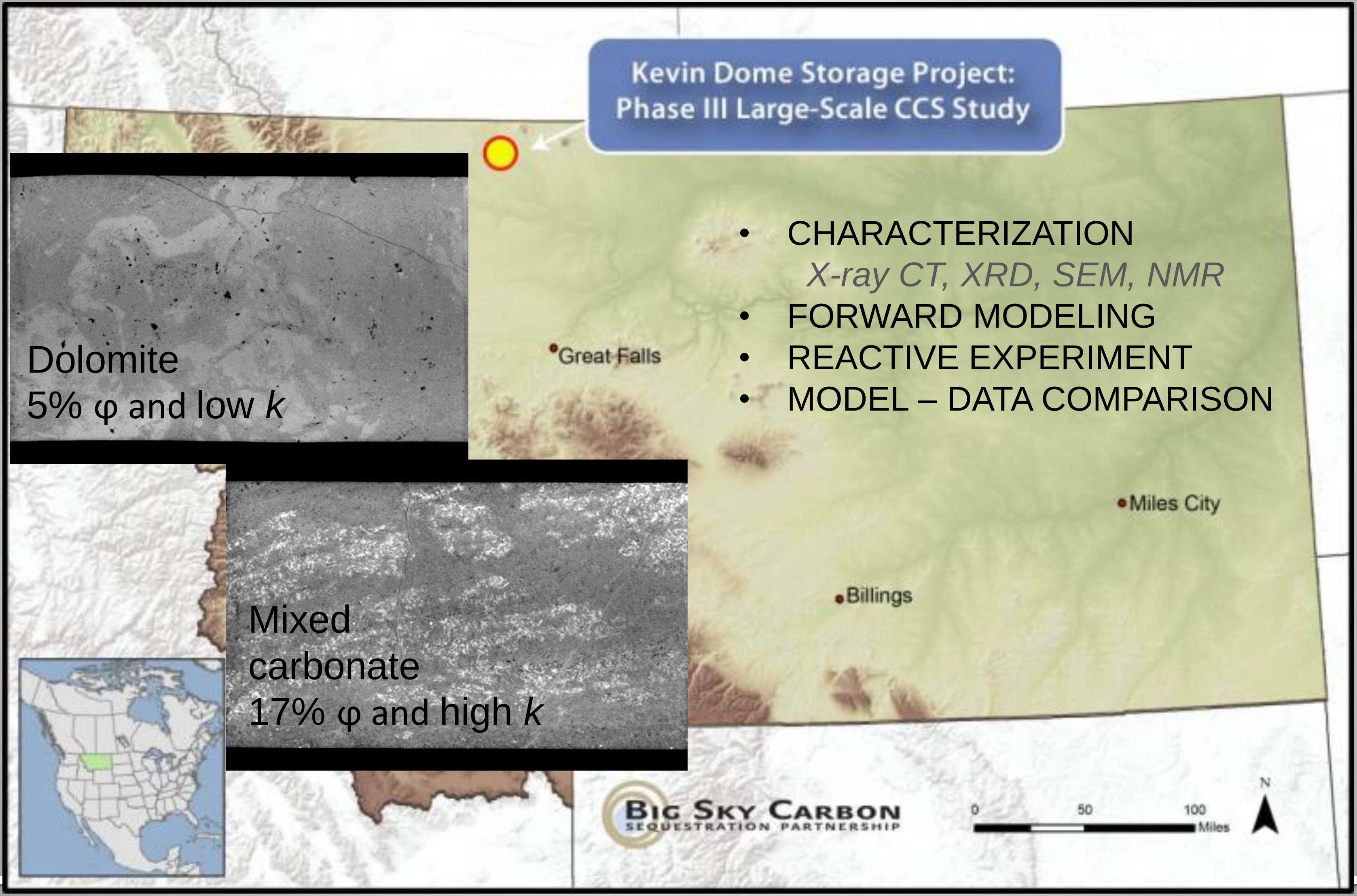
Mineral dissolution rates vary by 100 times and may require calibration of reactive surface area



	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

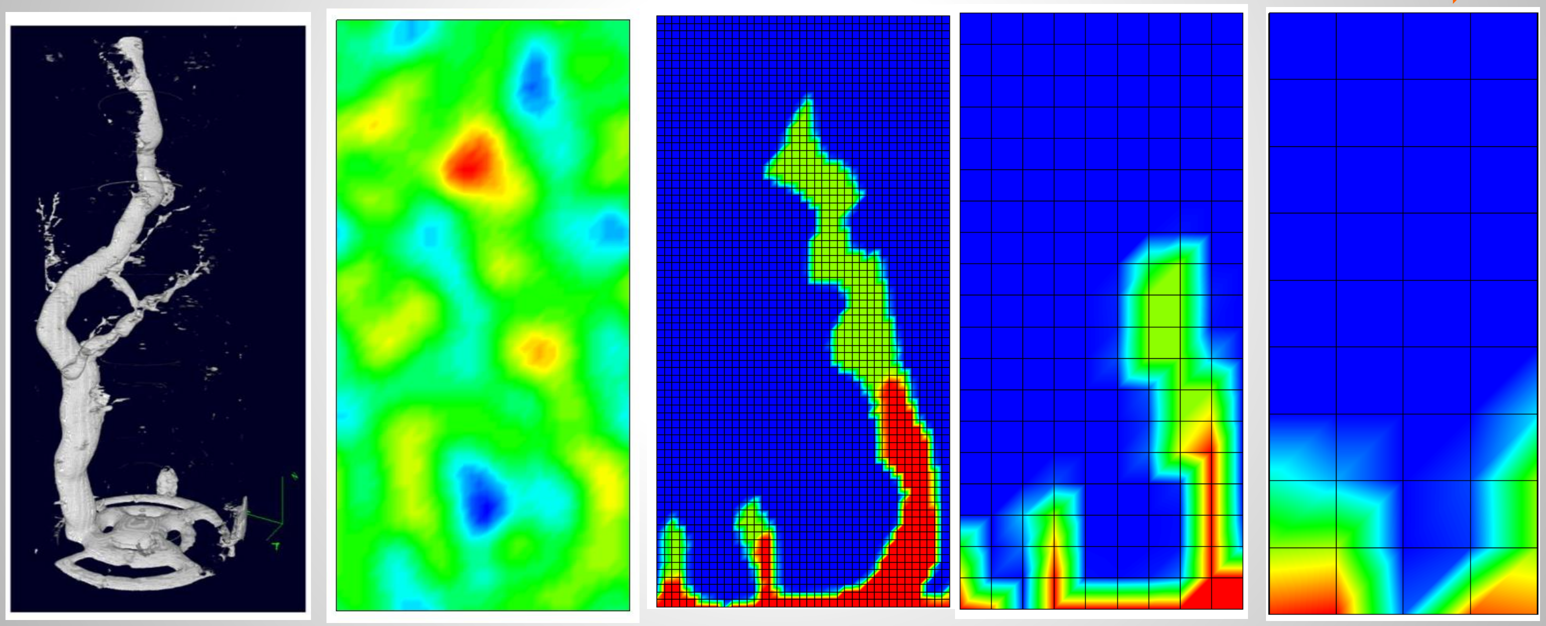
How do you scale lab experiments to the field?

Larger grid size reduces the permeability change

Initial porosity: 0.2
bulk permeability: 0.32 mD

Increase the grid area by 64

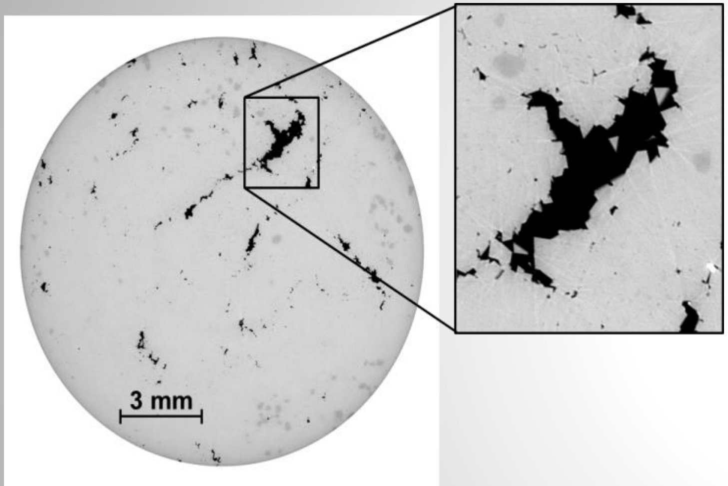
Decreases permeability change



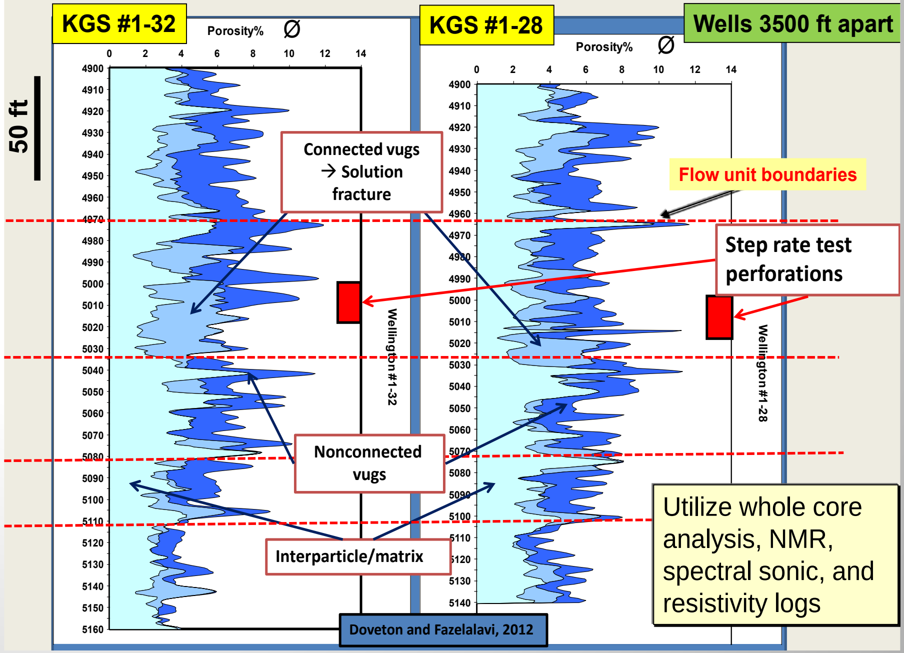
150% **100%** **50%**

bulk permeability increase

Calibration of down hole logs to better estimate variable permeability with depth in carbonate reservoirs



Flow Units in the **Lower Arbuckle Injection** Zone, ~4900-5160 ft
Gasconade Dolomite to Gunter Sandstone



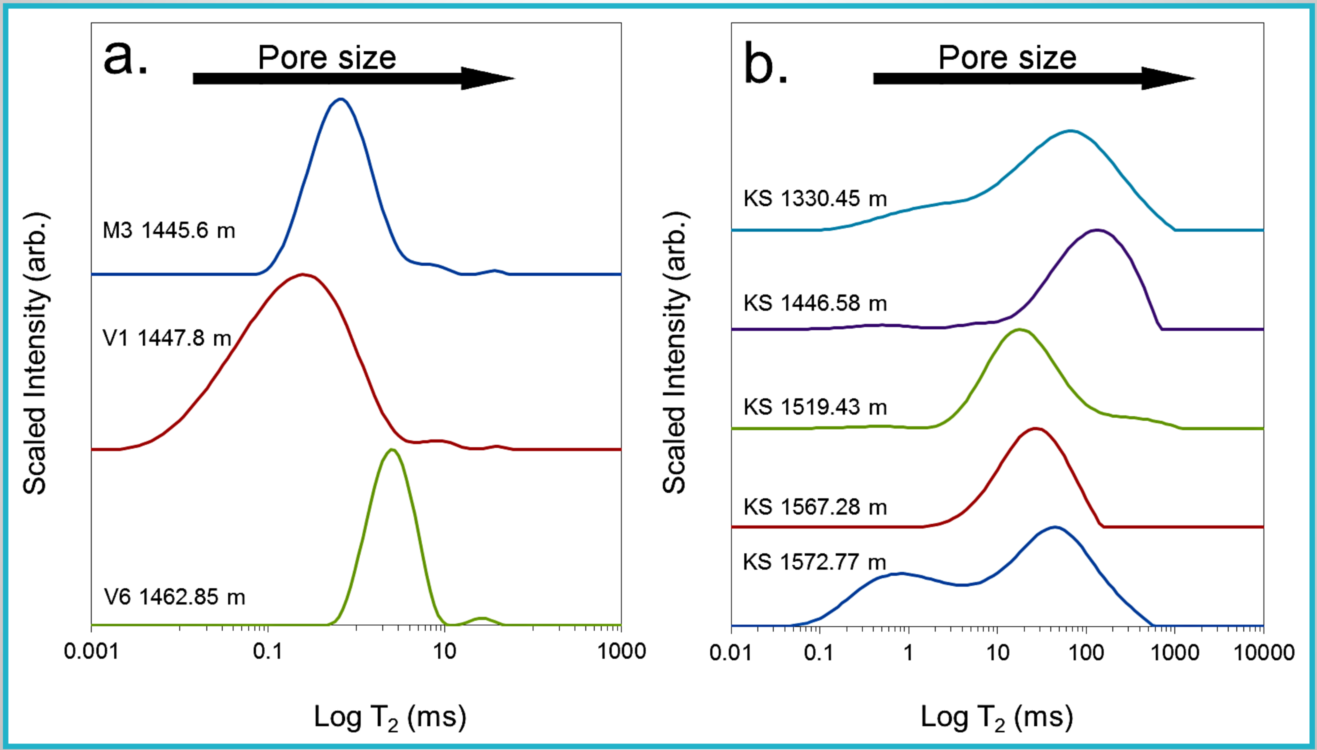
Utilize whole core analysis, NMR, spectral sonic, and resistivity logs

Doveton and Fazelalavi, 2012

NMR signal can be used to estimate down hole permeability

Weyburn,

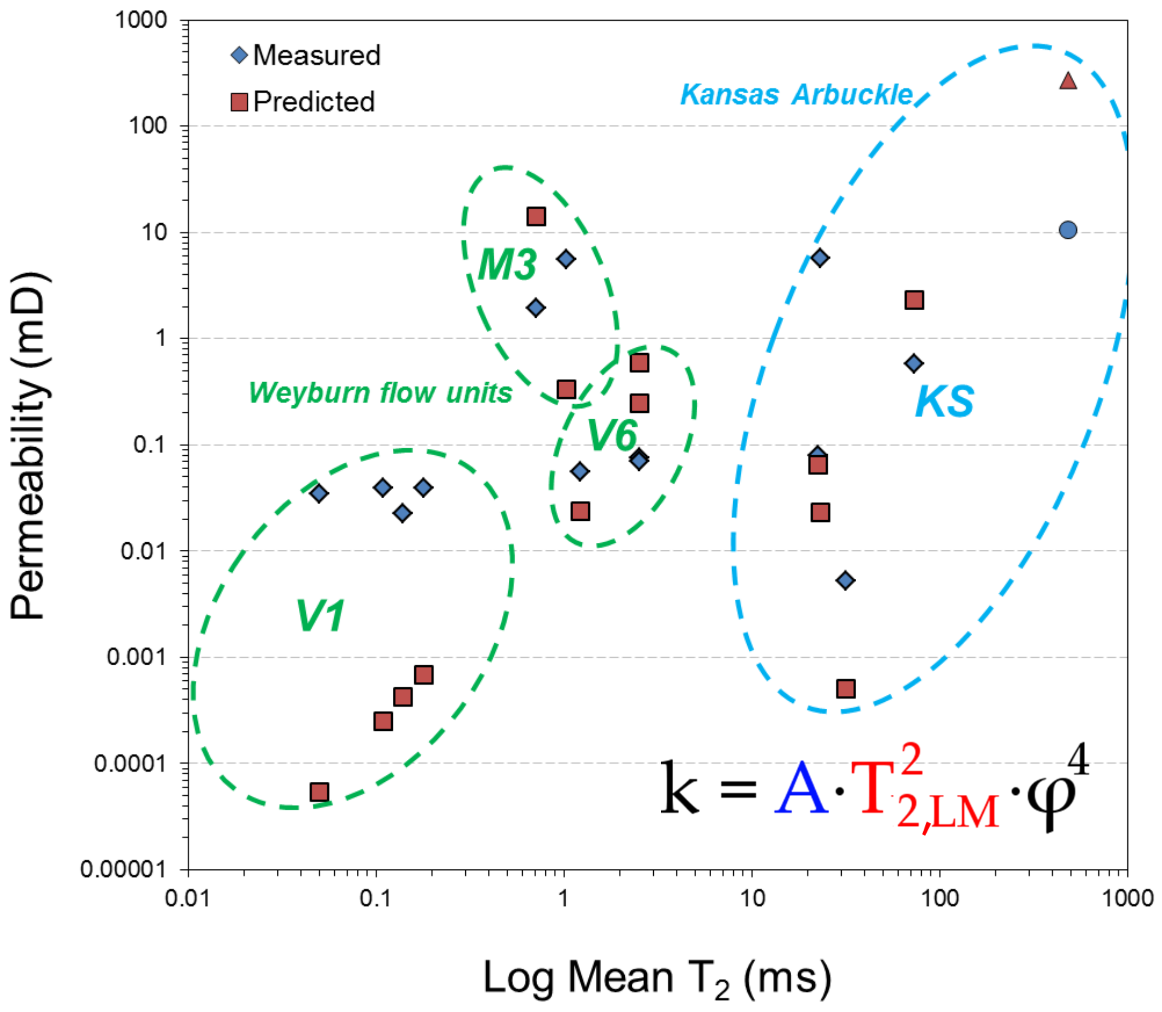
Wellington, Kansas



$$k = A \cdot T_{2,LM}^{2} \cdot \varphi^{4}$$

(Schlumberger Doll Research)

Predicted permeability differs by orders of magnitude using standard value of ***A***



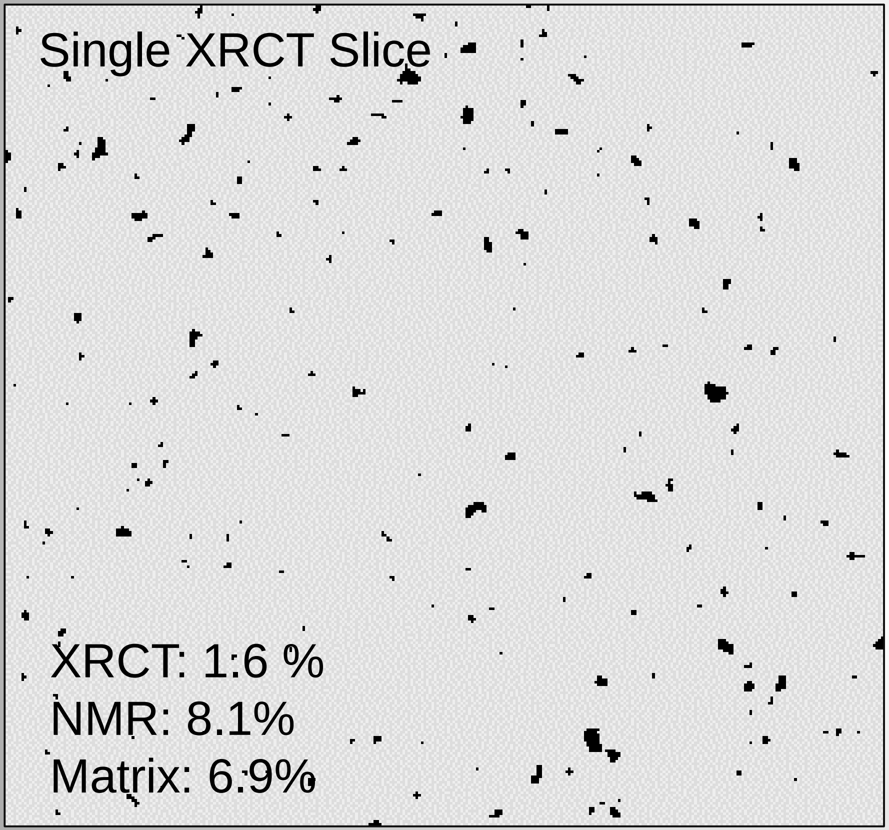
$$k = A \cdot T_{2,LM}^{2} \cdot \varphi^{4}$$

Calibrate $A = \frac{\rho^2}{\varphi^3 \upsilon \tau^2}$ using independent measures

- φ : porosity (*Nuclear Magnetic Resonance*)
- ν : pore shape factor (*2.5 for elliptical pores*)
- τ : tortuosity (*X-Ray Tomography, Nuclear Magnetic Resonance*)
- ρ : surface relaxivity (*Calibrated Nuclear Magnetic Resonance*)

Daigle and Dugan JGR 2011

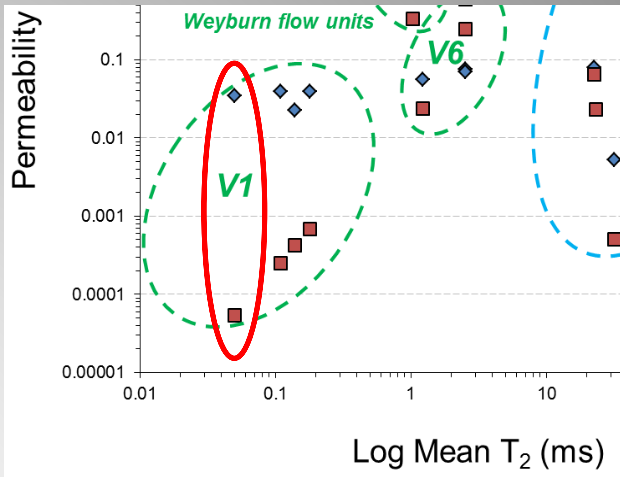
Tortuosity (τ) is extracted from high resolution tomography images and the NMR porosity



$$A = \frac{\rho^2}{\varphi^3 \upsilon \tau^2}$$

- Matrix porosity assessed by difference between XRCT and NMR porosity
- Use a random walk algorithm to extract tortuosity from segmented pore network

Test – Initial estimates of caprock-like permeability from SDR equation and standard A is due to high Fe concentrations



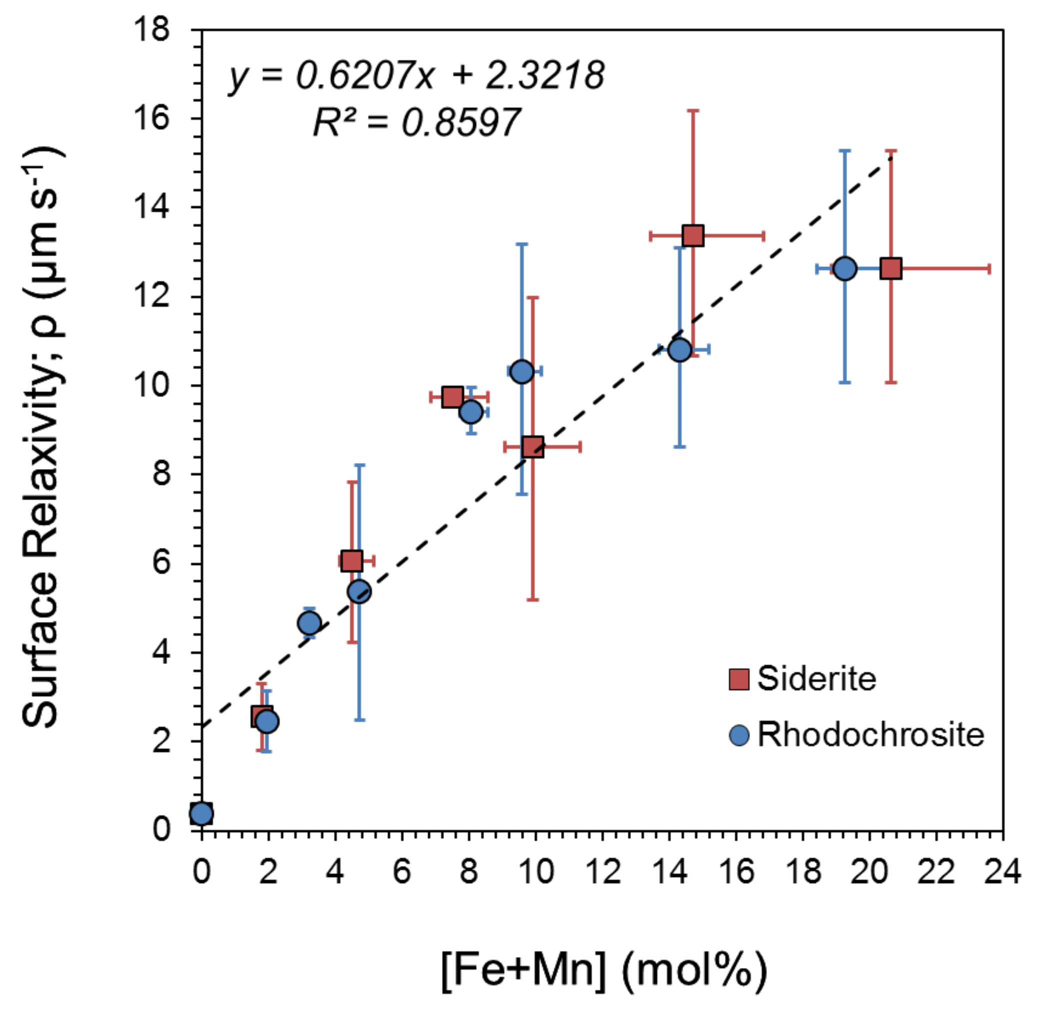
- Solve for A = 5.33×10^{-09} m^2/s^2
- NMR Porosity; $\varphi = 21.7\%$
- NMR – $T_{2,LM}$
- Measured Permeability; k = 0.027 mD

$$k = A \cdot T_{2,LM}^{2} \cdot \varphi^{4}$$

- Solve for Relaxivity; $\rho = 65.6$ μm/s
  - Standard for carbonates is 2 μm
  - Reflects high paramagnet content
- NMR Porosity; $\varphi = 21.6\%$
- XRCT Tortuosity; $\tau = 3.53$ m/m
- Pore shape factor; $\upsilon = 2.5$ m^2/m^2
  - elliptical pores
  - could be refined with XRCT data

$$A = \frac{\rho^2}{\varphi^3 \upsilon \tau^2}$$

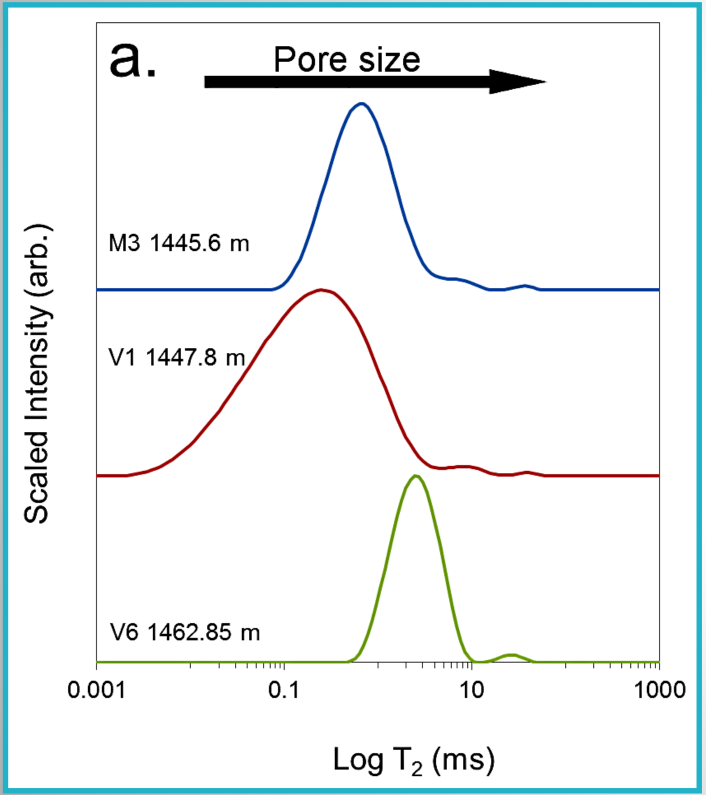
Surface relaxivity (ρ) depends on mineralogy and Mn and Fe content



But ρ cannot resolve difference between estimated and measured permeability

$$A = \frac{\rho^2}{\varphi^3 \upsilon \tau^2}$$

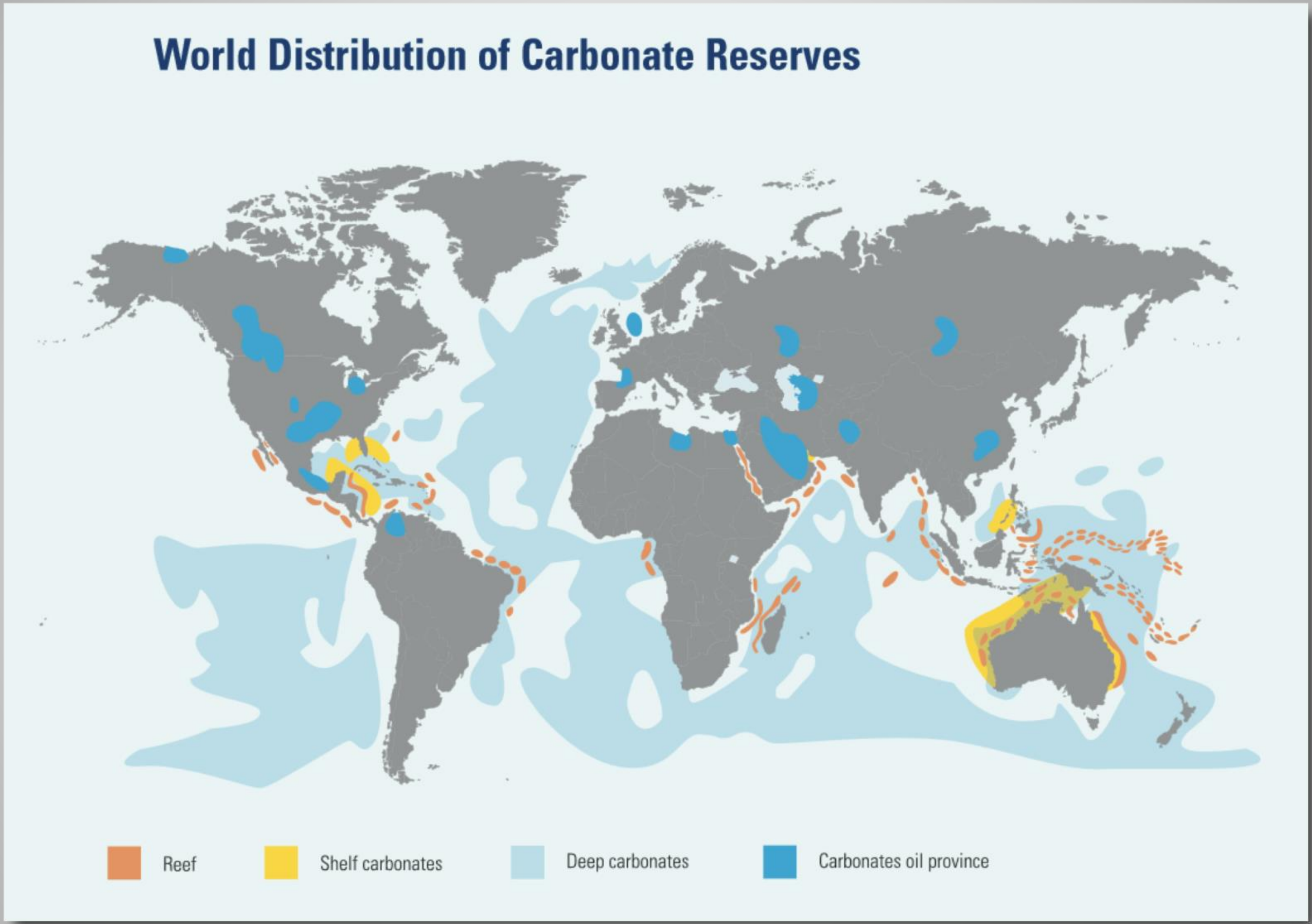
Next steps in the calibration



$$k = A \cdot T_{2,LM}^{2} \cdot \varphi^{4}$$

$$A = \frac{\rho^2}{\varphi^3 \upsilon \tau^2}$$

- Measure the Fe/Mn content for all samples
- Conduct a sensitivity study of the parameters and power functions



Schlumberger, “Carbonate Reservoirs,” 2007.

Synergy

- Weyburn-Midale Carbon Storage Demonstration
- Wellington, Kansas Carbon Storage Demonstration
- Big Sky Carbon Storage Demonstration

Summary and Future Plans

- Derived key reactive-transport parameters and their 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
- Developing a protocol for calibrating the NMR signal to provide meaningful in-situ permeability measurements
- Using numerical methods to scale laboratory parameters to reservoir
- Write final topical report on CO_2 storage potential in carbonate rocks.

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