

US EPA ARCHIVE DOCUMENT

Risks Posed by Brines Containing Dissolved CO₂

Ron Falta¹, Larry Murdoch¹, and Sally Benson²

Catherine Rupecht¹, Lin Zuo², Kirk Ellison¹, Chris Patterson¹,
Shuangshuang Xie¹, Miles Atkinson¹, Laura Daniels¹, Qi Zheng¹

¹Clemson University

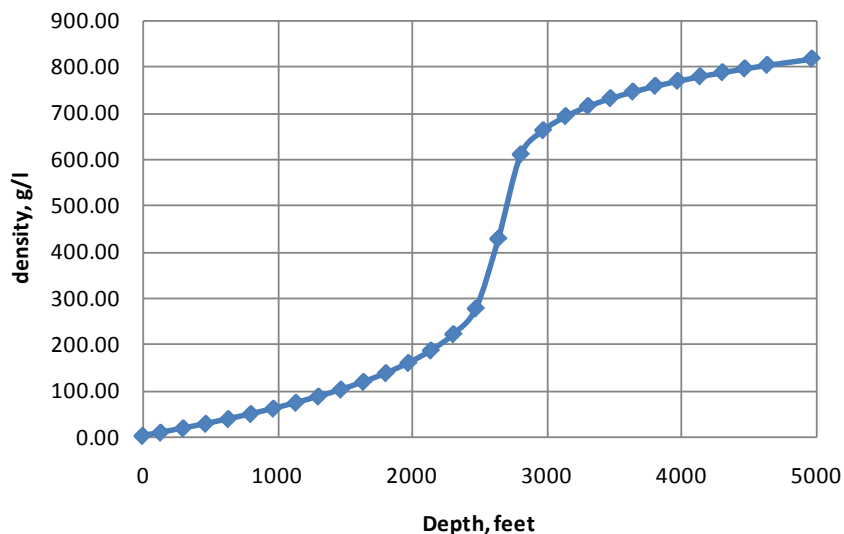
²Stanford University

January 7, 2013

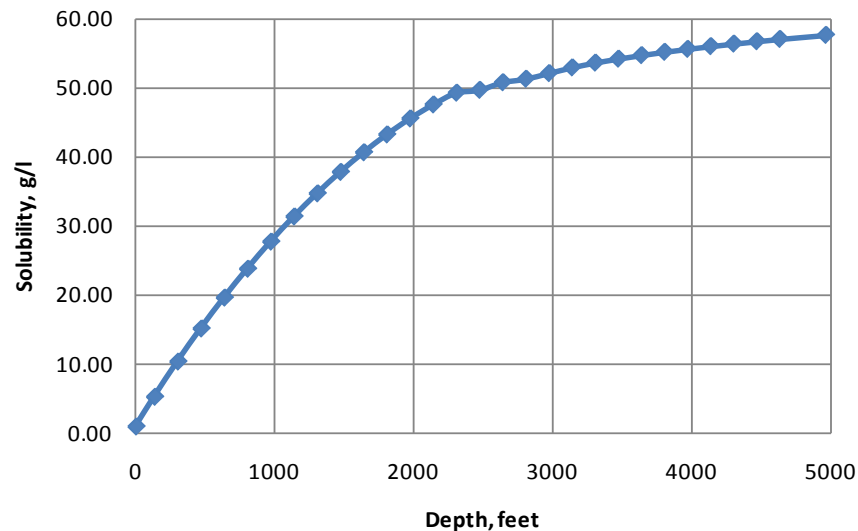


CO₂ Density and Solubility with Depth

CO2 Phase Density



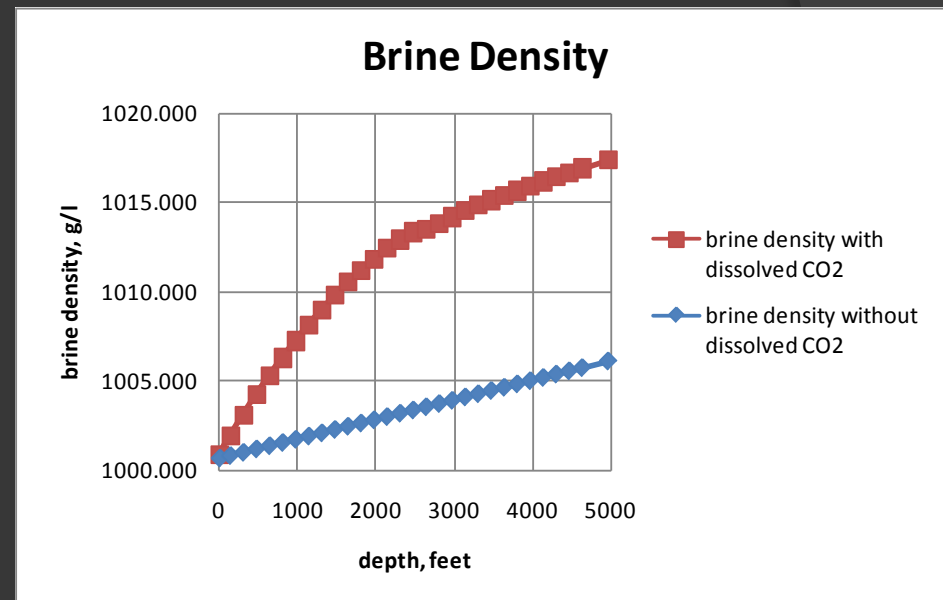
CO2 Solubility



Calculated using TOUGH2-ECO2N assuming 35° C and 10,000 mg/l NaCl

The high CO₂ solubility is significant

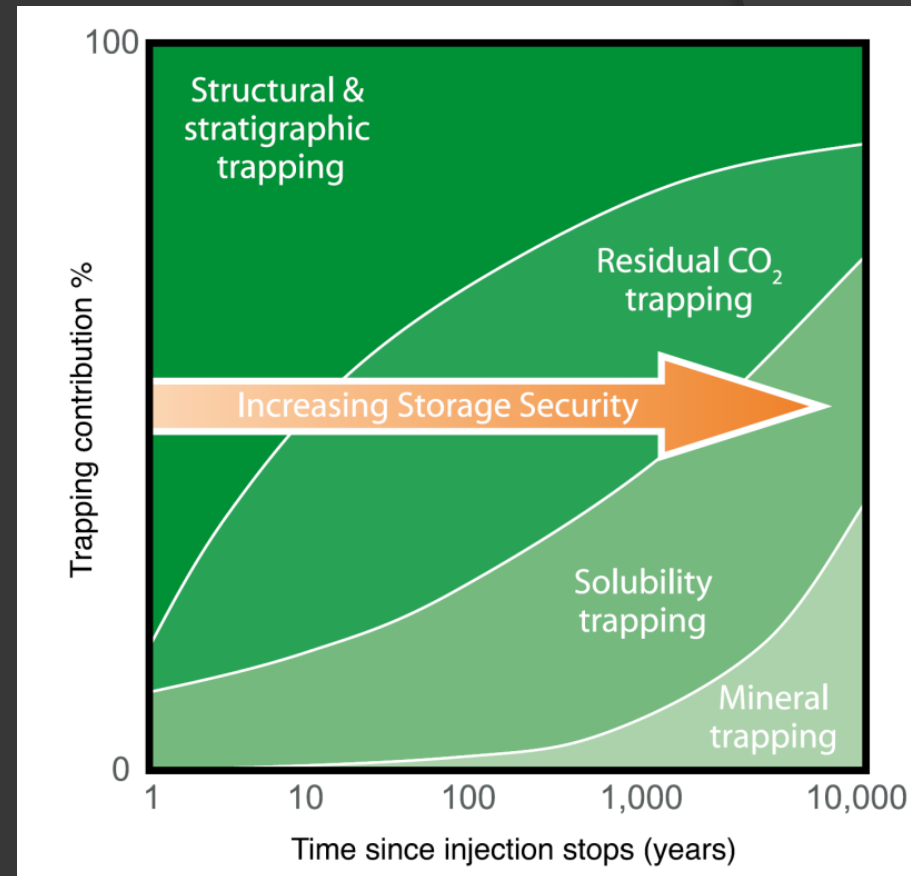
- At 3000 ft depth, we get ~50 g/l (50 times more CO₂ than beer!)
- When CO₂ dissolves, the aqueous phase becomes more dense (about 1% here)
- Upward flow would require a caprock defect, and an upward hydraulic gradient > density difference



Calculated using TOUGH2-ECO2N

The Dissolved CO₂ is Secure – Or Is It?

- Solubility trapping – CO₂ dissolves in pore water (up to 60 g/l)
- Density increase favors downward flow of CO₂ saturated brine
- Upward flow would require a caprock defect, and an upward hydraulic gradient > 1%
- **However, if a CO₂ saturated brine moved upward, the CO₂ would come out of solution (exsolve), leading to a potentially mobile gas phase**



IPCC, 2005

Outline

⊙ Experiments

- Pore
- Core
- Relative permeability

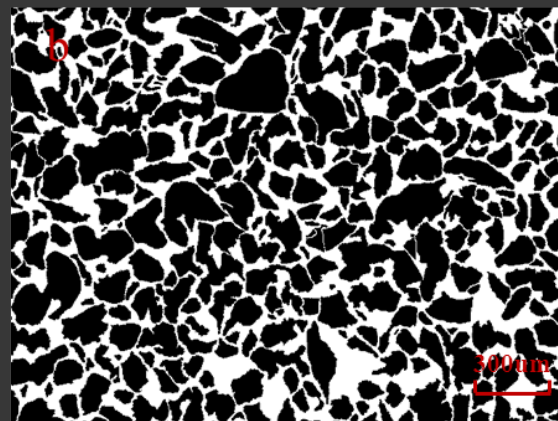
⊙ Modeling

- Fault
- Wells
- Dissolved and supercritical injection
- Outcrop

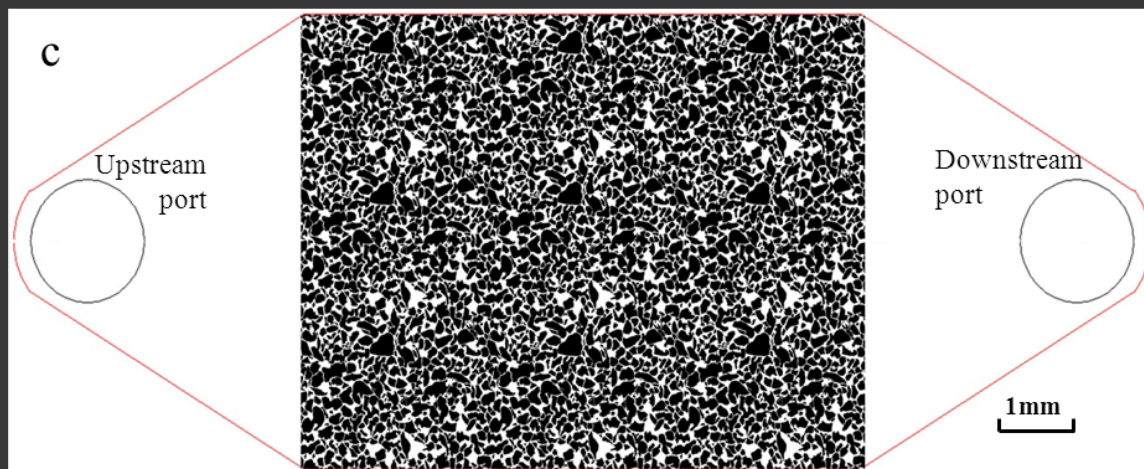
Laboratory Micromodel Study

(Zuo, Zhang, Falta, and Benson, AWR, 2013)

Thin section
micrograph
of Mt.
Simon
sandstone



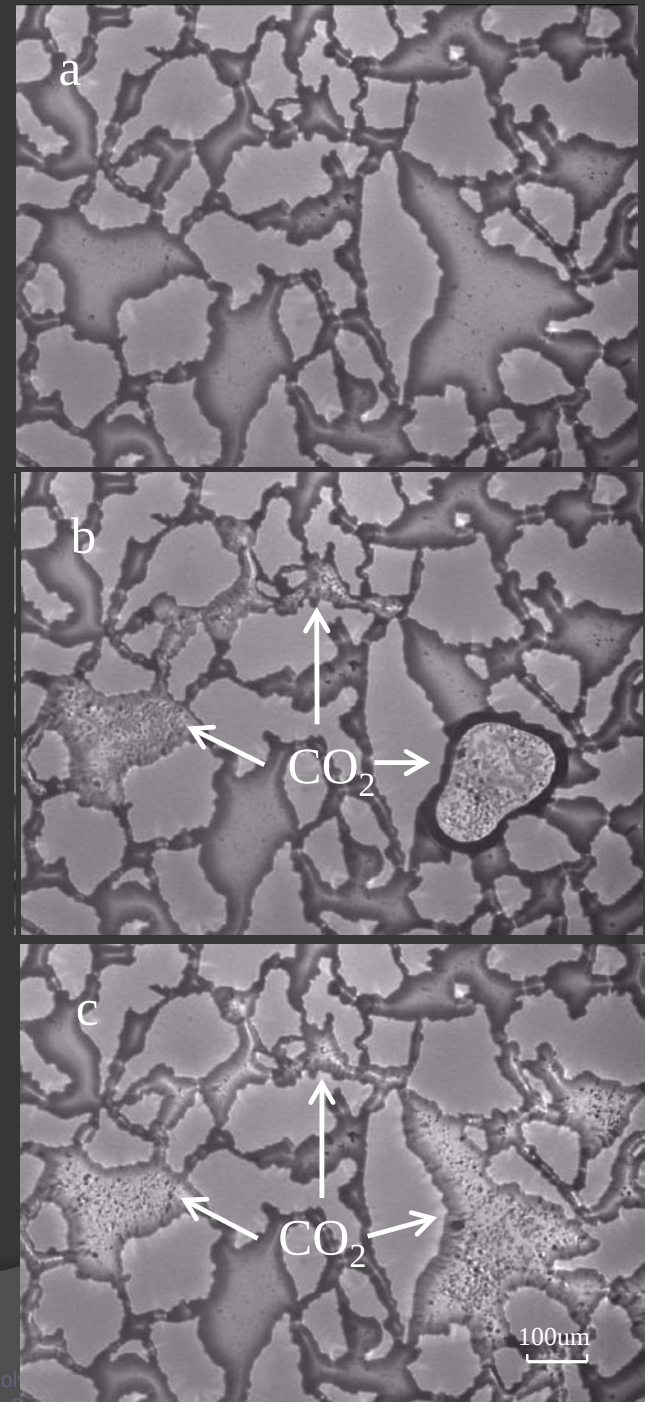
Binary
image used
for
micromodel



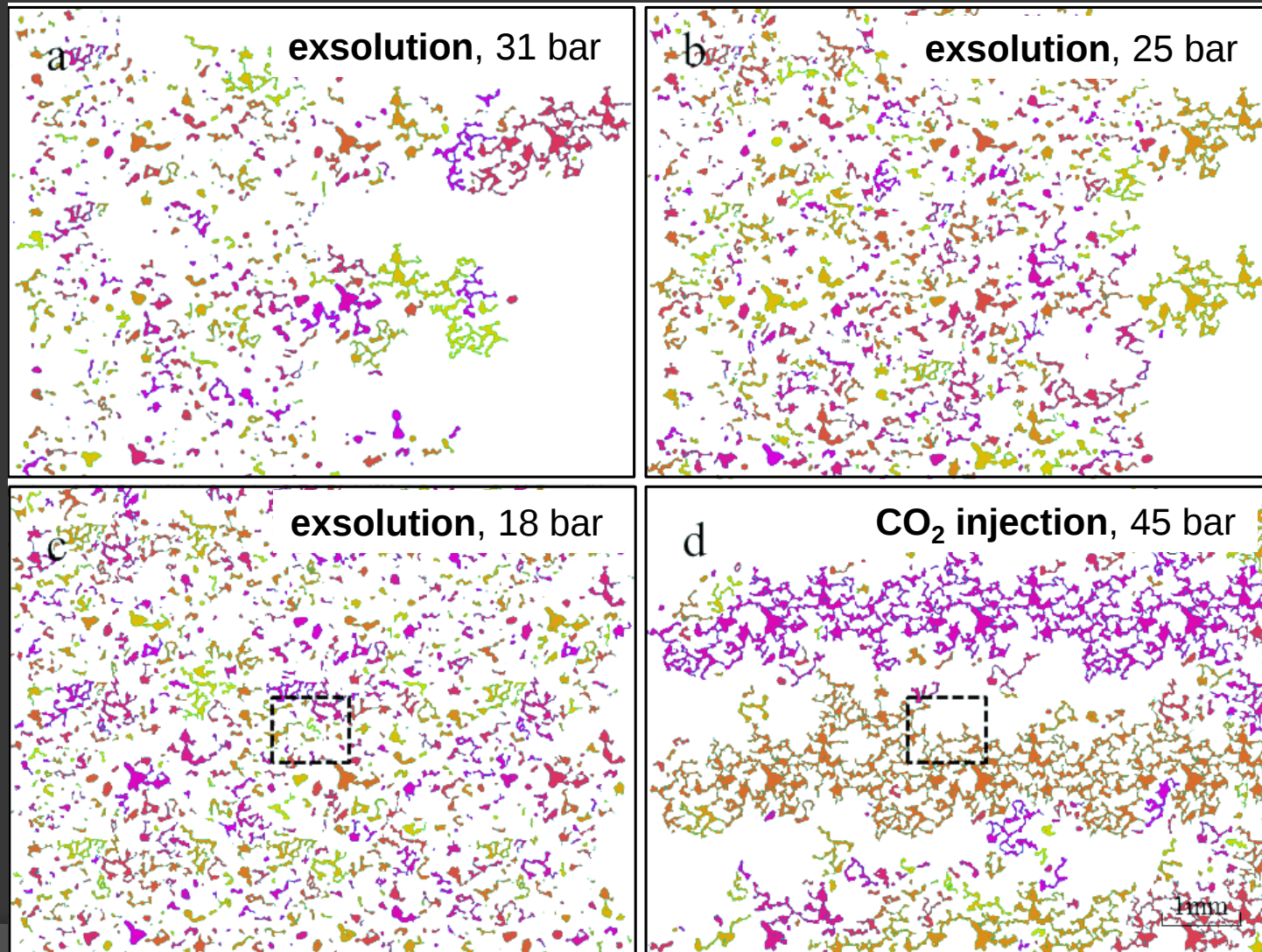
Micromodel: 530 mD; PV=1.35 μ L

Micromodel

- Initially fill micromodel with water saturated with dissolved CO_2 at 90 bars, 45 °C
- Depressurize at a rate of 10 bars/hr
- Images taken at 1 second intervals after onset of exsolution at 31 bars
- CO_2 first starts to flow out at 23.5 bars, with a CO_2 phase saturation of 56%

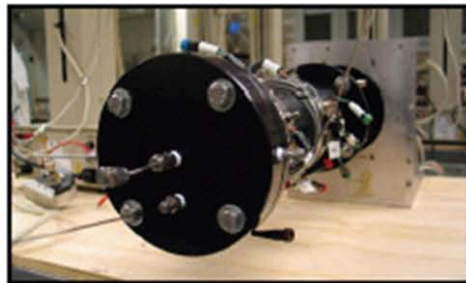


Comparison of Exsolution and Supercritical CO₂ Injection

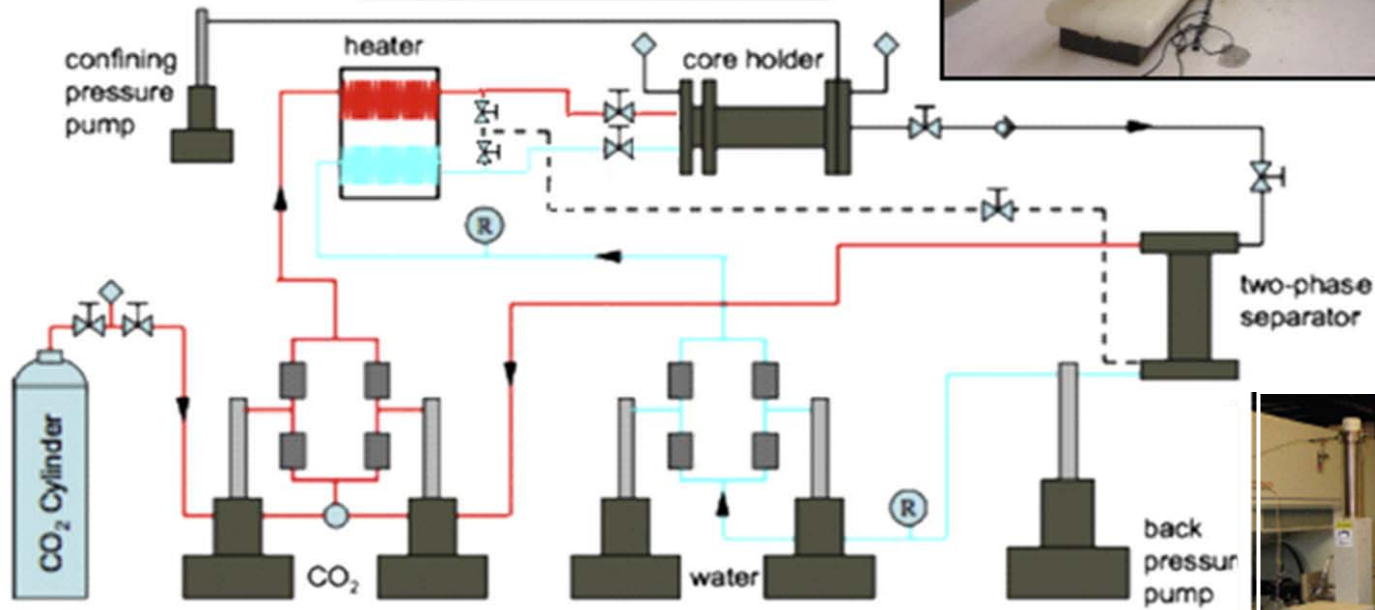


Core Scale Experimental Setup

Core Holder



CT Scanner



Dual-pump System

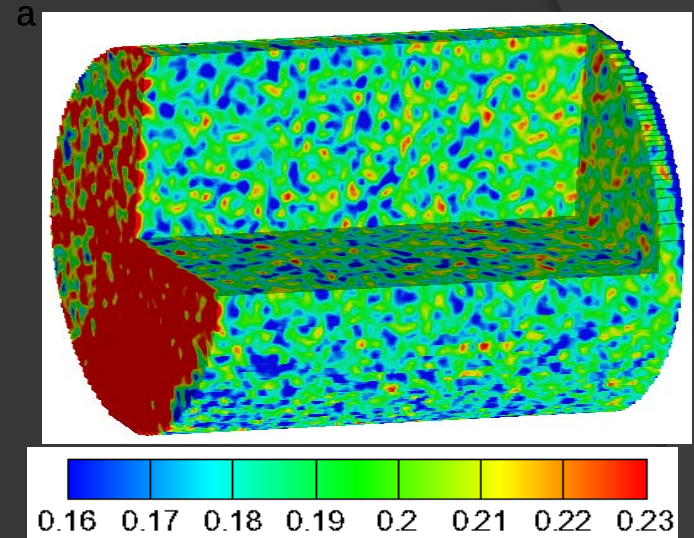
Core Experiments

Mobility of exsolved gas

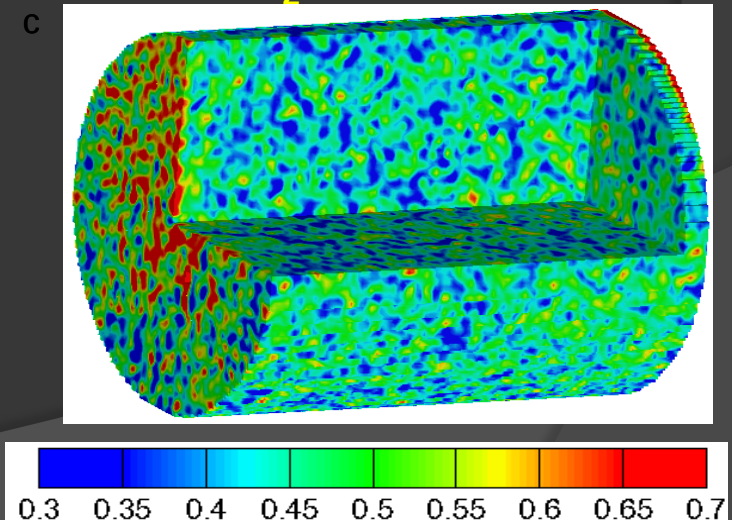
(Zuo, Krevor, Falta, and Benson, TIMP, 2012)

- Fill core with CO₂ saturated water at 124 bar, 50 °C
- Depressurize to 27 bar at a rate of 12 bars/hr
- CO₂ phase saturation reaches >40%, but very low mobility
- No gravity redistribution after 11 days.
- CO₂ is mobile at 3% gas saturation during flood of the same core

porosity



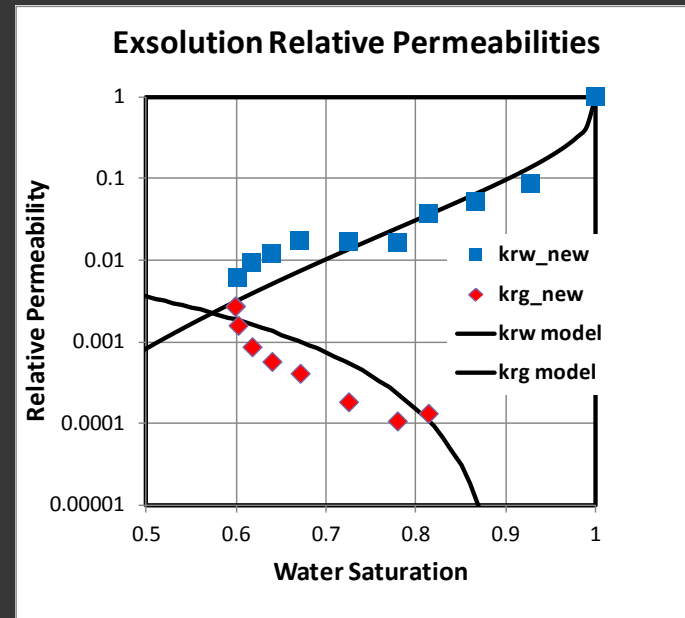
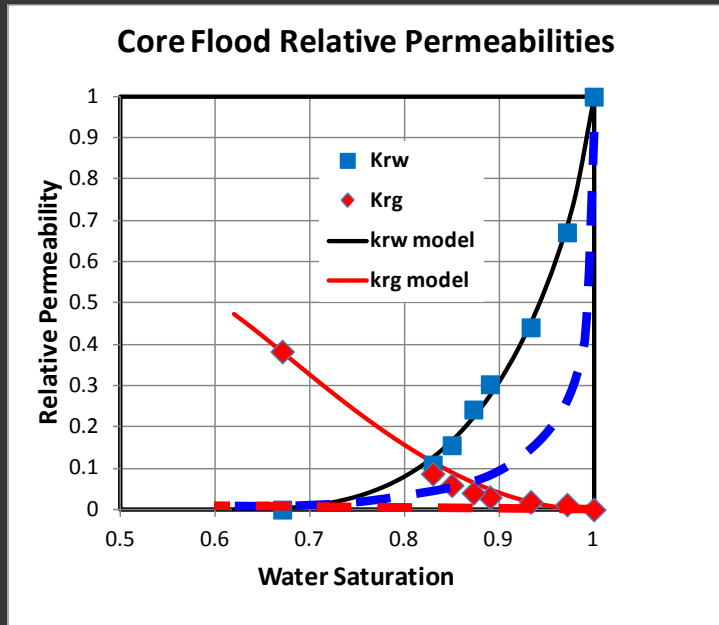
CO₂ saturation



Core Experiments

Relative permeability

Mt. Simon Sandstone (15.7 mD, 23.9 % porosity)



CO₂ phase injection



CO₂ exsolution from brine

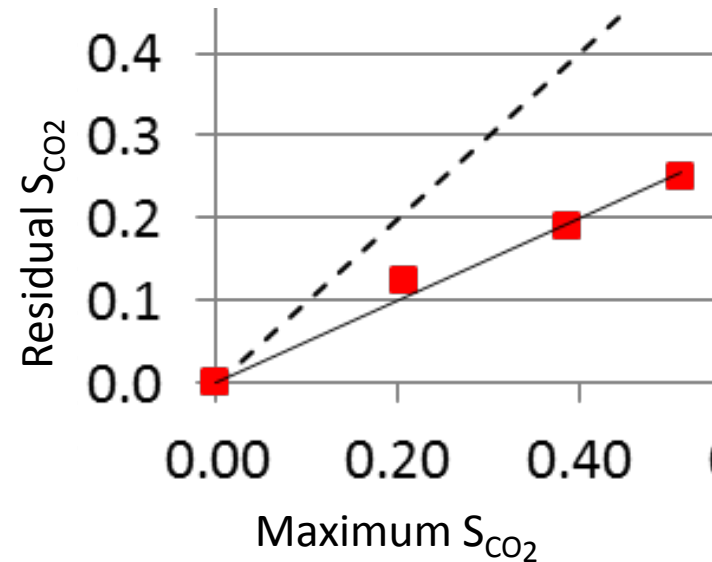


Core Experiments

Hysteretic CO₂ phase trapping

- Core flood experiments where CO₂ saturation was cyclically increased and decreased to measure trapping
- CO₂ saturation was measured by CT scan
- Trapped CO₂ is a linear function of maximum CO₂ saturation

Linear Trapping Model

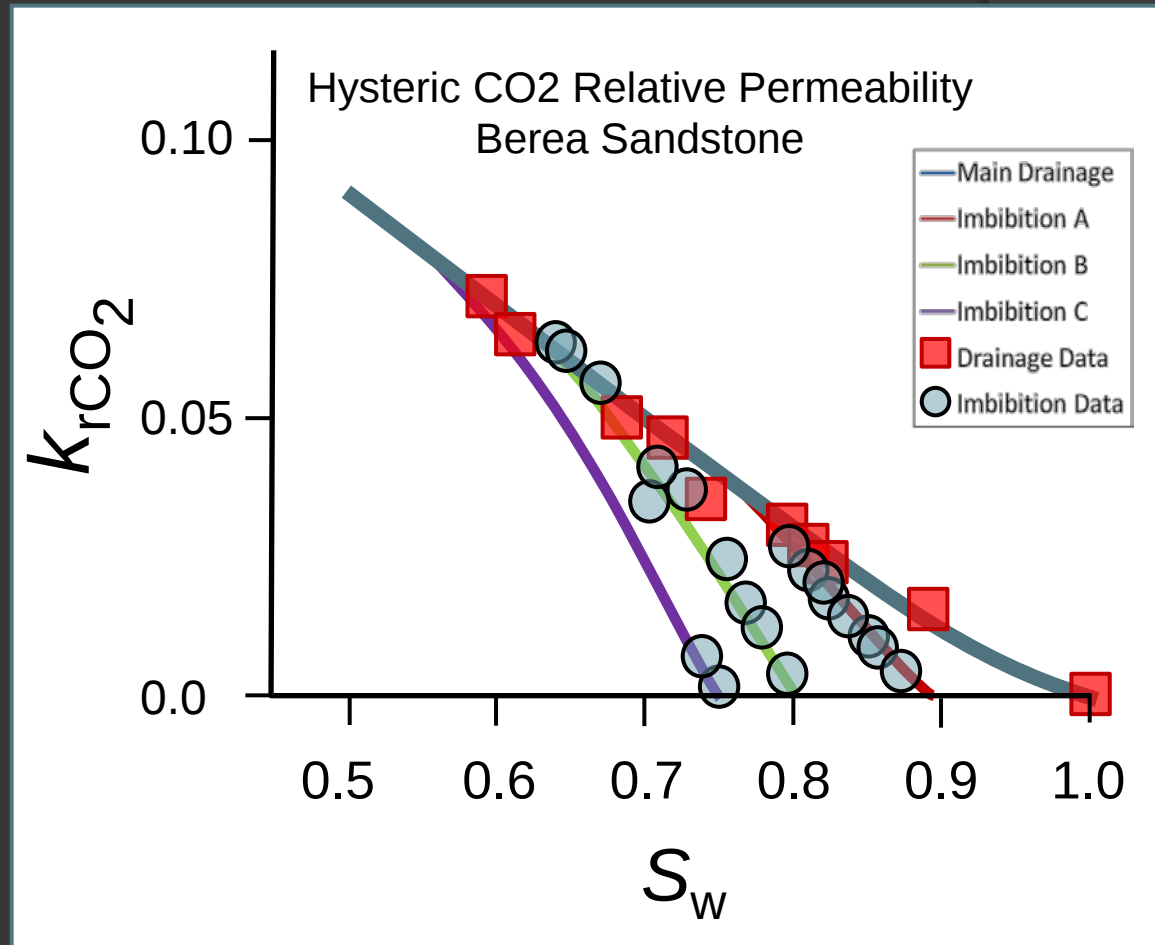


Core Experiments

New relative perm model for hysteretic CO₂ phase trapping

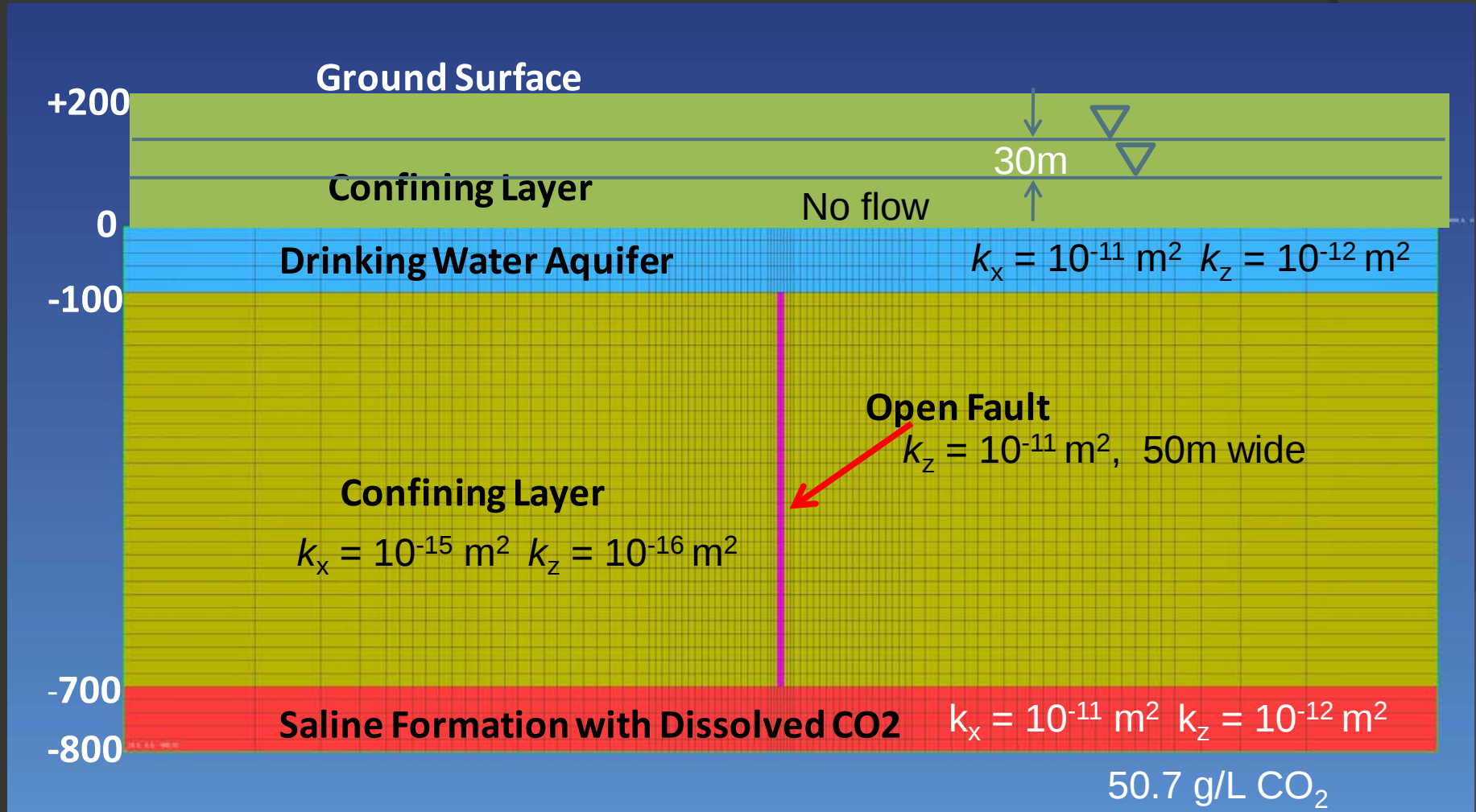
- Simple approach: residual saturation a function of maximum saturation
- Continuously update the max residual saturation
- Allows use of existing relative permeability models

$$k_{rg} = k_{rg \max} \sqrt{1 - \hat{S}_w} \left(1 - \hat{S}_w^{1/m}\right)^{2m}$$
$$\hat{S}_w = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}}$$



Modeling

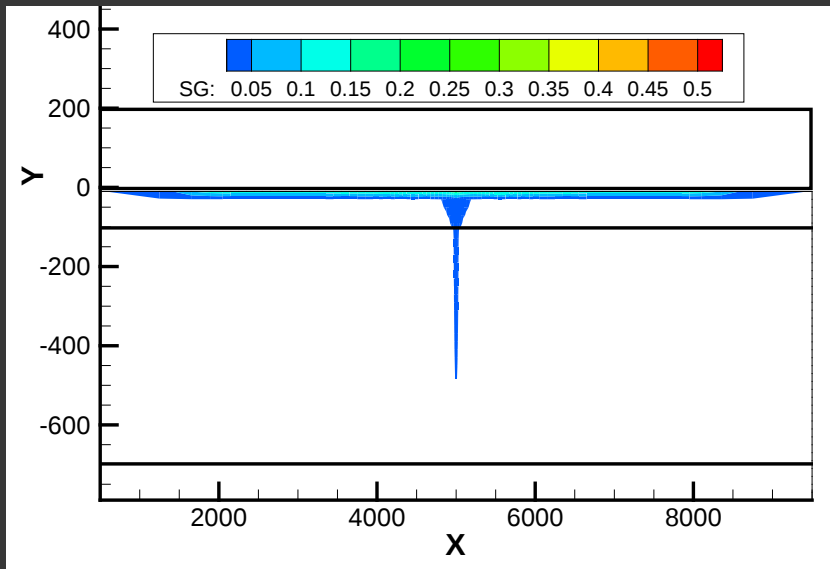
Open fault model using TOUGH2-ECO2N



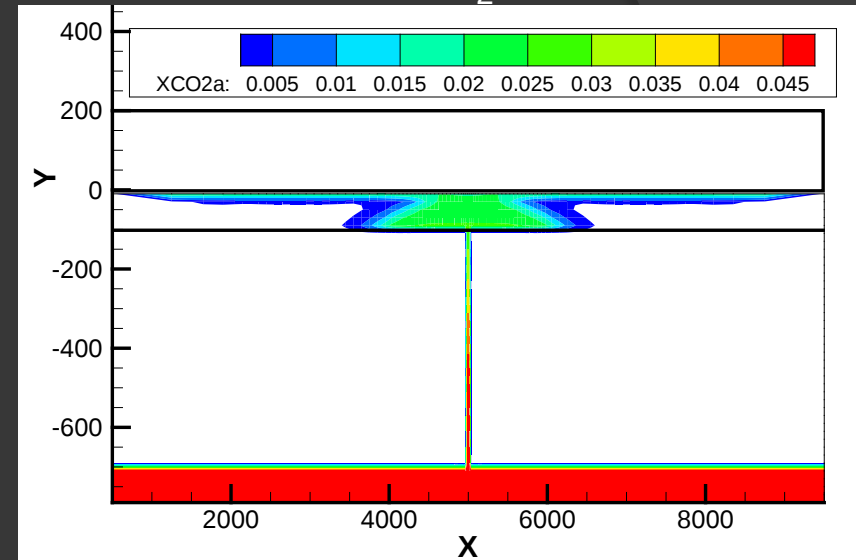
← Model extends 5,000m in either direction →

Model using regular core flood relative permeabilities. Time is 30 years.

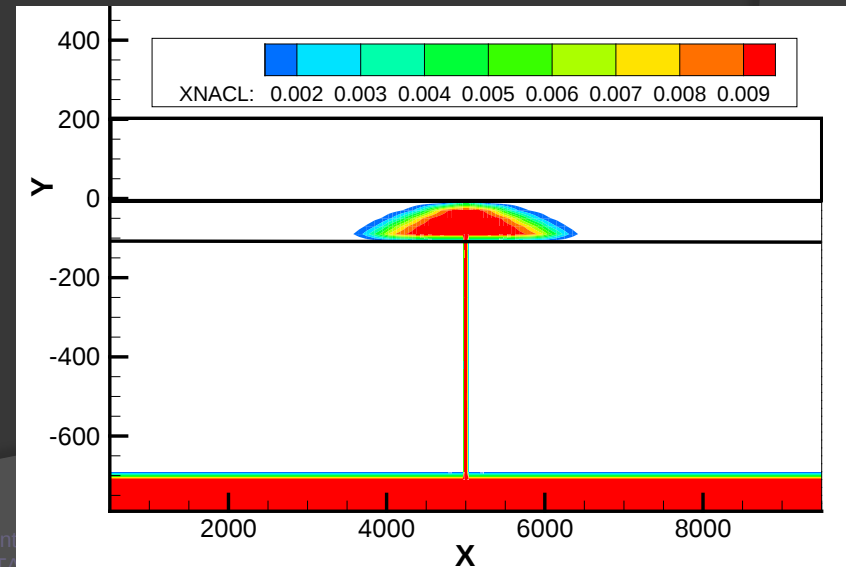
Gas saturation



Dissolved CO₂ mass fraction



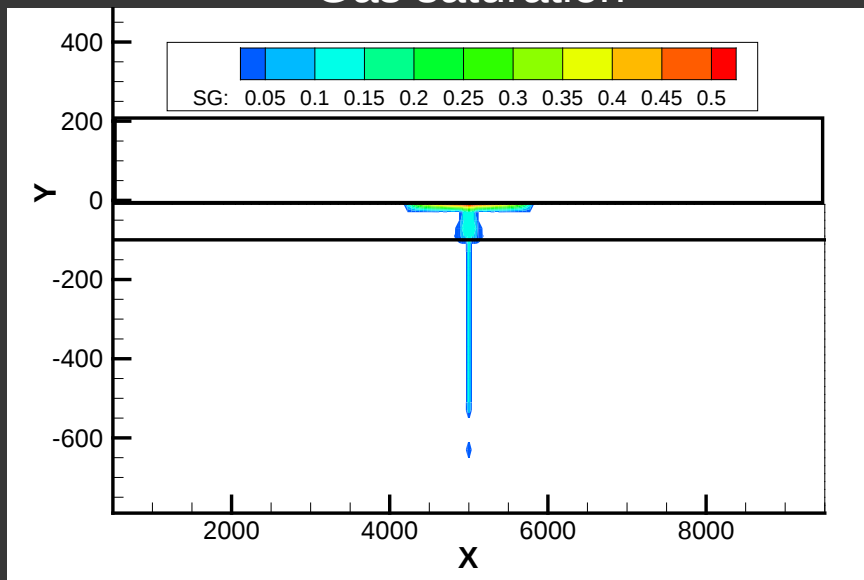
Dissolved salt mass fraction



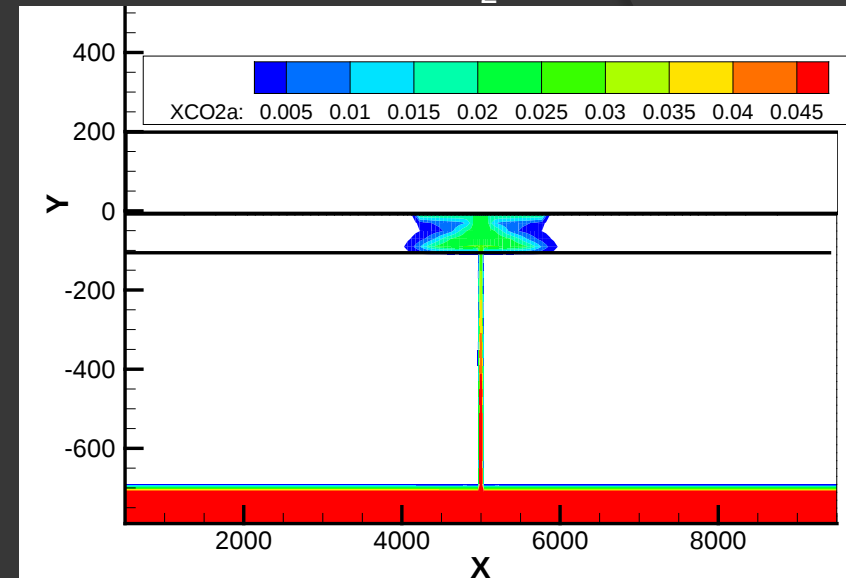
Gas phase CO₂ reaches the DWA, and spreads to the boundaries at 5000m within 30 years if the drawdown is maintained.

Model using exsolution relative permeabilities. Time is 30 years.

Gas saturation

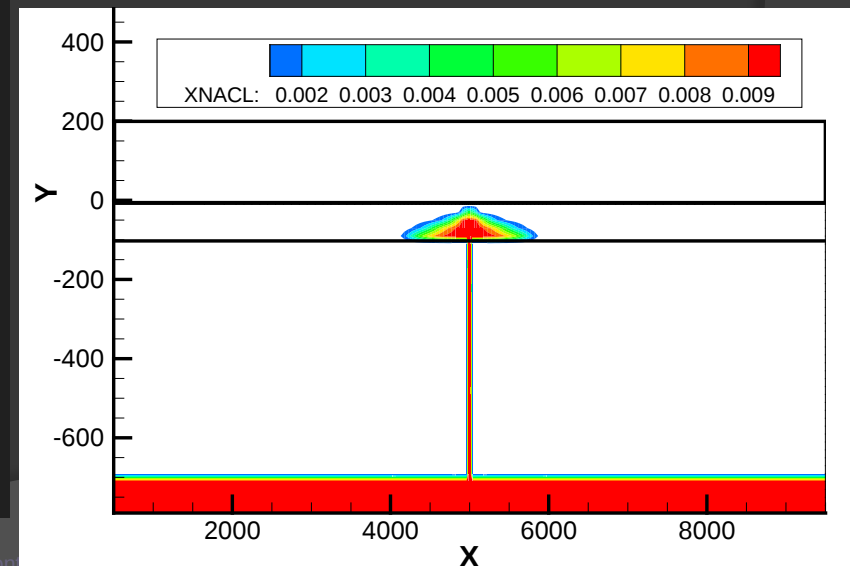


Dissolved CO₂ mass fraction



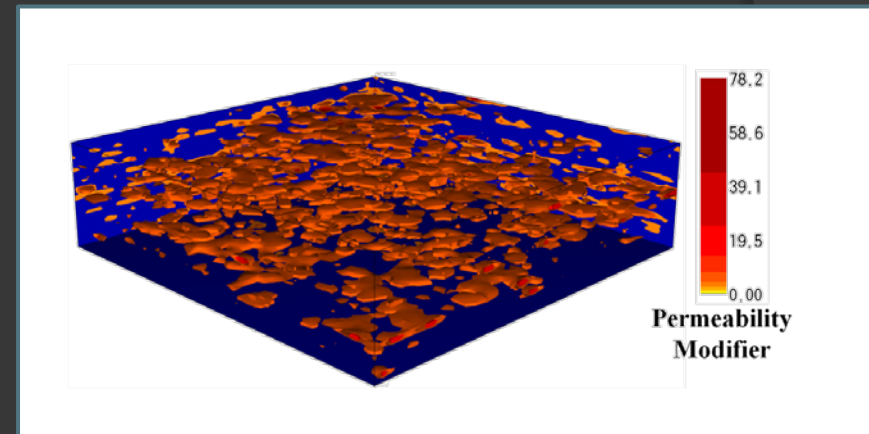
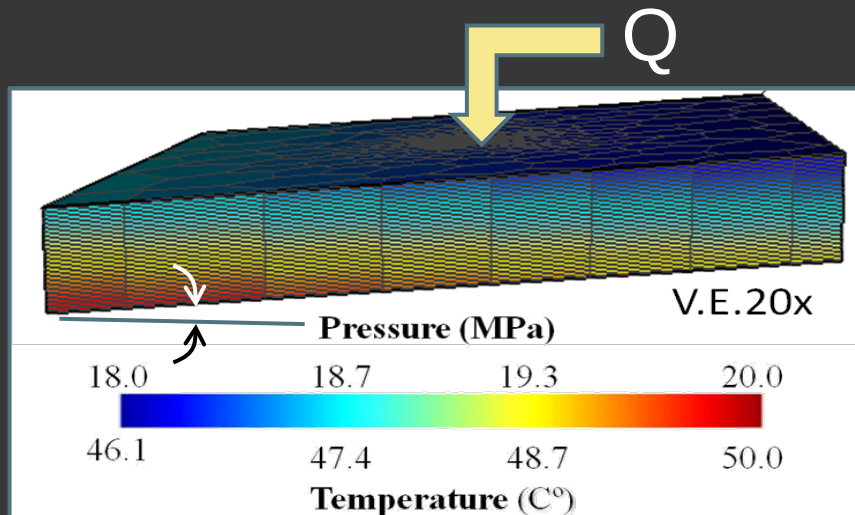
- Leakage much less using exsolution relative permeability
- Related simulations for wells similar
- In all cases, CO₂ migration stops when head imbalance is corrected, no runaway effect

Dissolved salt mass fraction



Modeling

CO₂ injection as dissolved or supercritical



Formation: 300m thick, 20km x 20 km
Slope: 0.008, 8m/1km
Injection rate: 10 kg CO₂/s for 20 years
Monitoring period: 30 years

Properties:

Typical of deep sandstone
Stochastic distribution
Hysteretic capillary and rel. perm functions

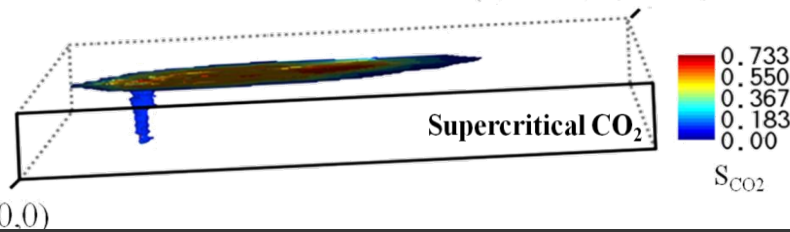
Modeling results

CO₂ injection as dissolved or supercritical

Supercritical

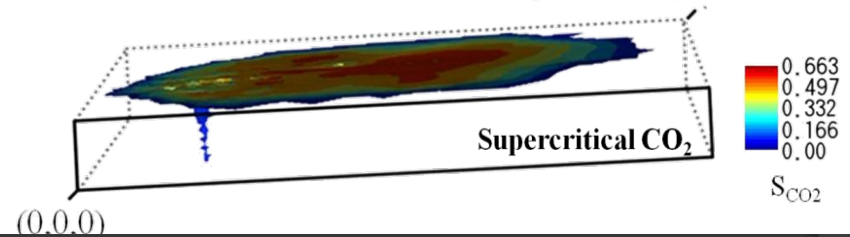
End of 20 Year Injection

(5,150m, 5,150m, 300m)



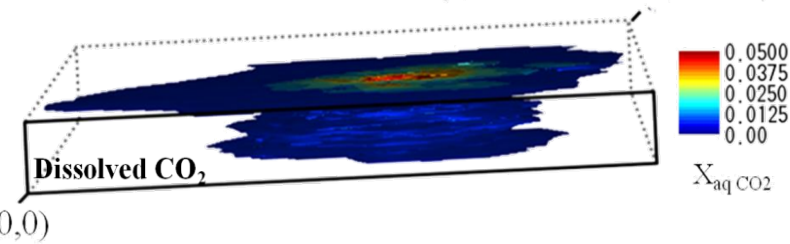
End of 30 Year Monitoring Period

(5,150m, 5,150m, 300m)

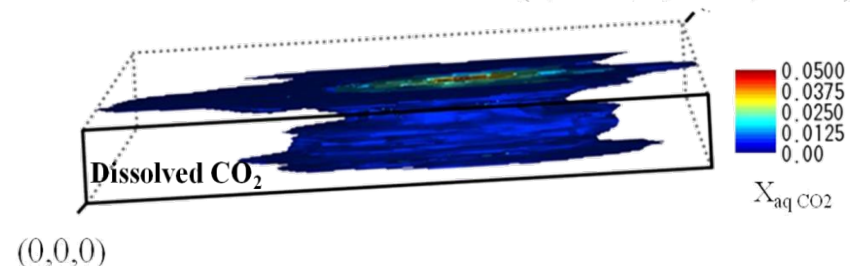


Dissolved

(5,150m, 5,150m, 300m)



(5,150m, 5,150m, 300m)



1 km

- Similar areal footprints after injection ~10 km²
- Supercritical CO₂ moves after injection, increasing area by 50% (14.9 km²)
- Dissolved CO₂ sinks after injection, decreasing area contacting caprock (8.9 km²)

Conclusions

- Brine containing dissolved CO₂ can be mobilized upward by modest hydraulic gradients
- As the carbonated brine is depressurized, the CO₂ comes out of solution (exsolves) throughout the pore space
- The exsolved CO₂ phase has a very low relative permeability, even at high phase saturations. Exsolution relative permeability function
- Hysteric relative permeability represented by updating residual saturation in standard models. Simple, fits data well.
- Upward flow of brines containing dissolved CO₂ stops when the external driving force is removed, no runaway instability seen.
- Injection of CO₂ as a dissolved phase is likely to have a similar “footprint” to supercritical CO₂ injection, less mobile after injection.