Risks Posed by Brines Containing Dissolved CO_2

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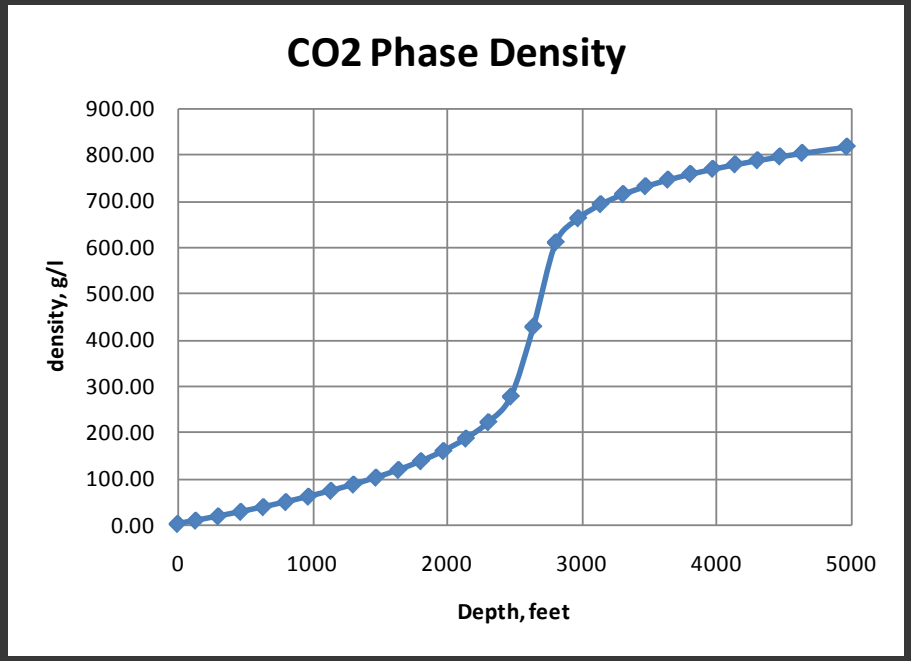
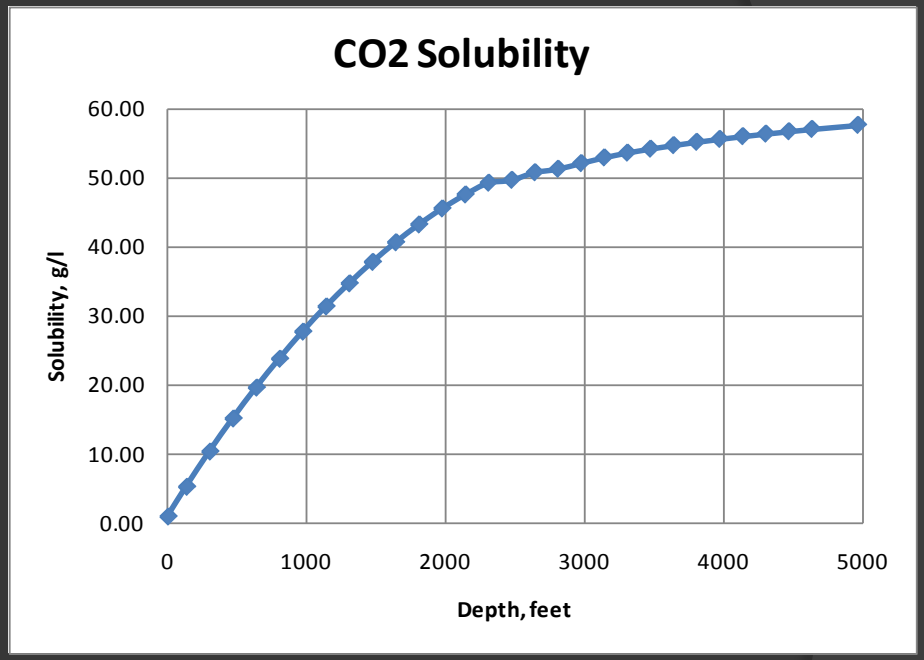
CO_2 Density and Solubility with Depth

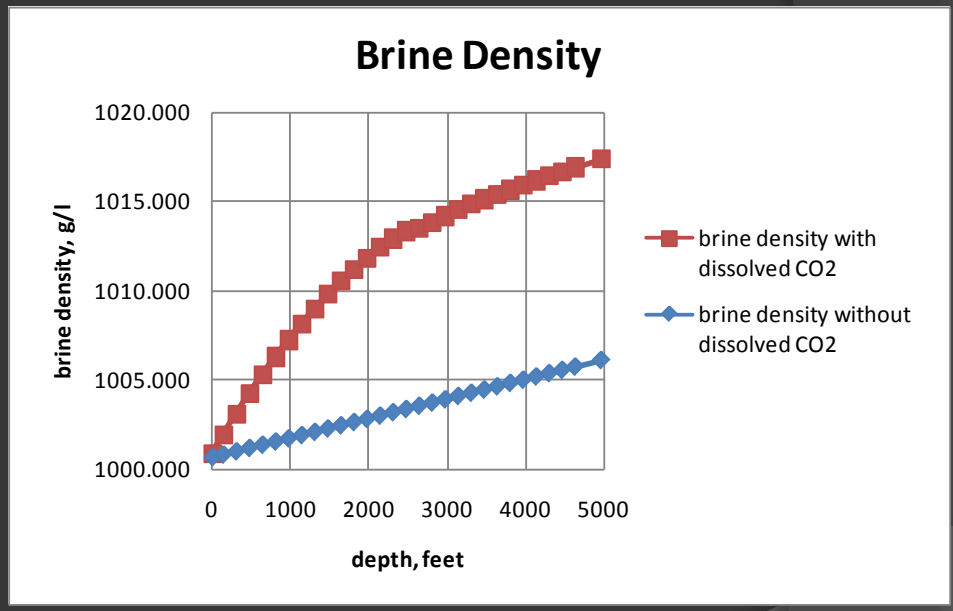




Calculated using TOUGH2-ECO2N assuming 35^{o} C and 10,000 mg/l NaCl

The high CO_2 solubility is significant

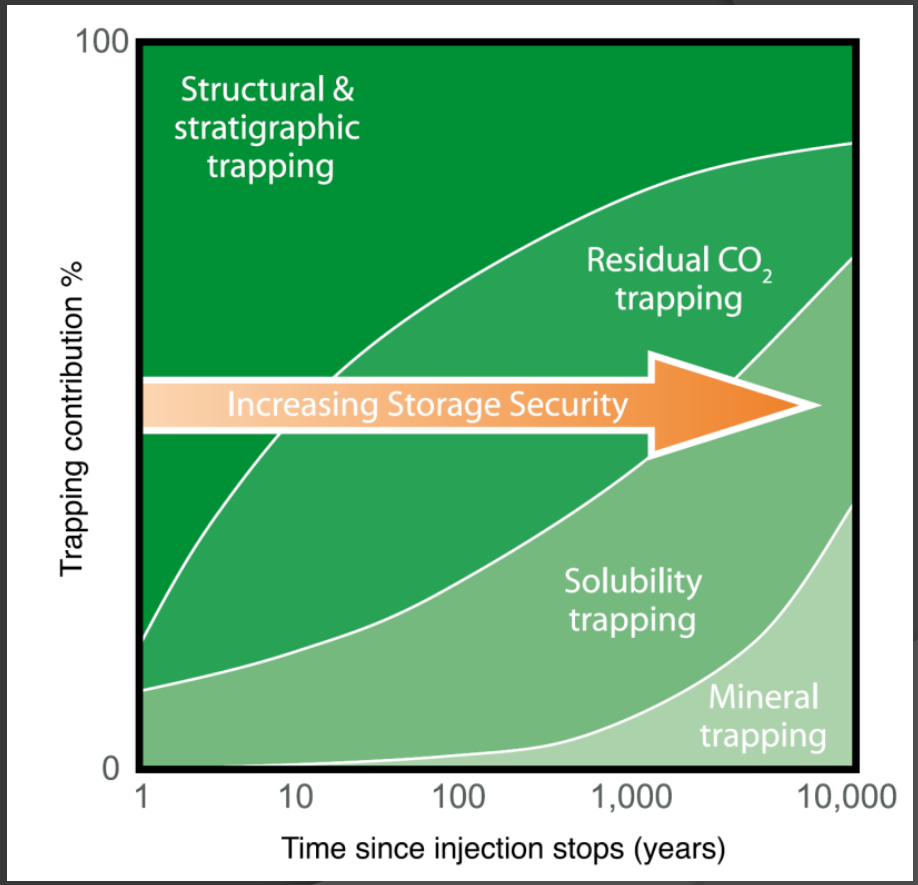
- At 3000 ft depth, we get ~50 g/l (50 times more CO_2 than beer!)
- When CO_2 dissolves, the aqueous phase becomes more dense (about 1% here)
- Upward flow would require a caprock defect, and an upward hydraulic gradient > density difference



Calculated using TOUGH2-ECO2N

The Dissolved CO_2 is Secure – Or Is It?

- Solubility trapping – CO_2 dissolves in pore water (up to 60 g/l)
- Density increase favors downward flow of CO_2 saturated brine
- Upward flow would require a caprock defect, and an upward hydraulic gradient > 1%
- **However, if a CO_2 saturated brine moved upward, the CO_2 would come out of solution (exsolve), leading to a potentially mobile gas phase**



IPCC, 2005

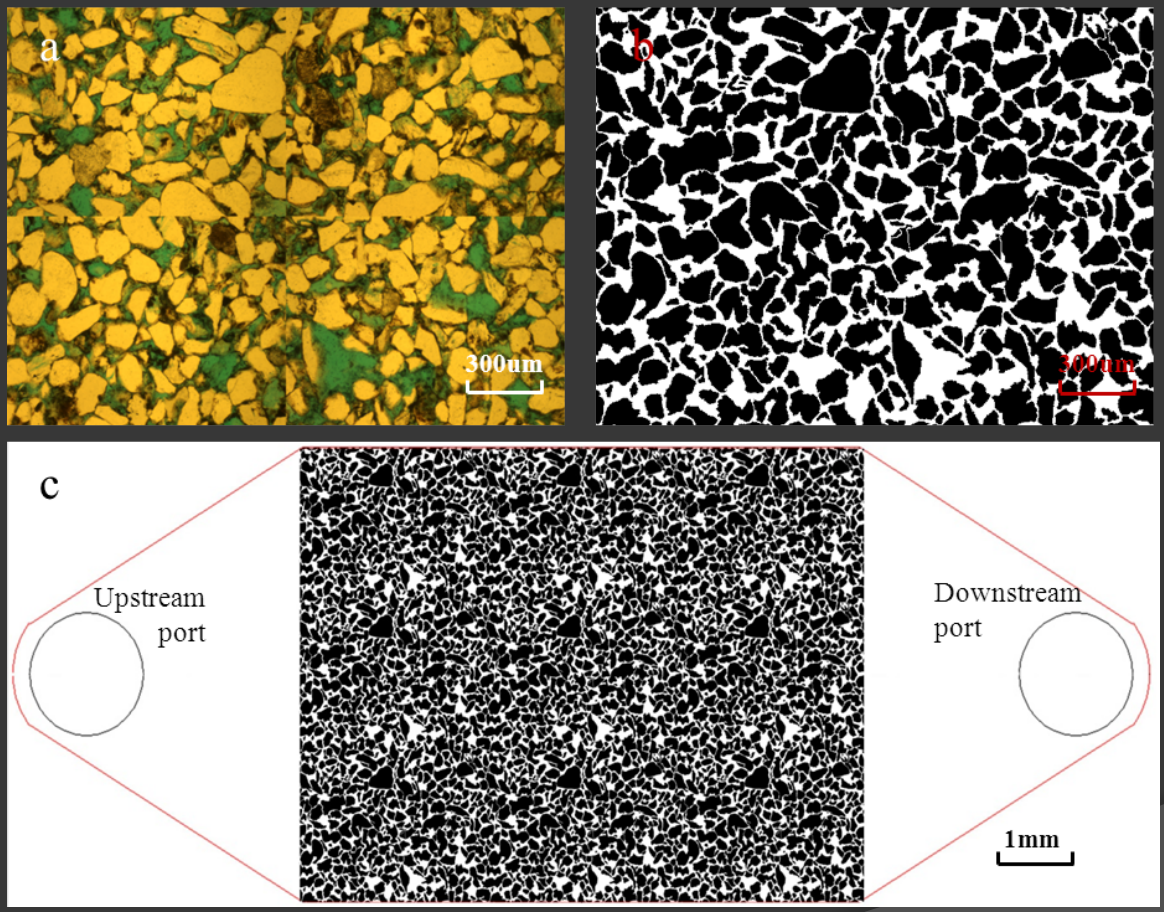
Outline

- 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



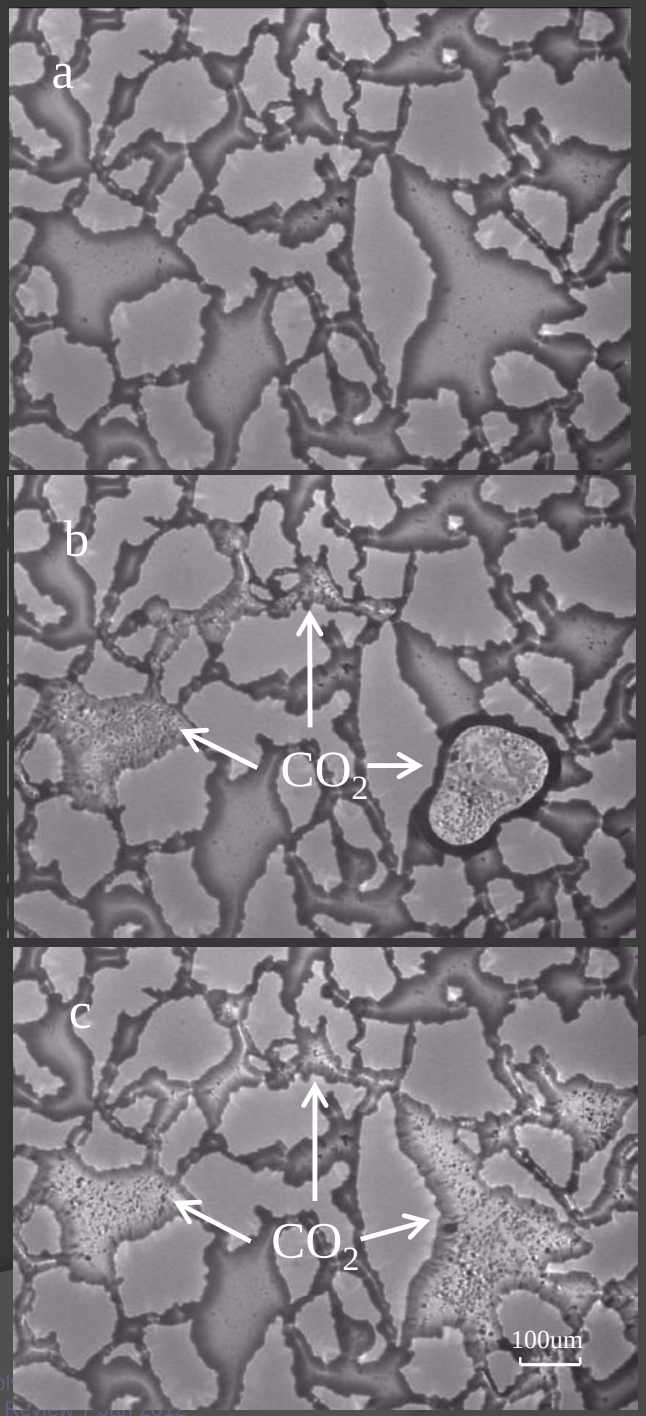
Binary image used for micromodel

Micromodel: 530 mD; PV=1.35 uL

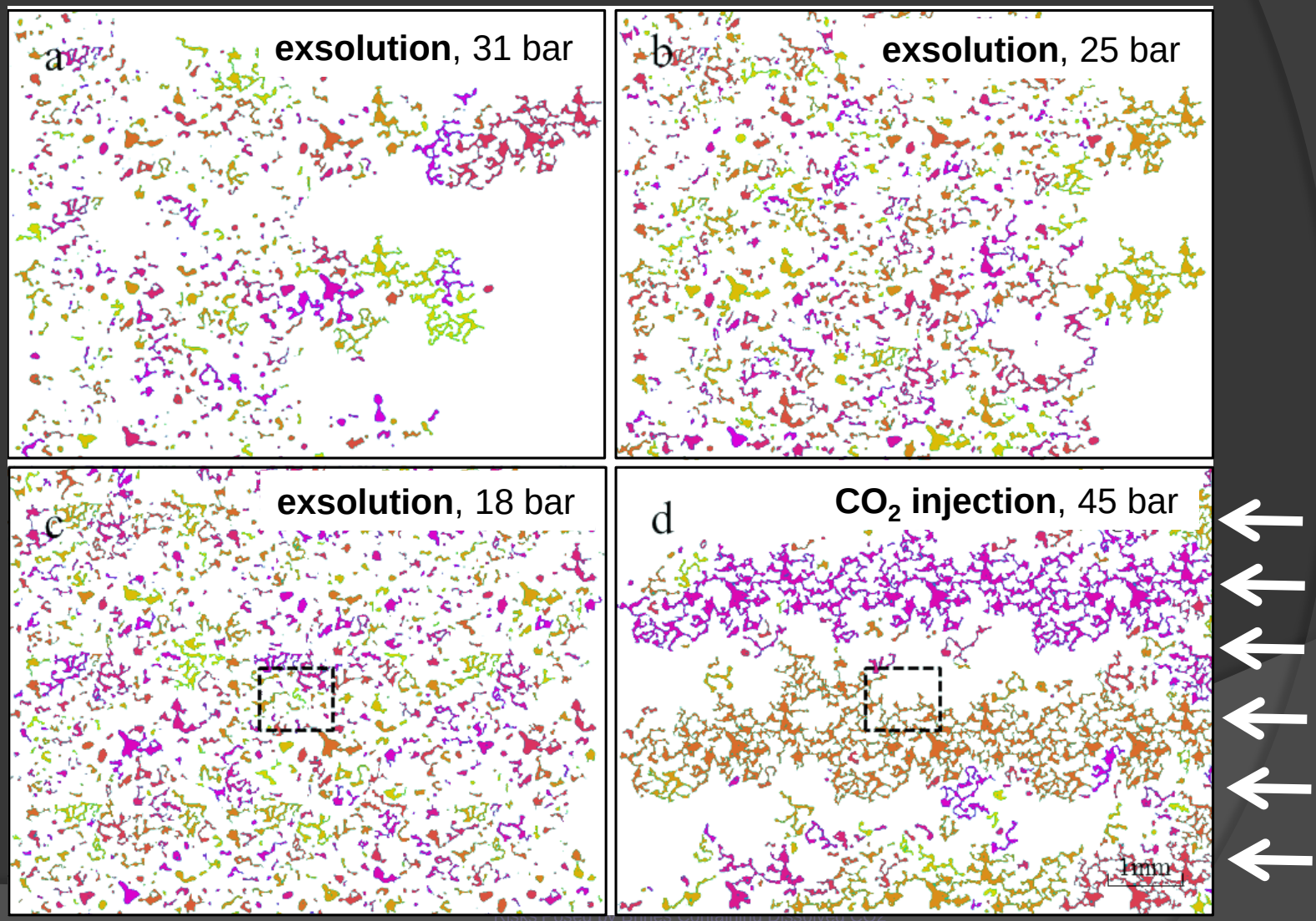
Micromodel

- Initially fill micromodel with water saturated with dissolved CO_2 at 90 bars, 45 ^oC
- 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%

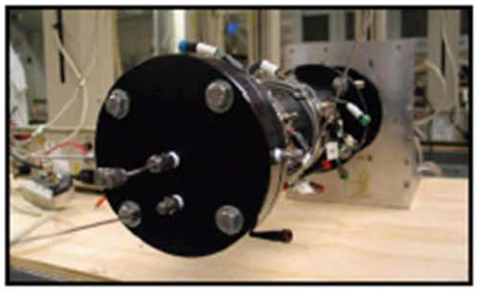


Comparison of Exsolution and Supercritical CO_2 Injection



Core Scale Experimental Setup

Core Holder



CT Scanner

Dual-pump System

Core Experiments

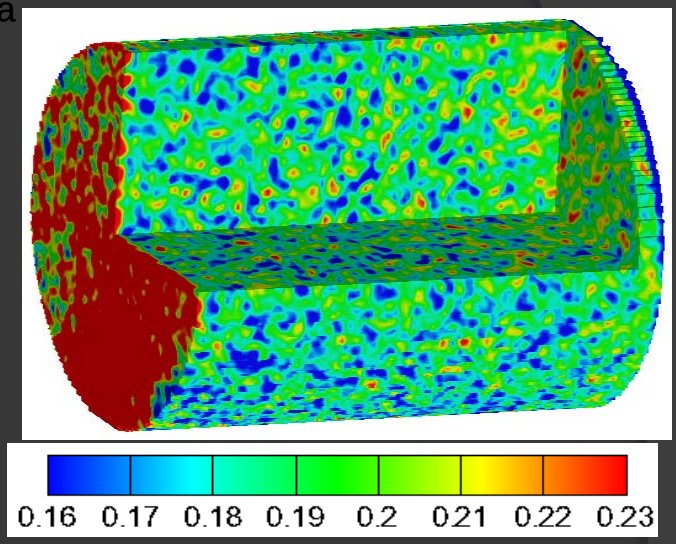
Mobility of exsolved gas

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

- Fill core with CO_2 saturated water at 124 bar, 50 ^oC
- Depressurize to 27 bar at a rate of 12 bars/hr
- CO_2 phase saturation reaches >40%, but very low mobility
- No gravity redistribution after 11days.
- CO_2 is mobile at 3% gas saturation during flood of the same core

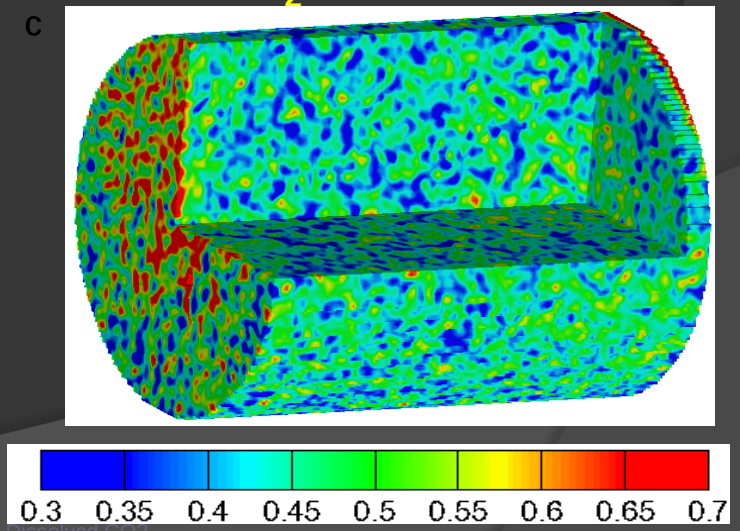
porosity

a



CO_2 saturation

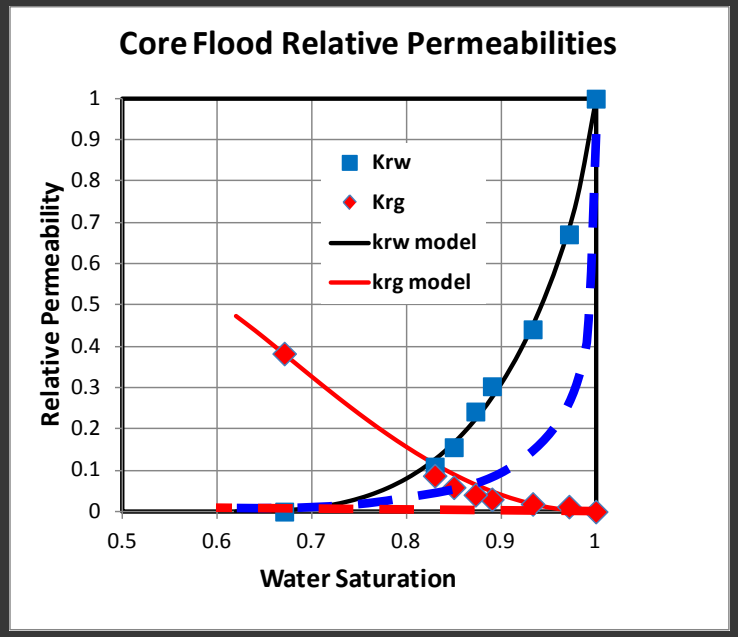
c

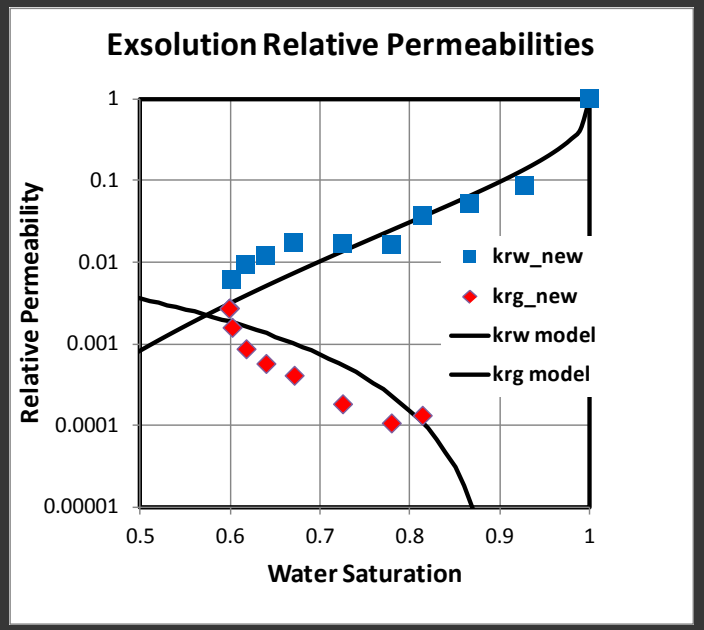


Core Experiments

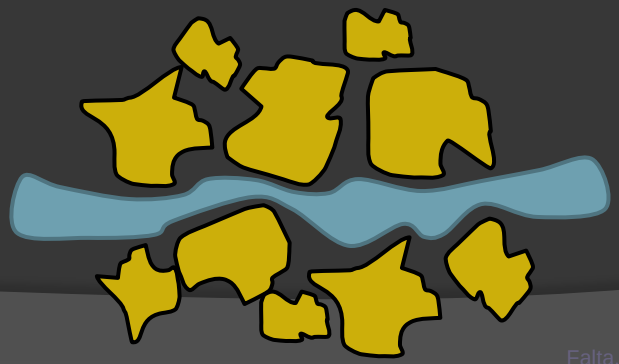
Relative permeability

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

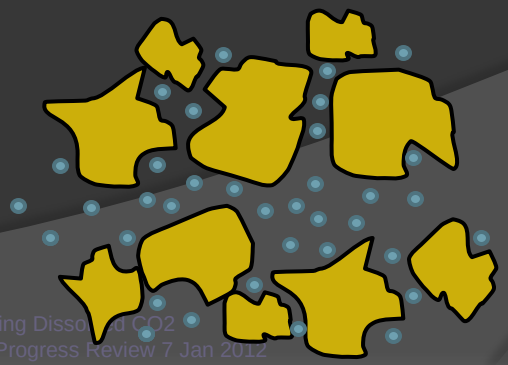




CO_2 phase injection



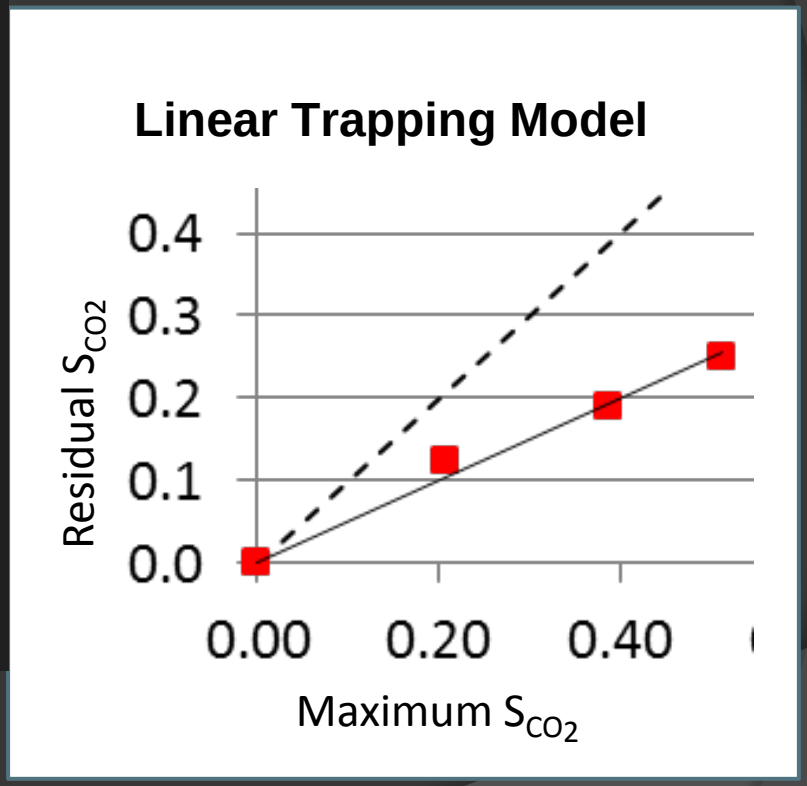
CO_2 exsolution from brine



Core Experiments

Hysteretic CO_2 phase trapping

- Core flood experiments where CO_2 saturation was cyclically increased and decreased to measure trapping
- CO_2 saturation was measured by CT scan
- Trapped CO_2 is a linear function of maximum CO_2 saturation



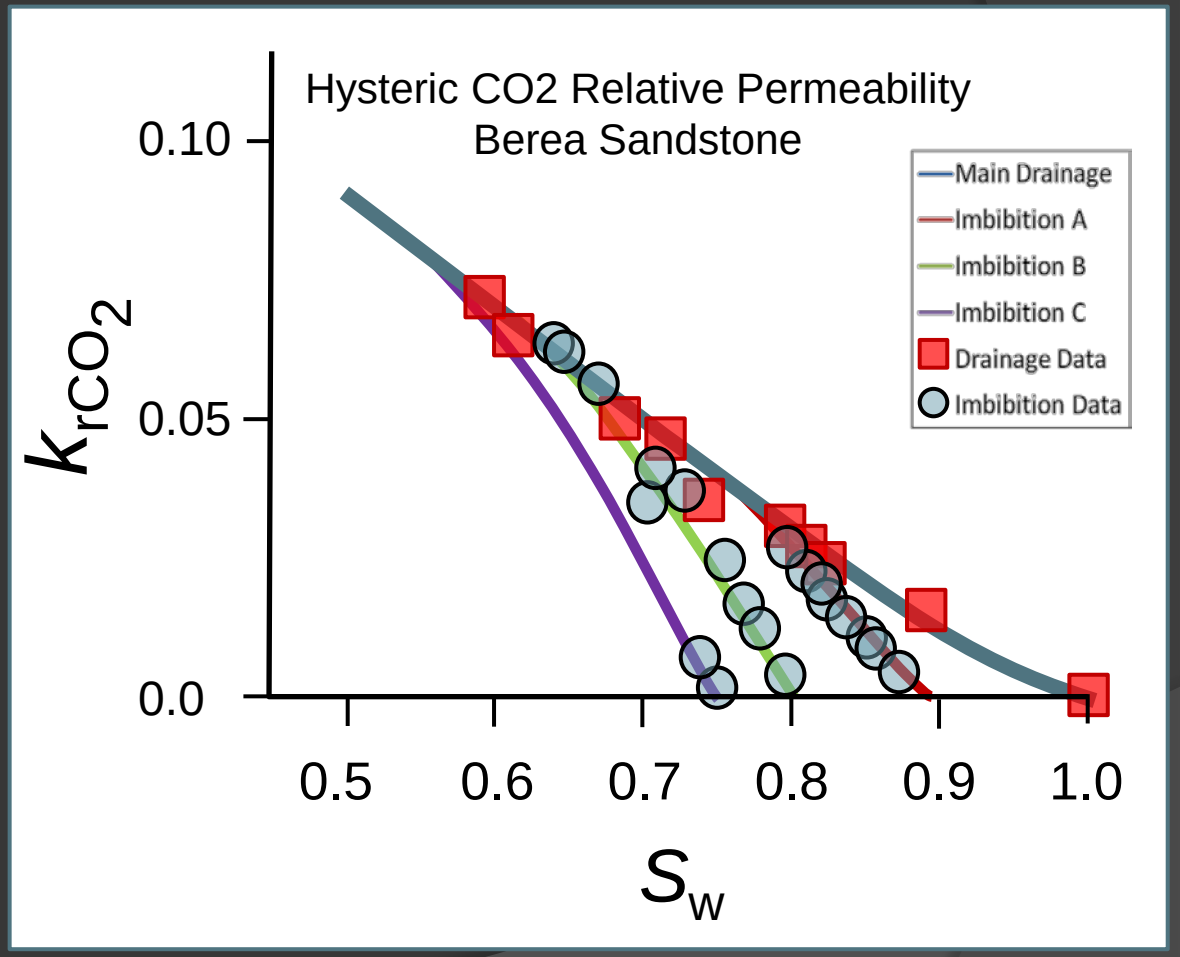
Core Experiments

New relative perm model for hysteretic CO_2 phase trapping

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

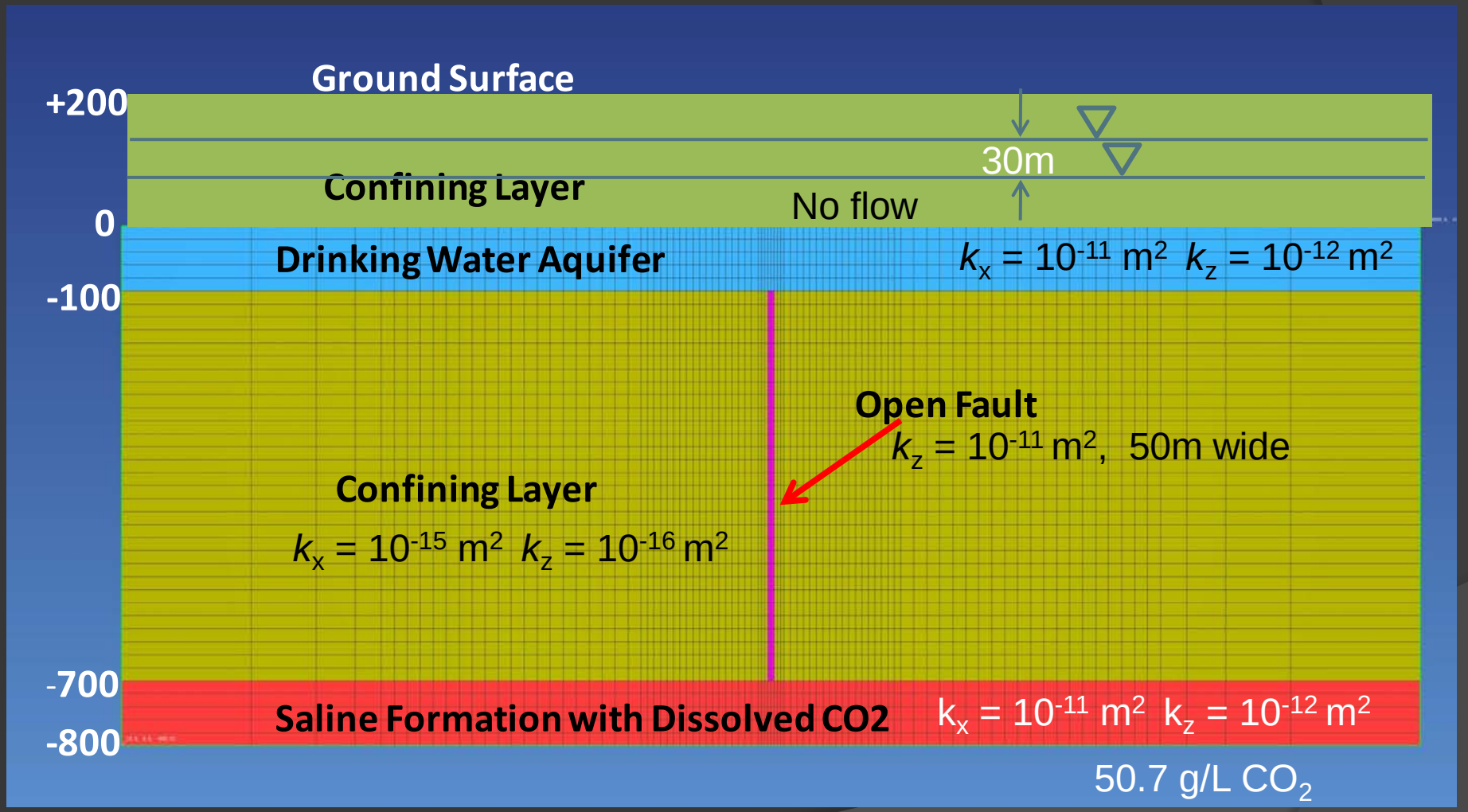
$$k_{rg} = k_{rg\max}\sqrt{1-\hat{S}_w}\left(1-\hat{S}_w^{1/m}\right)^{2m}$$

$$\hat{S}_w = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{gr}}$$



Modeling

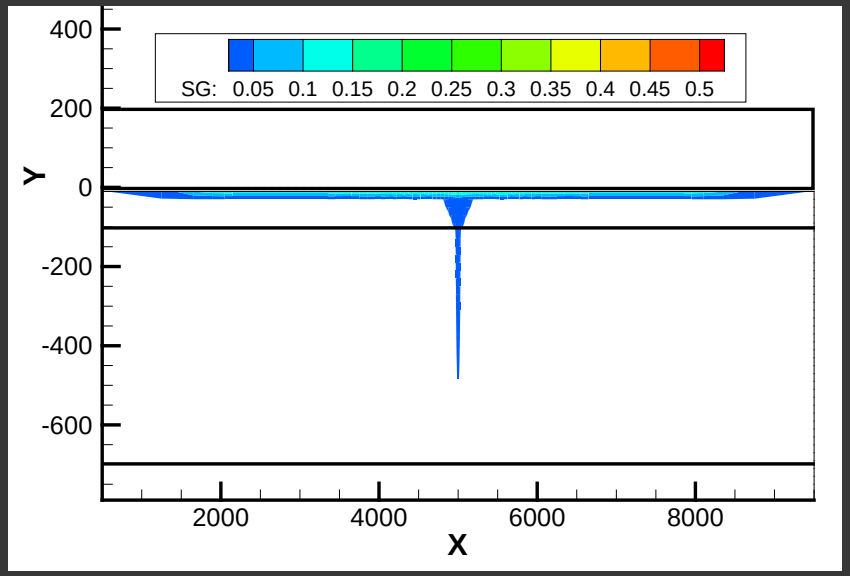
Open fault model using TOUGH2-ECO2N



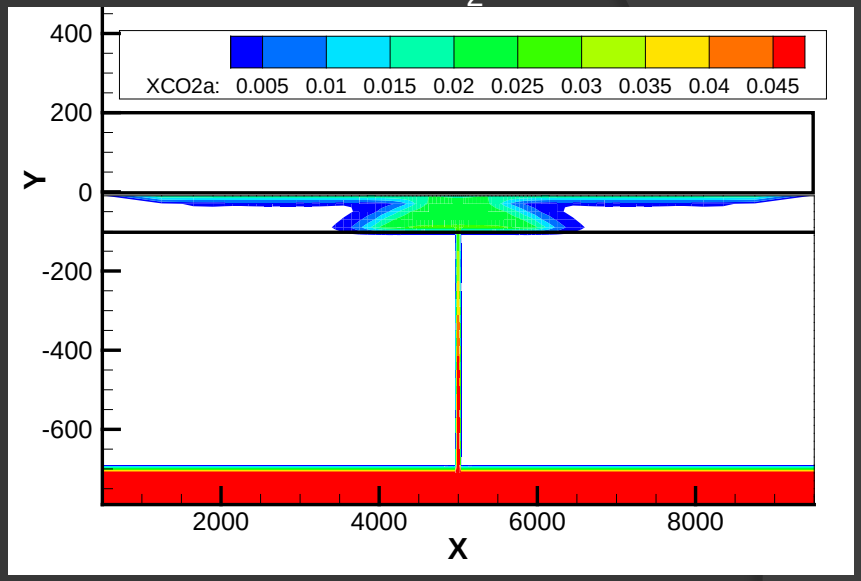
Model extends 5,000m in either direction

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

Gas saturation

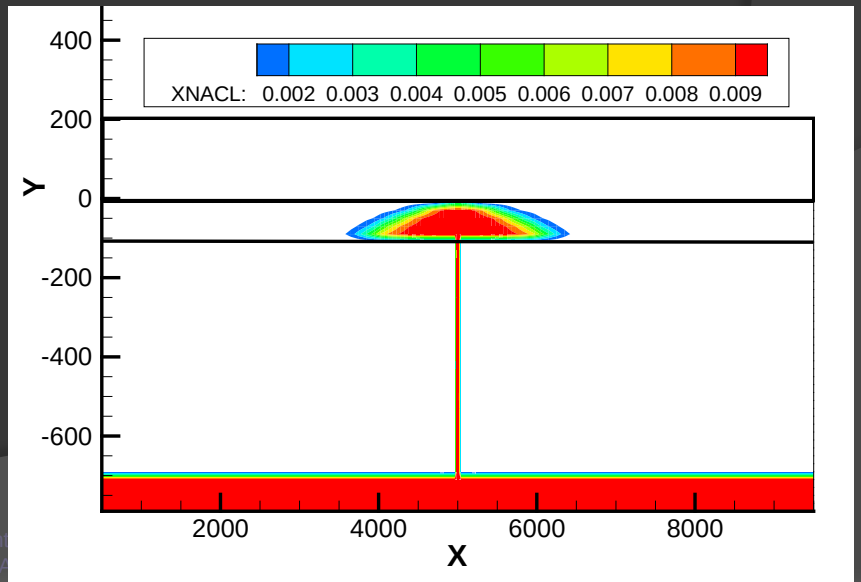


Dissolved CO_2 mass fraction



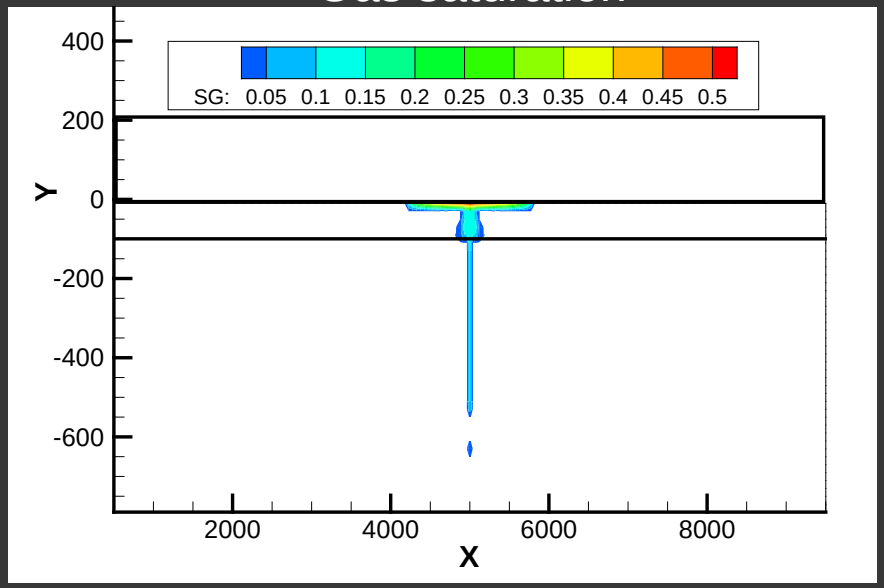
Gas phase CO_2 reaches the DWA, and spreads to the boundaries at 5000m within 30 years if the drawdown is maintained.

Dissolved salt mass fraction

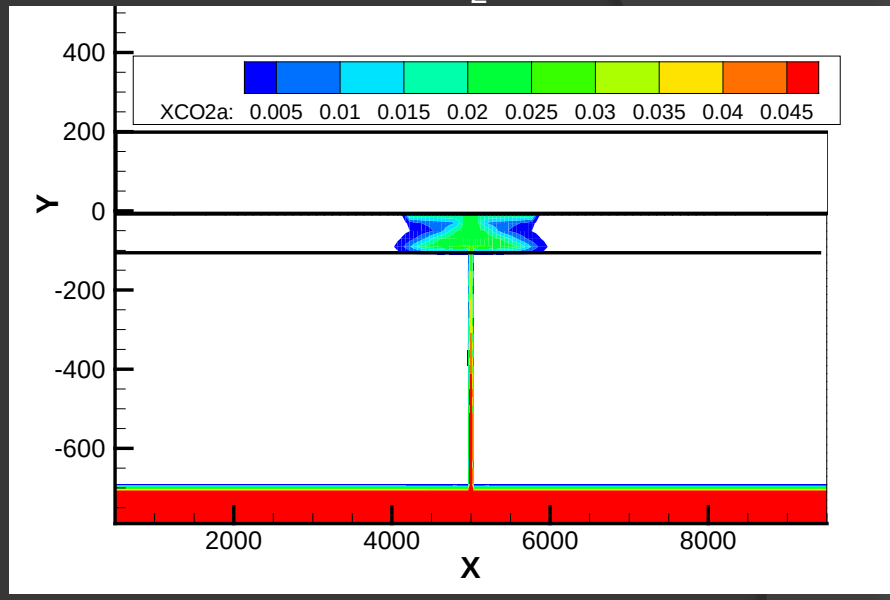


Model using exsolution relative permeabilities. Time is 30 years.

Gas saturation

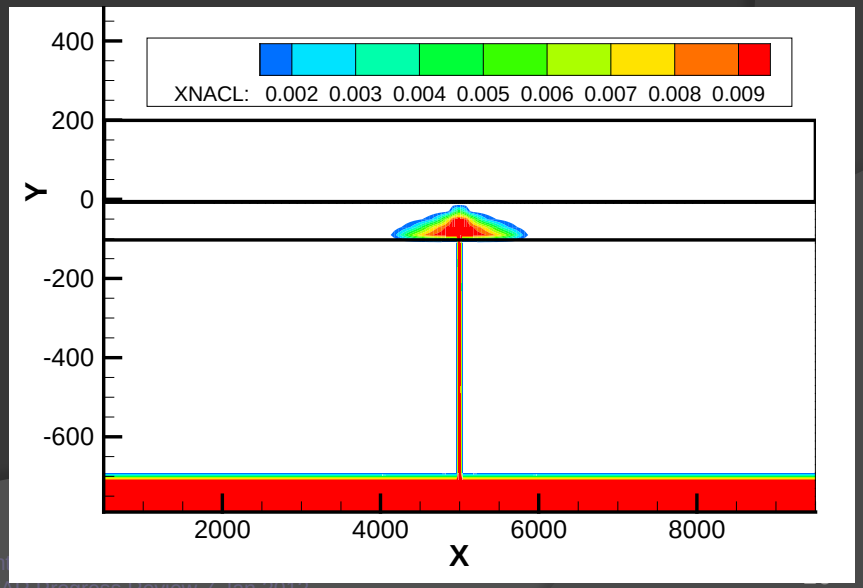


Dissolved CO_2 mass fraction



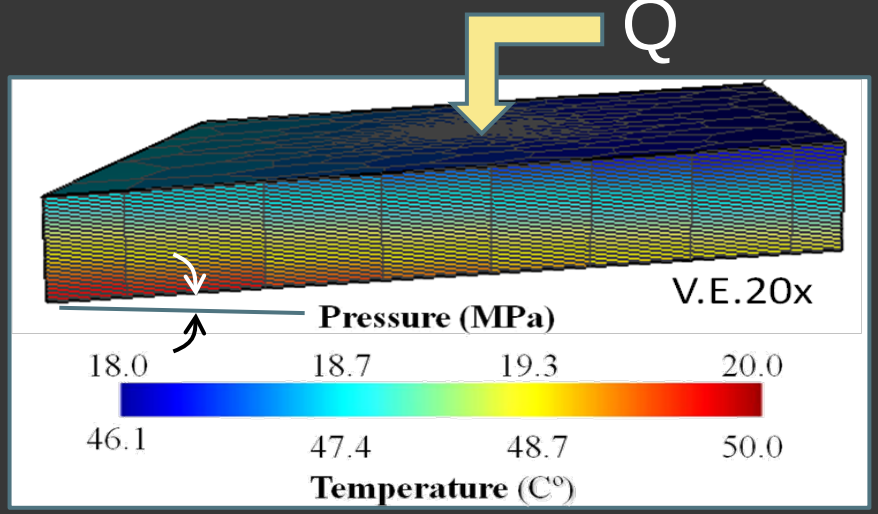
- Leakage much less using exsolution relative permeability
- Related simulations for wells similar
- In all cases, CO_2 migration stops when head imbalance is corrected, no runaway effect

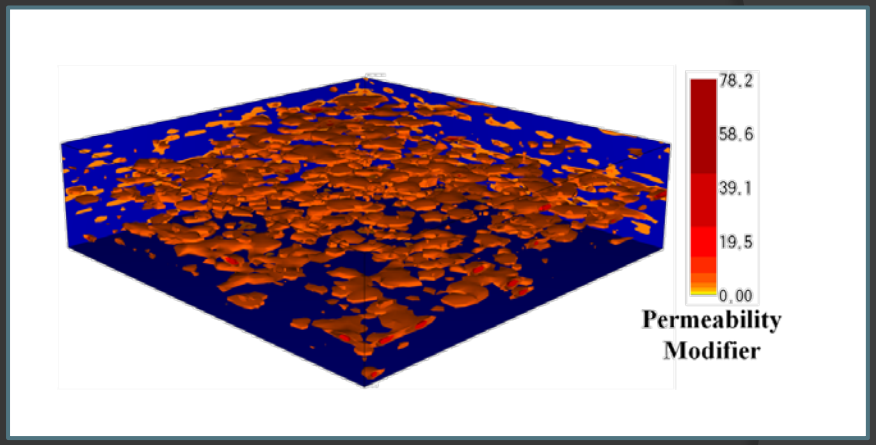
Dissolved salt mass fraction



Modeling

CO_2 injection as dissolved or supercritical





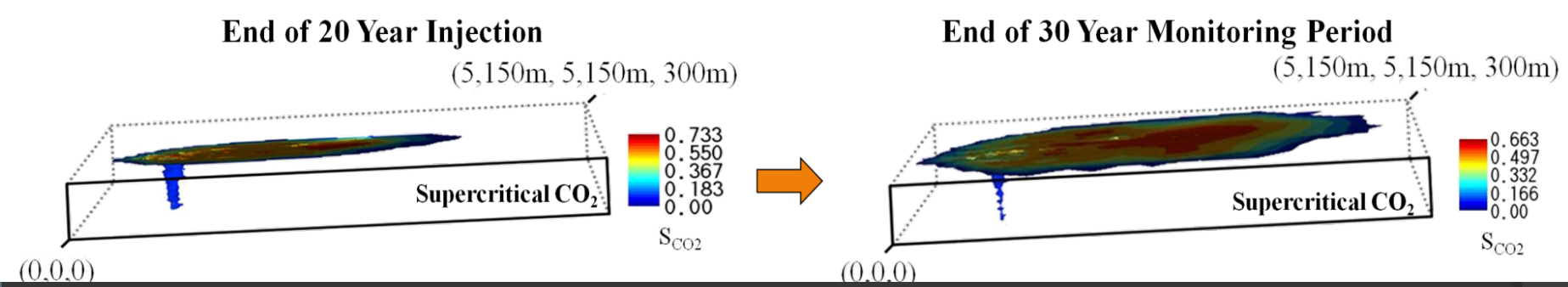
Formation: 300m thick, 20km x 20 km
Slope: 0.008, 8m/1km
Injection rate: 10 kg CO_2/s for 20 years
Monitoring period: 30 years

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

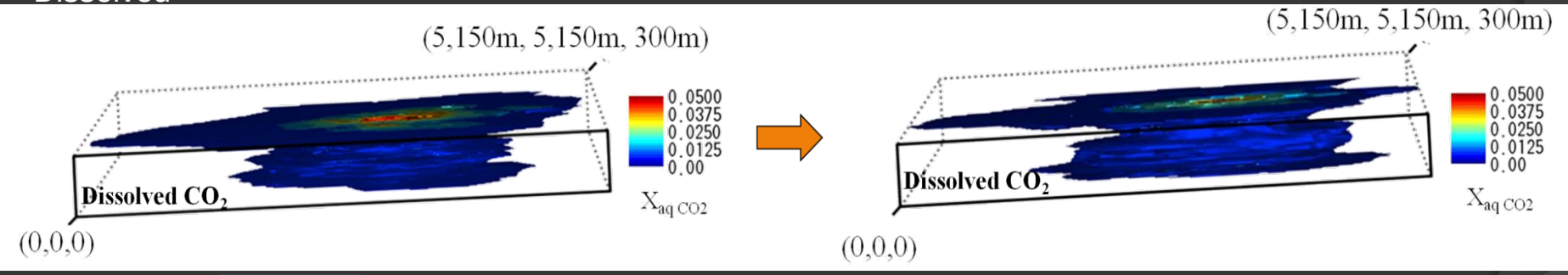
Modeling results

CO_2 injection as dissolved or supercritical

Supercritical



Dissolved



1 km

- Similar areal footprints after injection ~10 km^2
- Supercritical CO_2 moves after injection, increasing area by 50% (14.9 km^2)
- Dissolved CO_2 sinks after injection, decreasing area contacting caprock (8.9 km^2)

Conclusions

- Brine containing dissolved CO_2 can be mobilized upward by modest hydraulic gradients
- As the carbonated brine is depressurized, the CO_2 comes out of solution (exsolves) throughout the pore space
- The exsolved CO_2 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 CO_2 stops when the external driving force is removed, no runaway instability seen.
- Injection of CO_2 as a dissolved phase is likely to have a similar "footprint" to supercritical CO_2 injection, less mobile after injection.