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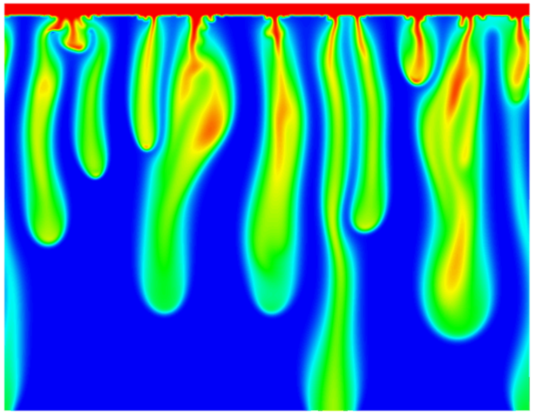

Role of the Capillary Transition Zone on the Dissolution of CO_2 into Brine in Saline Reservoirs

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December 16, 2014

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Impact of capillary transition zone on CO_2 dissolution into brine

Motivation:

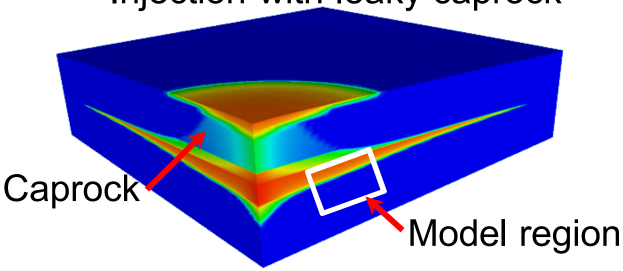
- Geologic carbon storage is a technically viable technology to reduce the impact of anthropogenic CO_2 emissions
- Solubility trapping is thought to be a critical step in geologic carbon storage
- Buoyantly driven convective dissolution can substantially enhance the rate of dissolution, but is difficult to quantify in the field
- Theory and computational models have been applied but few have included the two-phase region above the gas-water contact where dissolution actually takes place

Objectives of this research:

- We use a numerical model which includes the two-phase region to determine:
  - Impact of capillary transition zone on long-term dissolution rate
  - Role of strength of capillary forces (with entry pressure as surrogate)
  - limiting behavior

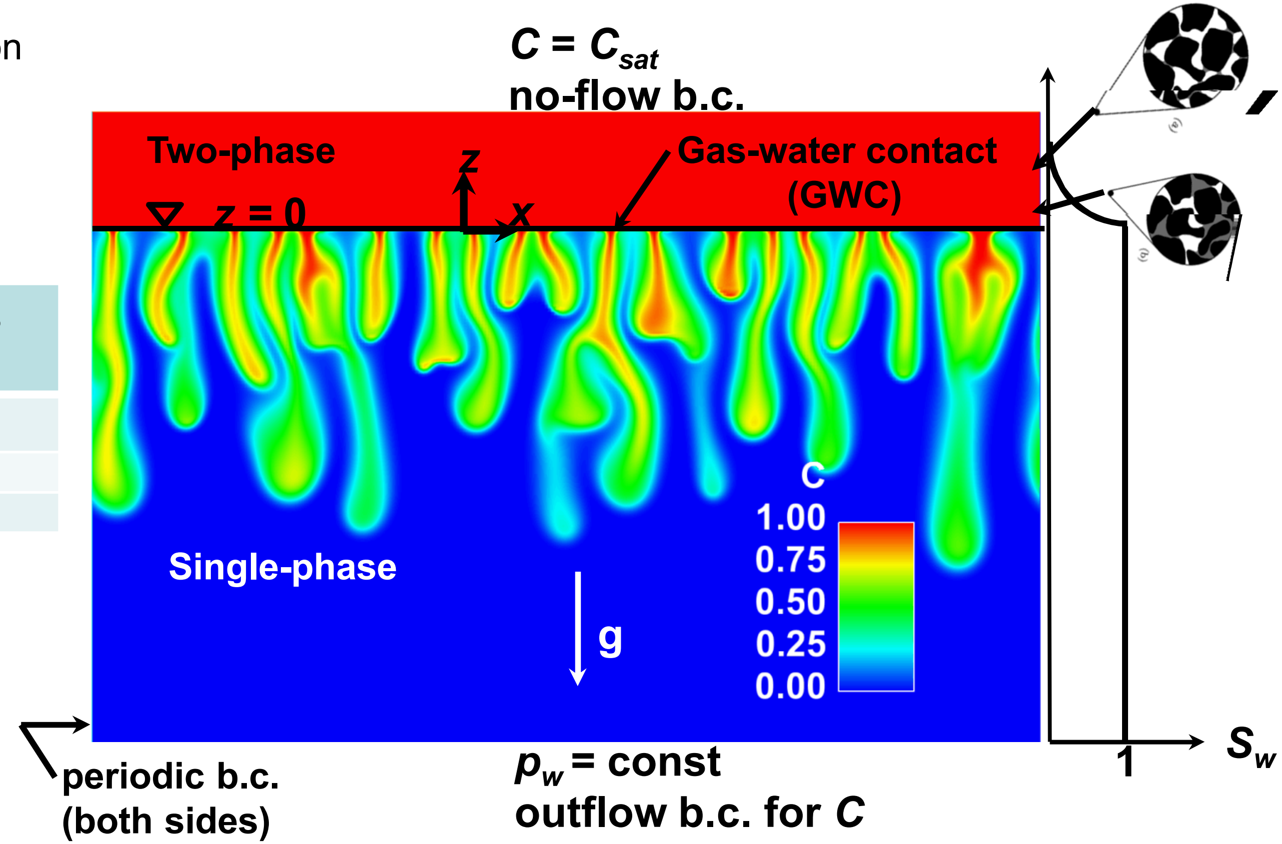
Model Problem

Injection with leaky caprock



Two reservoirs are modeled

Property	Sleipner Utsira	Bravo Dome
porosity	0.37	0.15
perm. (mD)	2000	50



Math Model

- Two-phase flow :
  - Brine: $$\frac{\partial\left(\rho_w\phi\left(1-S_n\right)\right)}{\partial t}=\nabla\bullet\left(\rho_w\frac{k_{rw}}{\mu_w}\mathbf{k}\bullet\left(\nabla p_w-\rho_w\mathbf{g}\right)\right)+Q_w$$
  - CO2: $$\frac{\partial\left(\rho_n\phi S_n\right)}{\partial t}=\nabla\bullet\left(\rho_n\frac{k_{rn}}{\mu_n}\mathbf{k}\bullet\left(\nabla p_w+\nabla p_c-\rho_n\mathbf{g}\right)\right)+Q_n$$
- Balance of dissolved CO_2:

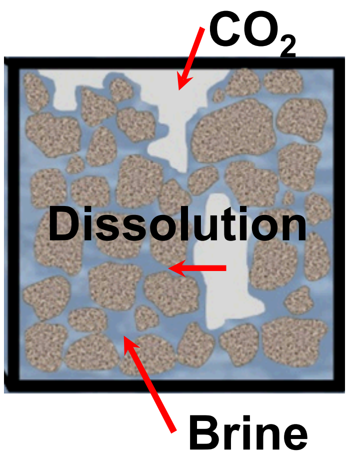
$$\frac{\partial}{\partial t}\phi\left(S_wC\right)+\nabla\bullet\left(\mathbf{v}_wC-\phi S_w\tau D_w^{CO_2}\nabla C\right)=Q_w^{CO_2}$$

- Dissolution rate:

$$Q_w^{CO_2}=\kappa S_n\phi\rho_w\left(x_{CO_2}^{sat}-x_{CO_2}\right)=-Q_n$$

- EoS:

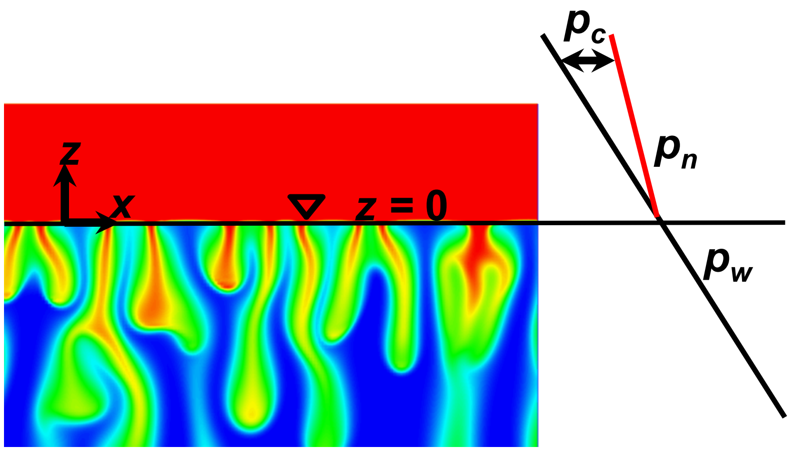
$$\rho_w=\rho_{w,ref}\left(1+\frac{\Delta\rho_w}{\rho_{w,ref}}\frac{C}{C_{sat}}\right),\qquad C\le C_{sat}$$

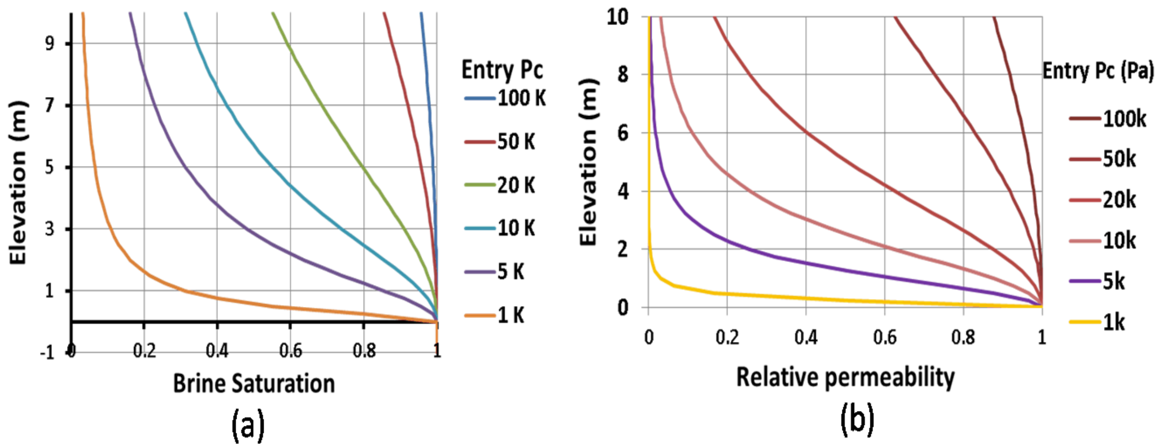


Initial state and capillary model

- Hydrostatic initial condition
- Van-Genunchten Pc model plus hydrostatic:

$$s_w\left(p_c(z)\right)=\left[\left(\frac{(\rho_w-\rho_n)\,g\,z}{p_{c0}}\right)^{\beta}+1\right]^{-\lambda}$$





Variation of (a) brine saturation and (b) relative permeability with elevation as a function of "entry pressure," p_{c0}

Impact of Capillary Transition Zone on CO_2 Dissolution Into Brine

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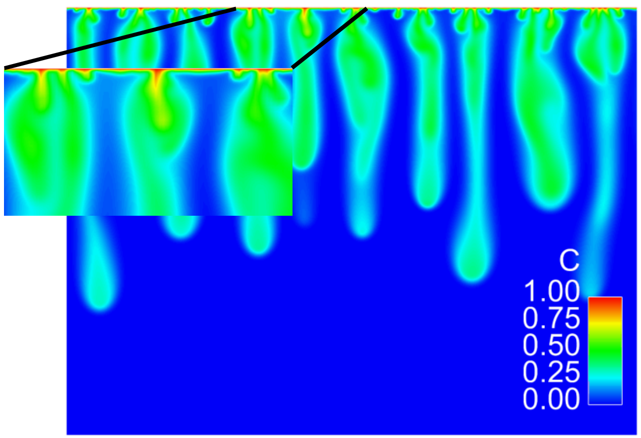
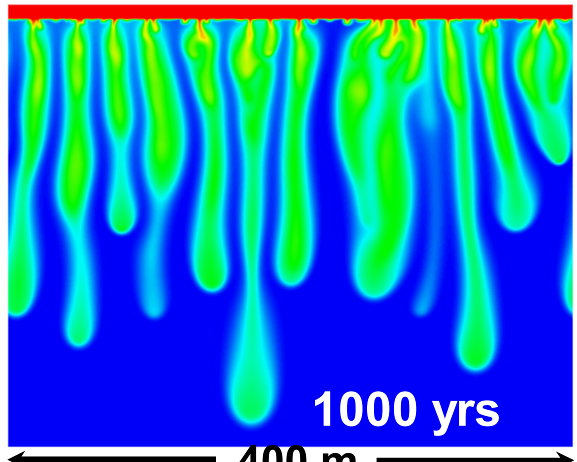
Dissolved CO_2 in Bravo Dome (k= 50 mD poro = 0.15) reservoir

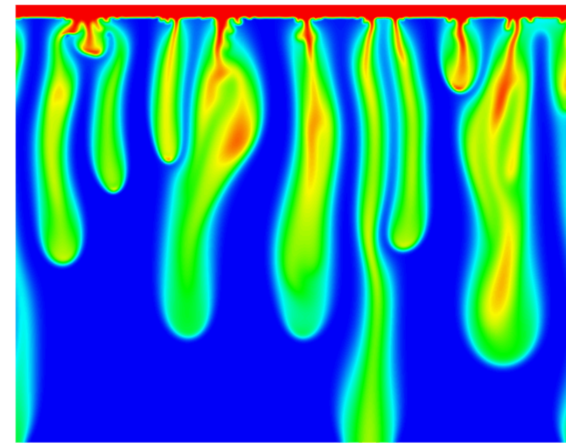
Single phase model

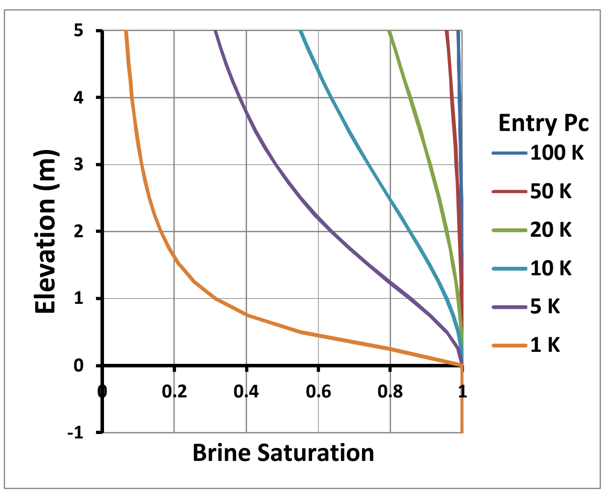


Pc = 5 K



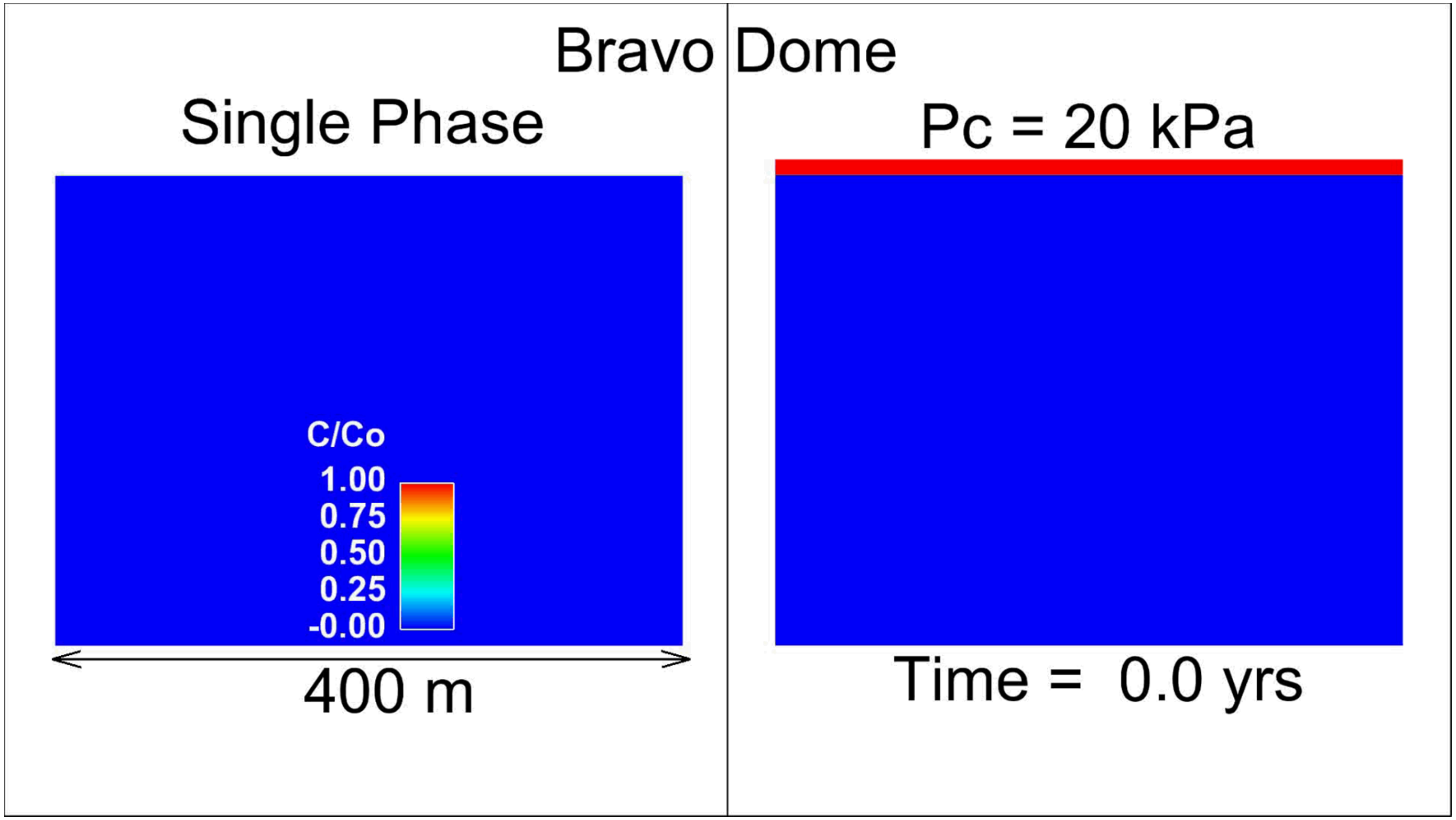
Pc = 100 K





- Least dissolution in single phase, closed top model
- Dissolution increases with cross-flow and entry pressure

Convective dissolution in a deep reservoir with Bravo Dome properties

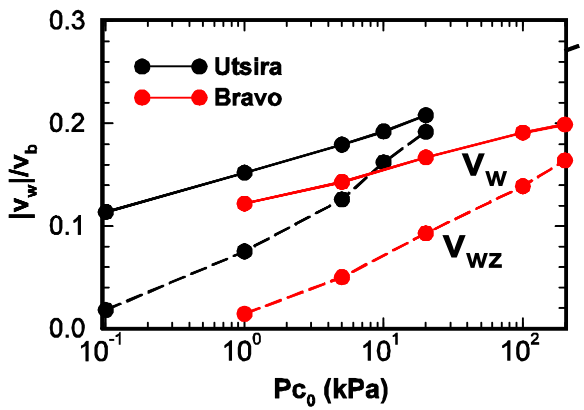


k = 50 mD Poro=0.15

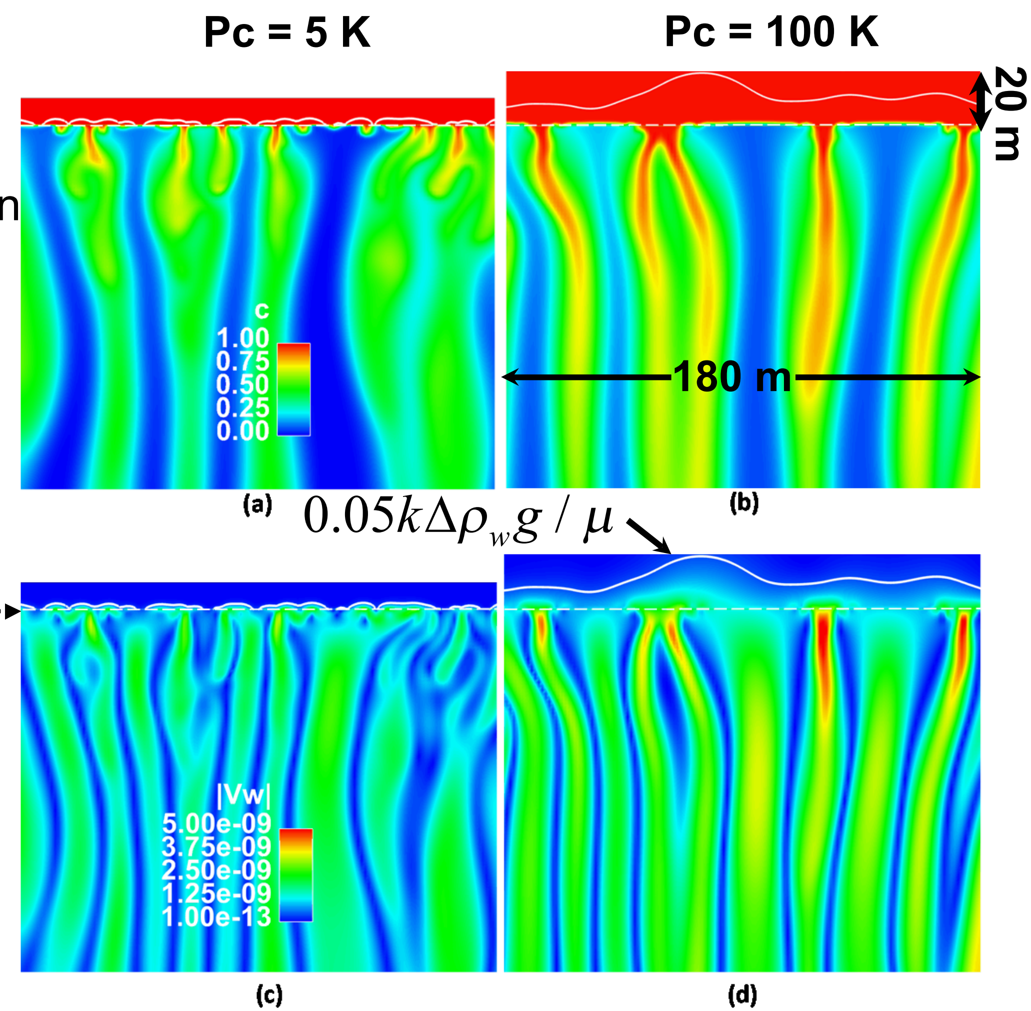
Approximate Convective Onset times: 85 (20 kPa) vs 120 (single phase) yrs

Two-phase model predicts higher dissolution

- Two phase model naturally allows currents loops above GWC
- The extent of currents increases with entry pressure (permeability stays high in two-phase region)
- Single phase, closed top:
  - boundary layer diffusion controlled
- Two-phase:
  - current loop → convectively-enhanced transport



Convection current strength at GWC increases with entry pressure



Extent of convection currents above GWC Bravo Dome

Dissolution flux history

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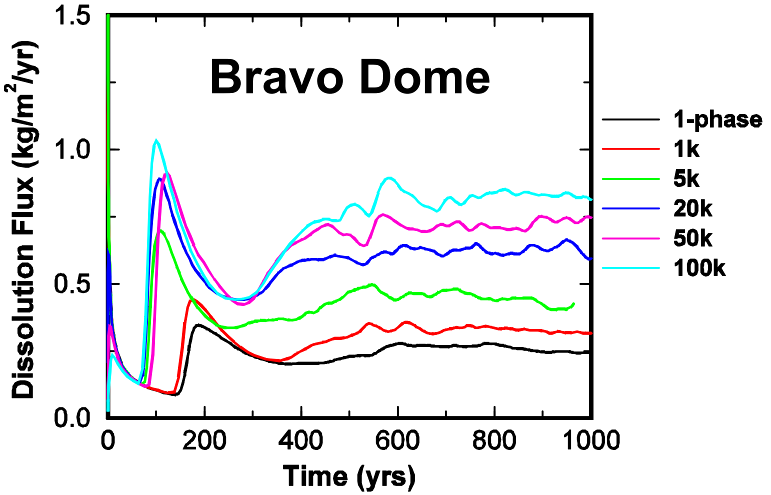


Observations:

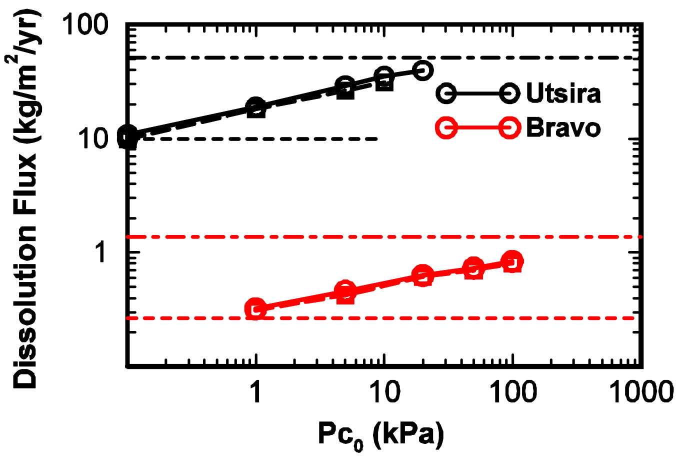
- F ~ 1/sqrt(t) early time diffusion before onset of convective currents
- Onset time decreases with cross-flow and entry pressure
- Quasi-steady flux rate eventually established

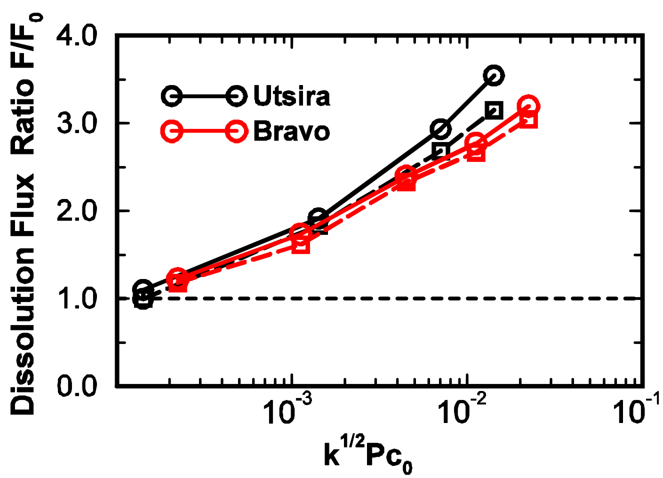
Flux calculation:

- Single phase
  - boundary flux via residual imbalance
- Two-phase

$$F(t) = \frac{1}{W} \int_{\Omega} Q_w^{CO_2} \, d\Omega$$

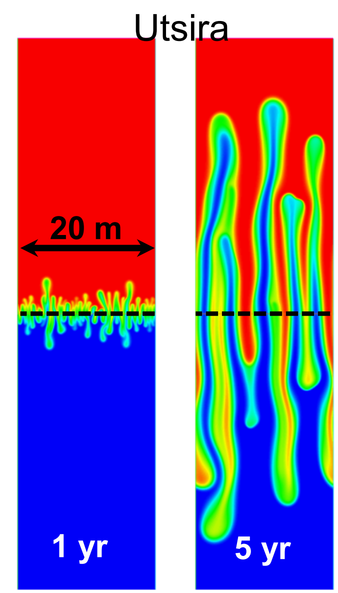
Long-term quasi-steady dissolution flux





- $p_{c0} \rightarrow 0$ recovers the single-phase, closed top dissolution rate
- For "large" but feasible p_{c0}, Flux ~ 3.5x single-phase fluxes
- An upper bound on flux is ~5x single-phase value, based on a convective mixing analog

Mixing Problem



Concluding remarks

- Inclusion of the two-phase region above the GWC provides a more realistic dissolution model:
  - Allows buoyantly driven convection current loops into the two-phase region
  - Dissolution of gas-phase CO_2 into brine is convectively assisted with current loops
  - For feasible values of entry pressure, the dissolution rate can be roughly 3.5 times the rate from a single-phase representation
  - An upper bound may be 5x based on a mixing model analog
- Single-phase, closed top model:
  - Generally under-predicts dissolution rate,
  - except for a reservoir with vanishing entry pressure (sand) $p_{c0} \rightarrow 0$ where the two model representations converge

Backup slides