

CO₂ Storage & Capillary Trapping

Motivation:

"Every week or so in the next 5 years, a new coal-fired power station will be built in China." (FT 22 Jan. 2007)



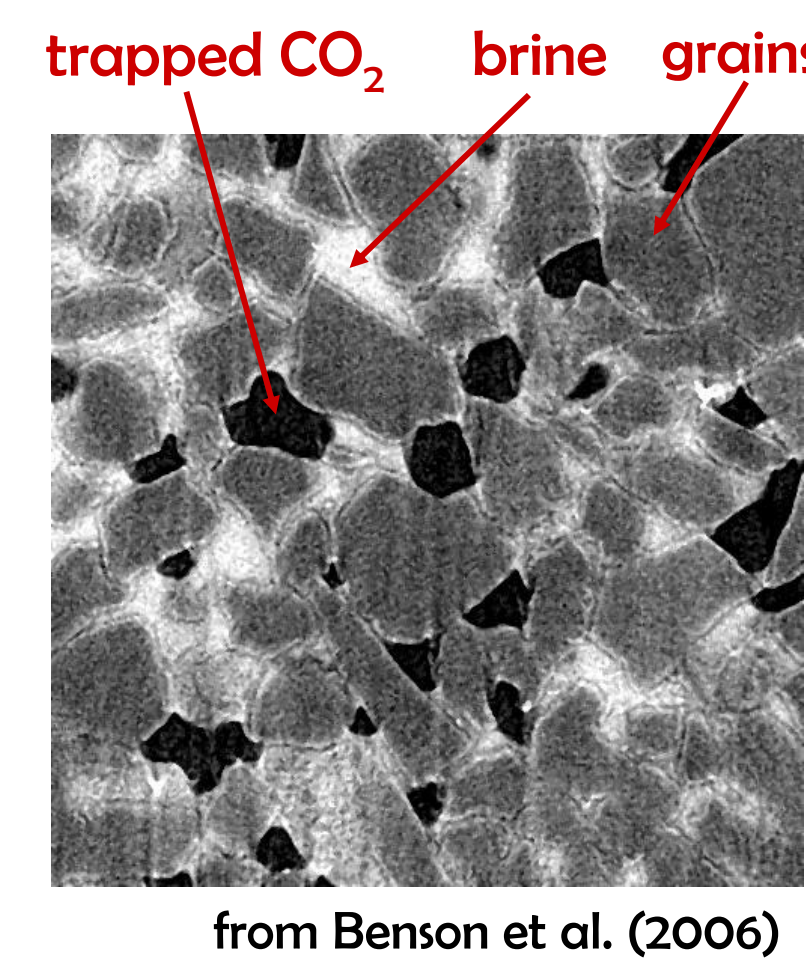
CO₂ Storage in Aquifers:

CO₂ storage in saline aquifers is only environmentally sound if leakage of CO₂ from the storage aquifer is limited. Leakage can occur, because positive buoyancy may drive CO₂ back to the surface along faults or old wells.

Capillary Trapping of CO₂

Capillary trapping is a pore scale mechanism that leads to the formation of isolated disconnected bubbles of CO₂ in the wake of a CO₂ plume. The high surface tension of the CO₂-brine interface keeps the CO₂ bubbles trapped in the pore body.

This well known phenomenon, has frustrated oil recovery for decades. In aquifer storage of CO₂, it may rapidly trap CO₂ underground and limit the time during which leakage is possible. Capillary trapping may therefore be a key mechanism allowing safe storage of CO₂ in saline aquifers.



from Benson et al. (2006)

Efficiency of Capillary Trapping:

To understand the efficiency of capillary trapping we need to address the following questions:

- 1) What fraction of the aquifer volume is swept by the CO₂-plume?
- 2) In the swept aquifer, what fraction of the pore space contains CO₂ trapped by capillary forces?

Here we try to understand the first question, and assume a constant amount of trapped CO₂.

We address following questions:

1. How do viscosity, the amount of trapping, and the slope of the aquifer affect the sweep of the CO₂ plume?
2. How rapidly does capillary trapping reduce the volume of mobile CO₂ in the aquifer?
3. What is the migration distance & time?

A Simple Model for the CO₂ Plume

Assuming a homogeneous aquifer, vertical equilibrium, and a sharp interface the evolution of the interface is governed by the following pde:

$$\frac{\partial \eta}{\partial \tau} + \sigma \frac{\partial}{\partial \xi} \left[\frac{\eta(1-\eta)}{\eta(M-1)+1} \right] = \frac{\sigma}{Pe} \frac{\partial}{\partial \xi} \left[\frac{\eta(1-\eta)}{\eta(M-1)+1} \frac{\partial \eta}{\partial \xi} \right], \quad \sigma = \begin{cases} 1; & \eta_c \leq 0 \\ 1-\varepsilon; & \eta_c > 0 \end{cases}$$

where $\eta = h/H$, $\xi = x/L_0$, and $\tau = t/t^*$ are dimensionless interface height, position and time respectively. The model has 3 governing parameters, the mobility ratio M , the Peclet number Pe , and the trapped fraction ε given by

$$M = \frac{k_{rg}^* \mu_w}{\mu_g k_{rw}^*}, \quad Pe = \frac{L_0}{H_0} \tan \theta, \quad \varepsilon = \frac{S_{gr}}{1-S_{wr}}$$

where H is the height of the aquifer, L_0 is the initial width of the plume, and θ is the dip angle of the aquifer. The fluid properties of phase i are, the viscosity μ_i , the relative permeability k_{ri} , and the residual saturation S_{ri} .

Horizontal Aquifer: Self-Similar Solution

In the limit $Pe \rightarrow 0$ and $M \rightarrow 0$ the shape to the plume becomes self-similar. The loss introduced by capillary trapping leads to scaling laws with an anomalous exponent β , which cannot be obtained from dimensional analysis. The scaling laws for the evolution of important quantities in the plume are:

- 1) The volume of CO₂-plume decreases as: $V \sim \tau^{2\beta-1}$
- 2) The plume front propagates as: $\xi_f \sim \tau^\beta$
- 3) The plume height decays as: $\eta \sim \tau^{2\beta-1}$

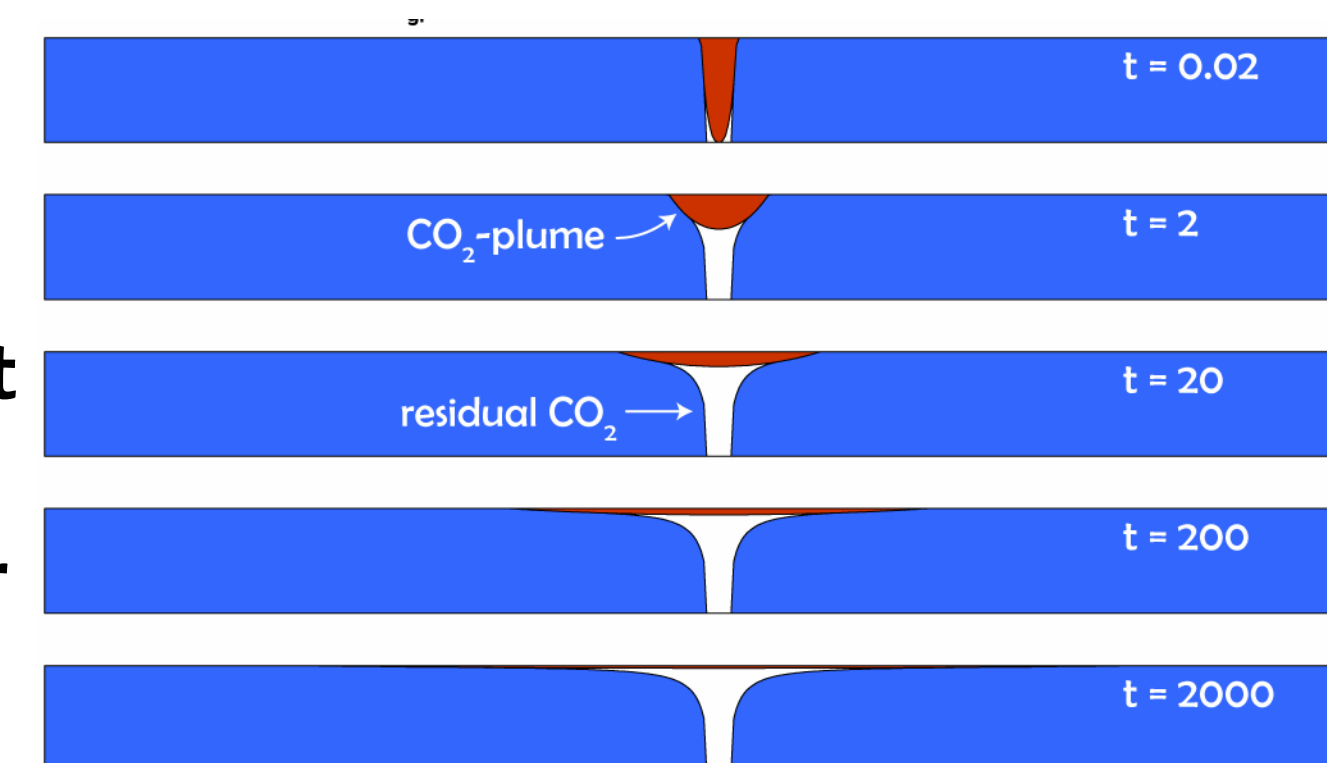
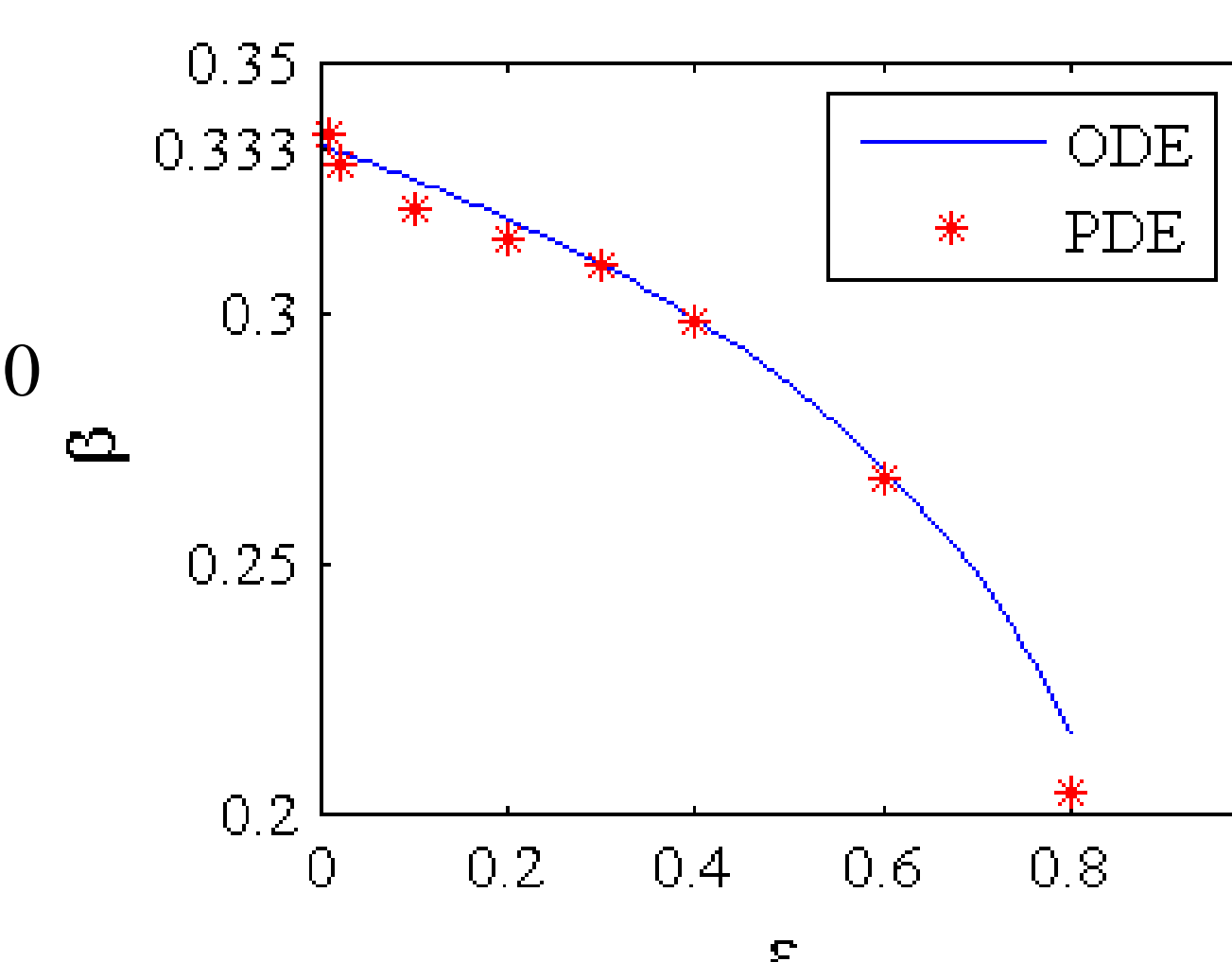
Note: The self-similarity implies that the current is never exhausted, and maximum migration distance and time cannot be determined. In reality capillary forces will arrest the current at some point.

Self-Similar Eigenvalue Problem for Anomalous Exponent:

The anomalous exponent β is the eigenvalue of following second order ode:

$$\phi_1 \frac{d^2 \phi_1}{d\xi^2} + \left(\frac{d\phi_1}{d\xi} \right)^2 + c(\xi) \left[(1-2\beta)\phi_1 + \beta \xi \frac{d\phi_1}{d\xi} \right] = 0$$

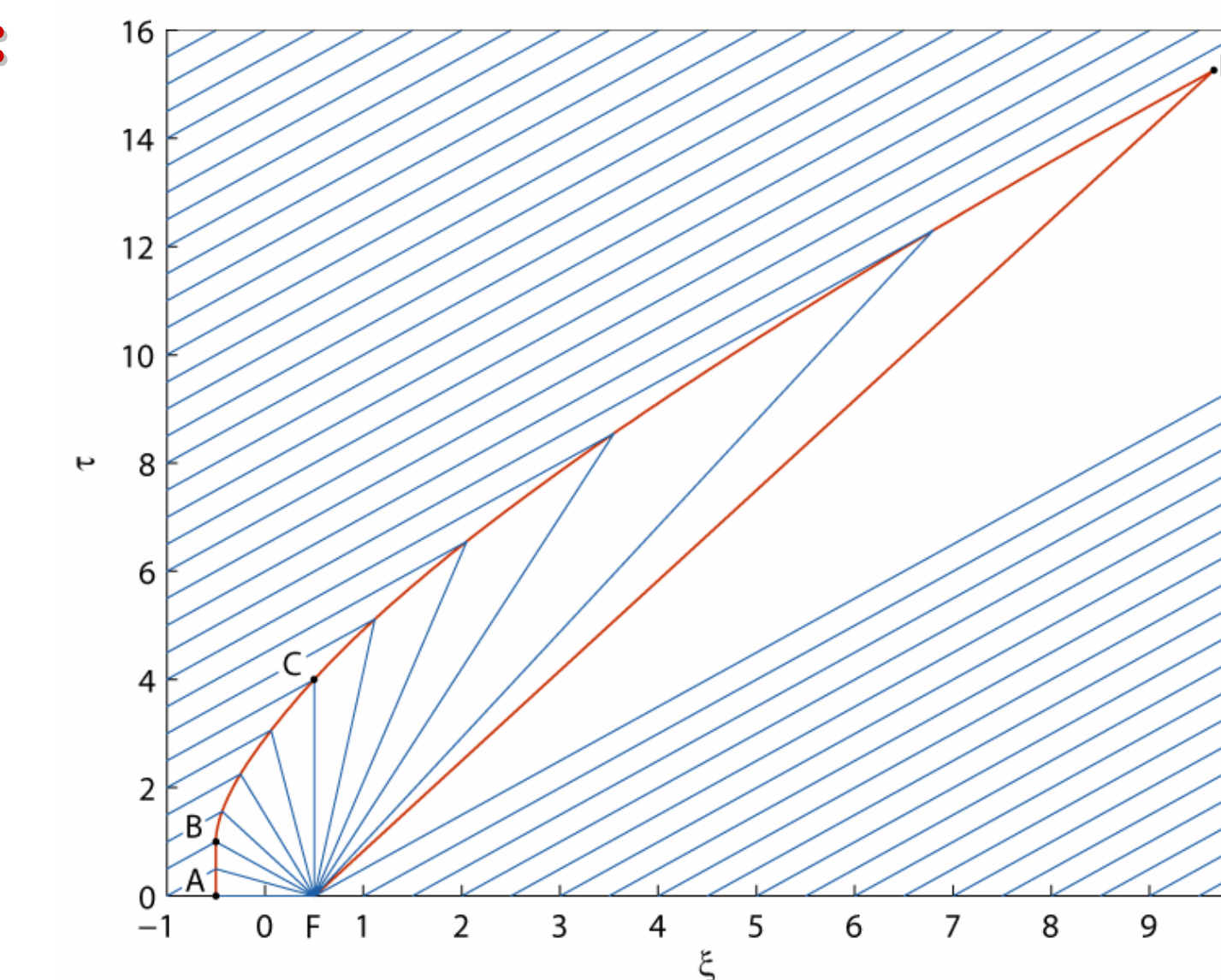
The eigenvalue is a decreasing function of the trapped fraction ε is shown on the right. In the absence of loss the $\beta = 1/3$, the result from dimensional analysis.



Sloping Aquifer: Travelling Wave Solutions

Method of Characteristics Solution:

In the limit of $Pe \gg 1$, but also for $M \gg 1$ and $Pe \sim 1$, the solution hyperbolic limit is a good approximation. In this case the front of the current is a rarefaction (F-D) and the trailing edge of the current is a shock (A-B-C-D). In the t - x plane the current widens initially (slumping), but as the current begins to translate (sliding), the width decreases rapidly.



Initially the volume decreases as a scaling law as in the horizontal case (slumping). Once the current is mostly translating, the volume decreases very rapidly.

$$V = \begin{cases} 1 - \frac{\tau\varepsilon}{4}, & \tau \leq 4, \\ \frac{(1-\varepsilon) \left(2^{-\frac{\varepsilon}{1-\varepsilon}} \tau^{2(1-\varepsilon)} - \varepsilon\tau \right)}{(1-2\varepsilon)^2 \tau}, & \tau > 4. \end{cases}$$

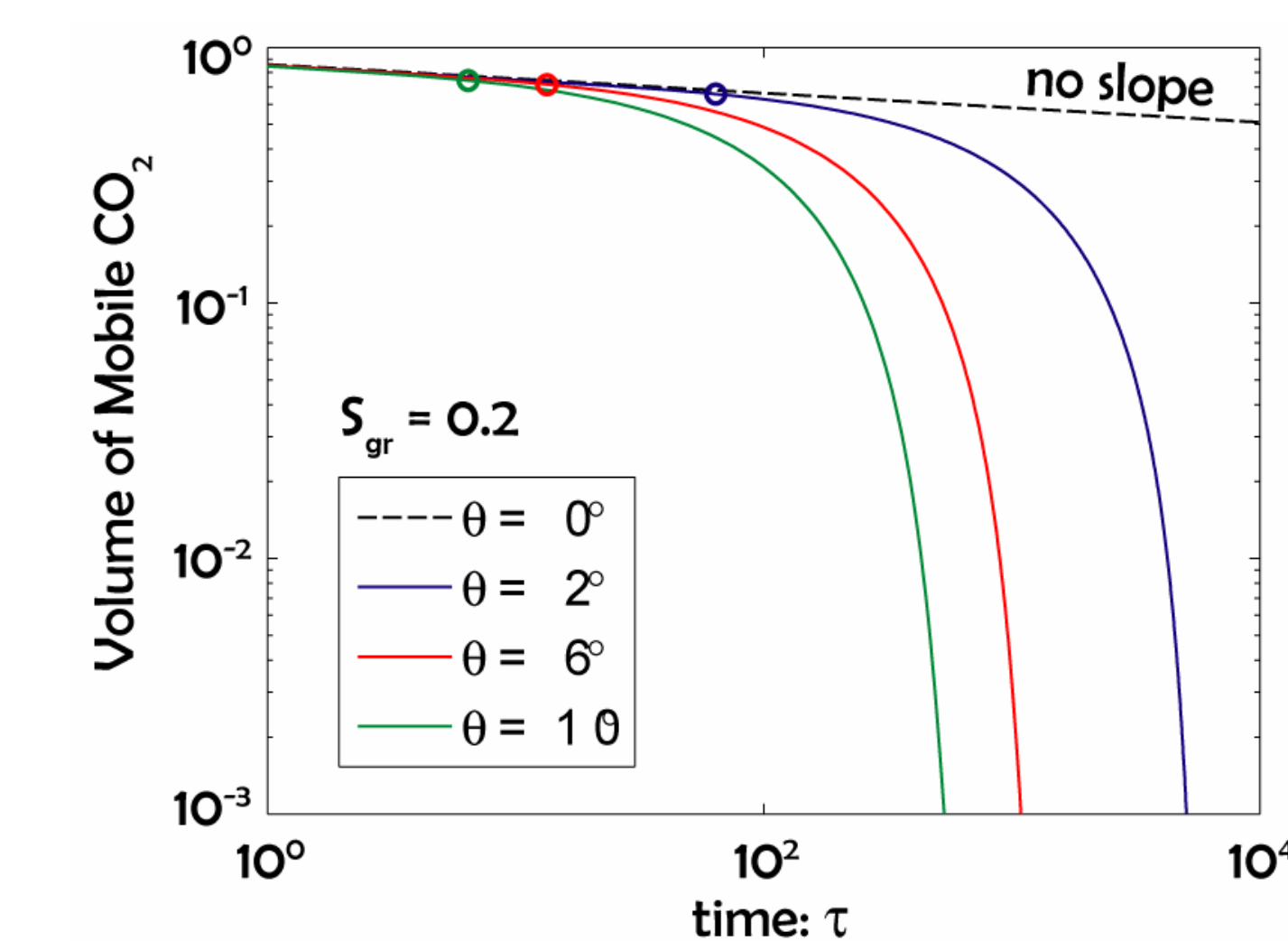
Expressions for the migration distance & time can also be obtained:

$$\xi_{\max} = \frac{1}{2} + (1-\varepsilon) 2^{1-\frac{1}{1-2\varepsilon}} \varepsilon^{-(1+\frac{1}{1-2\varepsilon})}, \quad \tau_{\max} = \left(2^{\frac{1}{1-\varepsilon}-1} \varepsilon \right)^{\frac{2(1-\varepsilon)}{1-2(1-\varepsilon)}}$$

Full Numerical Solutions: Effect of Slope

The full numerical solution clearly shows the behavior observed in the two limiting cases.

In a horizontal aquifer the plume volume decreases as a power law. In the sloping aquifer an initial phase of power law decay is followed by a very rapid decay in plume volume.



Conclusions

1. In horizontal aquifers the plume volume decreases as a power law.
⇒ capillary trapping becomes very slow at late times!
2. In sloping aquifers an initial phase of power-law volume decay is followed by very rapid volume decay.
⇒ capillary trapping becomes much more efficient at late times!
3. Sloping aquifers trap the injected CO₂ faster, and may be safe storage sites.