CO_2 Gravity Currents and Residual Trapping in Saline Aquifers: Part 1

[1]Marc Hesse, [1]Hamdi Tchelepi & [2]Brian Cantwell & [1]Franklin Orr, Jr.,

[1] Energy Resources Engineering, Stanford University; [2]Aeronautics & Astronautics, Stanford University

GCEP Global Climate & Energy Project STANFORD UNIVERSITY

Footprint of the Plume

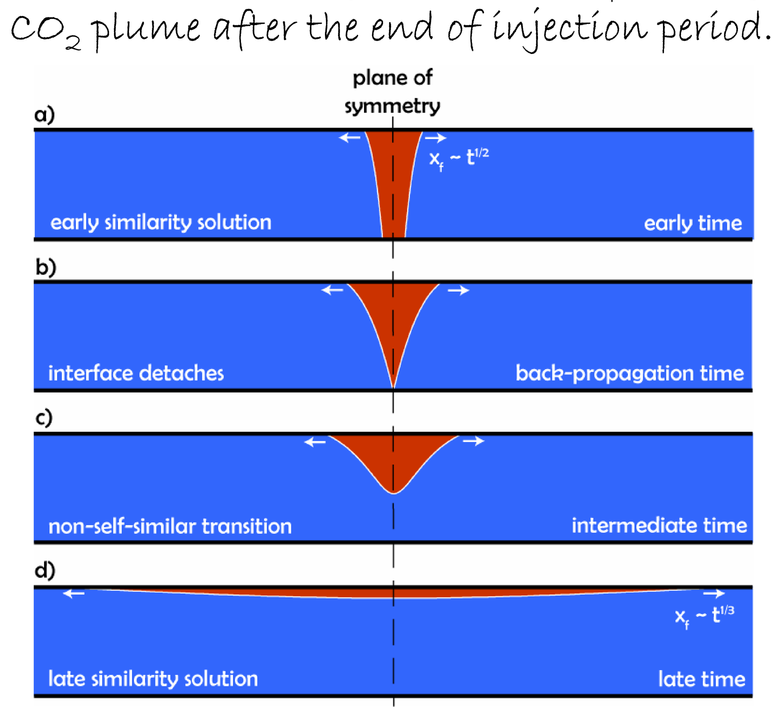
Carbon Capture & Storage

"Sir David King (U.K. chief scientist) told the BBC carbon capture and storage technology was the only way forward as China and India would inevitably burn their cheap coal." (BBC 12/06/2005)

Carbon Capture and Storage (CCS) calls for the capture of carbon dioxide from large point sources, such as power stations and refineries, and long term underground storage in deep saline aquifers and other reservoirs. CCS is expected to act as a bridging technology that has the potential to reduce the greenhouse gas emissions from fossil fuels, while renewable energies are developed to full scale.

The Footprint of the CO_2-Plume

The injected CO_2 is expected to move for several thousand years after injection as a gravity current. To ensure secure storage, estimates CO_2 migration are essential during site selection and monitoring.
The footprint of the CO_2 plume is the area invaded by CO_2 at a given time. We use a simple model to show that a transition in the propagation regime of the CO_2 plume has to be expected after several hundred years. The figure below shows the gravitational spreading of the injected CO_2 plume after the end of injection period.



References:

1. Hesse M., Tchelepi H., Cantwell B. & Orr Jr. F. (2006): Gravity currents in horizontal porous layers: transition from early to late self-similarity, submitted to *J. Fluid Mech.*
2. Hesse M., Tchelepi H. & Orr Jr. F. (2006): Scaling analysis of the migration of CO_2 in saline aquifers, SPE 102796, San Antonio TX

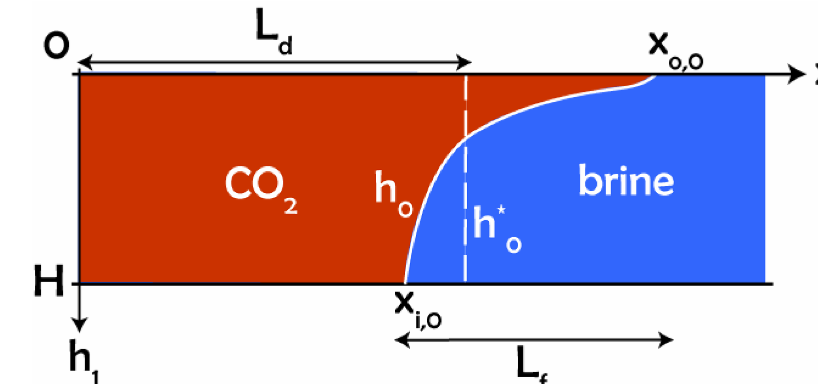
Early and Late Similarity Solution

Governing Equation, Initial Conditions & Length Scales:

The evolution of the interface h is governed by a partial differential equation:

$$\frac{\partial h}{\partial t} = \kappa \frac{\partial}{\partial x}\left[\frac{h(H-h)}{h(M-1)+H}\frac{\partial h}{\partial x}\right] \qquad M = \frac{\lambda_p}{\lambda_q} = \frac{\mu_q}{\mu_p} \qquad \kappa = \frac{kg\Delta\rho}{\mu_p \phi}$$

After the end of injection the CO_2 distribution in the aquifer is shown on the right. This distribution provides the initial condition for the buoyancy driven migration of the CO_2 in the post-injection phase.



This initial condition has 3 length scales that determine the evolution of the plume. The height of the aquifer H, the average displacement distance L_d, and the width of the front at early times L_f.

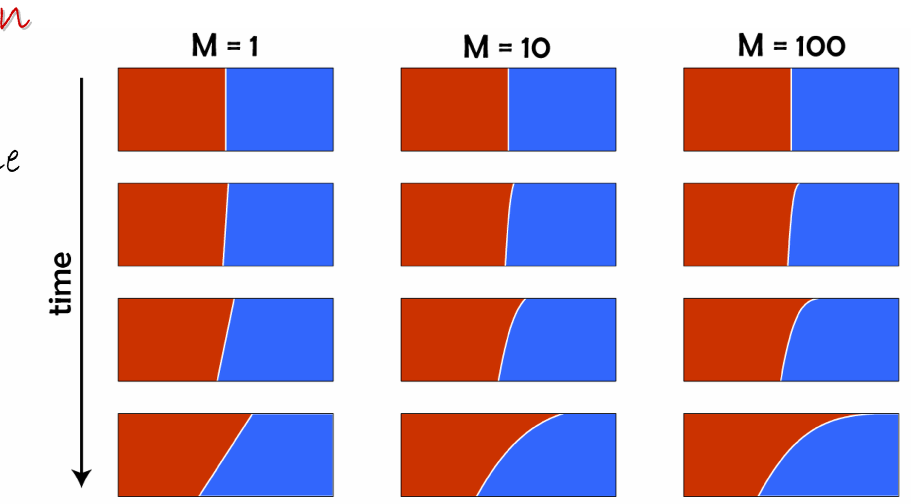
Early Self-Similar Solution

At early times the fronts don't interact and the similarity variable

$$\varsigma = \frac{x}{(\kappa H t)^{\frac{1}{2}}},$$

allows reduction to an ODE:

$$-\frac{\varsigma}{2}\frac{\partial \theta}{\partial \varsigma} = \frac{\partial}{\partial \varsigma}\left[\frac{\theta-\theta^2}{\theta(M-1)+1}\frac{\partial \theta}{\partial \varsigma}\right]$$



Therefore the tip of the CO_2 front migrates proportional to $t^{1/2}$ at early times, the early self-similar solution is a strong function of the mobility ratio M.

Late Self-Similar Solution

At late times the fronts have joined and once the plume occupies only a small fraction of the aquifer depths the governing equation simplifies to:

$$\frac{\partial h}{\partial t} = \kappa \frac{\partial}{\partial x}\left[h\frac{\partial h}{\partial x}\right]$$

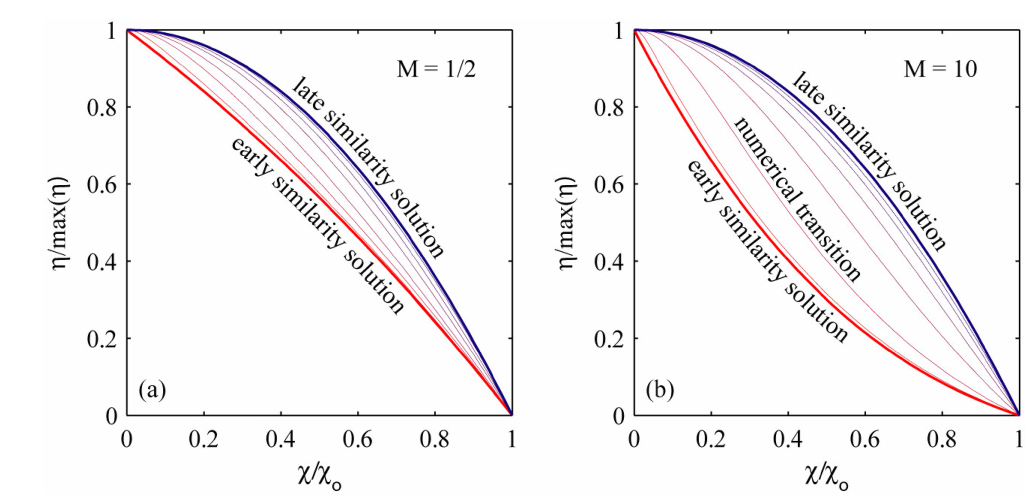
This equation admits a new similarity variable $\xi = \frac{x}{(\kappa V t)^{\frac{1}{3}}}$, that allows reduction to another ODE

$$-\frac{\xi}{2}\frac{\partial \varphi}{\partial \xi} = \frac{\partial}{\partial \xi}\left[\varphi\frac{\partial \varphi}{\partial \xi}\right]$$

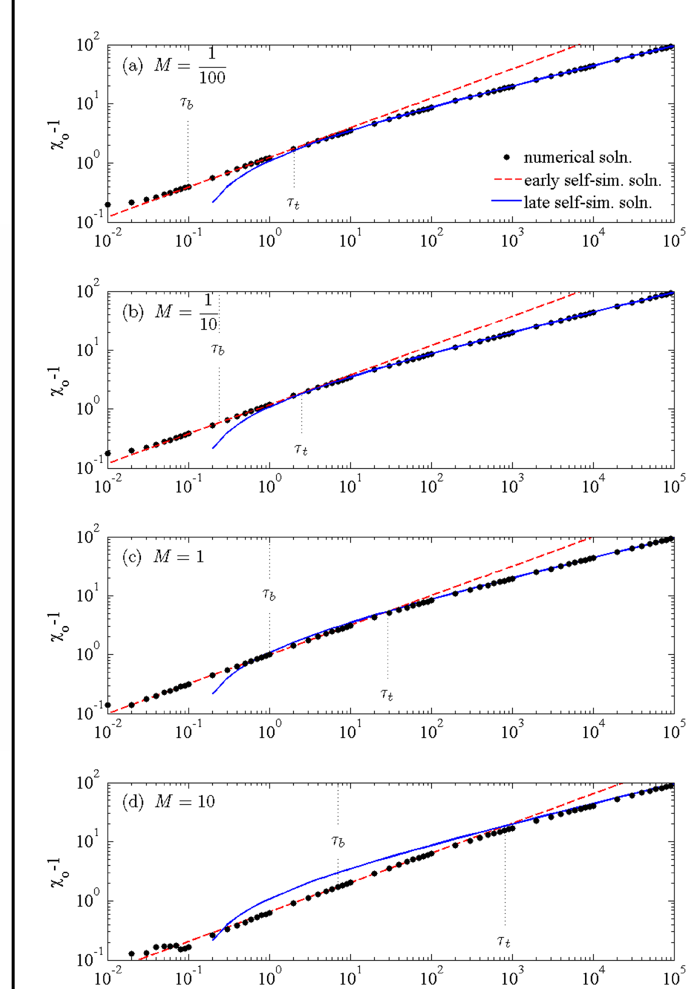
Therefore the tip of the CO_2 front migrates proportional to $t^{1/3}$ at late times, and independent of M.

Transition Time

Numerical Transition Between early and late solution:



Transition in the Tip Propagation Speed

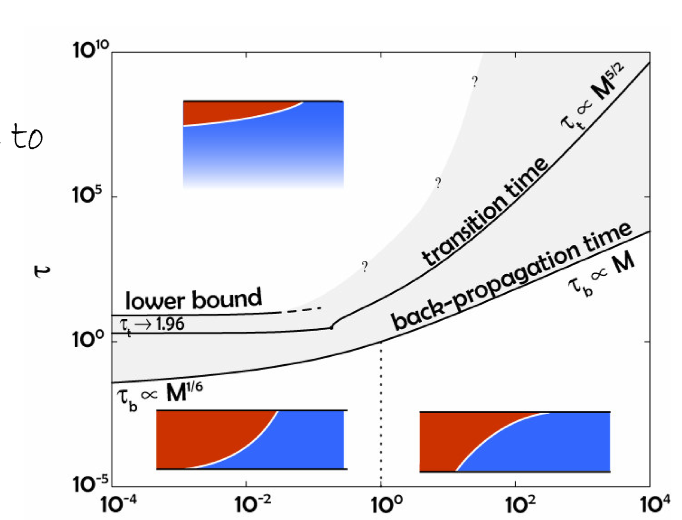


The tip of the CO_2 plume initially follows the scaling law derived from the early similarity solution, and after some time crosses over to the scaling law derived from the late similarity solution. The transition time increases as the mobility ratio M increases. For M<1/10 the increase is very slow, and very fast for M>1/10.

We have obtained an expression for the transition time as a function of M, shown in the regime diagram below. The mobility ratio M is the only parameter determining the evolution of the gravity current.

Conclusions:

Gravity currents in a horizontal porous medium initially propagate proportional to $t^{1/2}$ and later proportional to $t^{1/3}$.
If this transition is not anticipated the footprint of the CO_2 plume will be over estimated significantly at late times.
For Sleipner injection site the transition occurs after a few hundred years.



contact: mhesse@stanford.edu

CO_2 Gravity Currents and Residual Trapping in Saline Aquifers: Part 2

Marc Hesse, Franklin Orr, Jr.& Hamdi Tchelepi

Global Climate & Energy Project
STANFORD UNIVERSITY

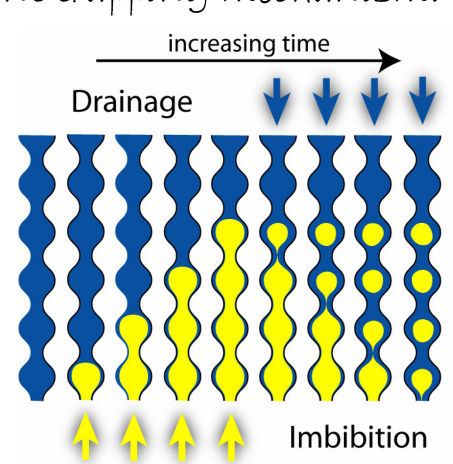
Capillary Trapping

Background: CO_2 Storage & Leakage

CO_2 capture and storage is only environmentally sound, if leakage of CO_2 into the atmosphere is limited. Positive buoyancy drives gaseous CO_2 back to the surface along faults or old wells. Trapping mechanisms that immobilize the CO_2 limit the time available for leakage. If trapping mechanisms are able to reduce the amount of mobile CO2 relatively quickly after injection, then leakage would be less of a concern.

Capillary Trapping of CO_2

Capillary trapping of CO_2 in the wake of a migrating CO_2 plume may be an important trapping mechanism. Capillary trapping is illustrated using a sinusoidal glass tube, initially saturated with brine (blue). CO_2 gas (yellow) is injected into the base of the tube, and brine displaced except for a wetting film of "connate water" S_{wc} along the boundary.



The displacement of wetting by non-wetting fluid is called "drainage". The height "h" of the connected CO_2 is increasing, until we reverse the flow direction and inject water into the top. During this "imbibition process" an capillary instability causes "snap-off" of CO_2 bubbles. These CO_2 bubbles are now isolated and large pressure gradients are necessary to squeeze them through the constrictions of the tube. So that we end up with a zone of residually trapped CO2 in the lower half of the tube.

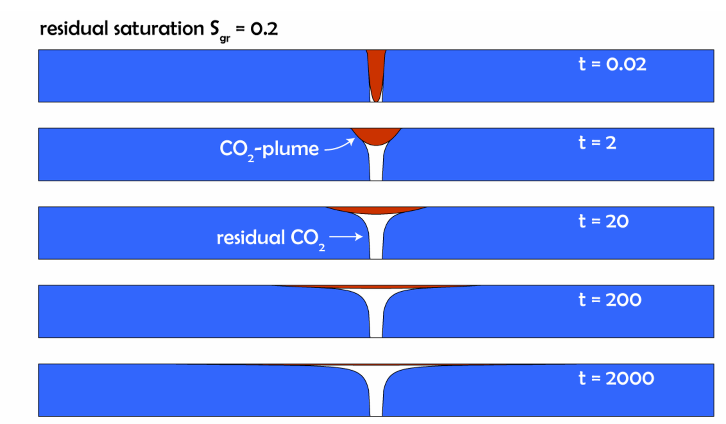
Important Questions we are Addressing:

1) How rapidly does capillary trapping reduce the volume of mobile CO_2 in the aquifer?
2) What is the maximum migration distance?
3) How does trapping affect the propagation speed of the CO_2 front?
4) What is the effect of a sloping top boundary?

Horizontal Aquifer

Evolution of the CO_2 Plume:

The figure shows the evolution of the CO2 plume in a horizontal aquifer. The plume of mobile CO2 (blue) slumps due to gravity and spreads along the top boundary of the aquifer. Leaving behind a zone of capillary trapped CO_2 (red).



Governing Equation

$$\frac{\partial h}{\partial t} = D(x,t)\frac{\partial}{\partial x}\left[h\frac{\partial h}{\partial x}\right] \qquad D(x,t) = \begin{cases} \kappa_1 = \dfrac{k\Delta\rho g}{\mu\phi(1-S_{gr}-S_{wc})}; & \dfrac{\partial h}{\partial t} \le 0 \\ \kappa = \dfrac{k\Delta\rho g}{\mu\phi(1-S_{wc})}; & \dfrac{\partial h}{\partial t} > 0 \end{cases}$$

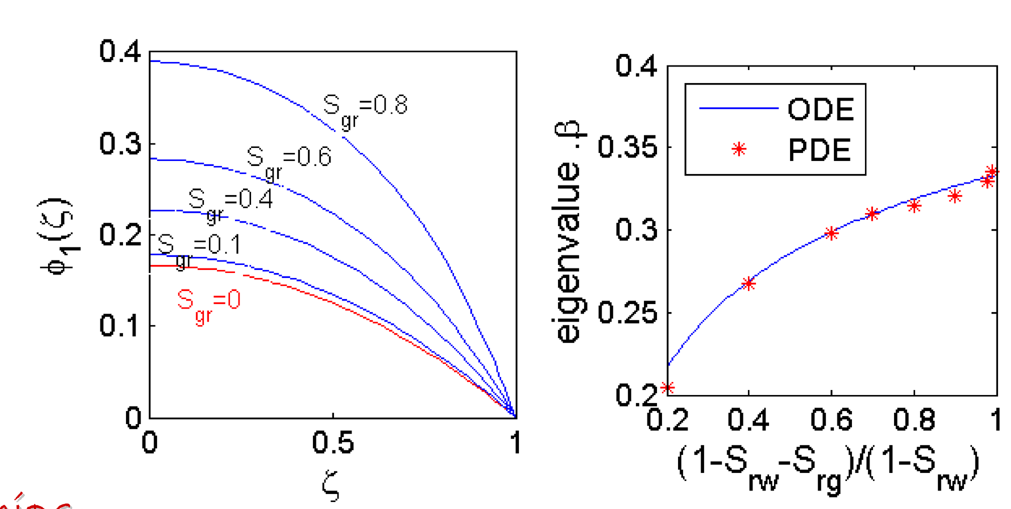
Self-Similar Eigenvalue Problem for Propagation Speed

The assumption of incomplete self similarity allows reduction to a non-linear 2[nd] order ode with eigenvalue β. The eigenvalue β gives the front propagation speed, and the scaling all other quantities. The ode has the following form

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

The numerical solution of this ode gives the self-similar shape of the current (left) and the eigenvalue β as a function of S_{gr} (right).

The eigenvalues β obtained from the solution of the ode (-) compare well with the front propagation speed measured from full numerical solution of the pde (*).



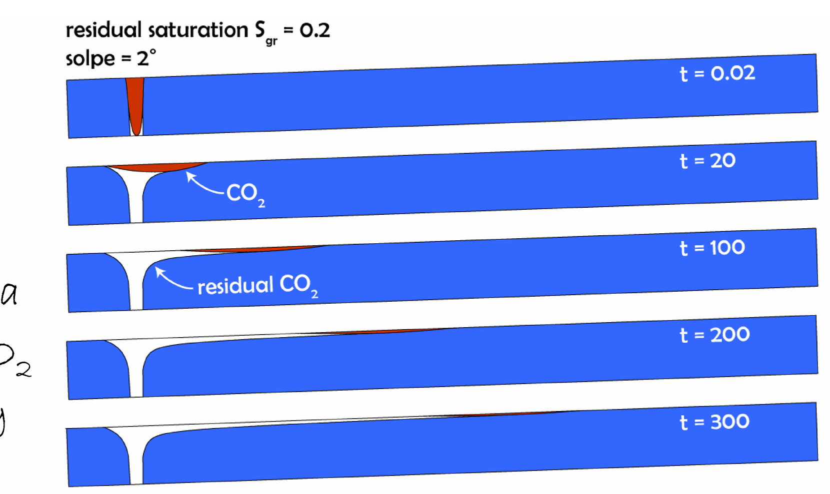
Scaling Reatiomships:

1) The volume of mobile CO_2 decreases as: $Q \sim t^{3\beta-1}$
2) The plume front propagates as: $x_f \sim t^{\beta}$
3) The plume height decays as: $h \sim t^{2\beta-1}$

Sloping Aquifer

Evolution of CO_2 Plume:

The figure shows the evolution of the plume CO_2 in an aquifer inclined by 6° and $S_{gr} = 0.2$. The plume of mobile CO_2 (blue) migrates up-dip until it is exhausted, leaving behind a zone of capillary trapped, residual CO_2 in its wake (red). Capillary trapping is more effective, because the vertical sweep is improved.

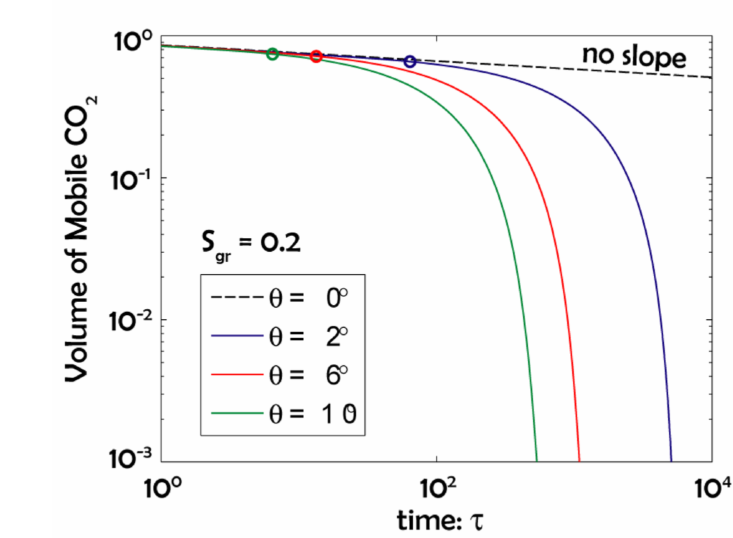


Governing Equation for the Sloping Aquifer:

$$\frac{\partial h}{\partial t} + D(x,t)\sin\theta\frac{\partial h}{\partial x} = D(x,t)\cos\theta\frac{\partial}{\partial x}\left[h\frac{\partial h}{\partial x}\right] \qquad D(x,t) = \begin{cases} \kappa_1 = \dfrac{k\Delta\rho g}{\mu\phi(1-S_{gr}-S_{wc})}; & \dfrac{\partial h}{\partial t} \le 0 \\ \kappa = \dfrac{k\Delta\rho g}{\mu\phi(1-S_{wc})}; & \dfrac{\partial h}{\partial t} > 0 \end{cases}$$

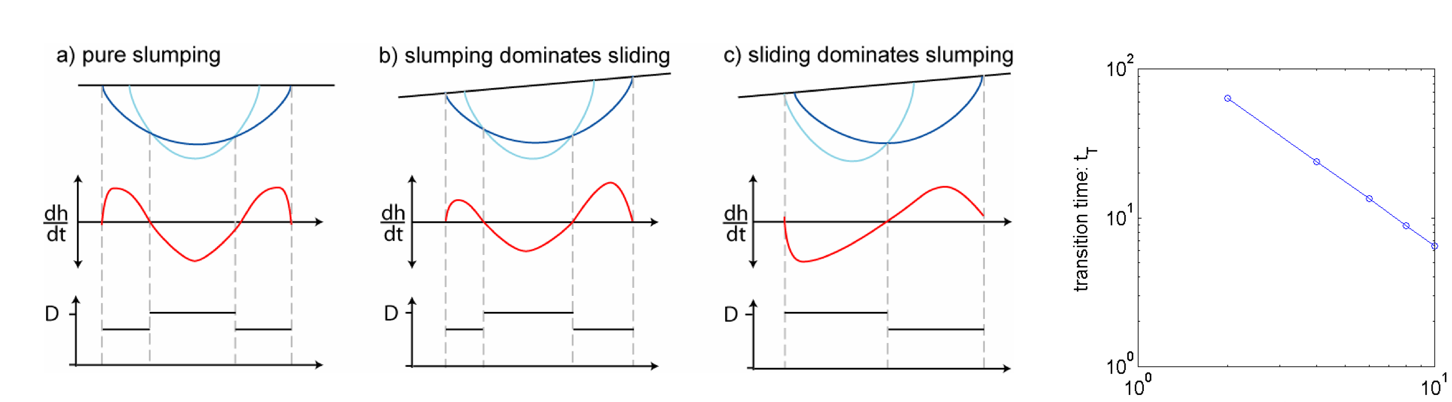
Evolution of the Volume of Mobile CO_2:

Initially the volume of mobile CO_2 follows a scaling law $V \sim t^{\beta}$ with a constant exponent β, similar to horizontal case (--). At later times the volume of mobile CO_2 decreases much more rapidly, and the exponent continues to decrease monotonically with time. The time of transition t_T decreases with increasing slope.



Transition from Slumping to Sliding:

Figure (b) shows situation at early times were slumping dominates, figure (c) the late time regime. The transition t_T is defined by the vanishing of the trailing maximum in the dh/dt plot (red). The transition time scales as $t_T \sim \theta^{-3/2}$.



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contact: mhesse@stanford.edu