High Resolution Simulation and Characterization of Density-Driven Flow in CO_2 Storage in Saline Aquifers

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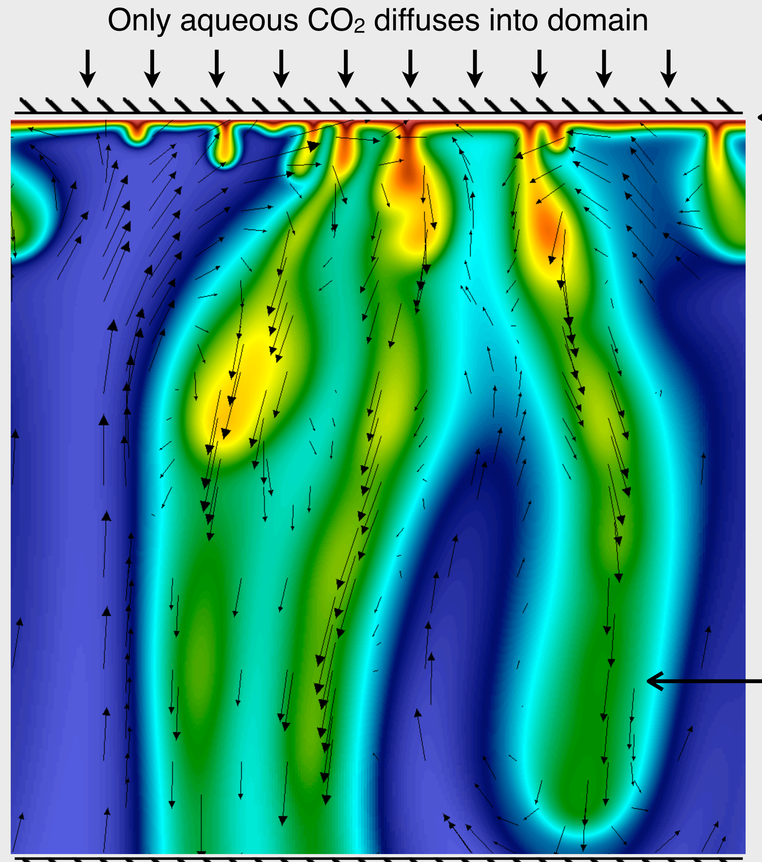
The Approach

Motivation

The dissolution-diffusion-convective process removes CO_2 from a highly mobile and buoyant gas phase and puts it into a less mobile and negatively buoyant aqueous phase. We study the short term and long term behaviors of the process through high resolution simulations using a second-order accurate sequential algorithm, implemented within a block structured adaptive mesh refinement framework.

Problem Setup

Variable-density single-phase incompressible model to efficiently capture the transport mechanisms.



- Equation of states: $\frac{1}{\rho} = \sum_{i=1}^{2} \frac{X_i}{\rho_i}$

  ρ_i, X_i : component density, mass fraction
- Density increase due to CO_2 dissolution = 10.45 kgm^{-3}.
- Convective flow is induced by random permeability or porosity.

Governing Equations

Based on a total velocity splitting approach:

- Velocity divergence constraint reflects dependence of fluid density on the mass fraction of dissolved CO_2:

$$\nabla \cdot \mathbf{u} = \sum_{i=1}^{2} \frac{1}{\rho_i} \nabla \cdot \phi \rho \tau D \nabla X_i, \quad i = 1(CO_2), 2(H_2O)$$

  ϕ: porosity D: diffusion coefficient
- Darcy flow.

$$\mathbf{u} = -\frac{\kappa}{\mu}(\nabla p - \rho \mathbf{g})$$

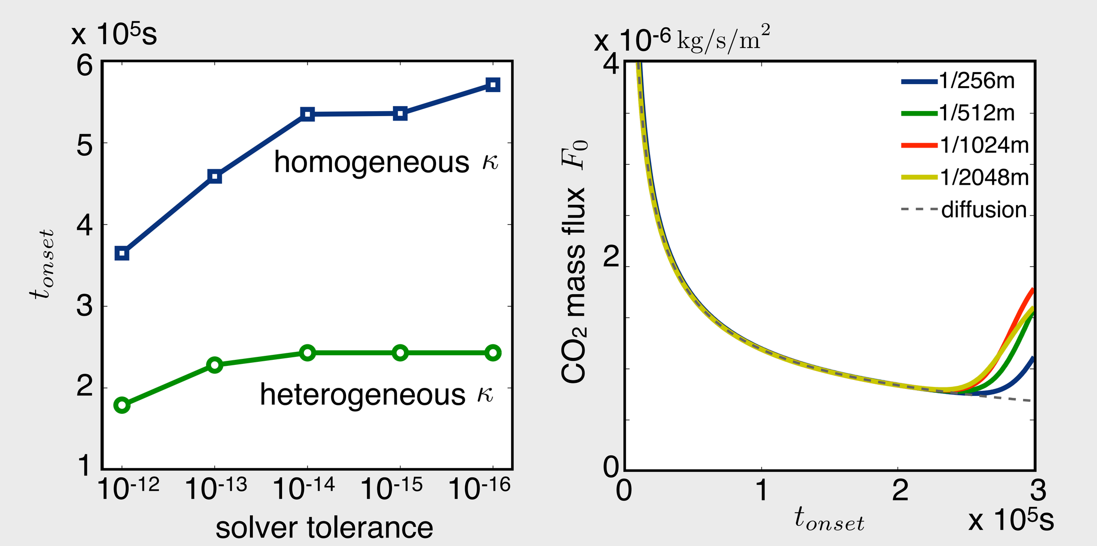
  κ: permeability μ: viscosity p: pressure
- Mass conservation.

$$\frac{\partial \phi \rho X_i}{\partial t} + \nabla \cdot (\rho X_i \mathbf{u}) = \nabla \cdot \phi \rho \tau D \nabla X_i, \quad i = 1, 2$$

Numerical Method

Second-order IMPES Algorithm

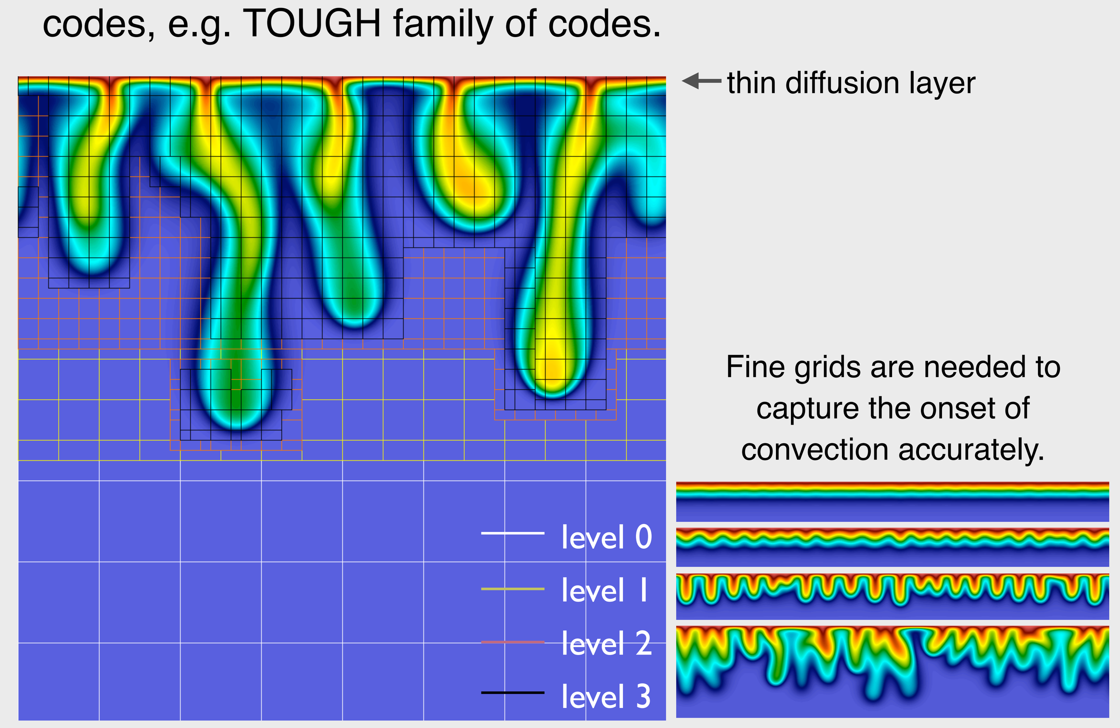
- Discretization
  - pressure equation → elliptic
    - ➥ finite difference, solved implicitly.
  - mass conservation equation → parabolic
    - ➥ advection term: 2nd order Godunov method;
    - ➥ diffusion term: Crank-Nicolson implicit scheme.
- Time stepping: time-centered.
- Advantages
  - minimizes numerical dispersion.
  - amenable to simple parallelization.



Accurate solver ensures the onset of convection is solely due to heterogeneity in rock properties and the onset time converges as grid spacing → 0.

Adaptive Mesh Refinement (AMR) Framework

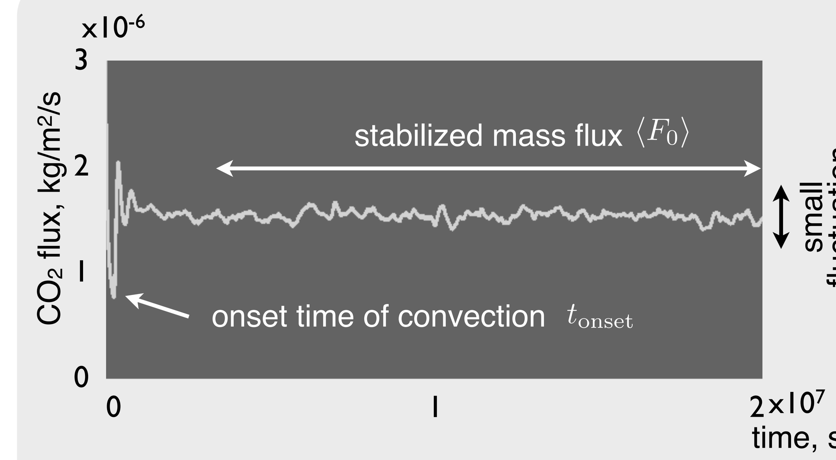
- Multiscale: resolves difference in length scales between flow regimes and time scales between flow and reaction.
- Parallelized codes: good scaling behavior up to several thousands CPUs, allowing large 3D simulation.
- Improved resolution: significant gain compared to existing codes, e.g. TOUGH family of codes.



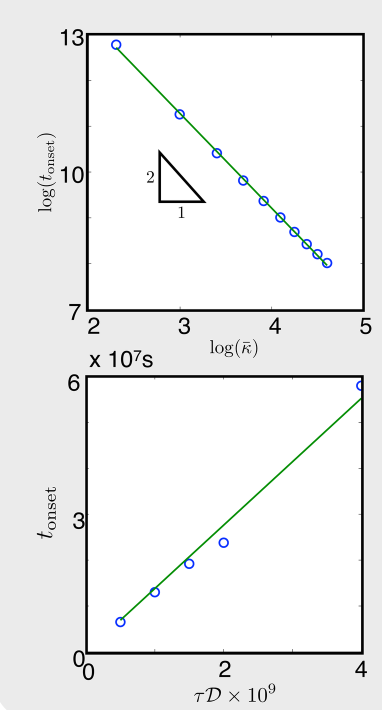
Relevant Publications

G. S. H. Pau, J. B. Bell, K. Pruess, A. S. Almgren, M. J. Lijewski and K. Zhang, "High resolution simulation and characterization of density-driven flow in CO_2 storage in saline aquifers", submitted, 2009.
G. S. H. Pau, A. S. Almgren, J. B. Bell, and M. J. Lijewski, "A parallel second-order adaptive mesh algorithm for incompressible flow in porous media", *Phil. Trans. R. Soc. A 367, 4633-4654*, 2009.
K. Pruess and K. Zhang, "Numerical modeling studies of the dissolution-diffusion-convection process during CO_2 storage in saline aquifers", Technical Report LBNL-1243E, LBNL, 2008.

Results



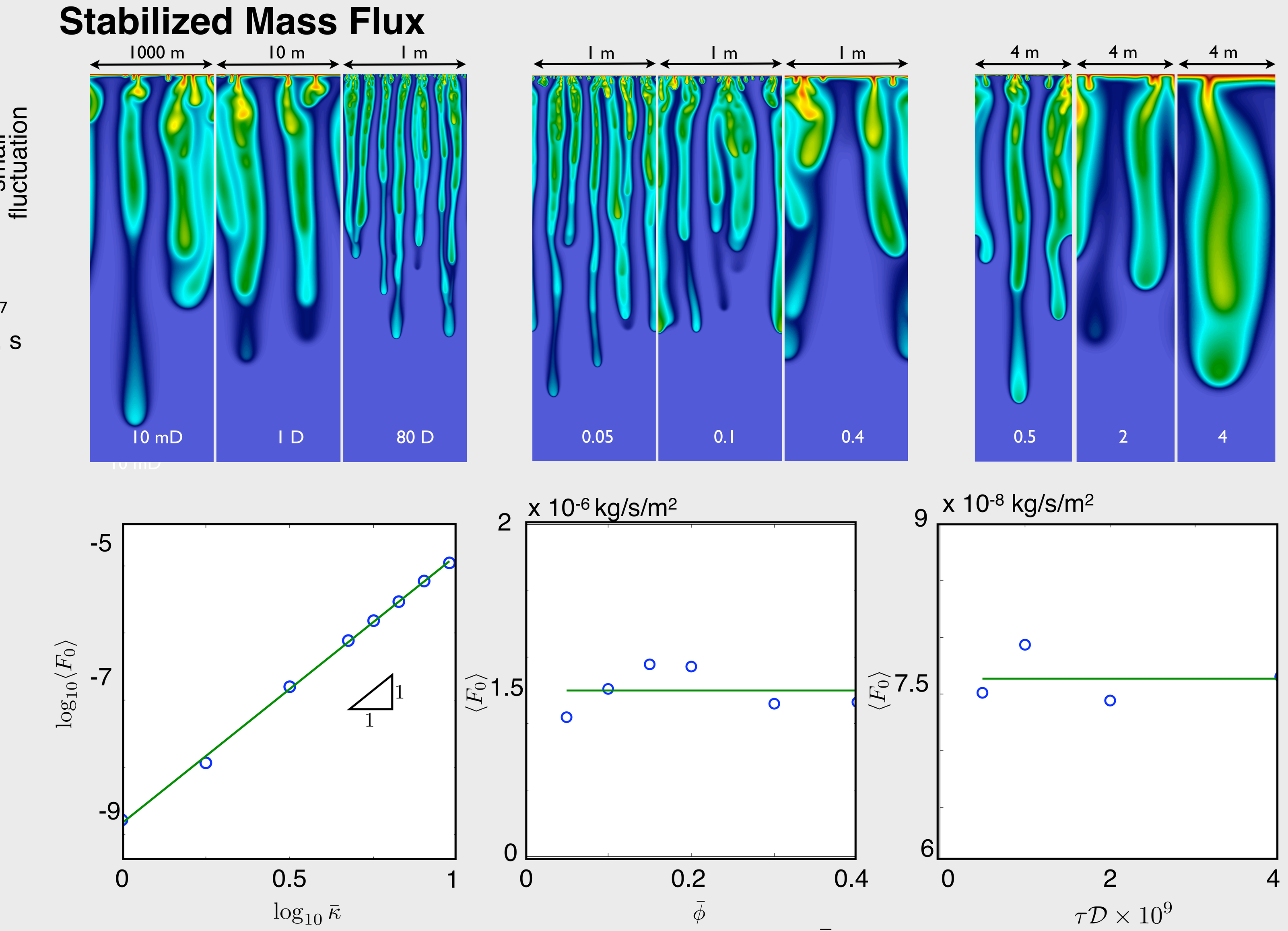
Onset time



- Results validates the relation from linear stability analysis:

$$t_{onset} = c_0 \frac{\mu^2 \phi^2 \tau D}{(\Delta\rho)^2 \mathbf{g}^2 \kappa^2}$$

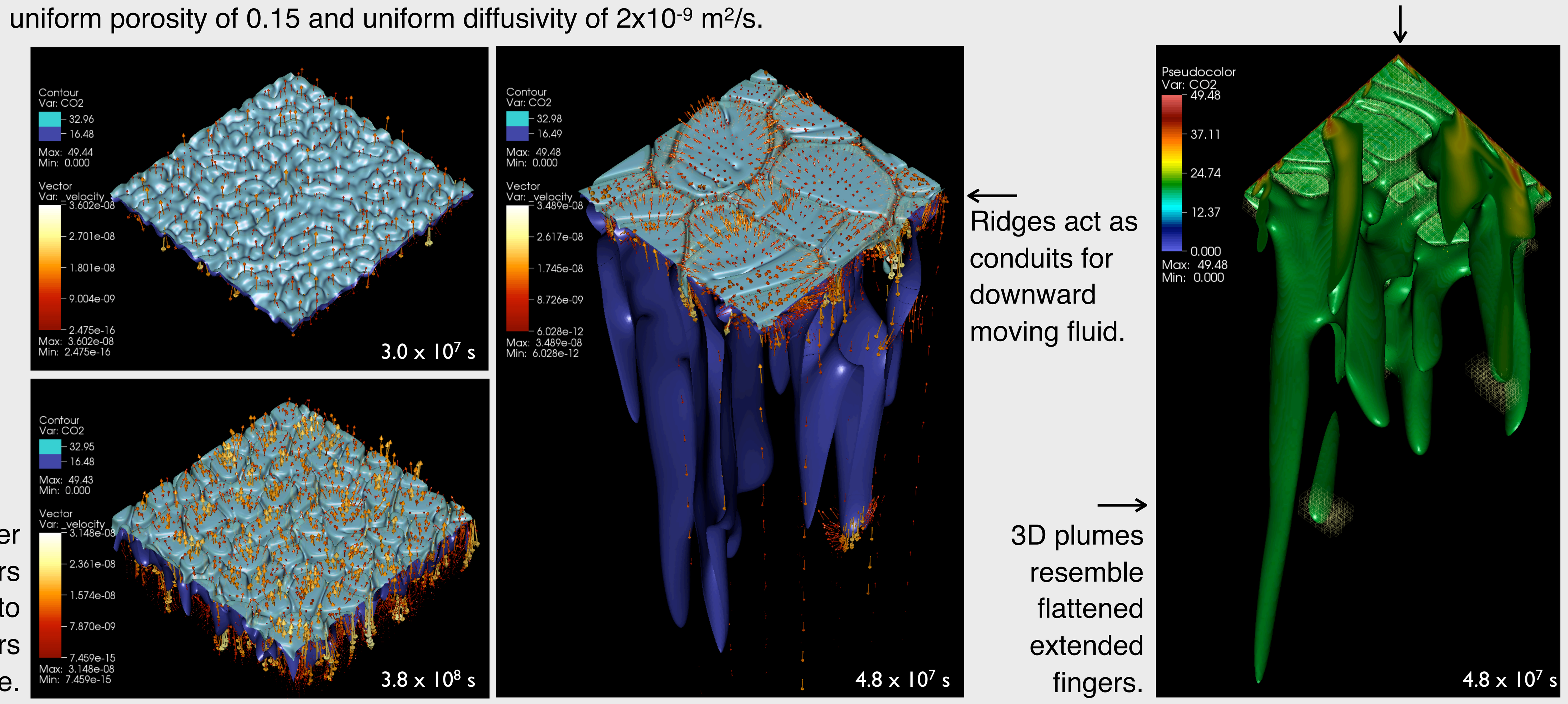
Stabilized Mass Flux



- Stabilized mass flux depends linearly on $\bar{\kappa}$ but not on $\bar{\phi}$ and τD : convection-dominated.

3D Simulation

- Based on the Carrizo-Wilcox aquifer modeled by a mean permeability of 500 mD, uniform porosity of 0.15 and uniform diffusivity of 2×10^{-9} m^2/s.



Conclusion

- Integral measures (onset time and stabilized mass flux) are robust and insensitive to details of fluctuation.
- The onset time of convection follows the prediction of linear stability analysis.
- At long time, convection is the dominant transport mechanism.

Acknowledgement

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