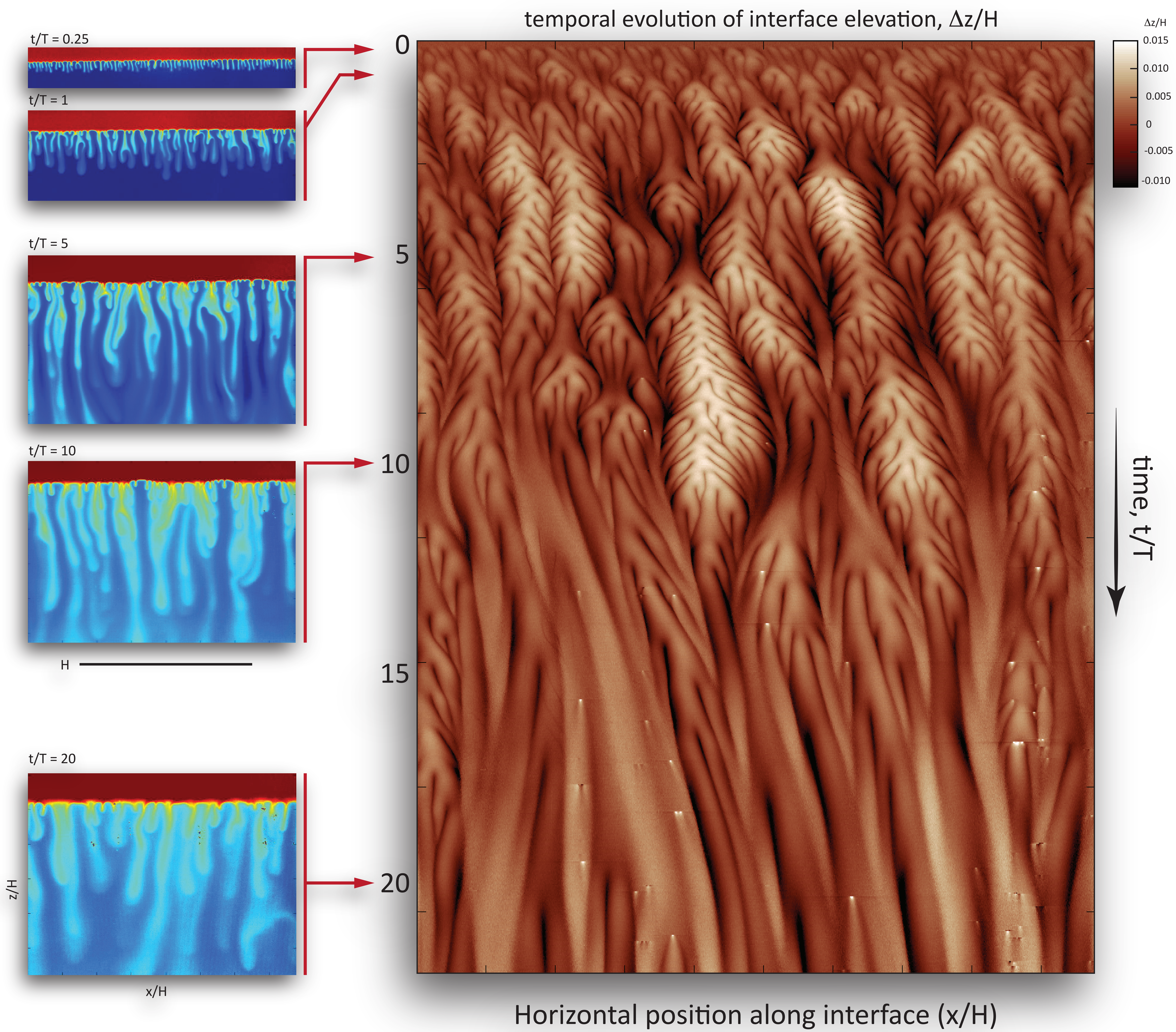
Meandering Fingers:

Growth, evolution and decay of convective instabilities within unstable fluid layers

Dana Ehyaei and Ken Kiger
Department of Mechanical Engineering, University of Maryland



The onset of convection is an important issue in determining suitable locations for the sequestration of carbon dioxide in deep saline aquifers. The convection process greatly accelerates the rate of mixing and dissolution of CO_2 into the brine, rendering it secure and preventing escape back into the atmosphere. The dynamics of the convection process are both scientifically interesting as well as aesthetically compelling.

We study this process in the laboratory within a Hele-Shaw cell using an aqueous mixture of Methanol+Ethylene Glycol (MEG) and water. MEG is buoyant relative to water, but aqueous dilutions of MEG have a density greater than water, creating a negatively buoyant layer at the interface between the fluids that is gravitationally unstable and results in the formation of convective "fingers" that drop down into the water.

In the current experiment, the concentration of MEG dissolving into the water is tracked using quantitative fluorescence imaging (see figures at far left for snapshots of the process as a function of time). A steep jump in concentration is observed at the upper boundary, and the origin of the convective fingers is tracked by isolating a concentration level that is approximately 15% below the reference level in the upper MEG layer. A map of the evolution of this interface is shown in the center image, with bright white areas showing broader locally elevated regions of the interface, while the dark regions indicated low elevations that show where the convective fingers originate.

Just after the onset of convection (t/T = 0.25) the fingers form at a nearly uniform spacing. This gradually gives way to a non-uniform modulation of the finger spacing (t/T = 1), resulting from displaced water pushing up between the fingers as the they descend. As this undiluted fluid reached the interface, it pushes the interface up and sweeps to the side, carrying newly formed fingers with it. This gives the interface history map to have an appearance of small overlapping feathers or parallel mountain ranges. The modulation wavelength appears to grow with the length of fingers, until the fingers reach the bottom of the reservoir (t/T = 5). After this point, the upwelling begins to carry slightly higher density mixed fluid to interface, which decreases the density difference driving the fingering initiation (t/T = 10), and there is a noticeable decrease in the formation of new fingers. Very little happens past this stage, as the convection is greatly diminished, with much fewer nascent fingers (t/T = 20).

The most important non-dimensional number controlling the process is given by the Rayleigh number, which for the current experiment is given by:

$$Ra = \frac{\Delta\rho g H \delta^2}{12 D \mu} = 2470$$

The reference length is given by the height of the water layer, H, and buoyant-viscous timescale, T.

$$H = 0.045 \text{ m and } T = \frac{12 H \mu}{\Delta\rho g \delta} = 683 \text{ s}$$