Thermo-chemical convection
Louise Kellogg, UC Davis

- Motivation: What is thermo-chemical convection, and how does it apply to the mantle?
- Methods: How do we study thermo-chemical convection?
- Examples of applications

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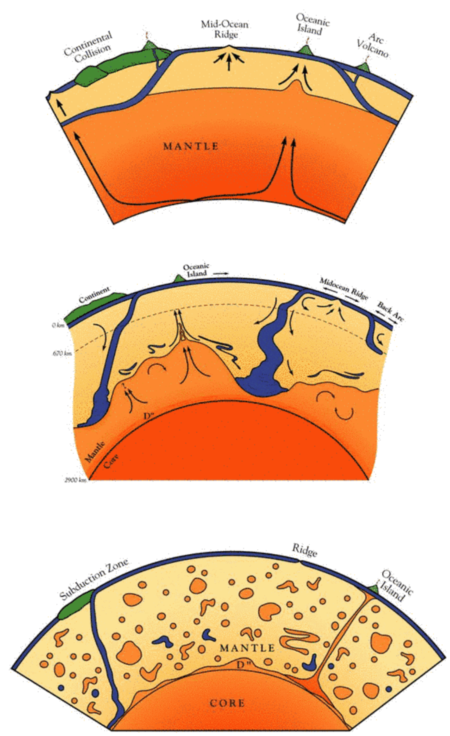
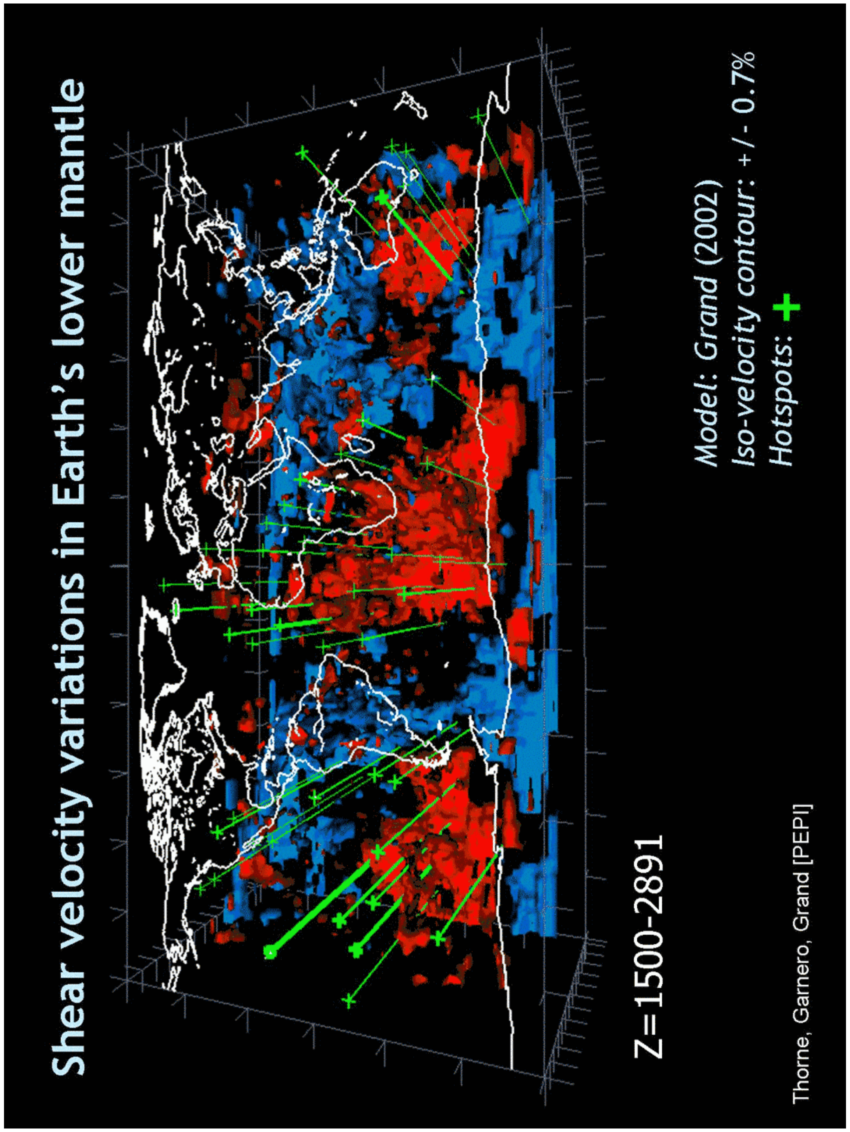
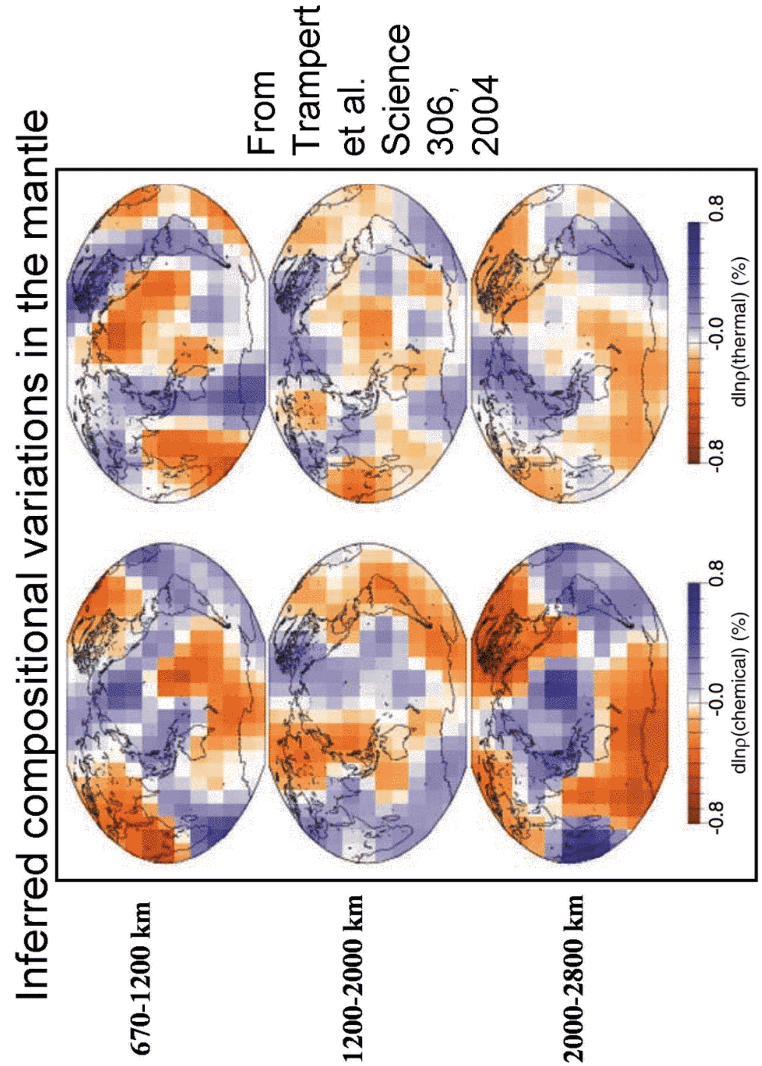
Lines of argument for some compositional layering

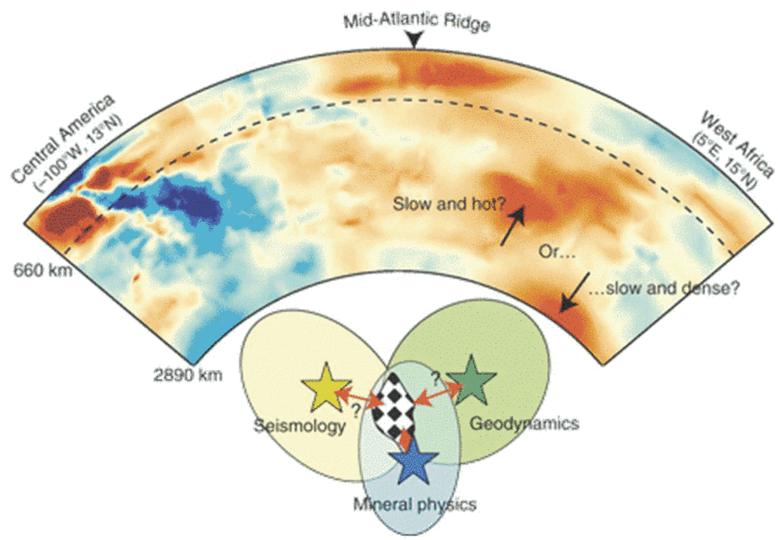
- Geochemical (i.e. Ar, He, etc.)
- Heat production
- Seismic velocities in lowermost mantle
- Mineral physics (combined with seismic velocities)




Shear velocity variations in Earth's lower mantle
Z=1500-2891
Model: Grand (2002)
Iso-velocity contour: +/- 0.7%
Hotspots: +
Thorne, Garnero, Grand [PEPI]


Inferred compositional variations in the mantle
From Trampert et al. Science 306, 2004
670-1200 km
1200-2000 km
2000-2800 km
dlnρ(thermal) (%)
dlnρ(chemical) (%)
-0.8
-0.0
0.8

Do the seismic velocities show any evidence for a layer?



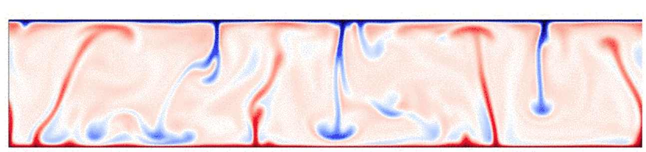
From R. van der Hilst

Mantle Convection:as seen last time

Conservation of mass: $\nabla \cdot \vec{u} = 0$

Momentum: $-\nabla P + \nabla \cdot \tau + RaT\hat{k}$

Heat flow: $\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \nabla^2 T + Ra_H / Ra$



$$Ra = \frac{\rho_m g \alpha \Delta T d^3}{\kappa \mu_0}$$

$$Ra_H = \frac{\rho_m^2 g \alpha H d^5}{k \kappa \mu_0}$$

Mantle Convection with chemical buoyancy:

Conservation of mass: $\nabla \cdot \vec{u} = 0$

Momentum: $-\nabla P + \nabla \cdot \tau + RaT\hat{k} - BRaC\hat{k} = 0$

Heat flow: $\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \nabla^2 T + Ra_H / Ra$

Advection/Diffusion: $\frac{\partial C}{\partial t} + \vec{u} \cdot \nabla C = \frac{1}{Le} \nabla^2 C$

$$Ra = \frac{\rho_m g \alpha \Delta T d^3}{\kappa \mu_0}$$

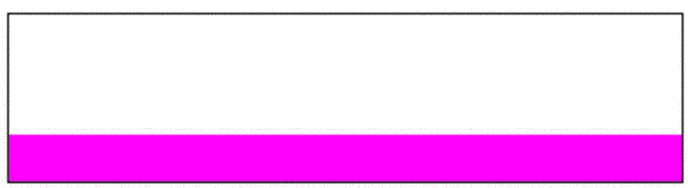
$$Ra_H = \frac{\rho_m^2 g \alpha H d^5}{k \kappa \mu_0}$$

Lewis number: $Le = \kappa / D$

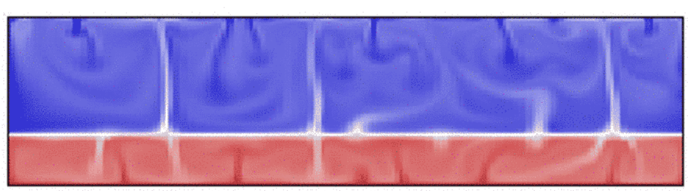
Compositional Buoyancy:

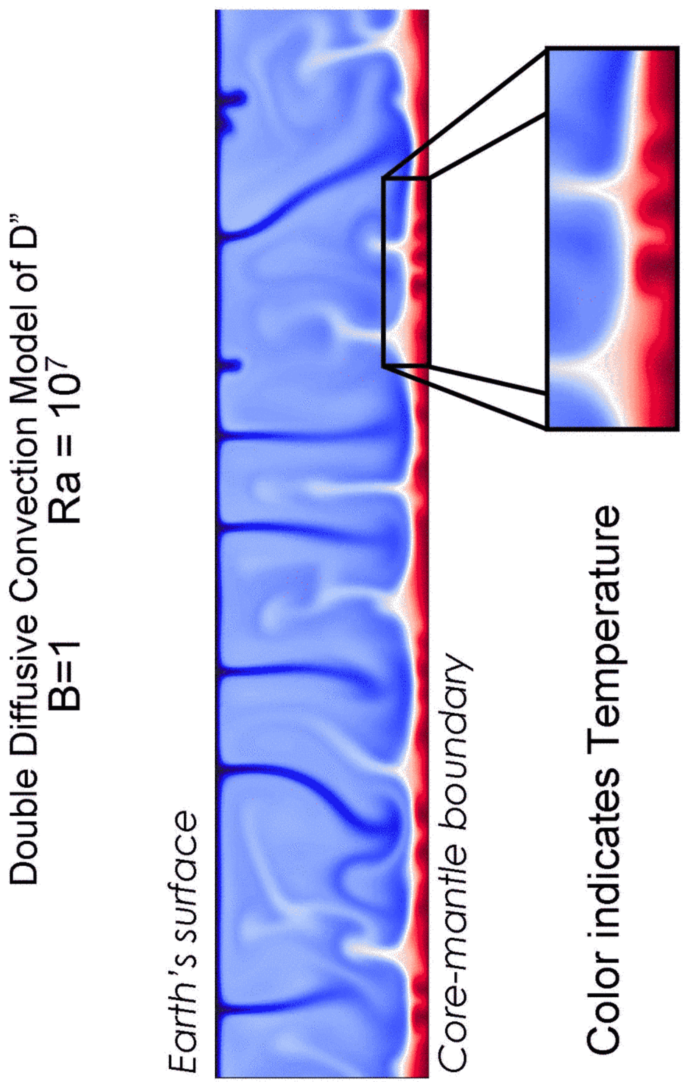
$$B = \frac{\Delta \rho_c}{\rho_0 \alpha \Delta T}$$

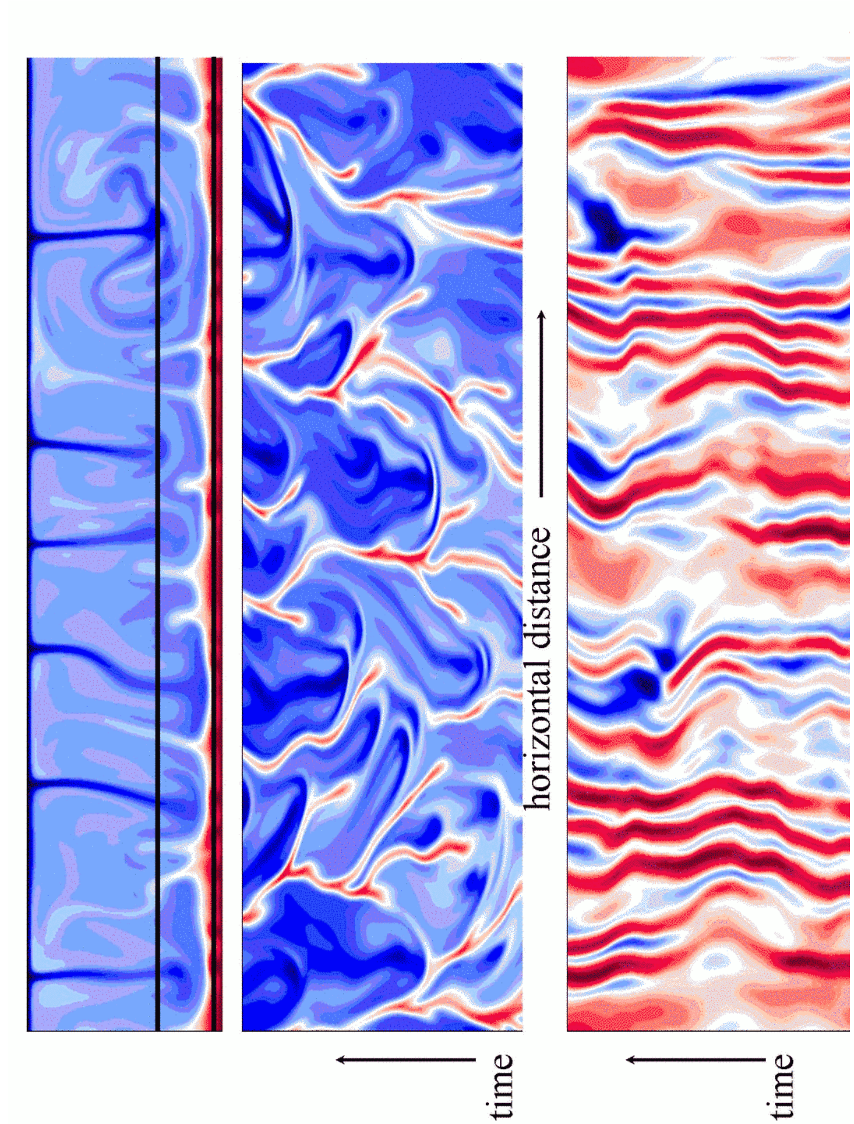
Initial Composition

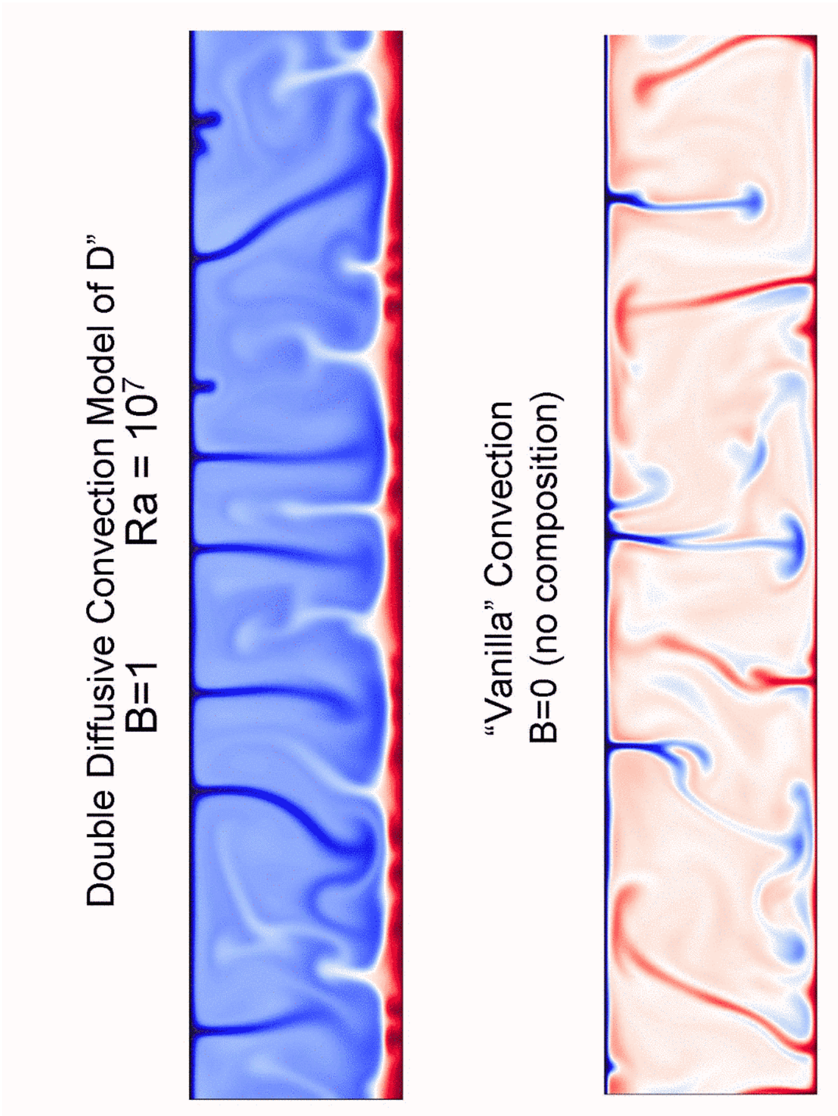


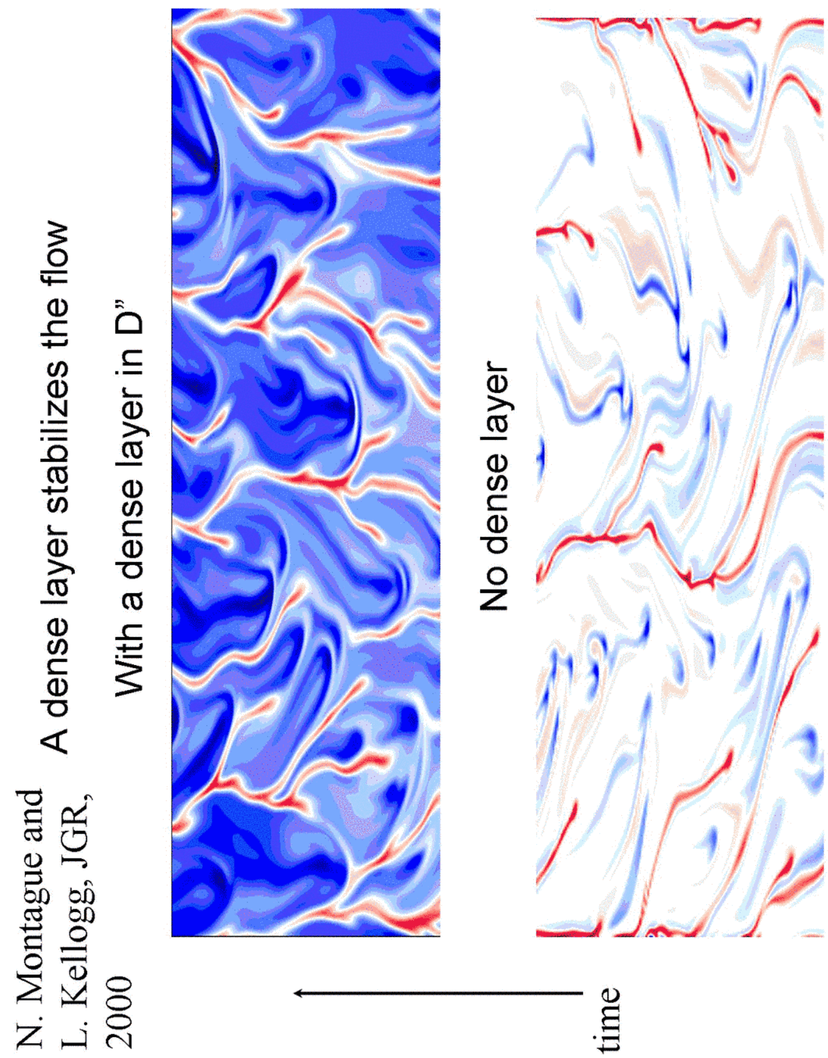
Initial temperature

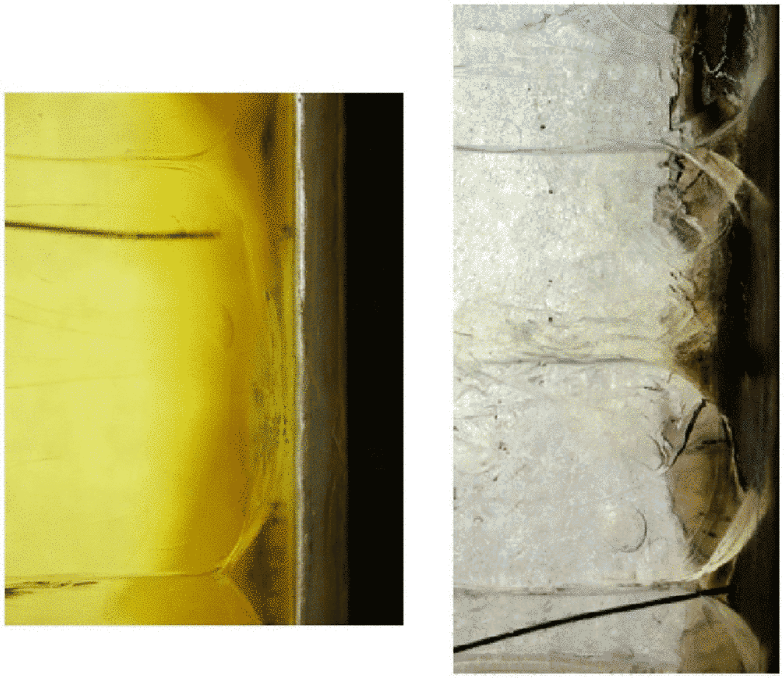



Double Diffusive Convection Model of D"
B=1 Ra = 10^7
Earth's surface
Core-mantle boundary
Color indicates Temperature


horizontal distance
time
time

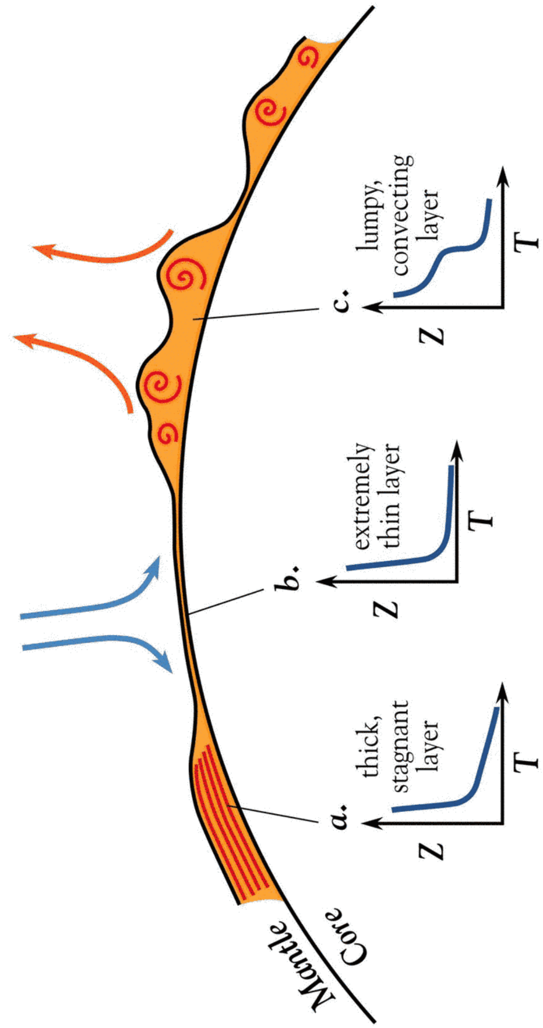

Double Diffusive Convection Model of D”
B=1 Ra = 10^7
“Vanilla” Convection
B=0 (no composition)


A dense layer stabilizes the flow
With a dense layer in D”
No dense layer
N. Montague and L. Kellogg, JGR, 2000
time



Jellinek and Manga [Rev Geophys., 2005]

Possible processes in lowermost mantle



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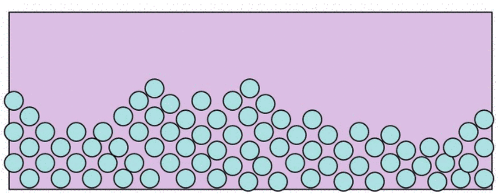
Lewis number: $Le = \kappa / D$

Compositional Buoyancy:

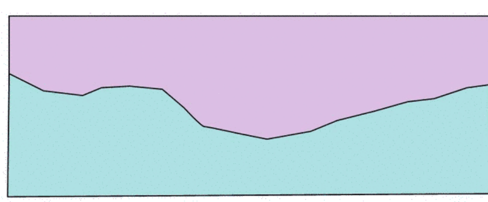
$$B = \frac{\Delta \rho_c}{\rho_0 \alpha \Delta T}$$

Some ways to represent thermo-chemical convection

- Particle method



- Field method diffusive



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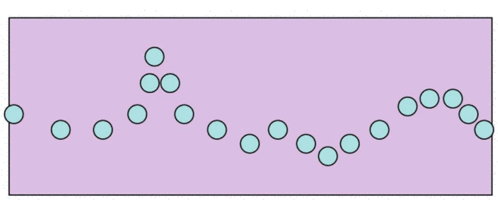
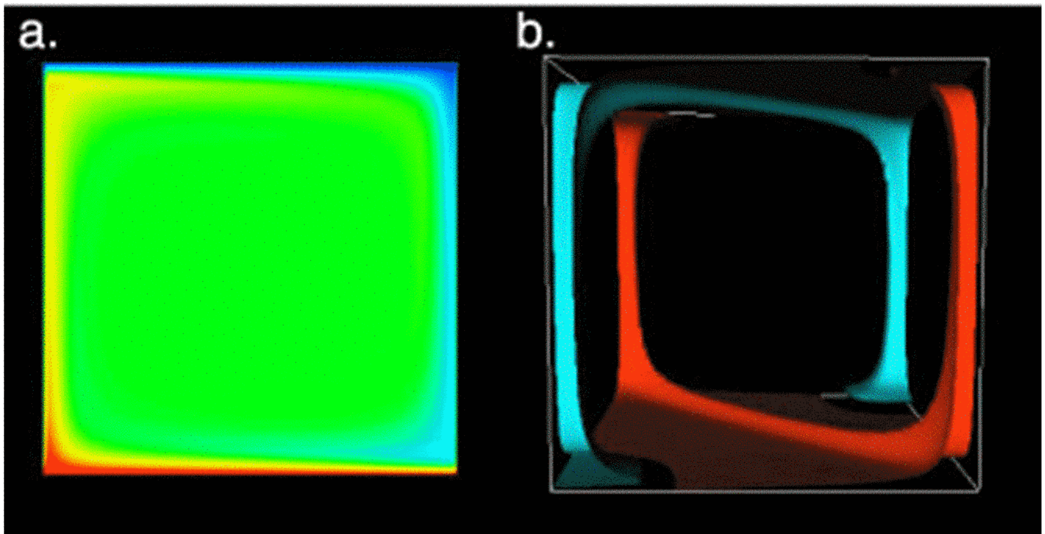
- Marker chain



Testing methods for thermochemical convection

(From Tackley & King, G-cubed, 2003)



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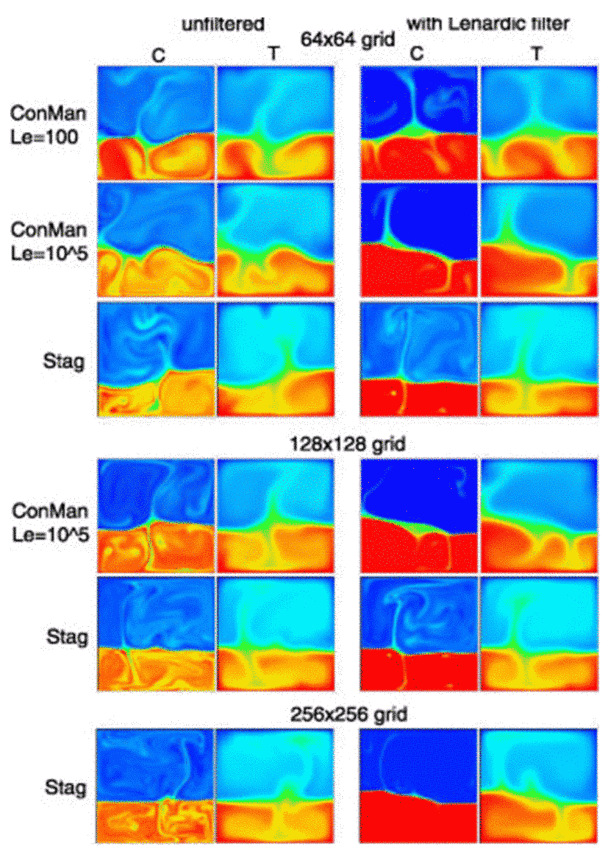
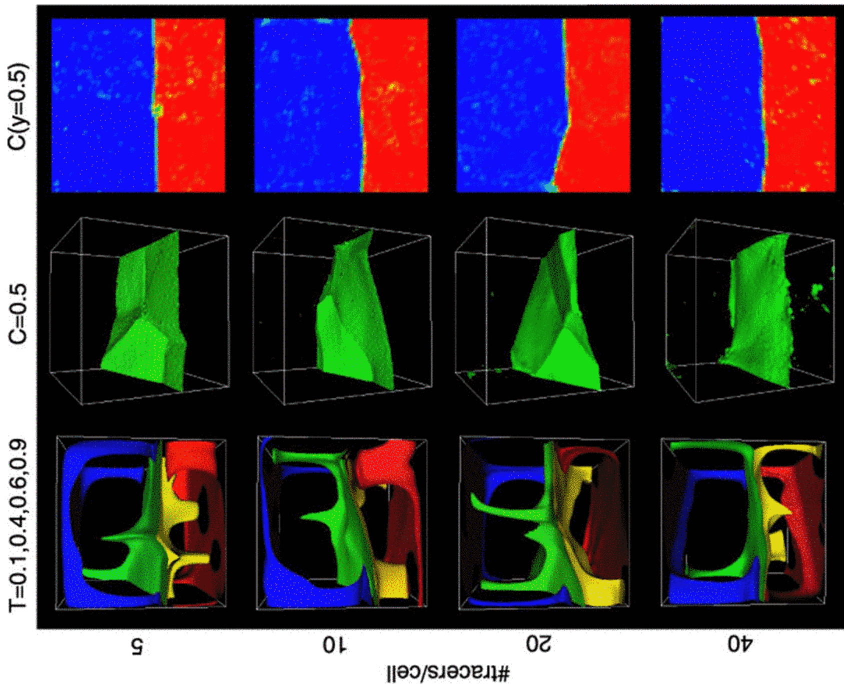
What's the best way to represent compositional heterogeneity in numerical models?

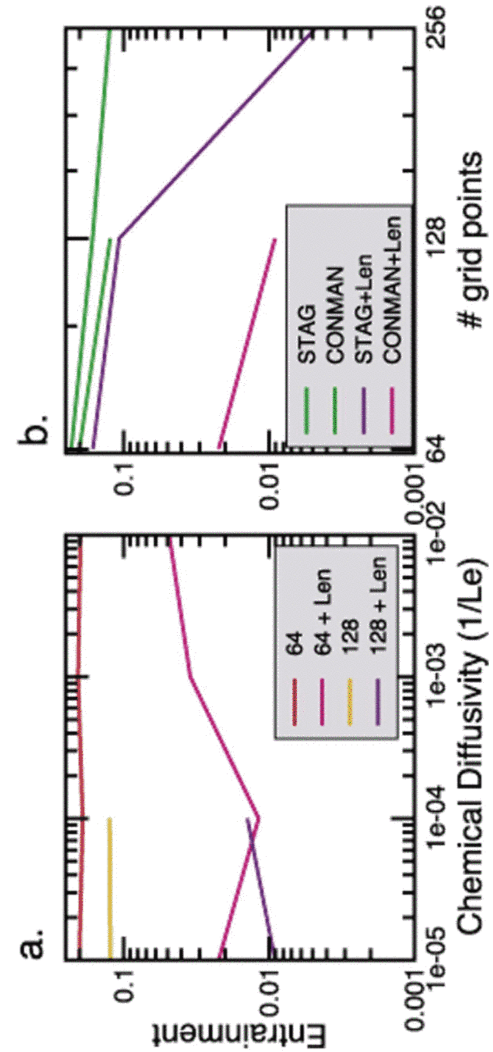


Tackley and King, 2003



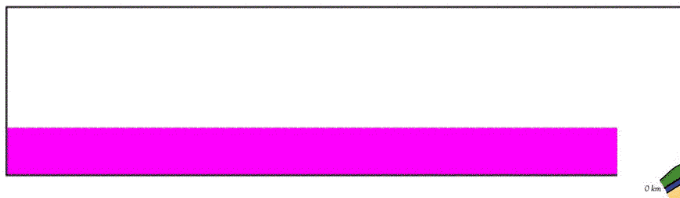
3D tests using a particle method

Comparisons of methods

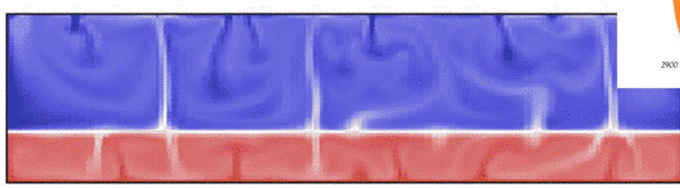


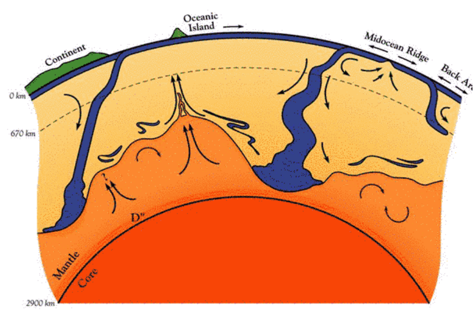
Other properties in conjunction with density: Effect of viscosity

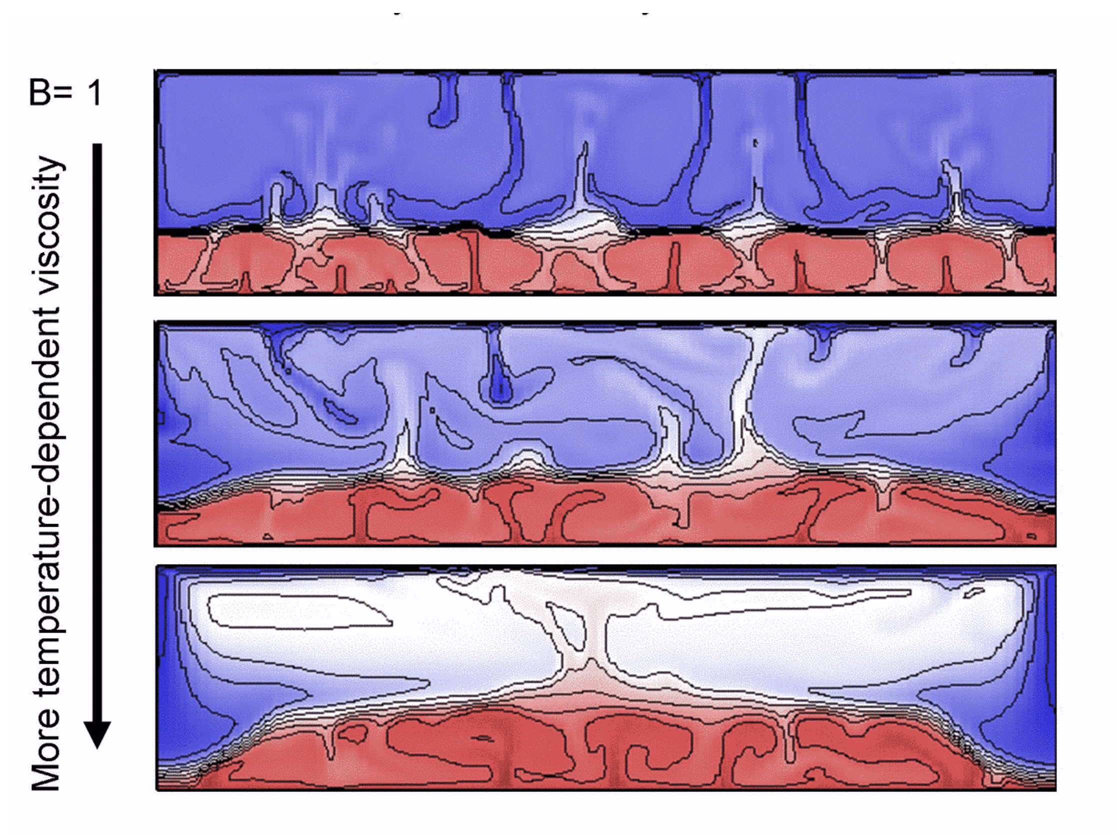
Initial Composition



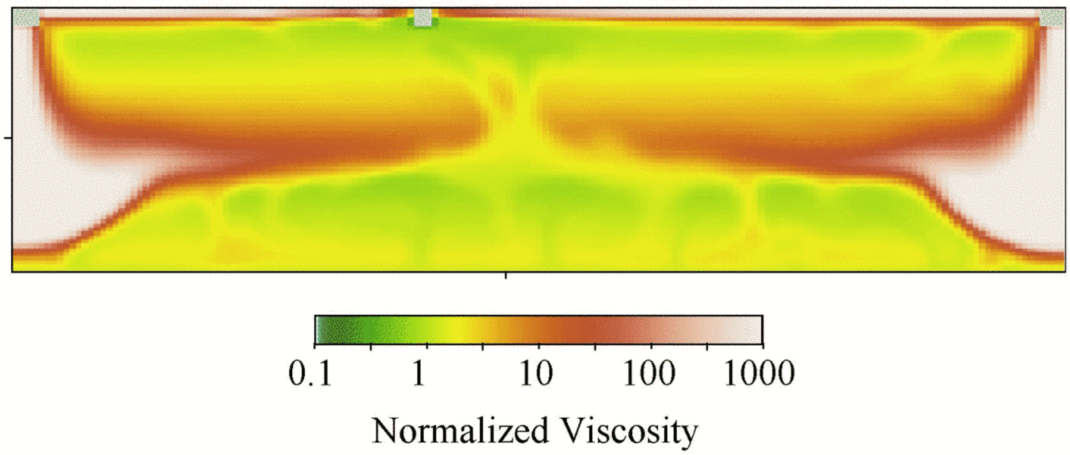
Initial temperature





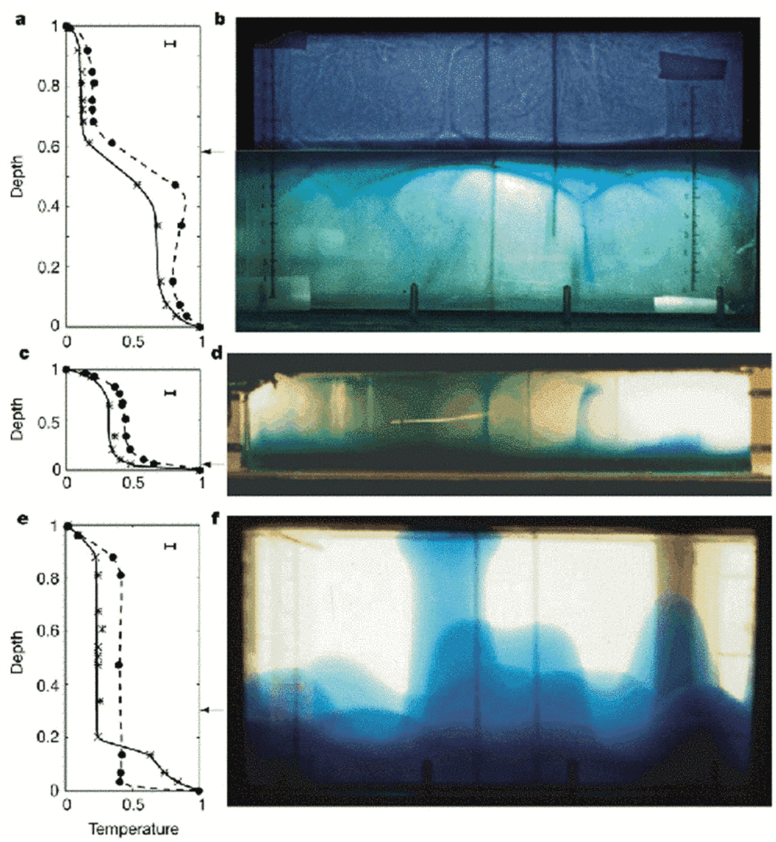


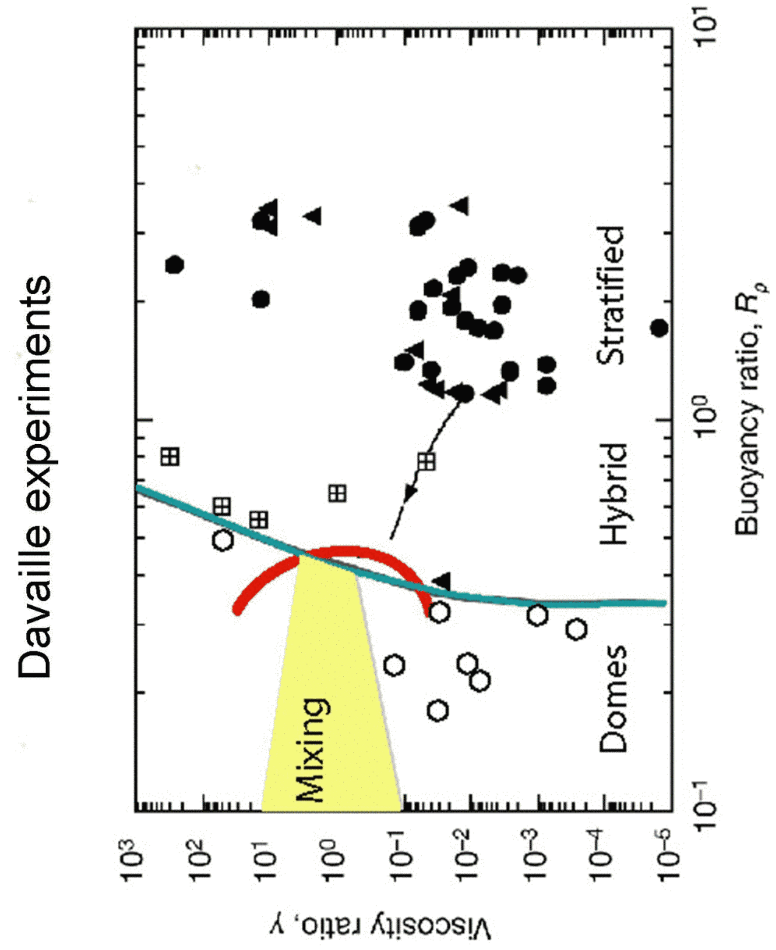
A viscosity inversion develops at the top of the layer

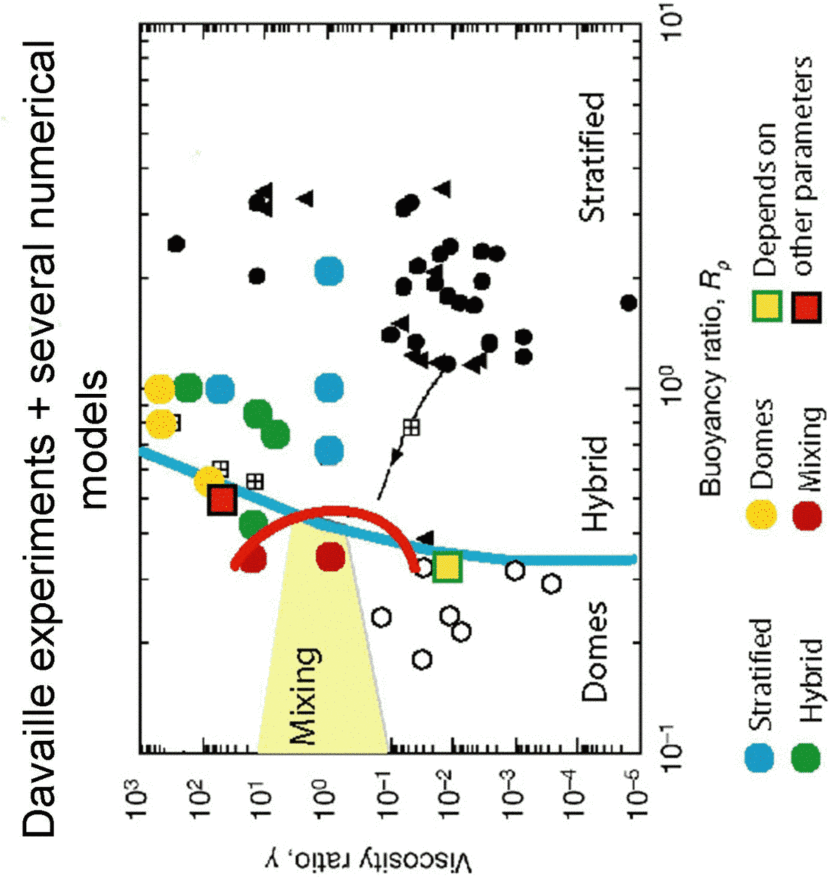


Layered convection experiments by Anne Davaille,

(Nature *402*, 756, Dec. 1999)




Davaille experiments
Viscosity ratio, γ
Buoyancy ratio, R_ρ
Mixing
Domes
Hybrid
Stratified

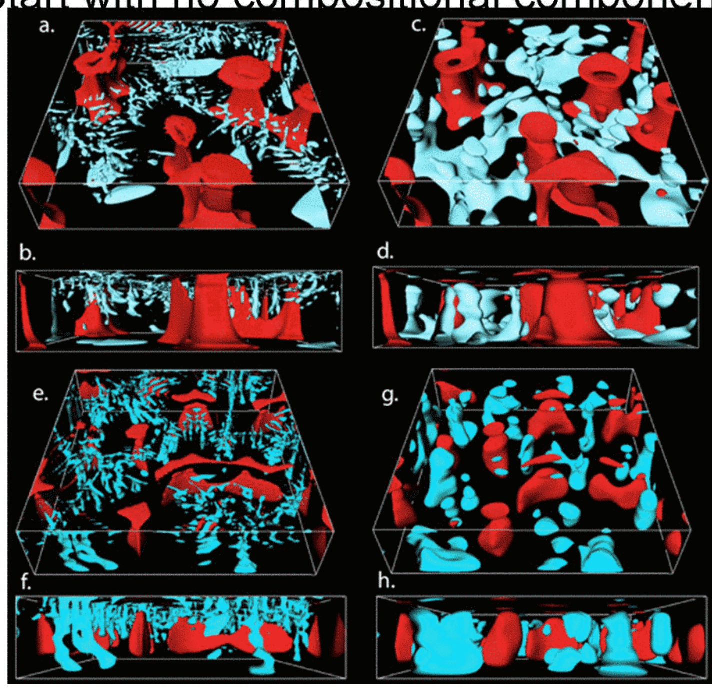

Davaille experiments + several numerical models
Viscosity ratio, γ
Buoyancy ratio, R_ρ
Mixing
Domes
Hybrid
Stratified
Stratified
Hybrid
Domes
Mixing
Depends on other parameters

Fate of a dense layer (from Tackley, G-cubed, 2002)

Start with no compositional component:

Fixed T CMB

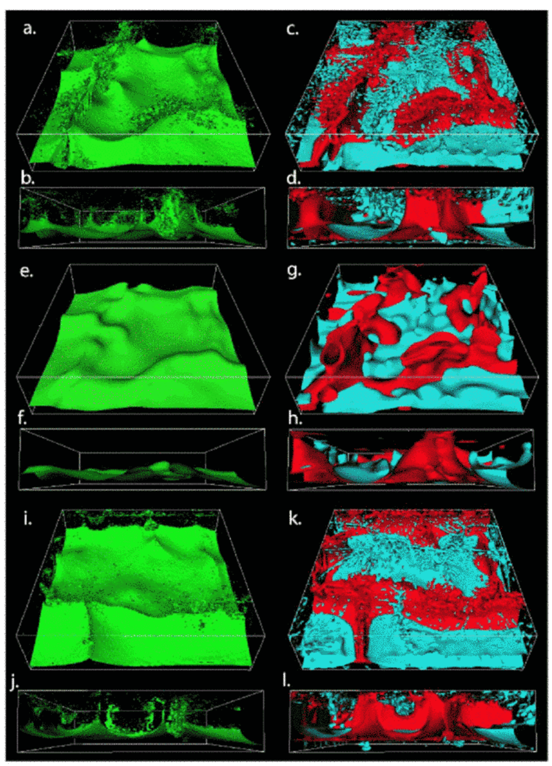
0 flux CMB



Next add a dense layer (30% of mantle)

Fixed T CMB
B= 0.3

0 flux CMB



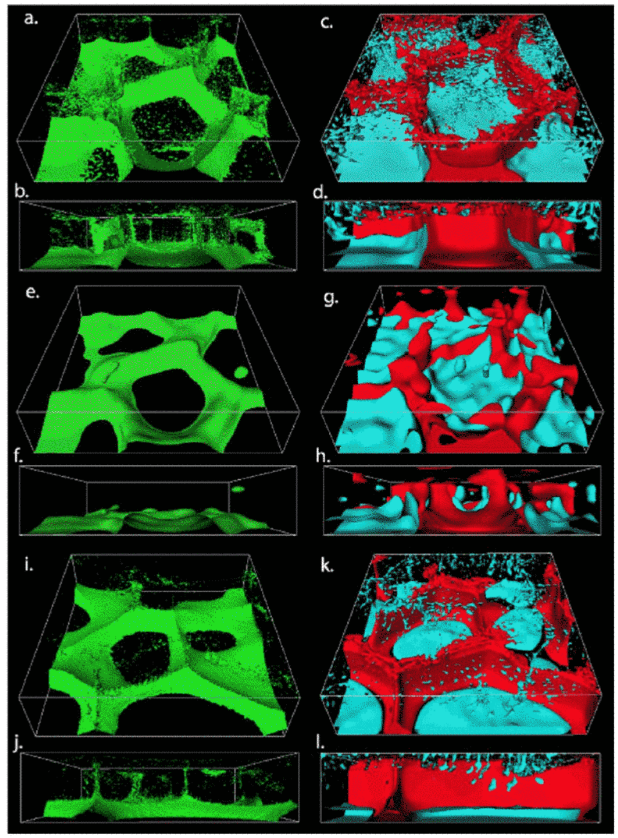
Tackley, G-cubed, 2002

A thinner dense layer can be discontinuous (10% of mantle)

Fixed T CMB
B = 0.3

0 flux CMB
B = 0.25

Tackley, G-cubed, 2002



Parameter space is many-dimensional!