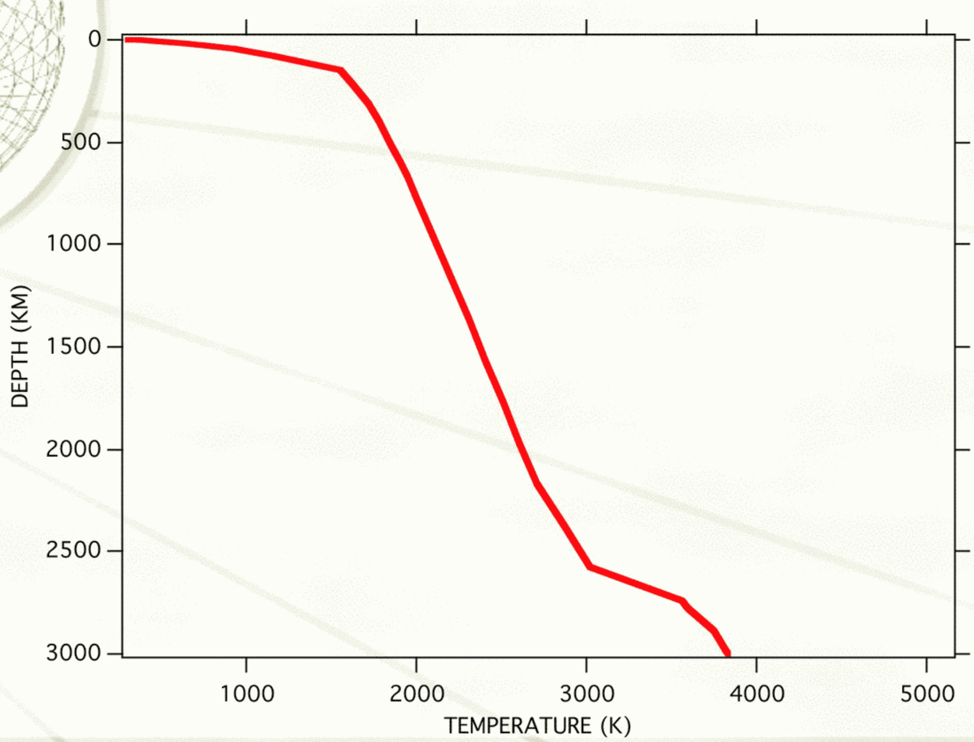
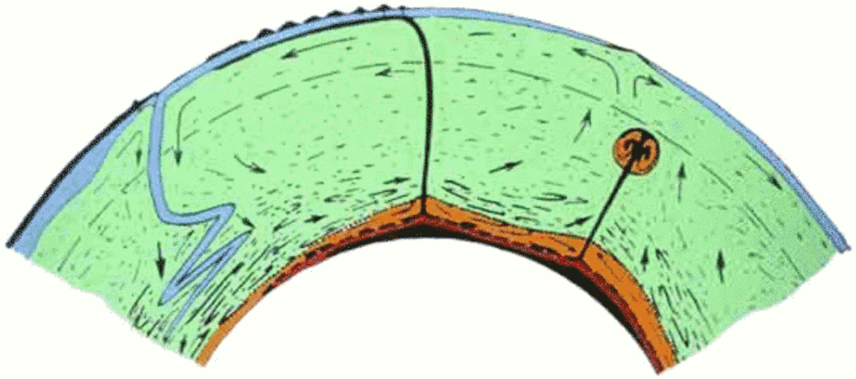
Plumes, hotspots and the CMB

Lecture 6: Geodynamics
Carolina Lithgow-Bertelloni

Earth’s temperature profile



Scales of Convection

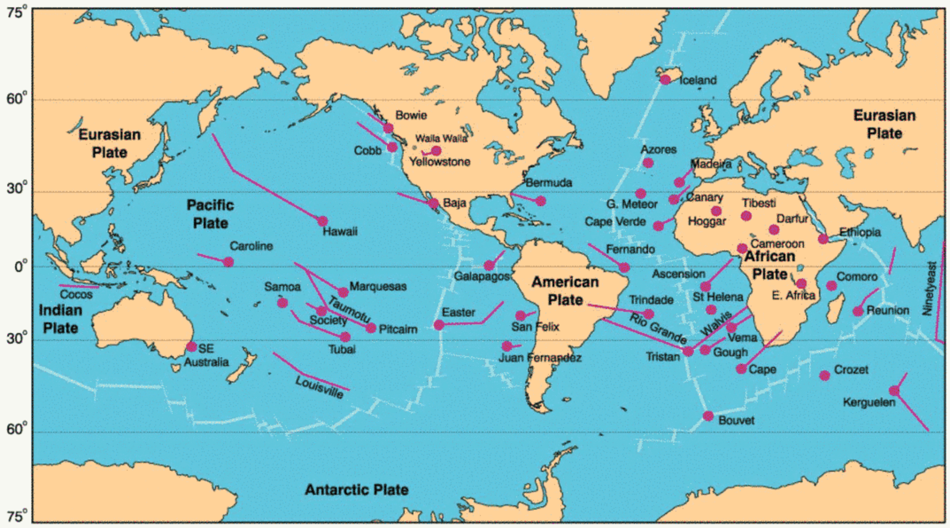


[from Geoff Davies]

Plumes and Hotspots

- Hotspots
  - Island chains and age progression
  - Importance for plate motions, TPW
  - Fixity
  - Chemistry
  - Origin
- Plumes
  - Difference with large-scale upwellings
  - Heads and tails
    - Effects of viscosity on morphology
    - Plume initiation and flood basalts
    - How much entrainment
    - Comparison to geochemistry
  - Effects of composition
    - Shape, heterogeneity, hotspot fixity
- Relationship between large-scale upwellings and plumes?
  - Capture by plate-scale flow
    - Consequences for heat flow
- Where do they come from?
- Relationship to CMB structure

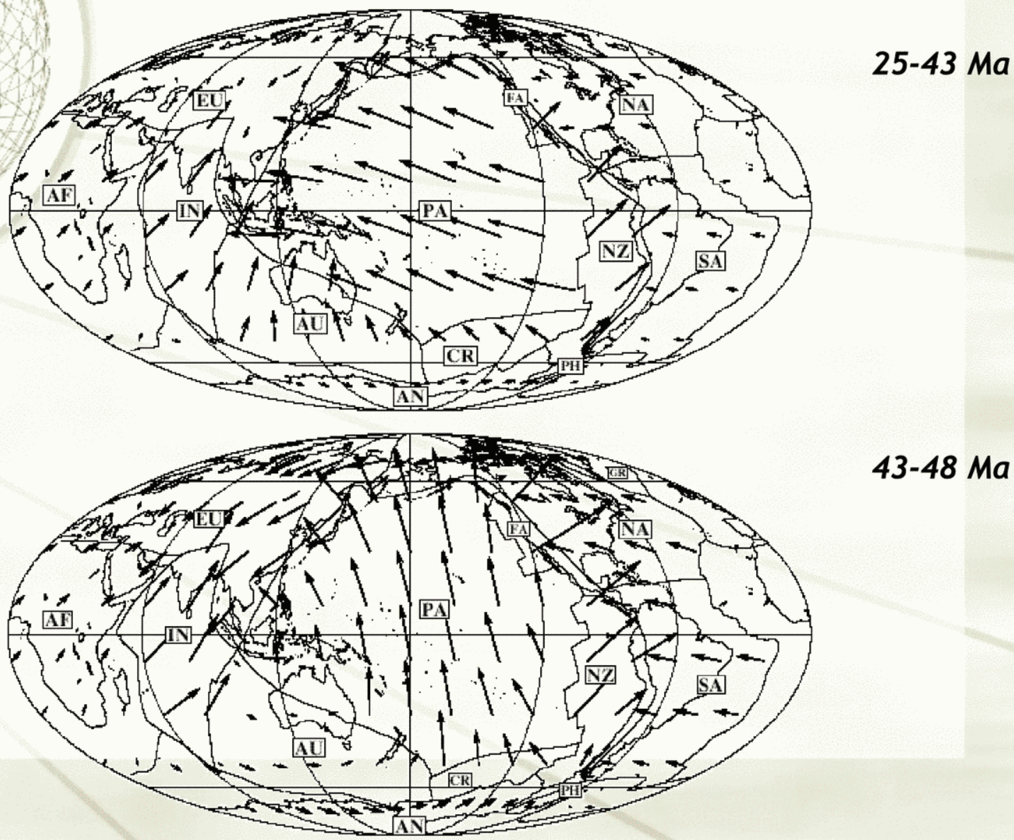
Hotspots



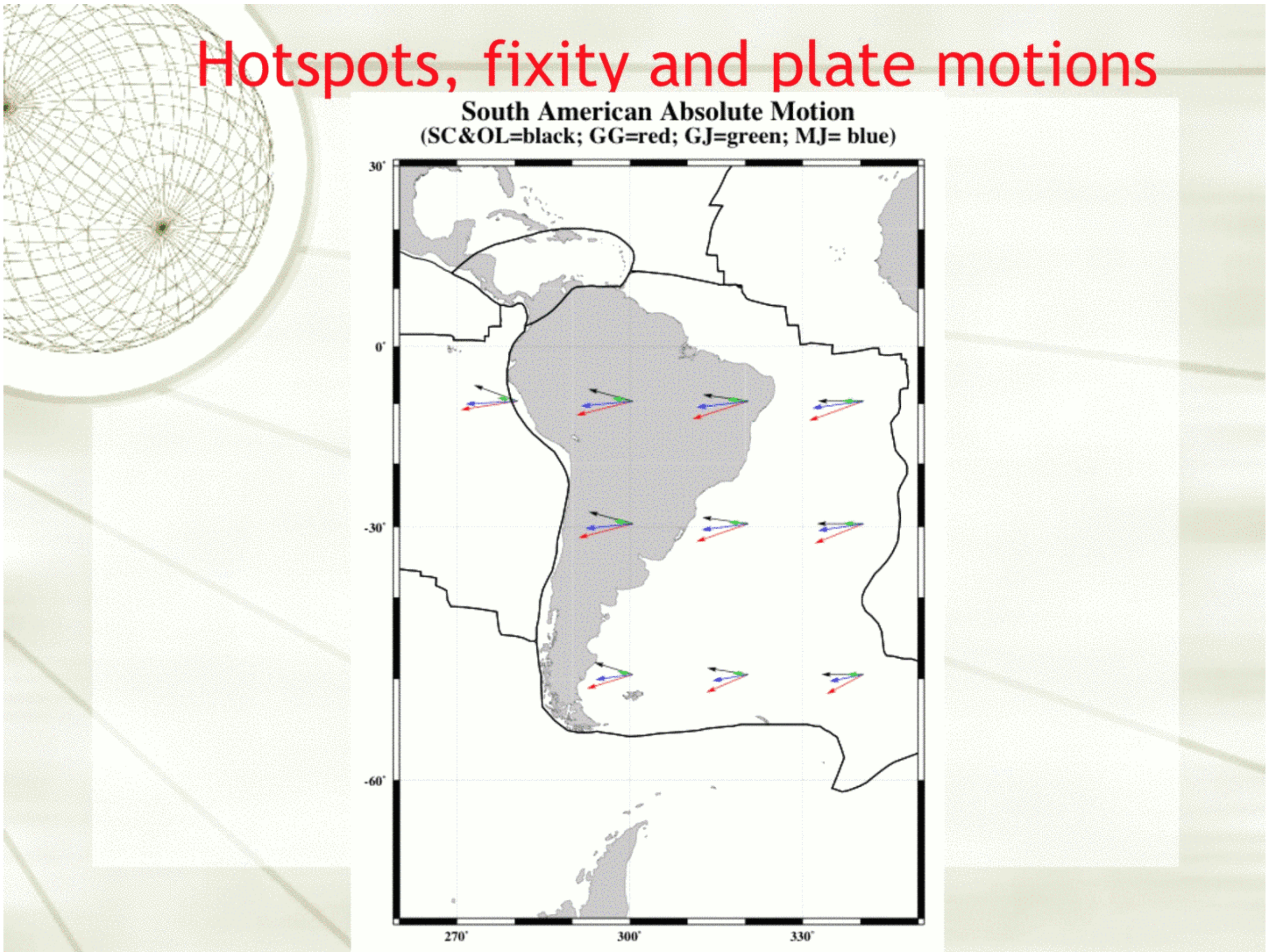
- Concentrated volcanic activity.
  - Linear volcanic chains in the interiors of the plates.
  - Age progression along chain
  - Chemistry of erupted lavas is significantly different than MOR or IA
  - Some hotspots have broad topographic swell ~ 1000 m

[*Steinberger et al.*, 2004]

Hotspots and Plates

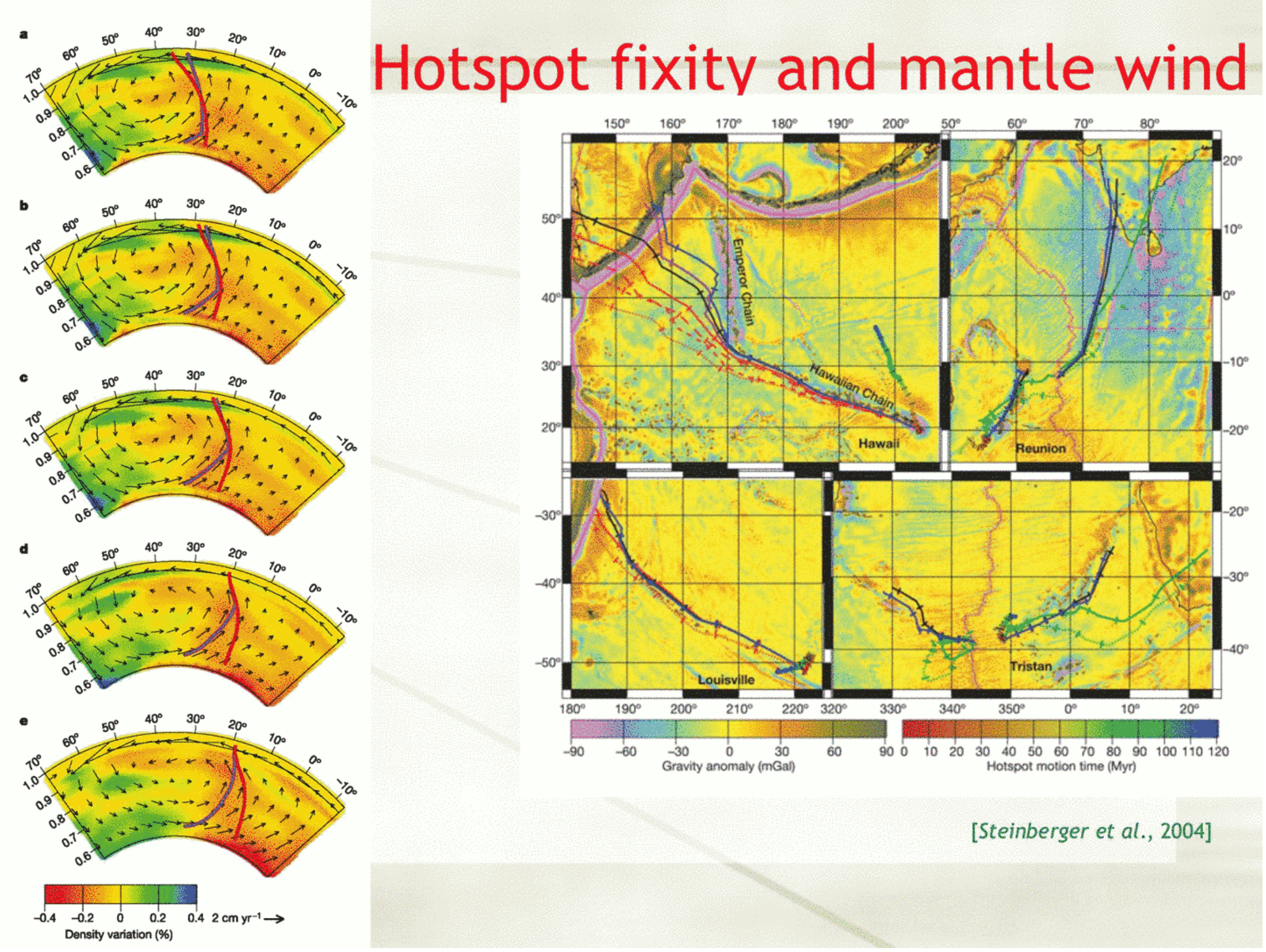

25-43 Ma

43-48 Ma



Hotspots, fixity and plate motions

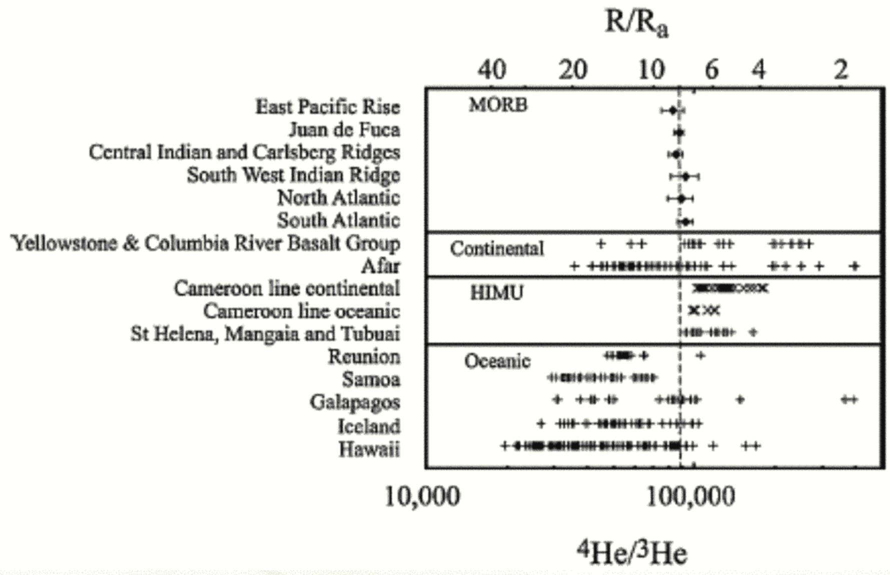
South American Absolute Motion
(SC&OL=black; GG=red; GJ=green; MJ= blue)



Hotspot fixity and mantle wind

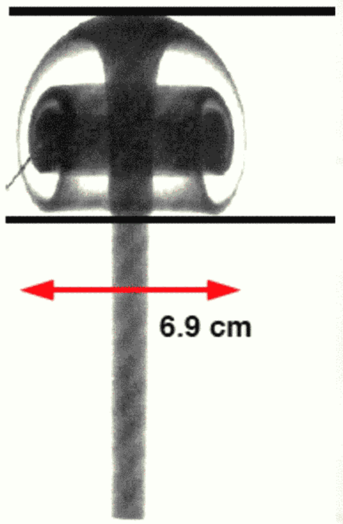
[*Steinberger et al.*, 2004]

Chemistry



[*Barfod et al.*, 1999]

Plumes and hotspots

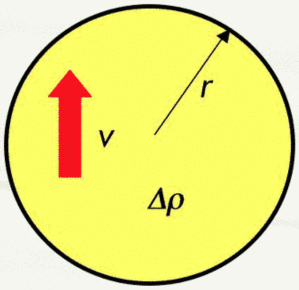


- ✶Rayleigh-Taylor instability
- ✶Large head, thin tail
  - ✶Rheology
  - ✶Vigor of convection
  - ✶Compositional vs thermal buoyancy
- ✶Ascent times
  - ✶Rheology
  - ✶Deflection, capture by mantle wind
  - ✶Compositional vs thermal buoyancy

[*Griffiths and Campbell*, 1990]

Rise time estimate

$r = 500$ km
$\Delta\rho = 30\ kg/m^3$
$\mu = 10^{22}$ Pa s
$V = 80$ km/My

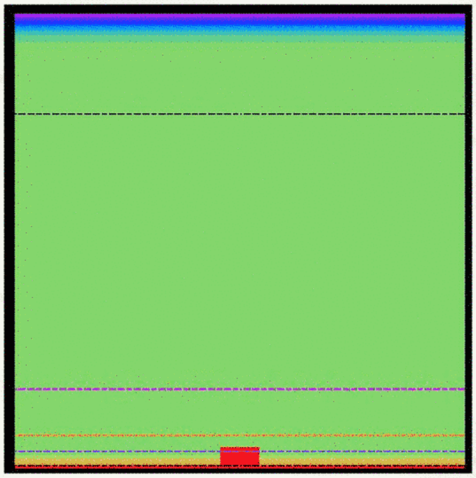


Ratio of buoyancy force to viscous forces
$B = -4\pi r^3 g\Delta\rho/3$
$\tau = \chi\mu\varpi/r$; $R = -4\pi r\ \chi\mu\varpi$

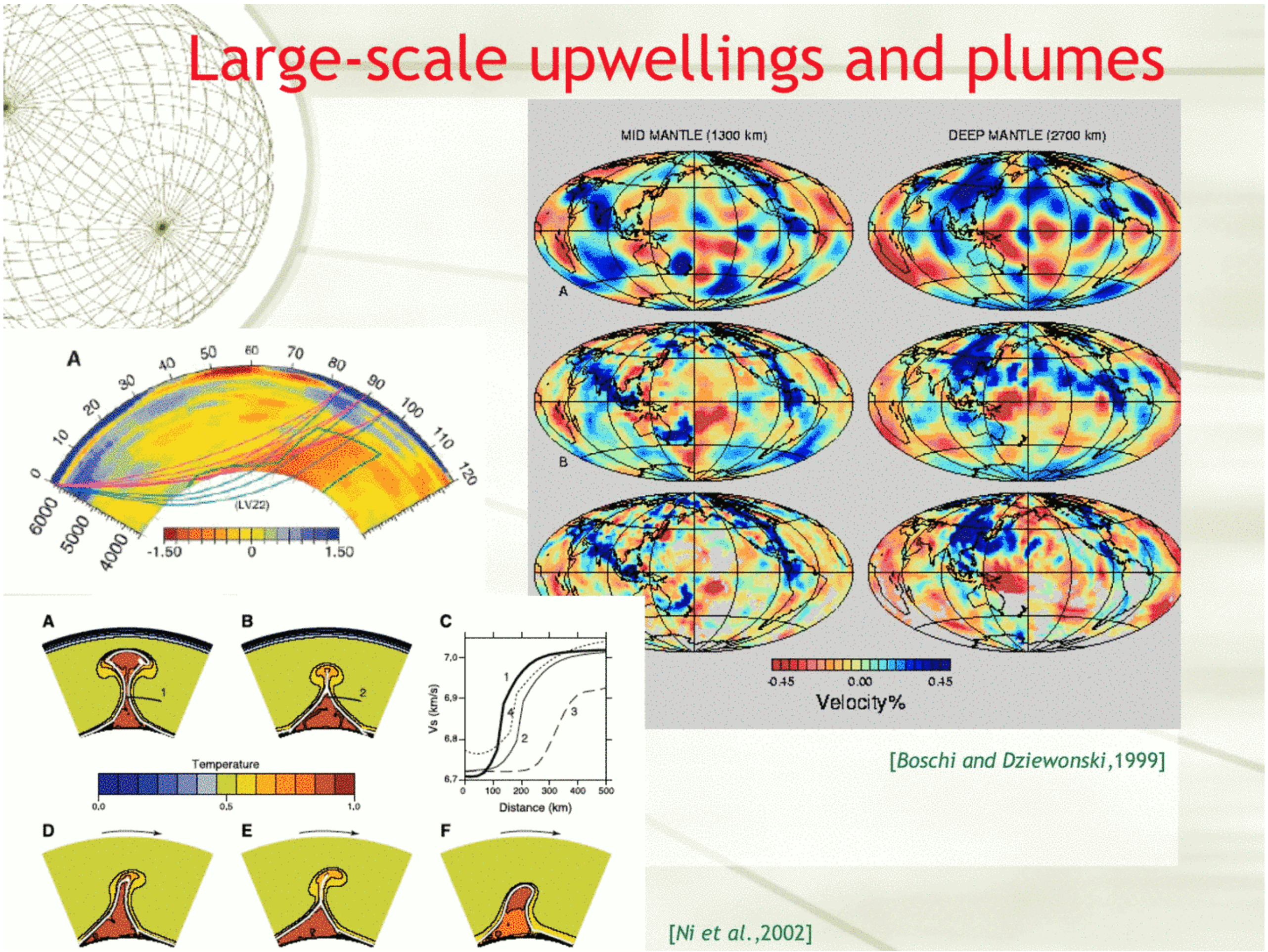
Forces on the sphere balanced velocity constant
$B+R=0$ $V= -g\Delta\rho r^2/3c\mu$

If viscosity of sphere and surrounding different
$c = \mu + 1.5\mu_s/\ \mu + \mu_s$
$c \sim 1\text{-}1.5$

Generating a mantle plume



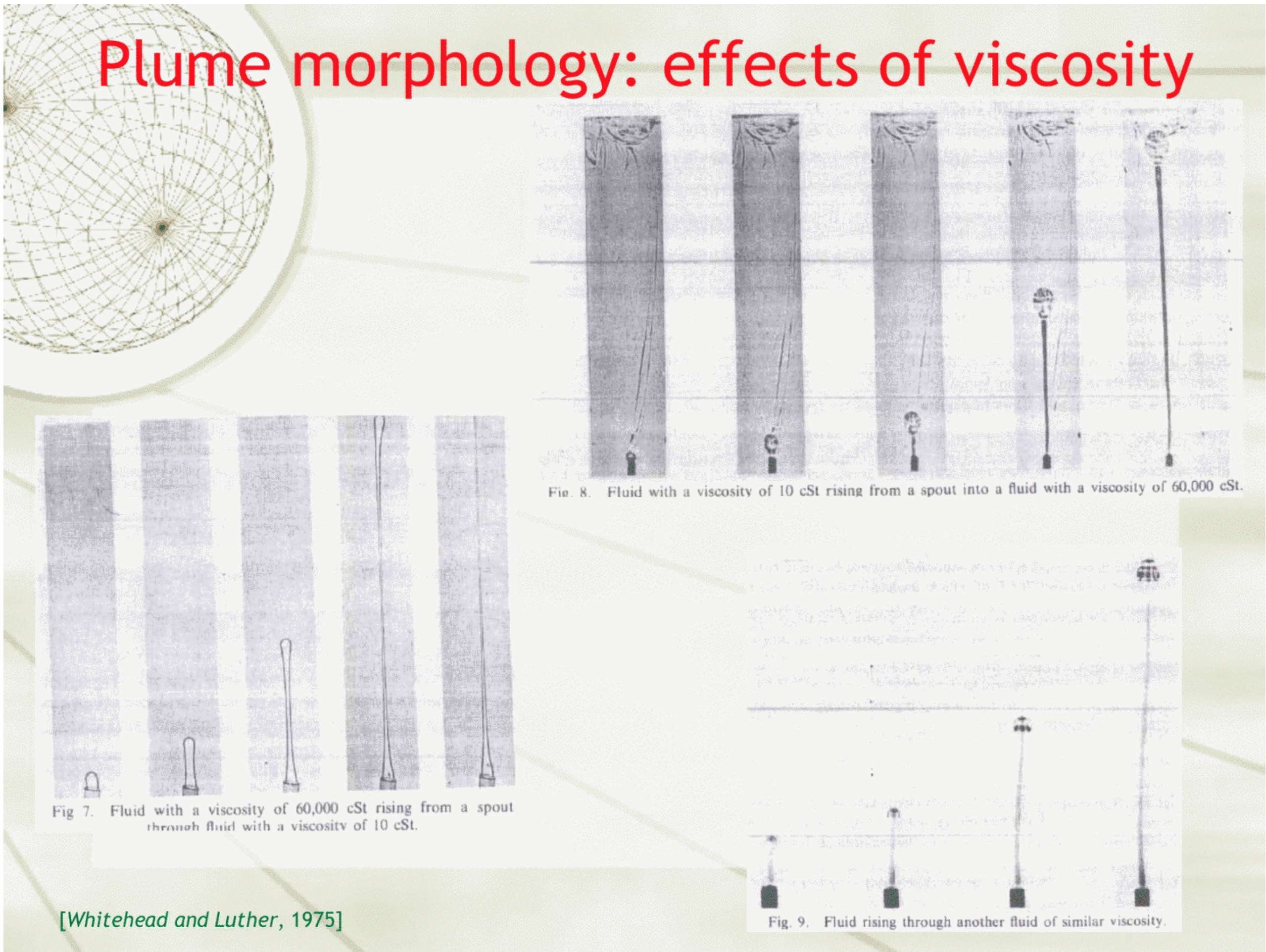
[from Geoff Davies]



Large-scale upwellings and plumes

[Boschi and Dziewonski, 1999]

[Ni et al., 2002]



Plume morphology: effects of viscosity

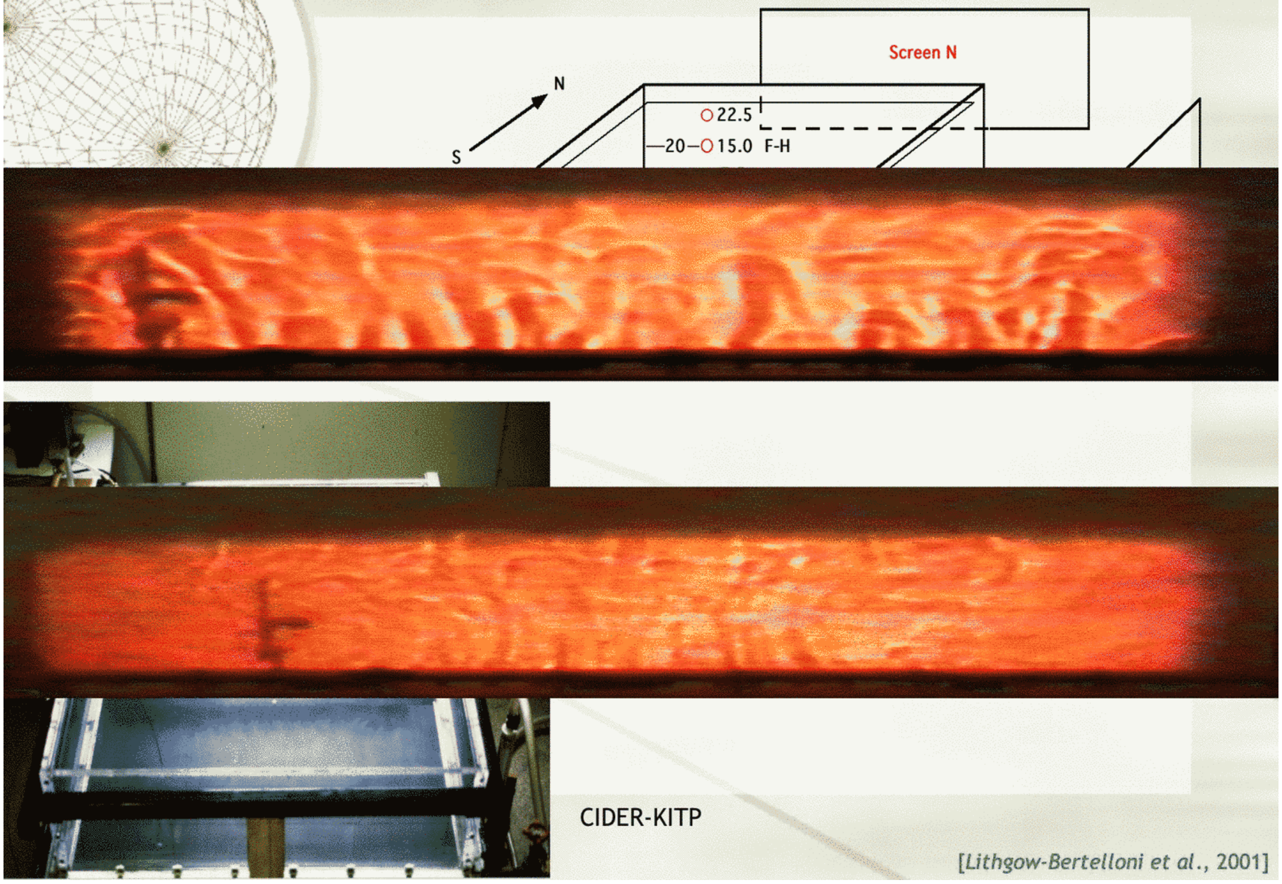
Fig. 8. Fluid with a viscosity of 10 cSt rising from a spout into a fluid with a viscosity of 60,000 cSt.

Fig 7. Fluid with a viscosity of 60,000 cSt rising from a spout through fluid with a viscosity of 10 cSt.

Fig. 9. Fluid rising through another fluid of similar viscosity.

[Whitehead and Luther, 1975]

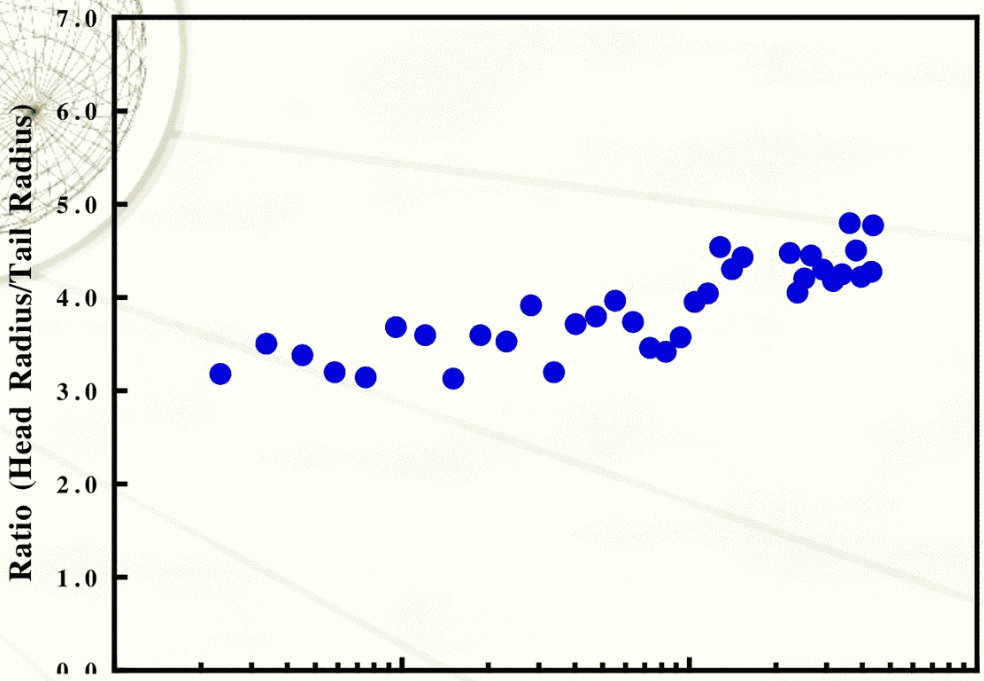
Plumes heads and tails



CIDER-KITP

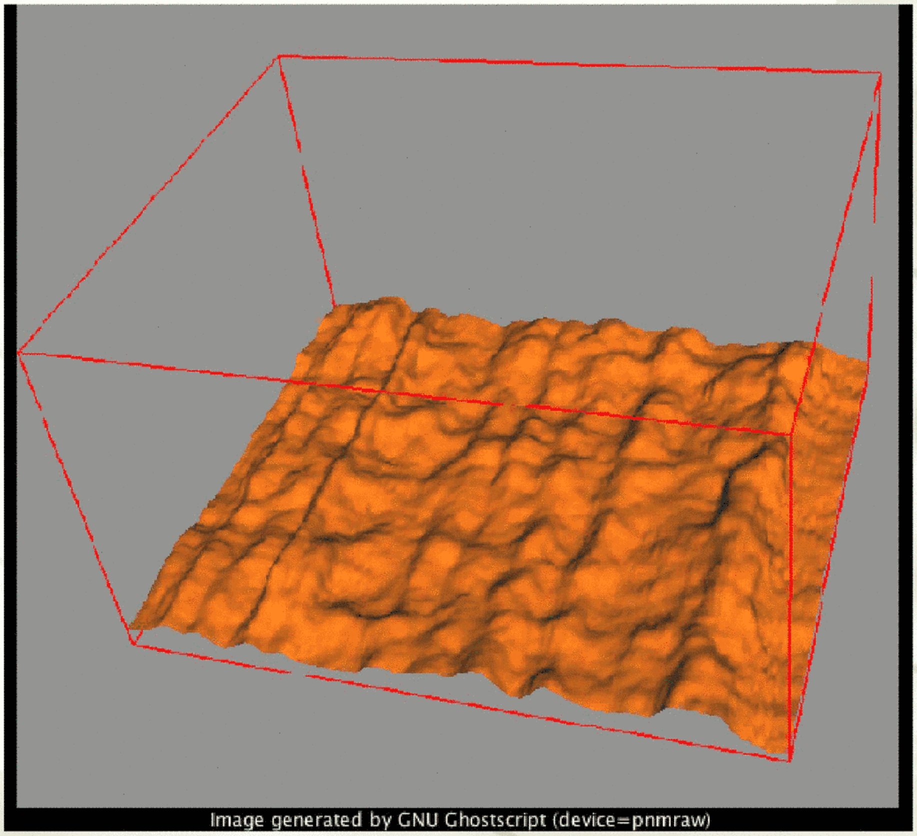
[*Lithgow-Bertelloni et al.*, 2001]

Head & Tail Radii



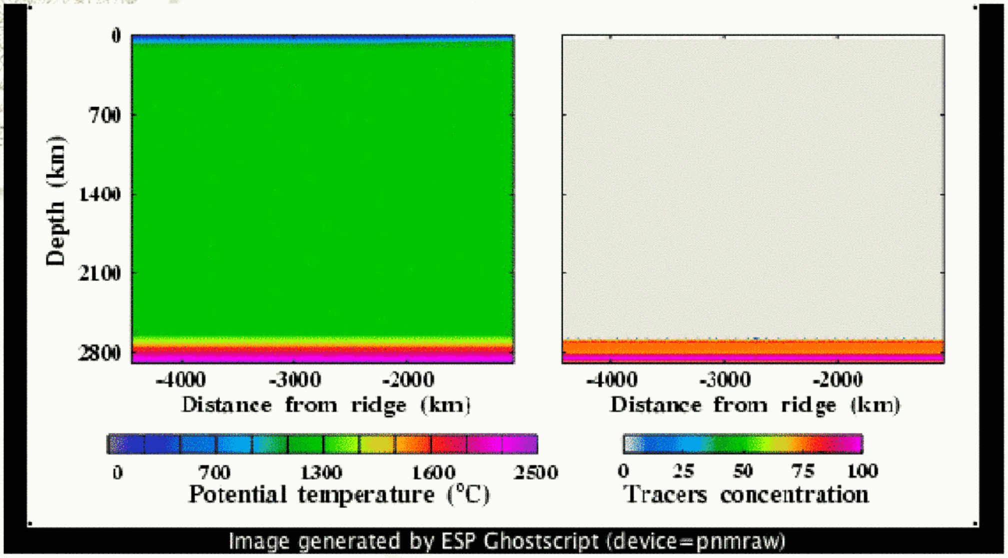
[*Lithgow-Bertelloni et al.*, 2001]

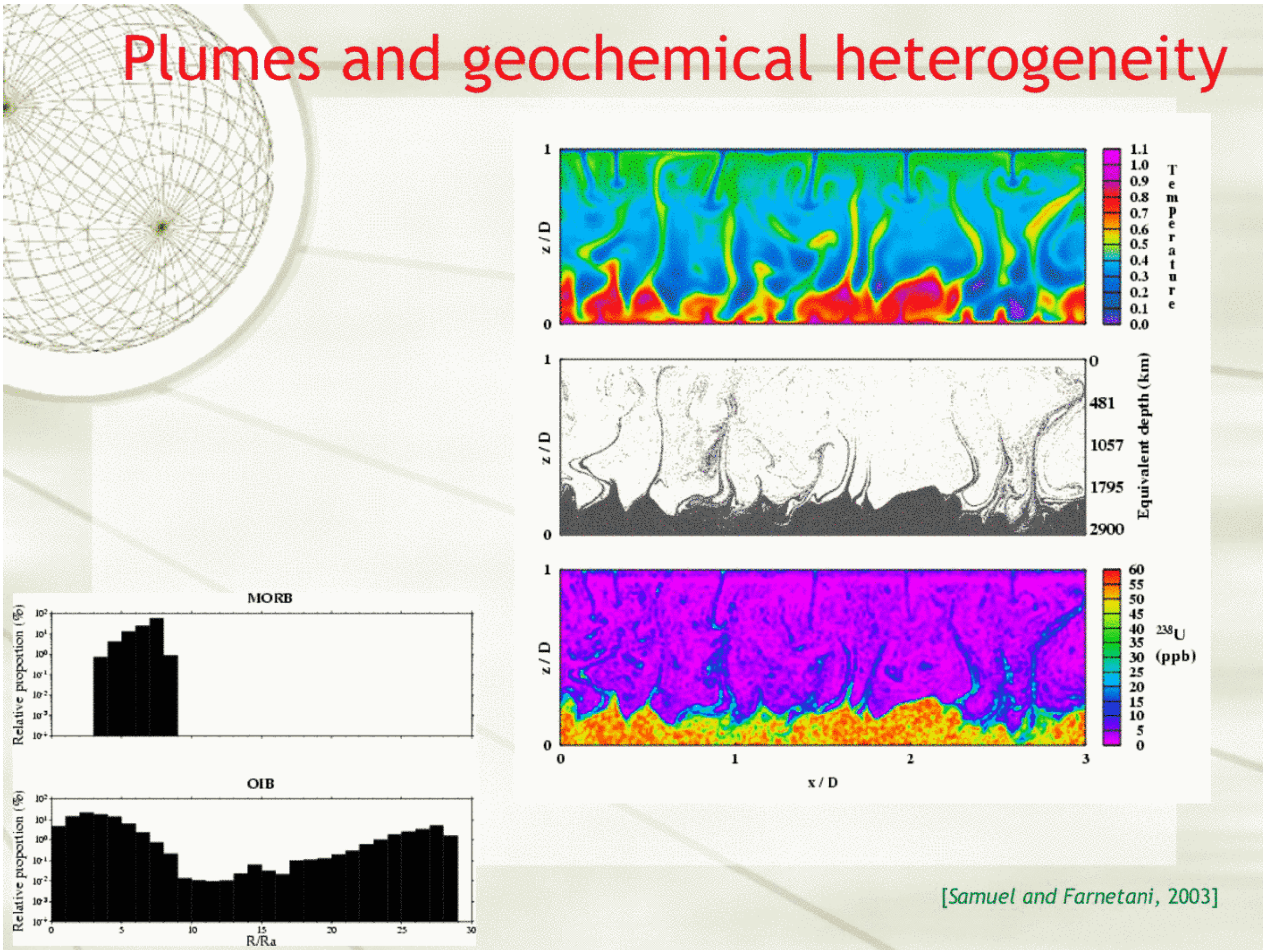
Thermochemical Plumes



[*Farnetani*, 2004]

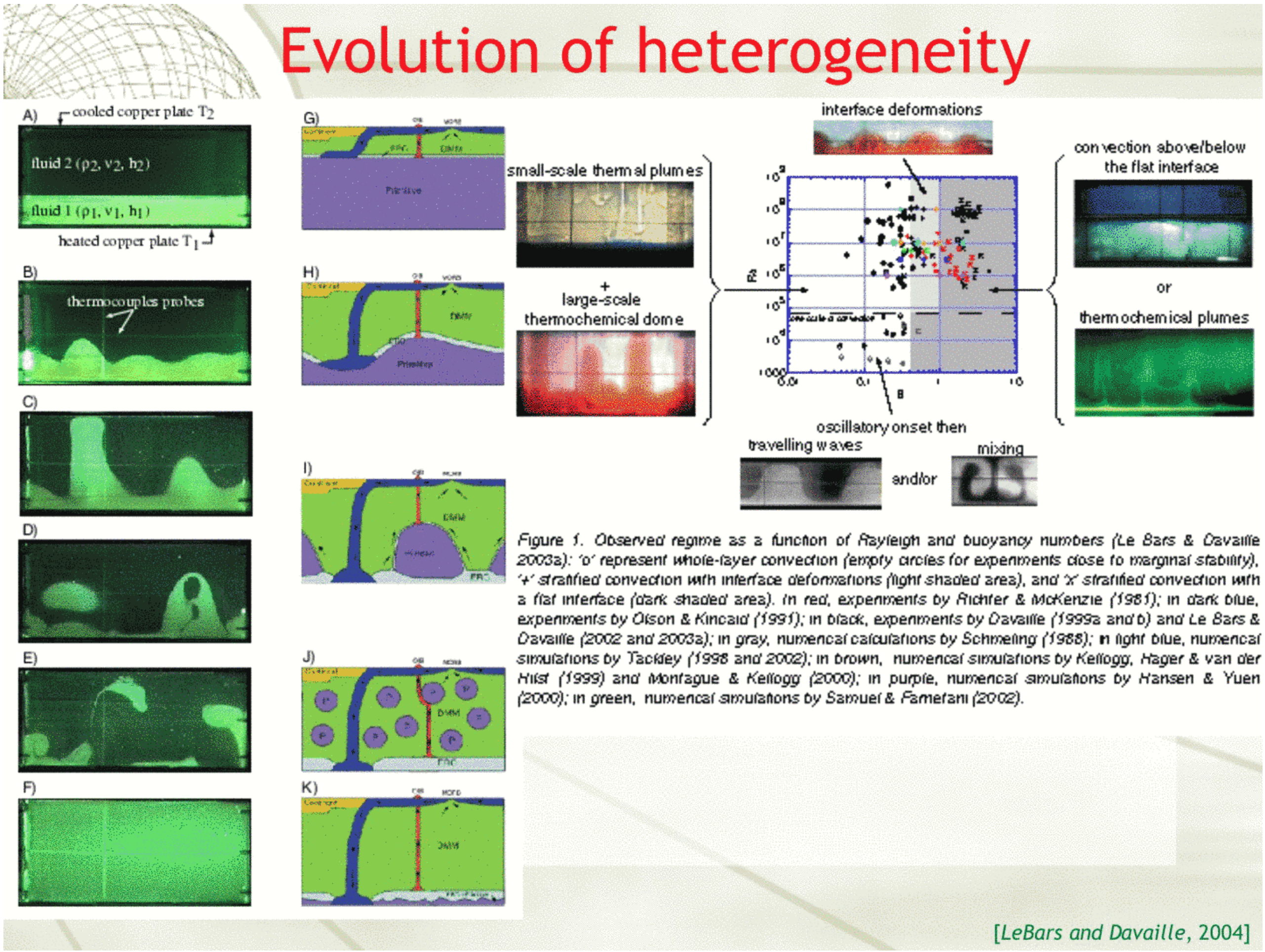
Entrainment and mixing





Plumes and geochemical heterogeneity

[*Samuel and Farnetani*, 2003]

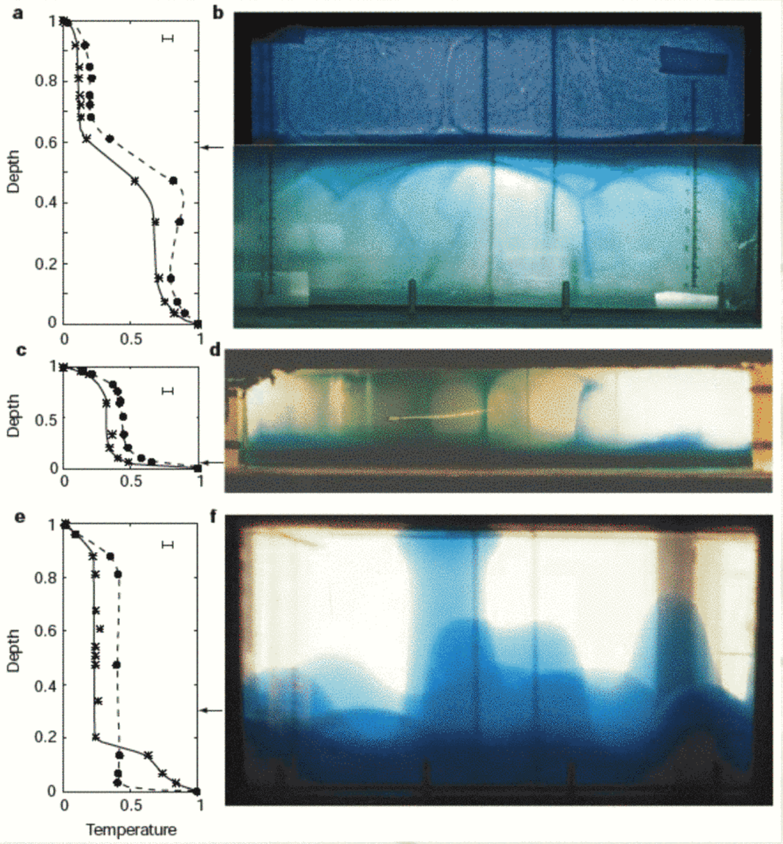


Evolution of heterogeneity

Figure 1. Observed regime as a function of Rayleigh and buoyancy numbers (Le Bars & Davaille 2003a): 'o' represent whole-layer convection (empty circles for experiments close to marginal stability), '+' stratified convection with interface deformations (light shaded area), and 'x' stratified convection with a flat interface (dark shaded area). In red, experiments by Richter & McKenzie (1981); in dark blue, experiments by Olson & Kincaid (1991); in black, experiments by Davaille (1999a and b) and Le Bars & Davaille (2002 and 2003a); in gray, numerical calculations by Schmeling (1988); in light blue, numerical simulations by Tackley (1998 and 2002); in brown, numerical simulations by Kellogg, Hager & van der Hilst (1999) and Montague & Kellogg (2000); in purple, numerical simulations by Hansen & Yuen (2000); in green, numerical simulations by Samuel & Farnetani (2002).

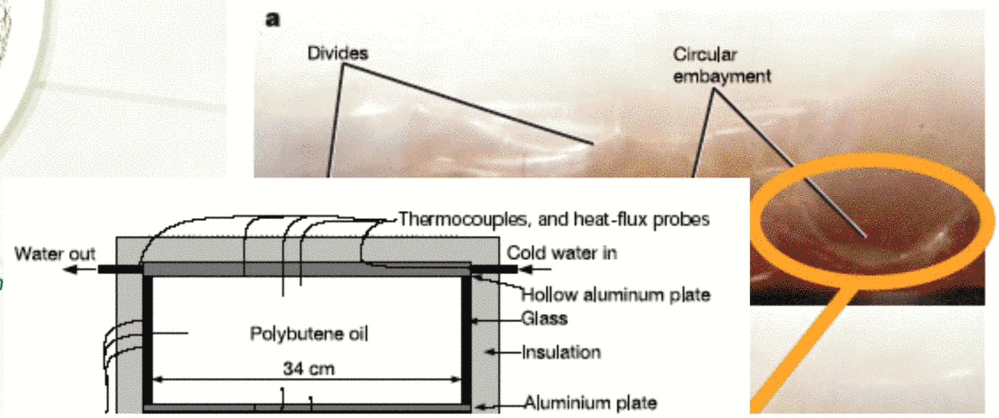
[*LeBars and Davaille*, 2004]

Plumes and large-scale upwellings



[*Davaille*, 2000]

Thermochemical plumes and fixity



[*Jellin*

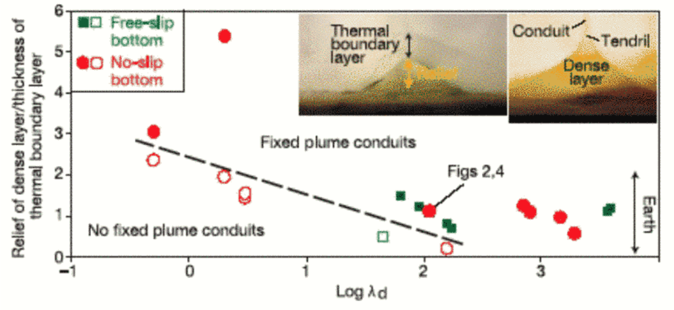
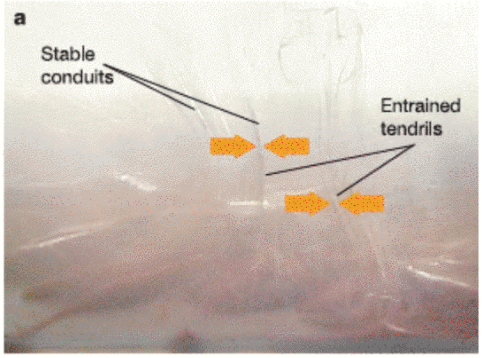
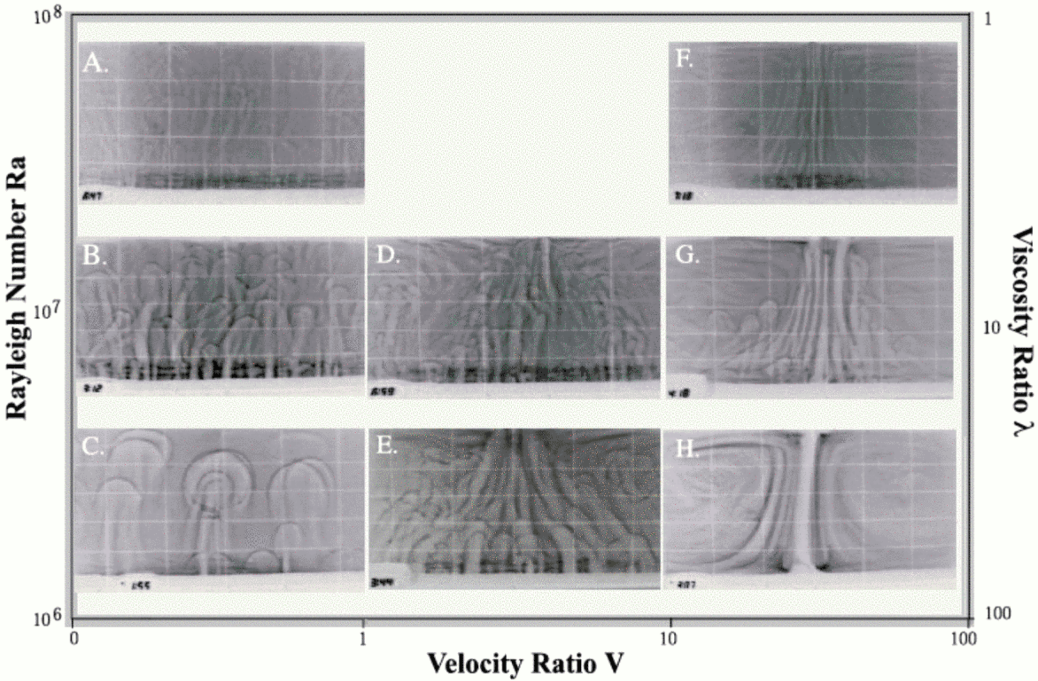


Figure 3 Plot summarizing the conditions leading either to spatially fixed (filled symbols) or not-fixed (open symbols) plumes. Except where indicated, the data are obtained using



Plume capture by large-scale flow



[*Jellinek et al.*, 2002]

λ and Pe control BLT and Q

λ --> 1 Q ~ $(Pe\lambda)^{1/3}$

λ > 10 Q ~ $(Pe)^{1/2}$

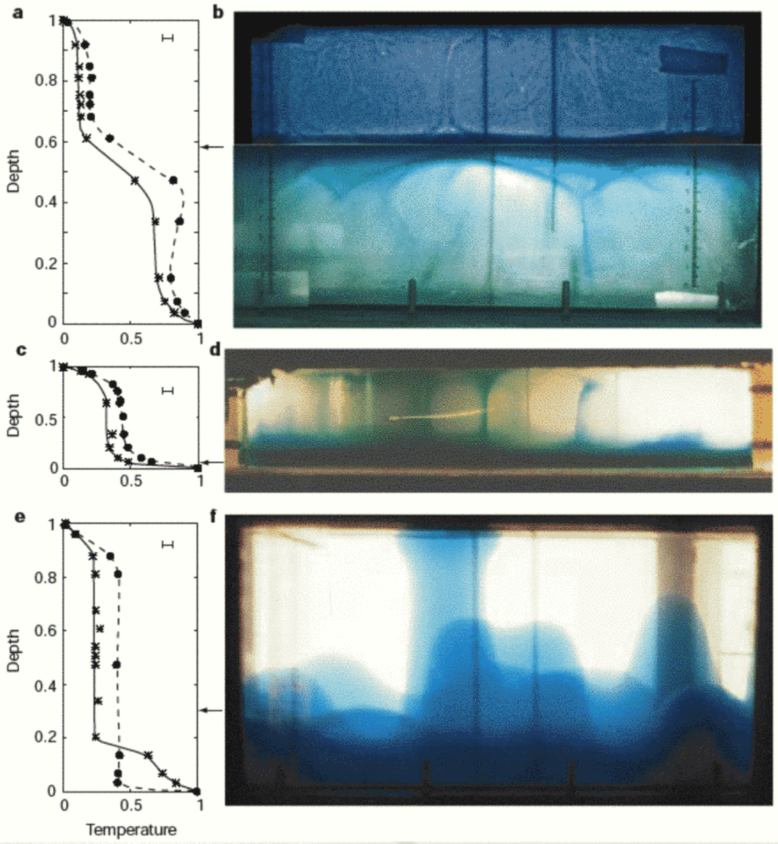
V and $\lambda = \eta_{hot} / \eta_{int}$

No effect V<< 1 λ ~ 1

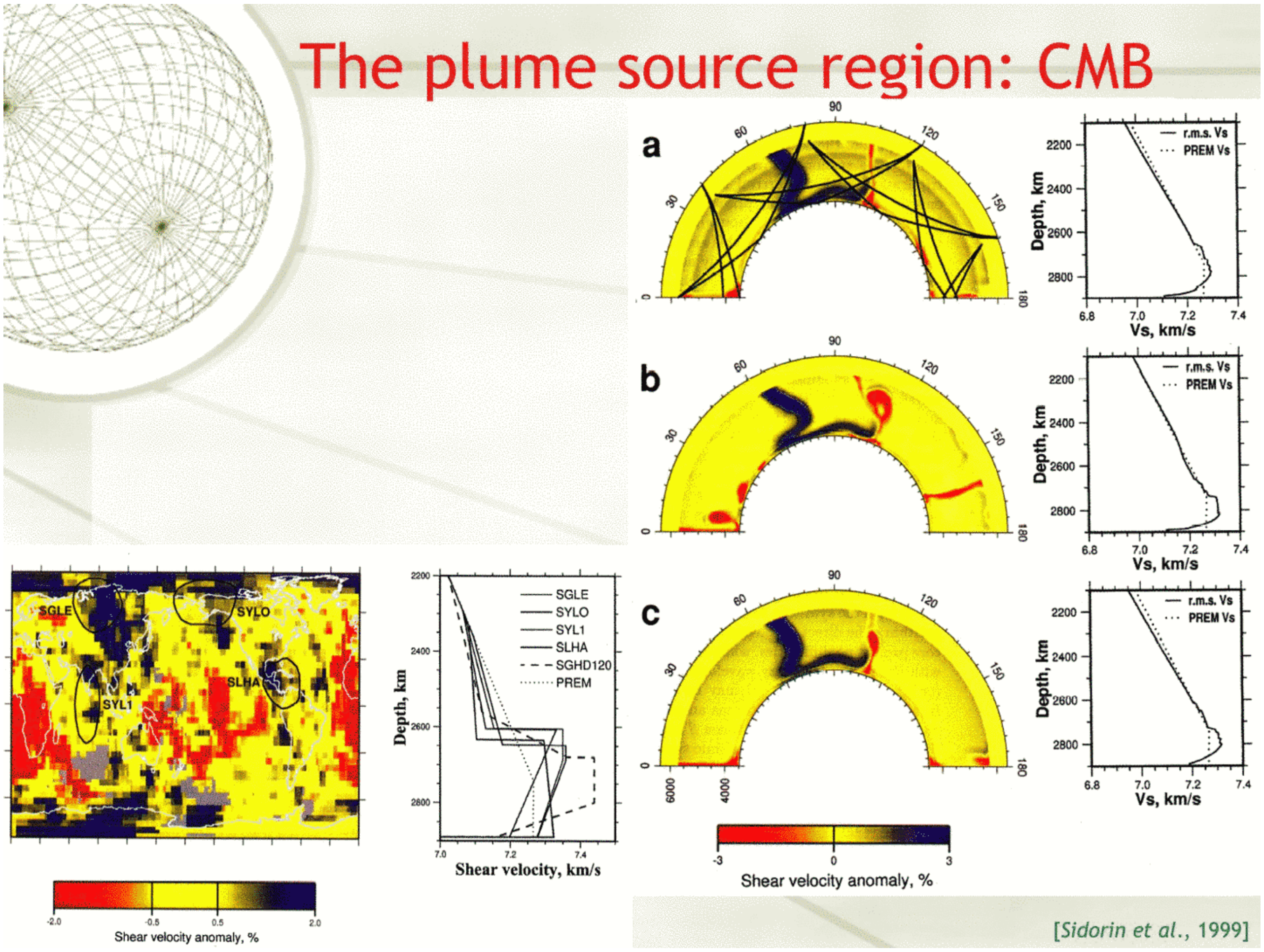
Suppression V> 10 λ > 100

Sweeping V intermediate f(λ)

Where do plumes originate?

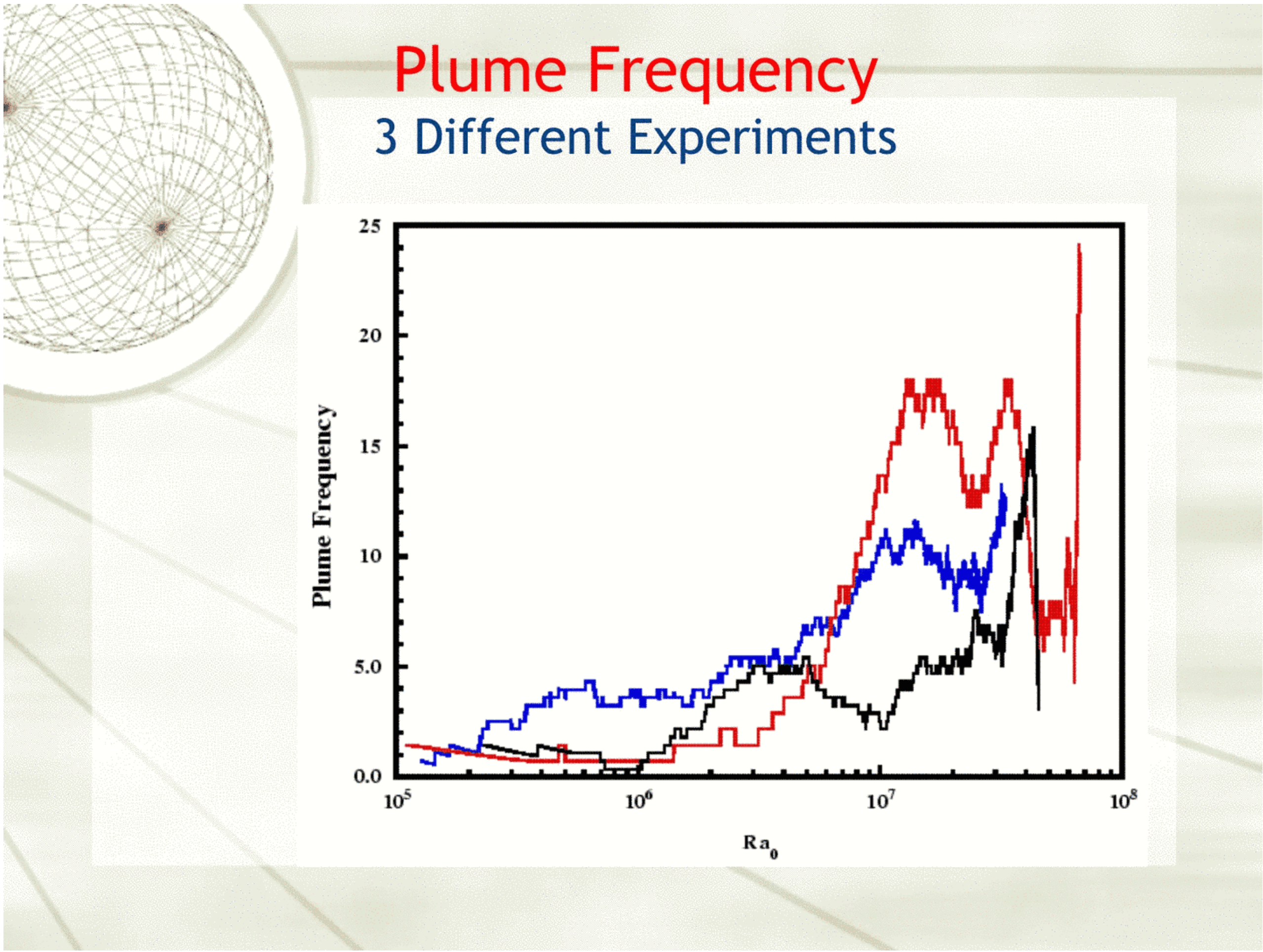


[*Davaille*, 2000]



The plume source region: CMB

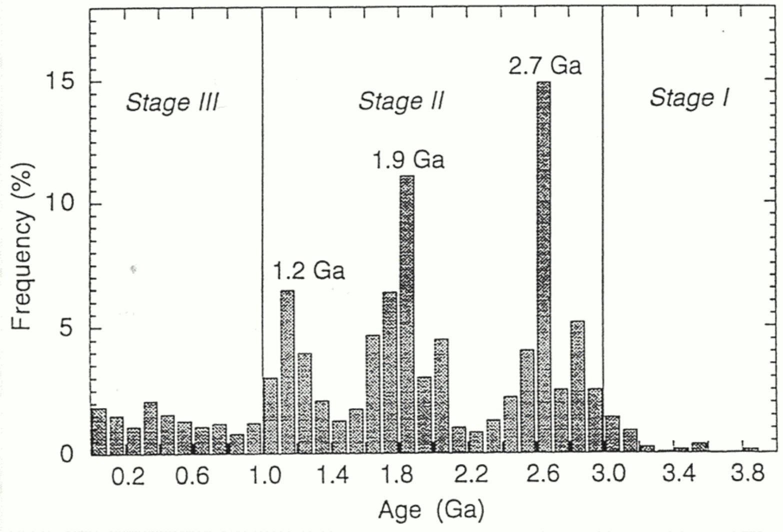
[*Sidorin et al.*, 1999]



Plume Frequency

3 Different Experiments

Episodic Crustal Production?



Condie, 1998