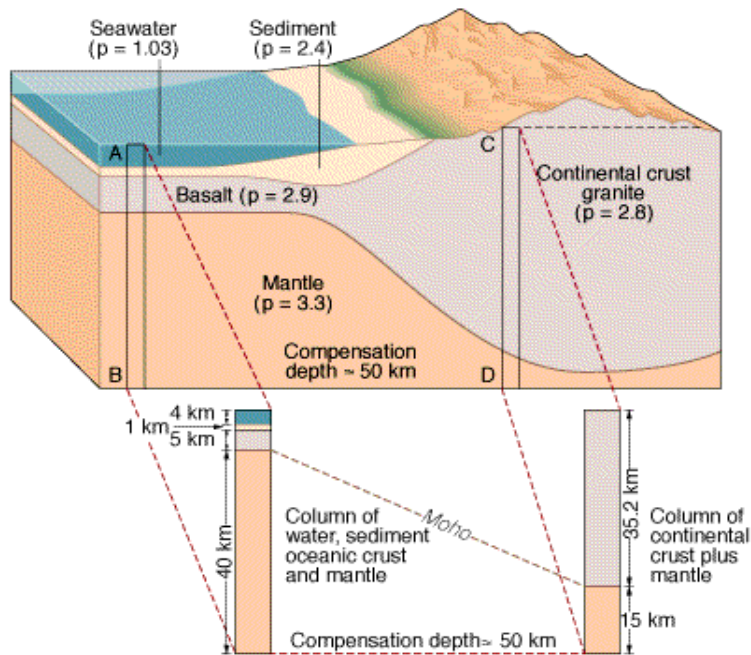


## **Comment étudier la convection?**

*Observations utiles:*

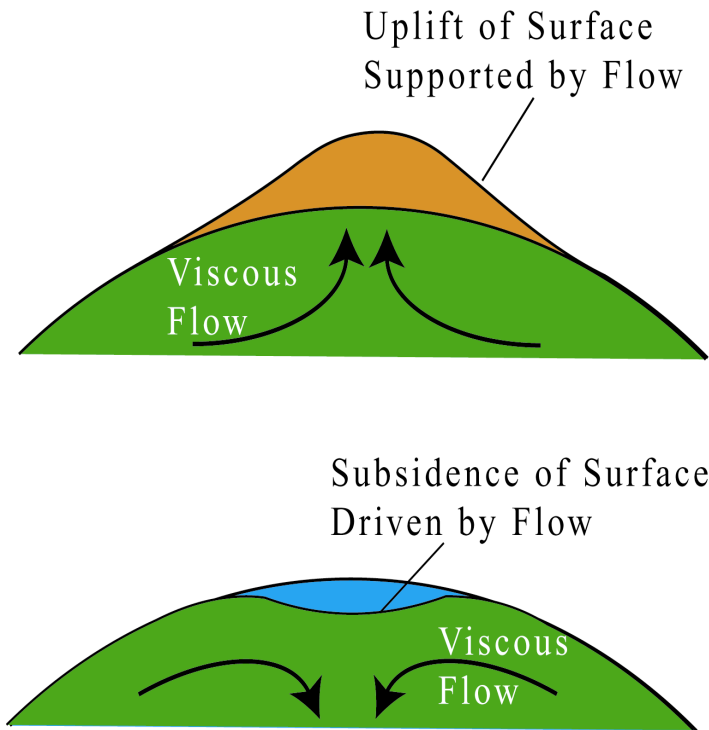
- **sismologie** : « snapshots » de anomalies de vitesse  
(tomographie sismique = champ de  $T$  et/ou composition)  
ou directions d'écoulement (anisotropie sismique)
- **géochimie** : échantillonnage de la composition (intégrée  
dans le temps)
- **vitesse de plaques**
- **flux de chaleur**
- **topographie dynamique**
- **géοide** : effet de la distribution de densité actuelle  
(intégration verticale)

# Topographie dynamique



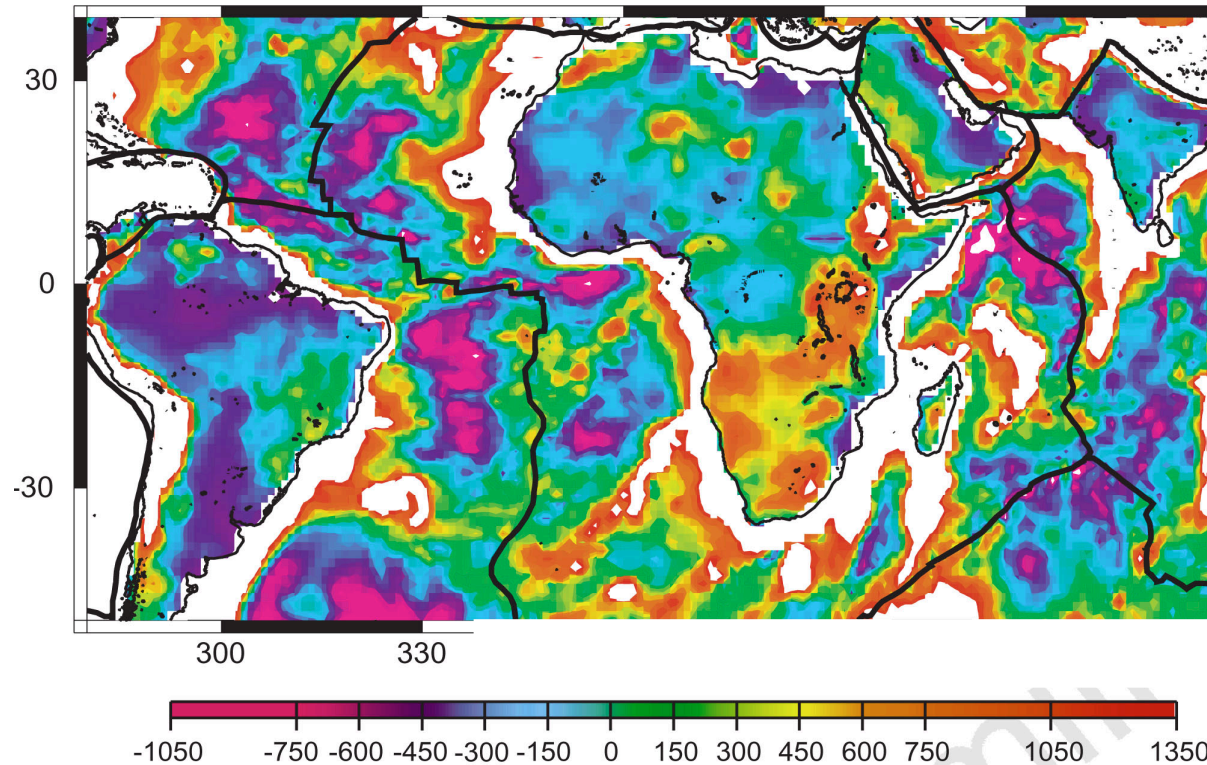
© 1998 Wadsworth Publishing Company/ITP

Isostatically Compensated



Dynamically Supported

# Topographie dynamique

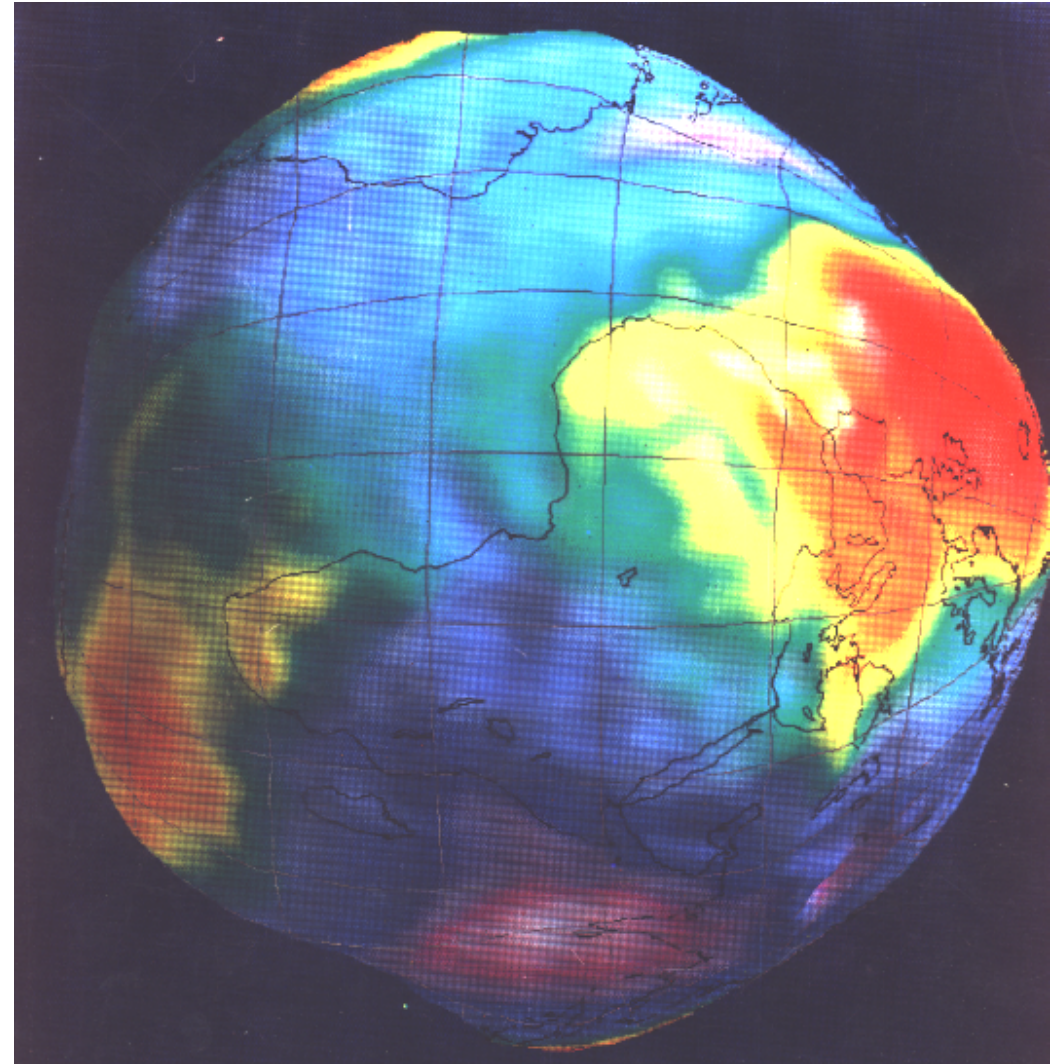
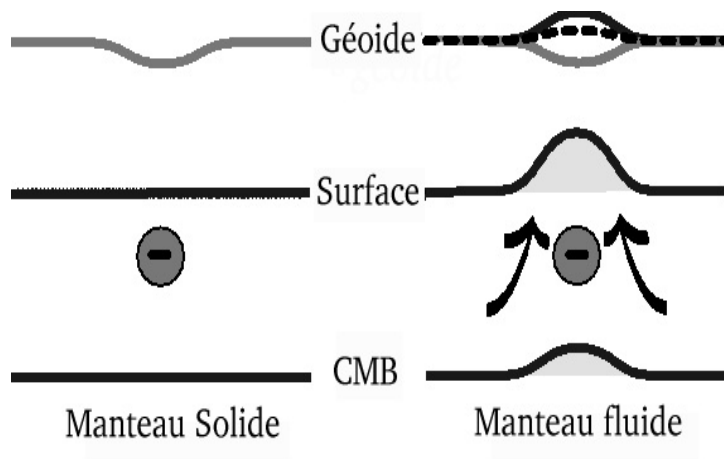


*From: Lithgow-Bertelloni & Silver, Nature 1998 (fig 1)*

*Difficile à mesurer, mais son amplitude (+/- 900 m) est une contrainte forte pour les modèles.*

# Le Géoïde

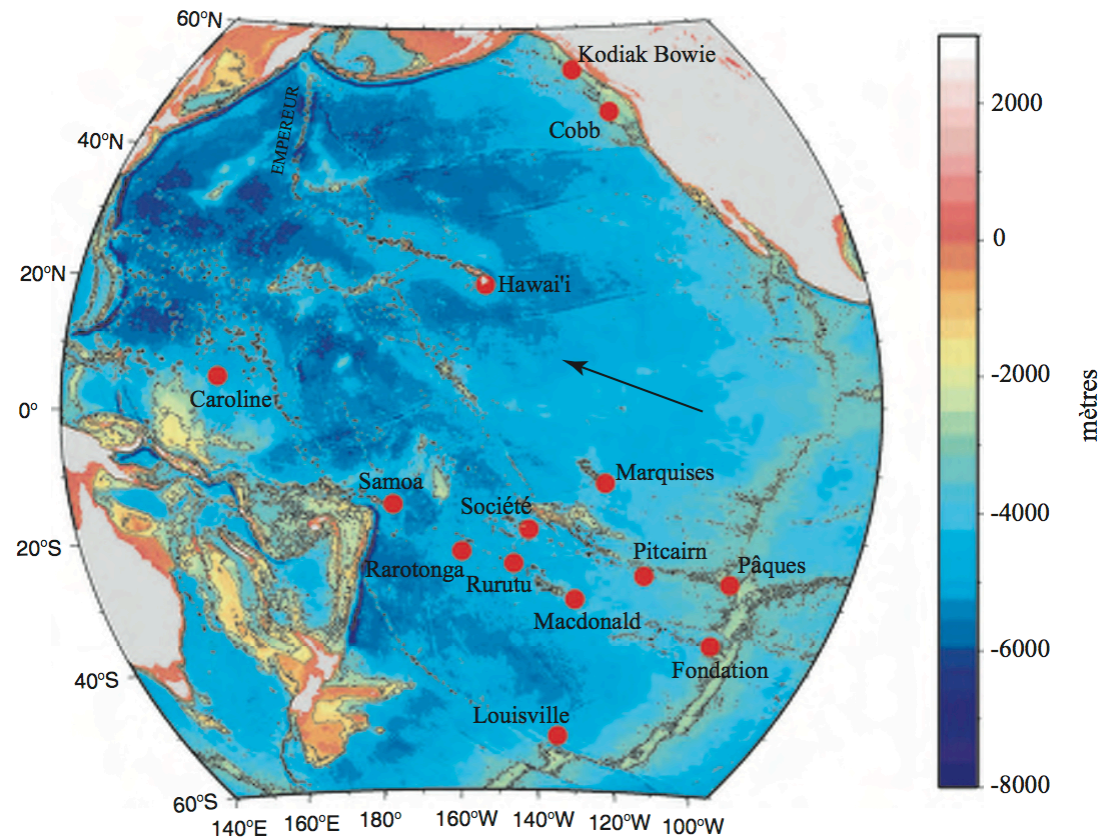
*équipotentielle de gravité =  
niveau moyen des mers  
(+80m sous l'Islande à  
-120m sous l'Inde)*



*2 contributions opposées:*

- Anomalies de densité dues aux déflexions des interfaces internes dans le manteau*
- Déflexion de la surface de la Terre due à l'écoulement (topographie dynamique)*

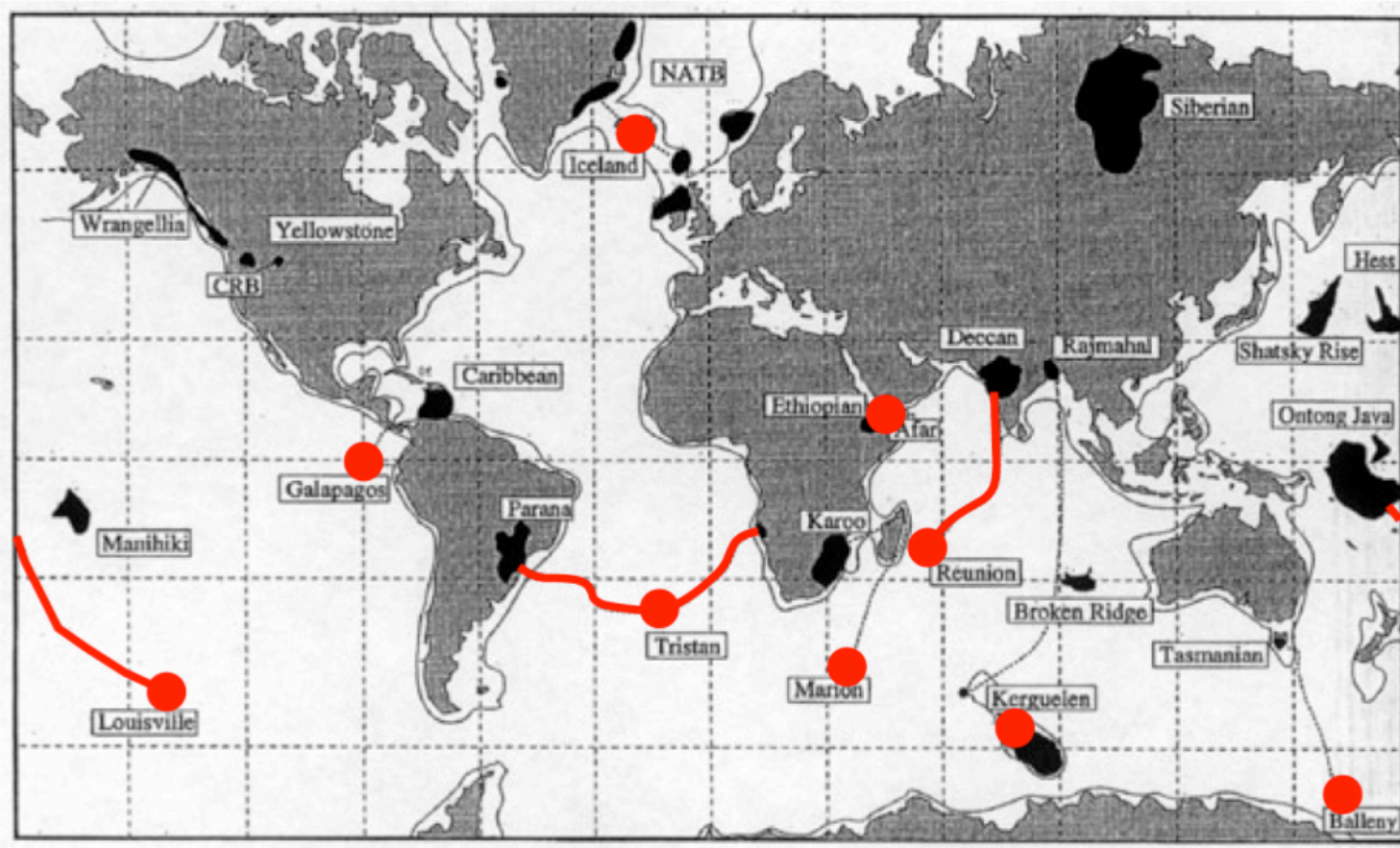
# Dynamique des « panaches » mantelliques



*Vidal,  
2004*

FIG. 2.3 – Le volcanisme de la plaque Pacifique sur fond topographique : en rouge sont indiqués les points chauds ; la flèche noire indique la direction actuelle du mouvement de la plaque Pacifique.

Intraplate volcanism : long track with traps  
=> plume = head + stem



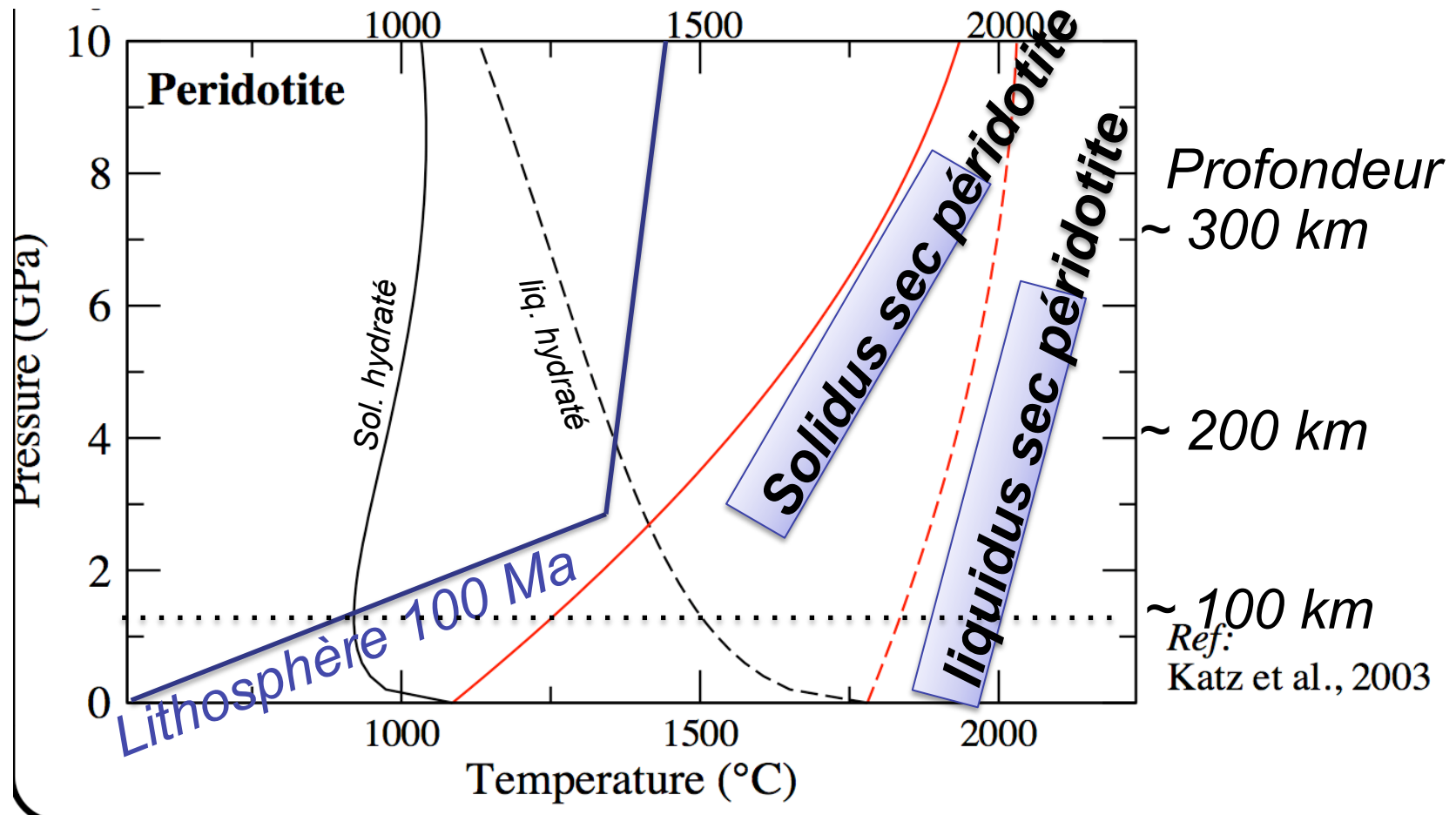
(Richards & al, 1989)



Dyment et al., 2007

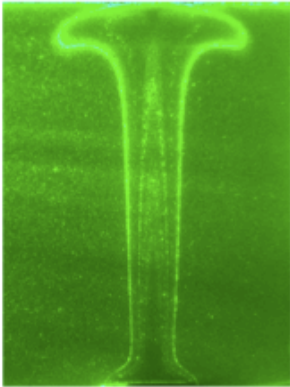
Analyse en éléments traces (isotopiques): réservoirs  
OIBs  $\neq$  réservoirs MORBs

# Volcanisme intraplaque au cœur d'une lithosphère épaisse



*Anomalie thermique basale d'au moins 100 °C (à 350°C)*



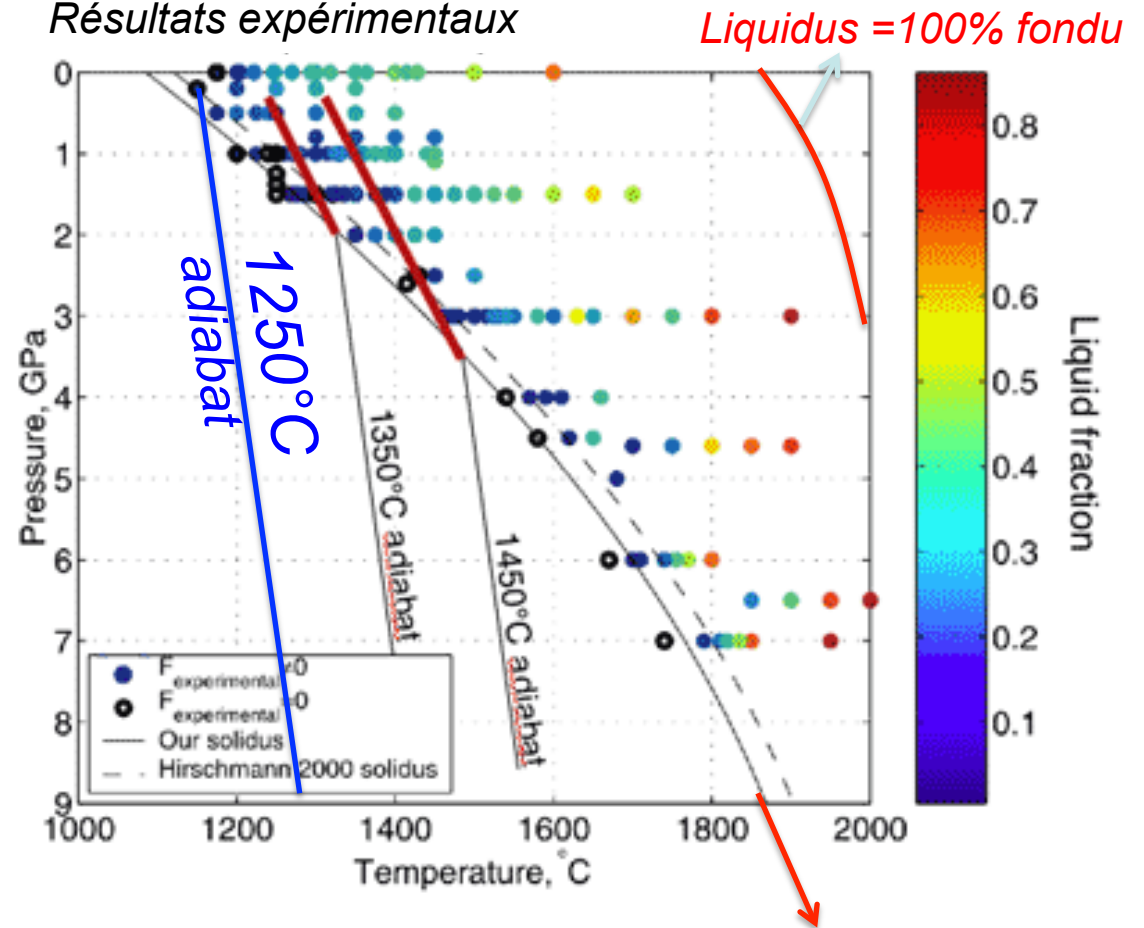


## Mise en évidence des panaches terrestres

$T_{\text{panaches}} > T_{\text{manteau normal}}$  : **fusion partielle**  
 Conséquence en surface: magmatisme



Fusion partielle d'une roche mantellique  
 Résultats expérimentaux



*Solidus = début de la fusion*

# Observations sismologiques

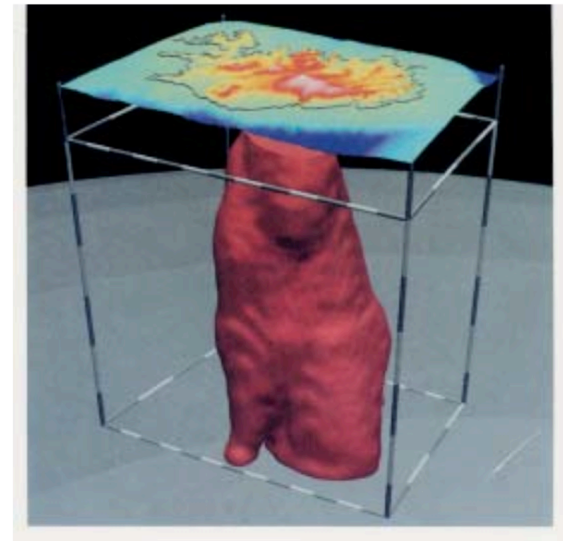
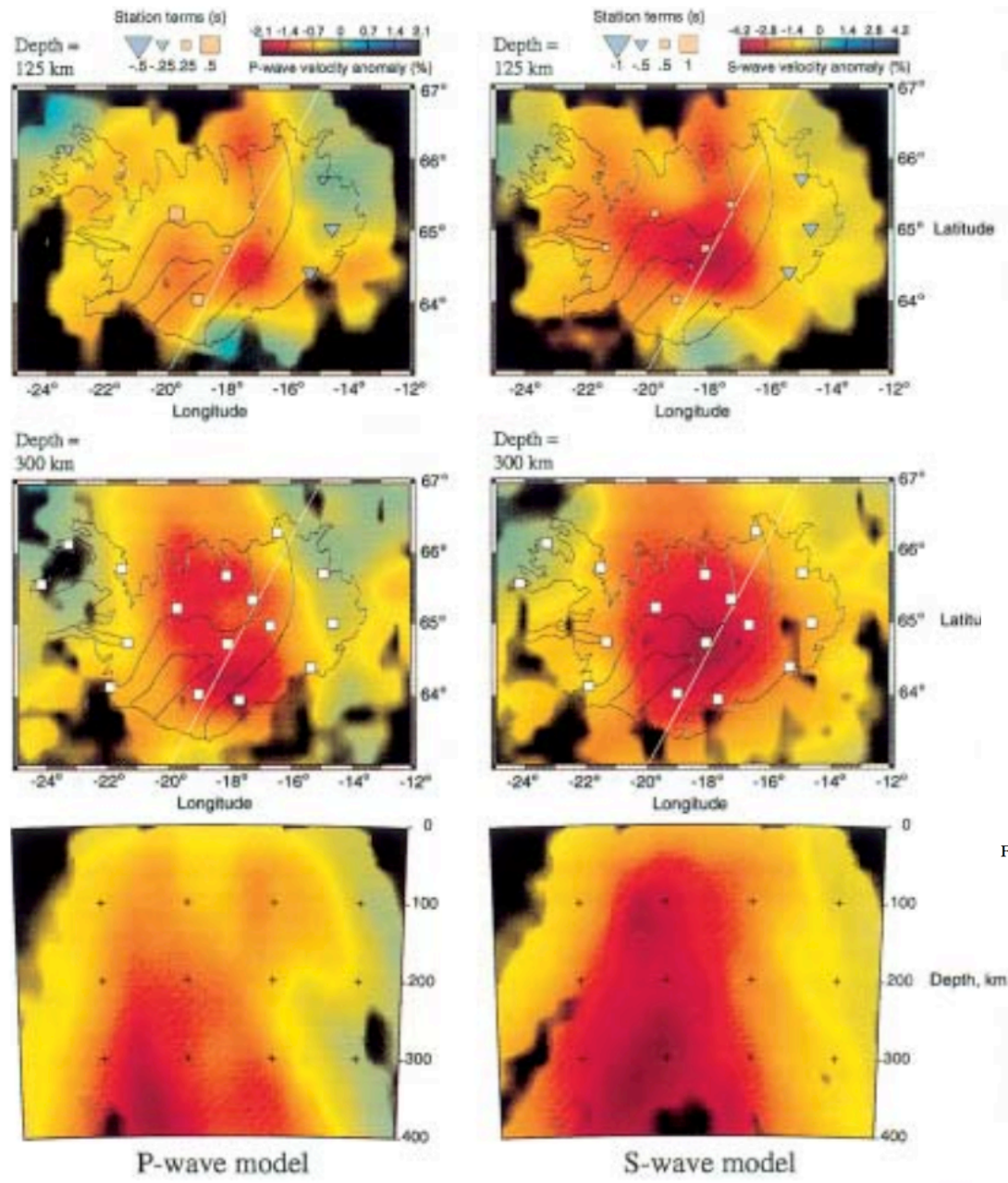
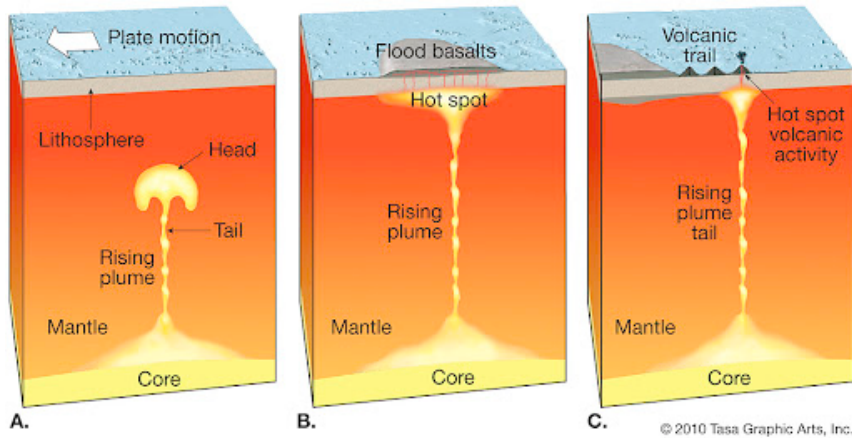


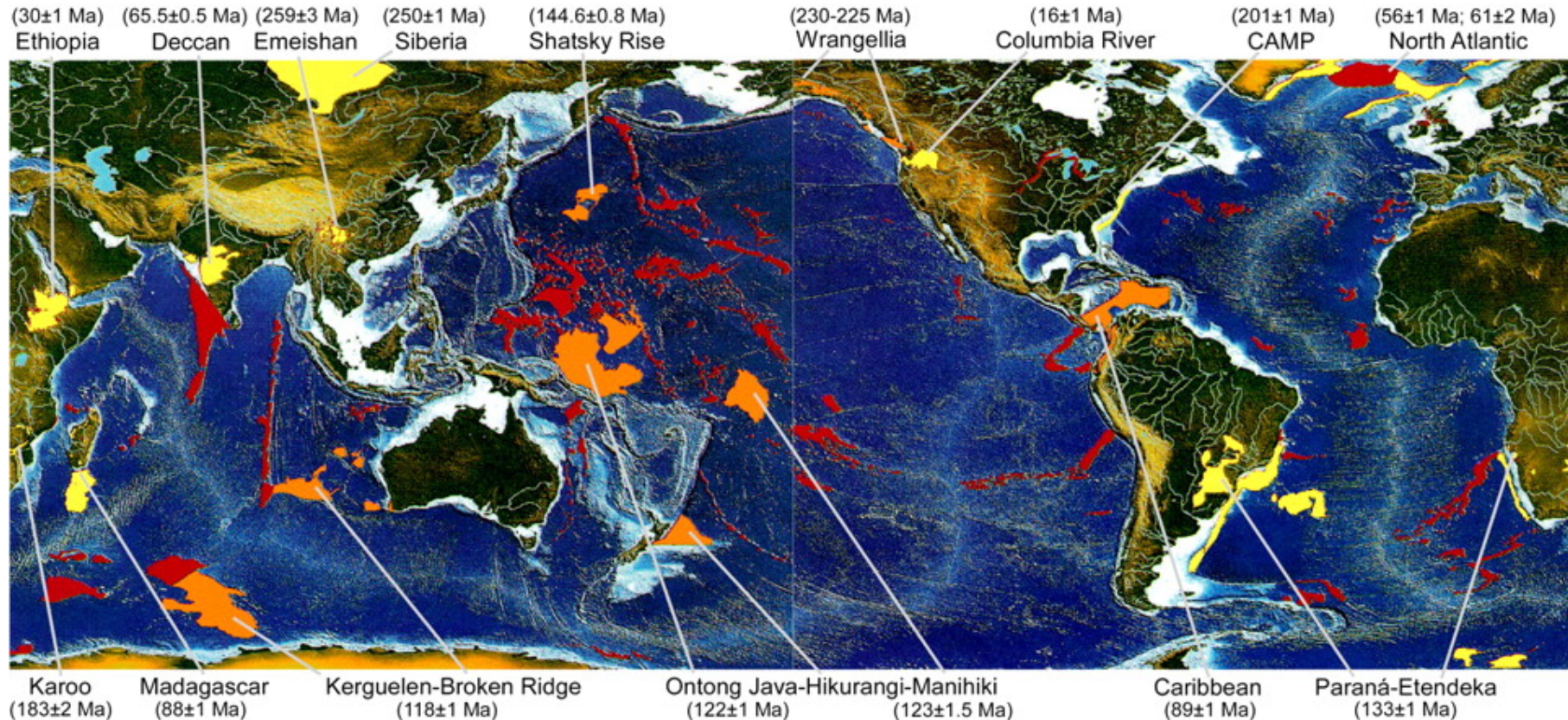
Figure 2.26. Seismically delineated plume structure beneath central Iceland (Wolfe et al., 1997).

Figure 11.9. Upper mantle compressional wave velocity (left) and shear wave velocity (right) variations beneath Iceland determined by Wolfe et al. (1997). Variations at 125 km depth (top row), 300 km depth (middle row), and in cross-section (bottom row).



## LIPs: Large Igneous Provinces

*Plateaux océaniques: Fusion partielle associée à la tête d'un panache (instabilité initiale =  $\Delta T$  et volume plus importants)*



**Map showing the distribution of Phanerozoic large igneous provinces (Mahoney and Coffin, 1997)**

# Phenomenology of Thermal Plumes

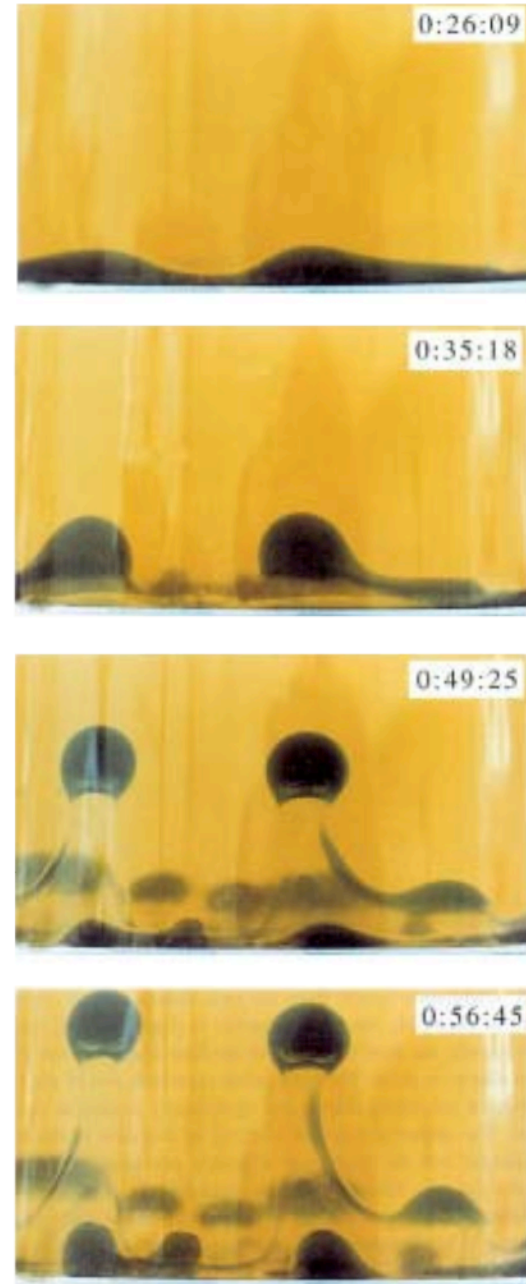
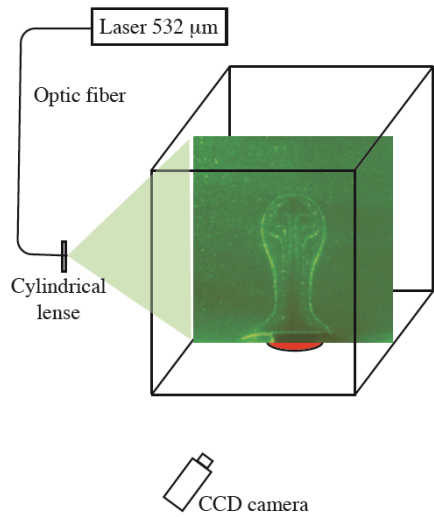
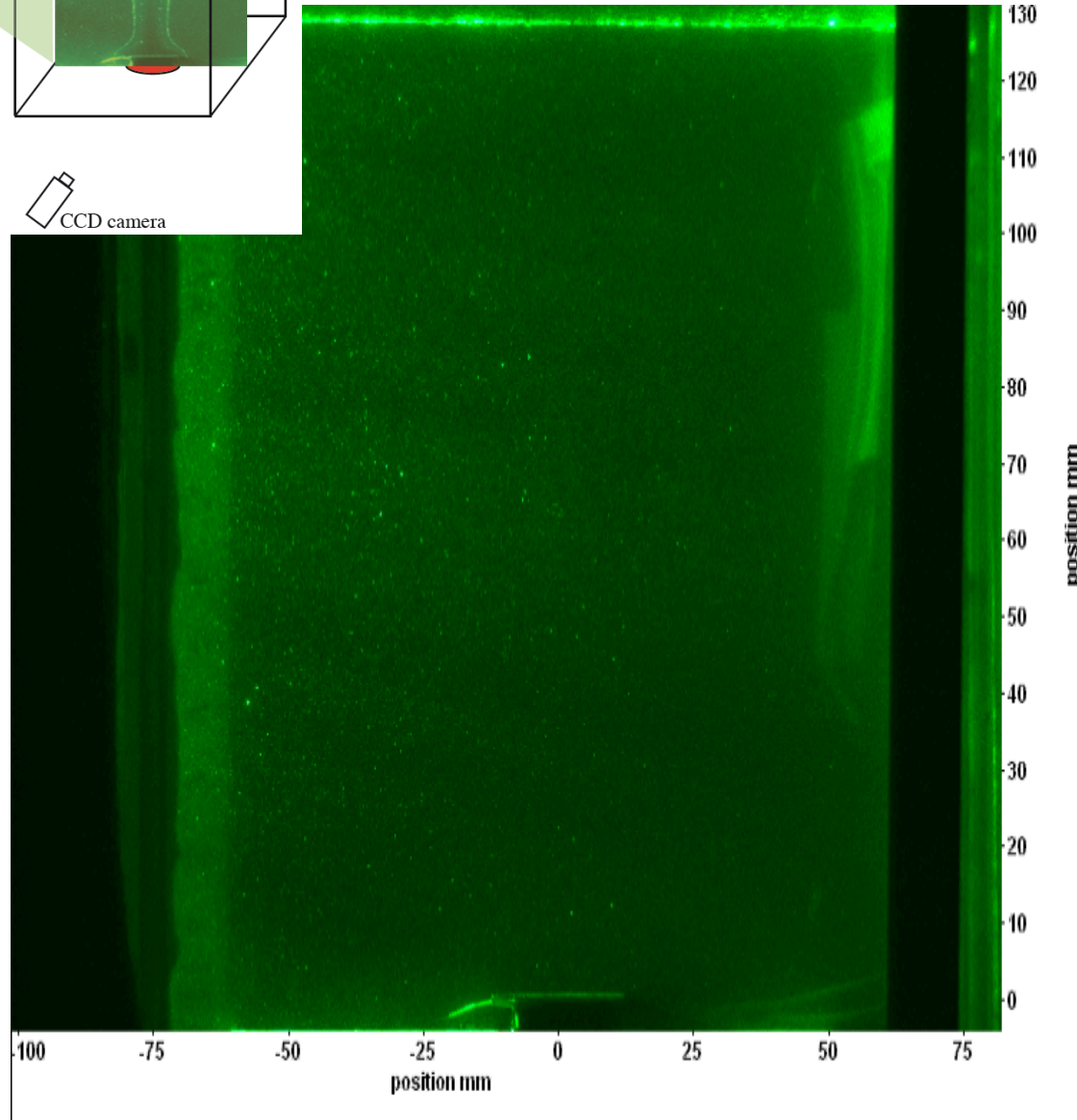


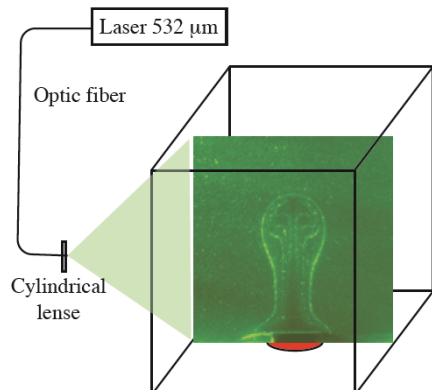
Figure 11.11. Photographs from a laboratory experiment showing plume initiation by instability of a thin, low-density, low-viscosity glucose fluid layer beneath a deep, high-density, high-viscosity glucose fluid layer. Times and depth scale are indicated. From Bercovici and Kelly (1997).



## *Convection dans le laboratoire: Développement d'un panache*

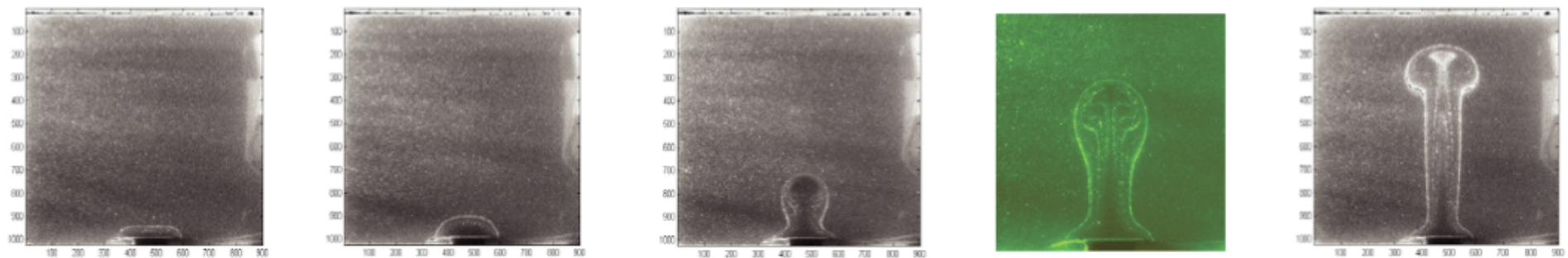


$$\begin{aligned}
 Ra &= \frac{\text{advection "velocity"}}{\text{diffusion "velocity"}} \\
 &= \left( \frac{\rho g \alpha \Delta T D^2}{\eta} \right) / \left( \frac{\kappa}{D} \right) \\
 &= \frac{\rho g \alpha \Delta T D^3}{\eta \kappa}
 \end{aligned}$$



# Convection dans le laboratoire: Développement d'un panache

(mainly from A. Davaille, FAST)



(1)

(2)

(3)

(4)

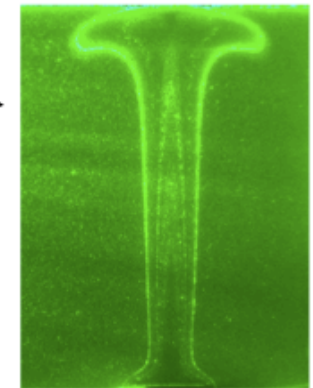
(5)

(6)

$$Ra = \frac{\text{advection "velocity"}}{\text{diffusion "velocity"}}$$

$$= \left( \frac{\rho g \alpha \Delta T D^2}{\eta} \right) / \left( \frac{\kappa}{D} \right)$$

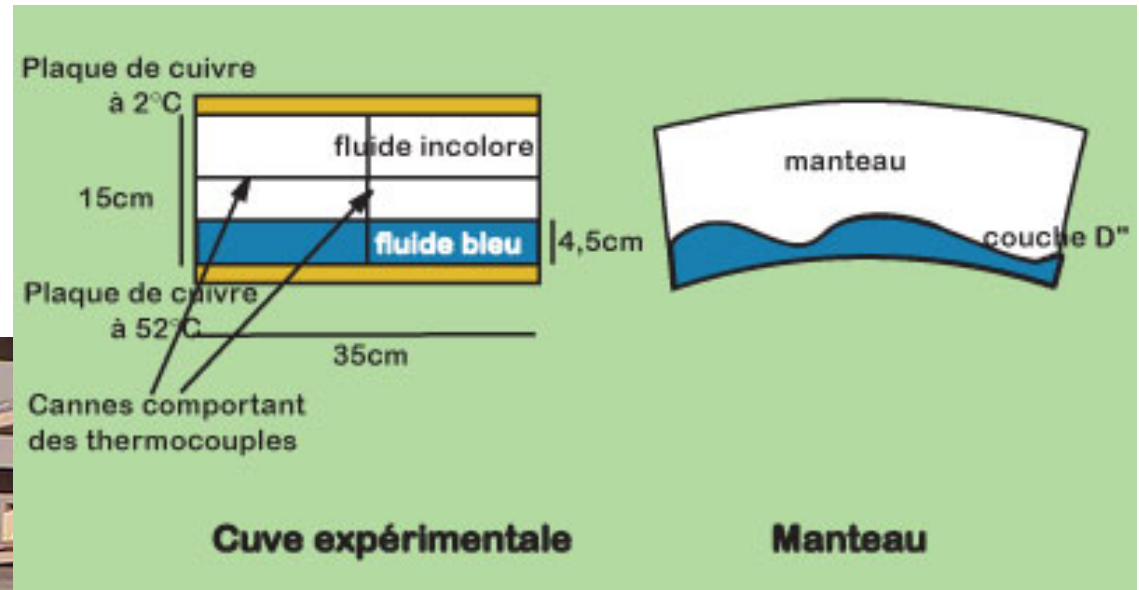
$$= \frac{\rho g \alpha \Delta T D^3}{\eta \kappa}$$



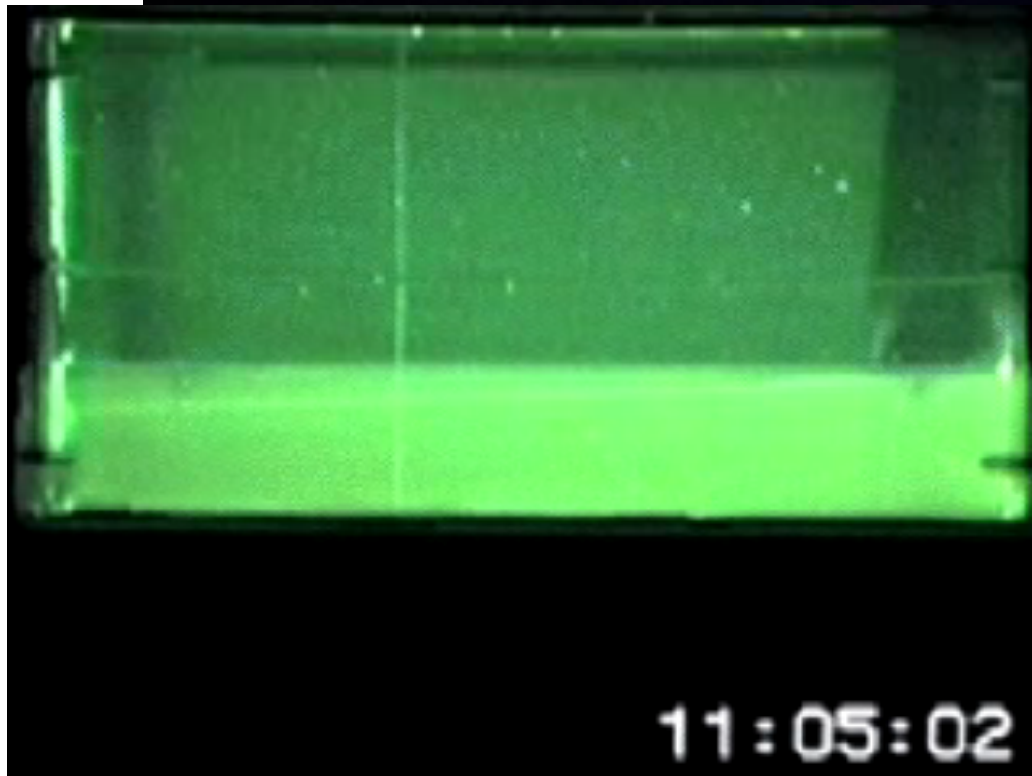
# ***Etudier la convection et les panaches mantelliques***

*Modélisation analogique ou numérique*

*- physique du système*



*Chauffage base et refroidissement haut: 2 couches avec densité et viscosité  $\neq$*



*Couche inférieure:  
+ dense & + visqueuse*

*Que se passe-t-il après  
plusieurs cycles?*

*Conséquences pour le  
manteau terrestre?*



# Thermochemical convection in a two-layer mantle

## Four dimensionless groups:

governing stability:

$$- Ra = \frac{\alpha g \Delta T d^3}{\kappa \nu}$$

$$- B = \frac{\Delta \rho_x / \rho}{\alpha \Delta T}$$

governing morphology:

$$- \gamma = \eta_1 / \eta_2$$

$$- a = d_1 / d_2$$

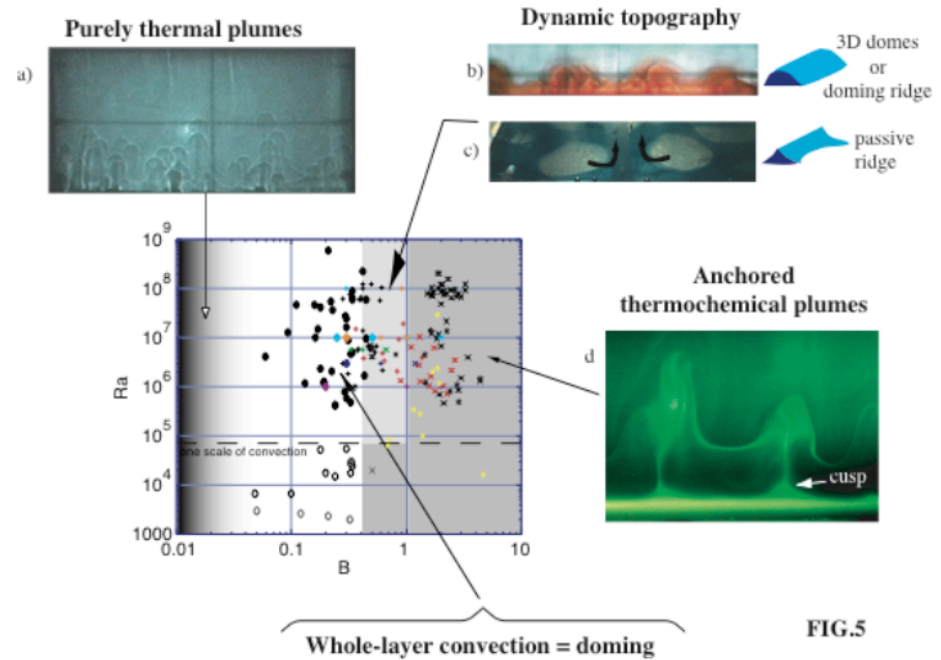
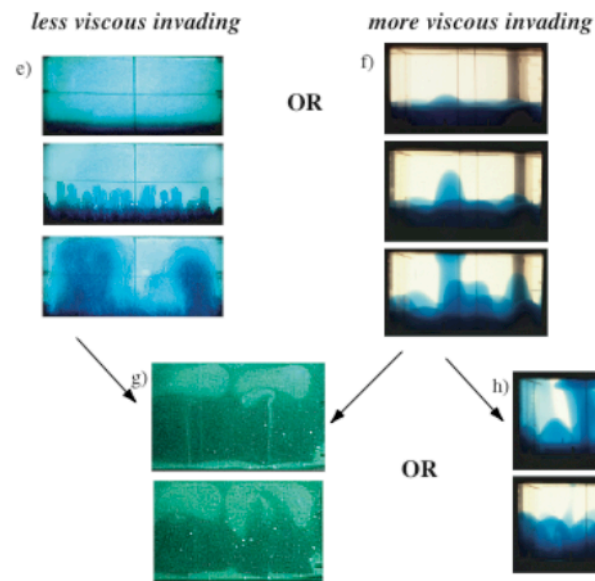


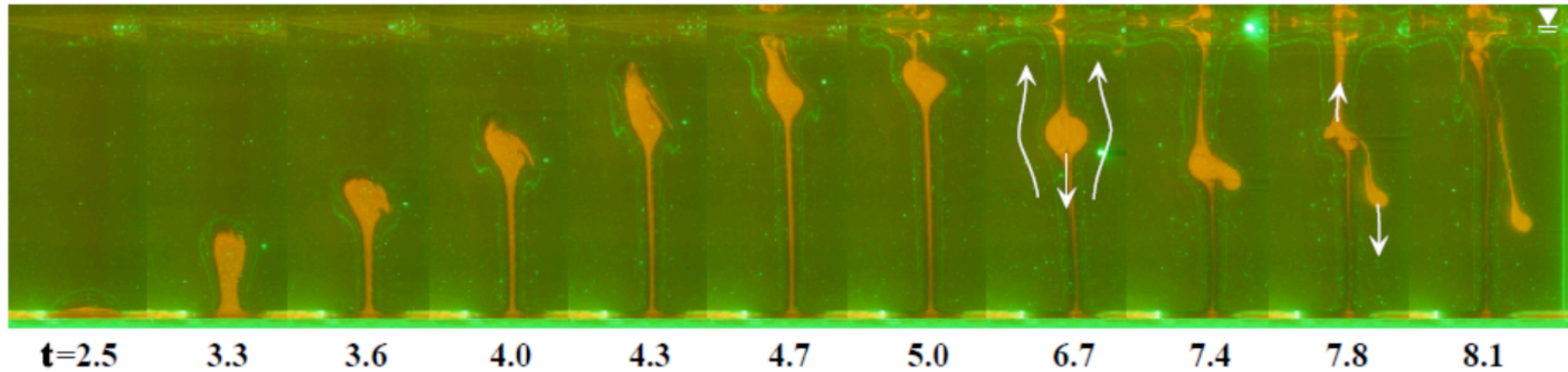
FIG.5



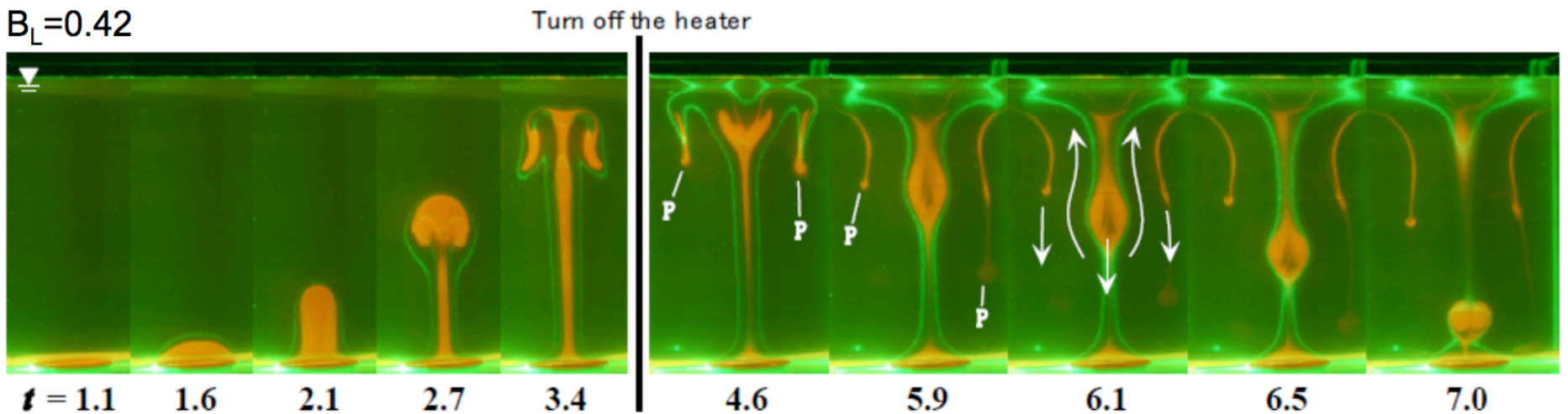
Davaille et al.

## Localized thermochemical plumes: Time-dependence

$B_L=0.59$



$B_L=0.42$



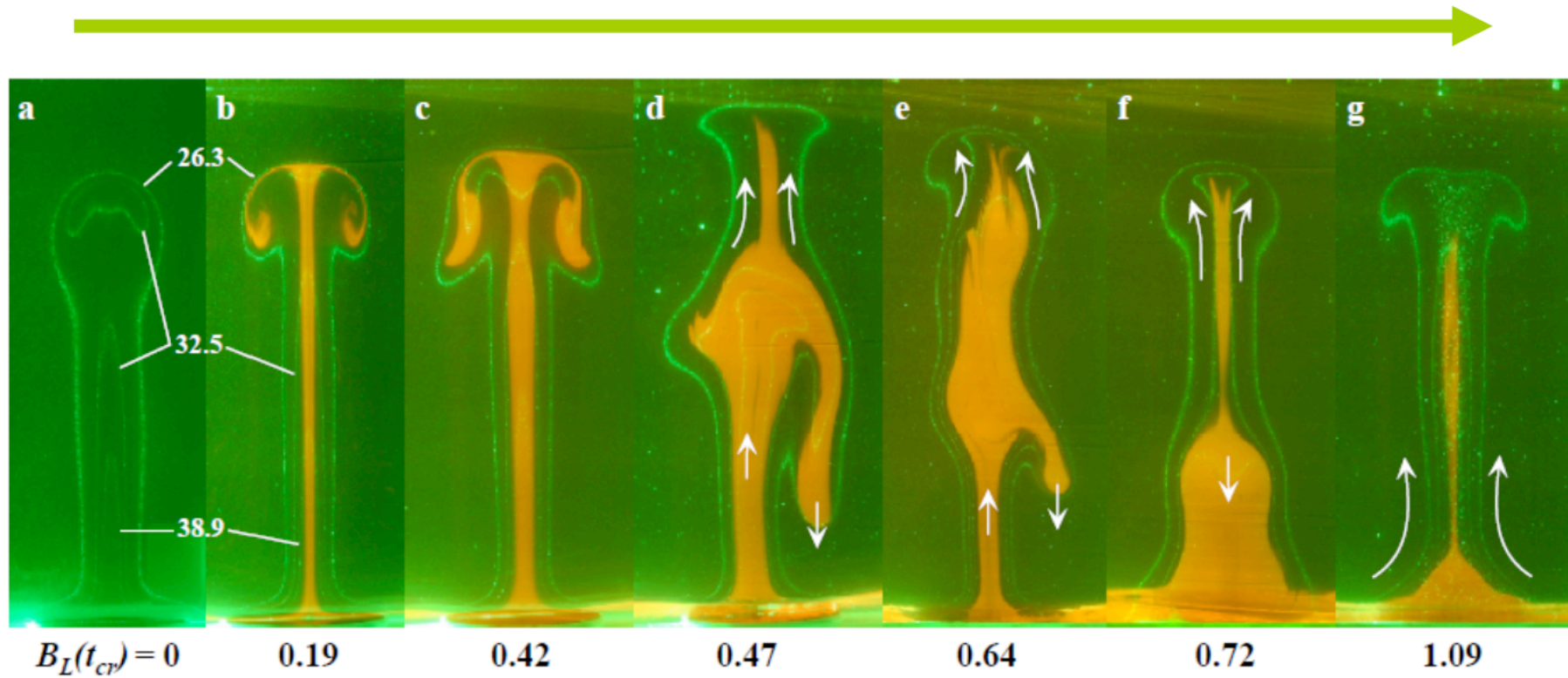
**All thermo-chemical plumes should "fail" because of cooling!!**

**Failing Plume**

*Davaille et al.*

## Localized thermochemical plumes

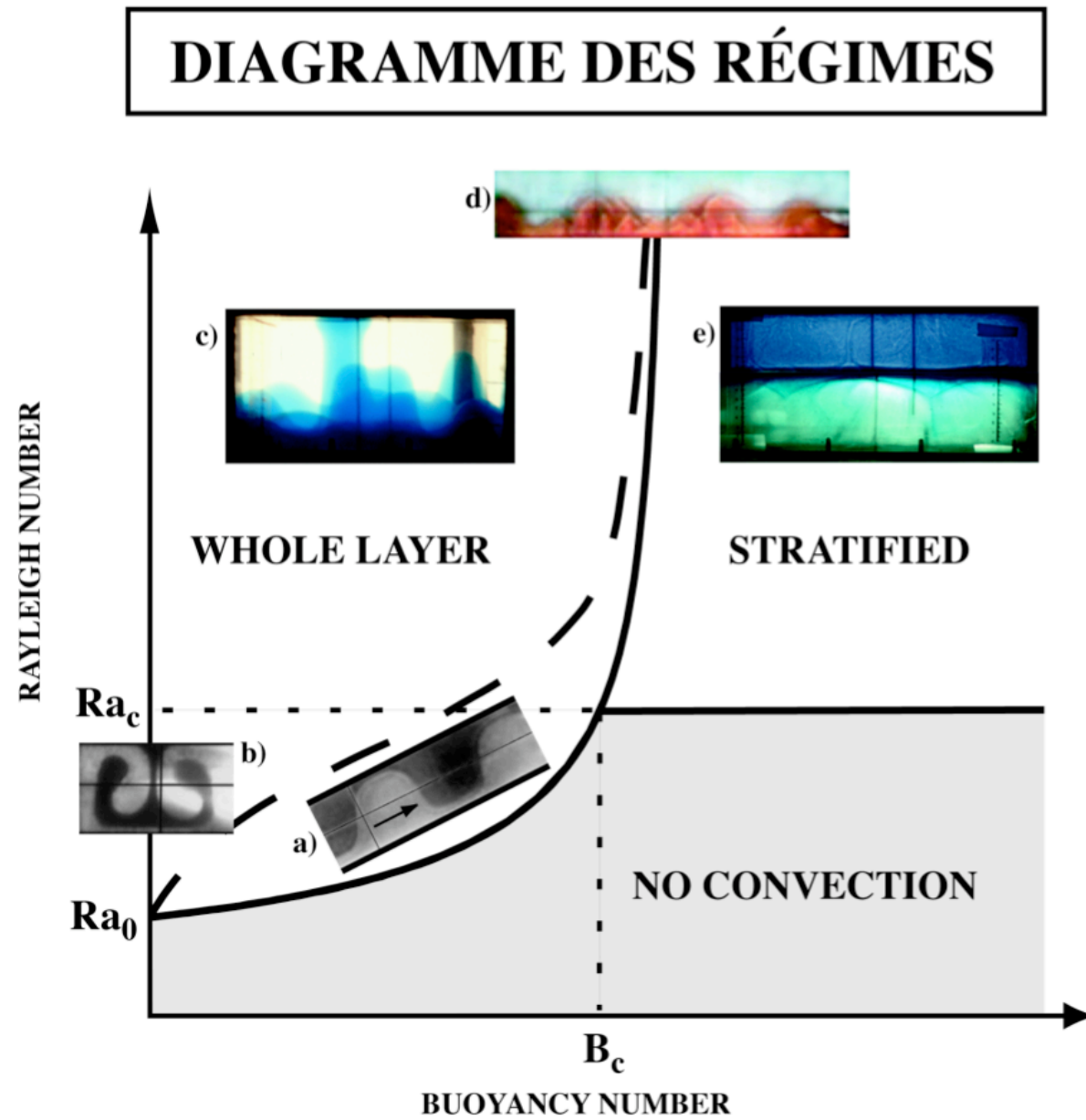
Initial buoyancy ratio



$$B_L = \Delta\rho_x / \rho_0 \alpha \Delta T$$

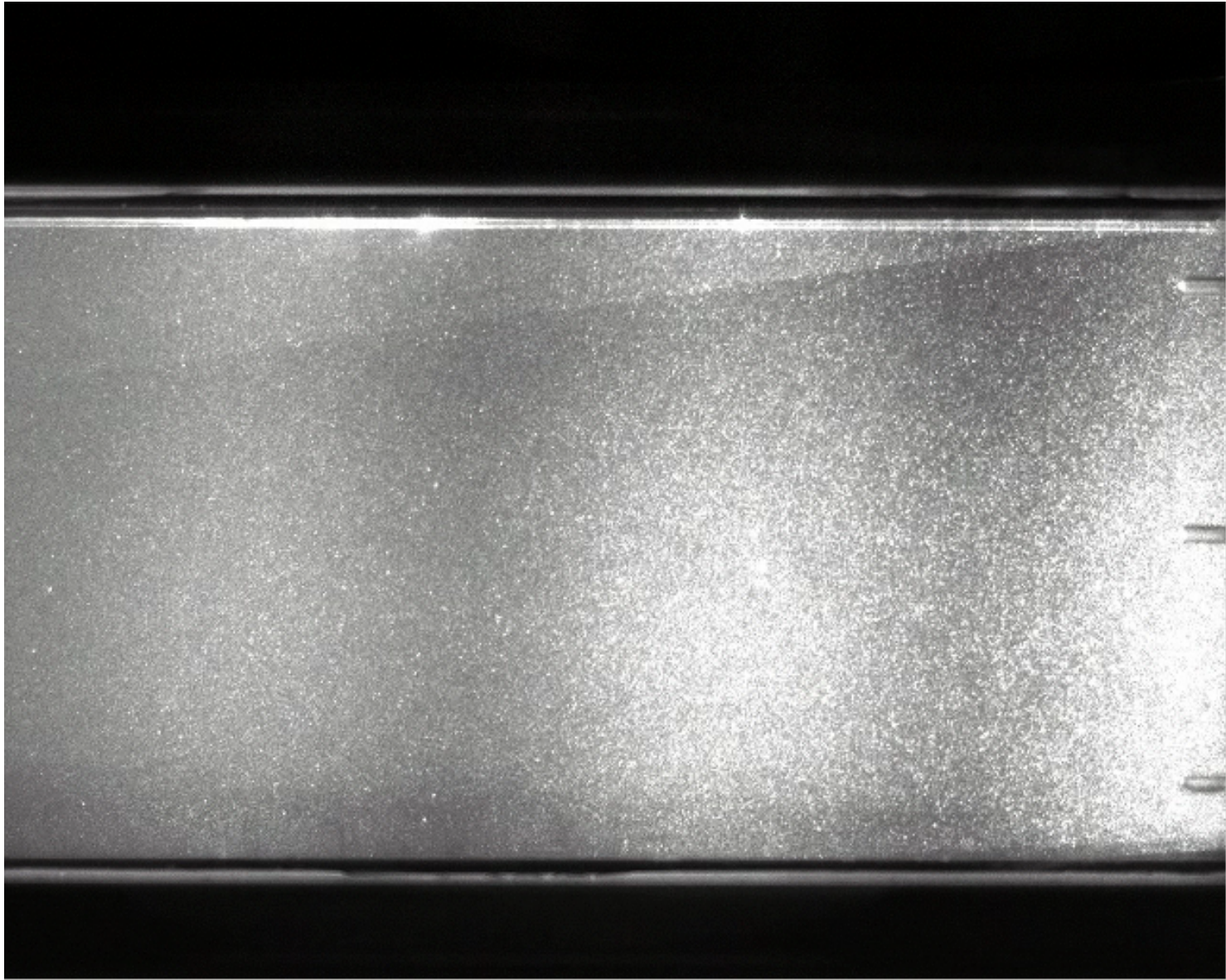
(Kumagai, Davaille & Kurita, 2007)

*Thermochemical convection : Regime diagram*

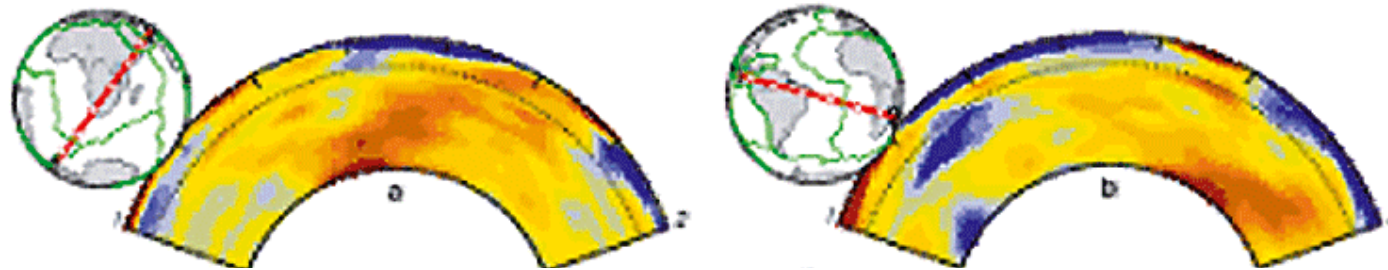


*Davaille et al.*

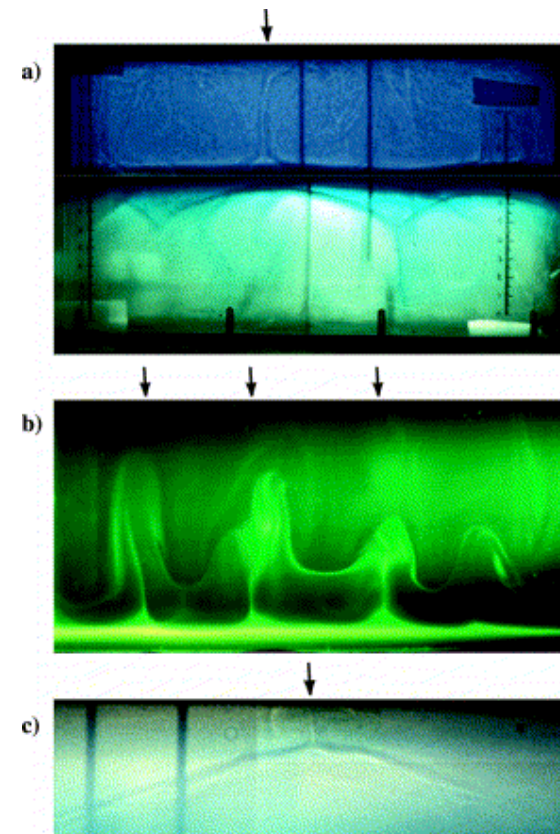
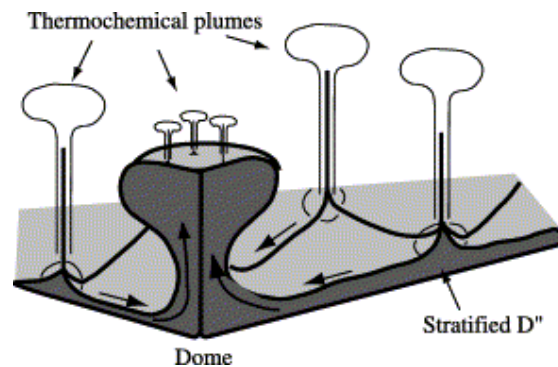
*Chauffage distribué à la base: panaches intermittents*



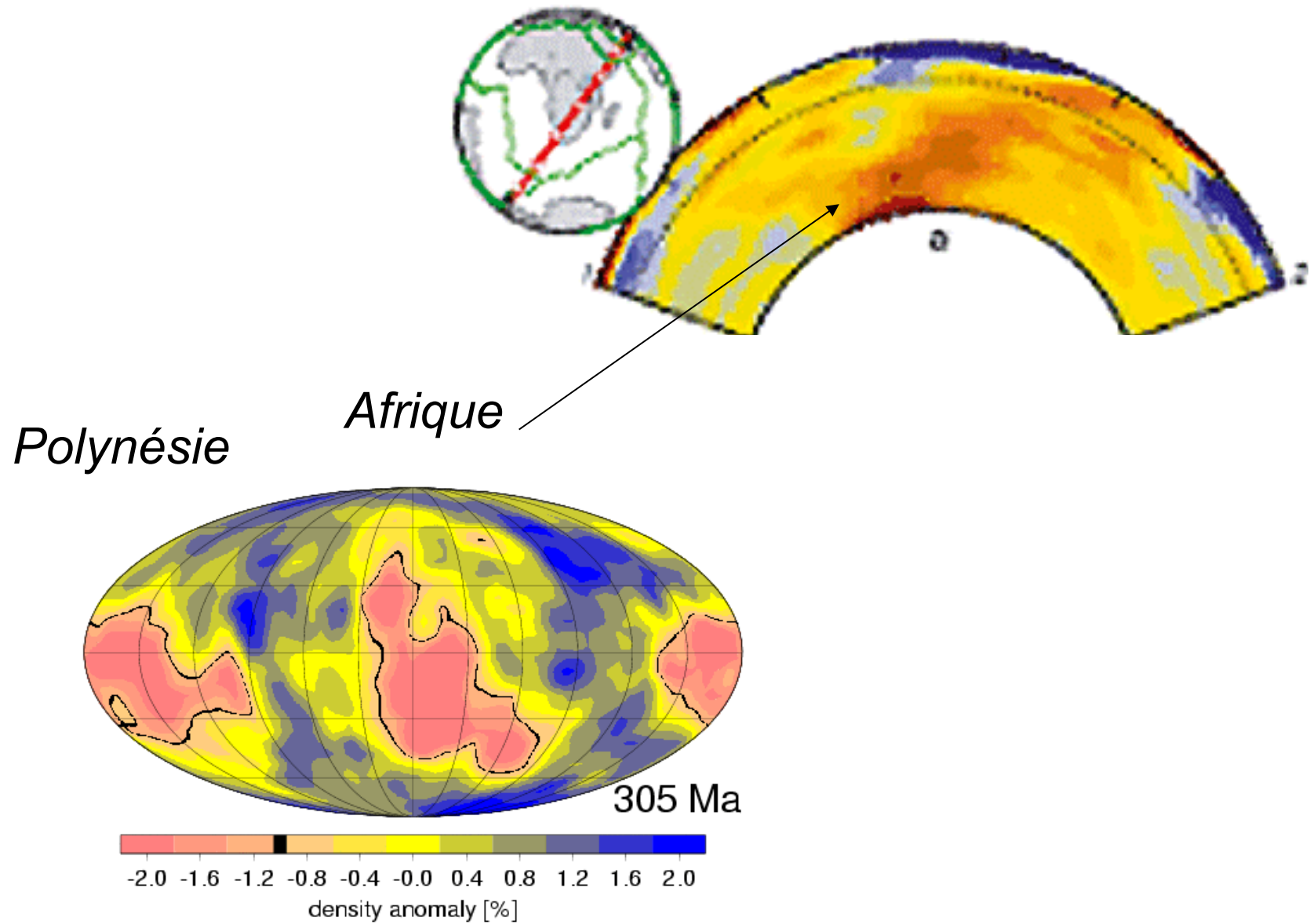
# Comment "ancrer" un panache?



- interactions noyau - manteau
- couche chimiquement  $\neq$   
à la base du manteau  
(+ dense & + visqueuse)



*anomalies de vitesse dans le manteau inférieur*







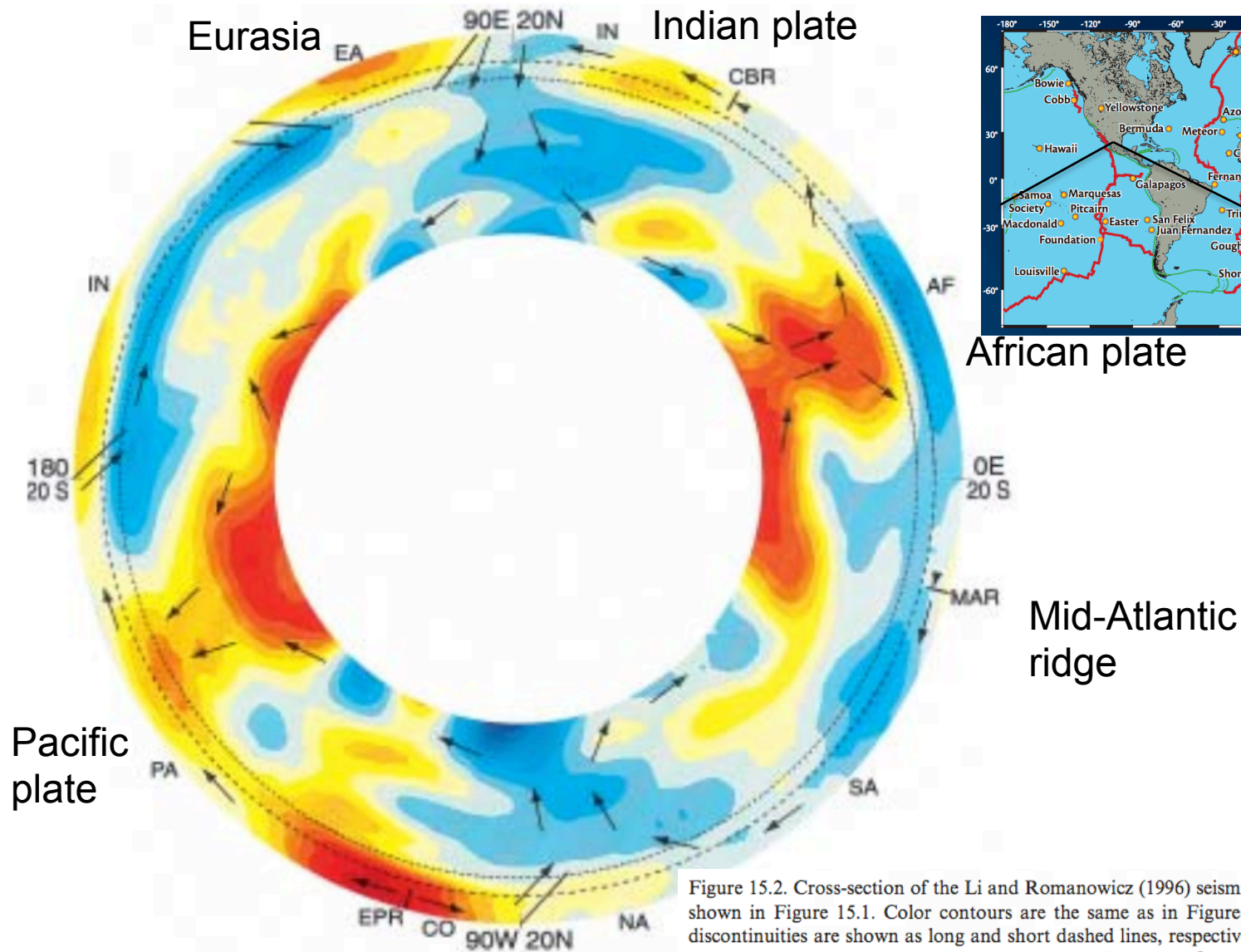


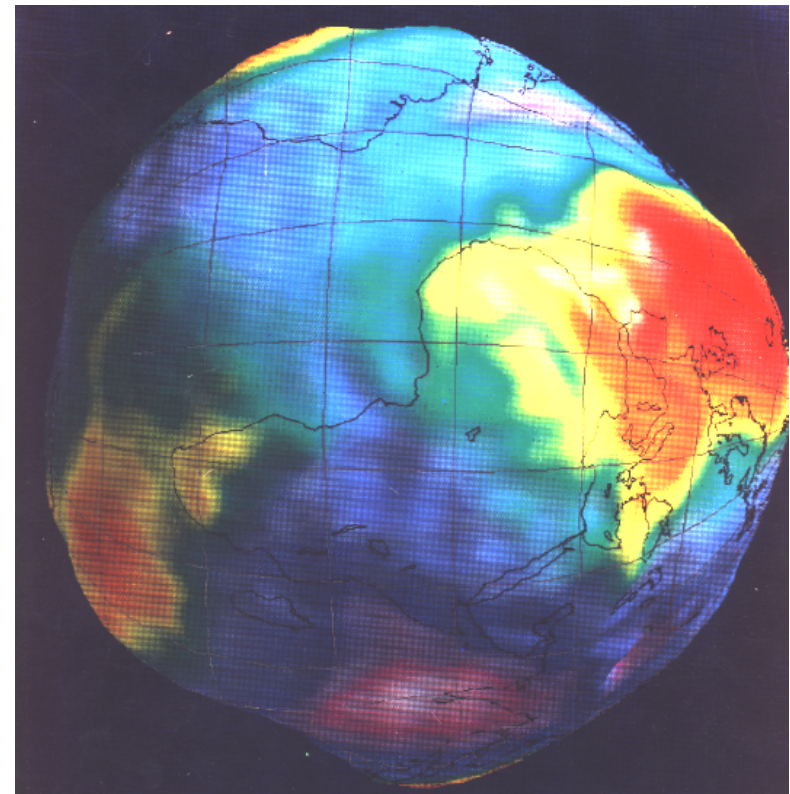
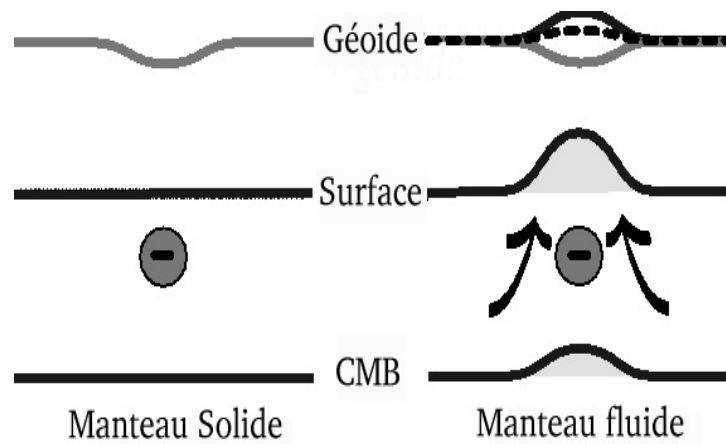
Figure 15.2. Cross-section of the Li and Romanowicz (1996) seismic tomography model along the slice shown in Figure 15.1. Color contours are the same as in Figure 15.1. The 410 and 660 km seismic discontinuities are shown as long and short dashed lines, respectively. The latitude of the slice  $\theta$  varies with longitude  $\phi$  as  $\theta_0 \cos(2\phi)$  with  $\theta_0$  corresponding to  $-20^\circ$ . The slice latitude is  $20^\circ$  N at longitudes  $90^\circ$  E and  $90^\circ$  W, and is  $20^\circ$  W at longitudes  $0^\circ$  and  $180^\circ$ , at the locations indicated on the diagram. This slice intersects the major seismic anomalies in the lower mantle and is oblique to the direction of plate motions. The plates, spreading centers, and subduction zones along the slice are shown for reference. Subduction zones are indicated by dipping line segments. Plate motion at spreading centers is indicated by double arrows, with direction of ridge migration indicated by parallel arrows. EPR = East Pacific Rise; MAR = Mid-Atlantic Ridge; CBR = Carlsburg Ridge. Plates: EA = Eurasian; IN = Indian; PA = Pacific; NA = North American; SA = South American; AF = African; CO = Cocos. The arrows indicate the pattern of large-scale flow assuming whole mantle convection, with the seismic heterogeneity proportional to density heterogeneity

# Comment sait-on que le manteau terrestre convecte?

## Observations de surface

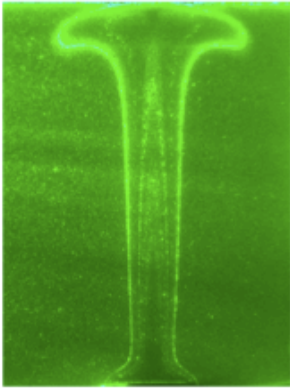
- mouvement de plaques : mesurés directement (GPS) + tremblements de terre
- magmatisme
- déformation de la surface de la planète = géoïde

Géoïde = équipotentielle de gravité = niveau moyen des mers (+80m sous l'Islande à -120m sous l'Inde)



## 2 contributions opposées:

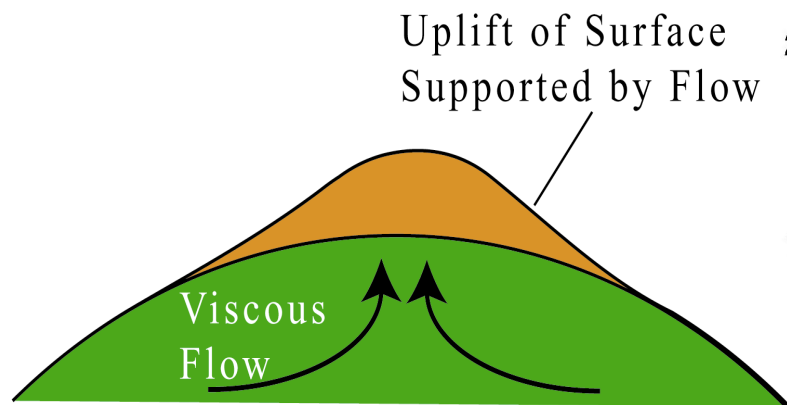
- Anomalies de densité dues aux déflexions des interfaces internes dans le manteau
- Déflexion de la surface de la Terre due à l'écoulement (topographie dynamique)



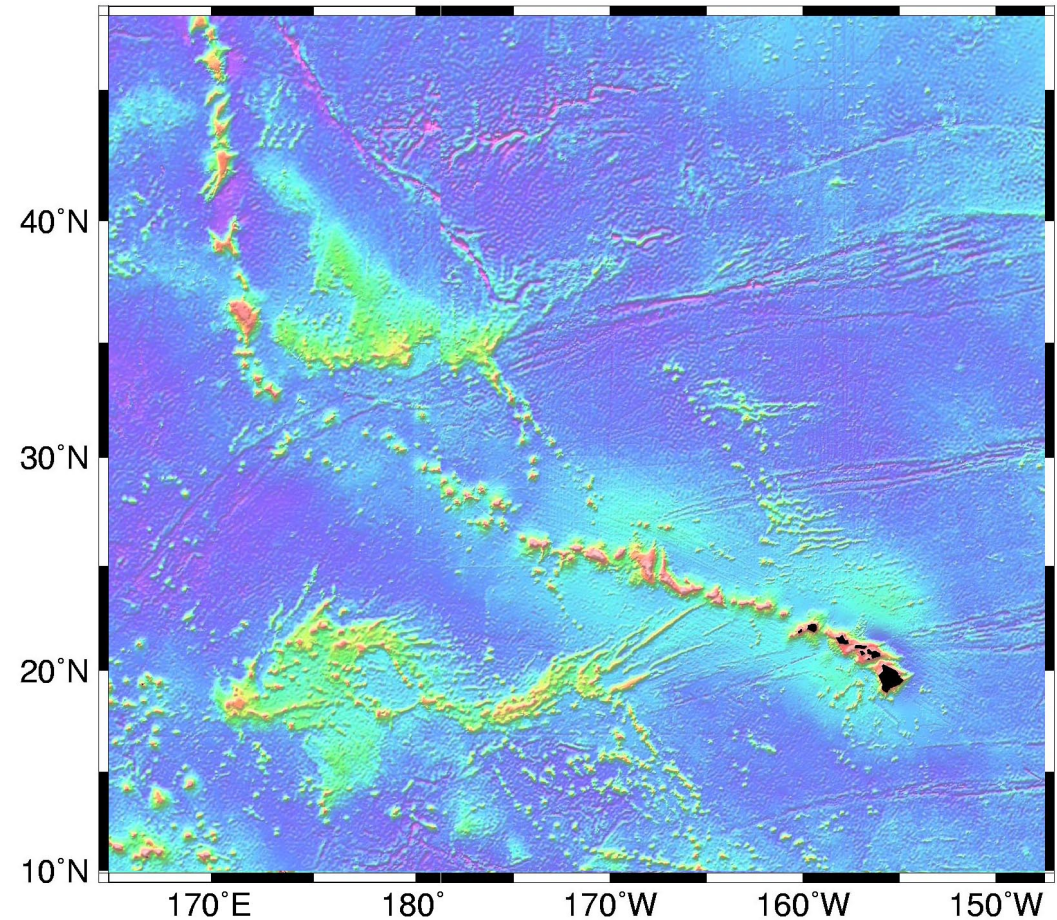
## ***Courants montants de la convection mantellique: panaches***

*Mise en évidence des  
panaches terrestres ?*

*- bombement de la surface  
(swell)*



*Hawaii*

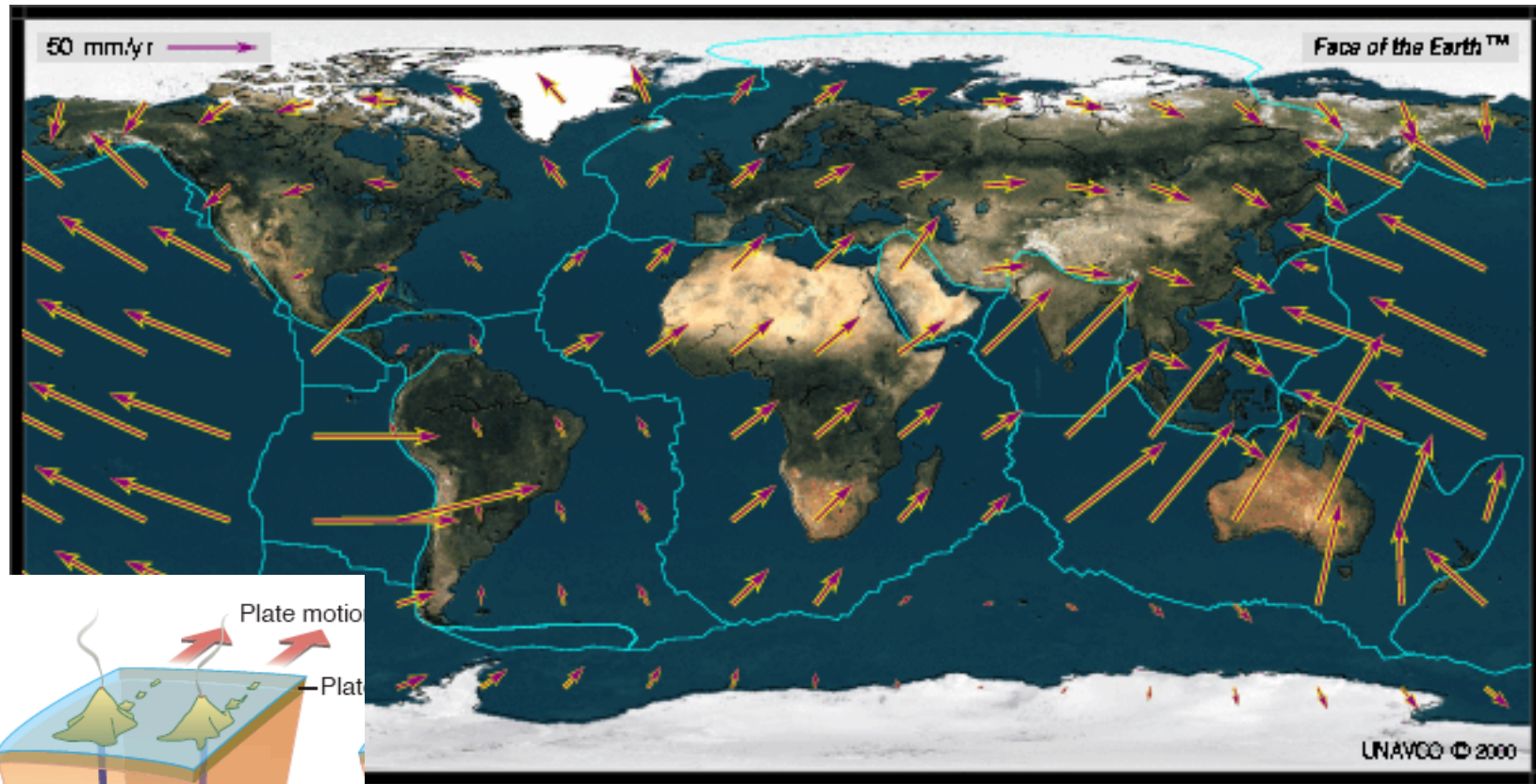


Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, 1996

**GMT** Oct 21 20:20

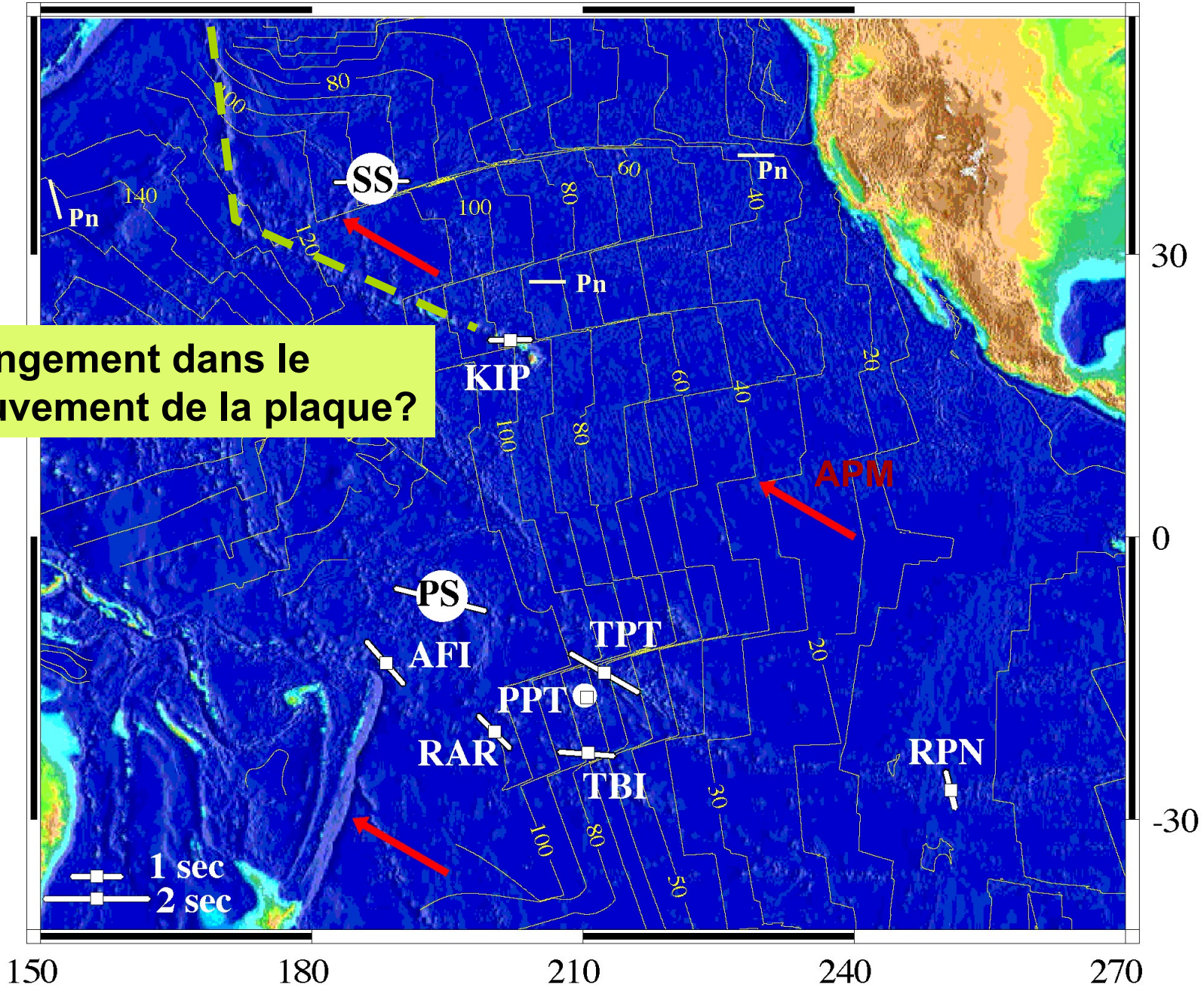
# *Panaches : fixes ou mobiles?*

*APM: absolute plate motion = mouvement absolu des plaques*

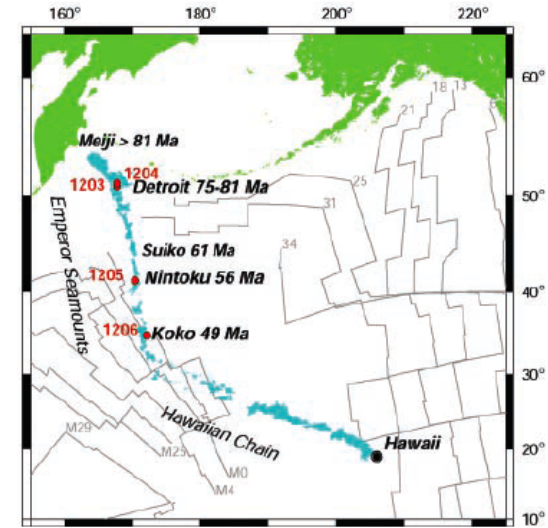
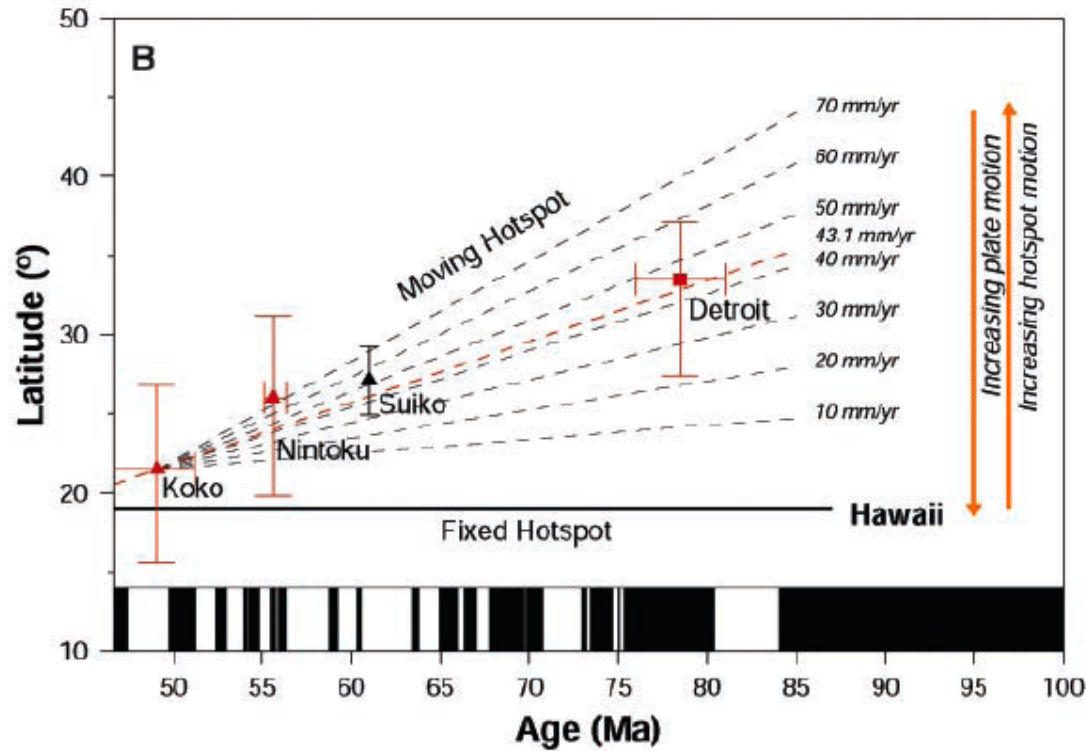


*référentiel : points chauds  
considérés fixes*

changement dans le mouvement de la plaque?



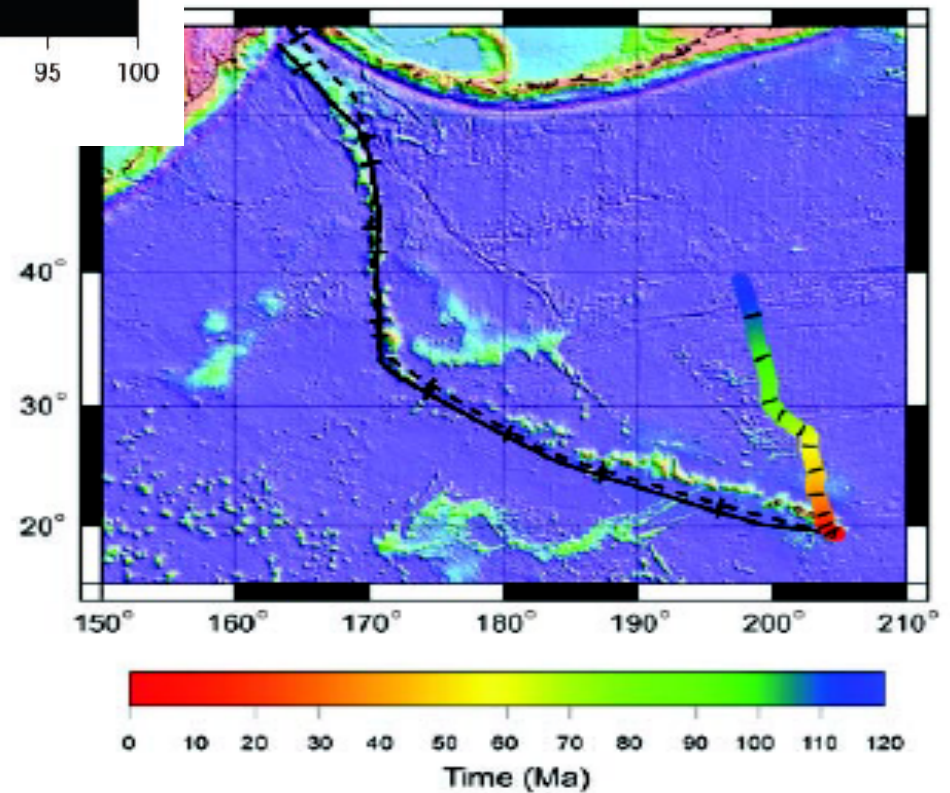
Data from Okal & Russo 1997 GJI, Wolfe & Silver 1997 JGR; Su and Park, 1994 PEPI

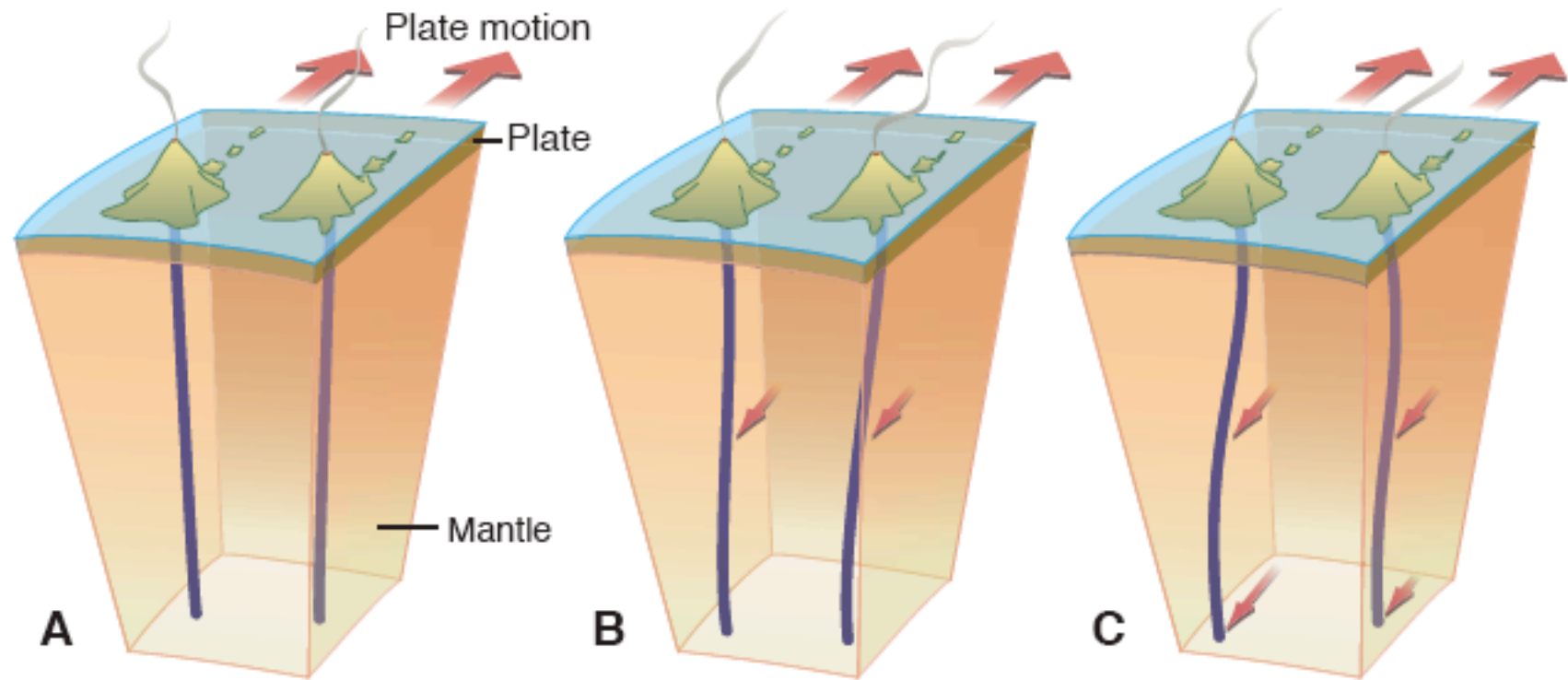


## The Emperor Seamounts: Southward Motion of the Hawaiian Hotspot Plume in Earth's Mantle

*Tarduno et al. Science 2003*

**Le test définitif:  
Paléomagnétisme – paléolatitudes  
enregistrées par les laves de la chaîne  
Emperor**



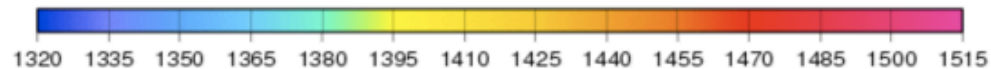


**Different views of hot spot plumes.** (A) The plumes are stationary and vertical. As the plate moves over them, the only control on the hot spot tracks is the plate velocity. (B) The plume bases are fixed relative to one another, but the plumes are at an angle due to mantle flow, with the plate moving over them. Thus, there are two controls on the hot spot tracks: mantle flow and plate motion. (C) The hot spot tracks are due to the sum of three effects: relative motion between the two plume sources, change in geometry of the plume conduits due to mantle flow, and plate motions at the surface.

# **entraînement d'un panache par la convection**

*panache =  $dT = 100^\circ\text{C}$ , 70 km*

$Ra = 4.75e5$   
manteau  
+ visqueux  
 $\sim 1.e20 \text{ Pa.s}$



$Ra = 4.75e6$   
manteau  
- visqueux  
 $\sim 1.e19 \text{ Pa.s}$

