Intertwined evolution of piles, plumes and slabs in the deep mantle

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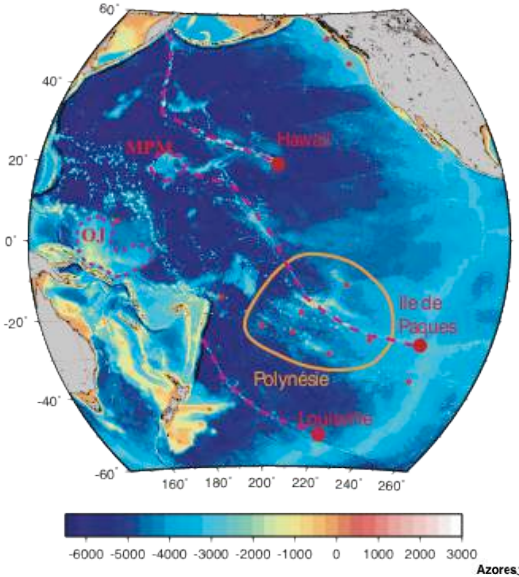
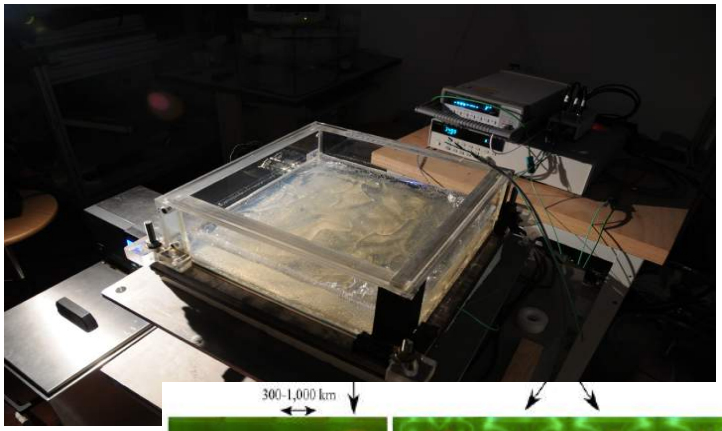
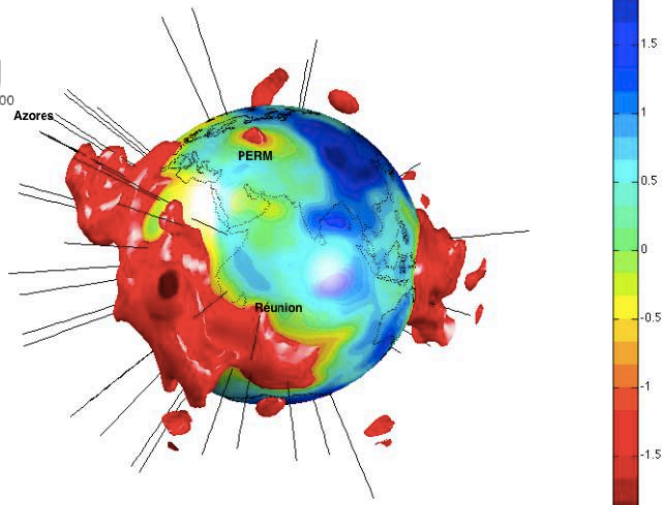
K. Kurita, A. Limare, E. Stutzmann, J. Besse, V. Courtillot, A. Ismail-Zadeh, I. Panet, M. Diament

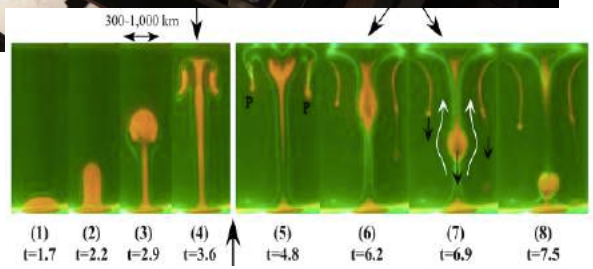
ANR - PNP



Observations
+
Fluid Mechanics

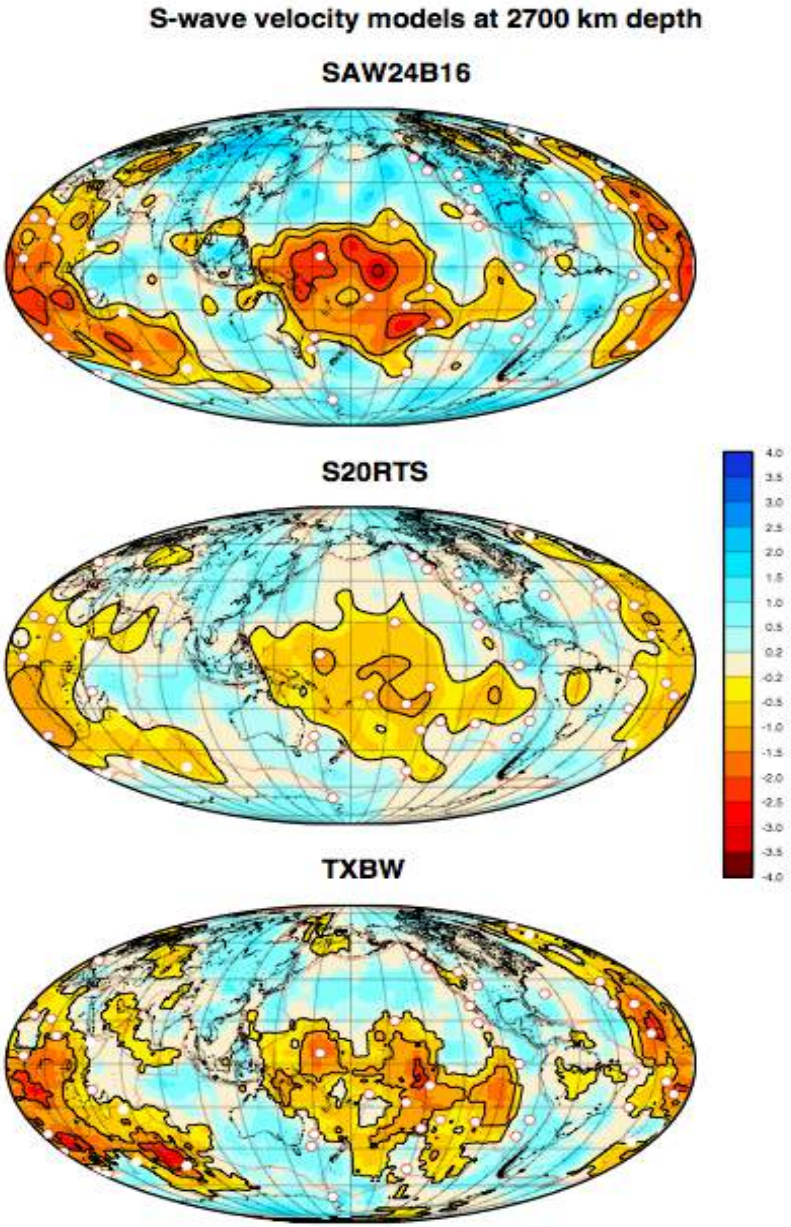


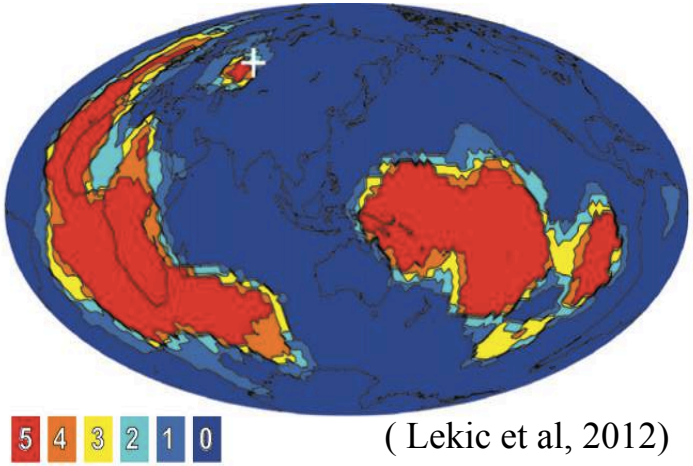




Morphology ?
Time-dependence ?

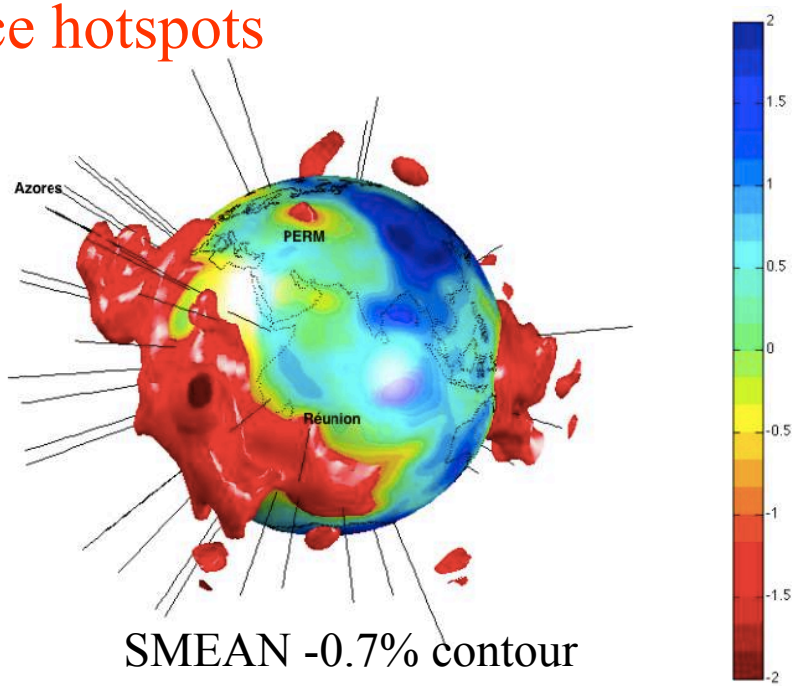
1- Observations: mantle « boxes »





(Lekic et al, 2012)

- 2 LLSVP + 1 + …
- chemical heterogeneity
- old material (e.g. Jackson et al, 2010)
- surface hotspots

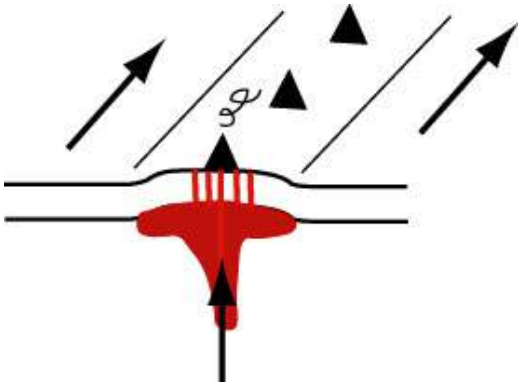


SMEAN -0.7% contour

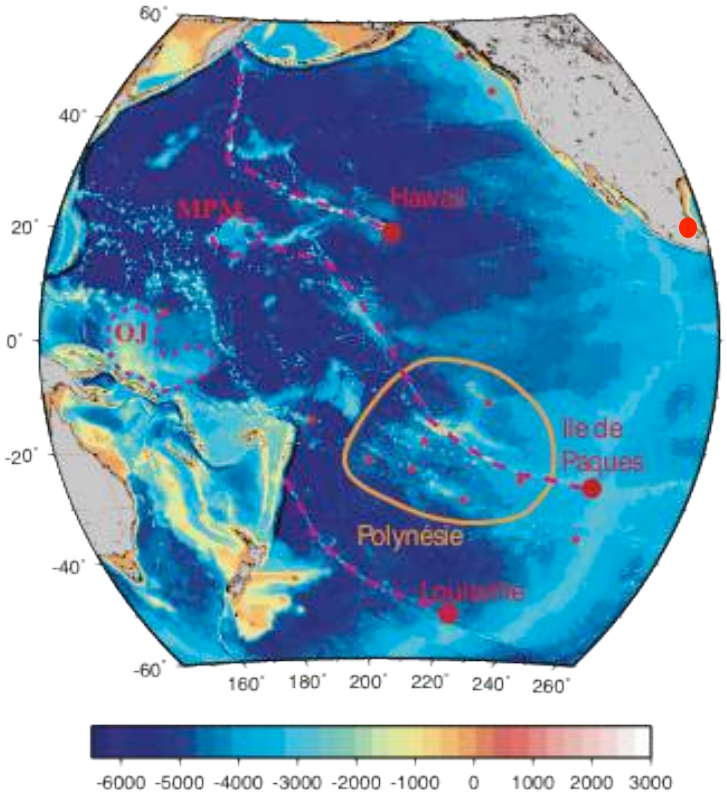
1- Observations: the hot spots « Zoo »

-Surface Hot spot

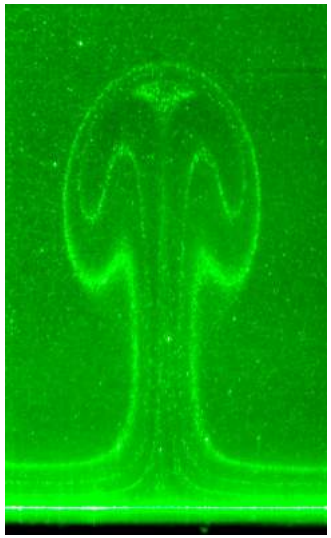
(Wilson 1963; Morgan 1971, 1972)

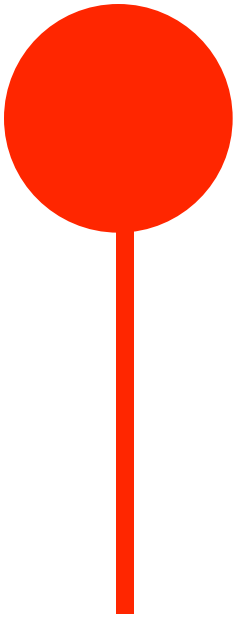


-Volcanism fixed / moving plate
-can start on by an oceanic plateau



(Clouard & Bonneville 2000)





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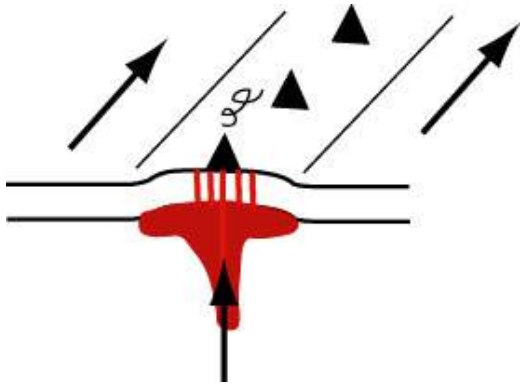
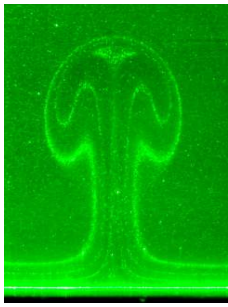
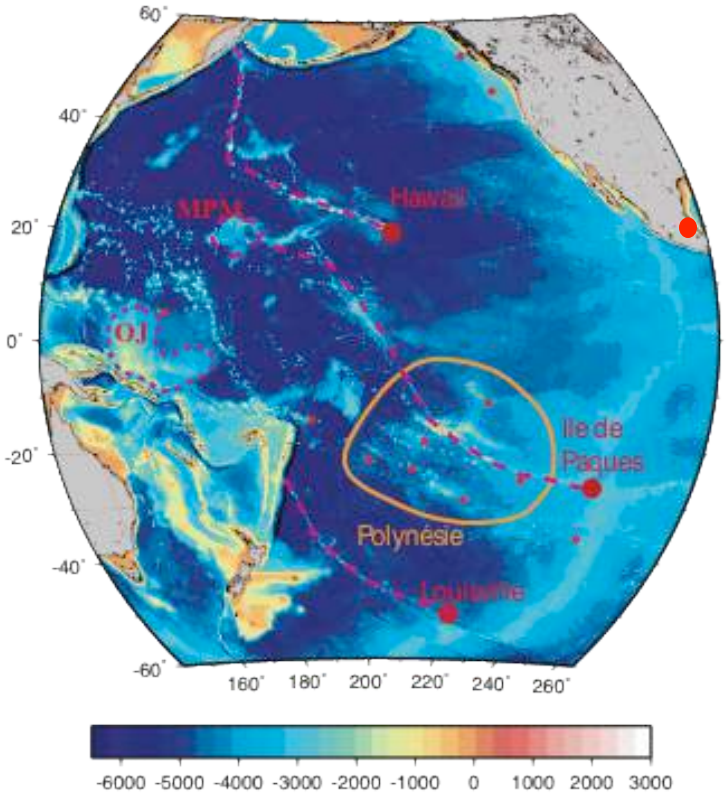
(Wilson 1963; Morgan 1971, 1972)

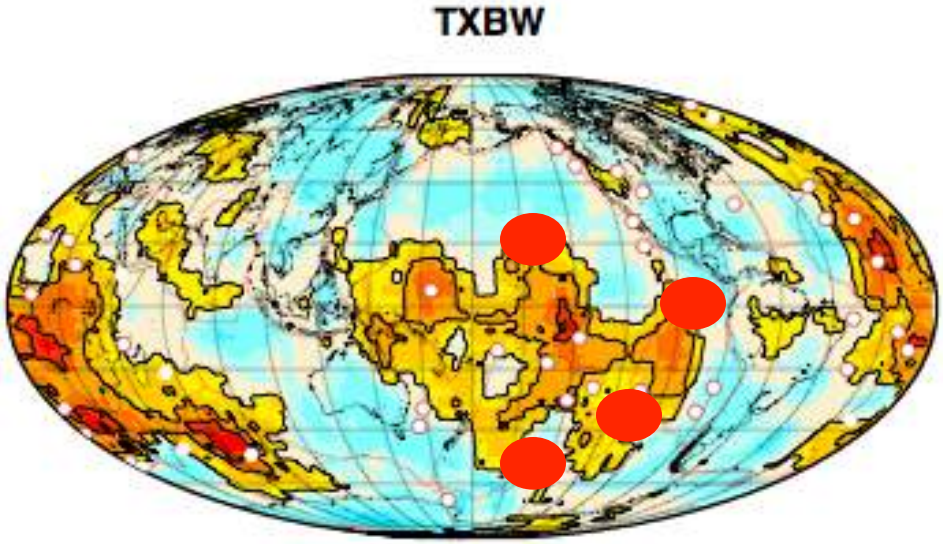






(Clouard & Bonneville 2000)

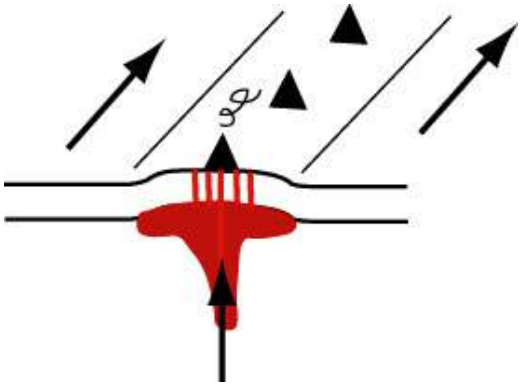
-Volcanism fixed / moving plate
-can start by an oceanic plateau
-Long tracks on the edges of slow anomaly

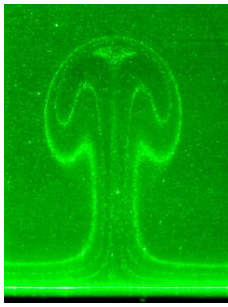


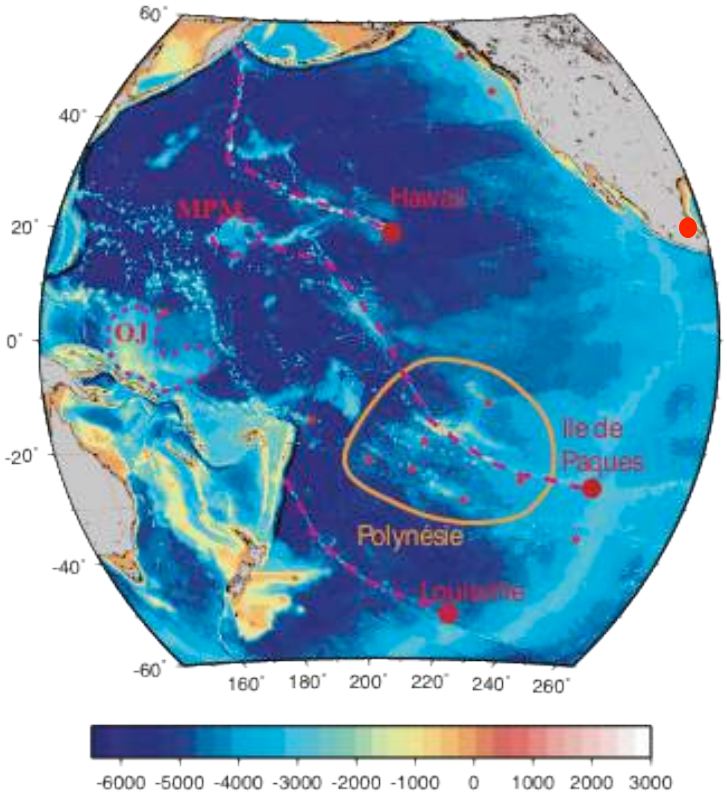
1- Observations: the hot spots « Zoo »

-Surface Hot spot

(Wilson 1963; Morgan 1971, 1972)

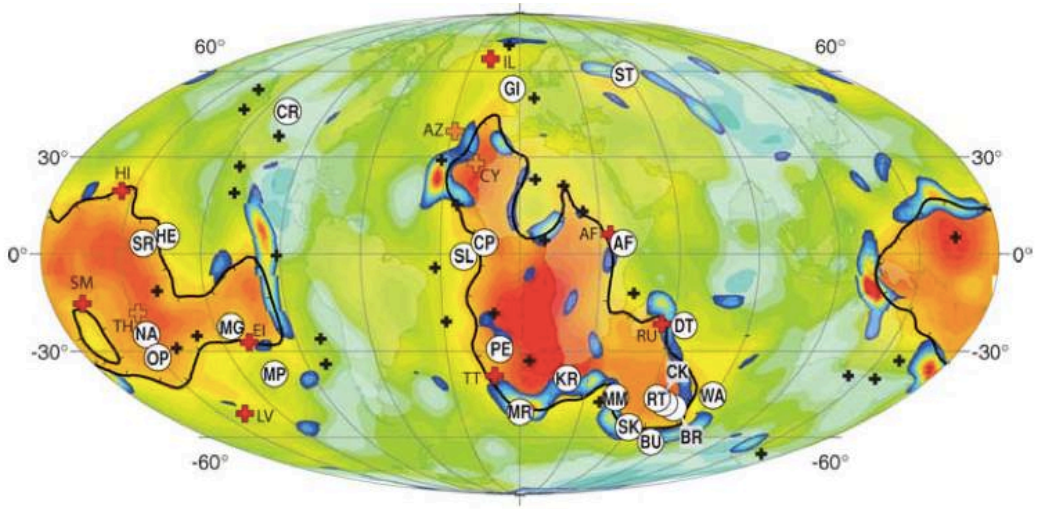






(Clouard & Bonneville 2000)

-Volcanism fixed / moving plate
-can start by an oceanic plateau
-Long tracks/LIPs on the edges of LLSVPs over the last 200 Ma



(Torsvik et al, 2004)

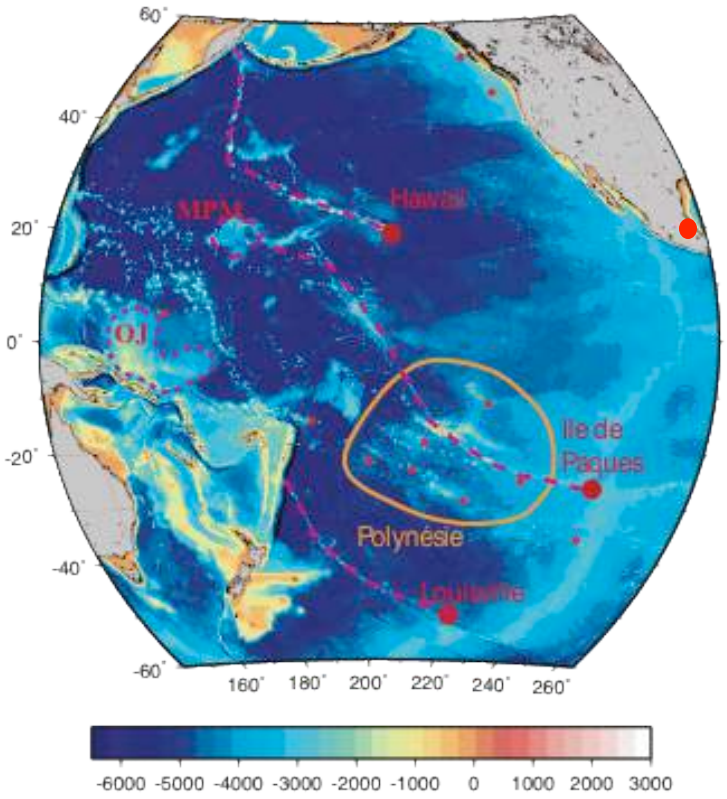
1- Observations: the hot spots « Zoo »

-Surface Hot spot

(Wilson 1963; Morgan 1971, 1972)

+ another type

= shorter tracks in « cluster »



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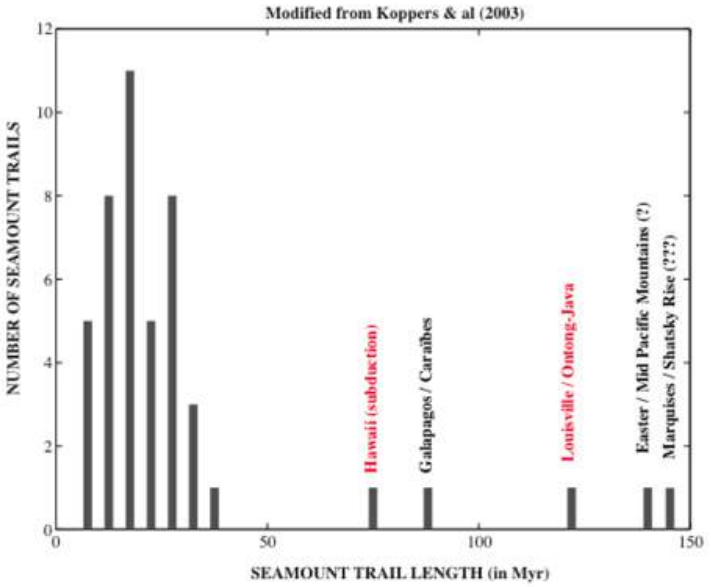
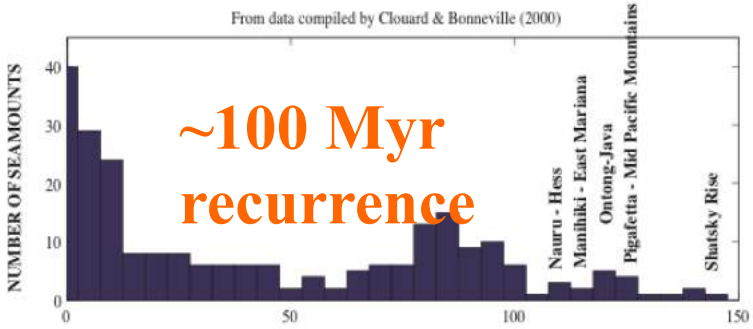
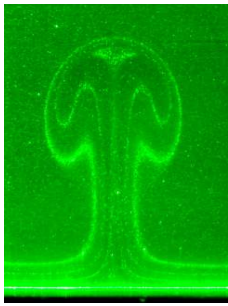
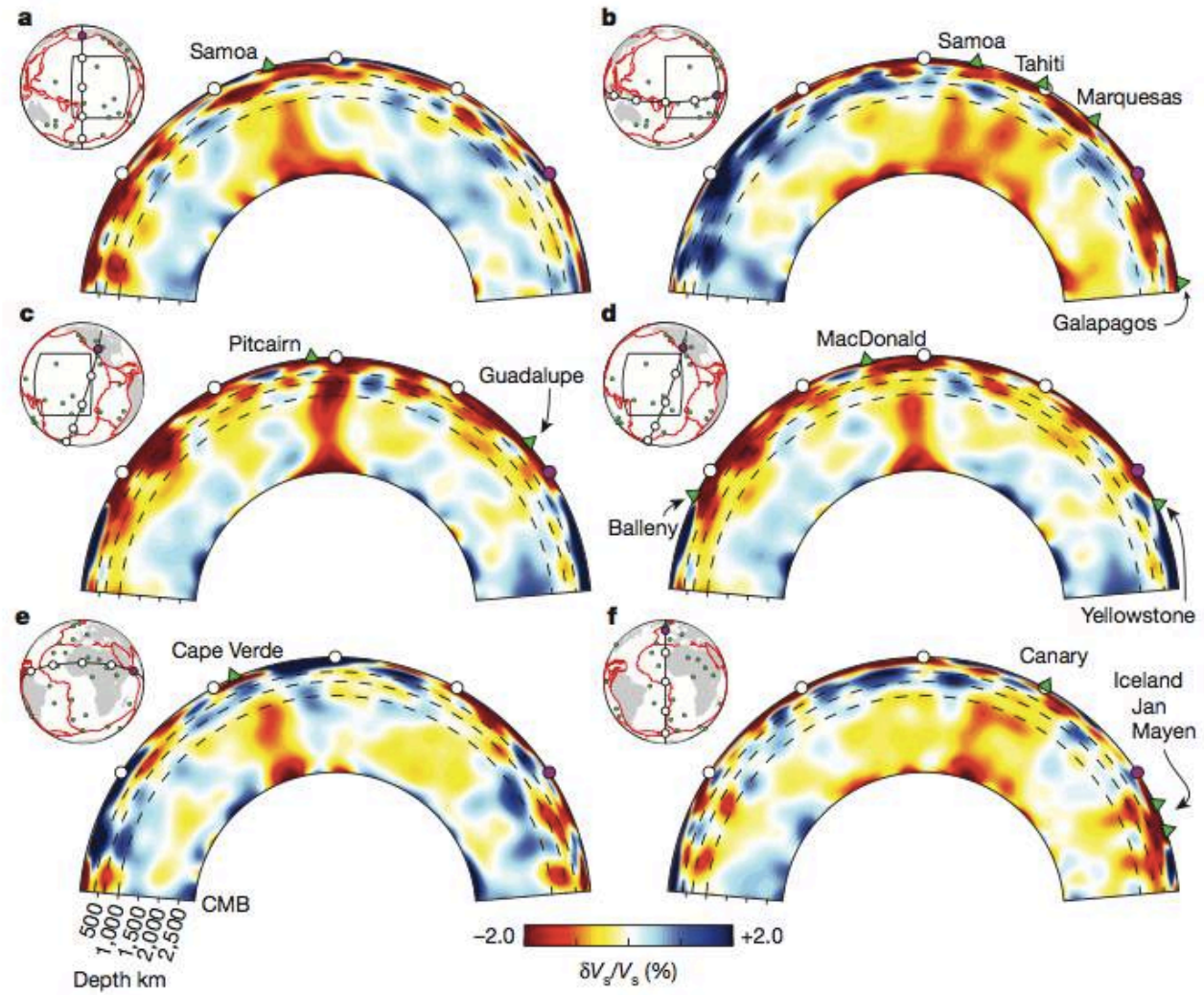




1- Observations: the hot spots « Zoo »

mantle hot upwelling : A- something is happening around 1000 km





B- FAT plumes

(French & Romanowicz, 2015; Montelli et al, 2006)

QUESTIONS :

A- Origin of mantle « boxes » ?

B- Upwellings

- **several types ?**
- **« fat » ?**
- **what happens around 1000 kms ?**

C- Do the mantle boxes / LLSVPs change shapes through time ?

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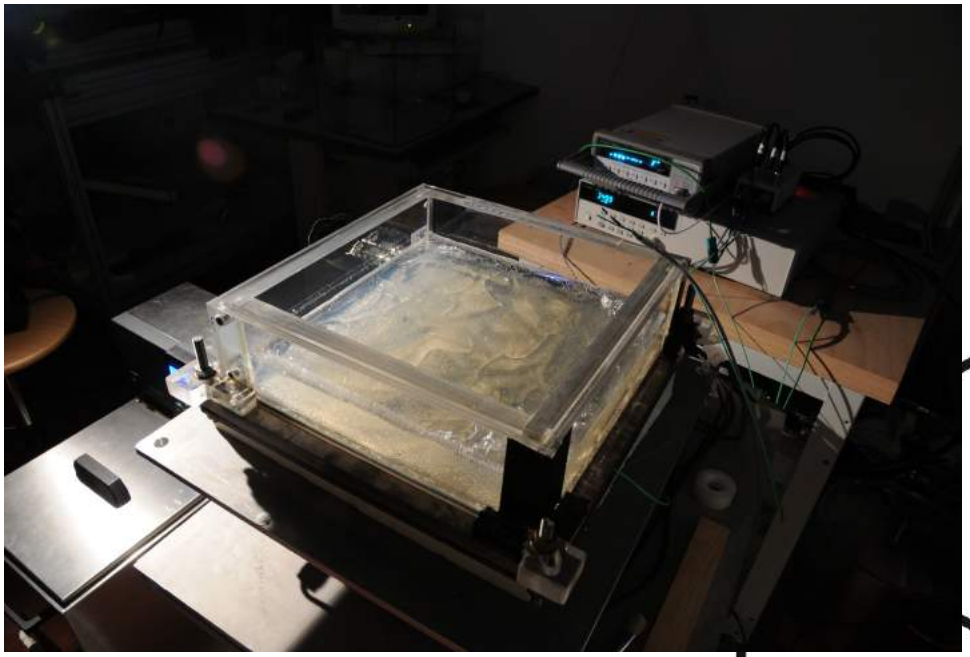
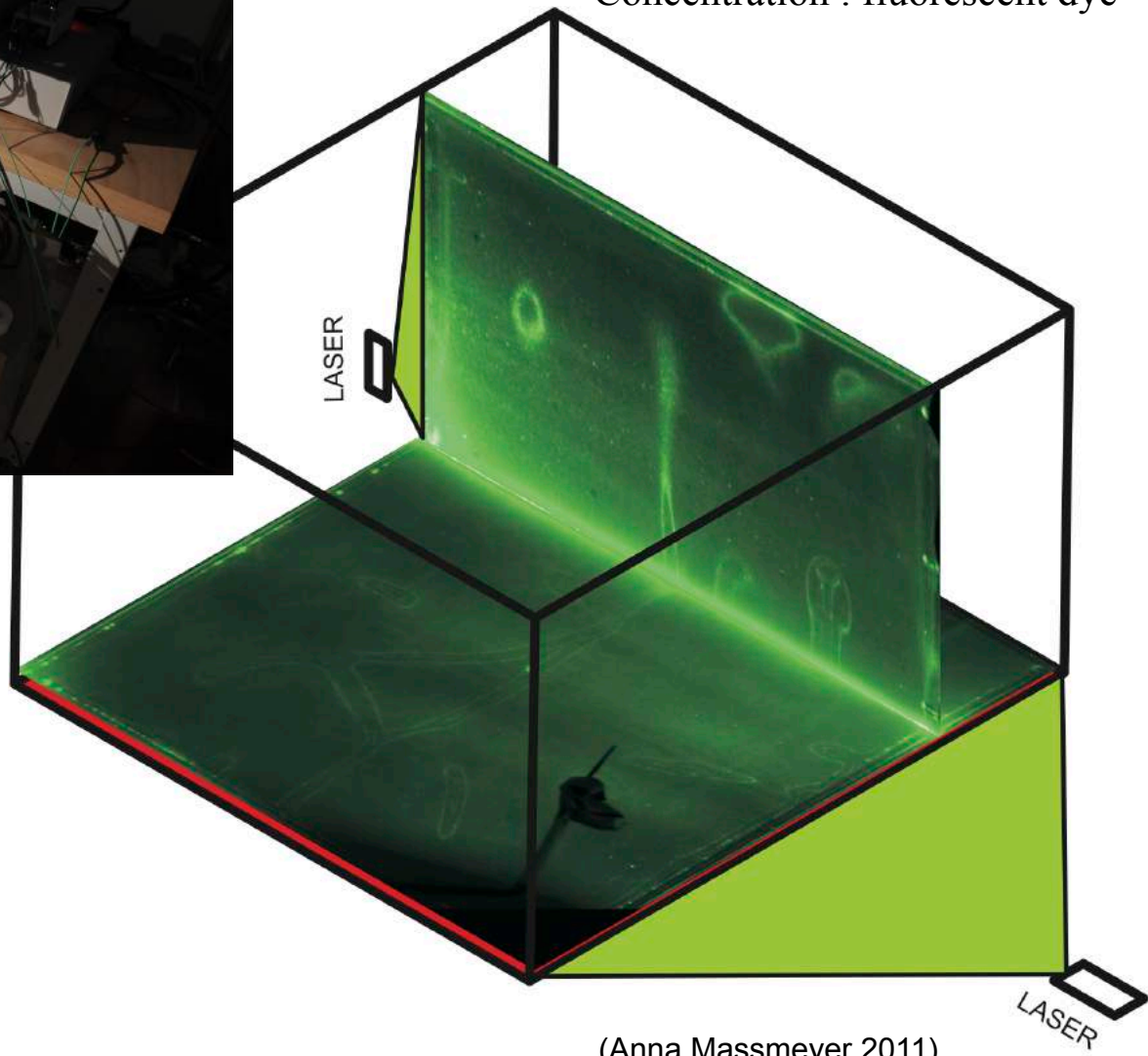
2- Experiments : set up



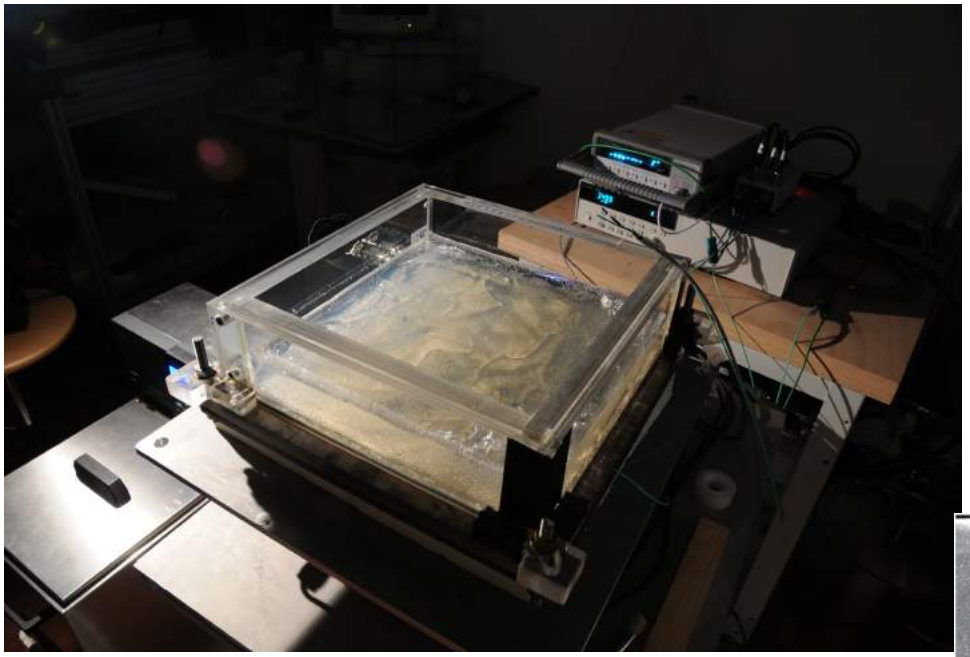
- Plexiglass Tank 30x30 cm
- Aspect ratio: 2 to 5
-Velocity field : PIV
-Temperature isotherms : TLCs
-Concentration : fluorescent dye



(Anna Massmeyer 2011)

FLUIDS :
- sugar : newtonian $\eta(T)$
- polymers : shear thinning, viscoplastic
- colloids :
  newtonian (bulk) → brittle (top)

2- Experiments : set up



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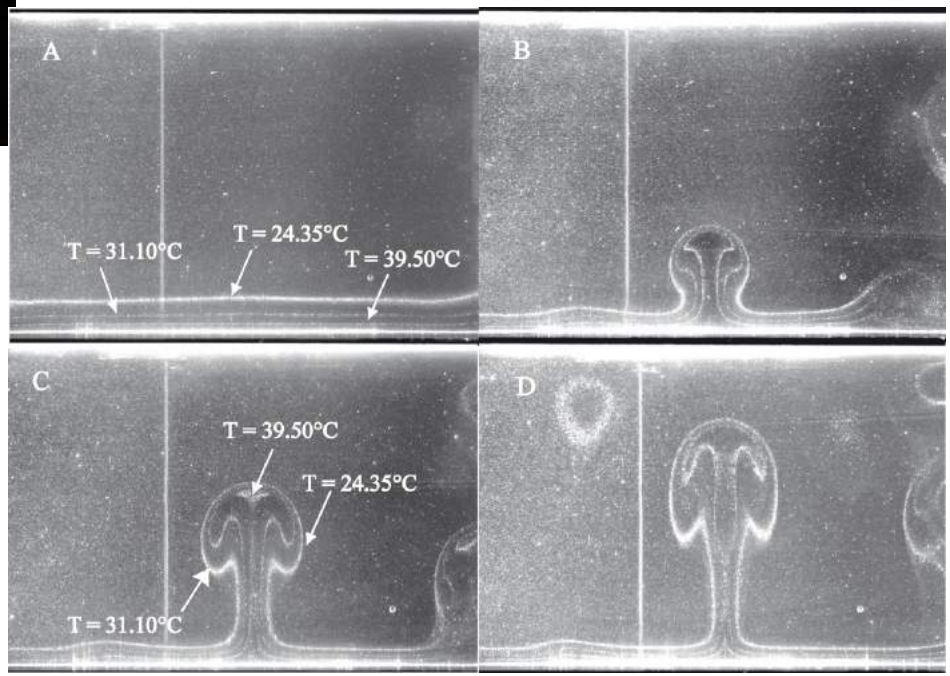
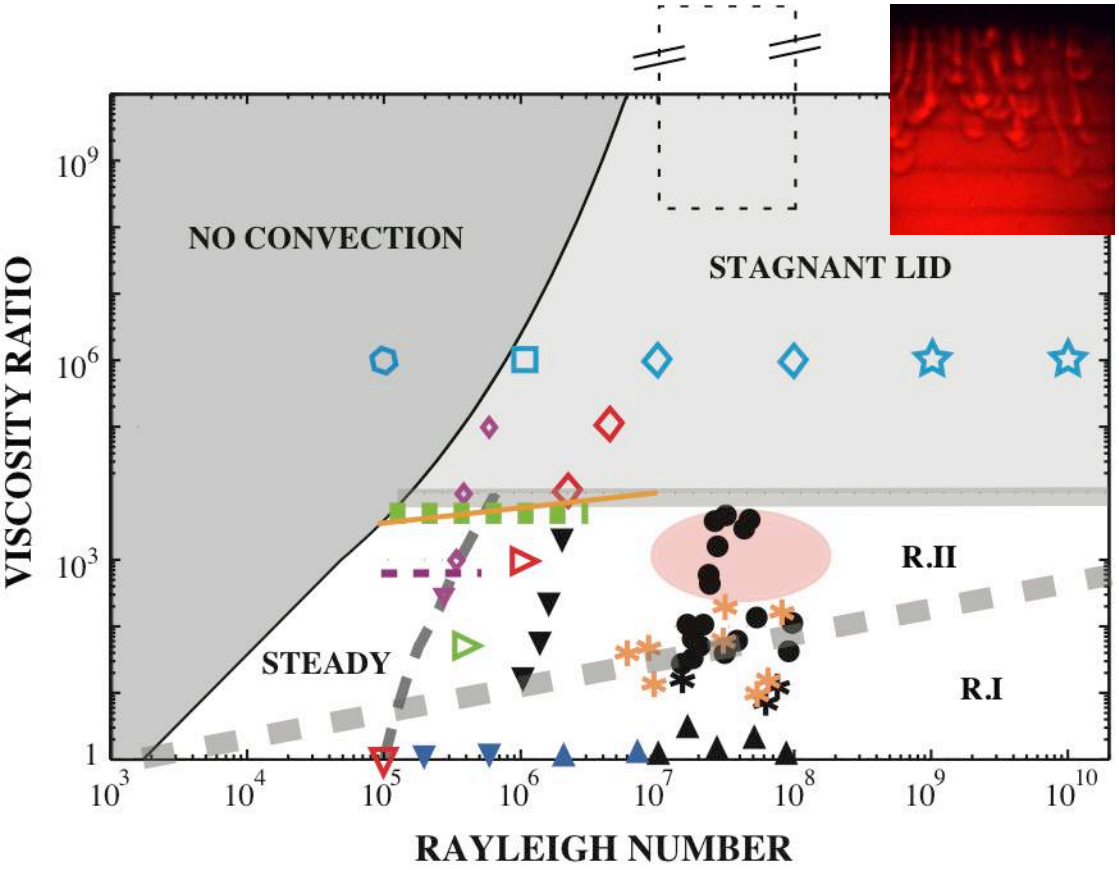
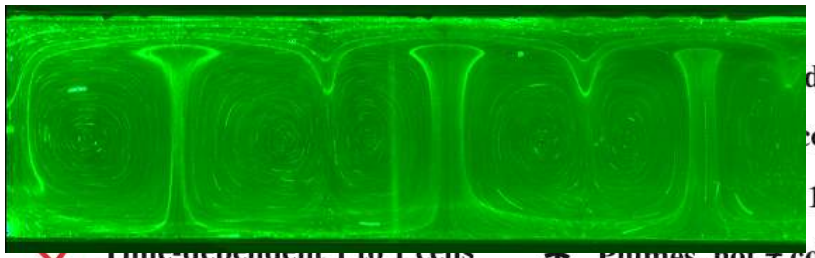
$$Ra = \alpha\, g\, \Delta T\, H^3 / \kappa\, \nu \sim 10^6 - 10^9$$



(Sophie Androvandi 2009)

3. Convection in a fluid with Temperature-dependent viscosity





dependent 1 to 1 cell

old

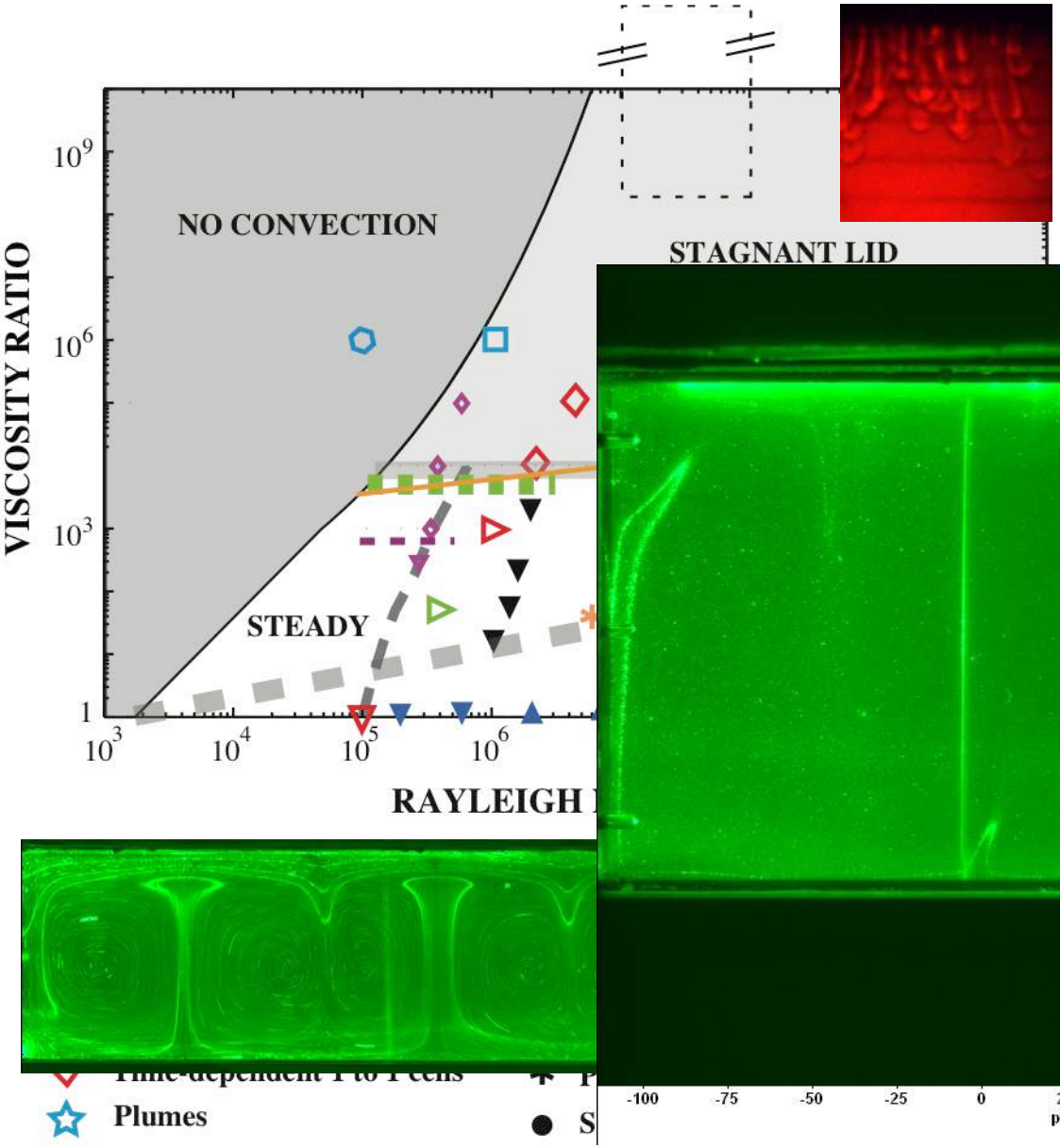
1 to 3 cell

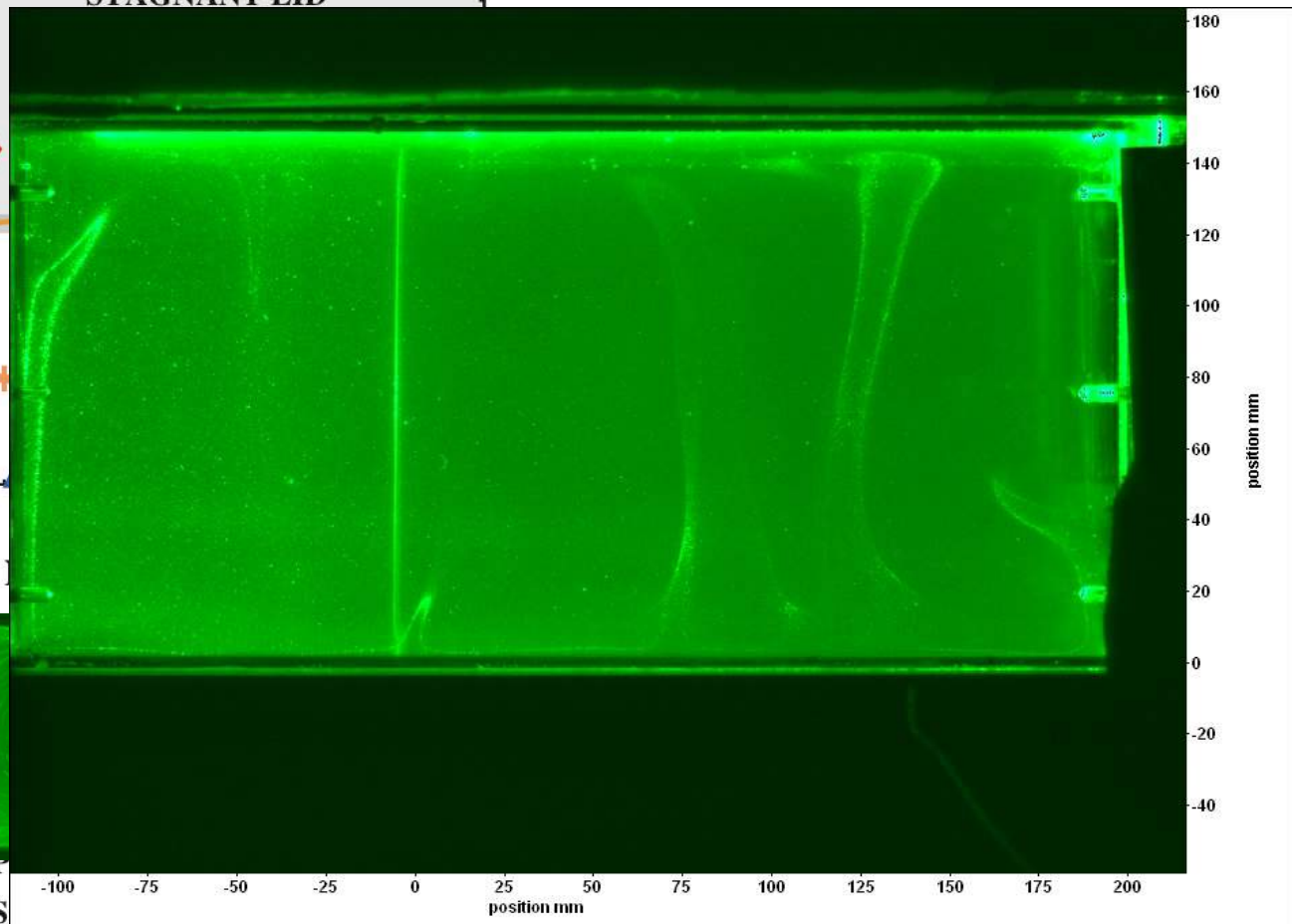
Plumes, hot ≠ cold

Plumes

Several hot plumes for 1 cold cell

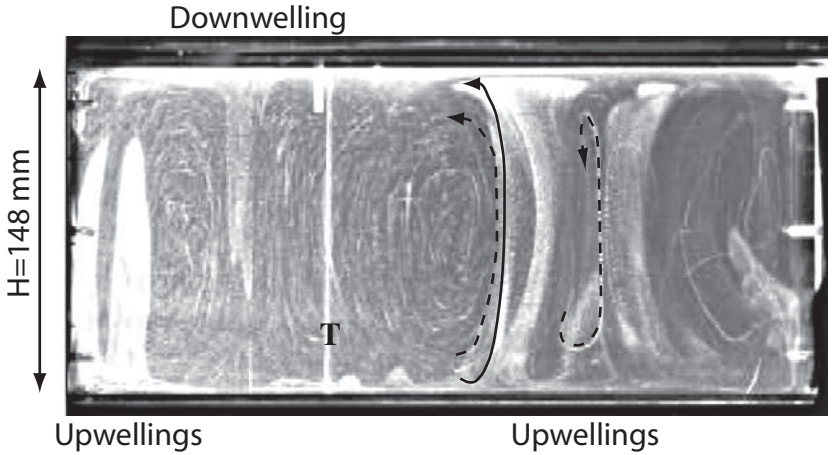
3. Convection in a fluid with Temperature-dependent viscosity

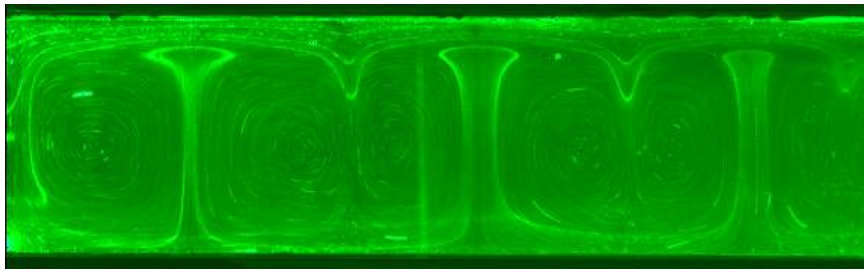




(Androvandi, AD, Limare, Fouquier, Marais, 2011)

3. Convection in a fluid with Temperature-dependent viscosity





Spacing:

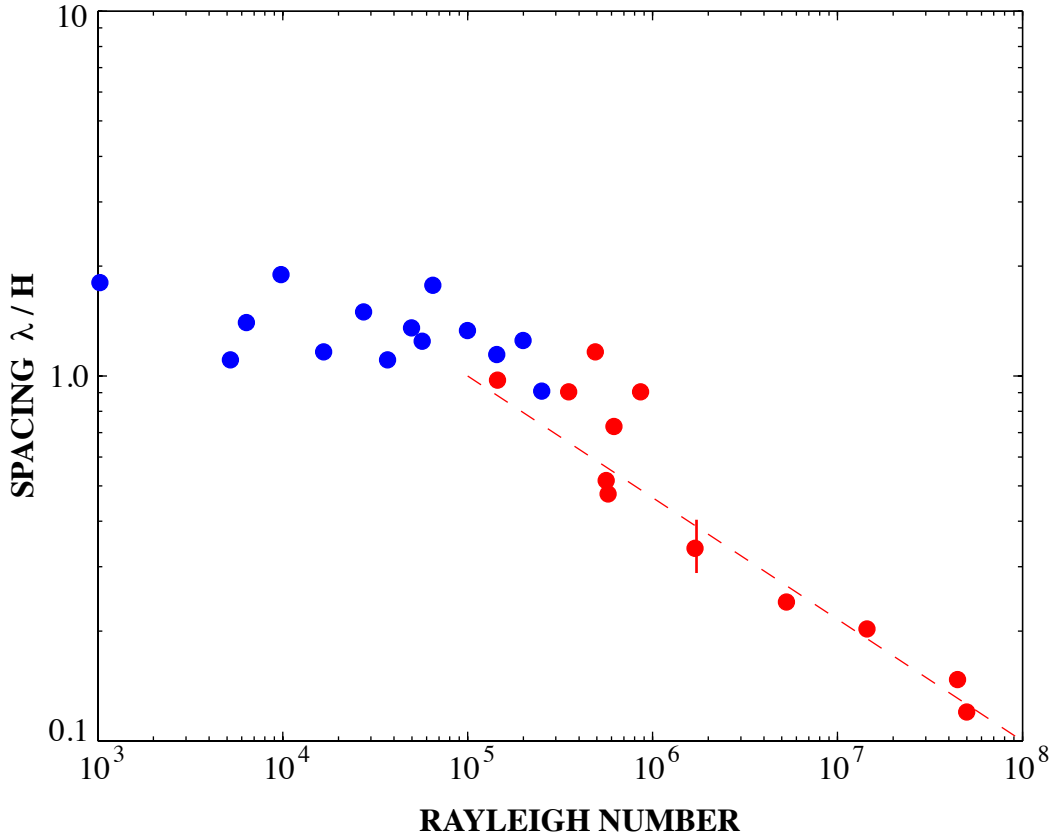
-cold : cell with l~1-2 H (R-R)

Giannandrea & Christensen (F-F)
=> l~3.5 H

=> **mantle => l=10 000 km** …

-hot : spacing ~ 2-4 H.$(Ra_c/Ra_{bot})^{1/3}$

=> ~ 200-1000 kms at CMB



(Androvandi & al, 2009, 2011)

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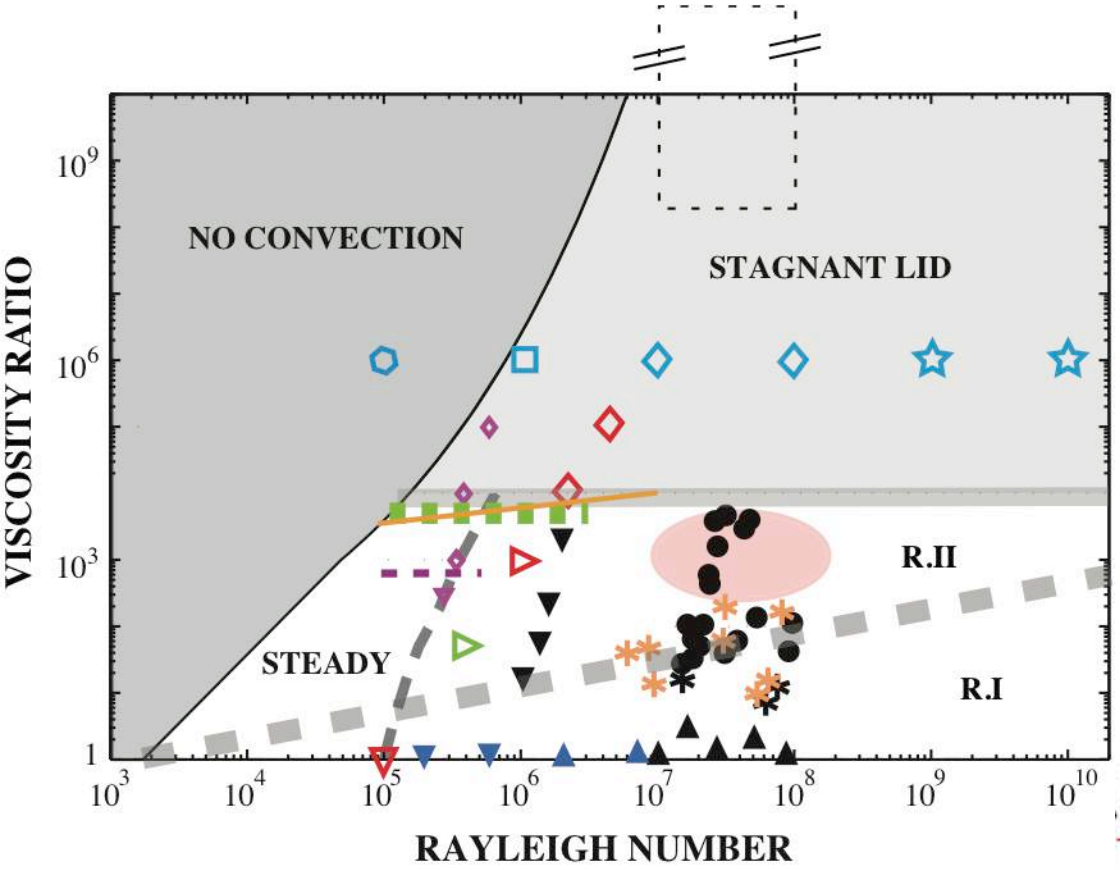
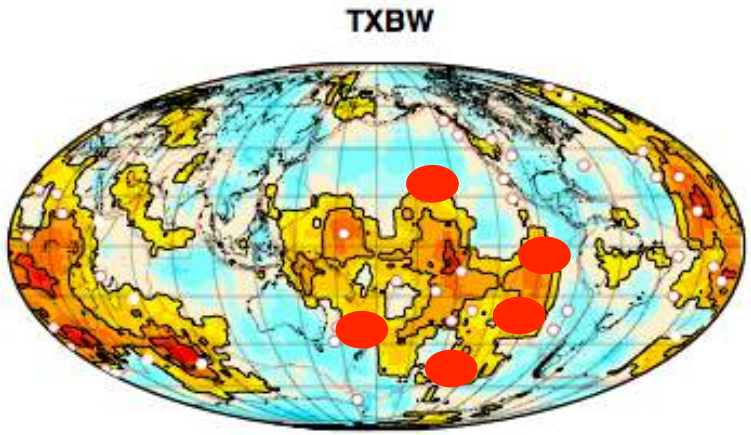
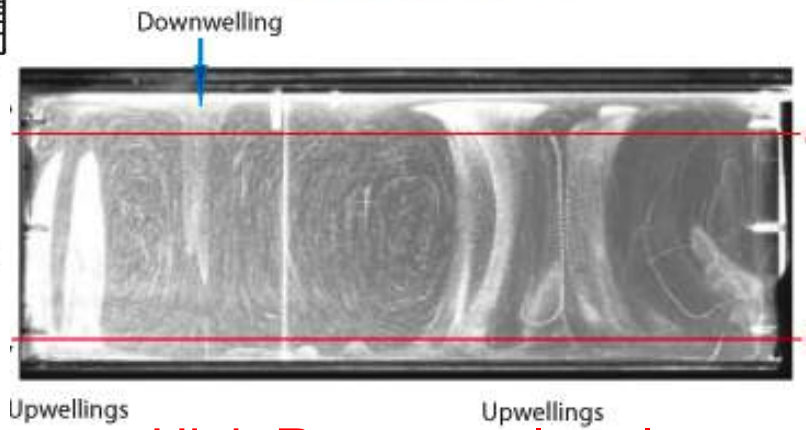






High Ra: several scales

- No convection

Stagnant Lid

- Steady 1 to 1 cells
- Time-dependent 1 to 1 cells
- Plumes
- Spokes = time-dependent 1 to 1 cell
- Plumes, hot = cold
- Spokes in L-L: 1 to 3 cell
- Plumes, hot ≠ cold
- Several hot plumes for 1 cold cell

(Androvandi & al, 2009, 2011)

QUESTIONS :

A- Origin of mantle « boxes » ? **Variable viscosity / Subduction**

B- Upwellings

- **several types ?**
- **« fat » ?**
- **what happens around 1000 kms ?**

C- Do the mantle boxes / LLSVPs change shapes through time ?

QUESTIONS :

A- Origin of mantle « boxes » ? **Variable viscosity / Subduction**

B- Upwellings : convection with density heterogeneities ?

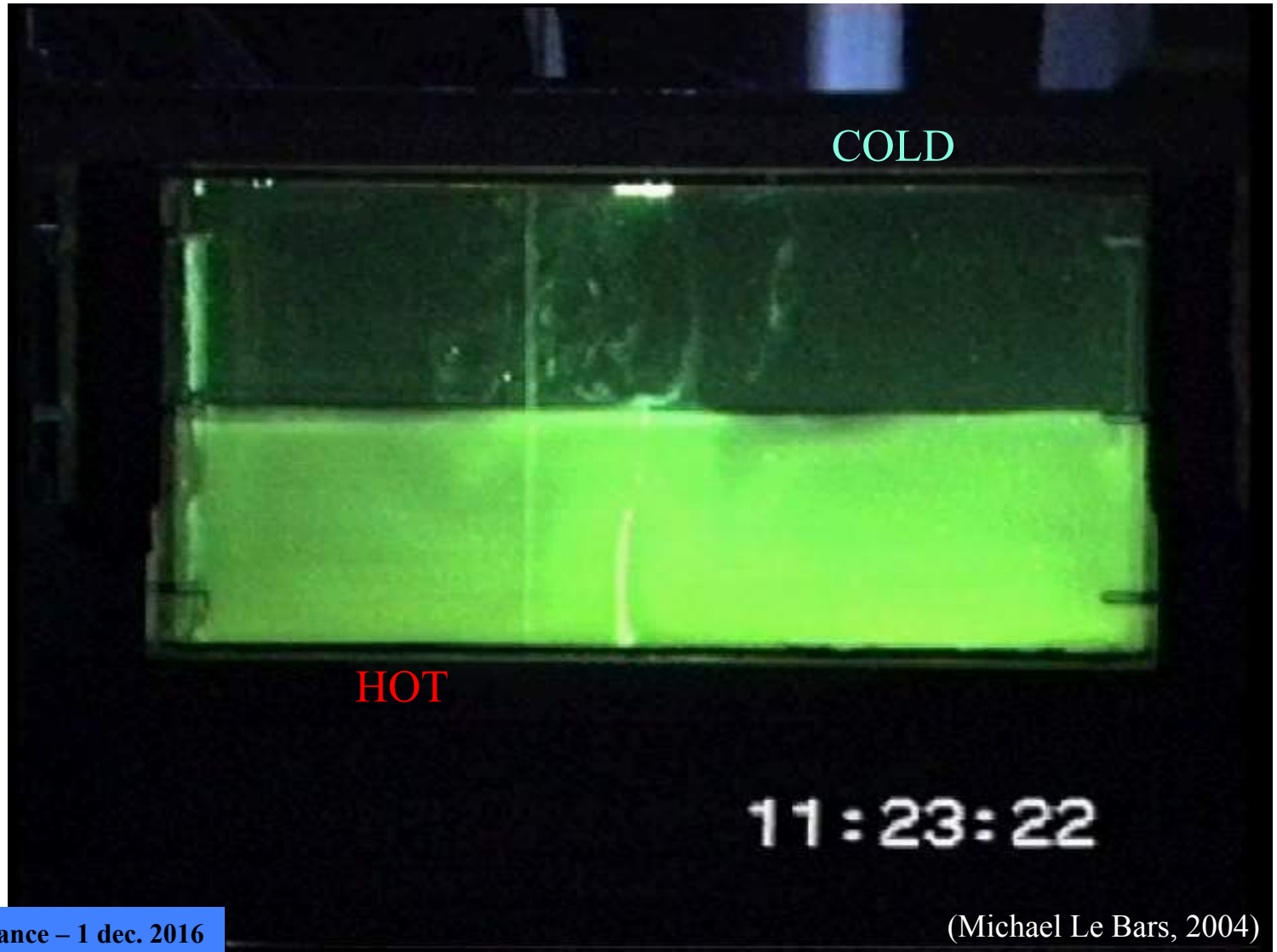
- **several types ?**
- **« fat » ?**
- **what happens around 1000 kms ?**

C- Do the mantle boxes / LLSVPs change shapes through time ?

4. Interaction Convection / Denser Reservoir

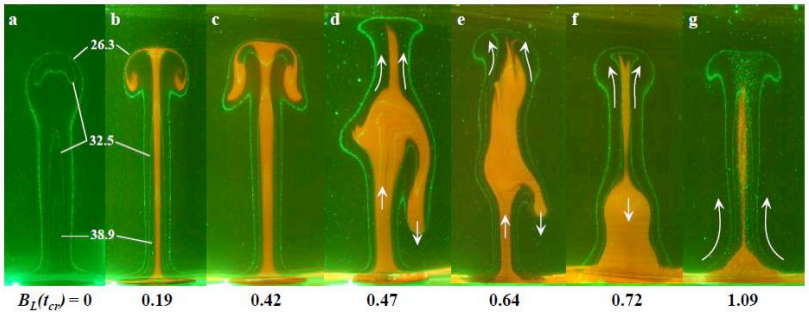
Key parameter : $B = \Delta\rho_c / \alpha \Delta T$ $(\sim 0 - 10)$

WHOLE-LAYER : B < 1 **hot more viscous (polymers)**



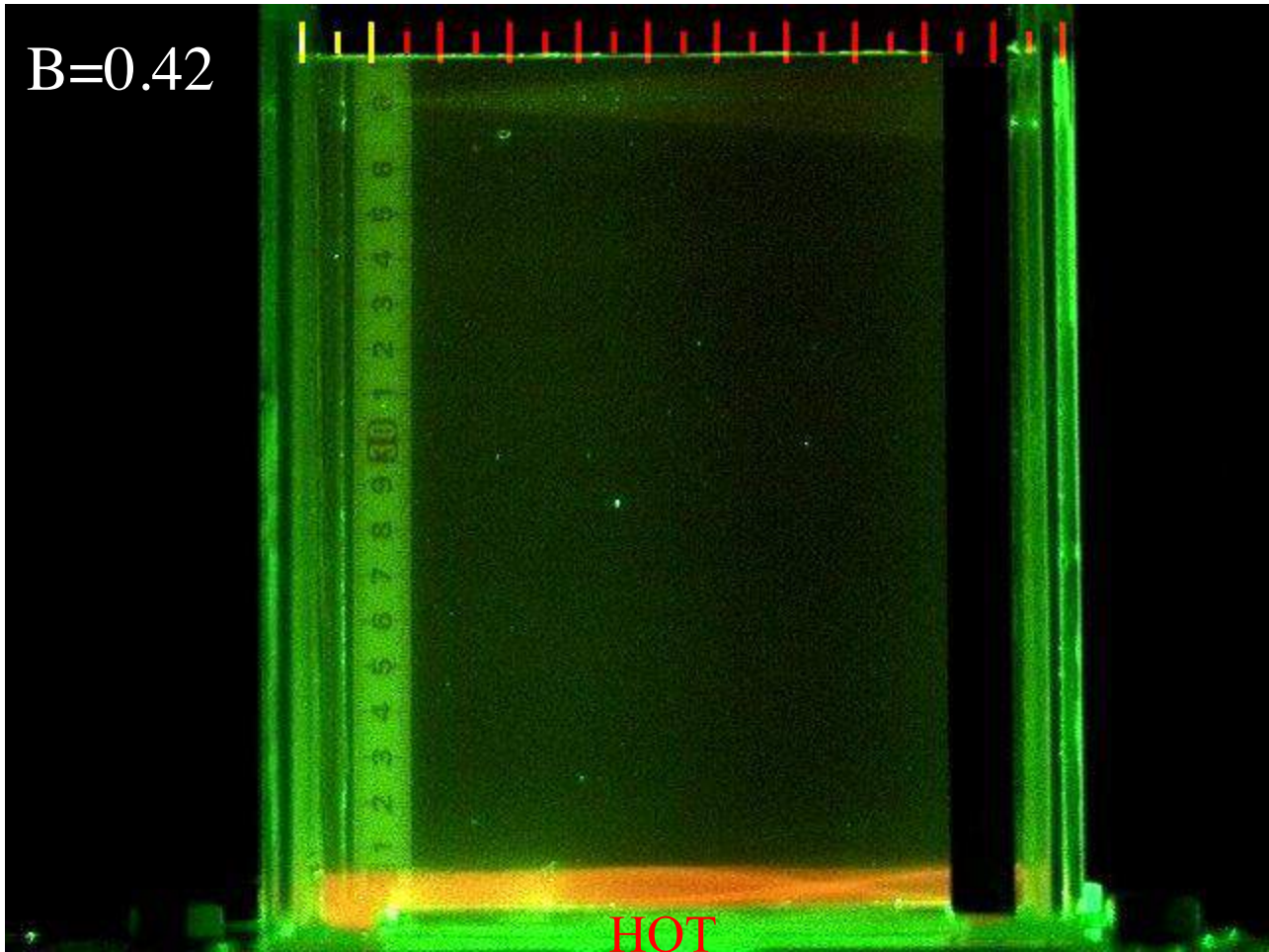
(Michael Le Bars, 2004)

4. Interaction Convection / Denser Reservoir



hot less viscous (Ichiro Kumagai, Kei Kurita)

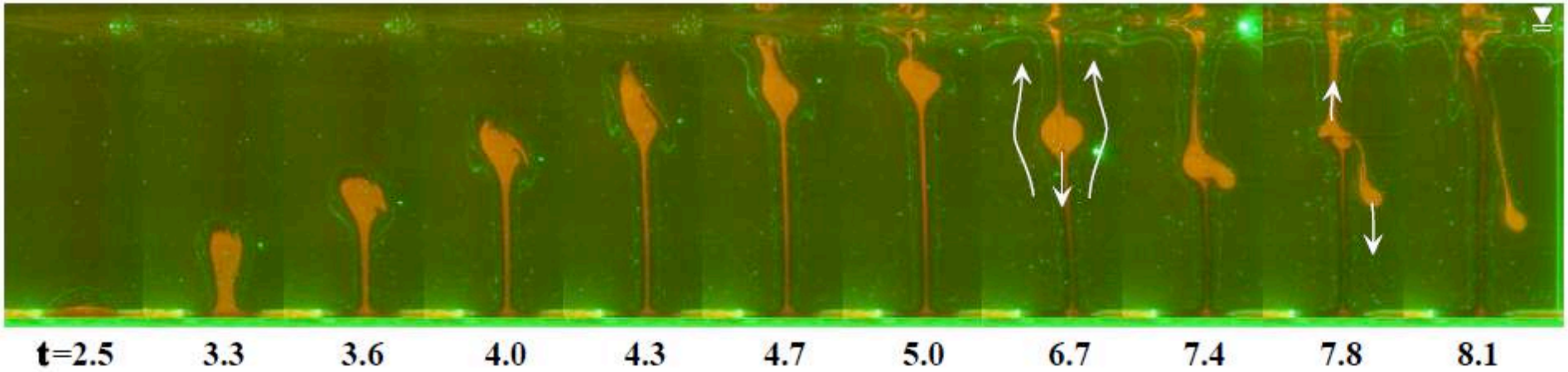
$B = \Delta\rho_c / \alpha \Delta T$



4. Interaction Convection / Denser Reservoir

B_L=0.59

Time-dependence



SUCCESSFULL…

FAILING…

While going up, the thermochemical plume looses its heat by diffusion

(Kumagai & al, 2008)

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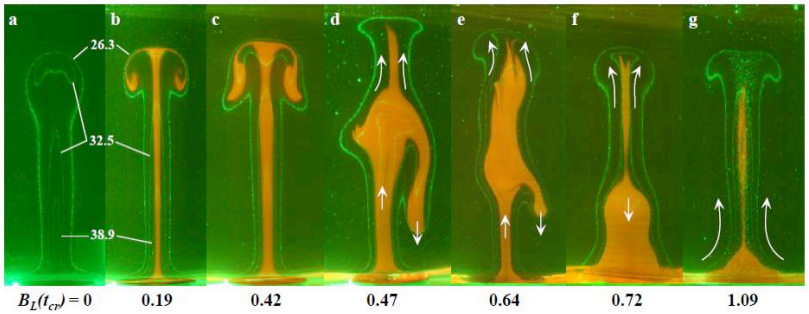

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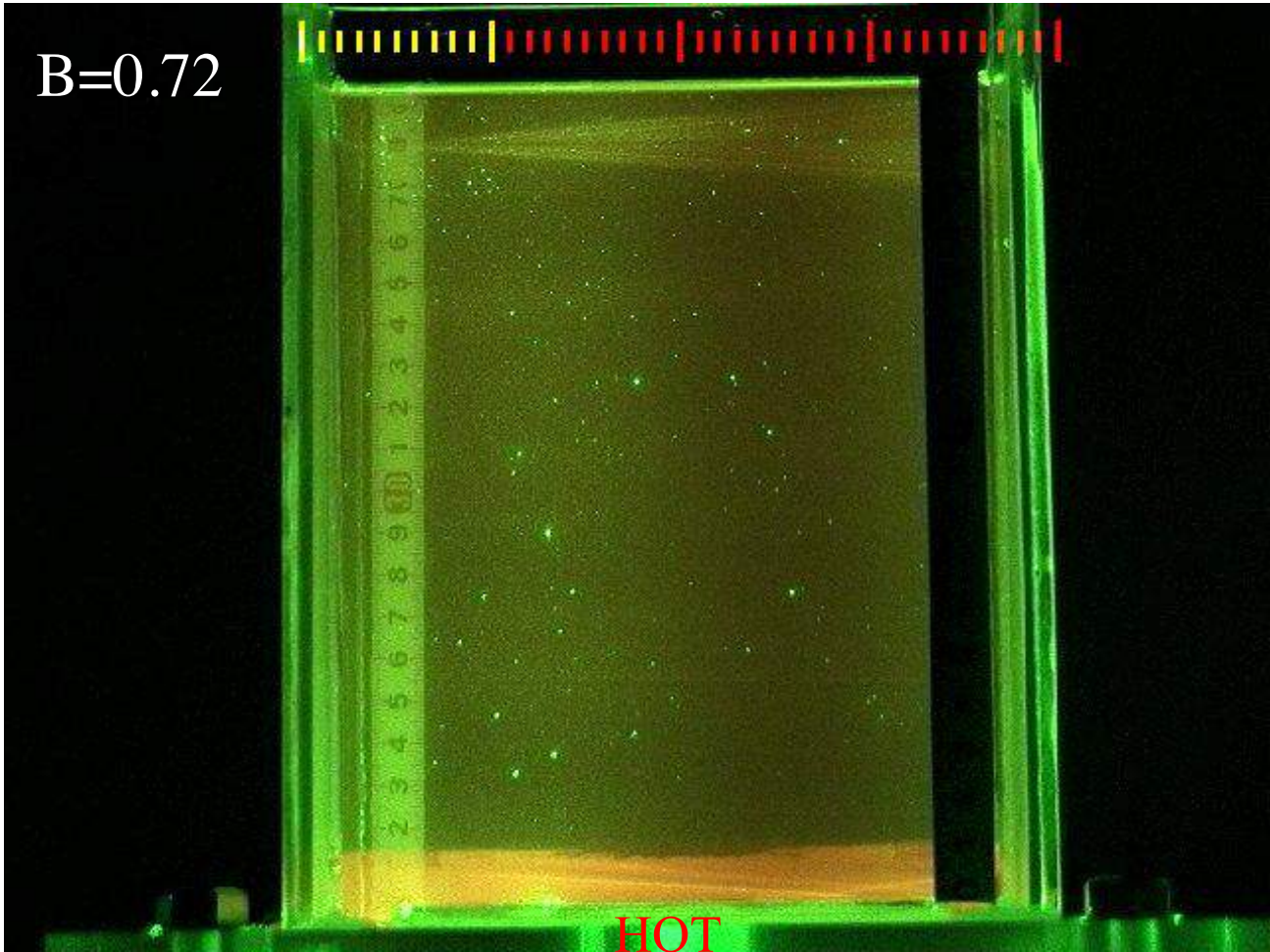

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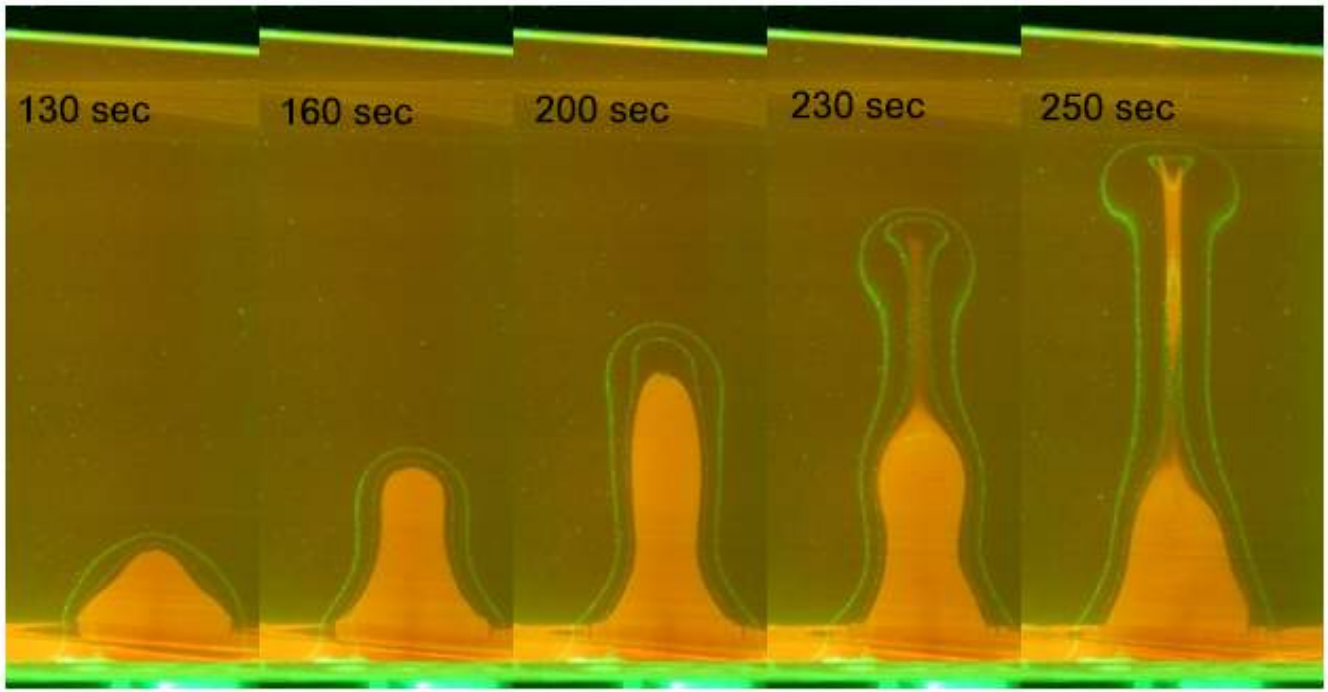
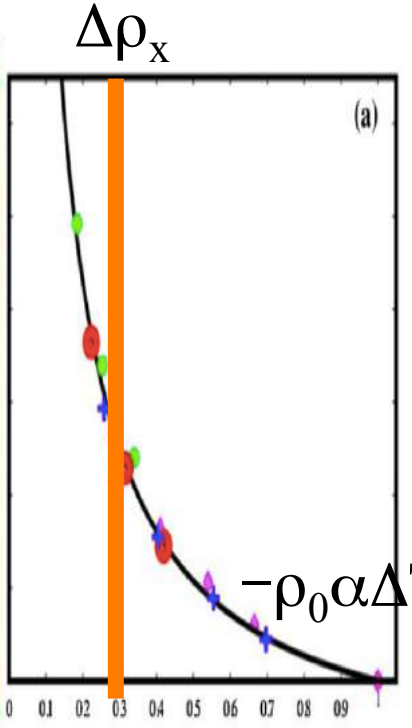


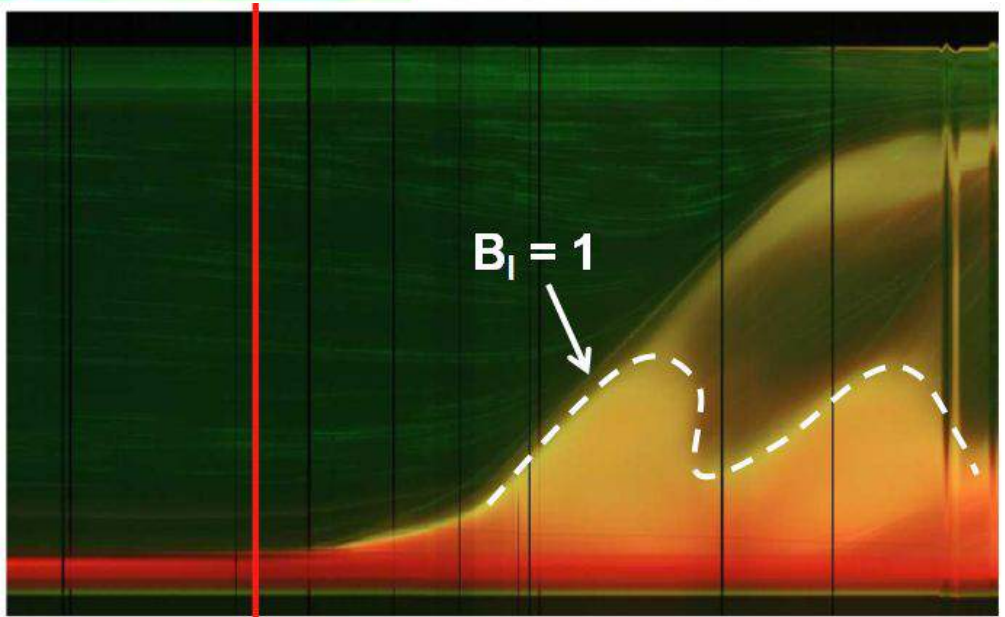


B=0.72

-Behaviour depends on time

-Dome + secondary plume

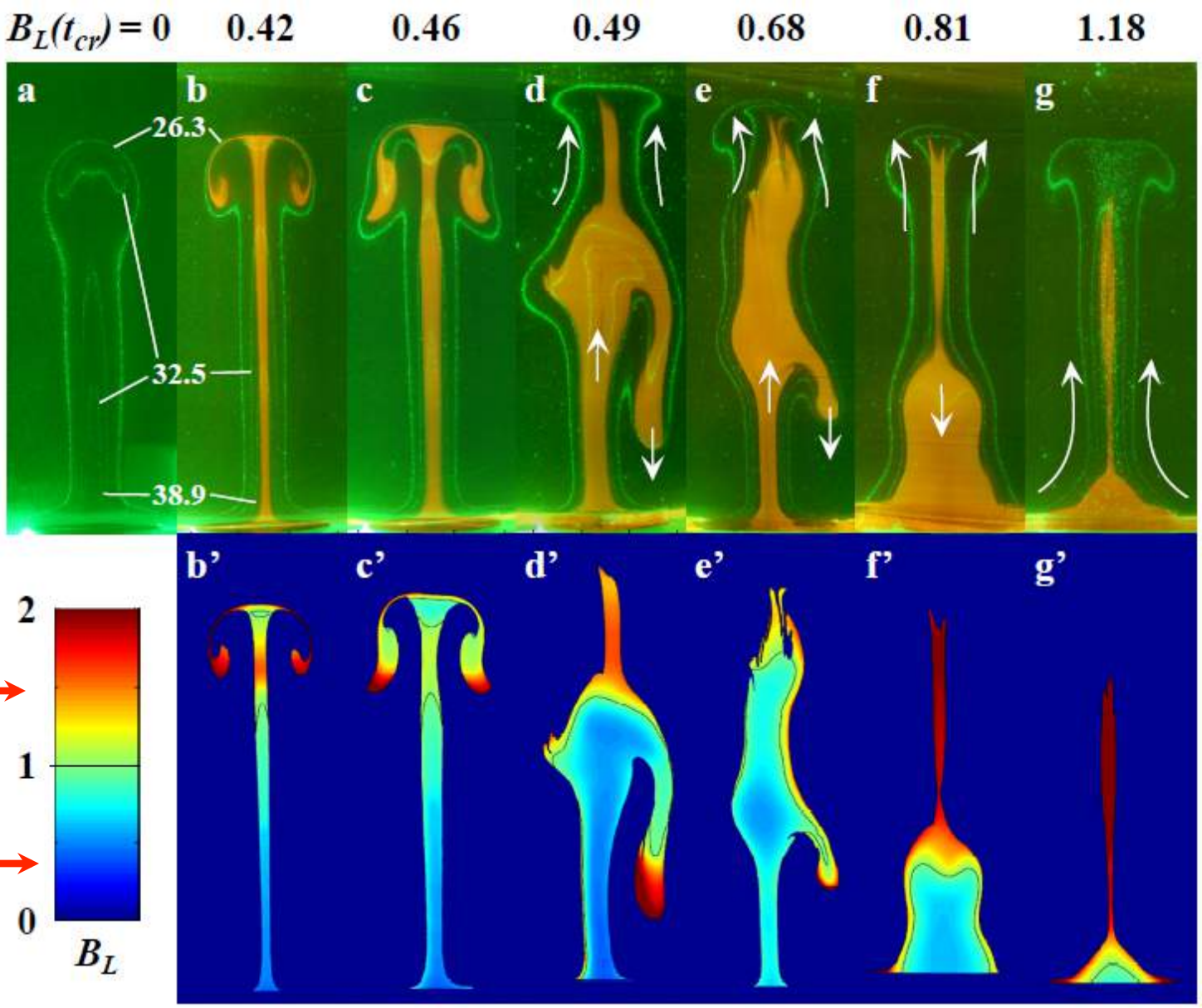
$B_l=\Delta\rho_x/\rho_0\alpha\Delta T(r,z)$



4. Interaction

KEY:

$B_1 >$ or < 1

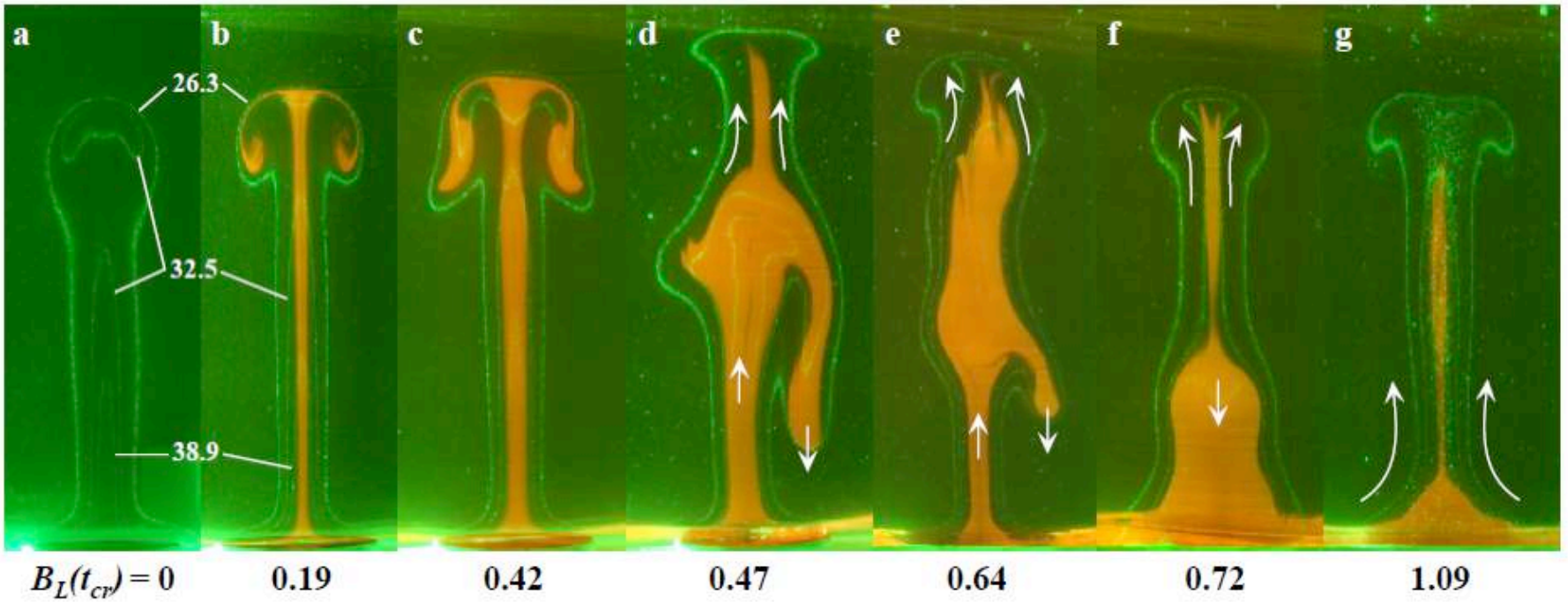


Going DOWN ⟷

Going UP ⟷

(Kumagai & al, 2008)

4. Interaction Convection / Denser Reservoir

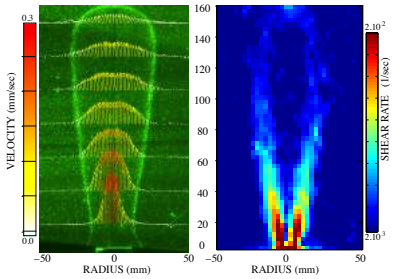


$\Delta\rho_x \geq 1\%$
for $\Delta T(r,z) \sim 300°$

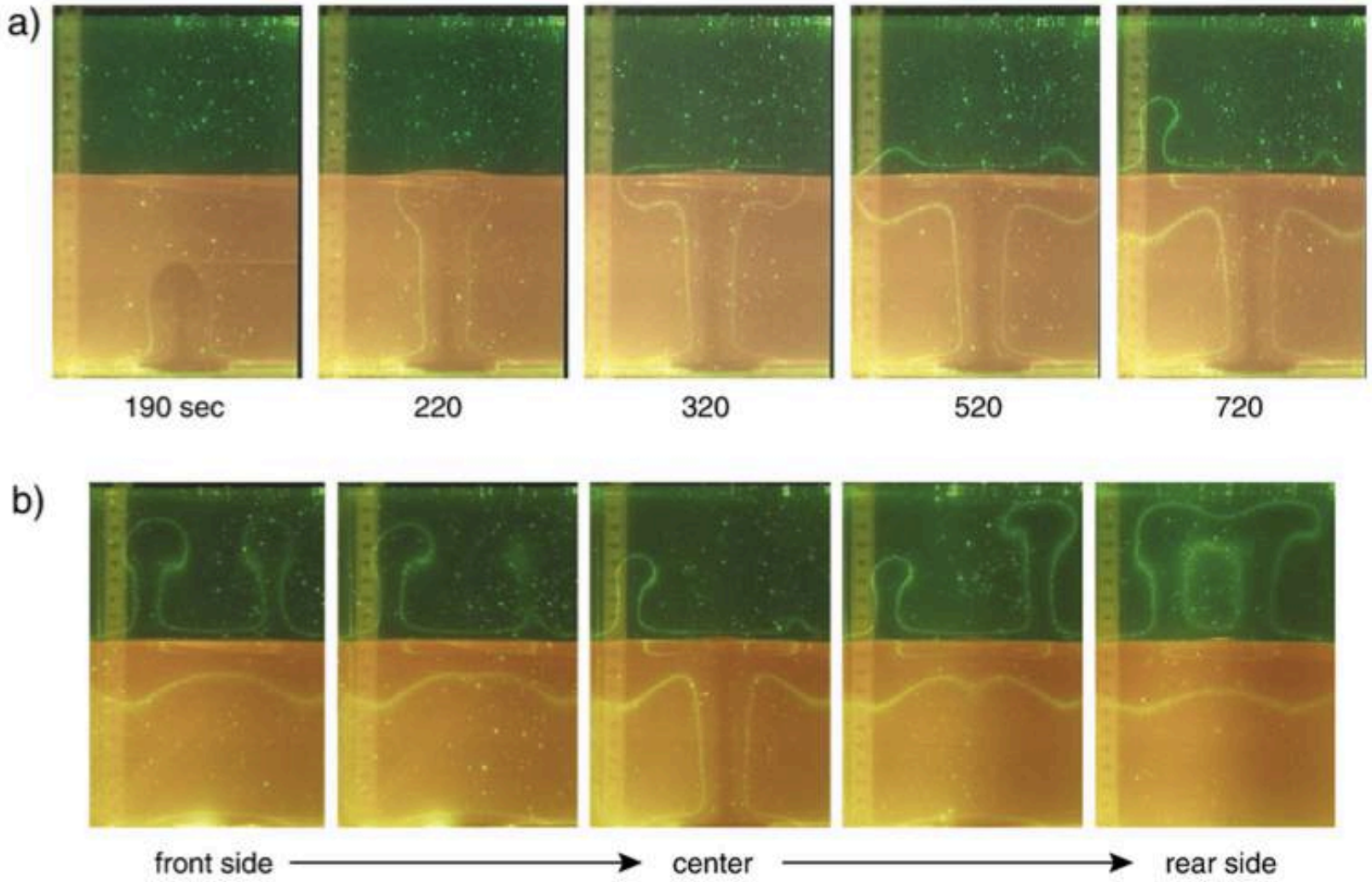
. FAT upwellings -> circulation + viscosity

. Complicated, time-dependent morphology

. B increases => level of neutral buoyancy decreases



4. Interaction Convection / Denser Reservoir



Delay through a boundary

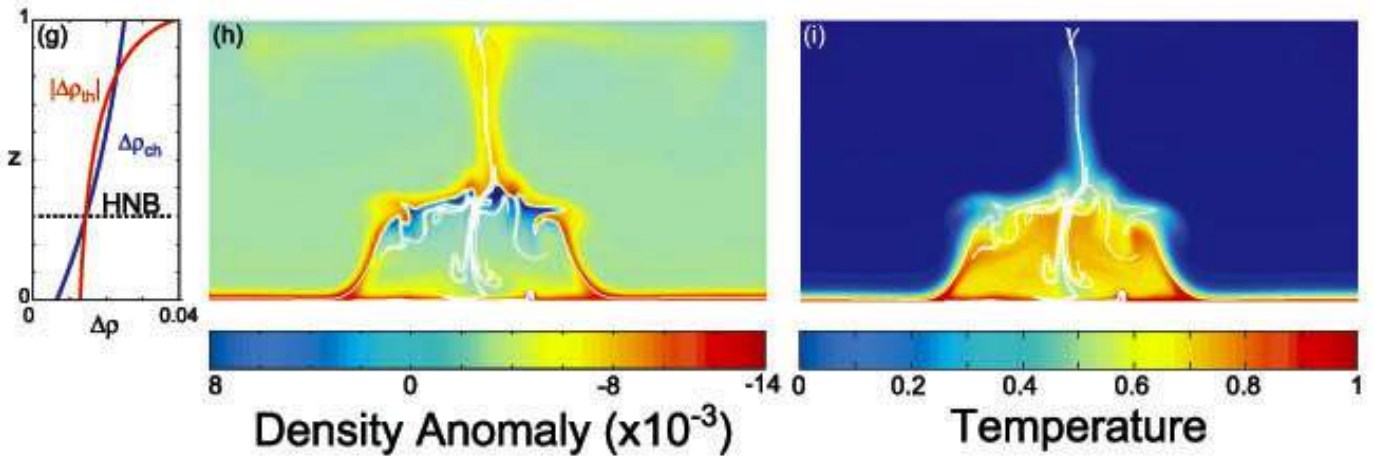
=> generation of a cluster of secondary plumes

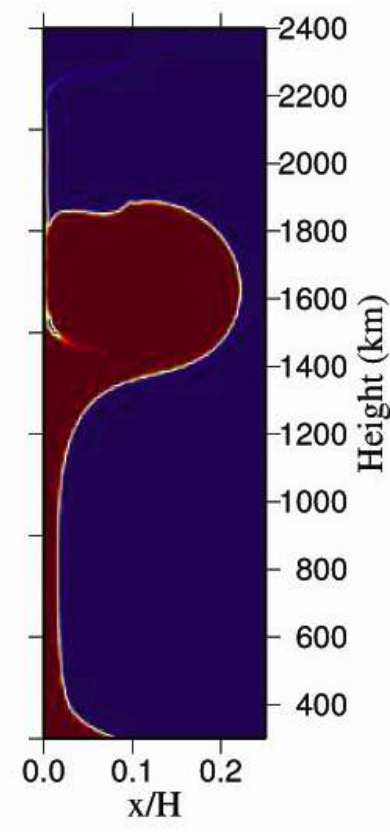
(Kumagai & al, 2007)

4. Interaction Convection / Denser Reservoir

- 'Real' Mantle => pressure/depth dependence of
density, phase, thermal expansion, viscosity,…

=> modify the level of neutral buoyancy

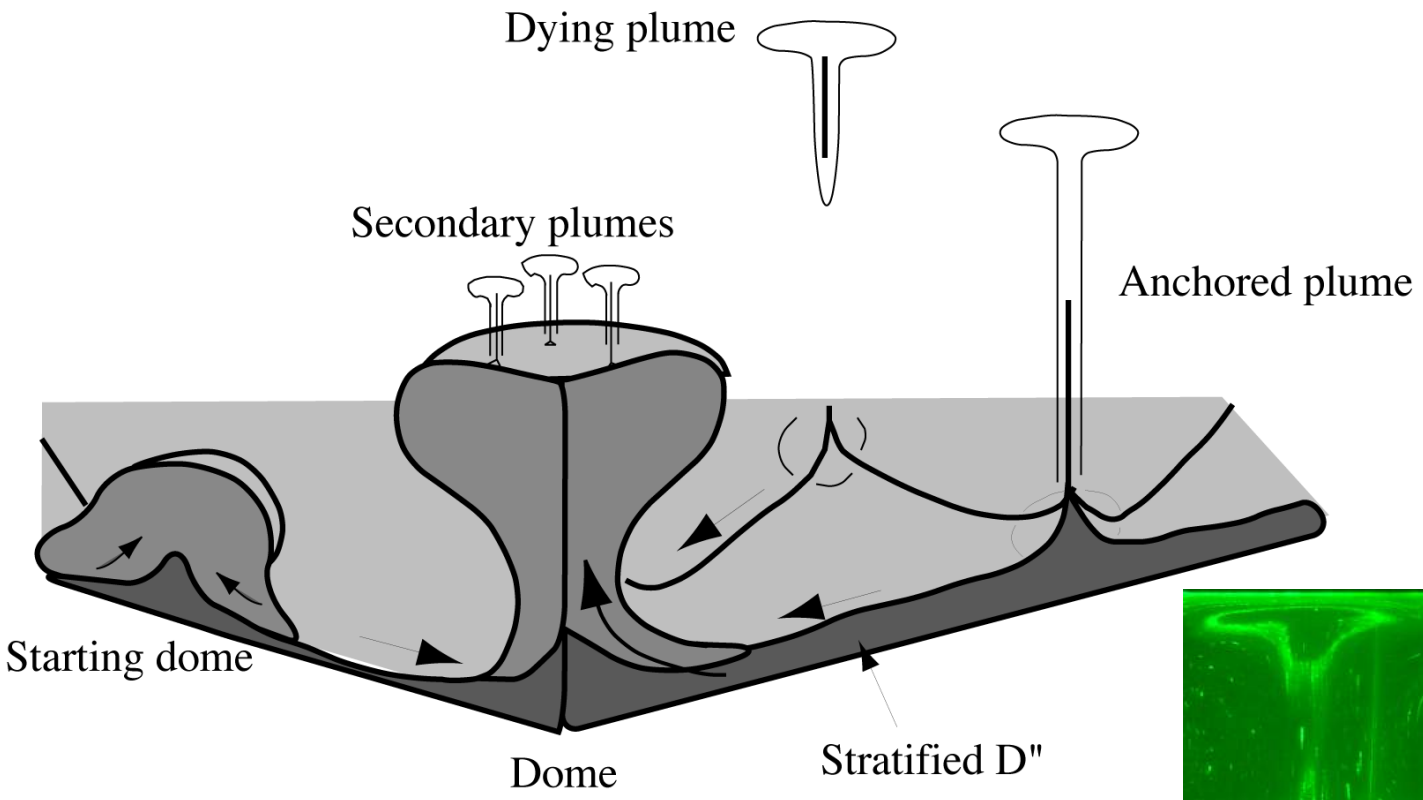


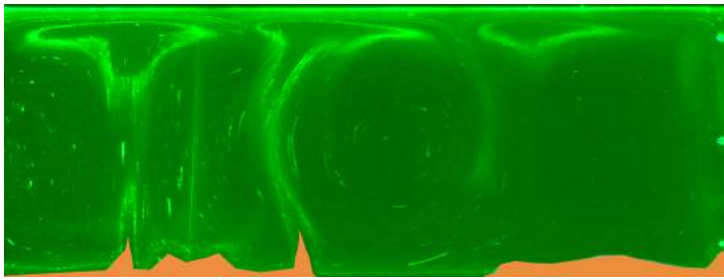


(Tan & Gurnis, 2008; Samuel & Bercovici, 2005; Ballmer et al, 2013; …)

4. Interaction Convection / Denser Reservoir

Coexistence of several types of hot instabilities

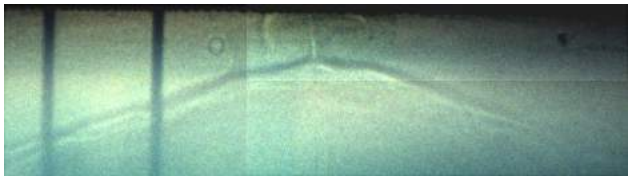


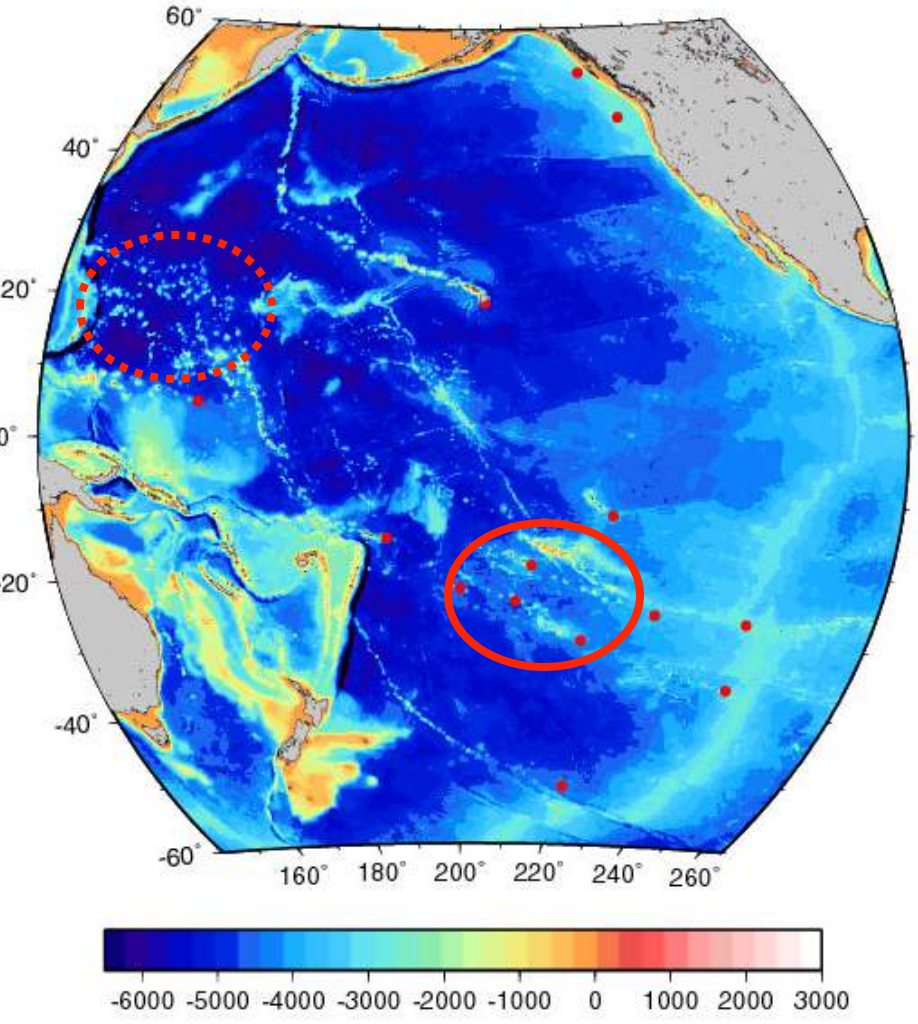


Laboratory experiments scalings => spacing ~2000-3500 km at CMB

5. Inside the boxes: hot upwellings in the Pacific

Polynesia = hot spot cluster (short tracks) + superswell



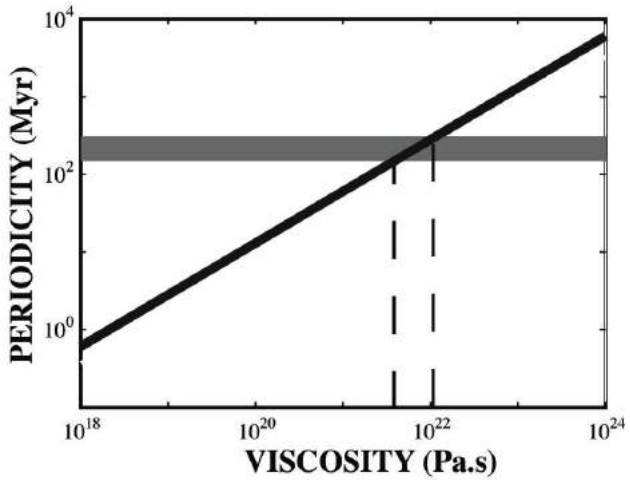


Pacific Bathymetry (Clouard & Bonneville, 2003)

Darwin Rise = 100 Ma

⇒ = 1 complete pulsation of a thermochemical dome

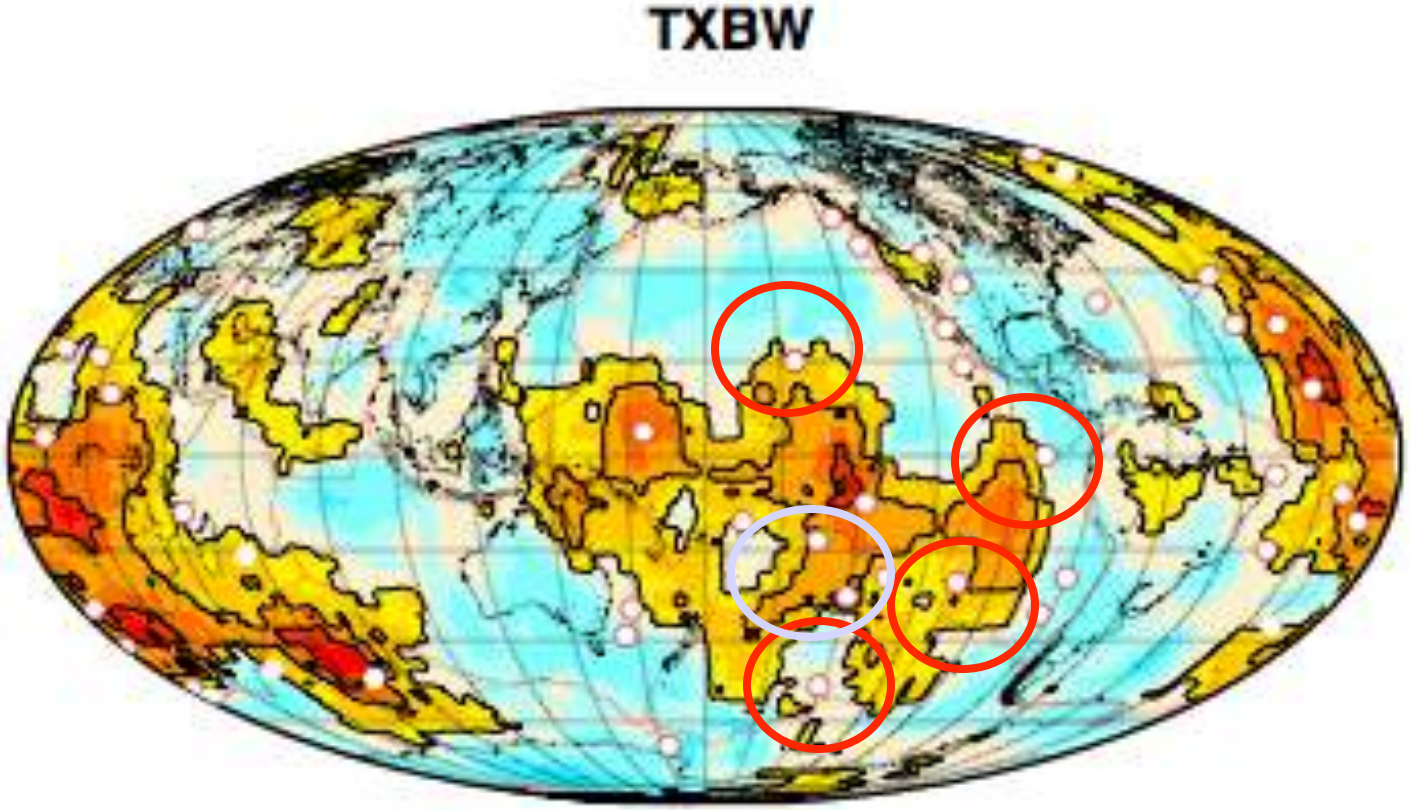
if Viscosity ~ 2-6 10^{21} Pa.s



(Davaille, 1999)

5. Inside the boxes: hot upwellings in the Pacific

Thermochemical instabilities => spacing ~2000-3500 km at CMB



=> missing 2 or 3 instabilities

5. Inside the boxes: hot upwellings in the Pacific

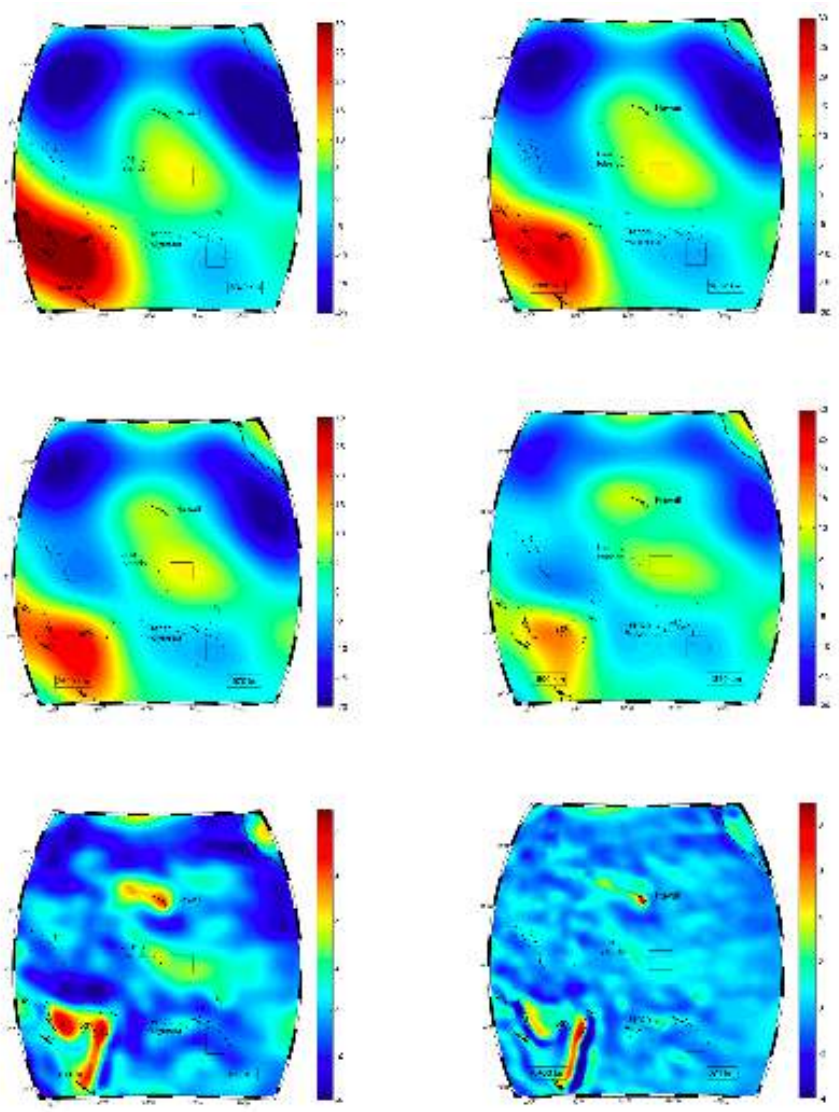


Figure 3. Continuous wavelet analysis of the EIGEN-GL04C geoid model in the Pacific Ocean at varying scales, from 3600 to 400 km. The analyzing wavelet scale and the

missing instability

Explain the data

=> **heavy dome => descending**

=> + would have been under part of Line Island ~ 35 Myr ago

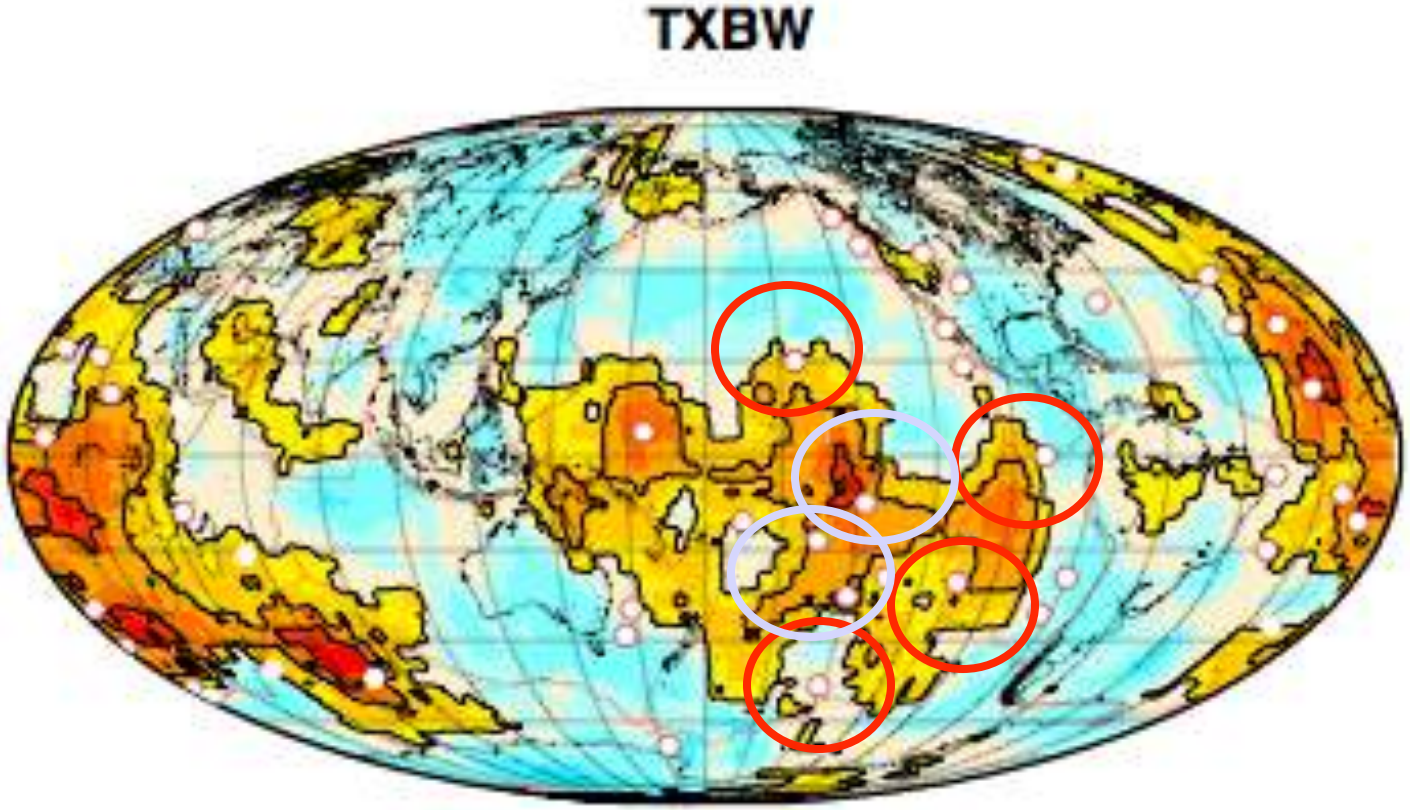
+ 140 Myr ago, Shatsky Rise was formed in the area

=> Another ~100 Myr cycle…

(Cecilia Cadio & al, 2011)

5. Inside the boxes: hot upwellings in the Pacific

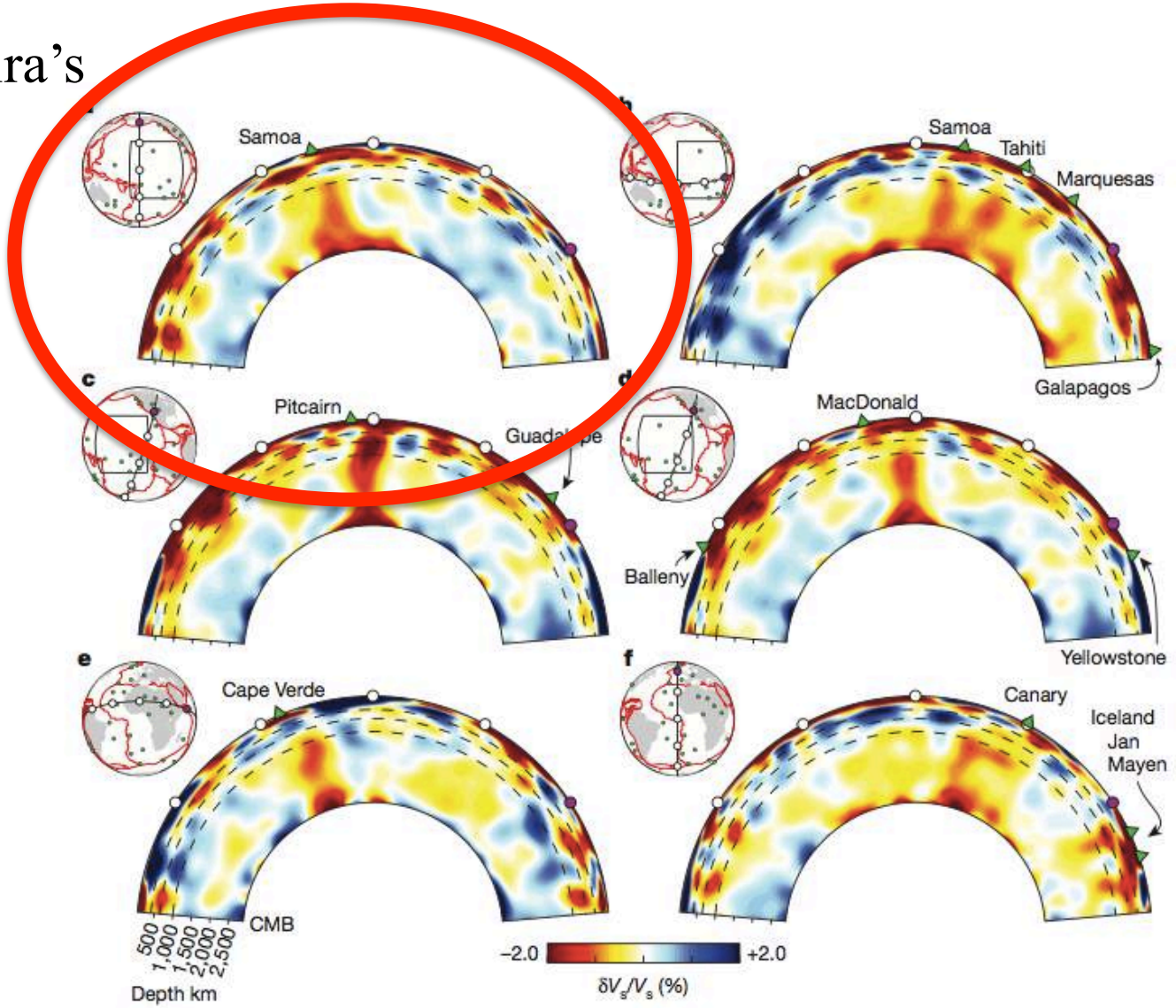
Thermochemical instabilities => spacing ~2000-3500 km at CMB



=> missing 1 or 2 instabilities

5. Inside the boxes: hot upwellings in the Pacific

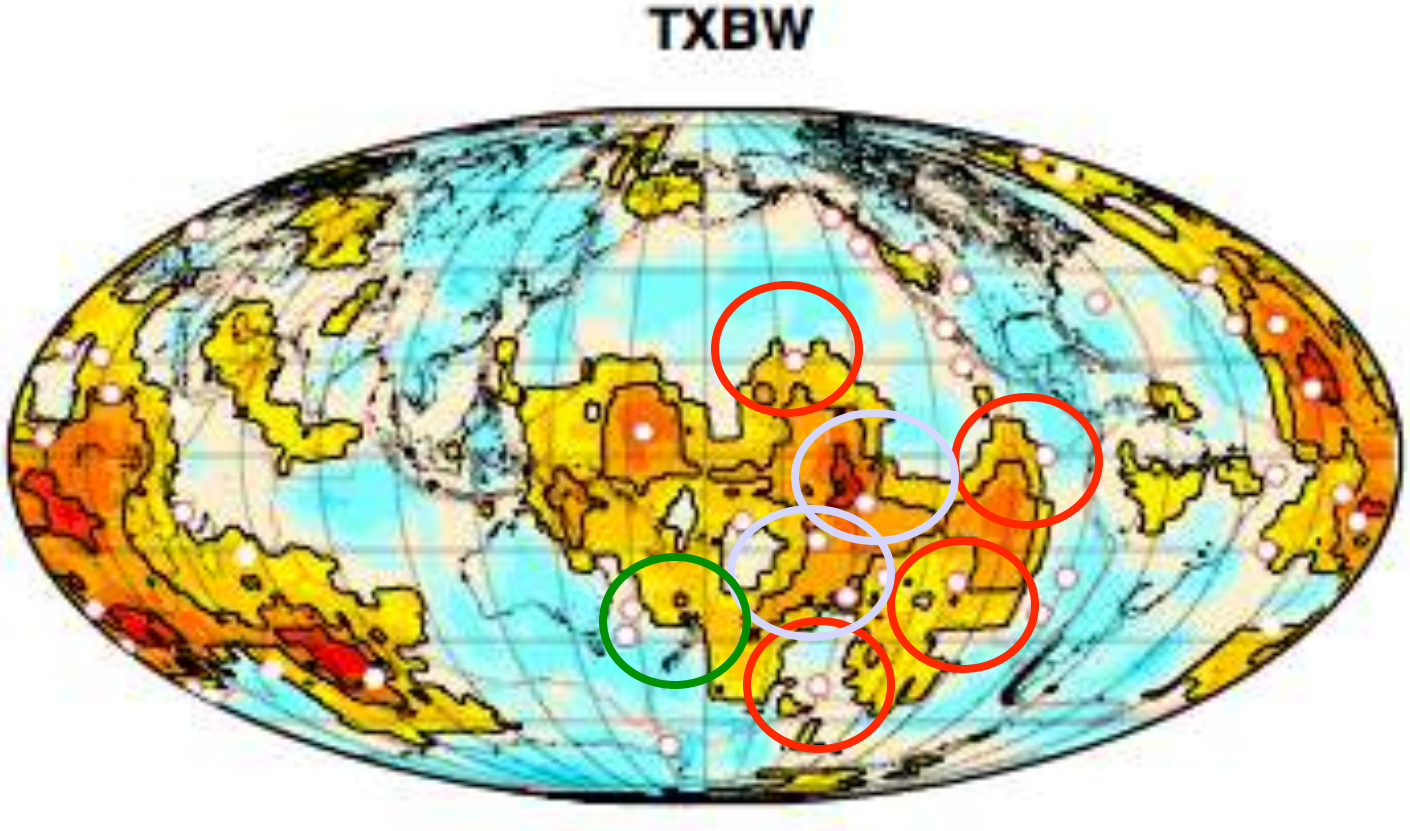
A. Ferreira's talk



(French & Romanowicz, 2015)

5. Inside the boxes: hot upwellings in the Pacific

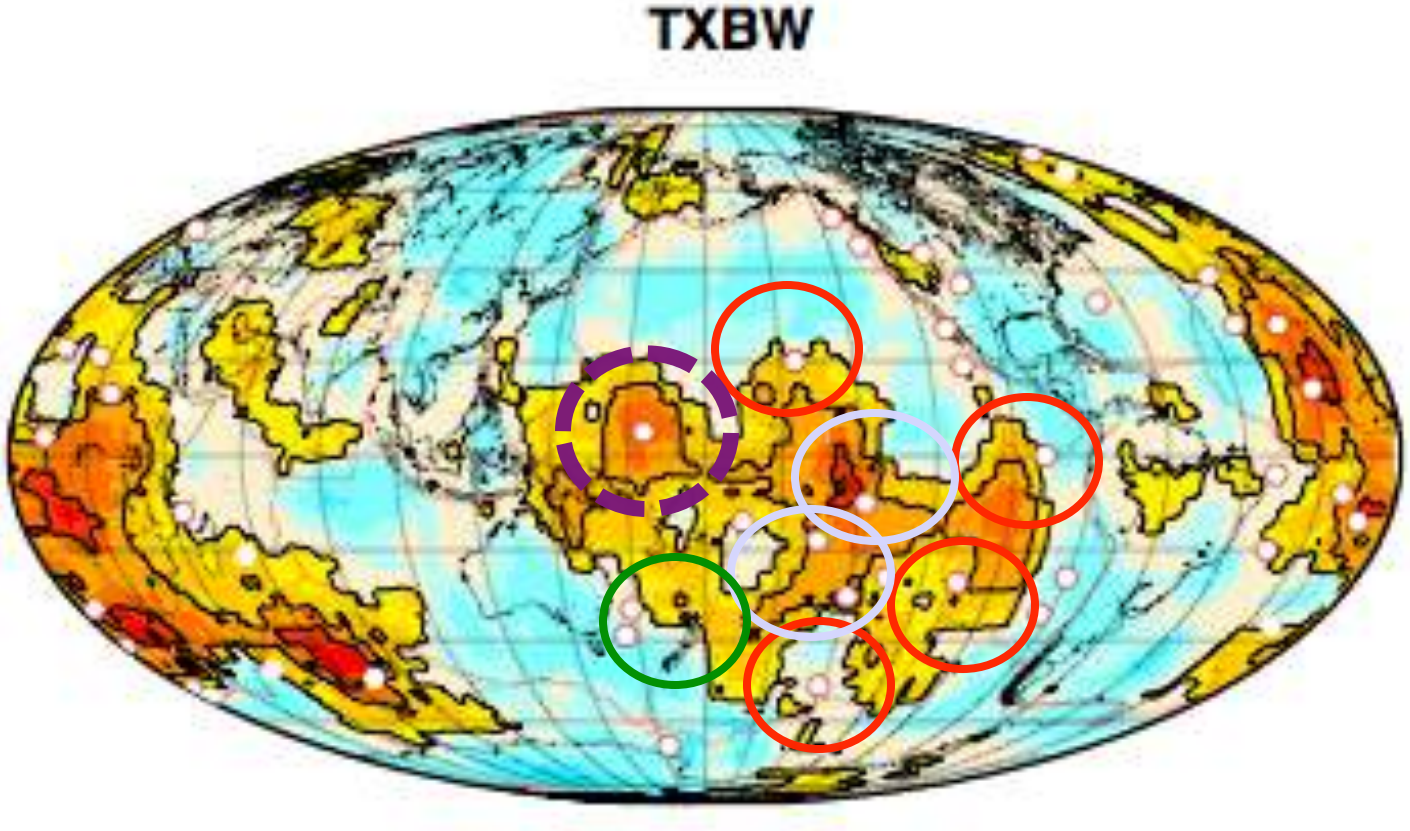
Thermochemical instabilities => spacing ~2000-3500 km at CMB



= > missing 1 instability

5. Inside the boxes: hot upwellings in the Pacific

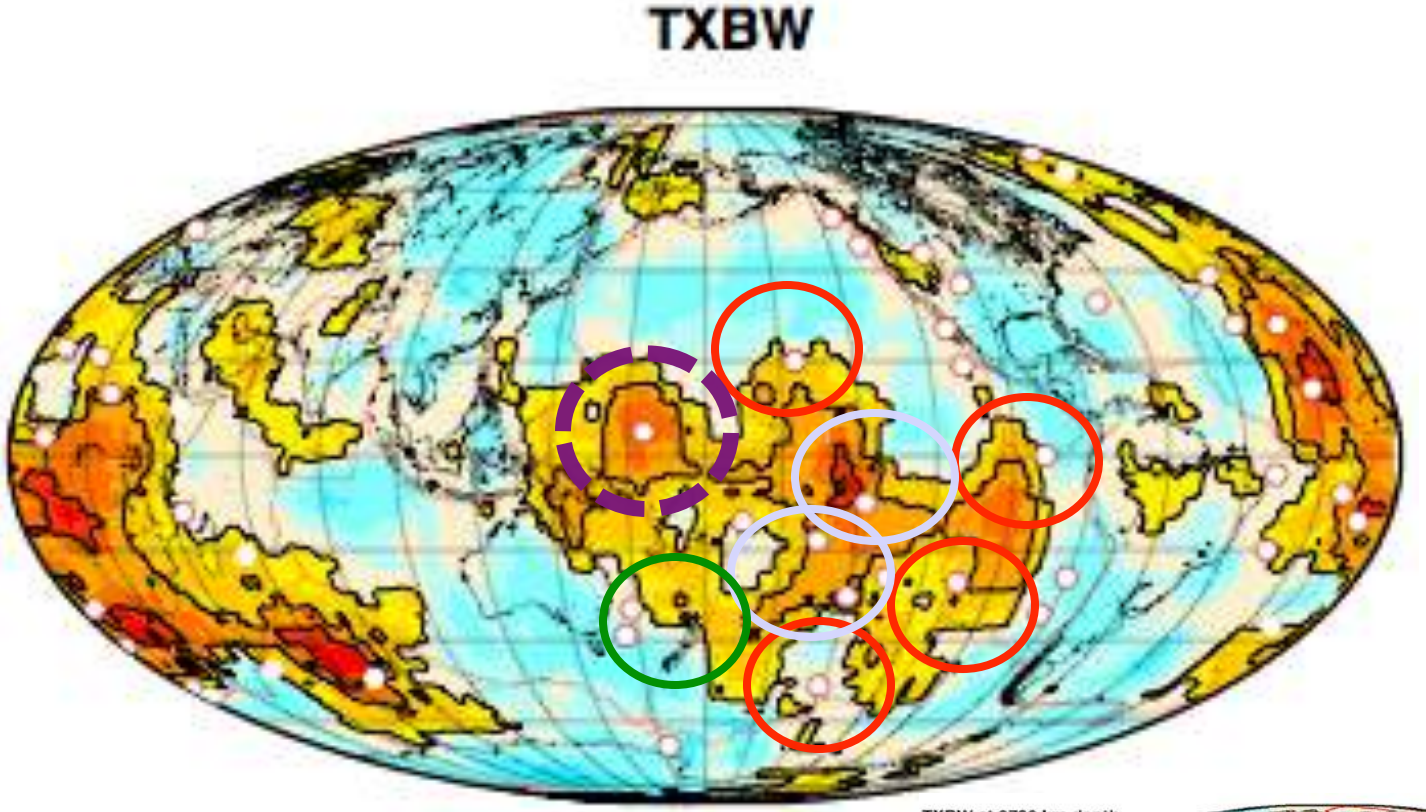
Thermochemical instabilities => spacing ~2000-3500 km at CMB

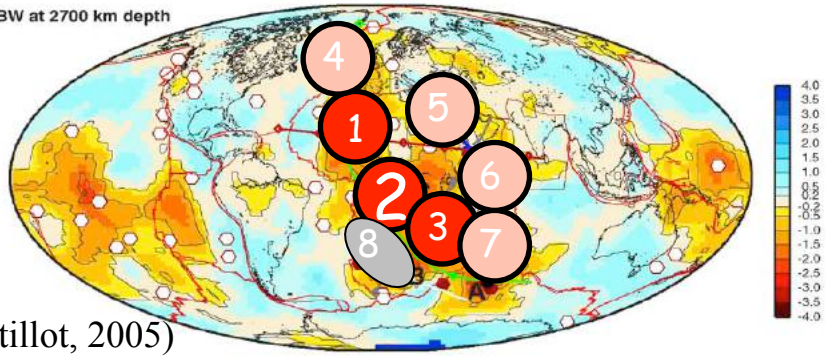


MOVIE => instability has not reached the surface yet

5. Inside the boxes:

Thermochemical instabilities => spacing ~2000-3500 km at CMB





(A.D, E. Stutzmann, J. Besse, V. Courtillot, 2005)

QUESTIONS :

A- Origin of mantle « boxes » ? **Variable viscosity / Subduction**

B- Upwellings **Compositional/density heterogeneities**

- **several types ?**
- **« fat » ?** **Composition / viscosity /circulation within the plume**
- **what happens around 1000 kms ?**

C- Do the mantle boxes / LLSVPs change shapes through time ?

QUESTIONS :

A- Origin of mantle « boxes » ? **Variable viscosity / Subduction**

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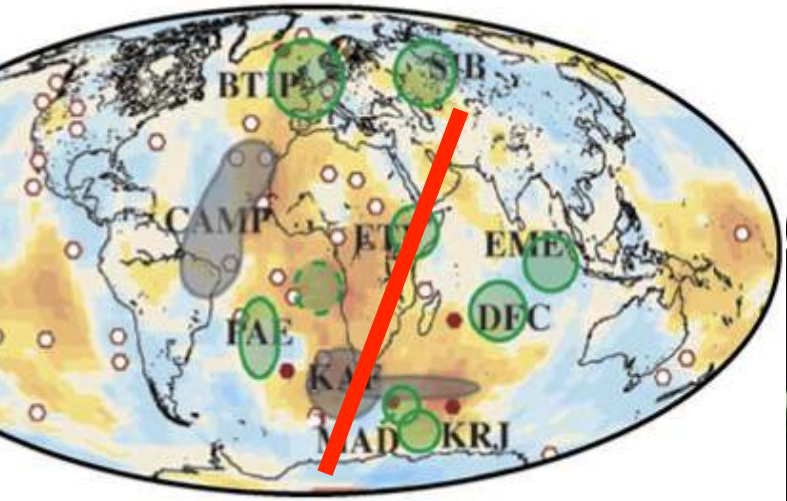
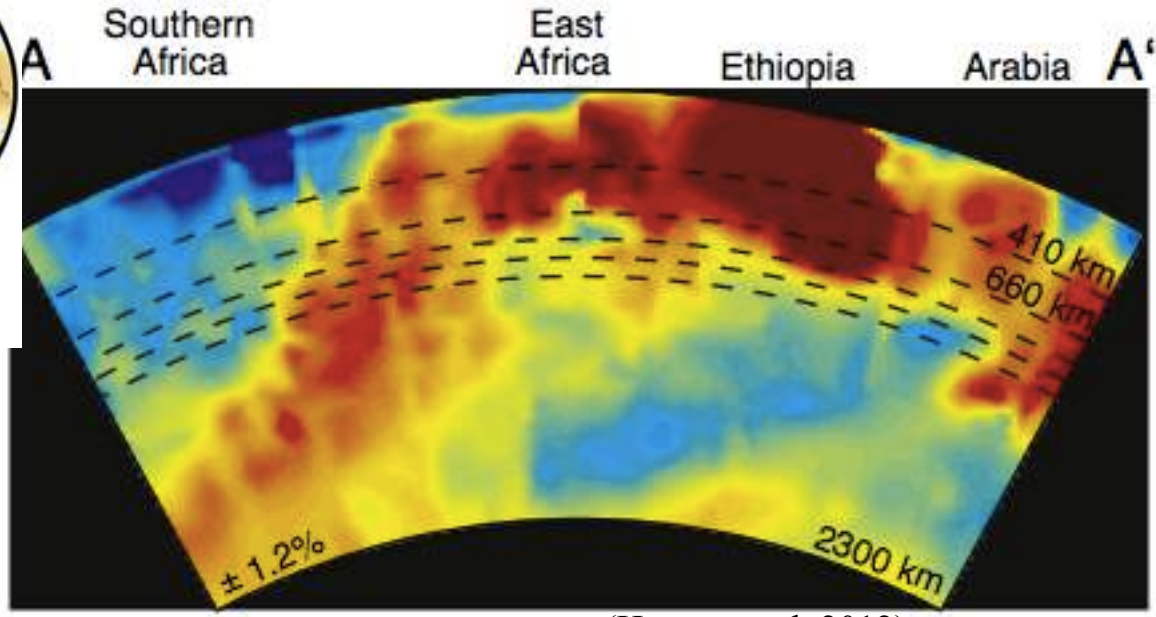
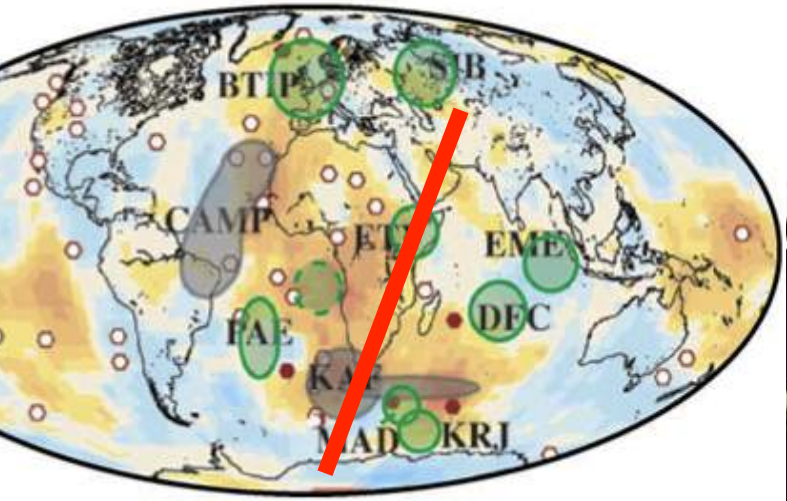
6. Time-dependence:

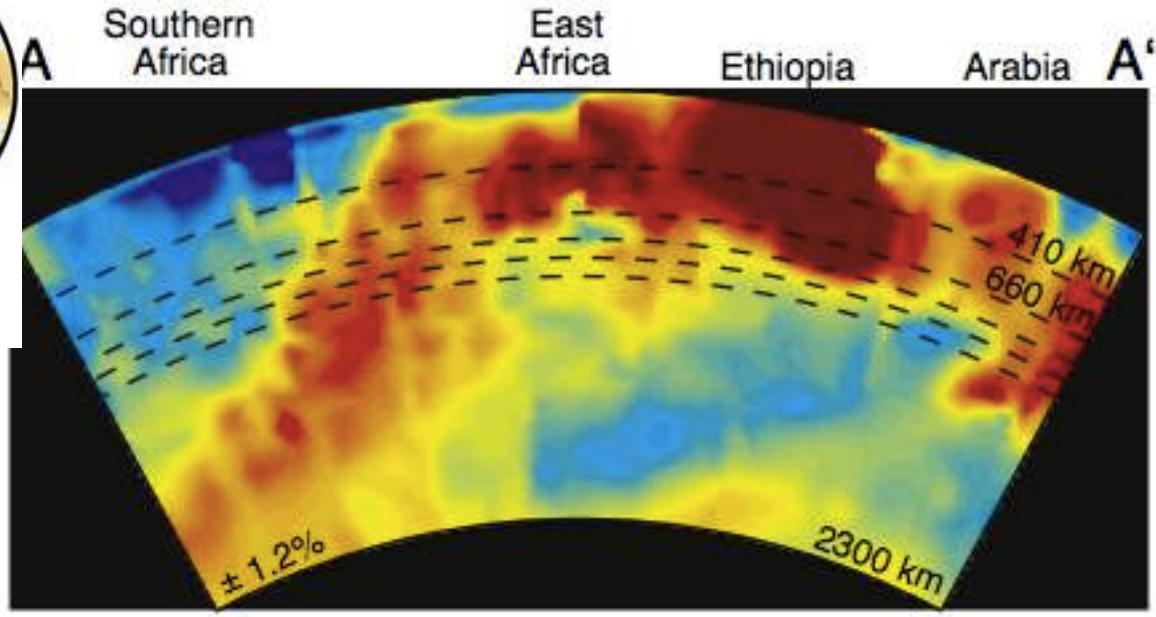


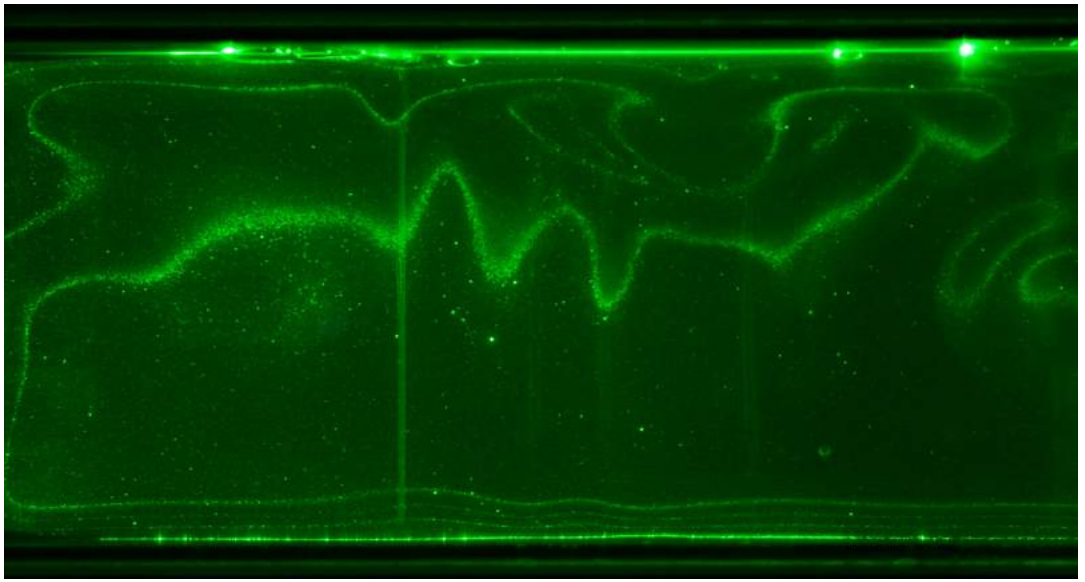


(Hansen et al, 2012)

6. Time-dependence:







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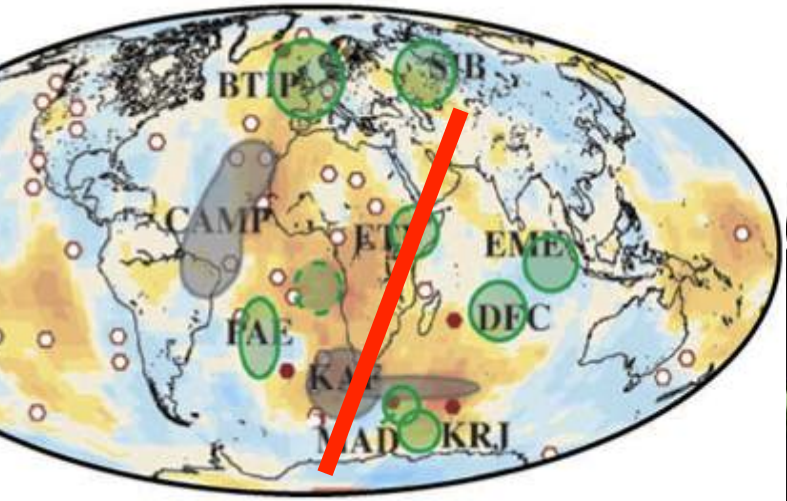

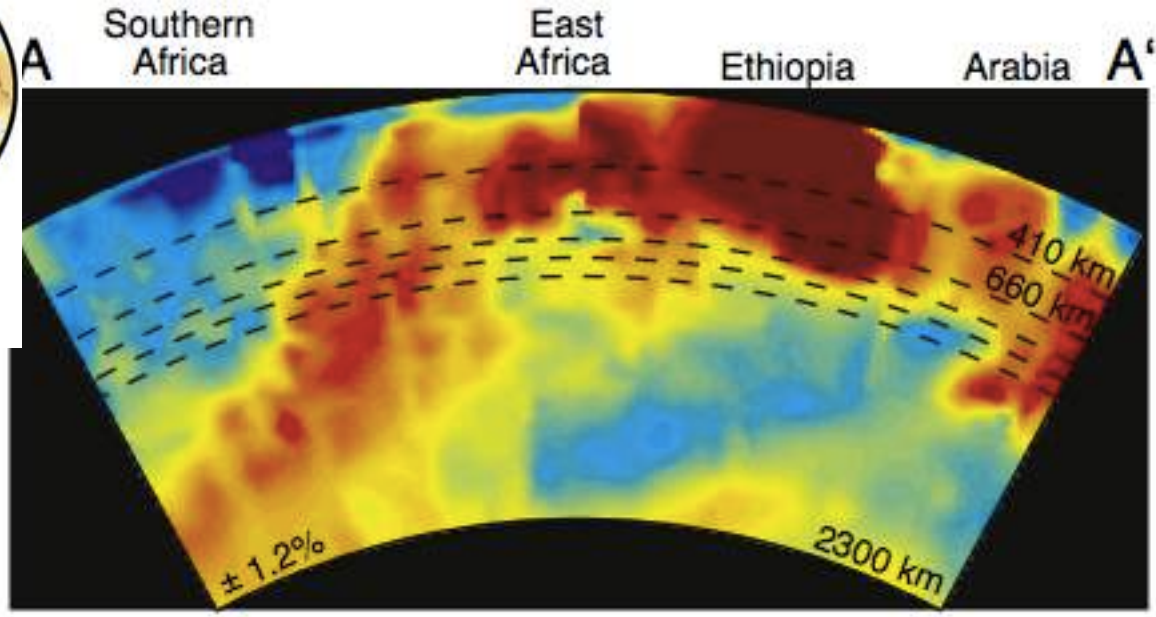

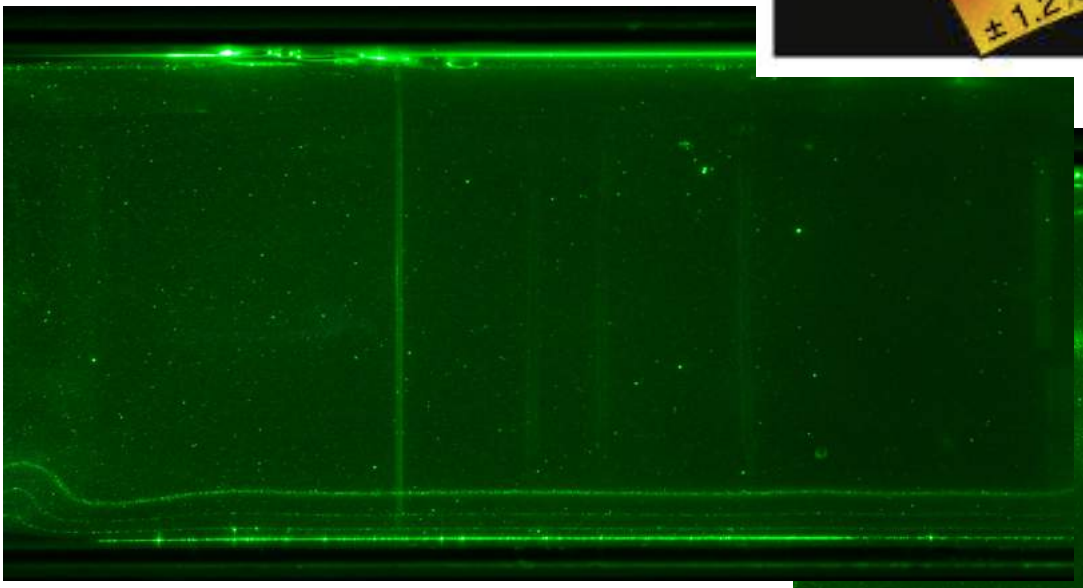

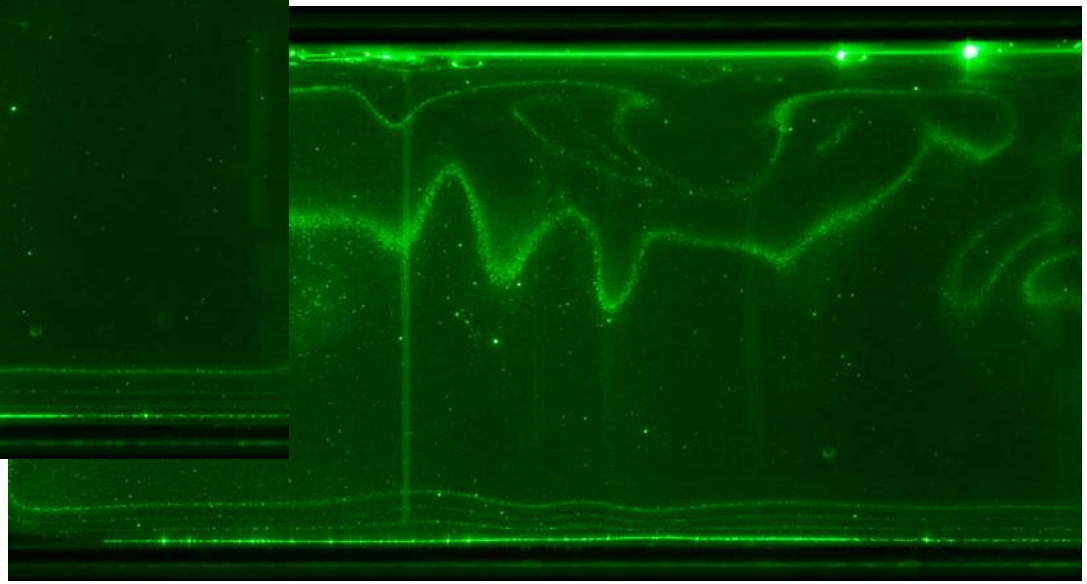

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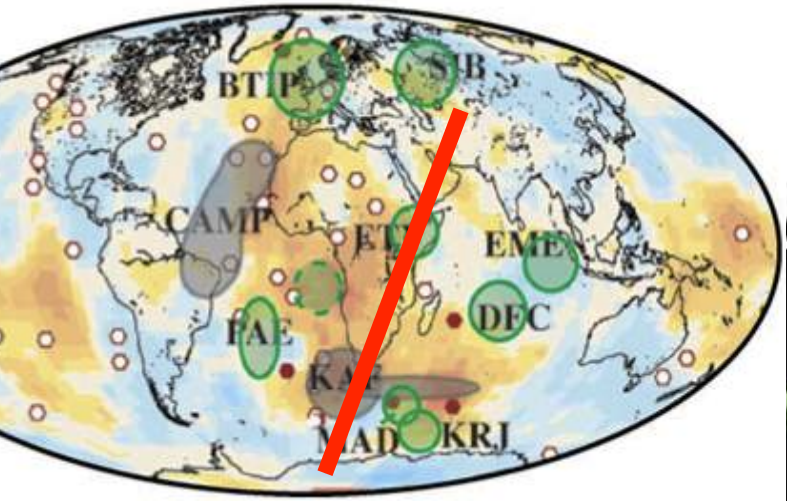

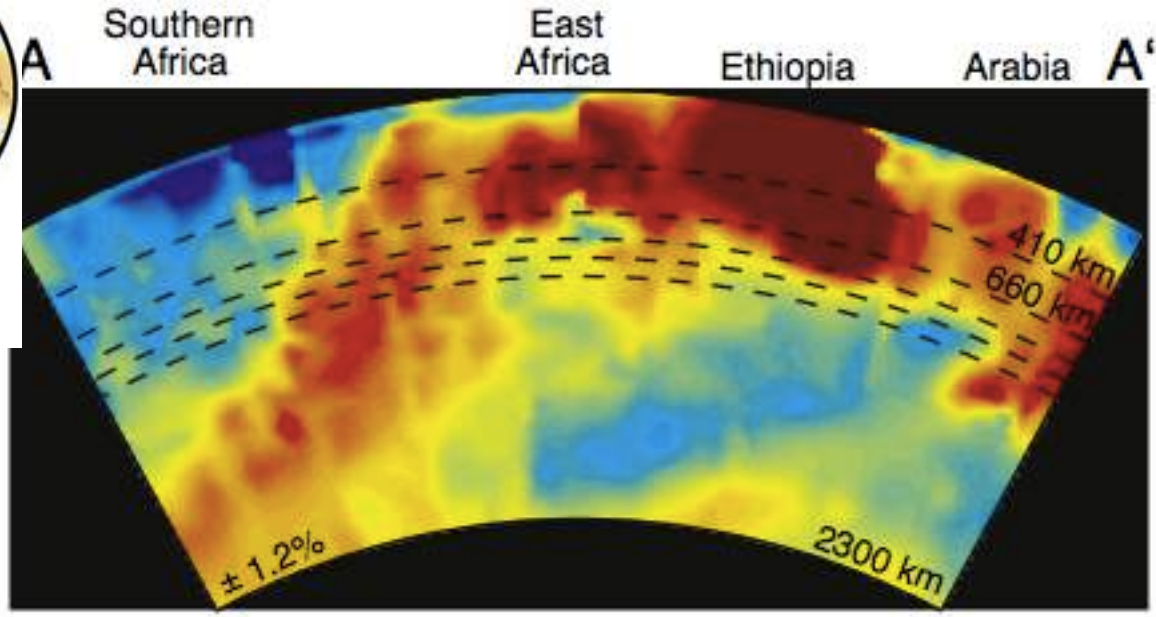

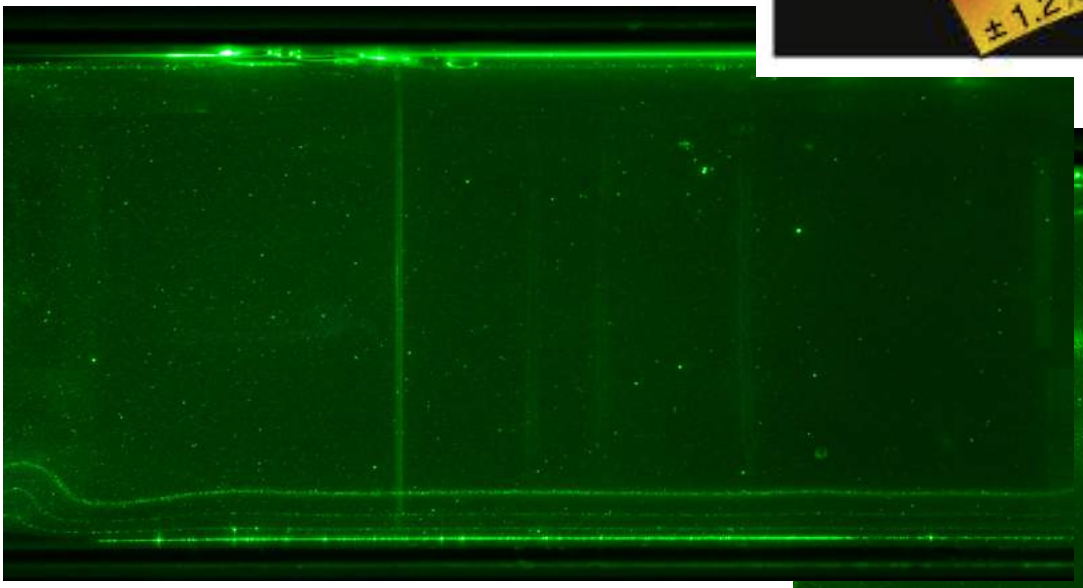

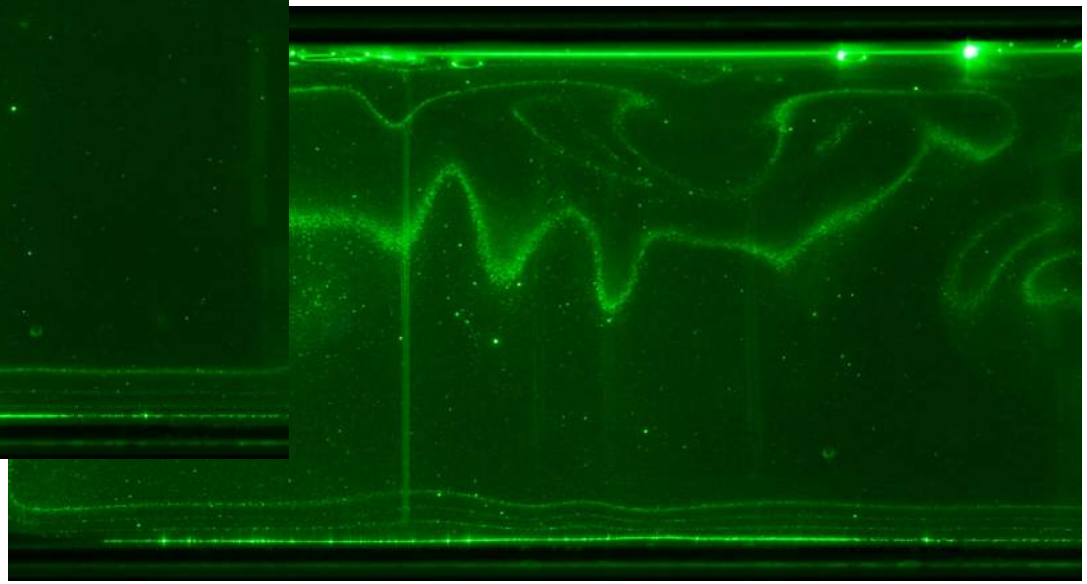

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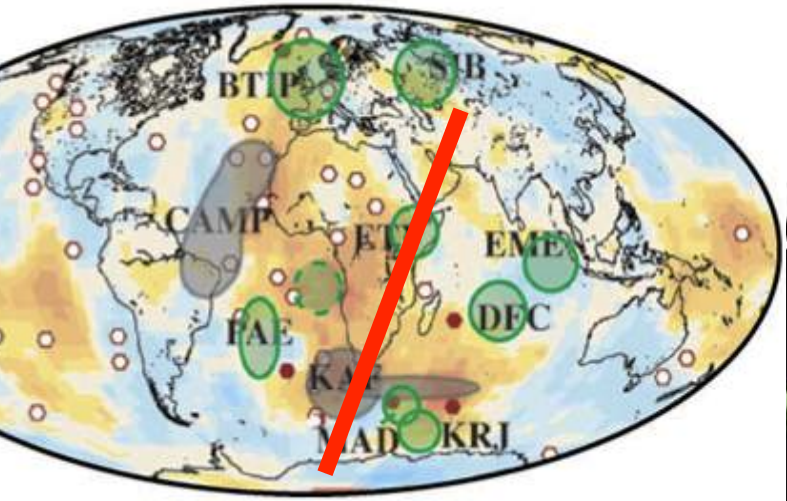

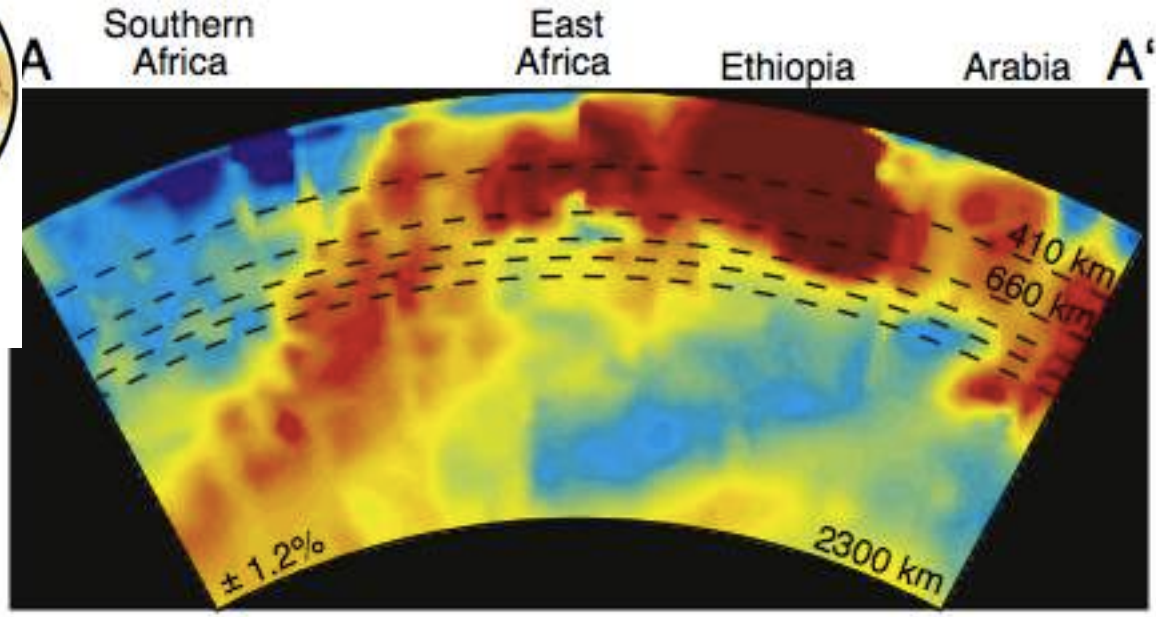

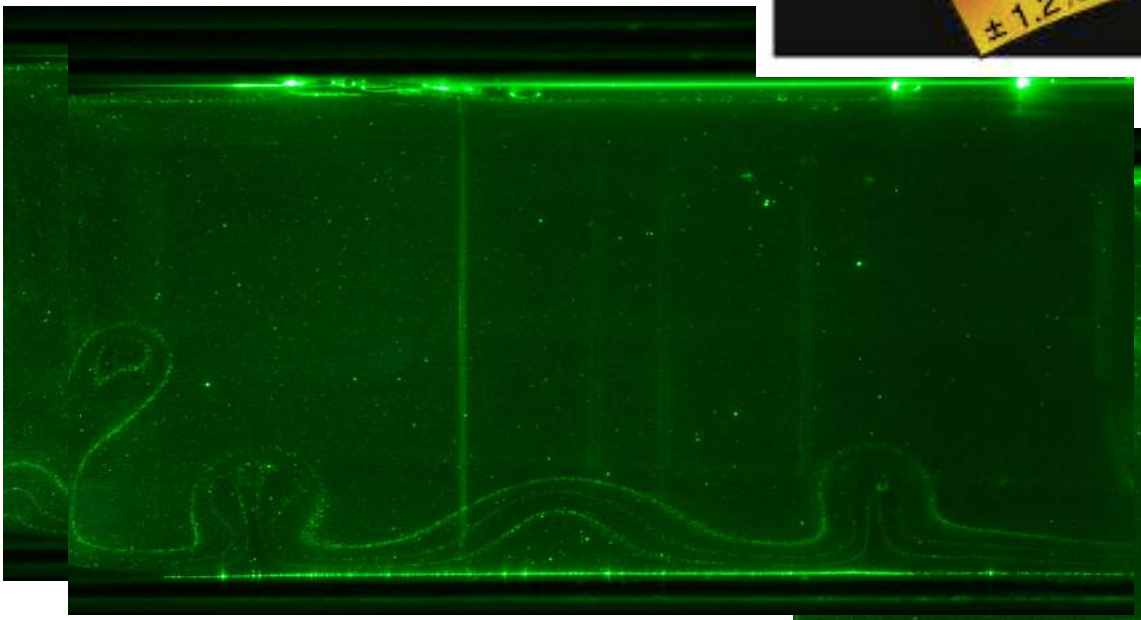

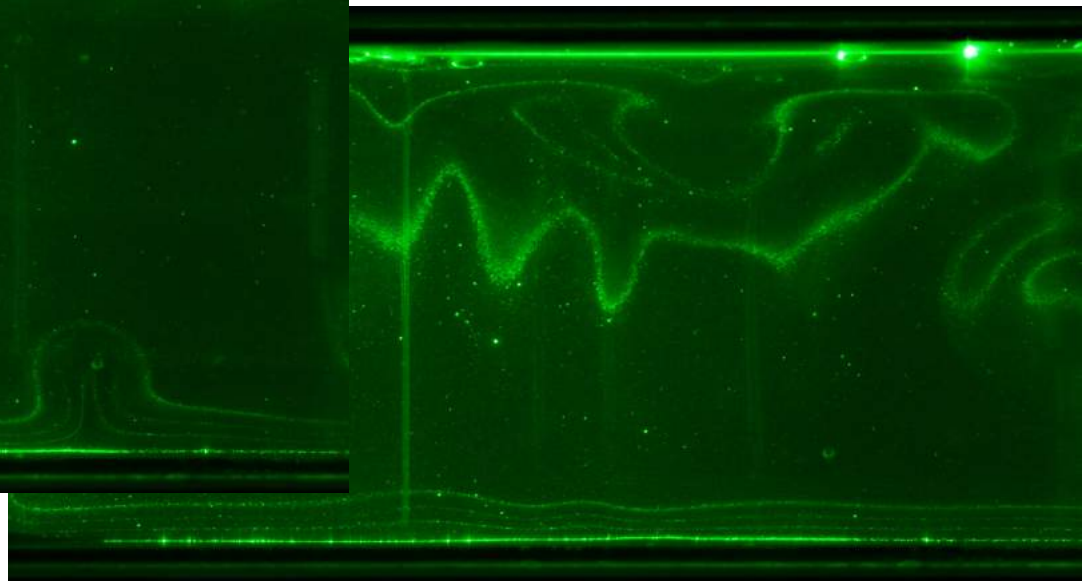

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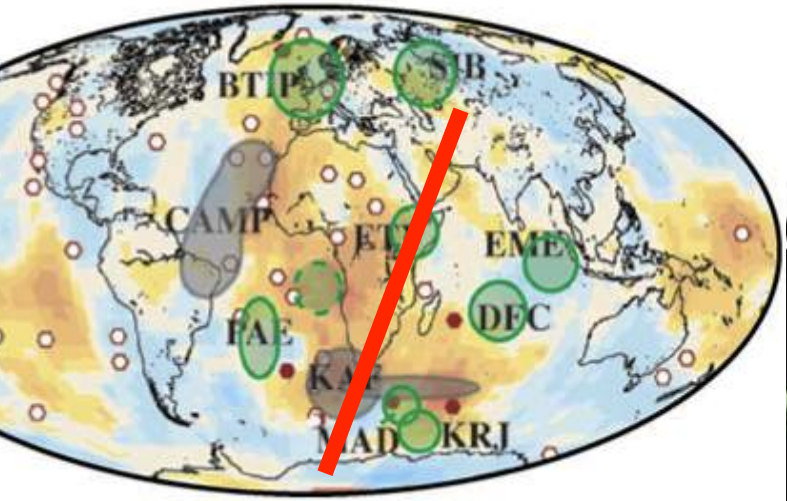

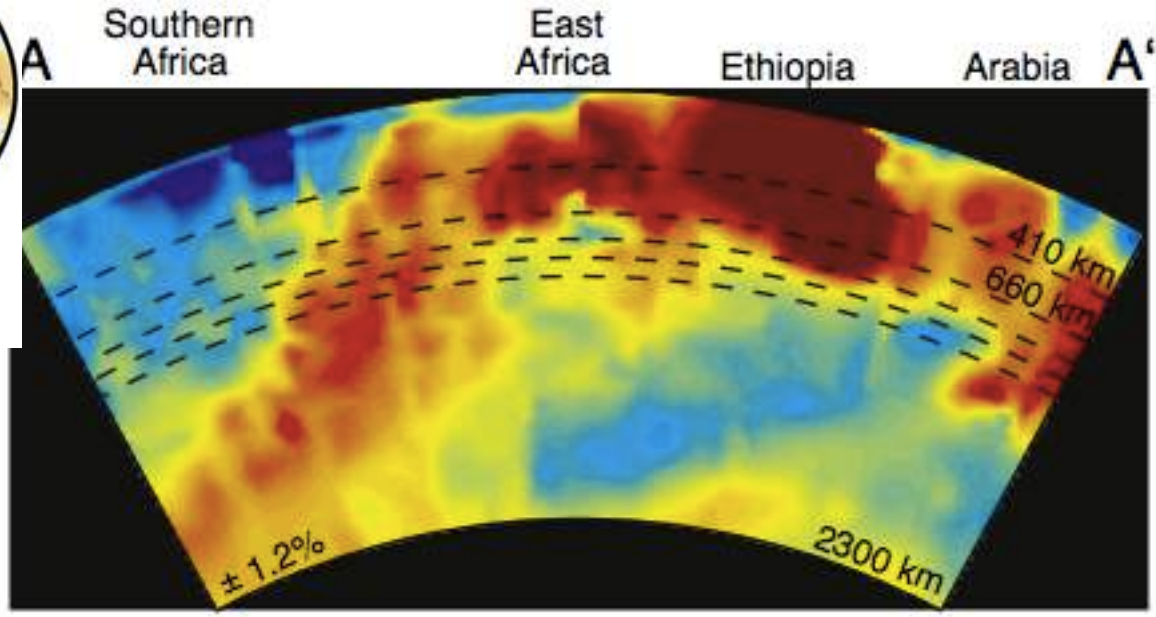

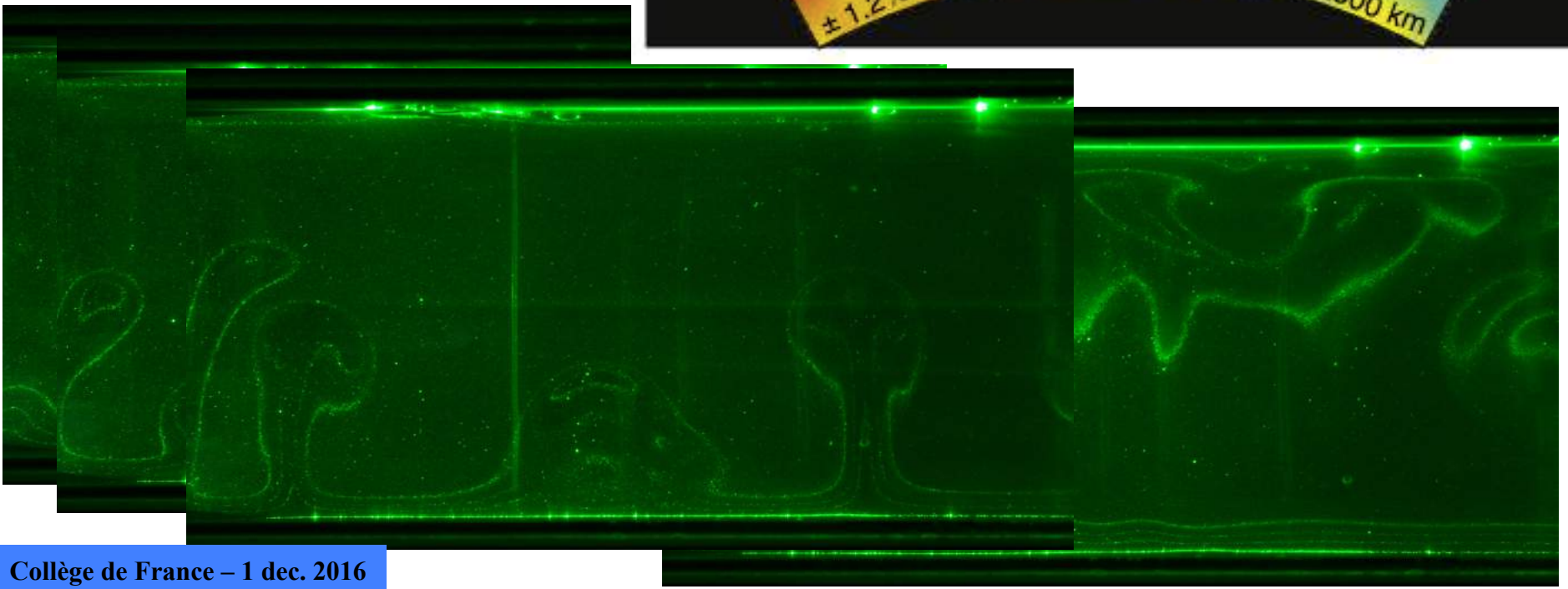

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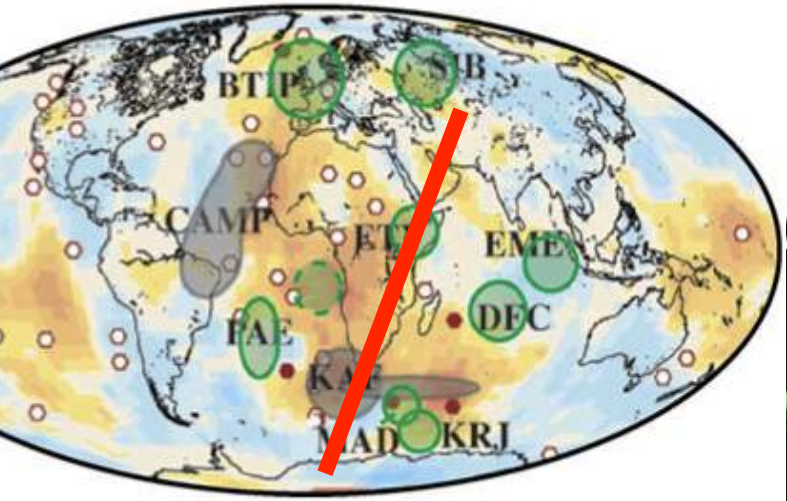

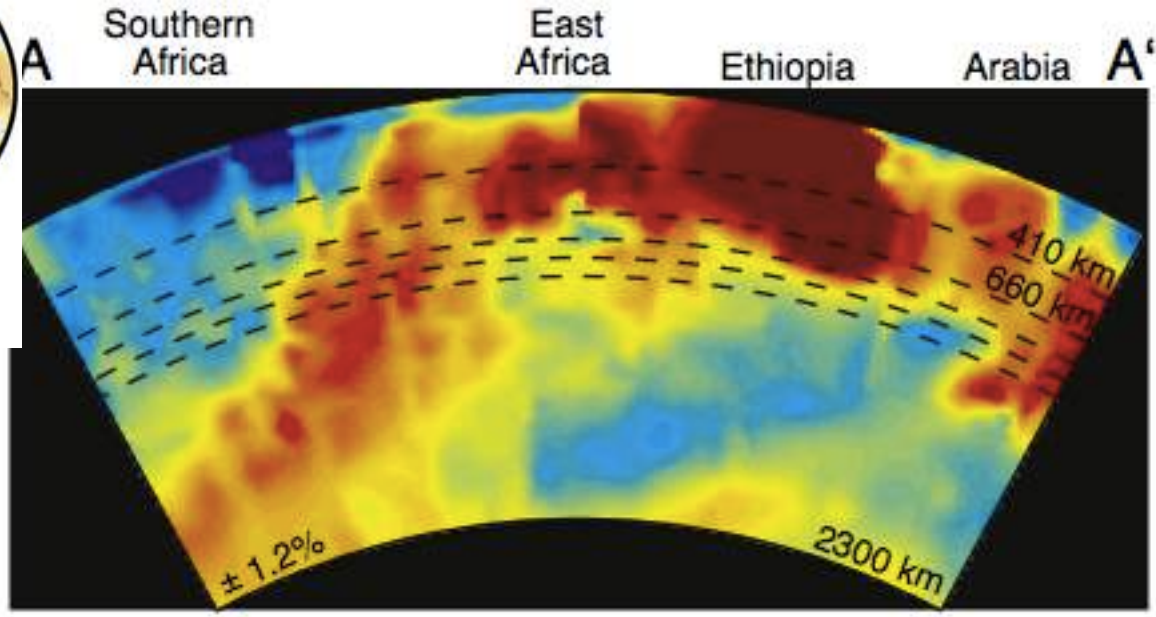

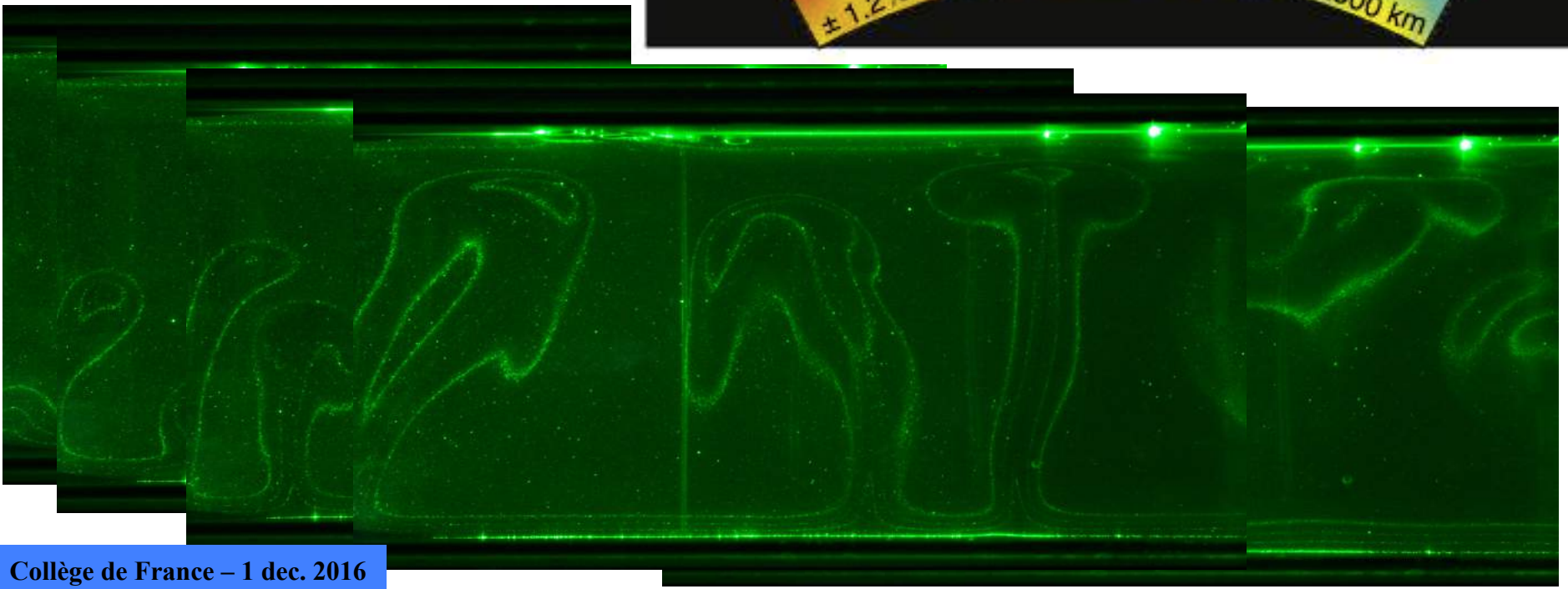

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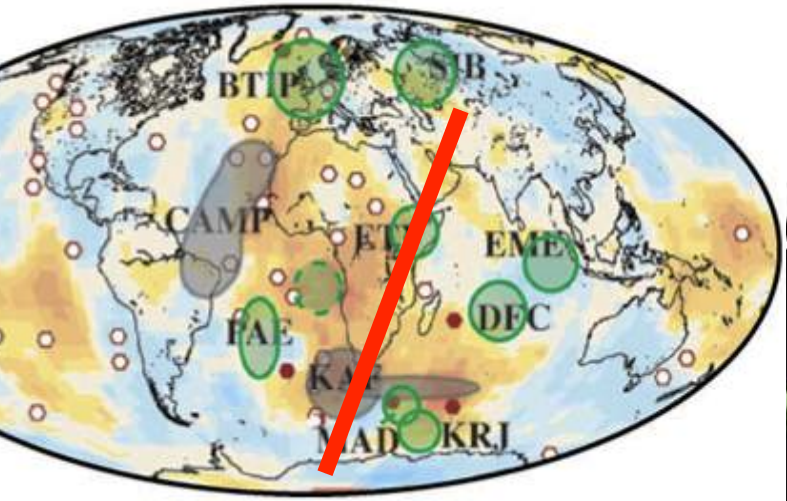
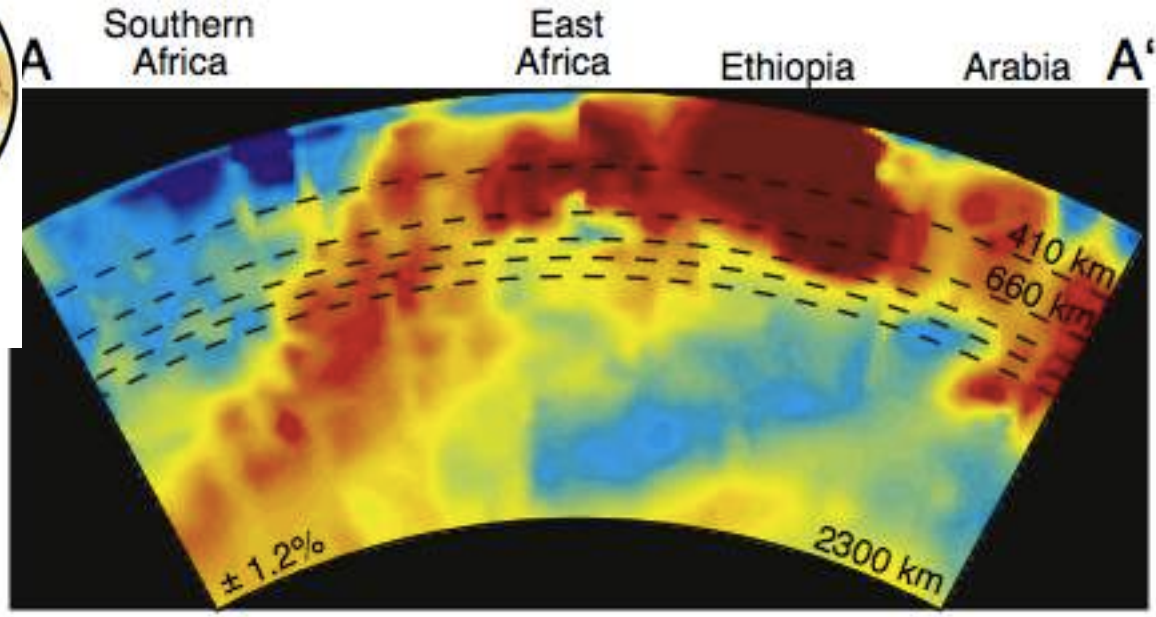
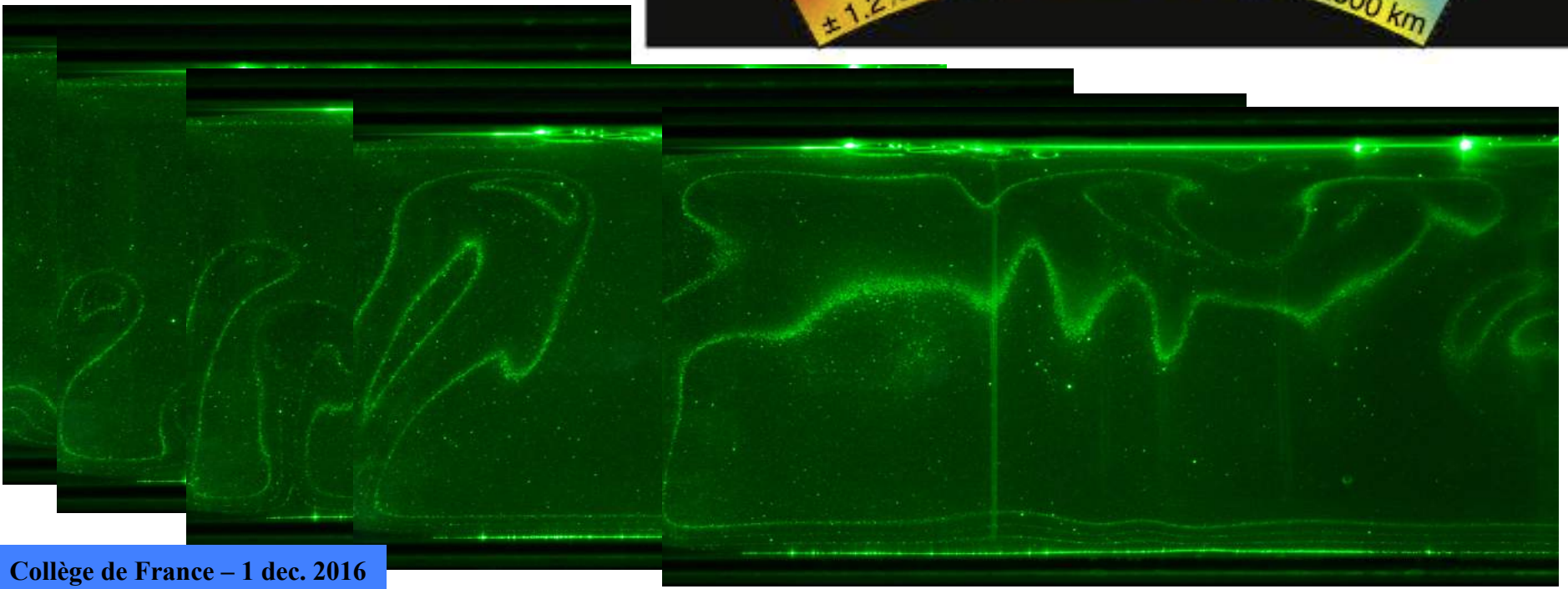


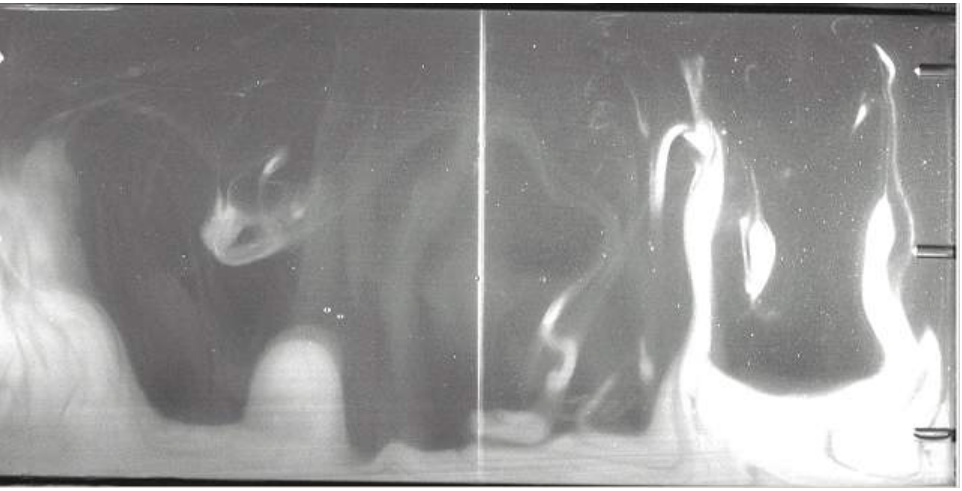




6. Time-dependence:

- Convection carries fast hot material from bottom to top

Same for thermochemical instabilities



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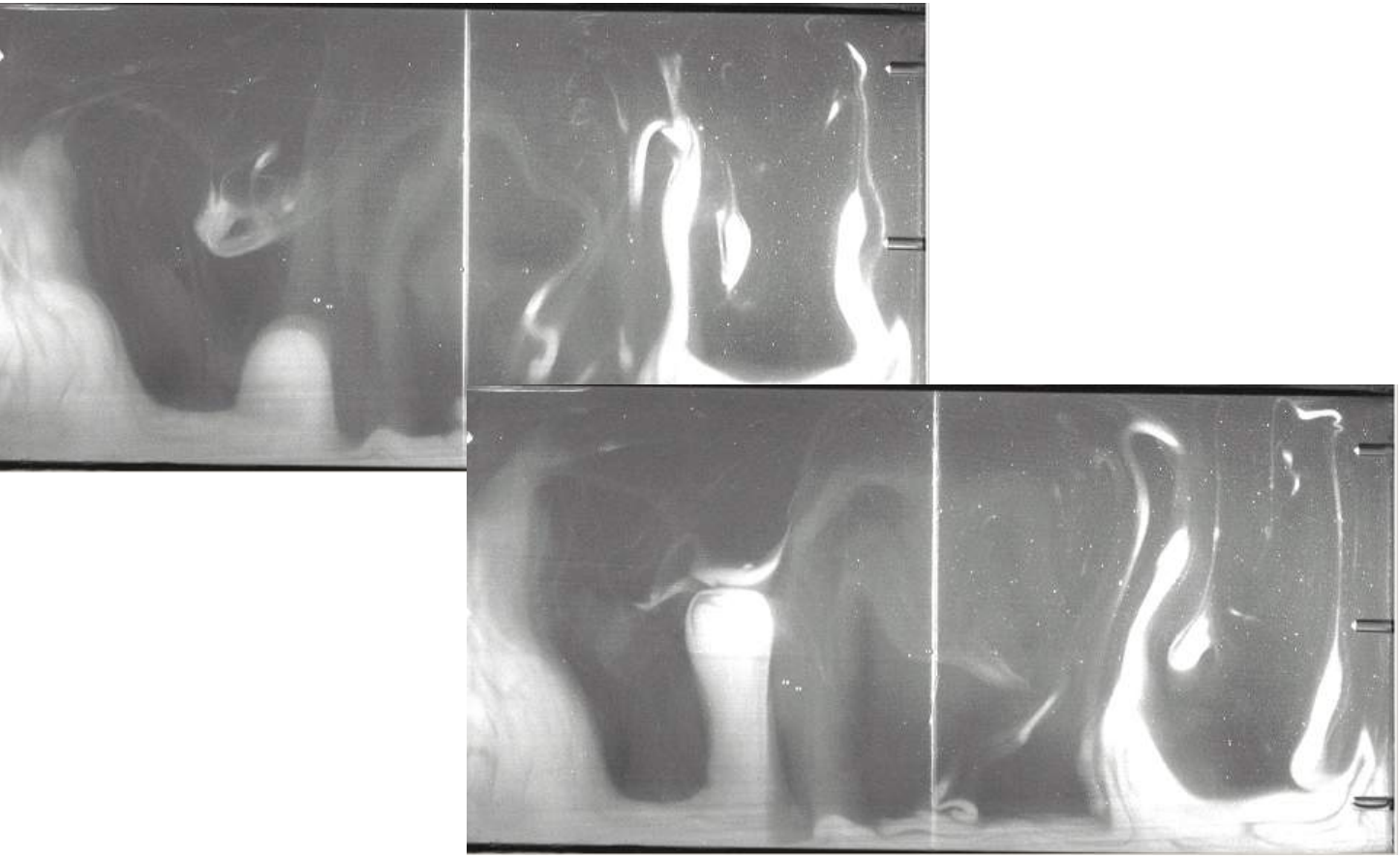

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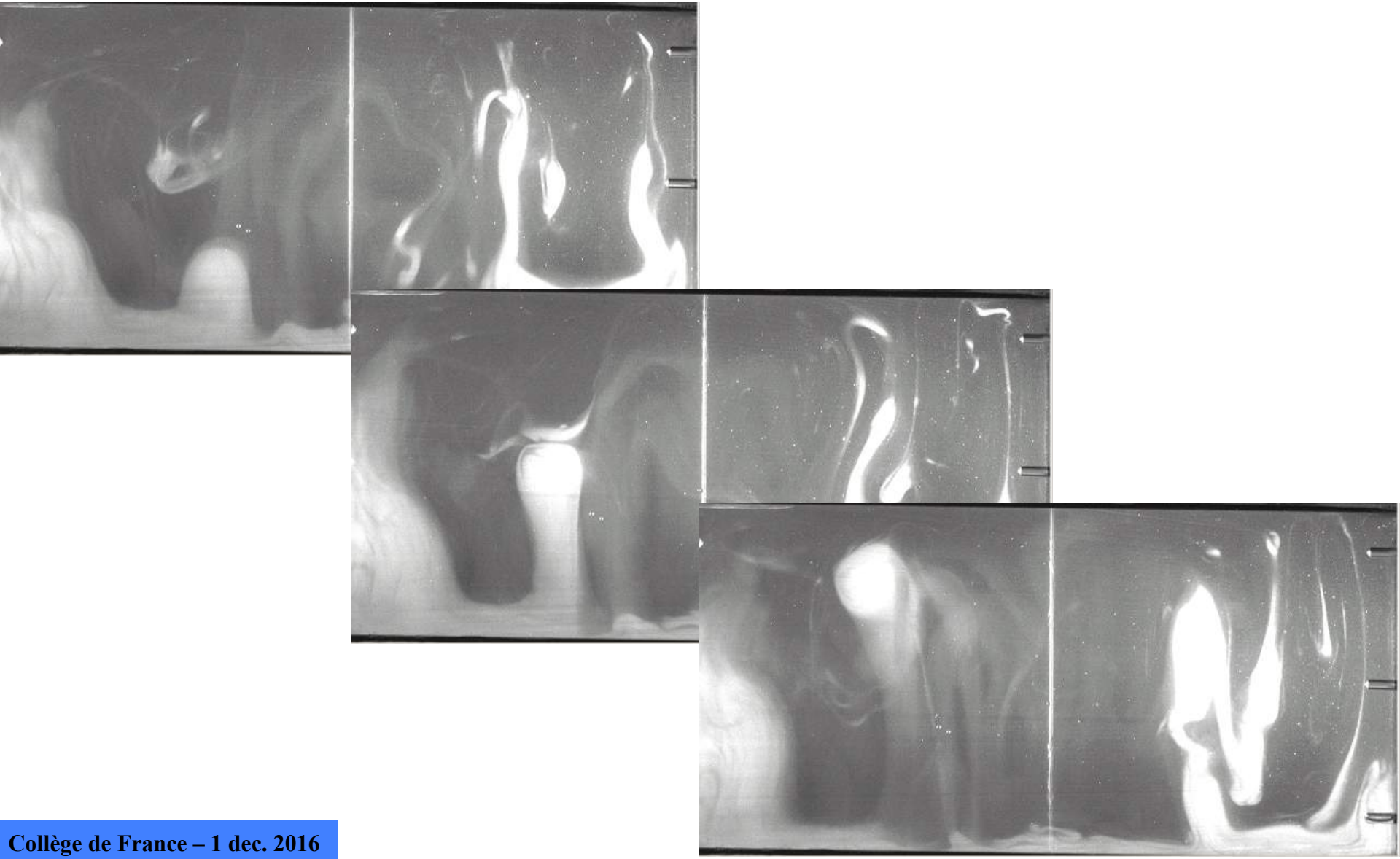

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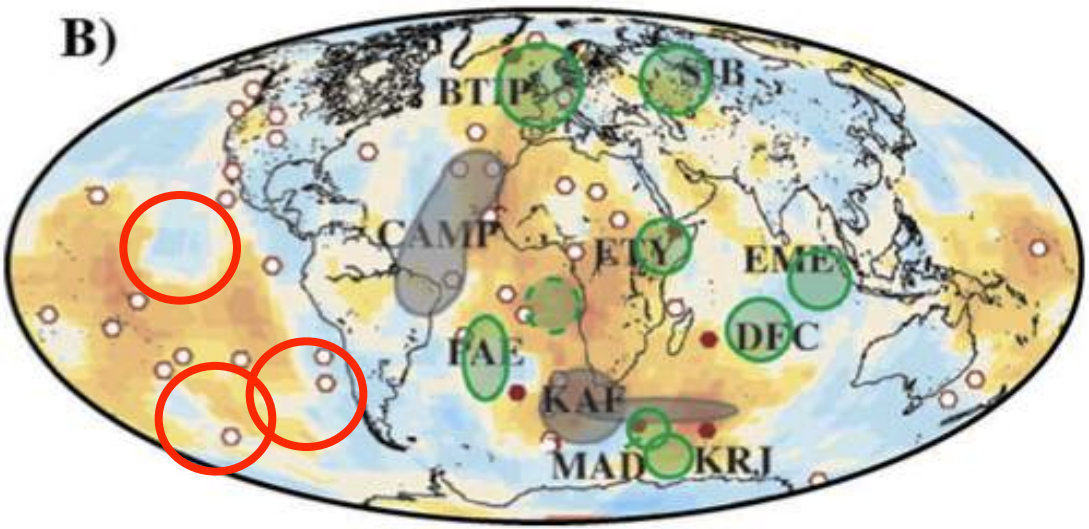
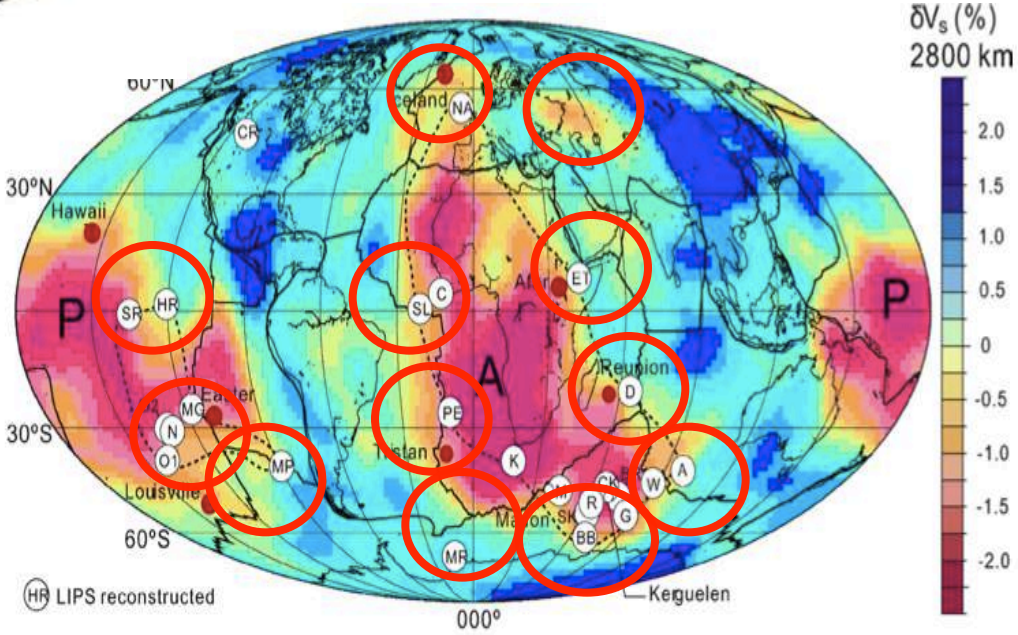
=> LLSVP area decreases at each plume head (LIP) event

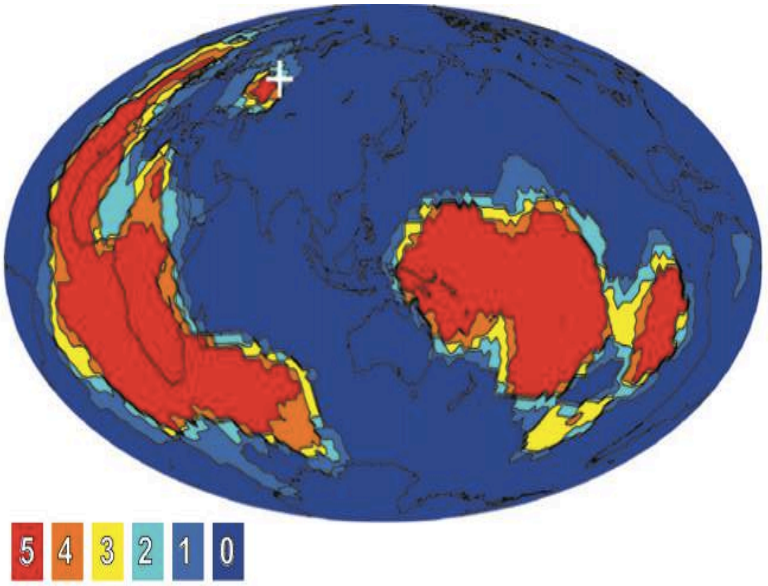
1 every ~ 30 Myr

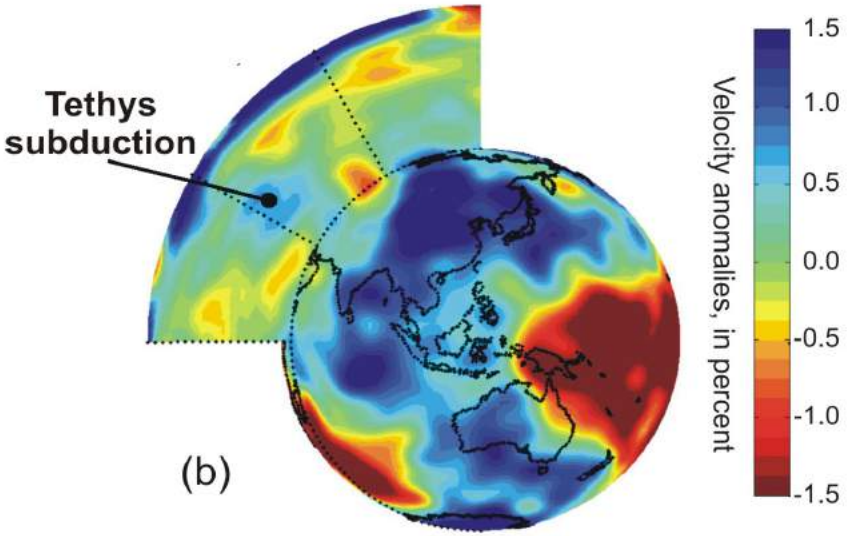


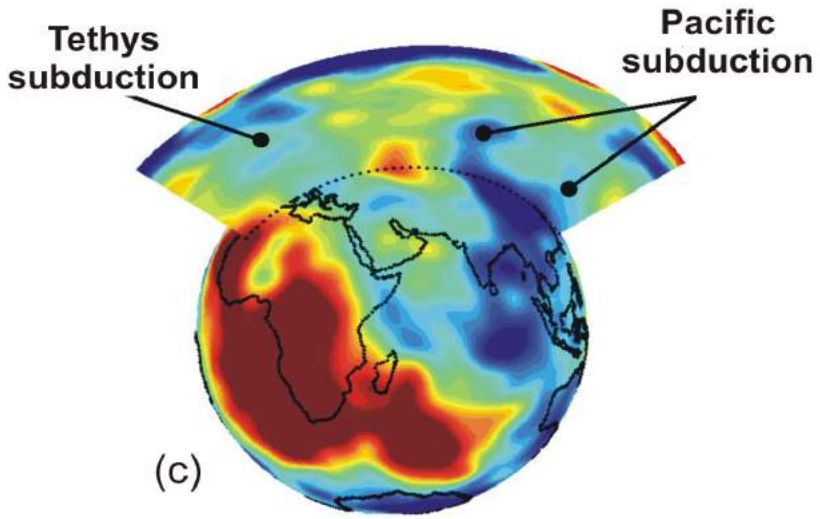


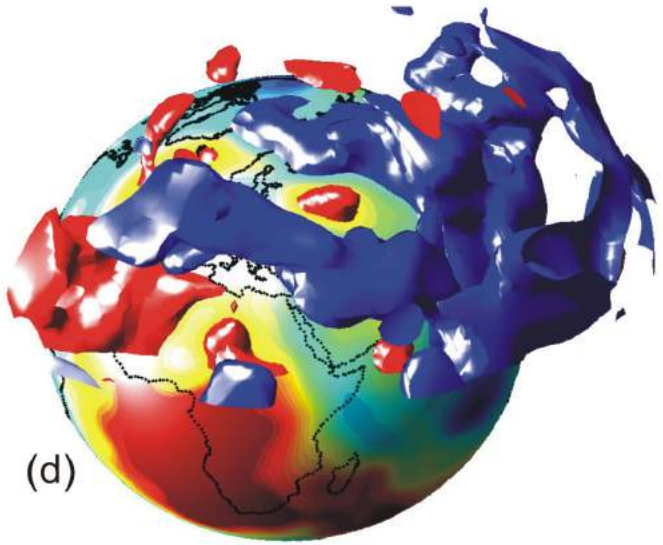
6. Time-dependence:

Existence of a THIRD mantle box ?









(A.D, A. Ismail-Zadeh, J. Besse 2013, 2016)

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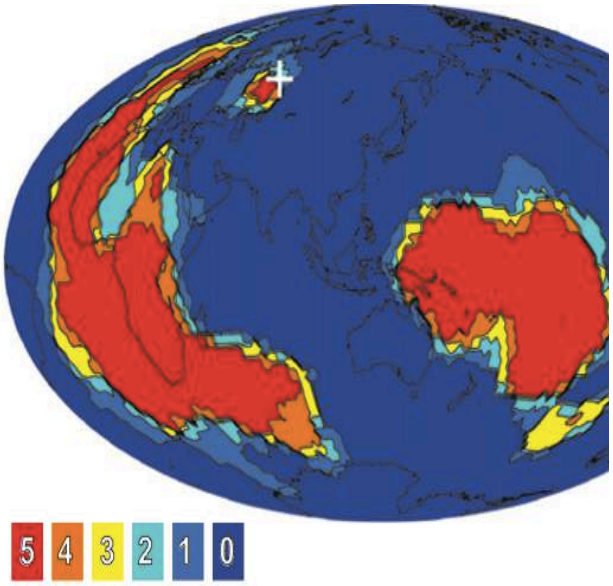
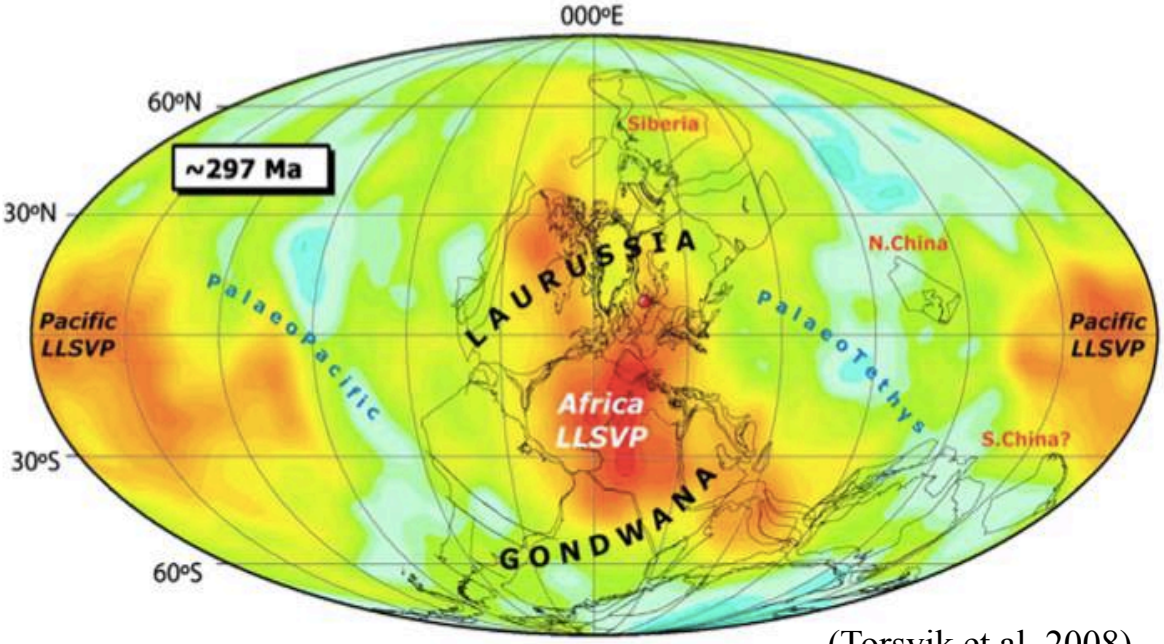
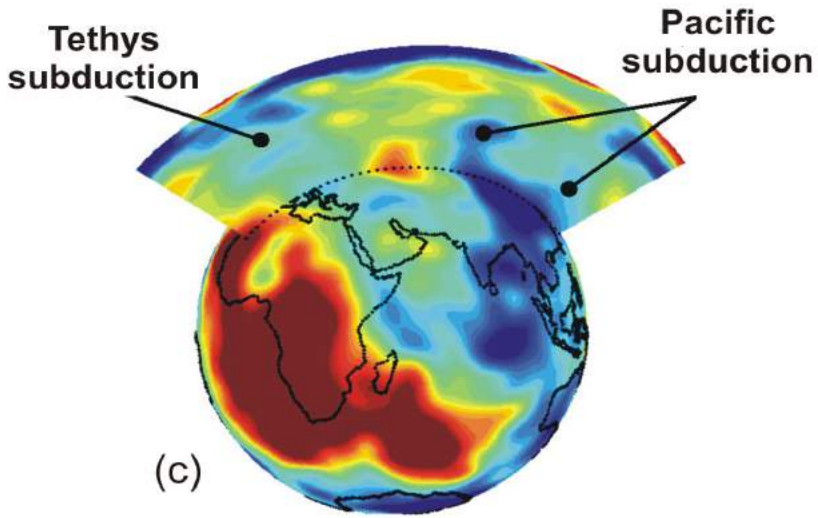
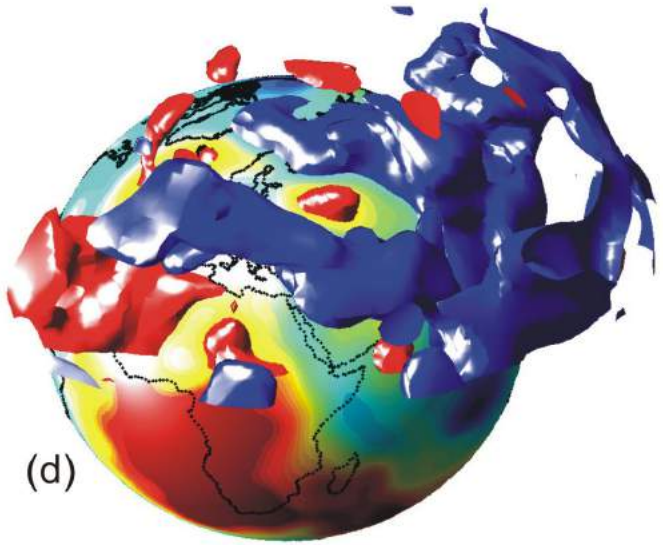




(Torsvik et al, 2008)

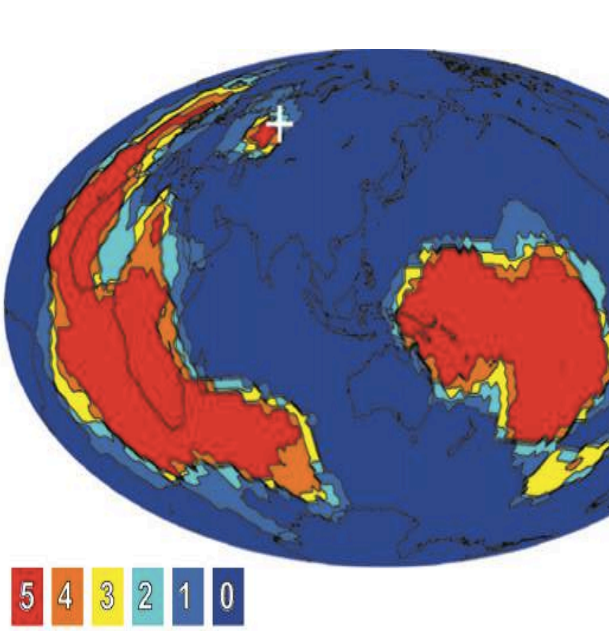


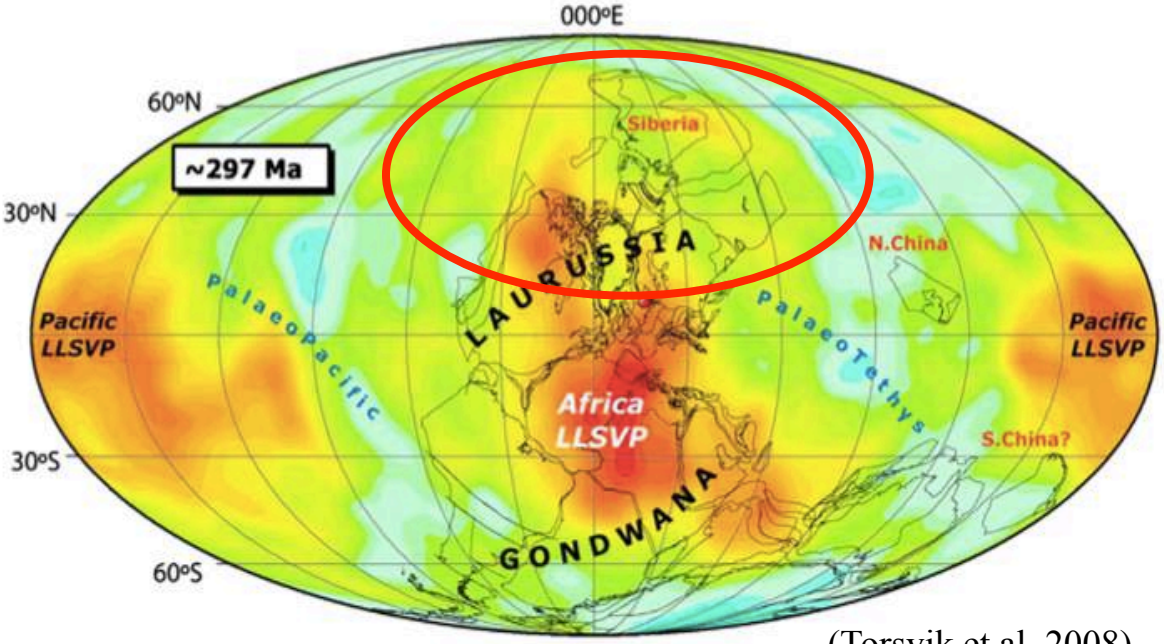


(A.D, A. Ismail-Zadeh, J. Besse 2013, 2016)

6. Time-dependence:

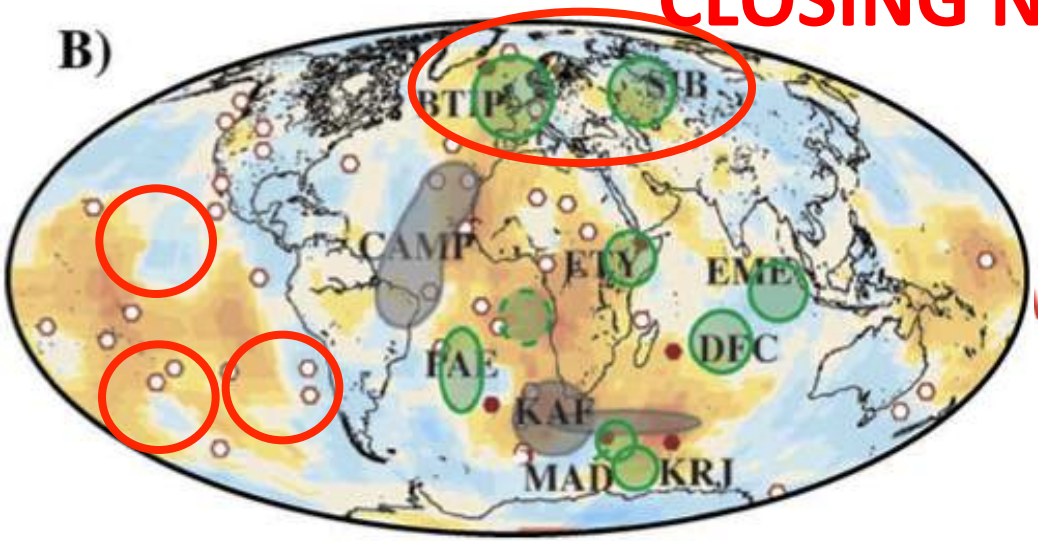
Existence of a THIRD mantle box ?





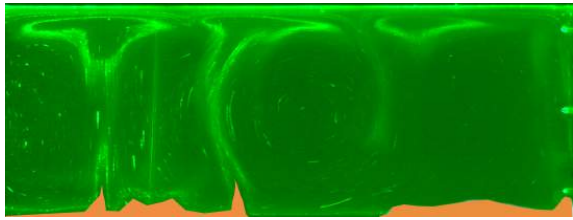
(Torsvik et al, 2008)

CLOSING NOW ?



(A.D, A. Ismail-Zadeh, J. Besse 2013, 2016)

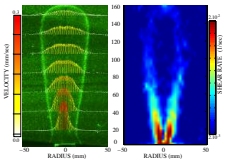
CONCLUSIONS :



A- Origin of mantle « boxes » ? **Variable viscosity / Subduction**

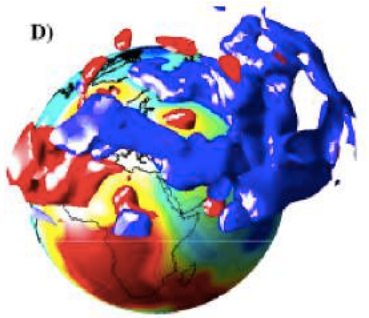
B- Upwellings **Compositional/density heterogeneities**

- **several types ?**
- **« fat » ?** **Composition / viscosity /circulation within the plume**
- **what happens around 1000 kms ?**



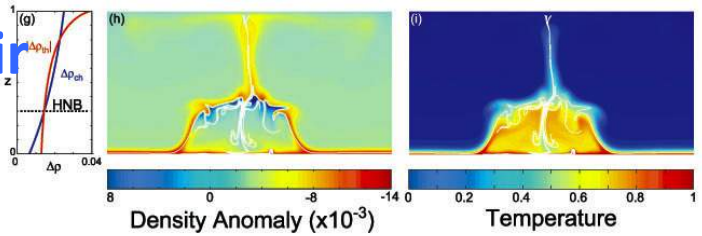
C- Do the mantle boxes / LLSVPs change shapes through time ?

- LLSVP morphology shaped by :
  . **plume head emission** (~30 Myr)
  . **subduction location** (~ 100Myr - 1 Gyr)
  . **heating up of old subducted material** (~ Gyr)
- LLSVP = old material but CHANGING morphology
- 3rd box around Siberian Trap => closing ?



THANK YOU !

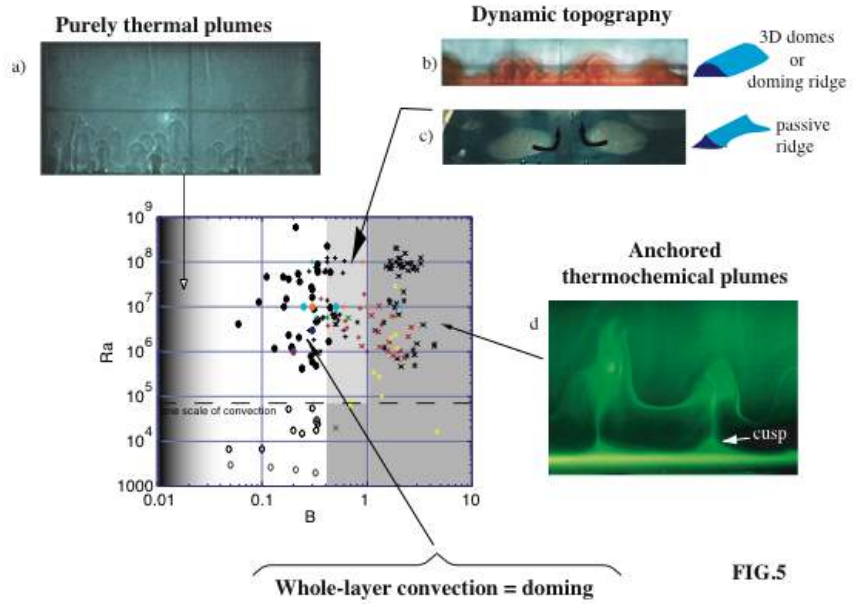
4. Interaction Convection / Denser Reservoir

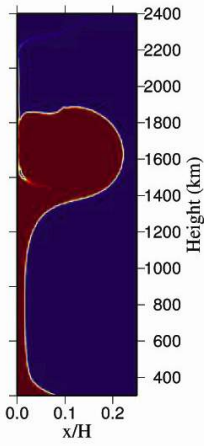


Stability:

- Ra= $\dfrac{\qquad\qquad}{\qquad\qquad}$

- B = $\dfrac{\Delta\rho_\chi/\rho}{\alpha\Delta T}$

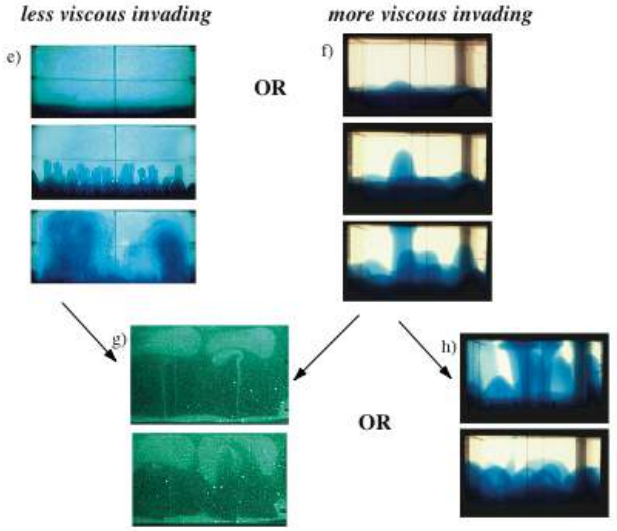




Tan & Gurnis, 2005;
Samuel & Bercovici, 2006

Morphology:

- $\gamma = \eta_1/\eta_2$
- $a = d_1/d_2$



Richter & McKenzie, 1981;
Olson, 1984;
Schmeling, 1988;
Olson & Kincaid, 1991;
Tackley, 1998; 2002;
Davaille, 1999; Davaille & al, 2002;
Kellogg & al, 1999;
Montague & Kellogg, 2000;
Hansen & Yuen, 2000;
Le Bars & Davaille, 2002, 2004;
Jellinek & Manga, 2002, 2004;
Samuel & Farnetani, 2002, 2005;
McNamara & Zhong, 2004, 2005
Lin & Van Keken, 2005