Structure of Mantle Convection: Plumes and Plates

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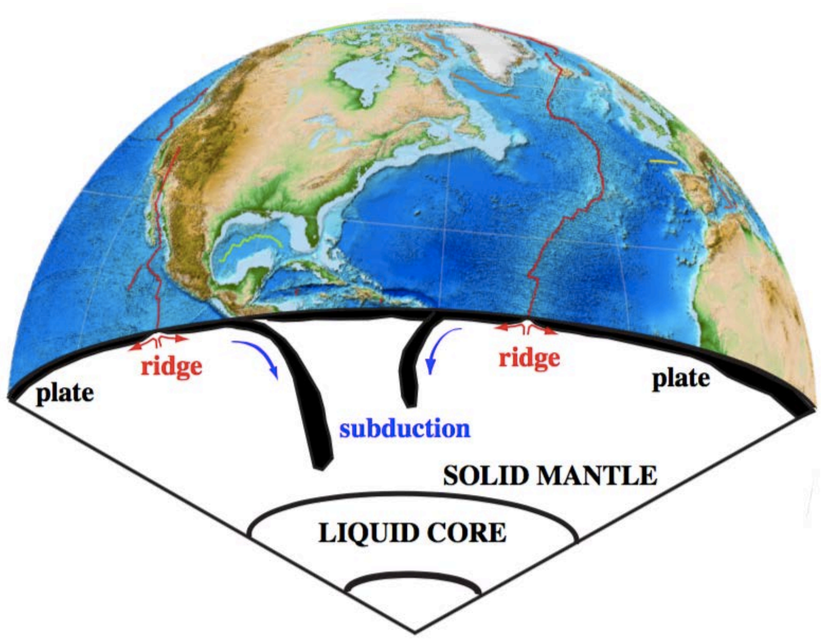
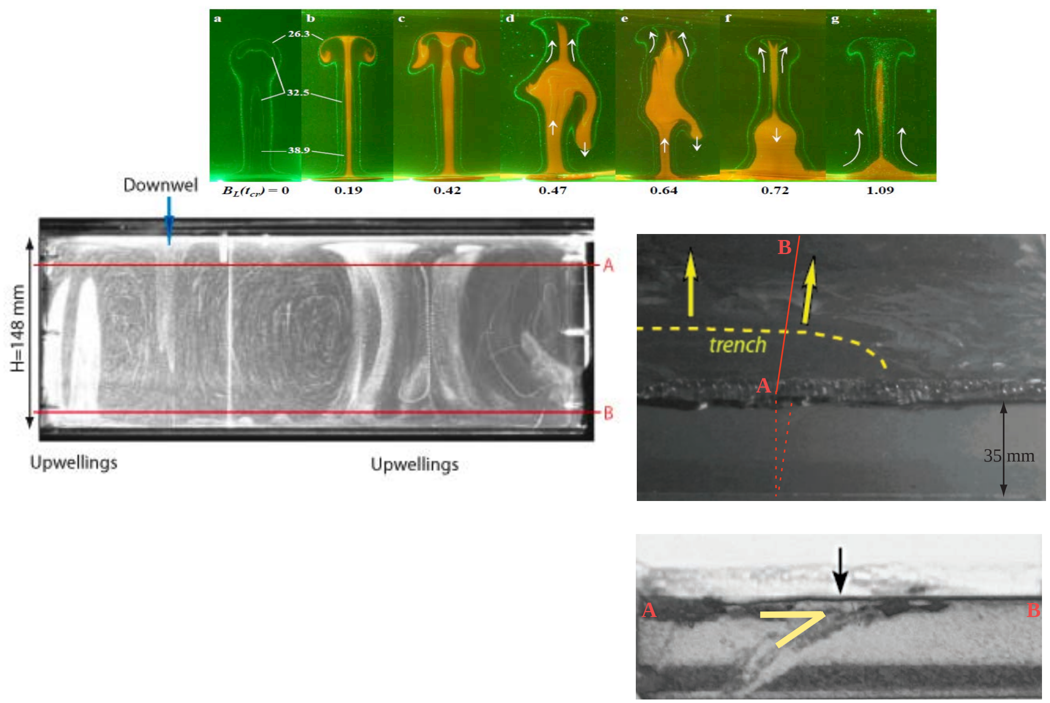
Erika Di Giuseppe, Eric Mittelstaedt, Aurore Sibrant (FAST)
,Ichiro Kumagai, Kei Kurita (ERI, Tokyo), Sue Smrekar (JPL, USA), Nick Arndt (ISTerre, Gernoble)

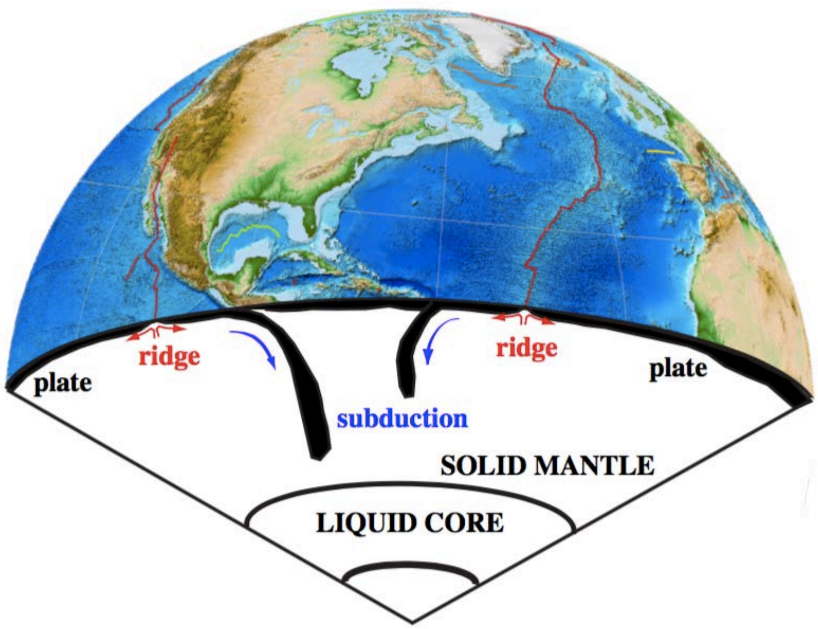




The view of a physicist …

= provide a framework to predict and to interpret the observations

Evolution of a planet = cooling ⇔ Thermal convection

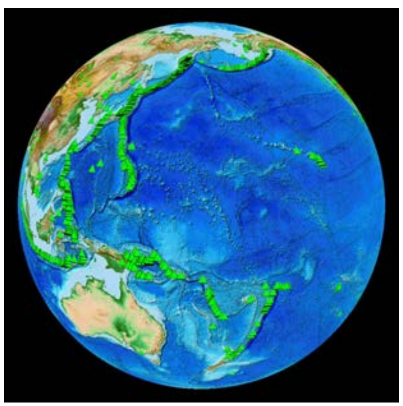


1-What are the conditions for thermal convection to produce plate tectonics ?

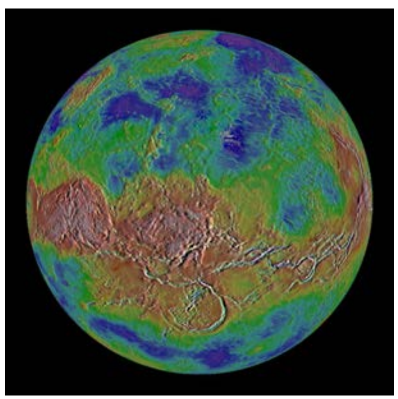
2- Structure of convection

3-Evolution of a planet?

4- What type of planet ? Exoplanet ?



Continuous Resurfacing

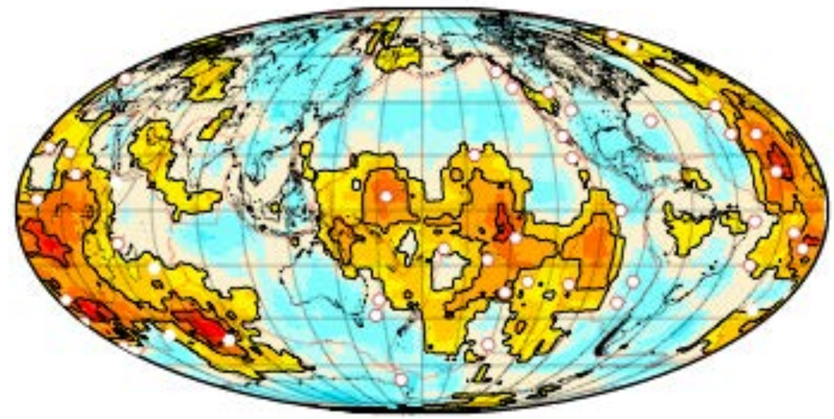


Episodic Resurfacing

No Resurfacing

2- Observations :

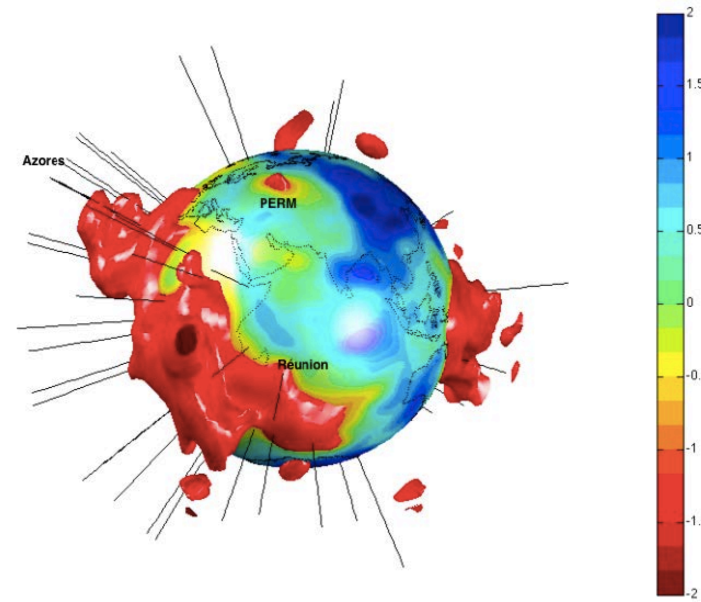
TXBW (Grand, 1997)



A- Seismic Tomography:

- Ridges are shallow features
- Blue (COLD) tracable at all depth

☞ Delimit 2 main « boxes »
and 2 LLSVPs
(Large Low S-Velocity Provinces)



SMEAN (Boschi & Becker, 2002)

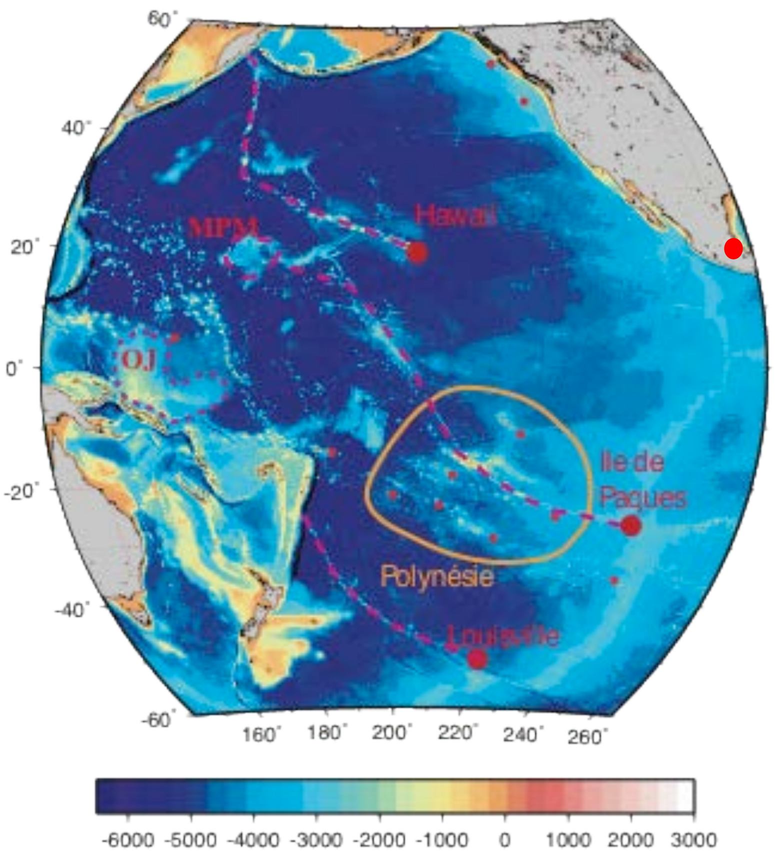
B- Geochemistry:

-MORB ≠ OIB
-Existence of long-lived reservoirs
primitive material
recycled crust
=> density heterogeneities

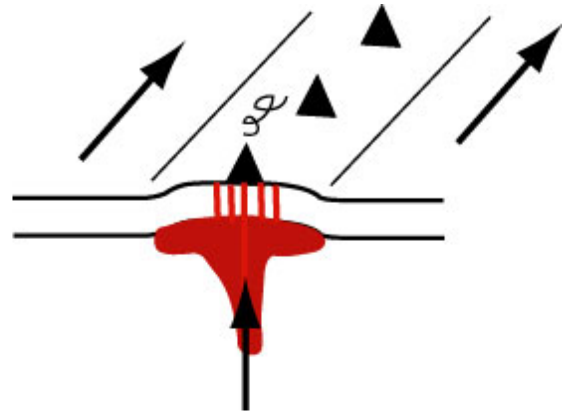
2- Observations :

C- the « Hot spots » Zoo:

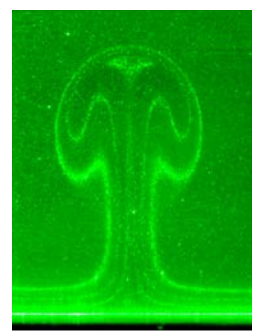
(Wilson 1963; Morgan 1971, 1972)

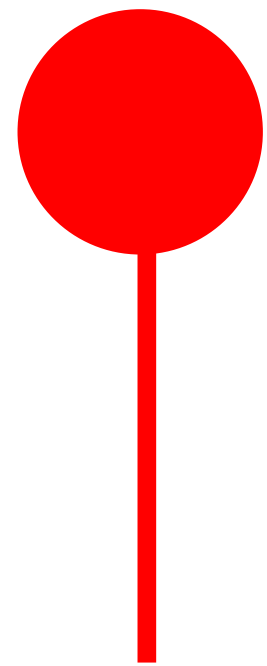


(Clouard & Bonneville 2000)



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





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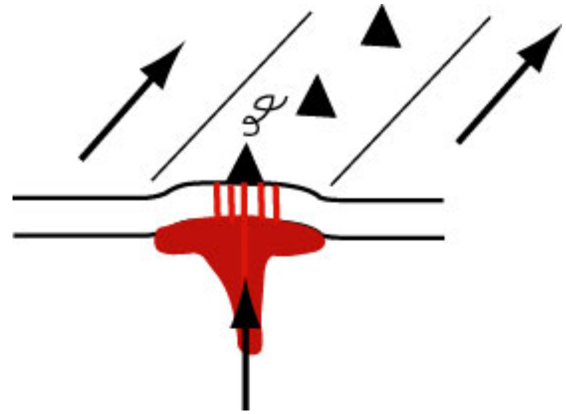
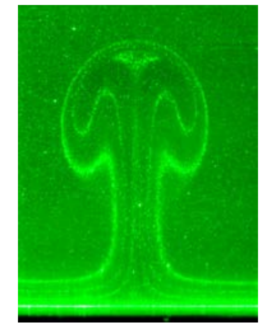
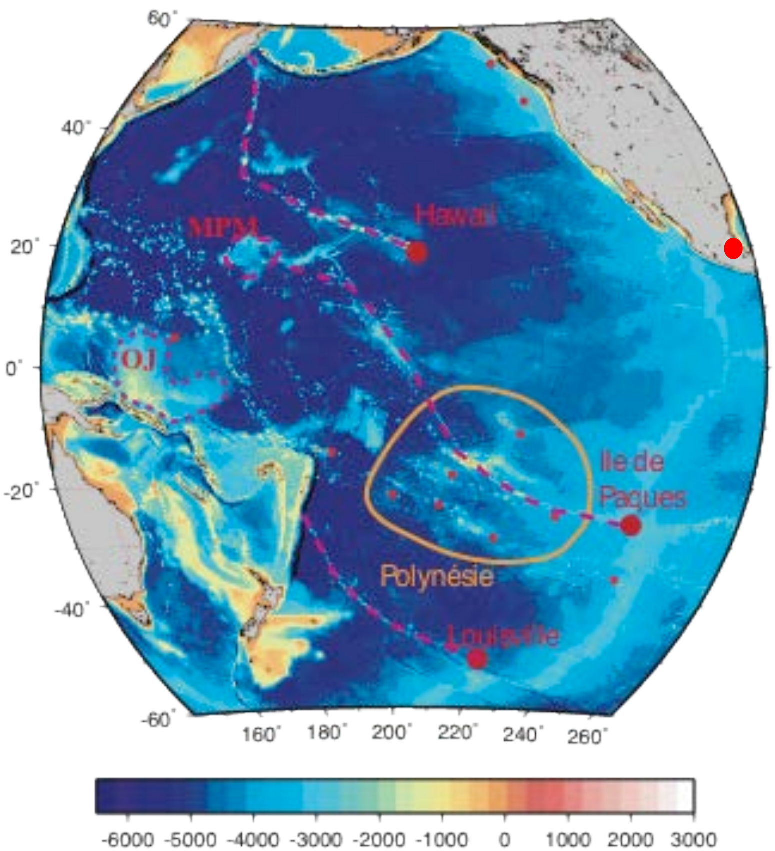
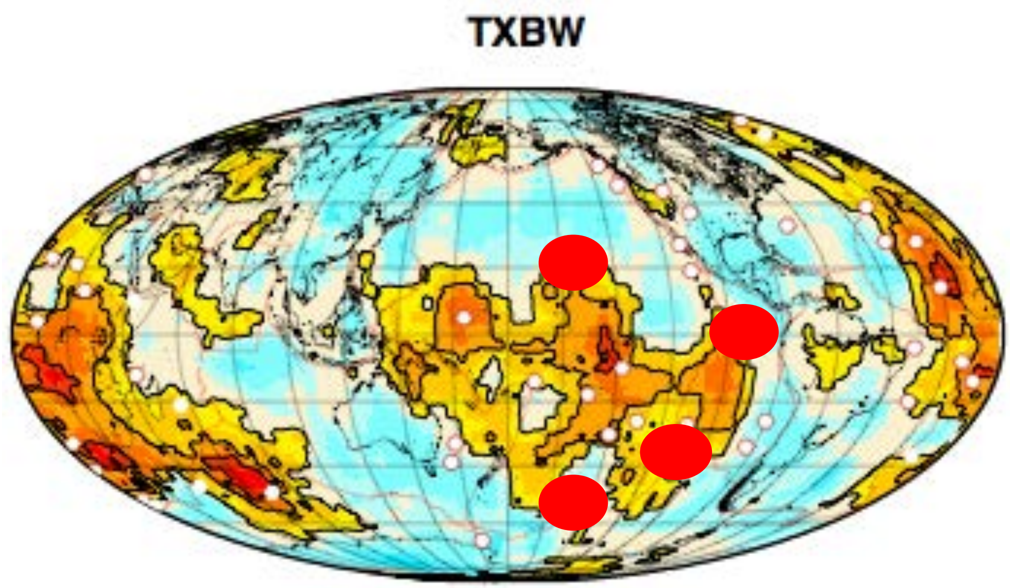




- -Volcanism fixed / moving plate
- -can start by an oceanic plateau
- -Long tracks on the edges of slow anomaly



(Clouard & Bonneville 2000)



2- Observations :

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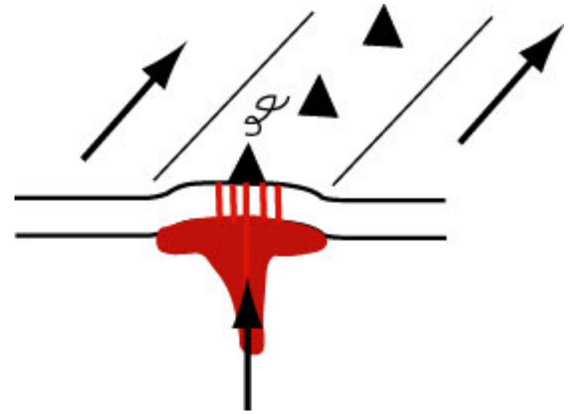
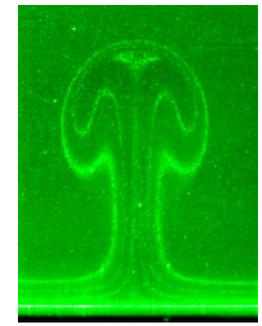
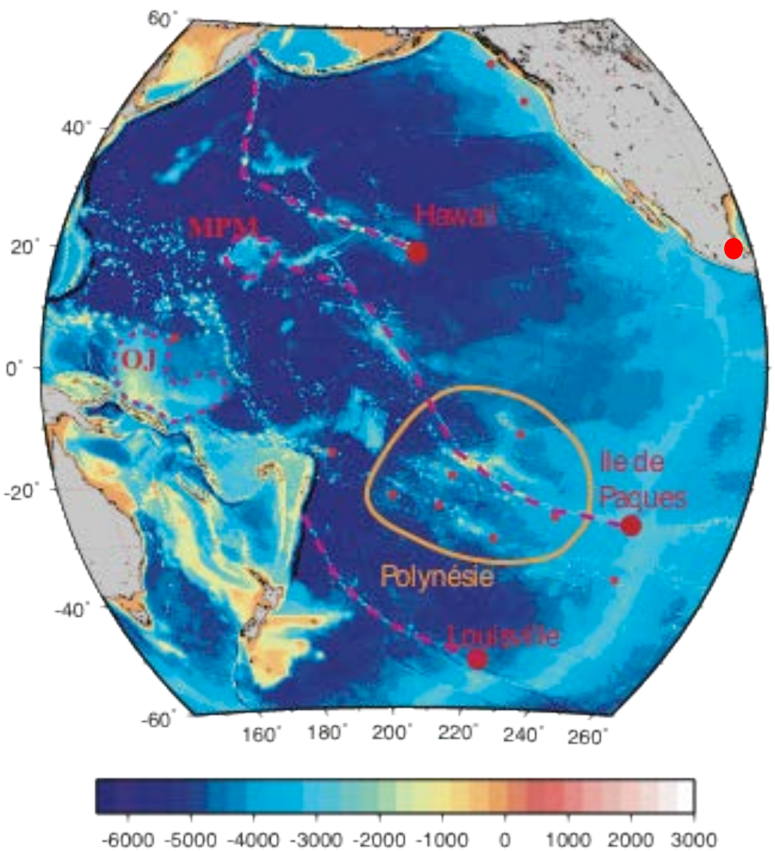




- -Volcanism fixed / moving plate
- -can start by an oceanic plateau
- -Long tracks/LIPs on the edges of slow anomaly



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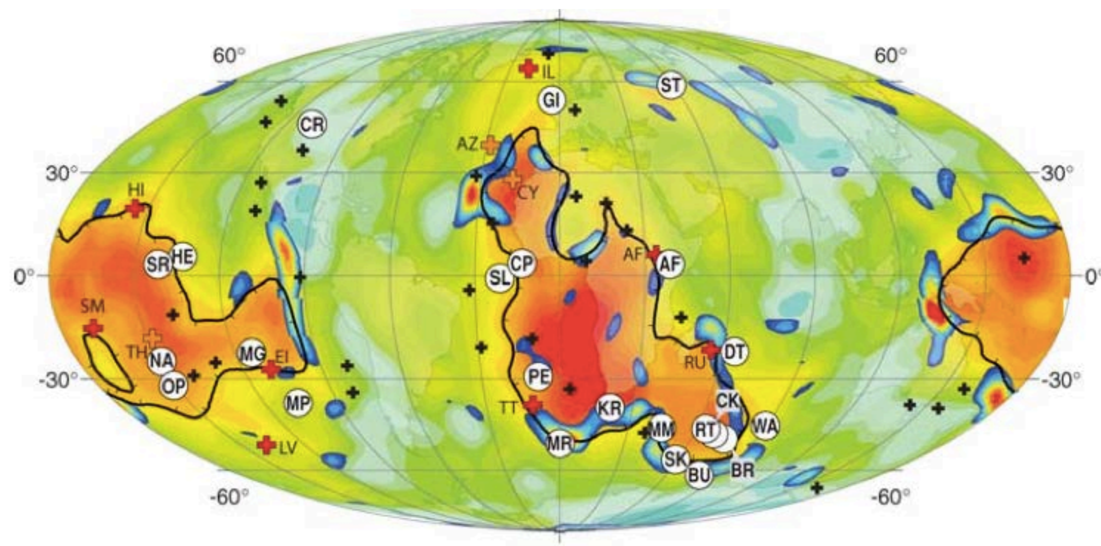


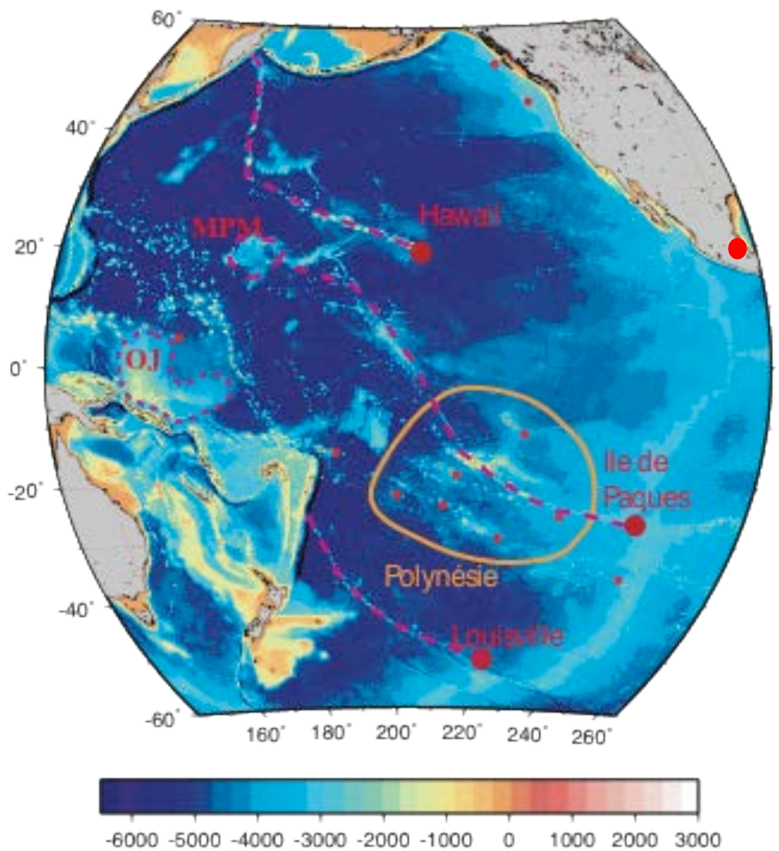
(Torsvik et al, 2004)

2- Observations :

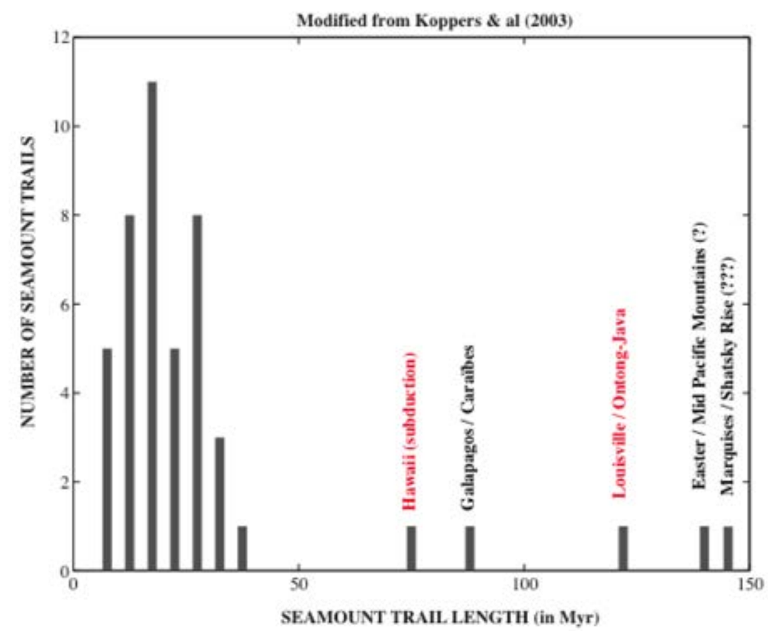
C- the « Hot spots » zoo:

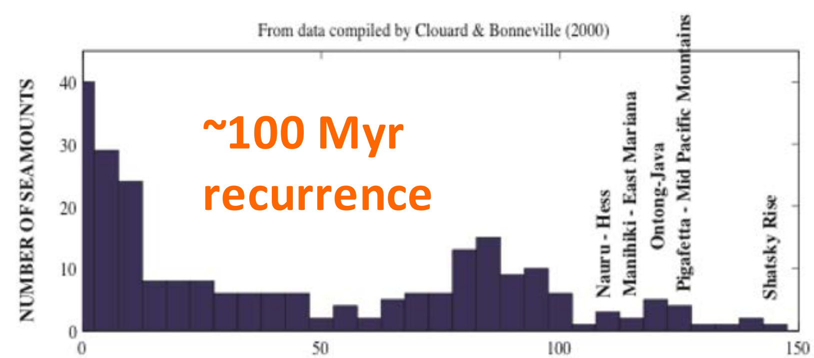
(Wilson 1963; Morgan 1971, 1972)

+ another type
= shorter tracks in « cluster »

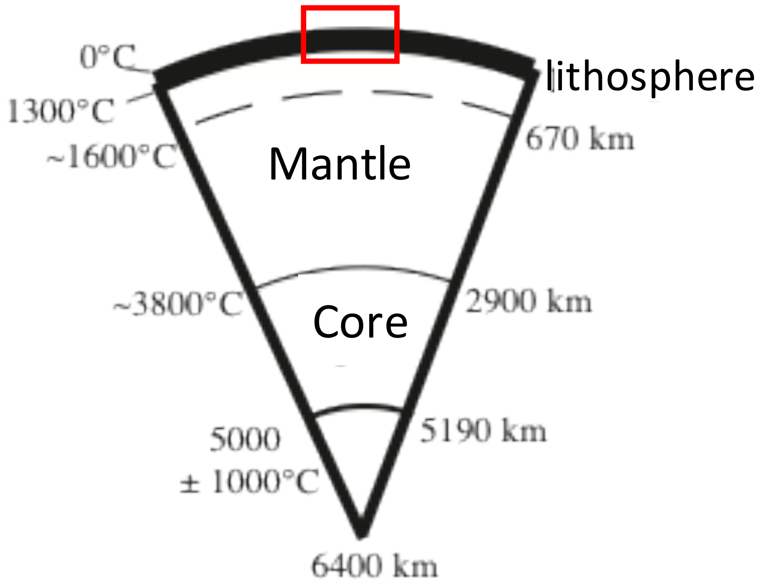


(Clouard & Bonneville 2000)





3-Thermal convection:



+ Boundary conditions= fixed temperatures
T~0°C at surface
T~3500°C at CMB

+ Free surfaces

+ **Rheology** : in cold Thermal Boundary Layer
depends on Tp, P, stress, composition

Evolution of a planet = cooling ⇔ Thermal convection

. Pr = [illegible]

. Ra = [illegible].g.[illegible]T.d^3 / ([illegible])

Continuity: $\vec{\nabla}\vec{u}=0$

Momentum conservation:

$$\frac{1}{Pr}\left(\frac{d\vec{u}}{dt}+(\vec{u}.\vec{\nabla})\vec{u}\right)=-\vec{\nabla}P+\vec{\nabla}.\left(\eta(\vec{\nabla}\vec{u}+\vec{\nabla}\vec{u}^{t})\right)-Ra\,T\,\vec{n}$$

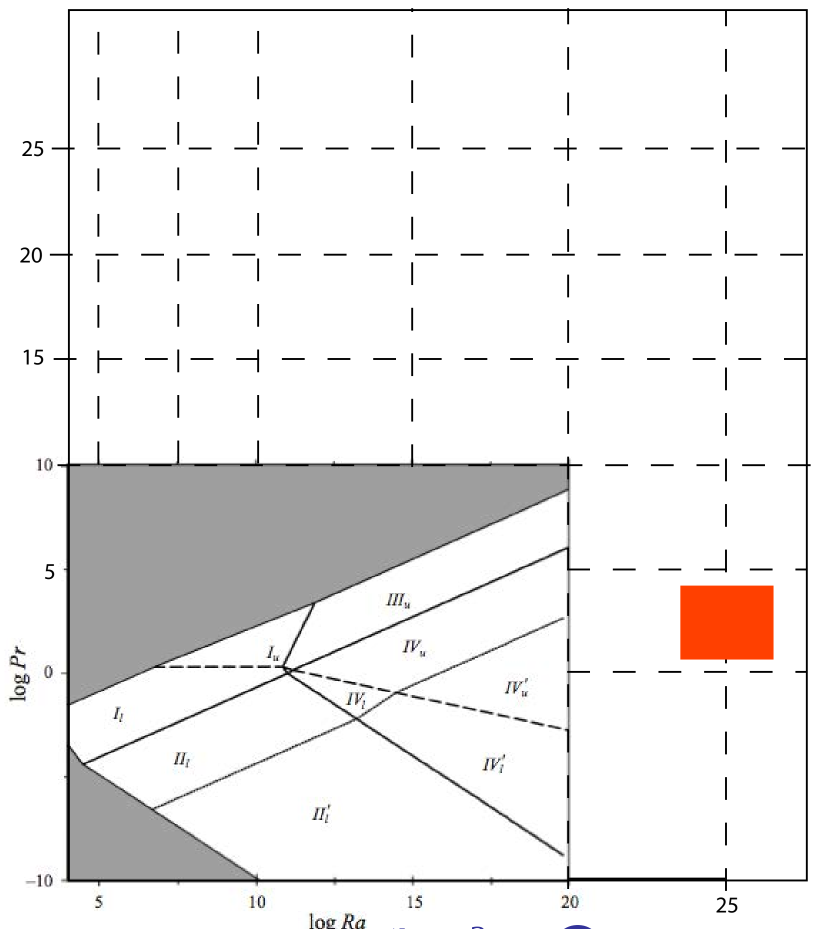
Heat conservation:

$$\frac{dT}{dt}+\vec{u}.\vec{\nabla}T=\vec{\nabla}.(k.\vec{\nabla}T)$$

*

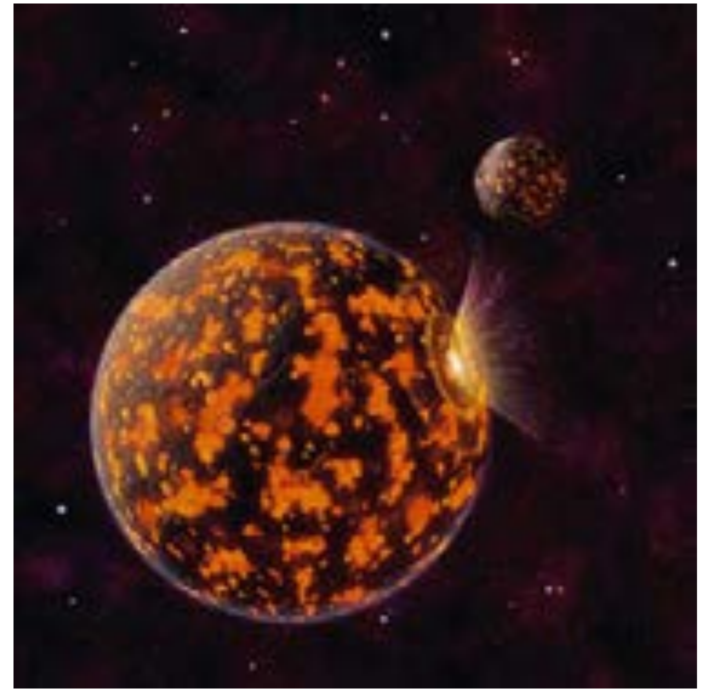
3-Thermal convection:

(Grossman & Lohse, 2010)



Pr = ν/κ

Ra = $\alpha g \Delta T h^3/\kappa\nu$



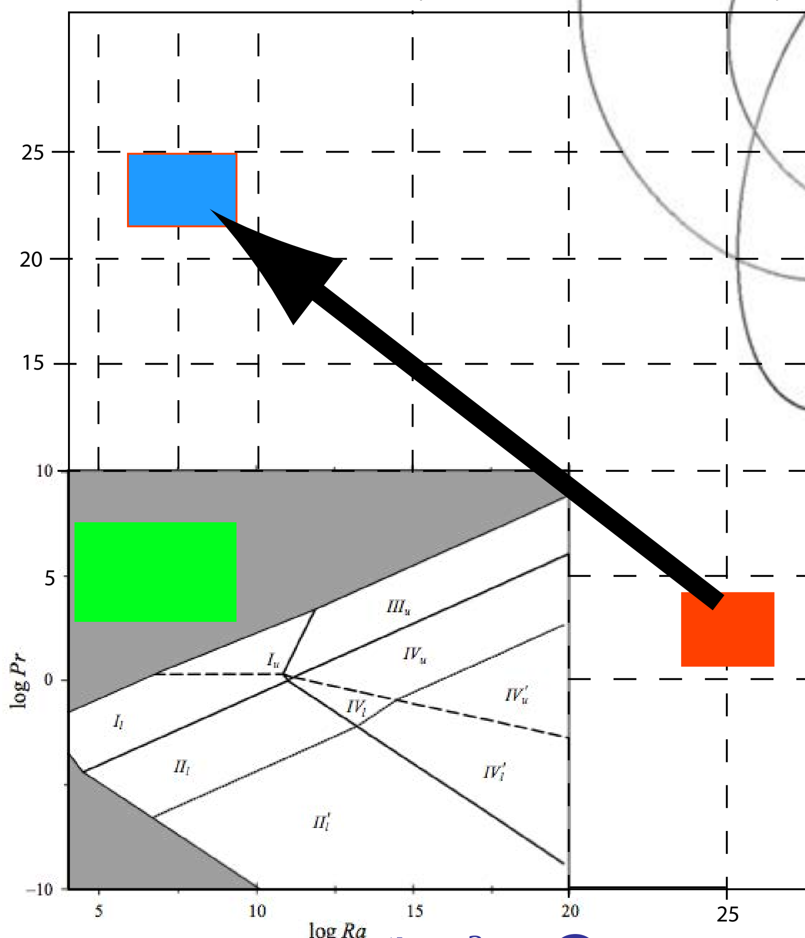
Primitive Earth (4.5 Gyr ago):

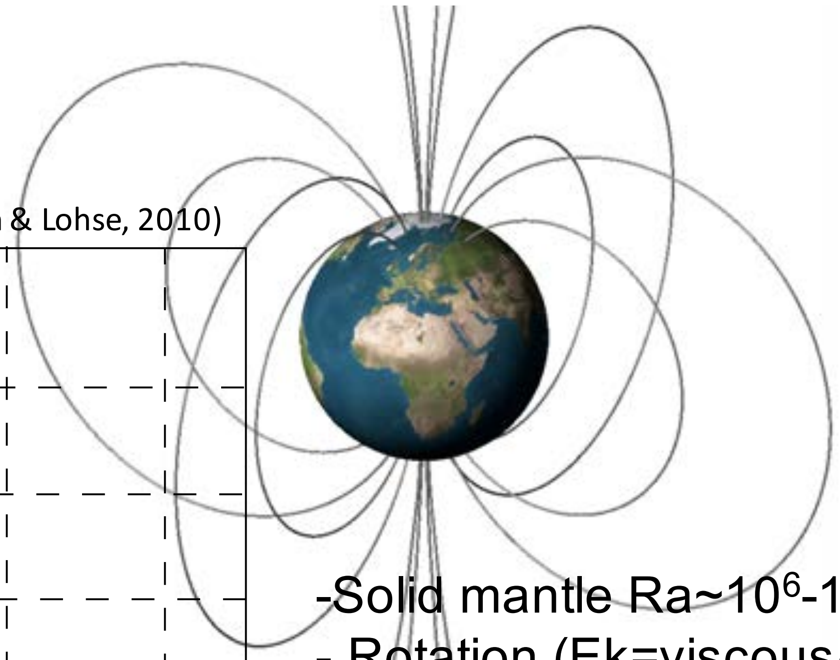
- Magma Ocean Ra~10^{25}
- Rotation (Ek=viscous/Coriolis)

  Ek~10^{-13}-10^{-14}

3-Thermal convection:

(Grossman & Lohse, 2010)





TODAY

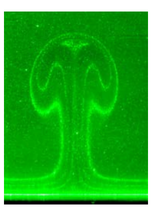
-Solid mantle Ra~10^6-10^9

- Rotation (Ek=viscous/Coriolis)

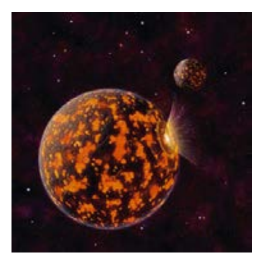
Ek ~ 10^{10}

$Pr = \nu/\kappa$

LAB



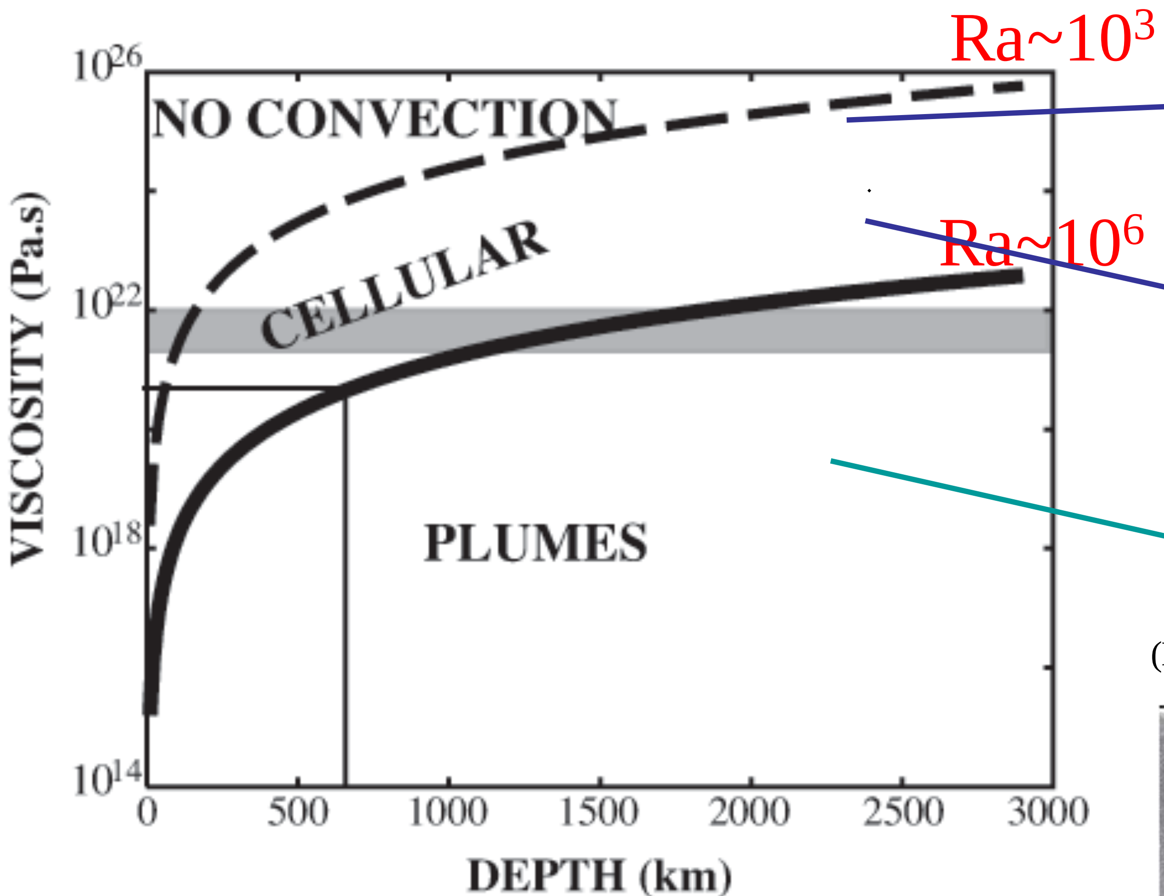
$Ra = \alpha g \Delta T h^3/\kappa\nu$

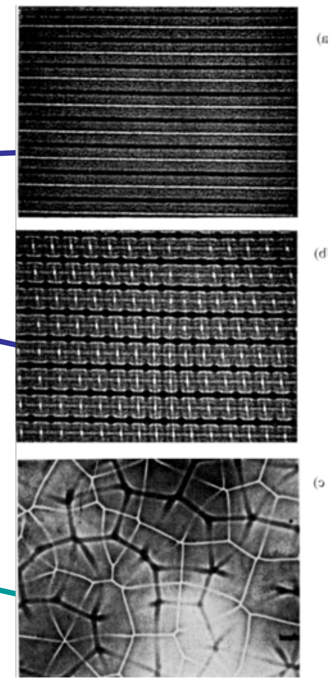


4.5 Gyr ago

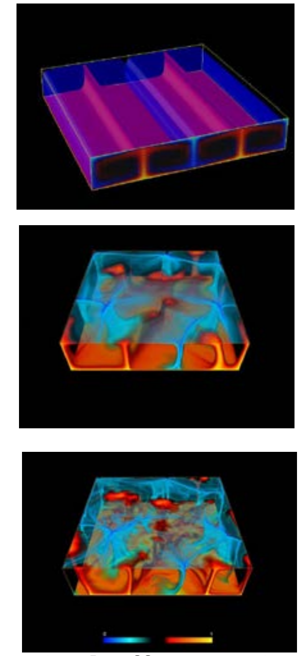
3.B. Convection with nearly constant viscosity

$$Ra = \frac{\alpha . g . \Delta T . h^3}{\kappa . \eta / \rho}$$

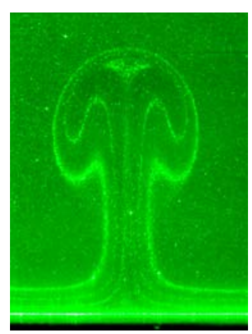


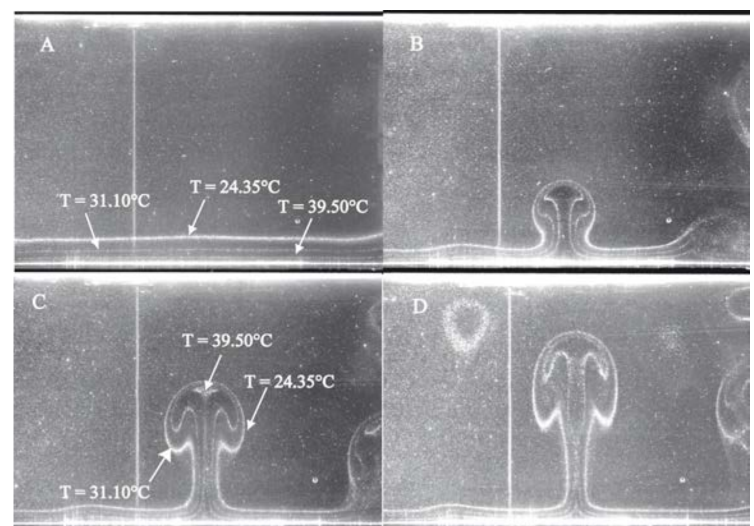


(Busse & Whitehead, 1971)



(Dubuffet, 2008)

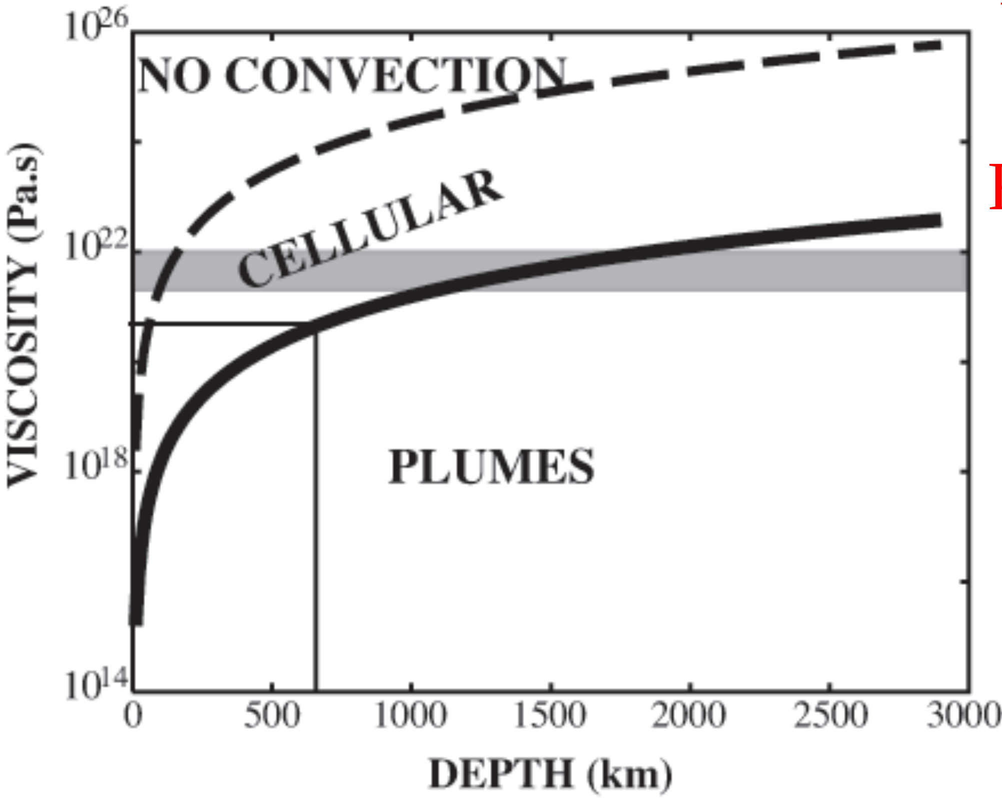


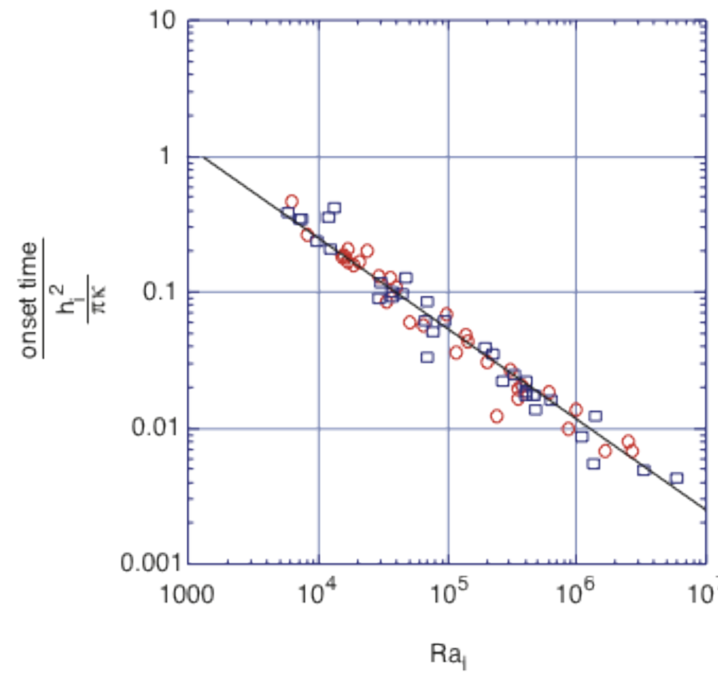


3.B. Convection with nearly constant viscosity

Ra~10^3

Ra~10^6





Hot narrow plumes in the mantle:

transient

$\tau_c = (H^2/\kappa).(Ra_c/Ra_{visq})^{2/3}$

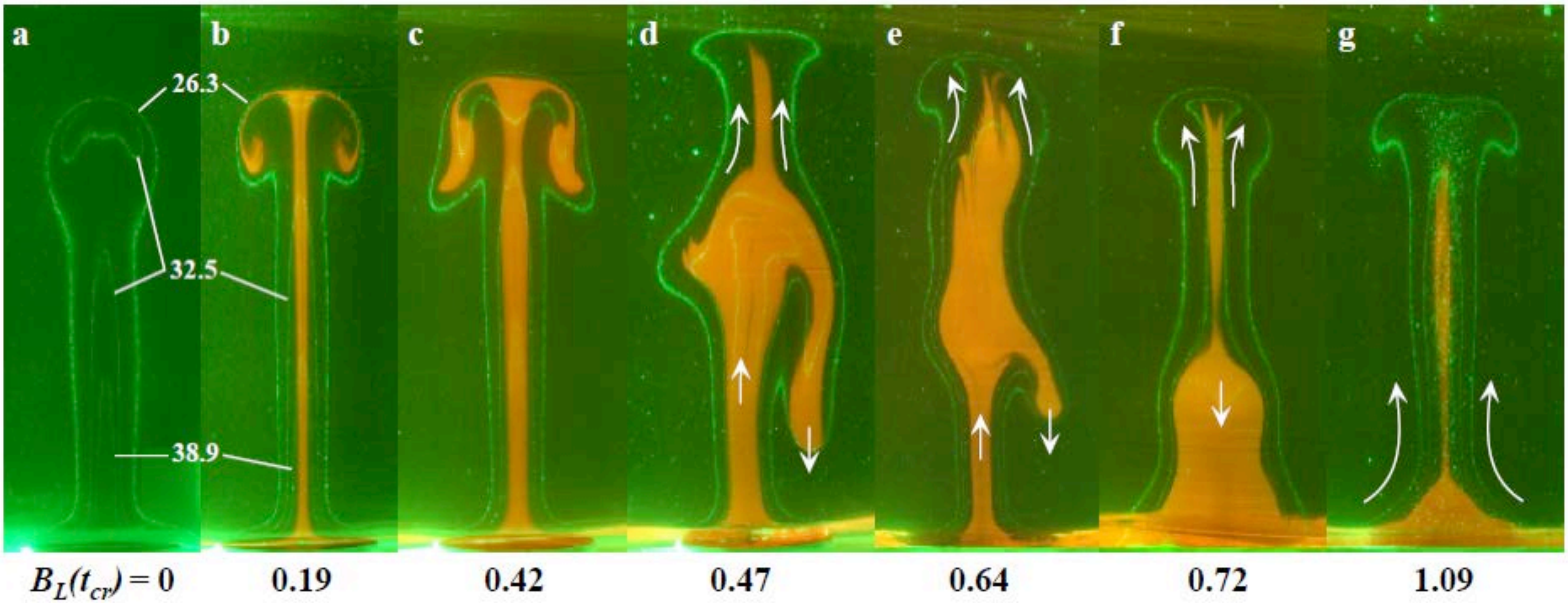
=> τ_c~10, 40, 200 Ma

for η~10^{19},5.10^{20},10^{22} Pa.s

BUT no cold plates, no LLSVPs

4. Interaction Convection / Denser Reservoir

Initial Buoyancy ratio



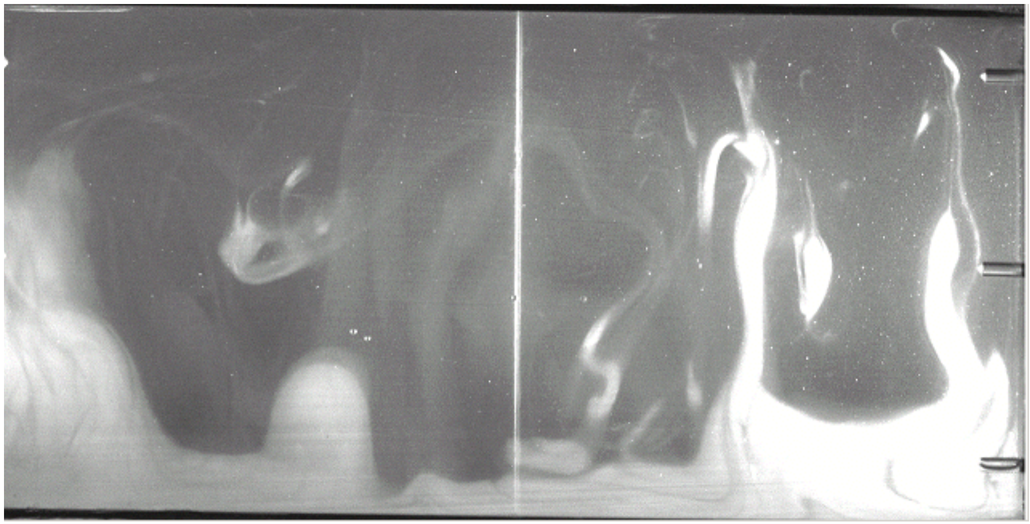
- Fat plumes
- Contorted plumes
- Hot is not rising if too dense => piles

$B_L =$ [illegible]

(Kumagai et al, 2008)

4. Interaction Convection / Denser Reservoir

- Convection carries fast hot material from bottom to top



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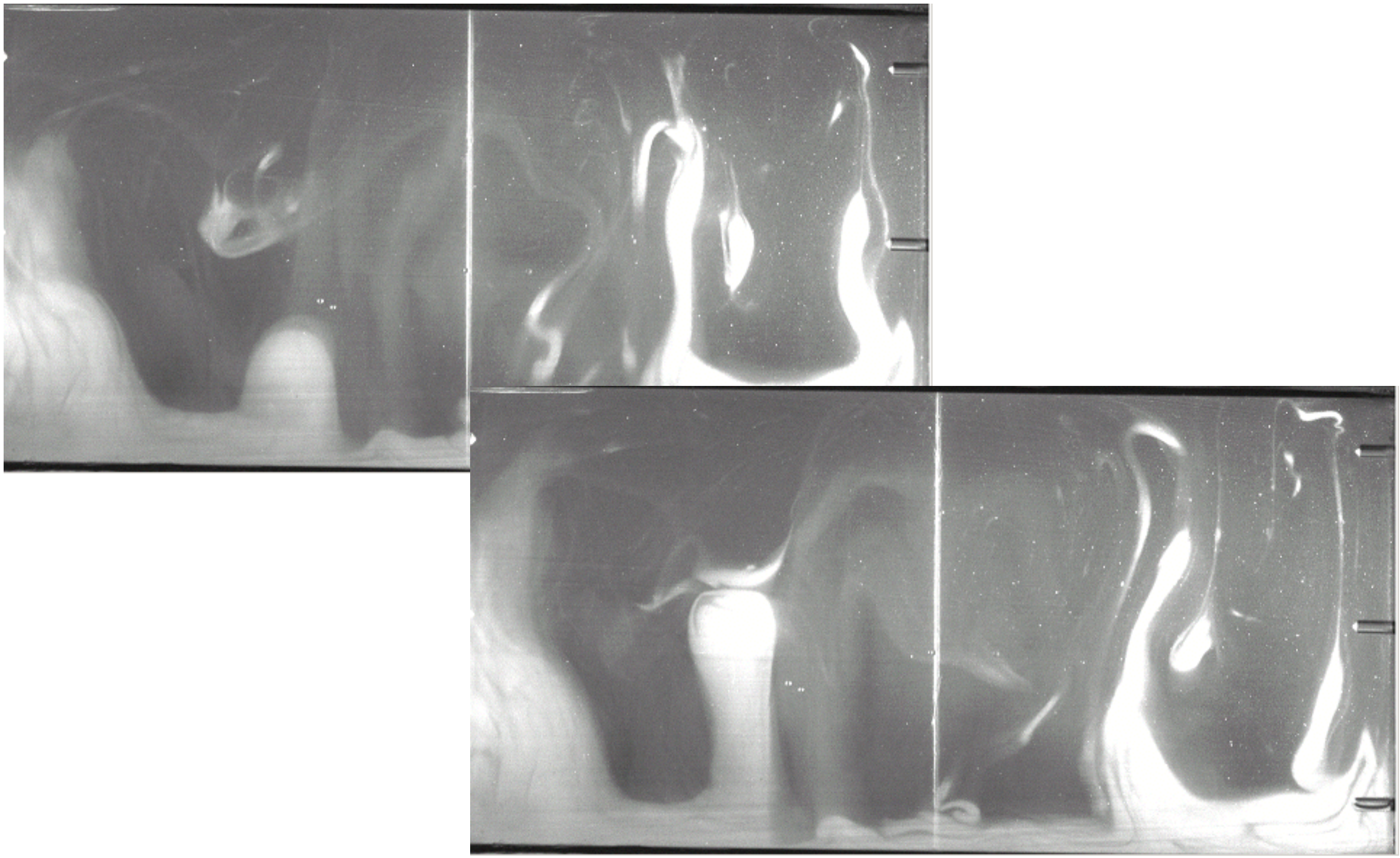

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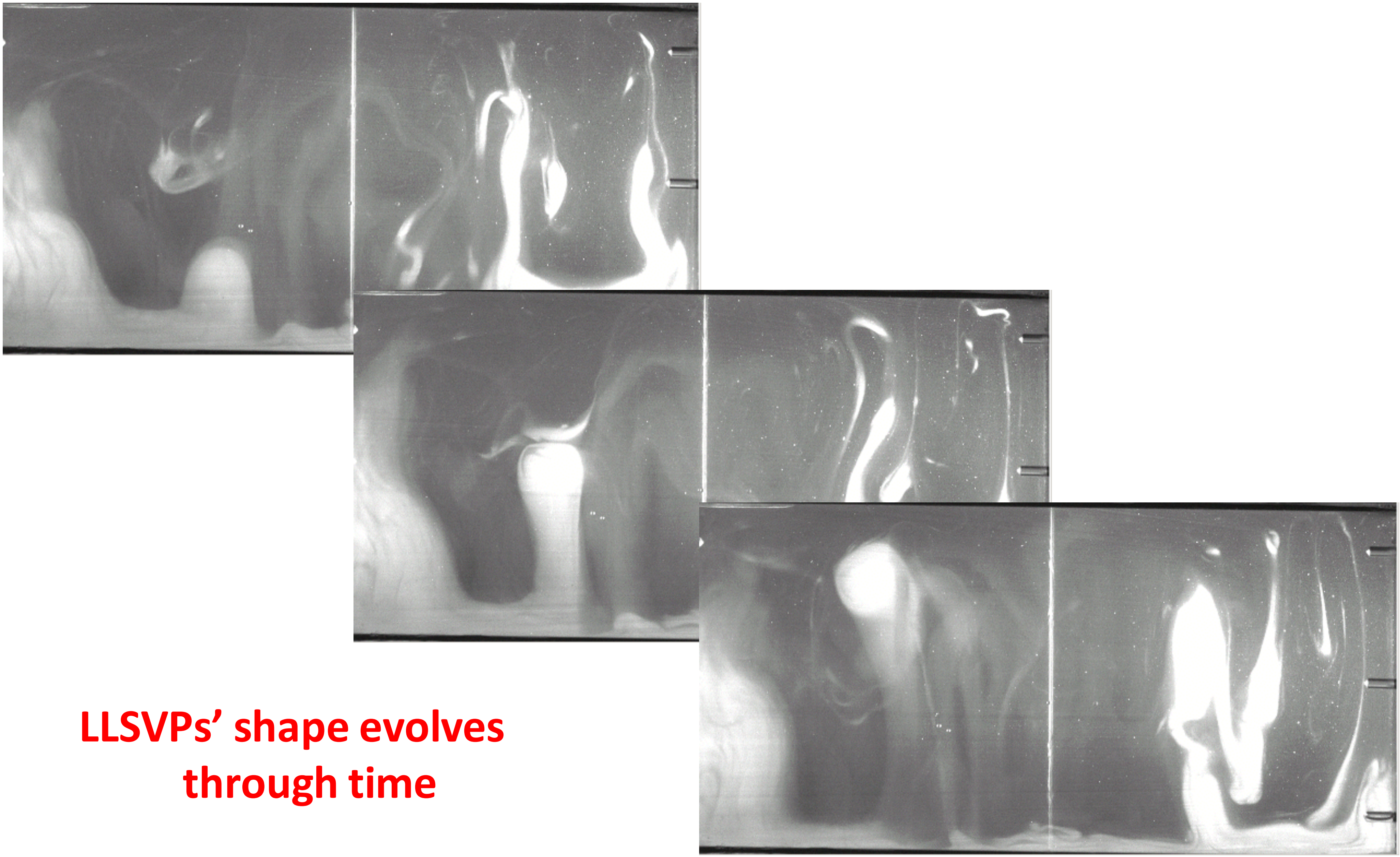
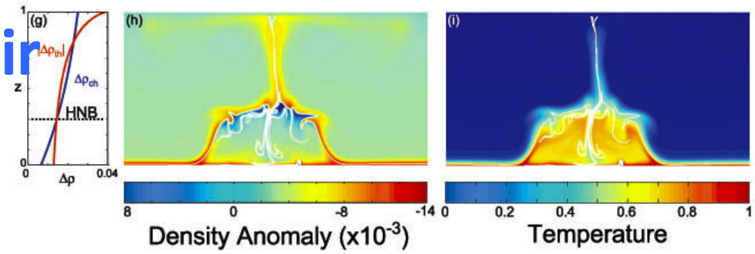


LLSVPs' shape evolves through time

4. Interaction Convection / Denser Reservoir



Stability:

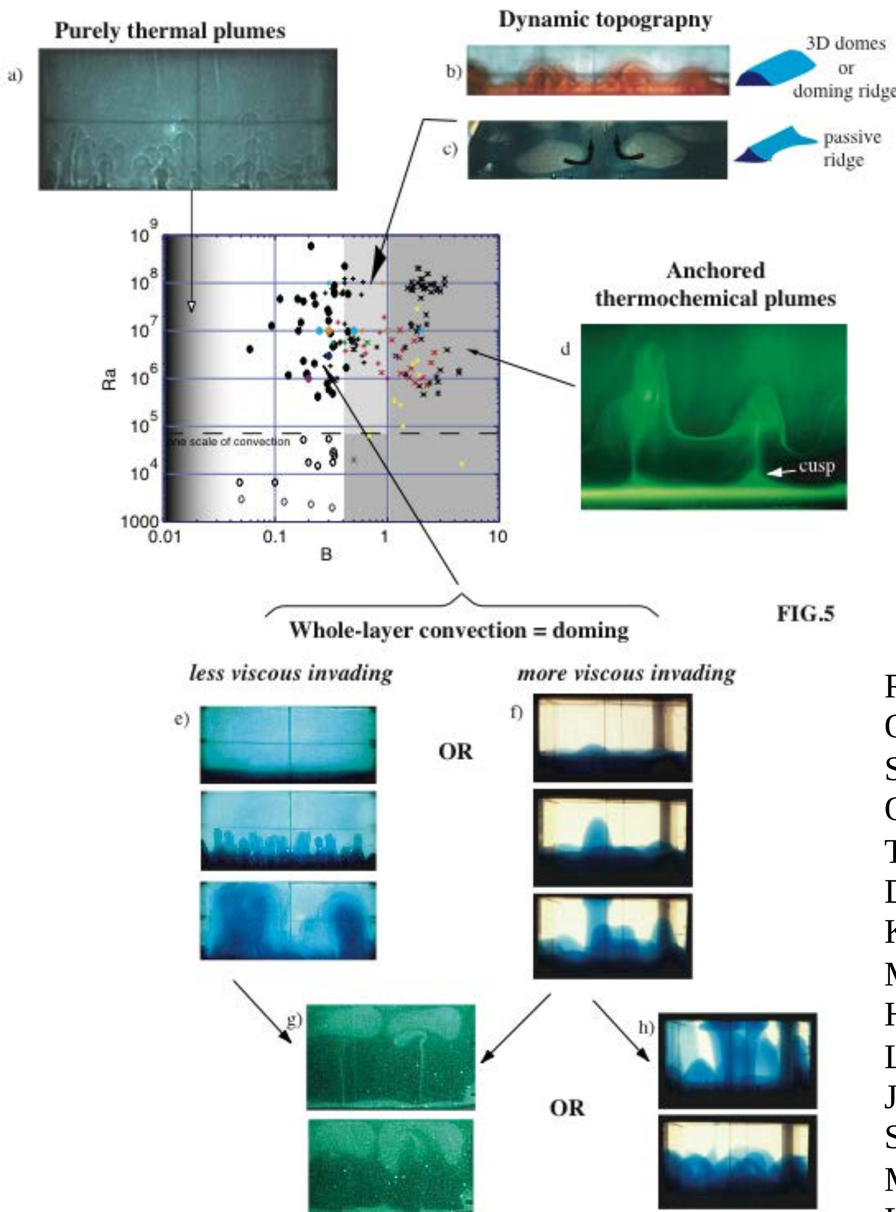
- Ra= g T d³ / —

- B = — / T

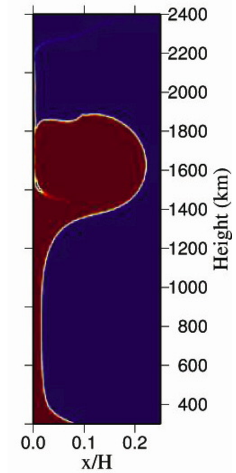
Morphology:

- = /
- $a = d_1/d_2$

< 2%



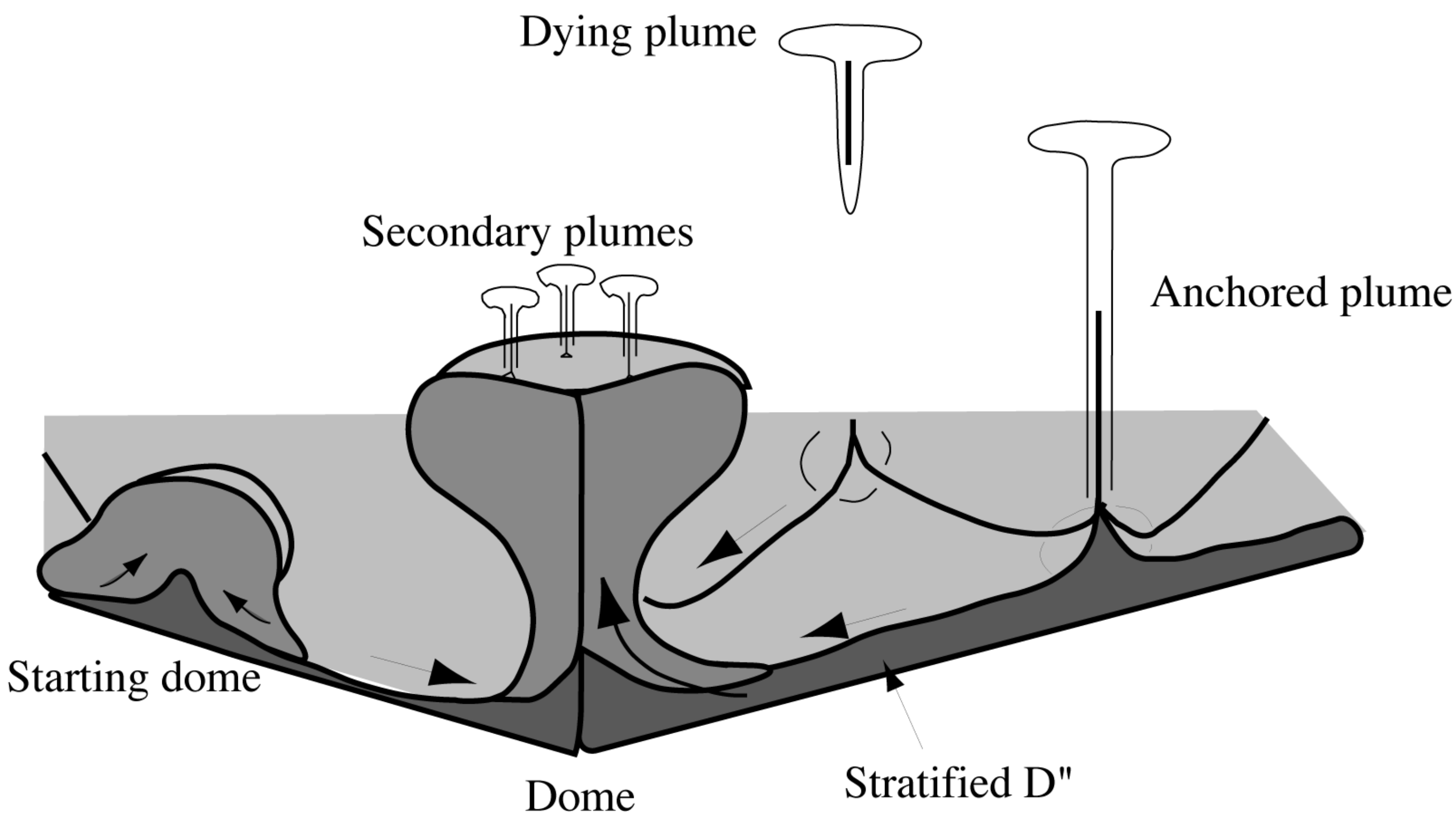
(Davaille & al, 2005)



Tan & Gurnis, 2005, 2007;
Samuel & Bercovici, 2006

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

Several types of plumes



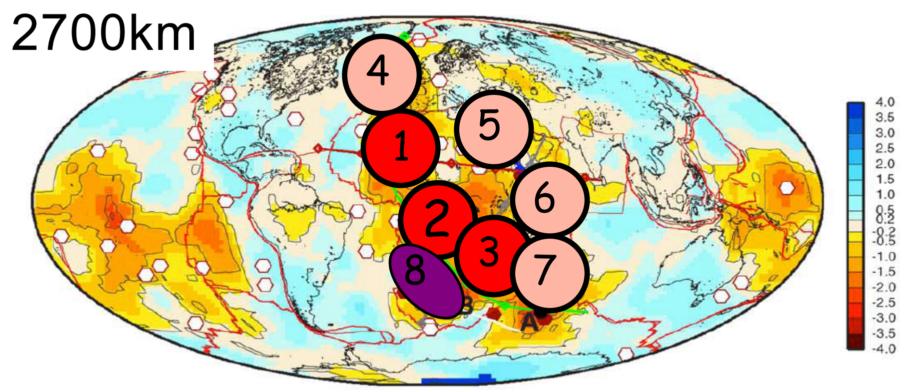
4. Interaction Convection / Denser Reservoir

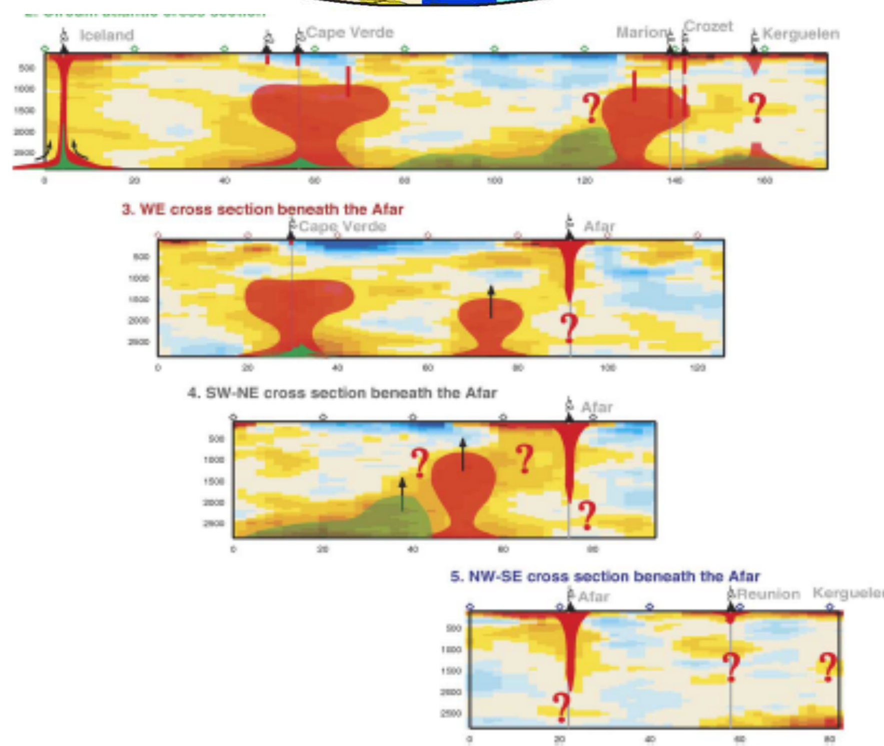
- $\Delta\rho_\chi/\rho$ ~0.1-0.6%
- h_{dense} < 700 km

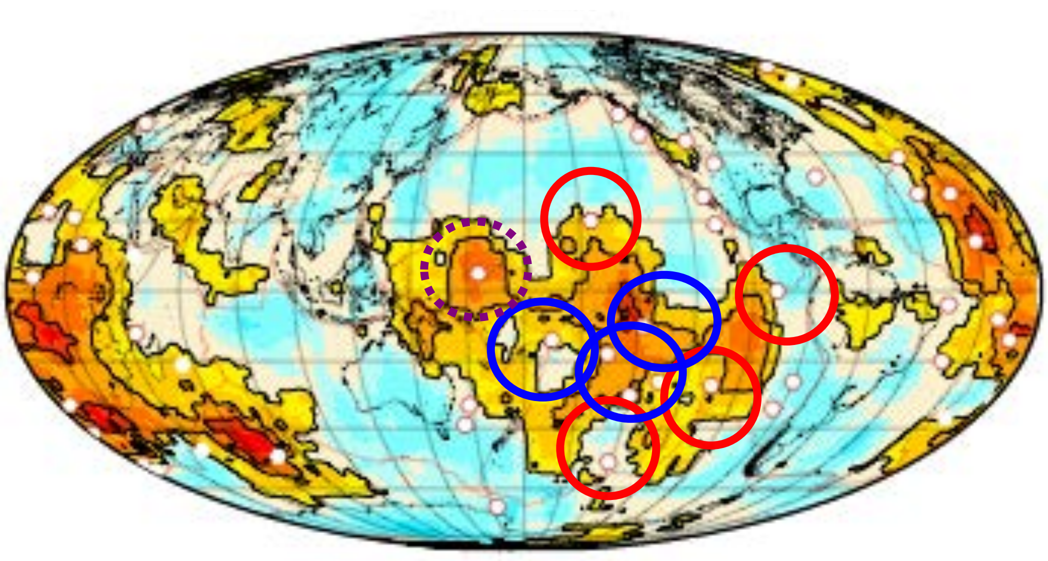
- spacing at CMB ~3000-4000 km

- recurrence time ~100-200 Myr

- 5 to 9 thermochemical hot instabilities
  - long-lived hotspots, traps, superswells
  - large-scale slow seismic anomalies





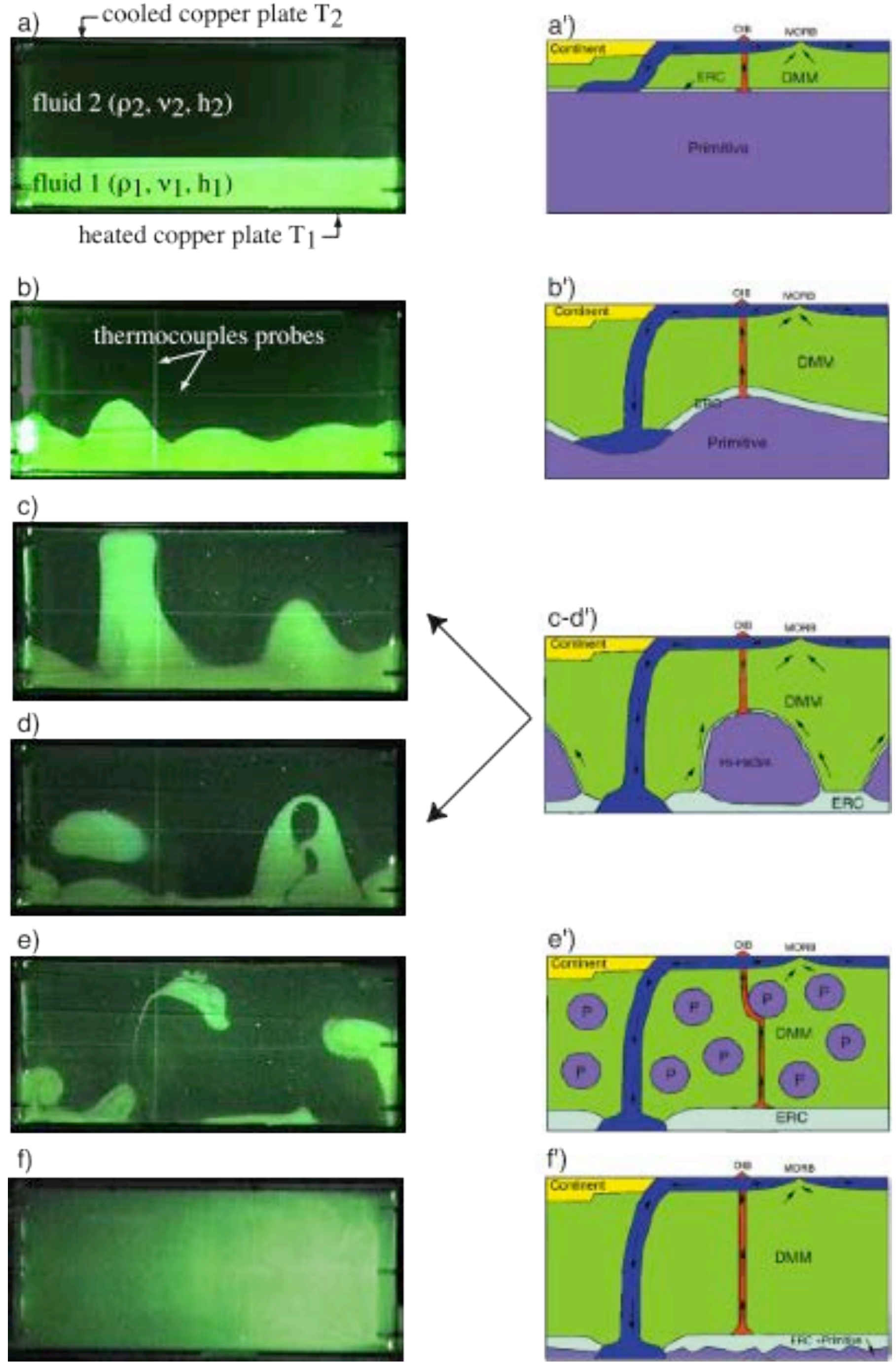


Davaille et al., 2005

4. Interaction Convection / Denser Reservoir

MANTLE
TEMPORAL
EVOLUTION ?

Today?



(LeBars and Davaille, JGR 2004)

2-layer

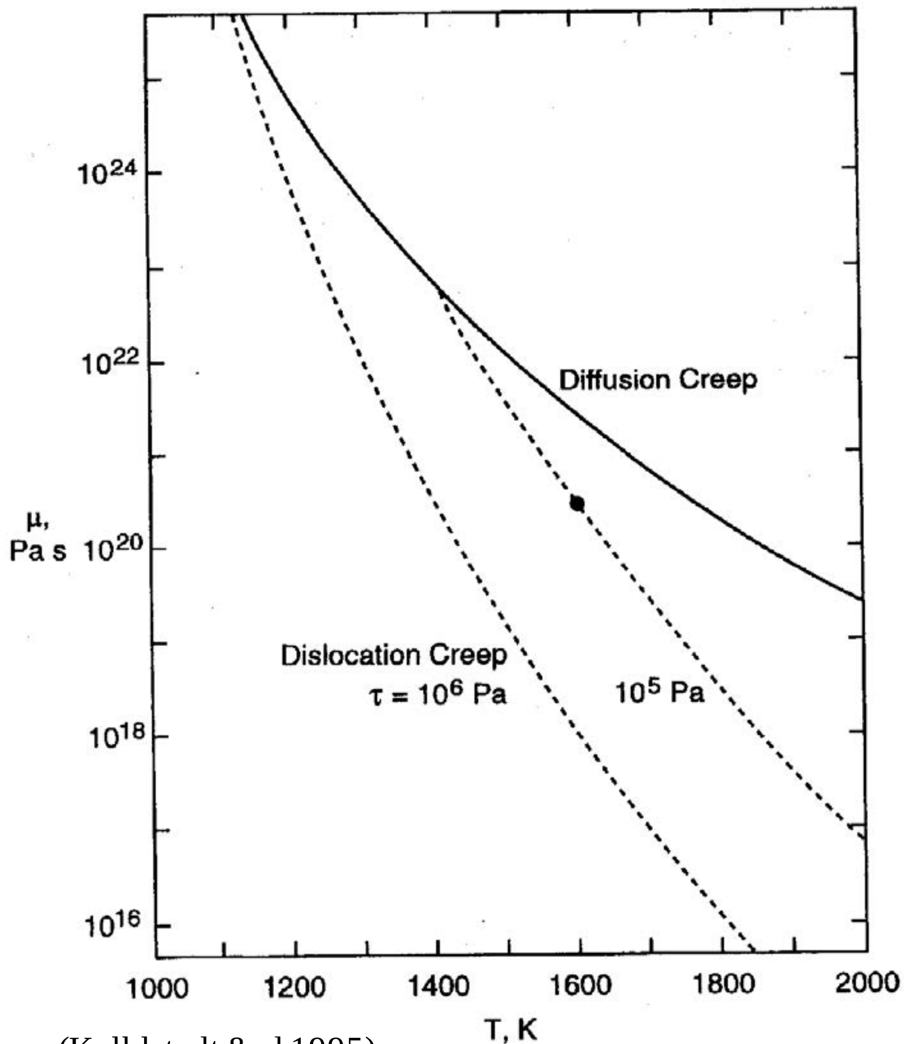
Kellogg & al, 1999

Tackley, 1998
Davaille 1999

Davies 1984,
Becker & al 1999

1-layer

5- Making a plate: Convection with strongly Tp-dependent viscosity

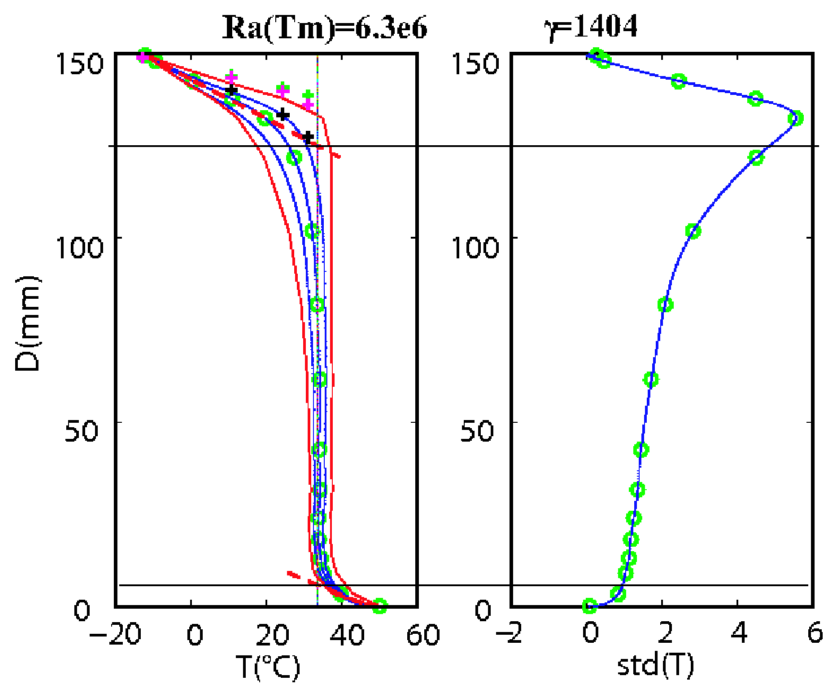


(Kolhlstedt & al 1995)

=> Asymmetry hot/cold

Viscosity Ratio

top / bot



5- Making a plate: Convection with strongly Tp-dependent viscosity

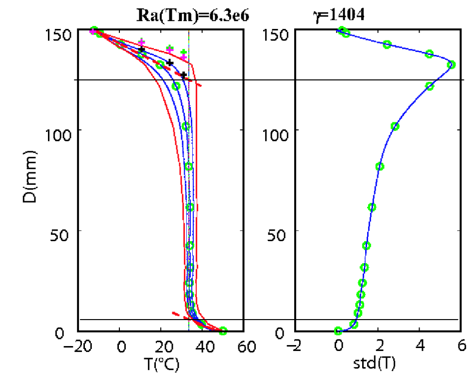
Richter, 1973, 1976
Booker, 1976
Stengel & al, 1982
Richter & al, 1983
White, 1988
Weinstein & Christensen, 1991
Davaille & Jaupart, 1993

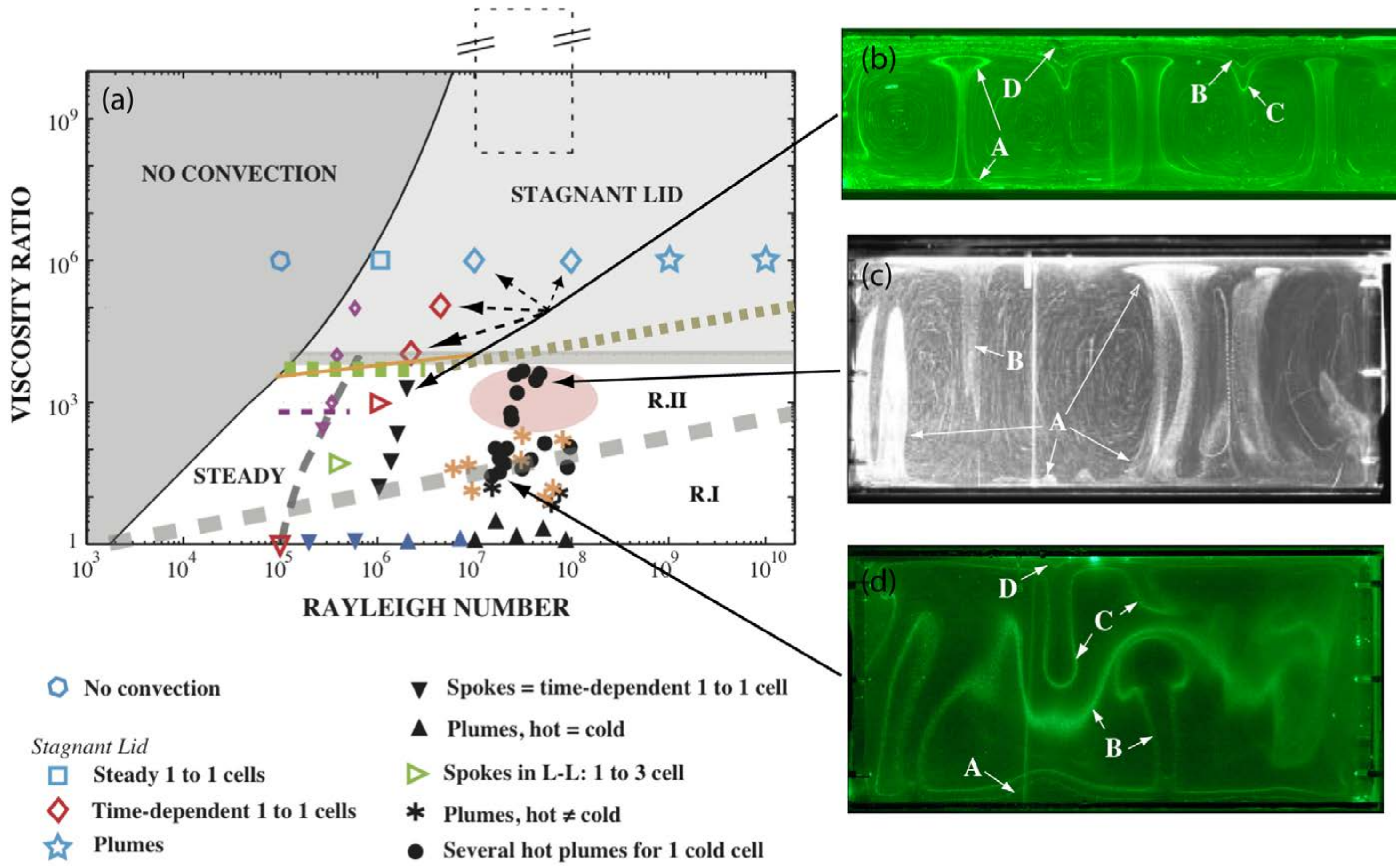
Giannandrea & Christensen, 1993
Manga et al, 1998-2001
Shaeffer & Manga, 2001
Davaille et Vatteville, 2005
Androvandi et al, 2011

Christensen & Harder, 1991
Tackley, 1993, 1996

Ratcliff & al, 1997
Trompert & Hansen, 1998
Kageyama & Ogawa, 2000
Stemmer & al, 2006
Weber et al, 2017

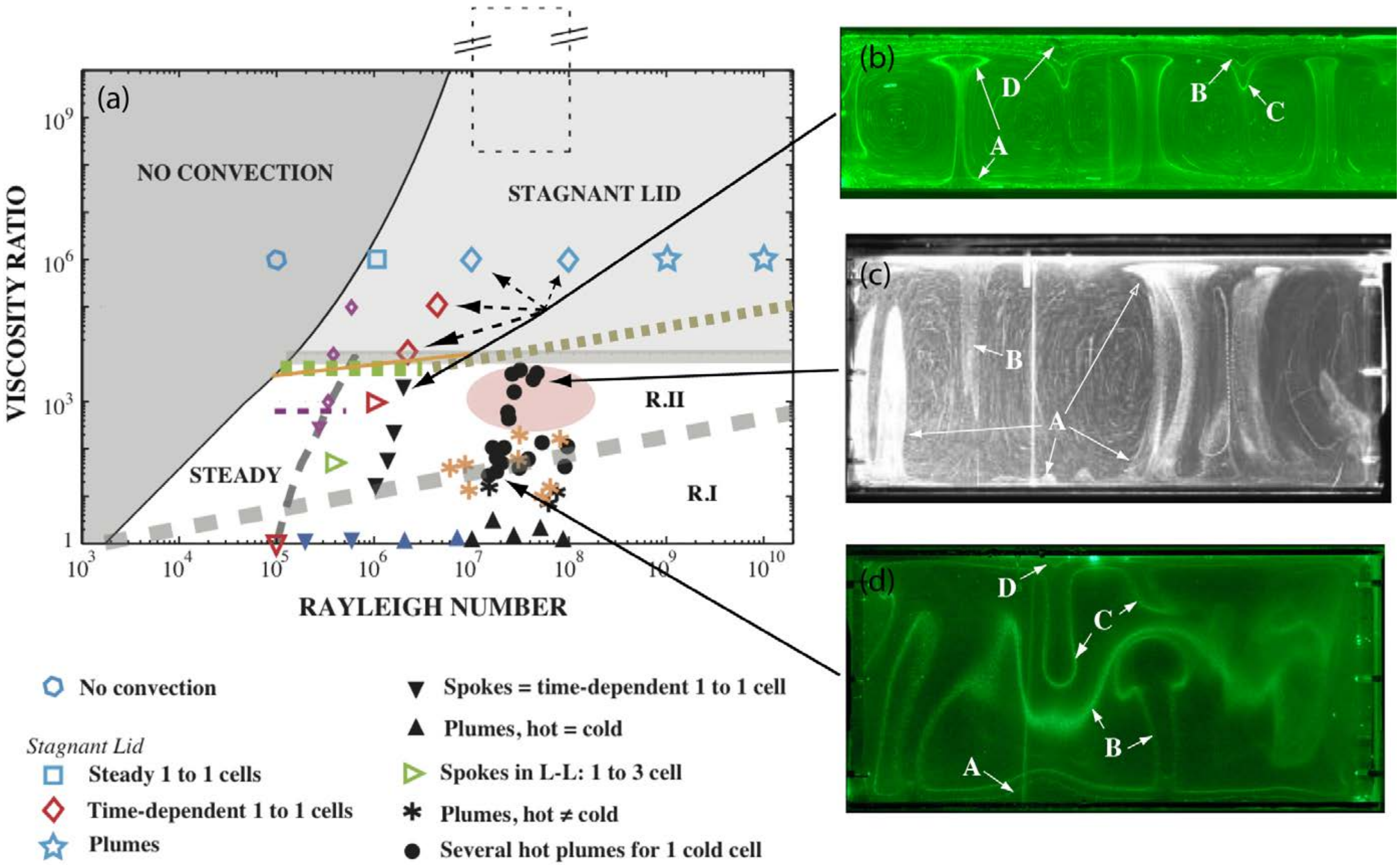
Morris, 1984
Solomatov, 1995





5- Making a plate: Convection with strongly Tp-dependent viscosity

High viscosity ratio => Plate



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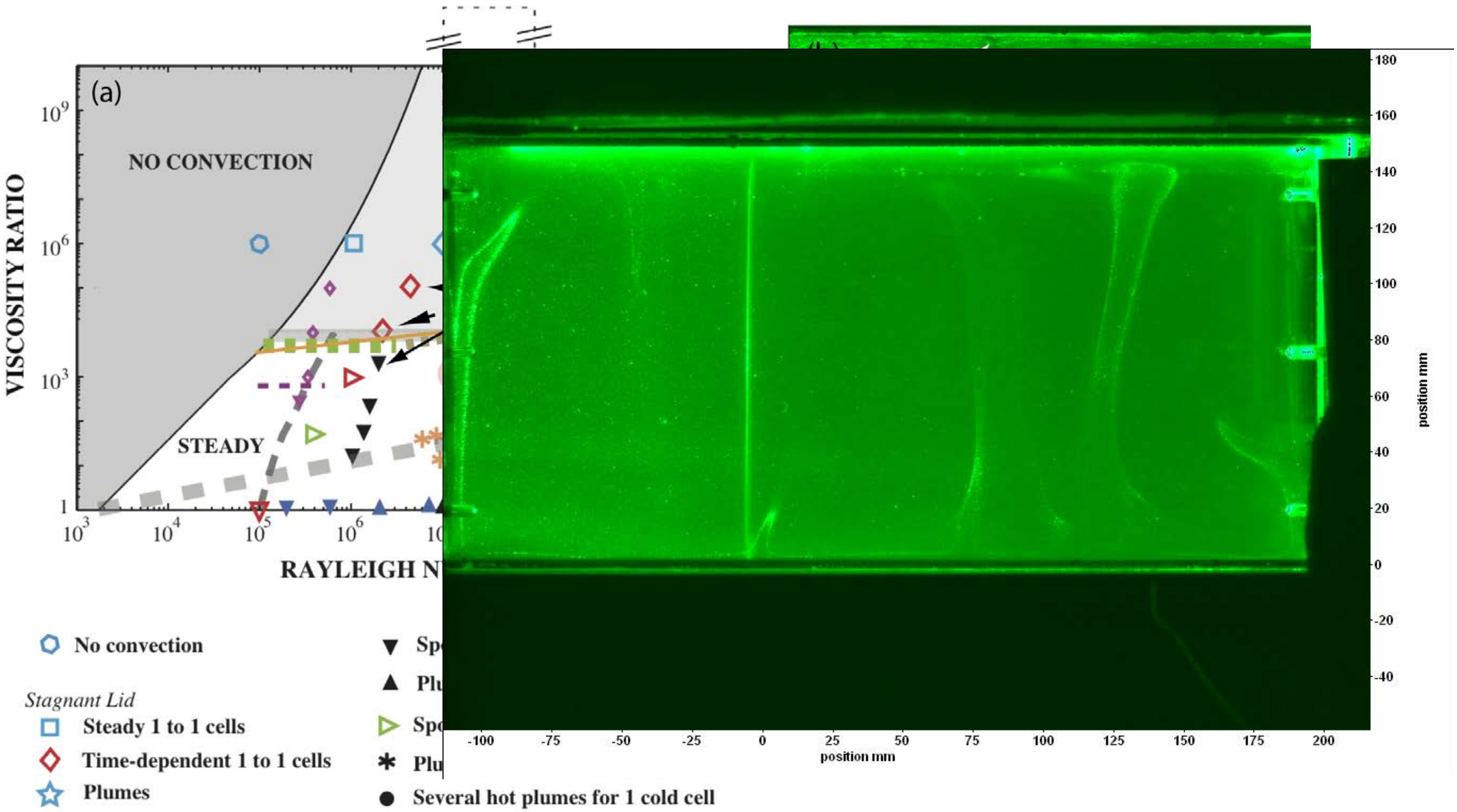
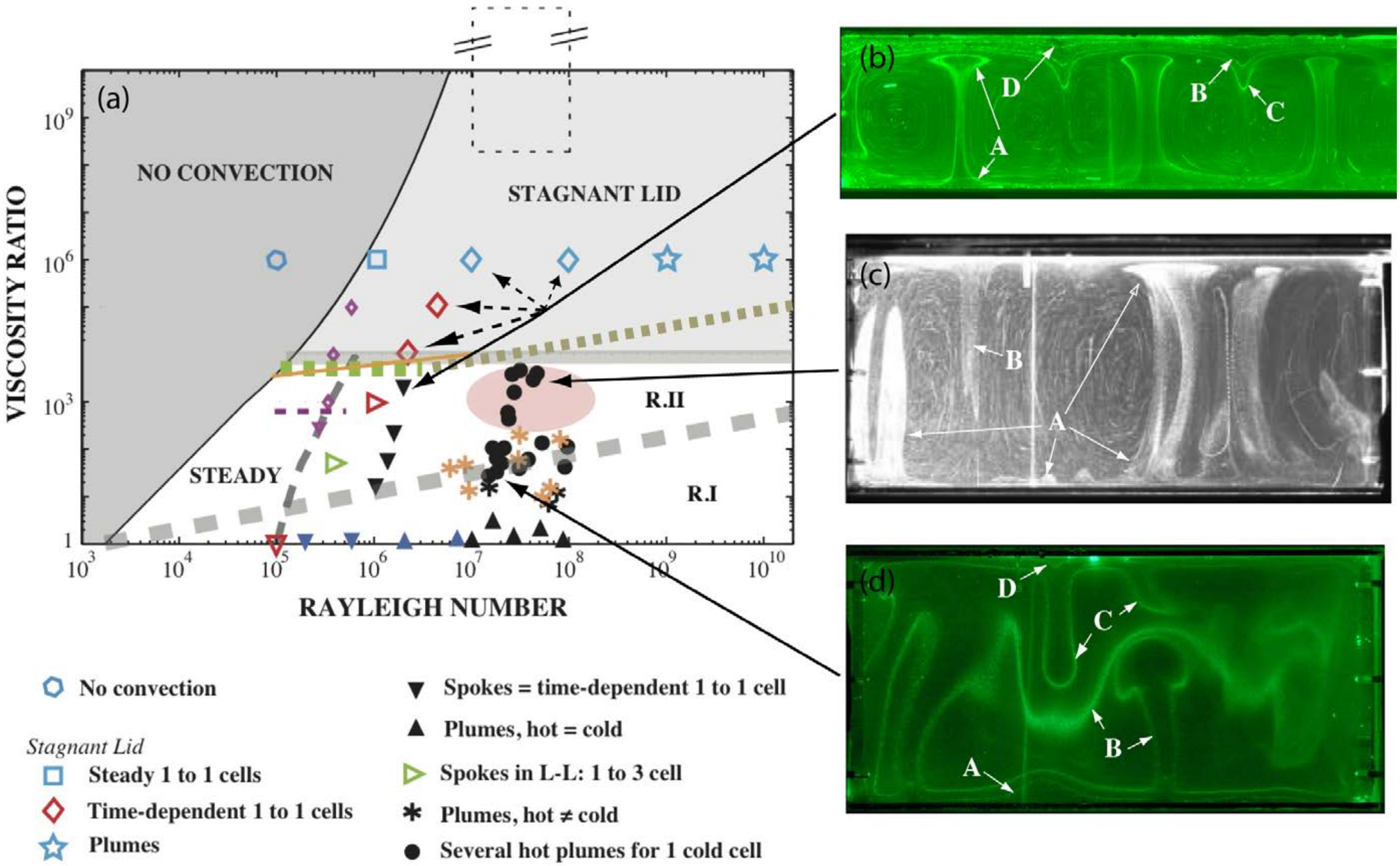


5- Making a plate: Convection with strongly Tp-dependent viscosity

Strong influence of downwellings on plume stability and generation area



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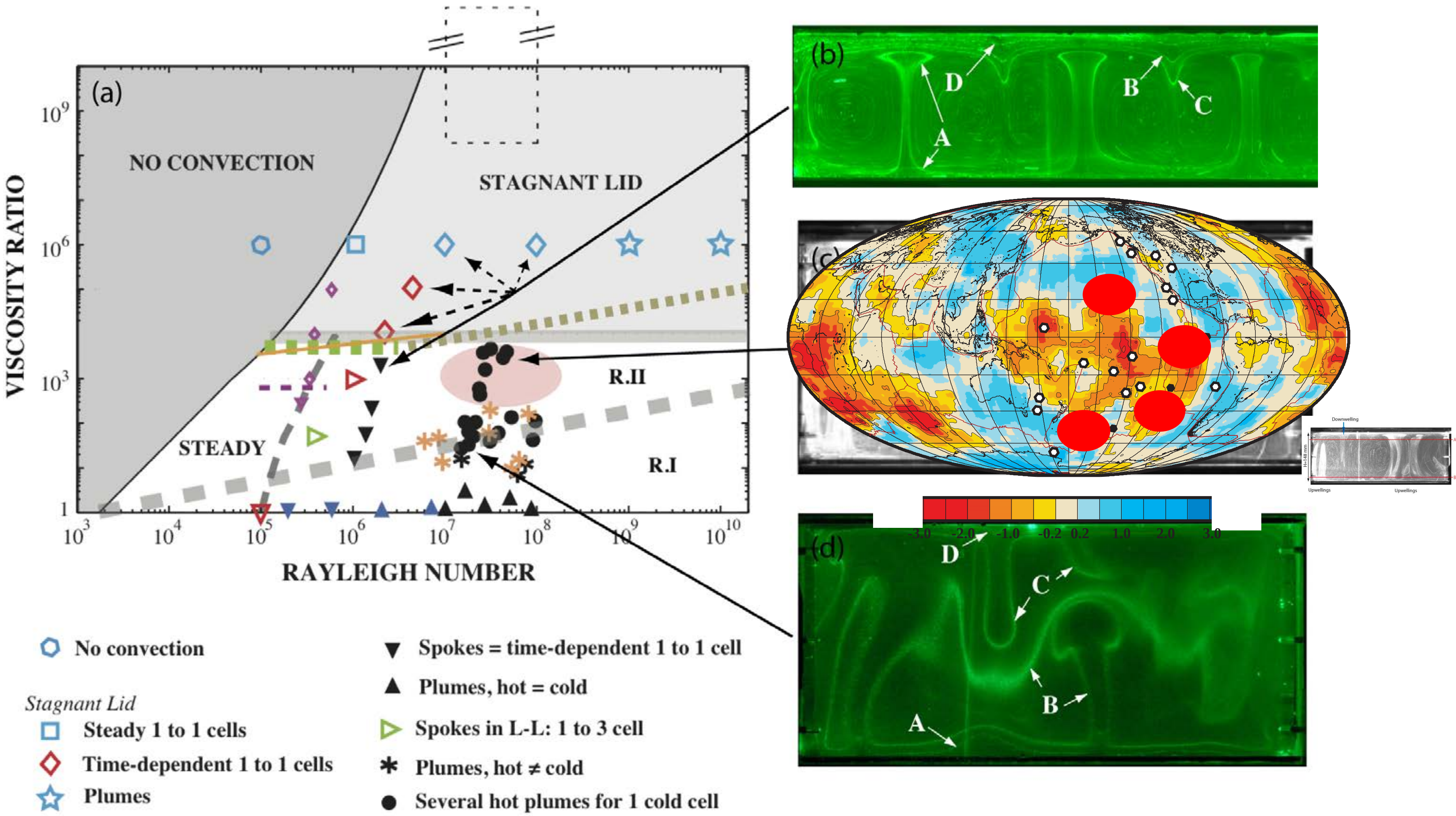
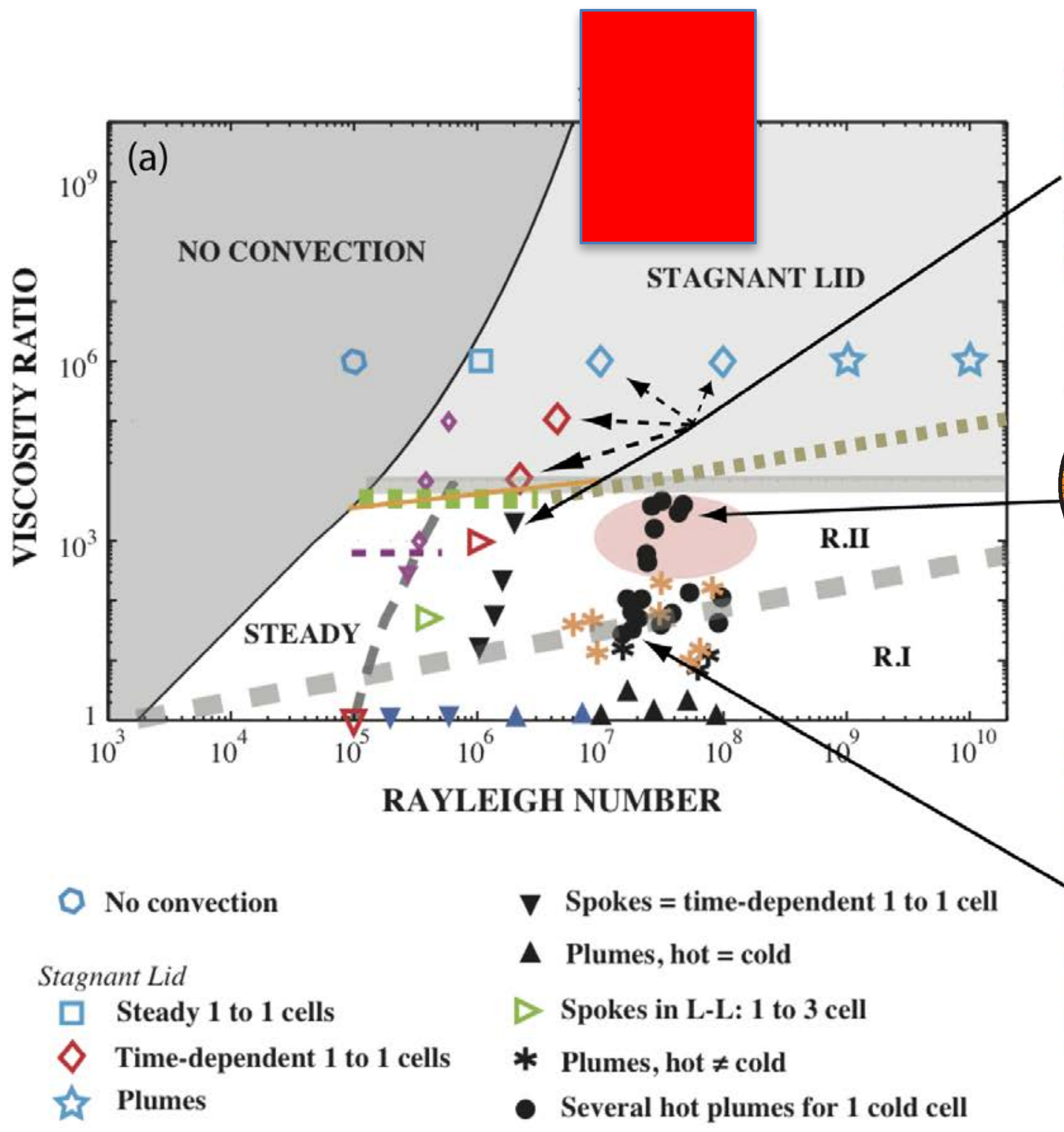
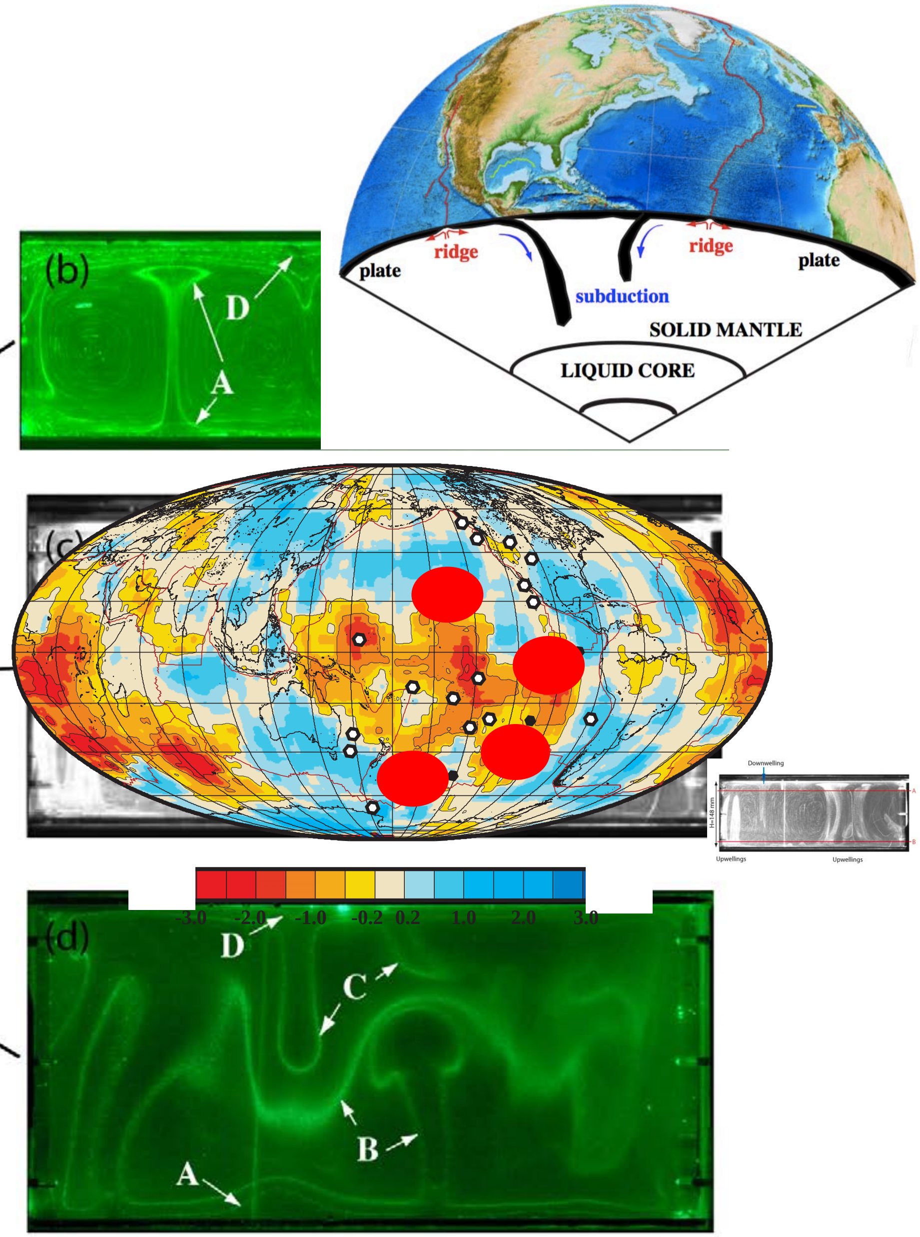


5- Making a plate: Convection with strongly Tp-dependent viscosity

=> How to break the lid ?



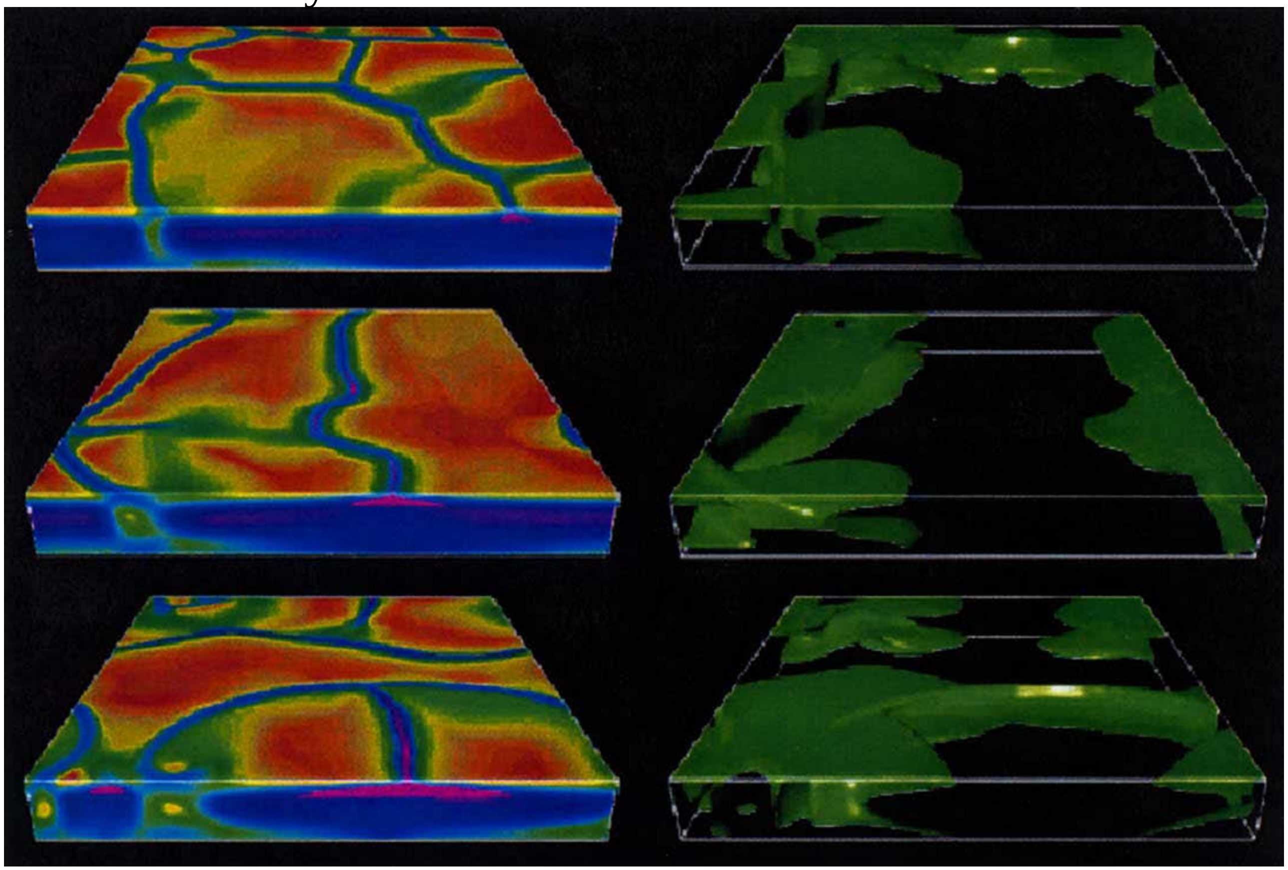


6- Non-newtonian rheology: « Kick Hard to Break »

Ex: Yield stress + viscosity decrease under the plates due to melting

(Tackley 2000) + shear heating , + pre-existing weaknesses , + …

Viscosity field Cold isotherm

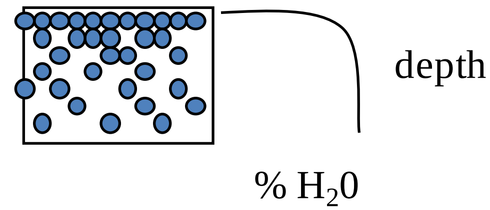


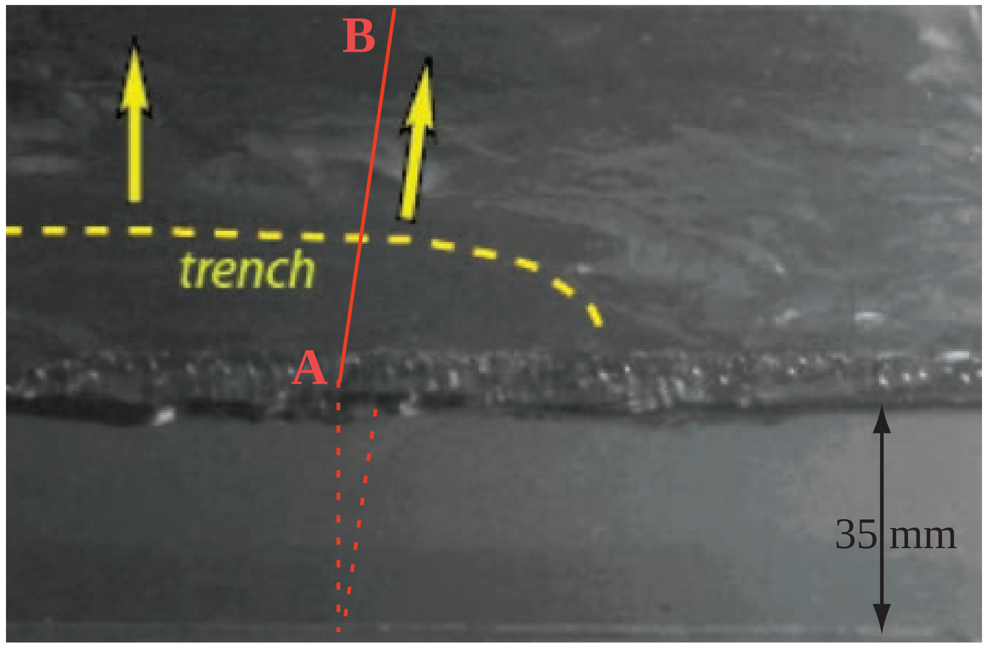
Moresi and Solomatov, 1998
Regenauer-Lieb et al., 2001
Solomatov, 2004
Stein & al, 2004
Enns et al., 2005
Stegman et al., 2006
Ueda et al., 2008
Gerya et al., 2008
Thielmann & Kaus, 2014
…

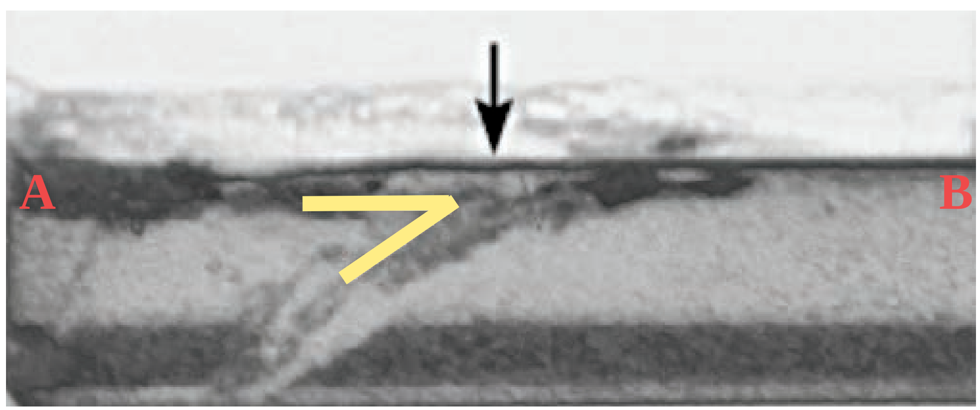
.Localize deformation => plates
.Instantaneous rheology
=> require yield stress much lower than measured…

6- Non-newtonian rheology:

Can we learn from Soft Matter material ?

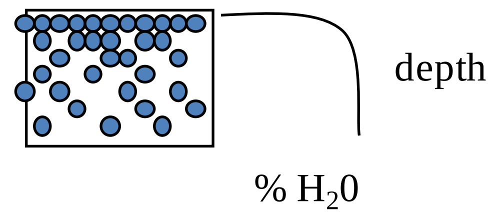


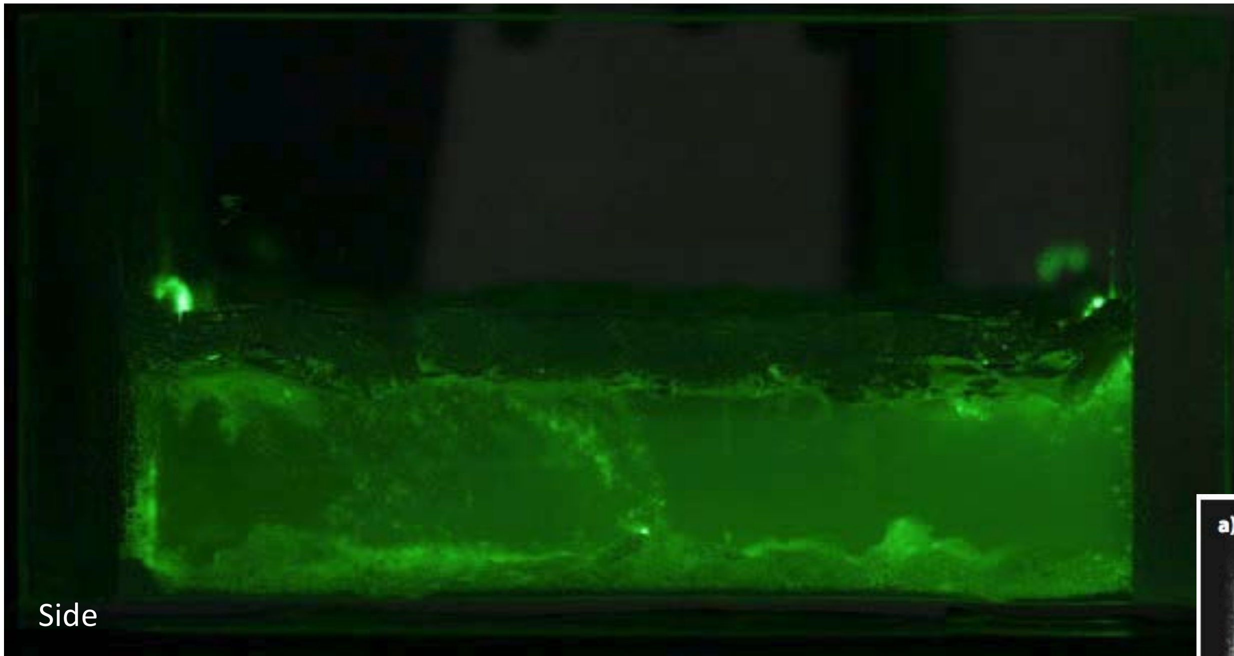




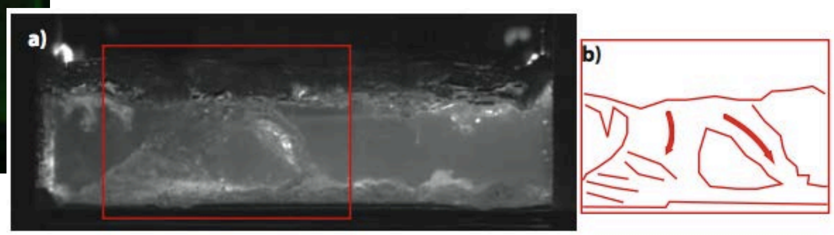
(Di Giuseppe et al, 2011)

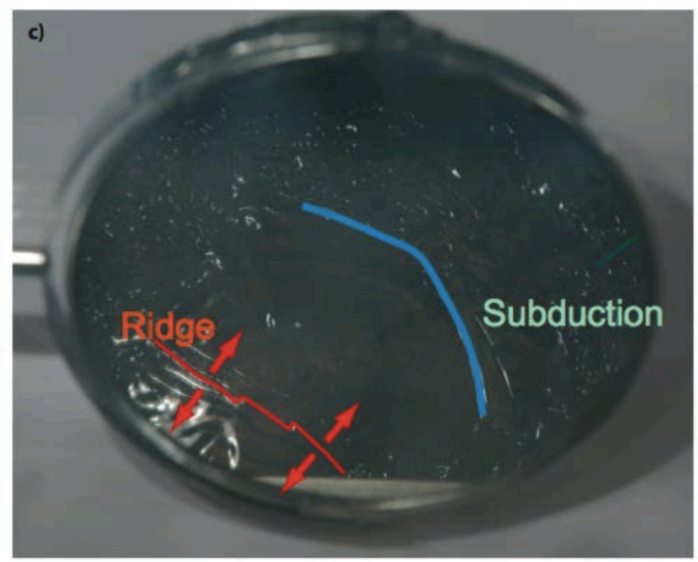
6- Non-newtonian rheology:



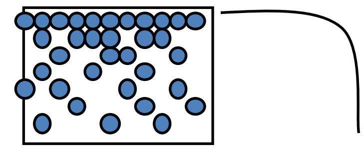


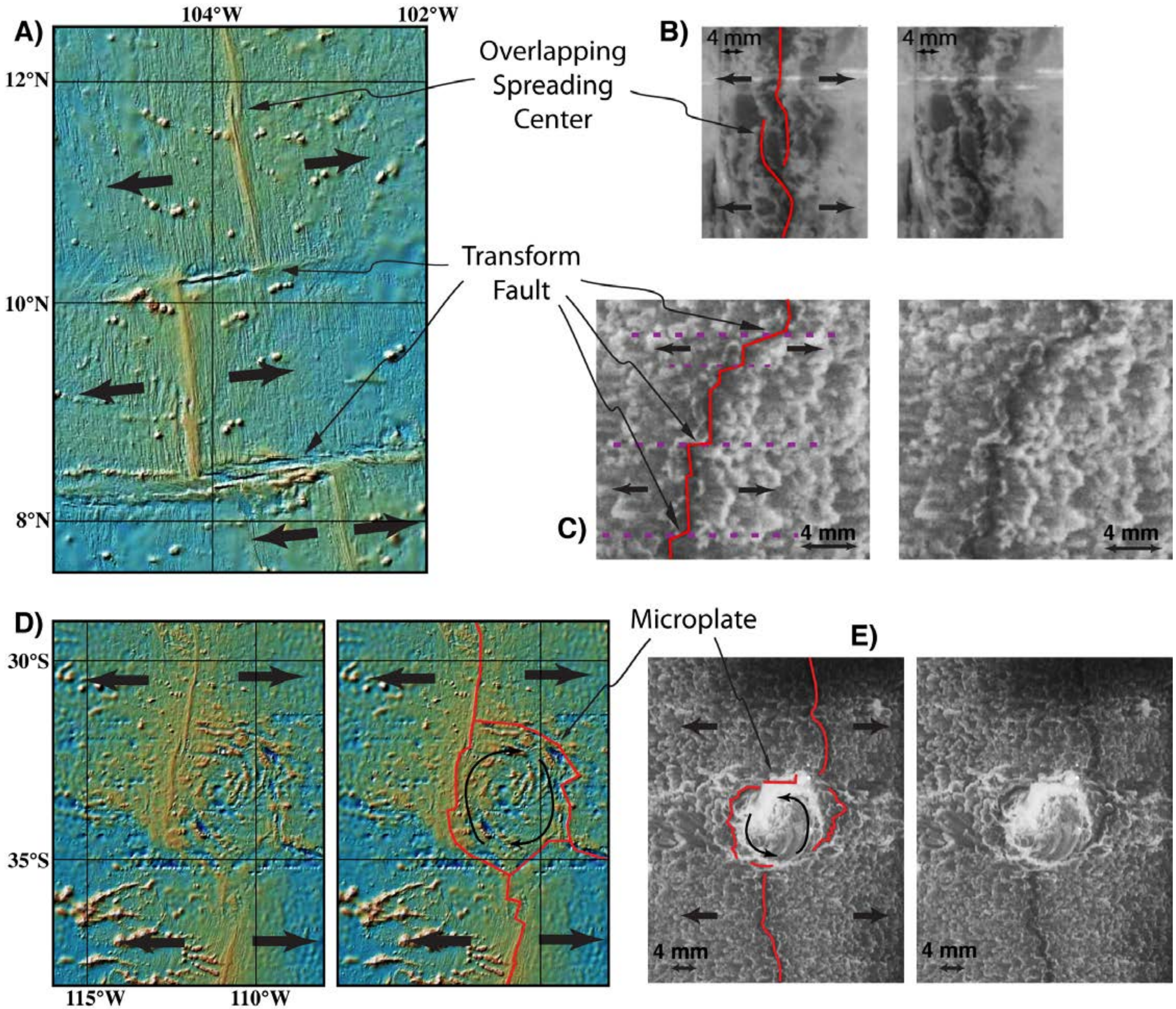
-Ridges and subduction.
-Several plates coexist.
-Plumes





6- Non-newtonian rheology:

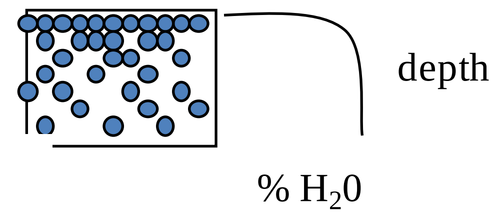


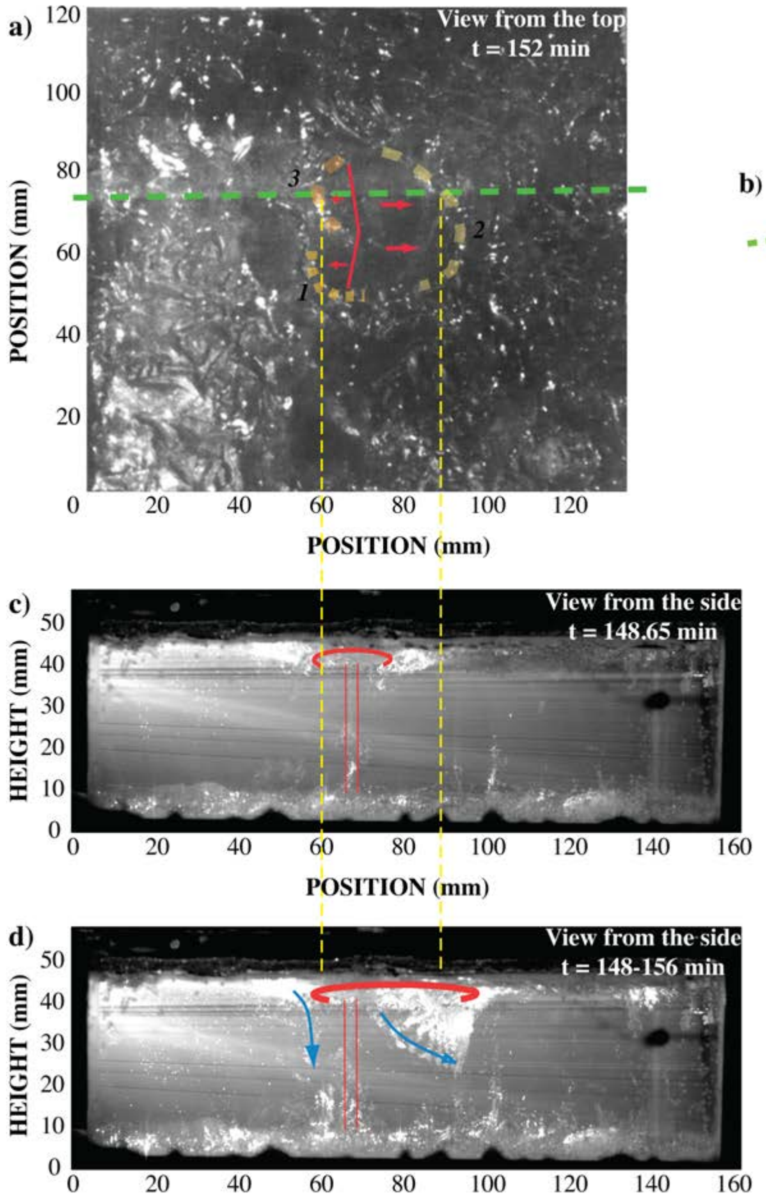


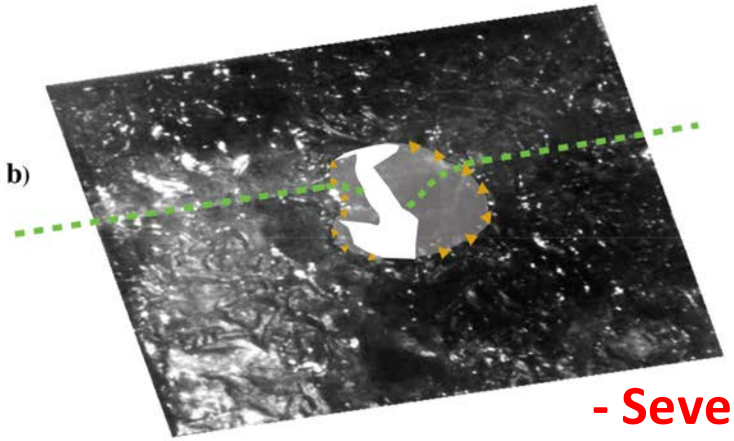
(Sibrant et al, 2018)

6- « Kick Hard to Break » :

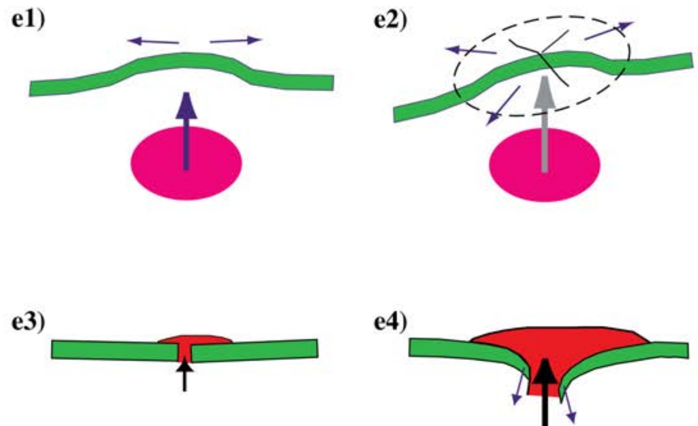
Plume-induced subduction







- Several arcuate slabs



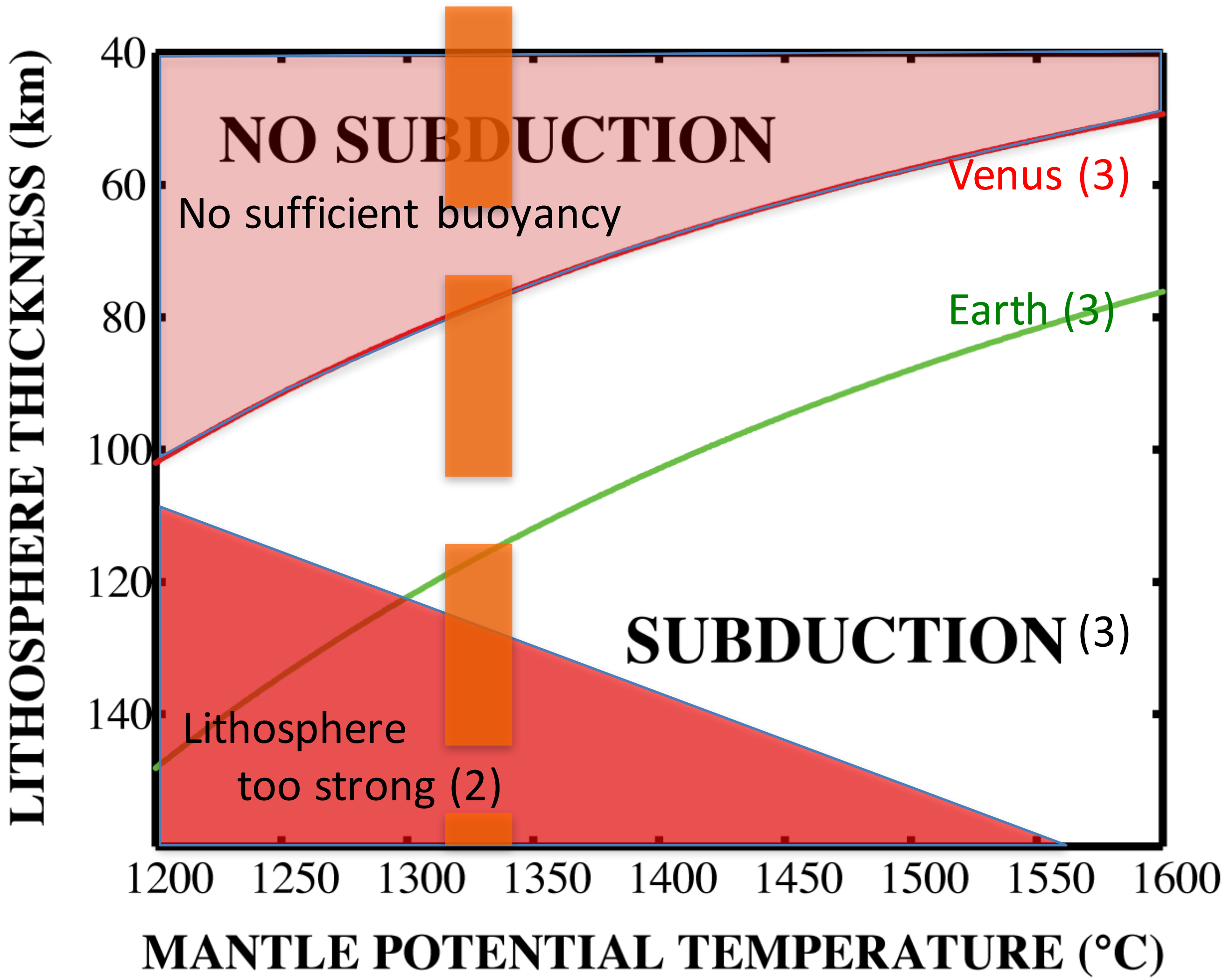
- Localized re-surfacing

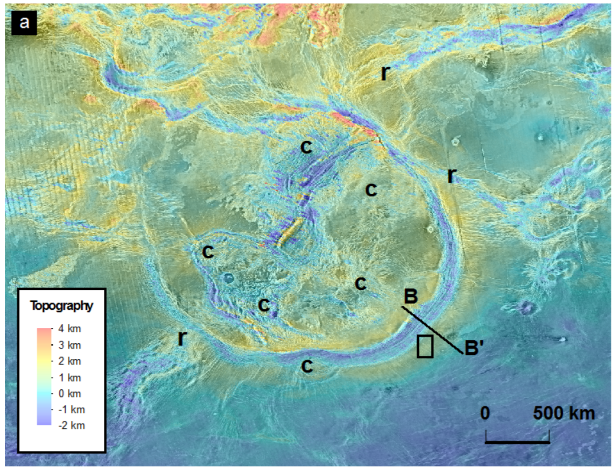
roll-back => tearing at slab edges

=> subduction stops when plume spreading stops

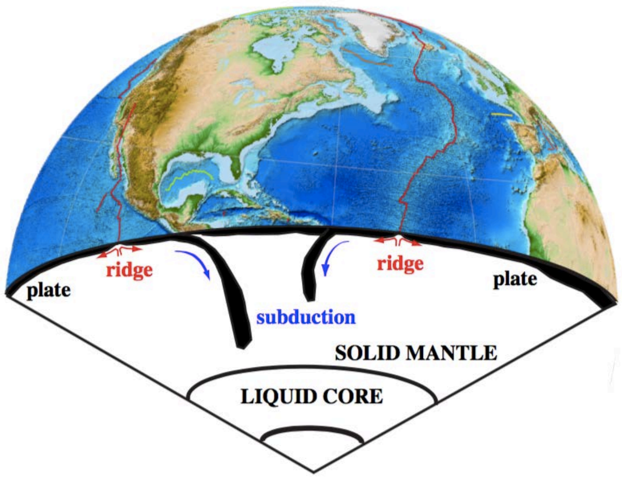
6- « Kick Hard to Break » :

Plume-induced subduction





Artemis Coronae (Venus)

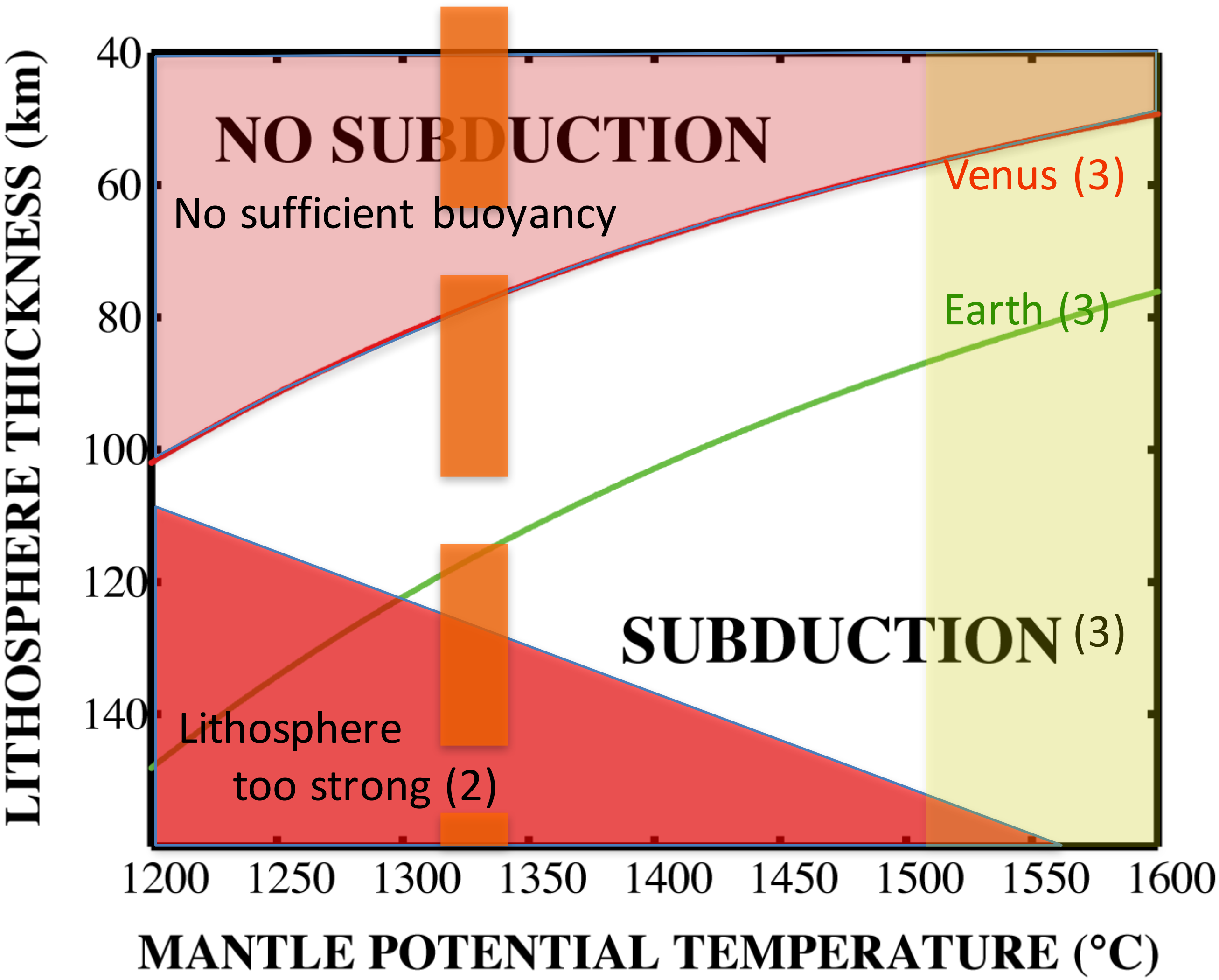


Carribean (Earth)

(Davaille, Smrekar & Tomlinson, 2014, 2017)

6- « Kick Hard to Break » :

Plume-induced subduction



Archean:

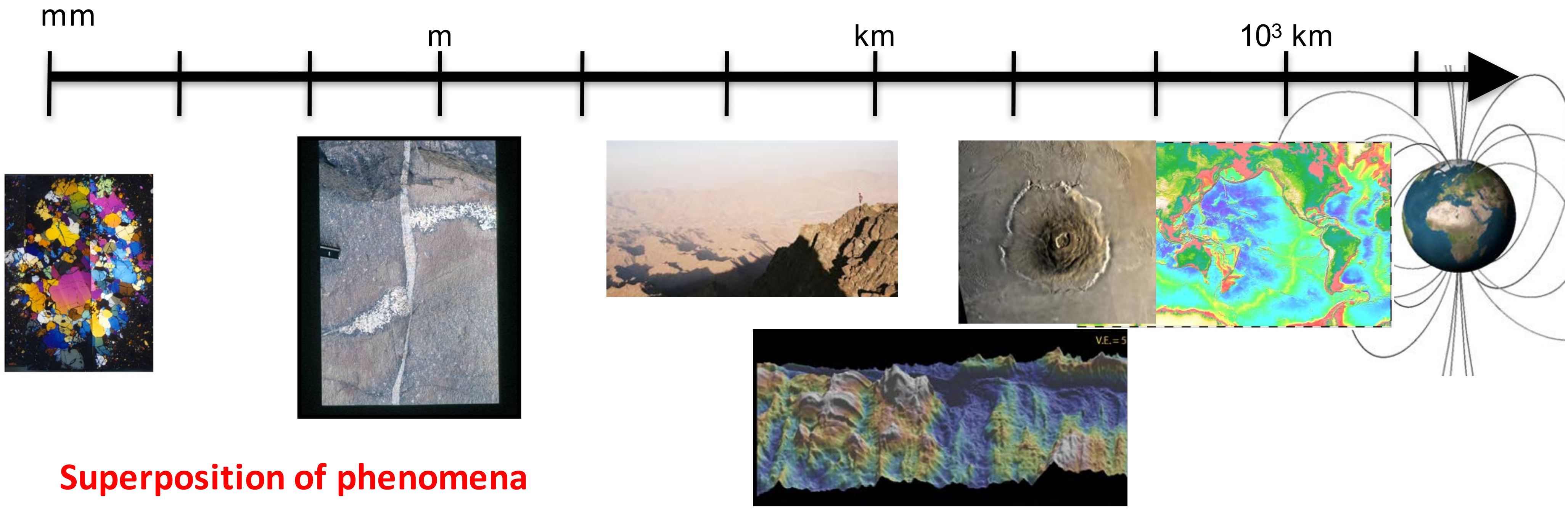
Continent formation

(1) Plume

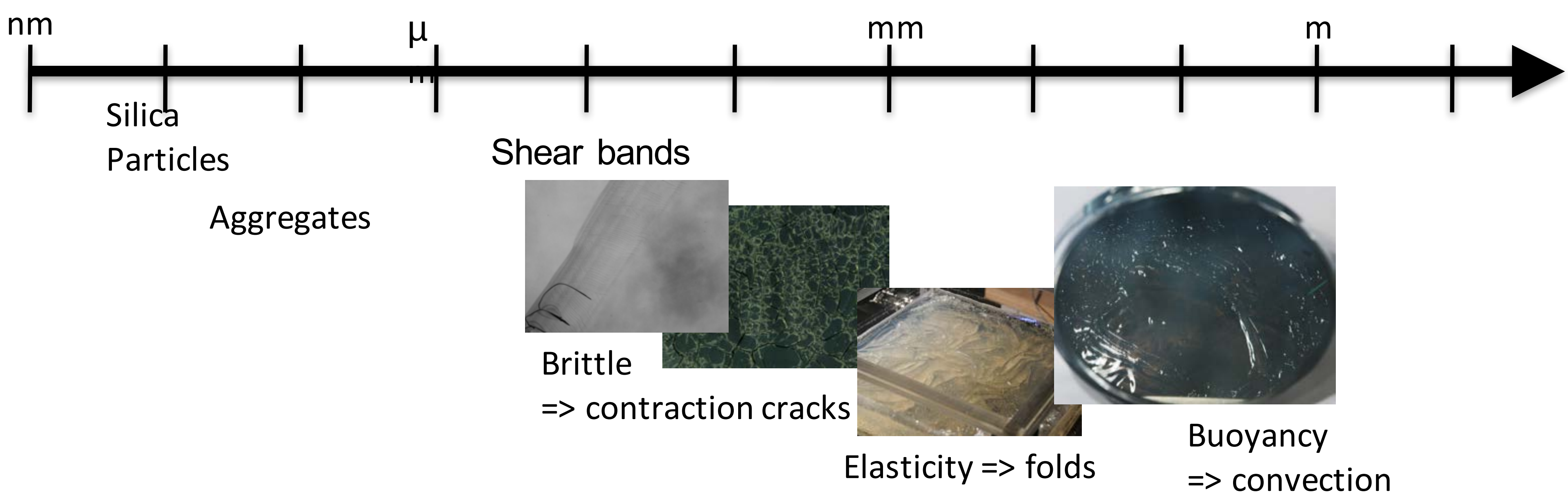
+ (2) Subduction

(Arndt & Davaille, 2013; Davaille, Smrekar & Tomlinson, 2014, 2017)

A visco-elasto-plastic « lithosphere » which has memory



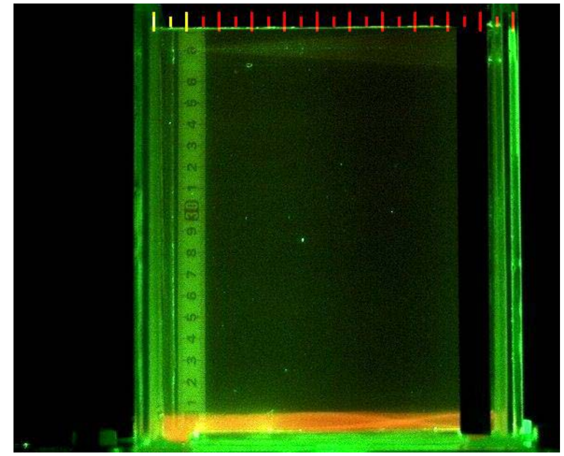
Superposition of phenomena at different scales



CONCLUSIONS:

1- NO dichotomy between plate tectonics and mantle convection

slabs = cold limbs of mantle convection



2- Mantle convection is time-dependent

CMB= slab graveyard ; asthenosphere = plume graveyard

3- Several types of hot spots/plumes

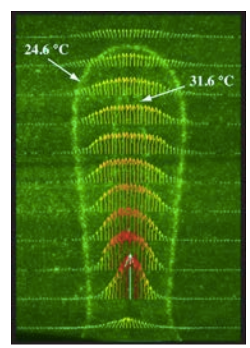
4- To make a plate : strongly temperature-dependent viscosity

To break a plate : two-phase mixture (solids, liquid) + memory

5- Plate tectonics is only one regime out of many

NEXT: - find the « effective rheology » ?

- map the different regimes
- evolution of the Earth ?



THANK YOU