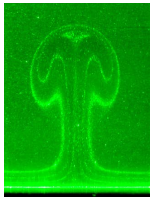
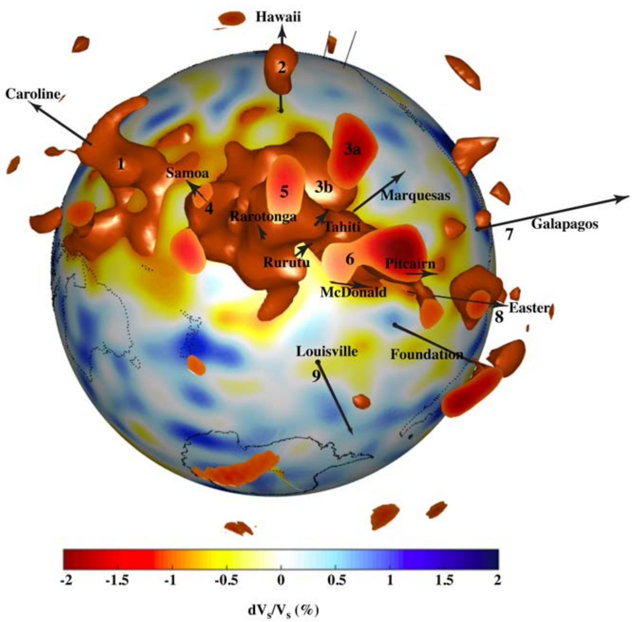
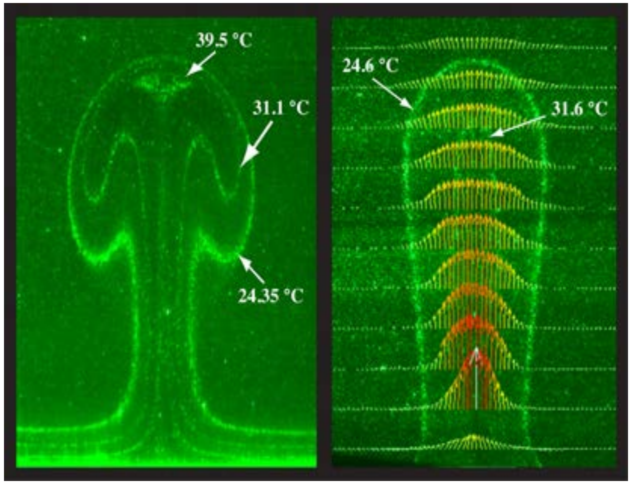


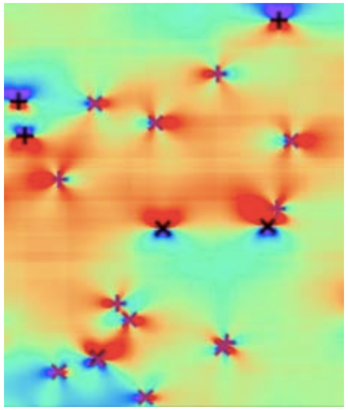
Influence of mantle complex rheology on lower mantle dynamics

Anne Davaille (1), **Nicolo Sgreva** (1), **Thibaut Chasse** (1), **Anna Massmeyer** (1)**, Erika Di Giuseppe** (1)
Neil Ribe (1), **Philippe Carrez** (2), and **Patrick Cordier** (2)

(1) Laboratoire FAST (CNRS / Univ. Paris-Saclay), Orsay, France
(2) UMET-Unite Materiaux et Transformations, Univ. Lille / INRA / ENSCL / CNRS, Lille, France

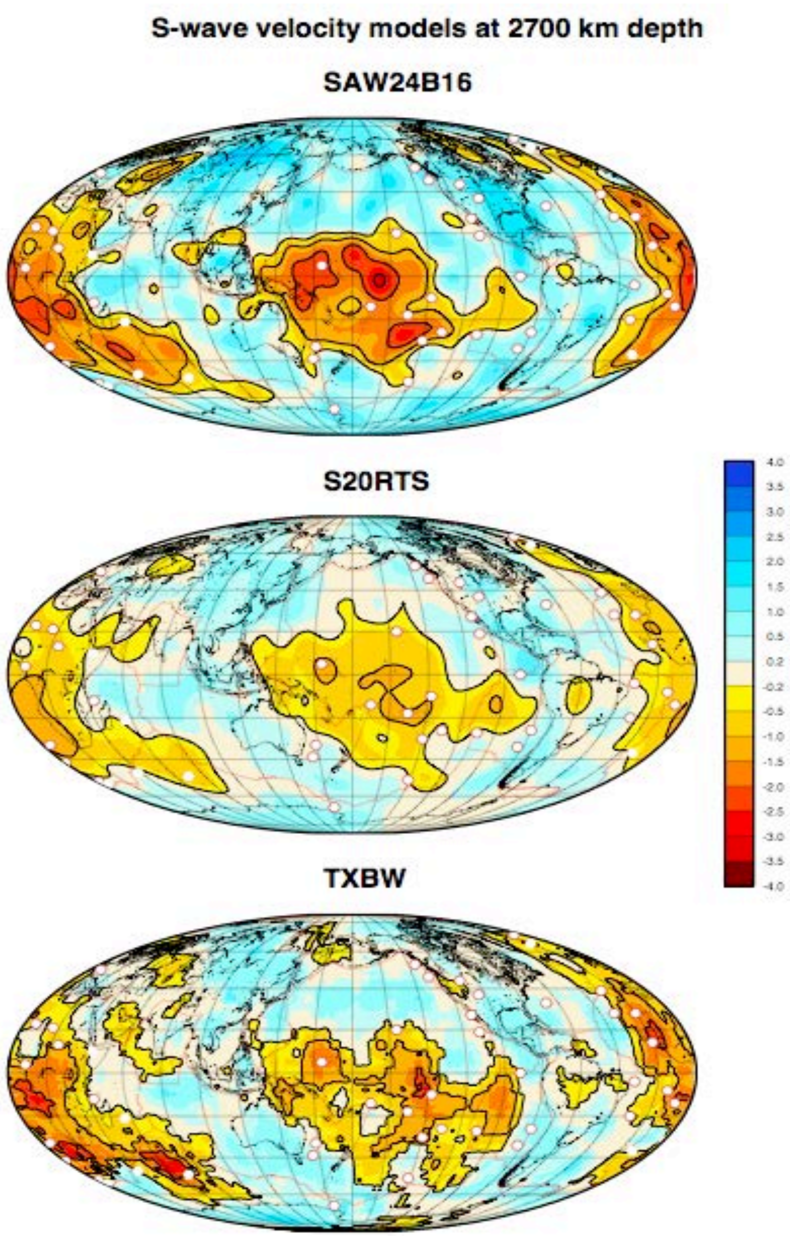


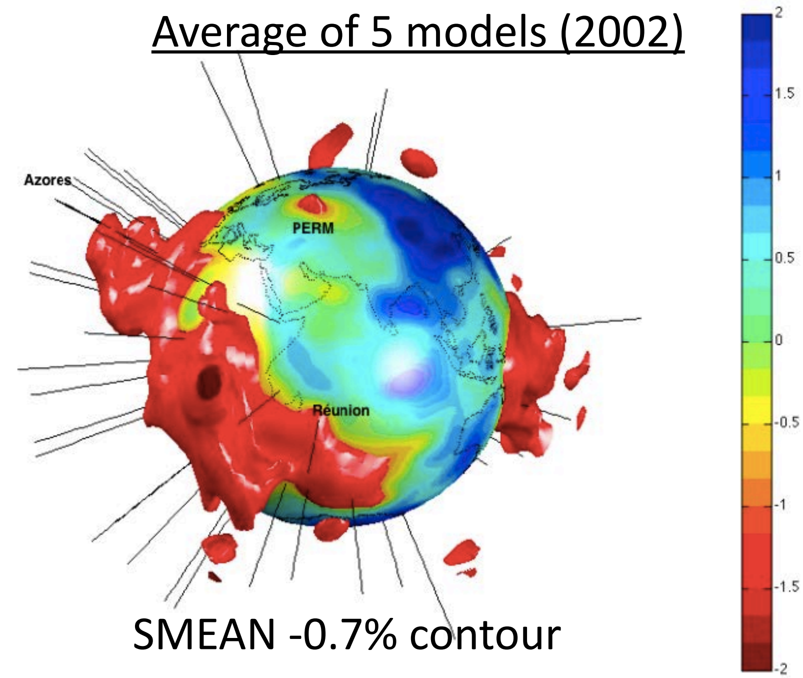




1-Observations: large-scale structures

1980s-Early 2000's

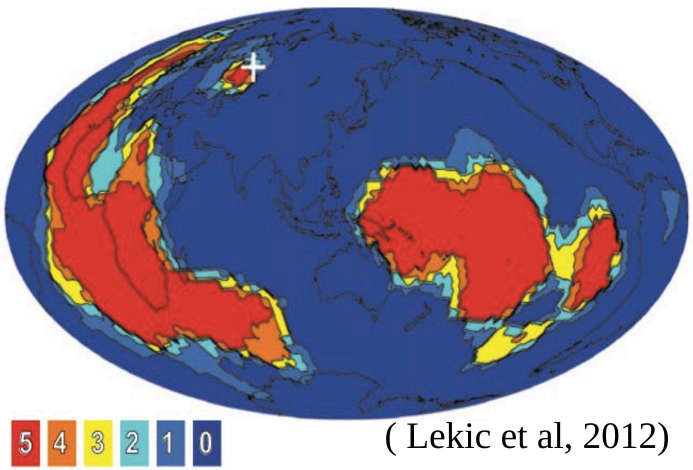




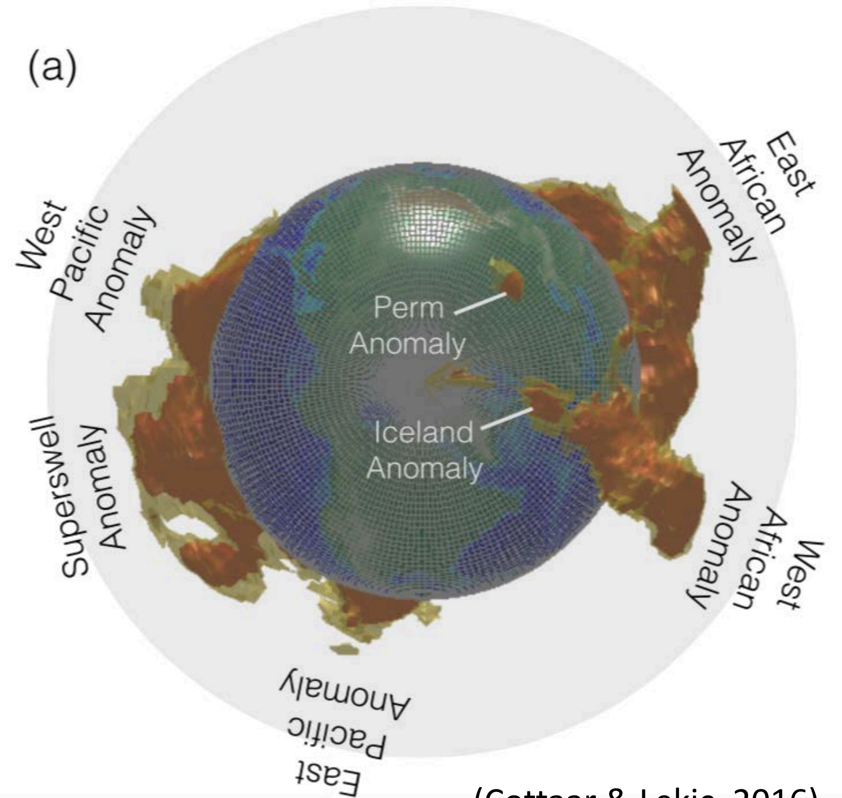
- 2 LLSVP delimited by subduction
- surface hotspots
- Chemical heterogeneities
    .anticorrelation of shear and bulk sound V
    .sharp edges

1-Observations: large-scale structures

Voting maps



(Lekic et al, 2012)



(Cottaar & Lekic, 2016)

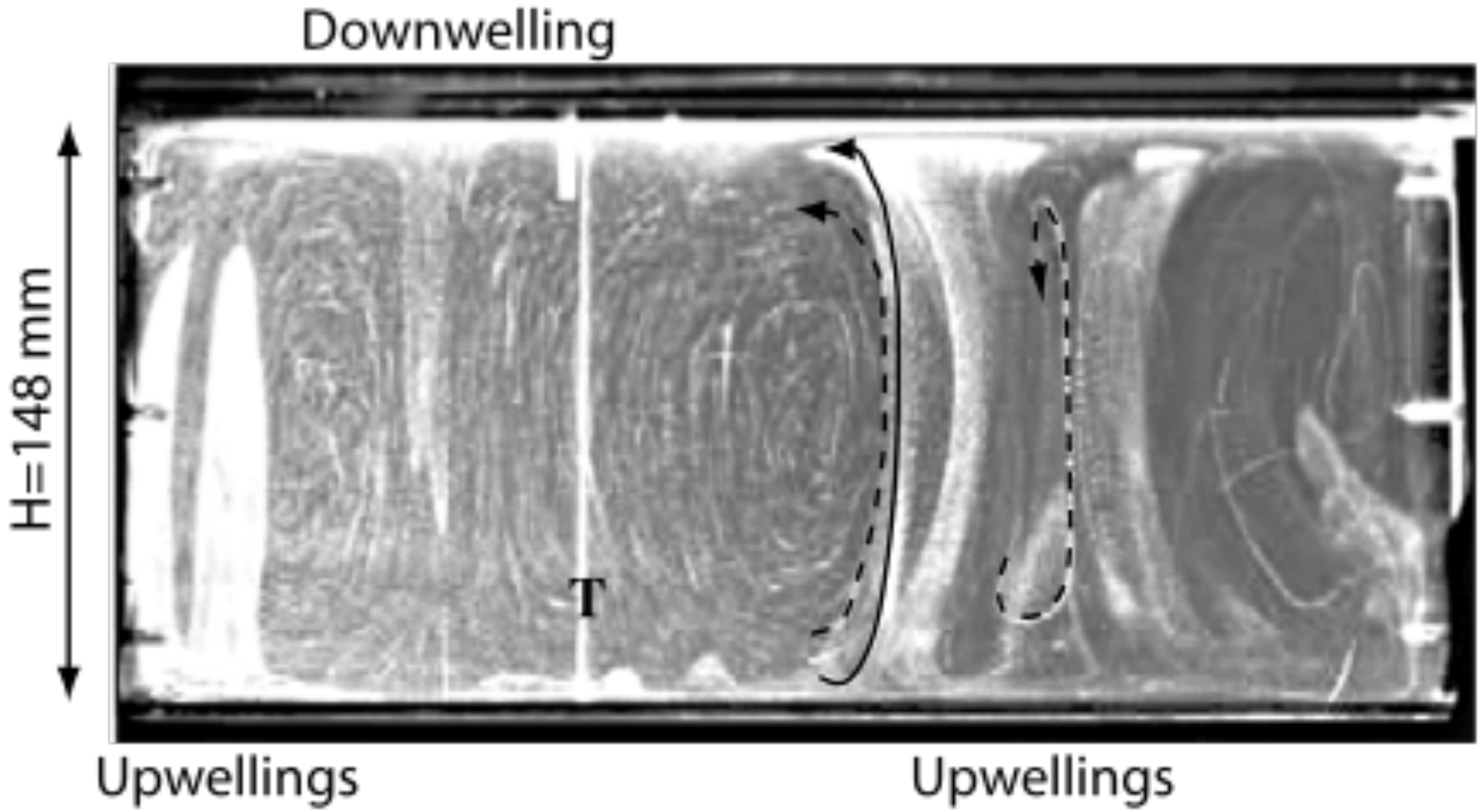
- 2 LLSVP + 1 + …
- chemical heterogeneity
- old material (e.g. Jackson et al, 2010)
- surface hotspots

=> Hot, stagnant, and denser piles ?

NB: Normal modes, tides, CMB topo => denser or lighter than ambient mantle ?

1-Convection characteristics

In a mantle with strongly temperature-dependent viscosity, the cold slabs circulation delimits the LLSVPs

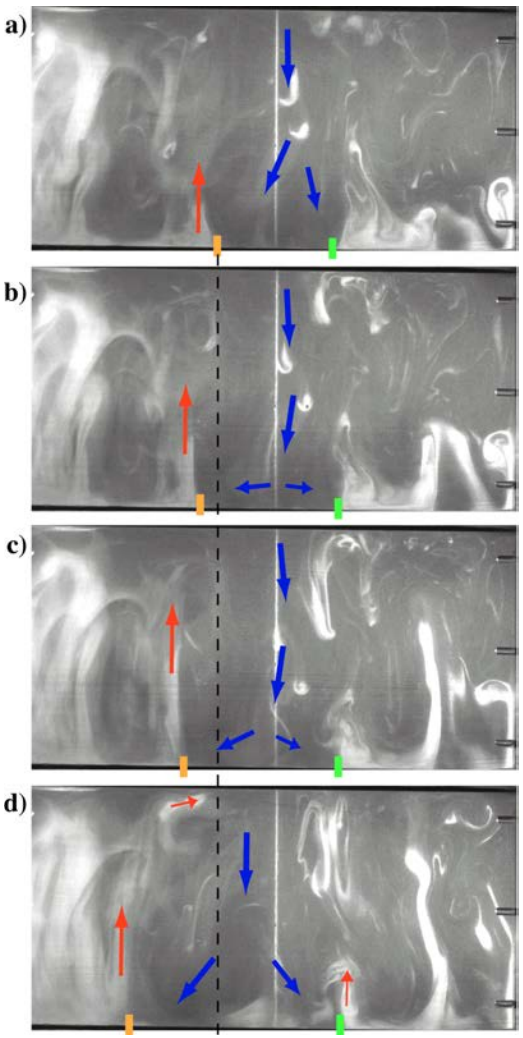


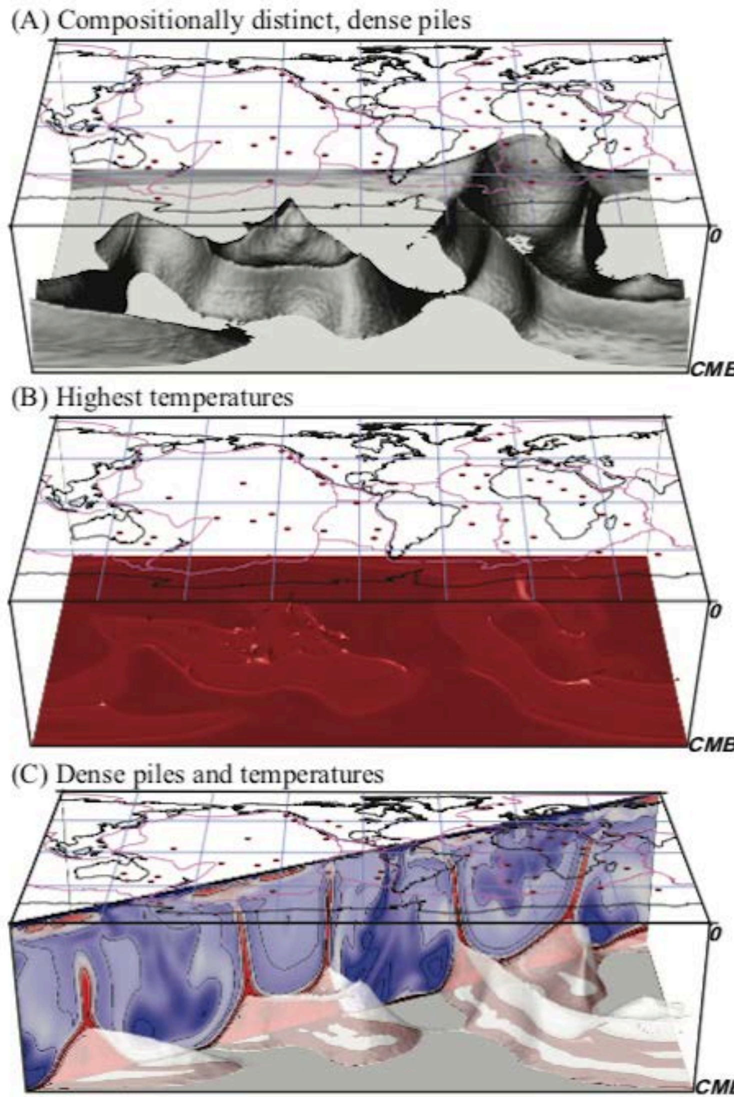
Ra ~ 4. 10^7 ; intermediate viscosity ratio

(Androvandi & al, 2009, 2011)

1-Convection characteristics

Even in the presence of a dense material at the bottom of the mantle, the cold slabs circulation creates LLSVPs





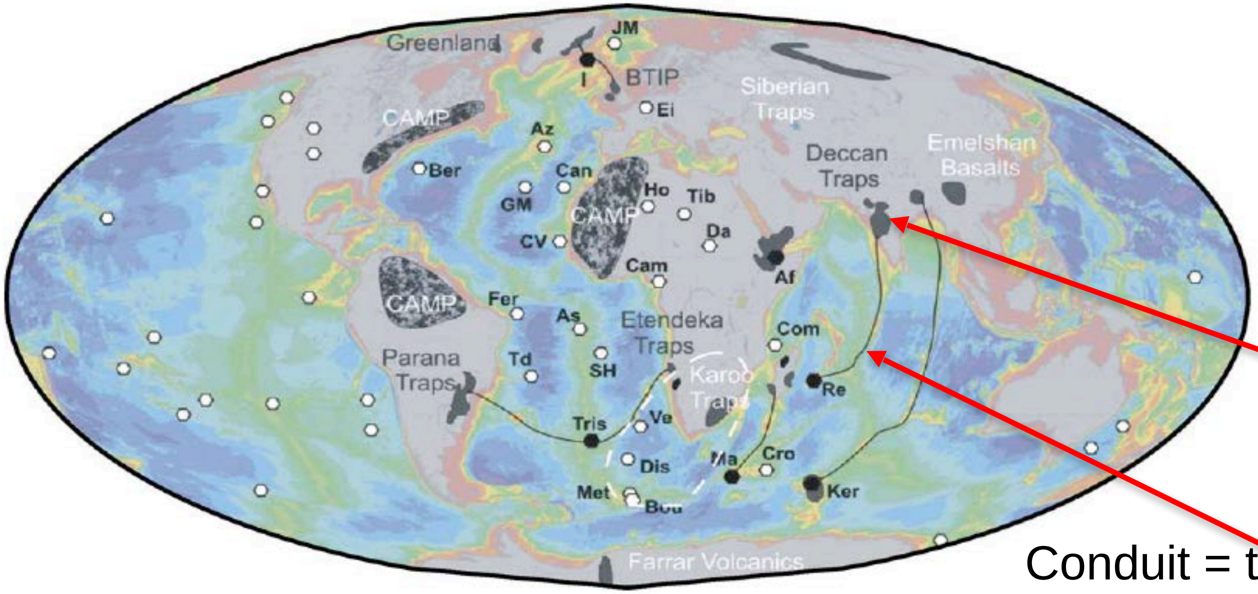
Patterns after 120 Myr of cold slabs history

(McNamara & Zhong, 2005)

2-Plumes characteristics

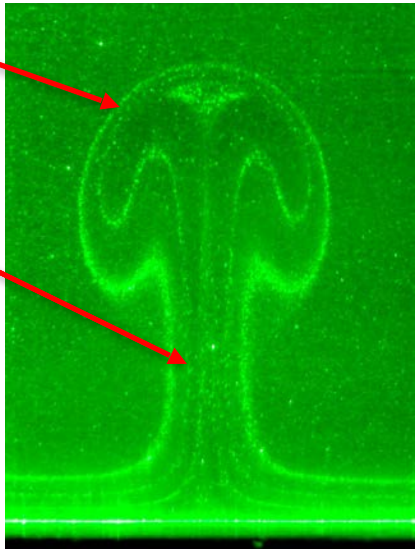
In a newtonian mantle when hot is less viscous

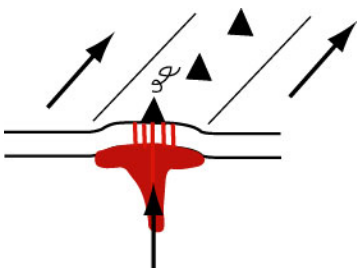
(Wilson, 1963; Morgan 1971, 1972; Richards et al, 1989; …)



Head = traps

Conduit = track





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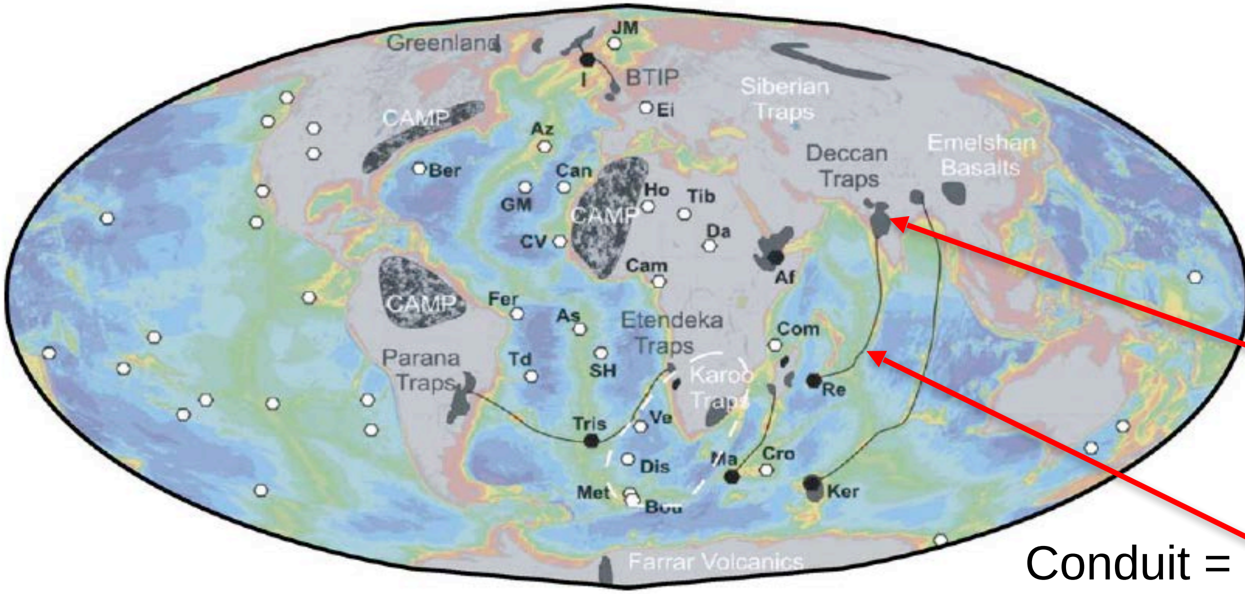
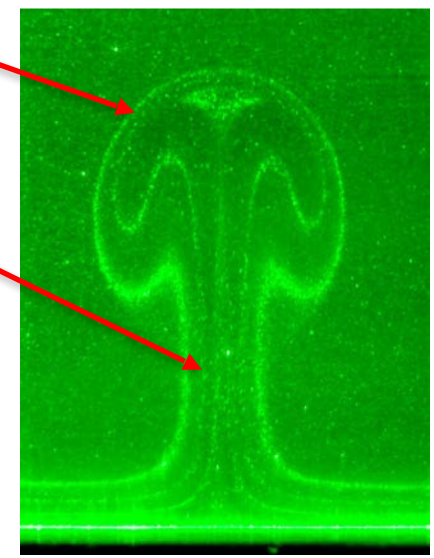


Head = traps

Conduit = track



Hot, less viscous => conduit diameter ~100-200 km

(e.g. Whitehead & Luther, 1975; Olson & Singer, 1985; Griffiths, 1986; Sleep, 1990 …)

=> Challenge for tomography

2-Slow (hot) seimic anomalies in the mantle:

Zhao (2001) large anomalies below ~ hotspots

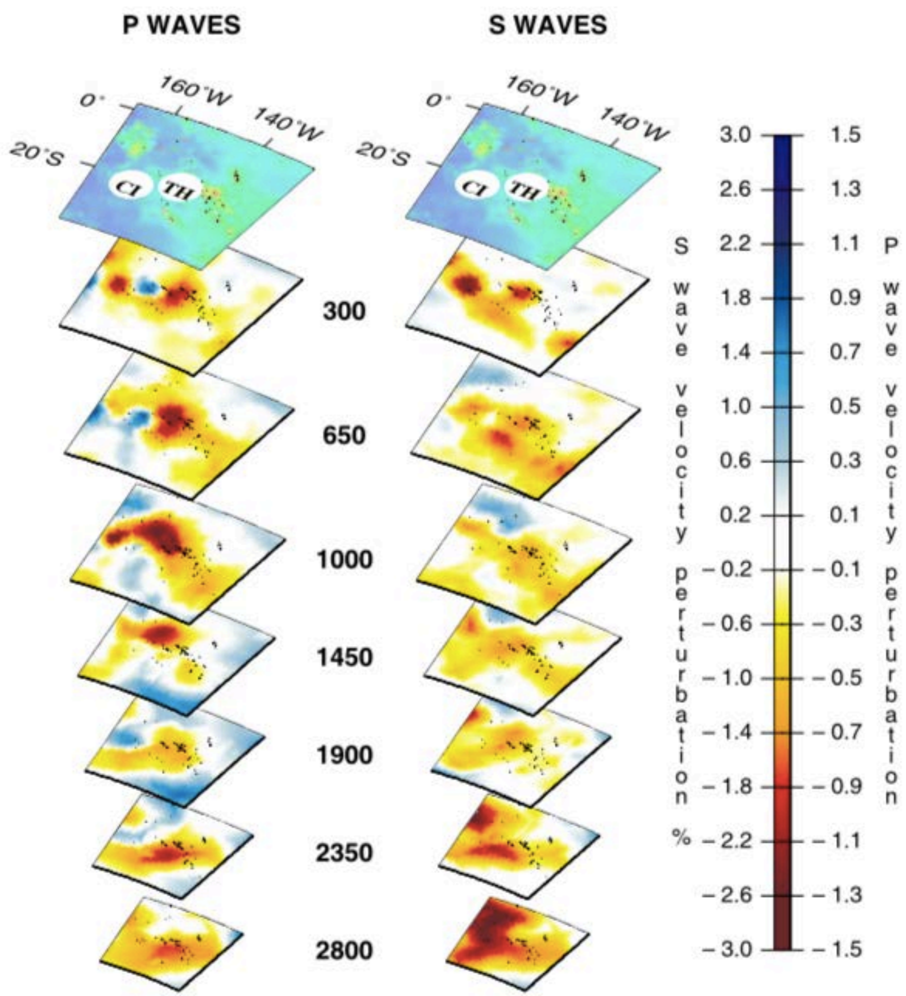


Figure 22. Three-dimensional view of the plumes beneath Cook Island and Tahiti in both the (left) *P*-model and (right) *S*-model. Plotting format as in Figure 12a.

.Travel times
.Finite frequency

<u>Resolution tests</u>:
D<600 km not visible

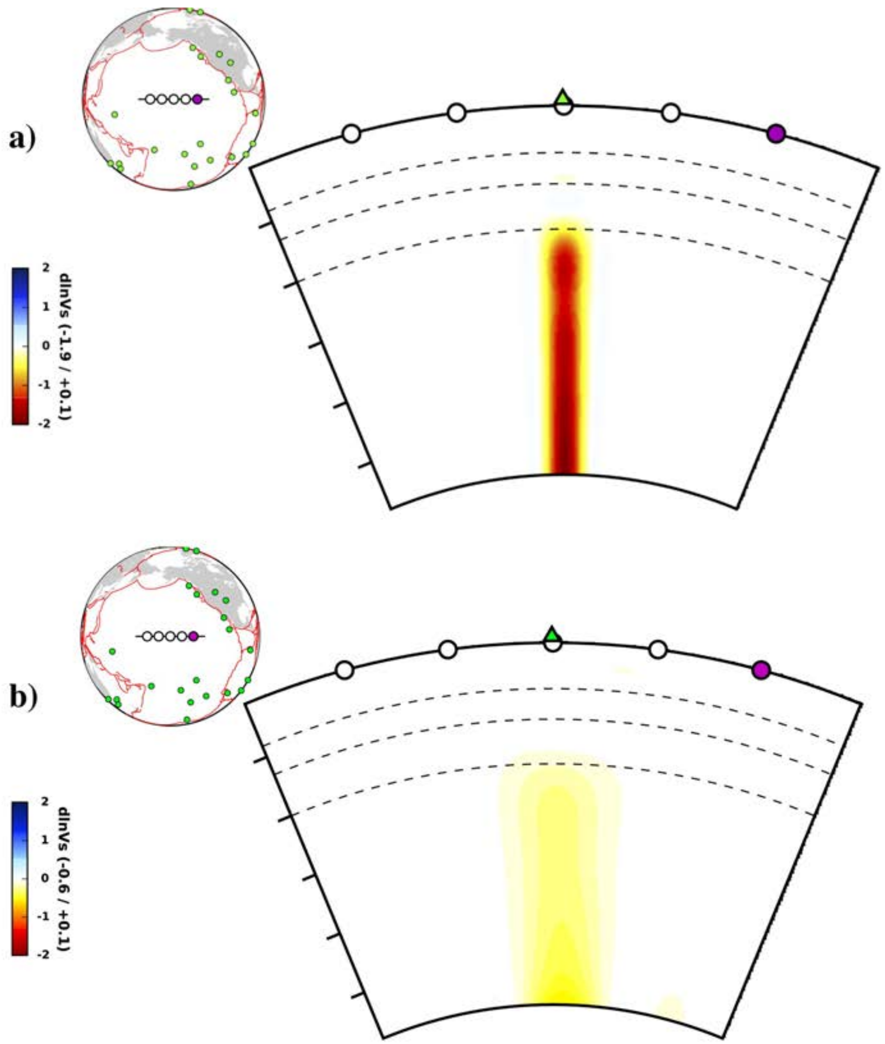
Below ~10 hot spots:
tubes with D~600-800 km

FAT plumes

(Montelli et al, 2004; 2006)

2-Slow (hot) seimic anomalies in the mantle:

Resolution: loss of amplitude (1/4) for cylinders 400 km in diameter

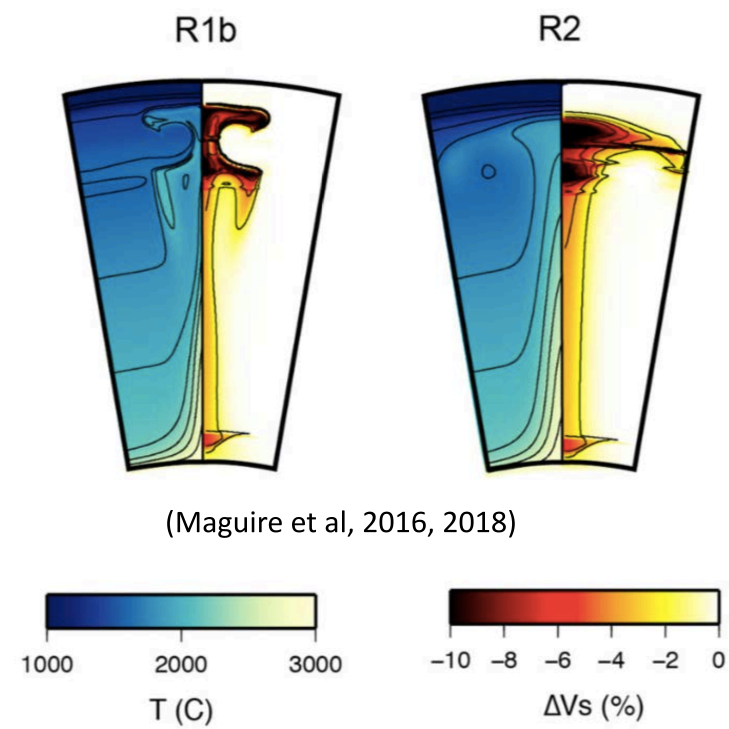


(French & Romanowicz, 2014, 2015)

⇒ **A purely thermal plume (=> thin) would be:**

hard to see

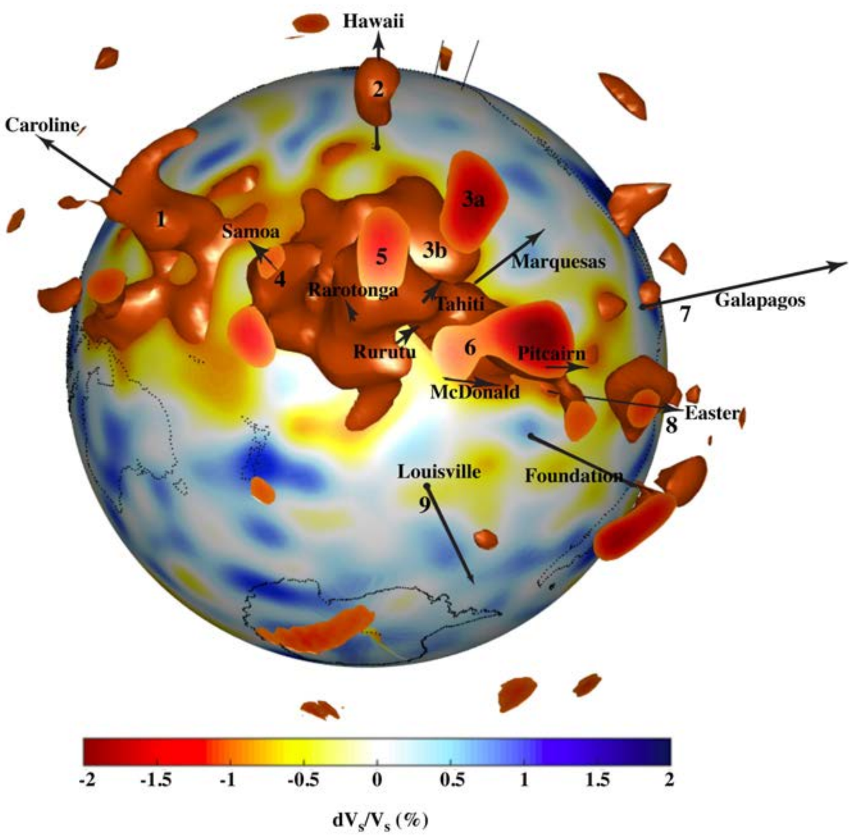
very attenuated

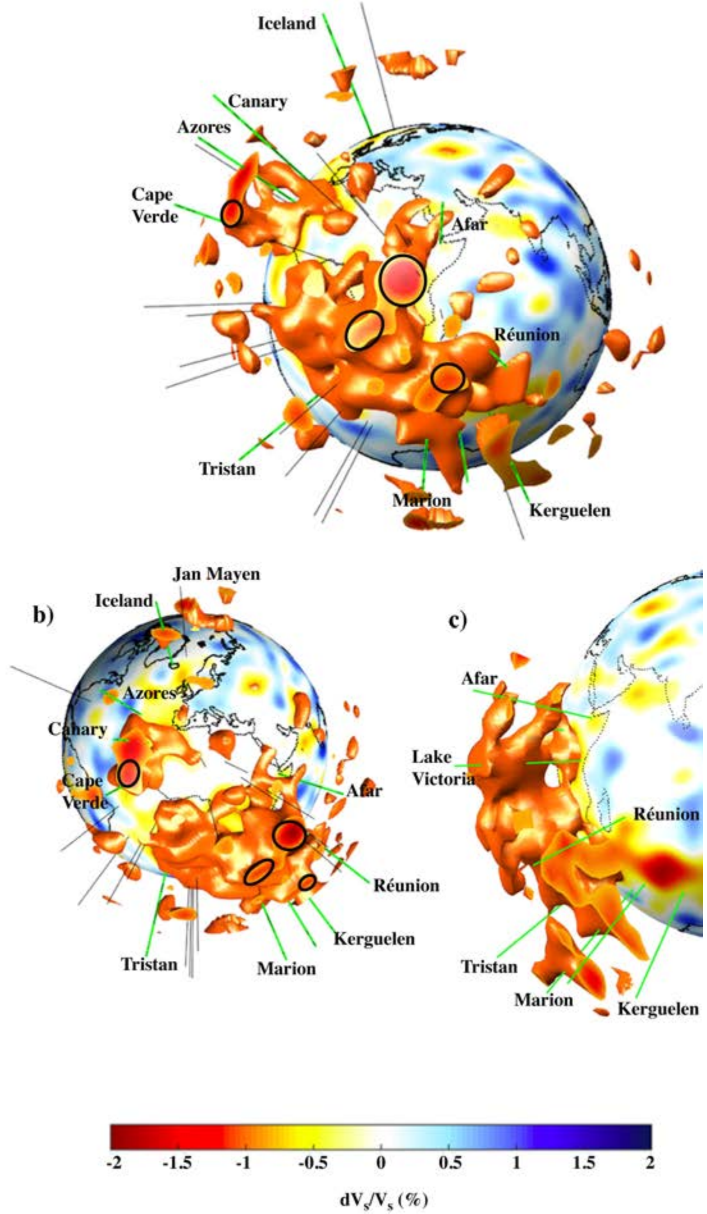


(Maguire et al, 2016, 2018)

2-Slow (hot) seimic anomalies in the mantle:

SEMUCB-WM1 (French & Romanowicz, 2014, 2015)

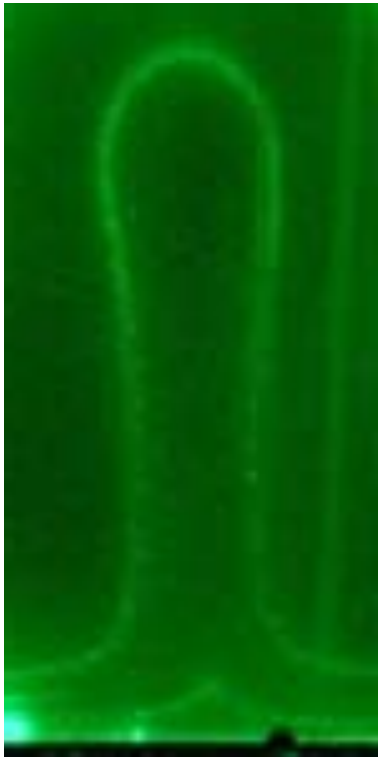


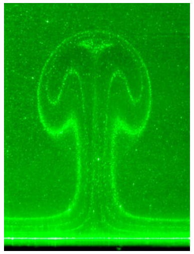


⇒ **At least 2 bundles of thermochemical plumes**

(Davaille & Romanowicz, 2020)

How to create fat plumes in a newtonian mantle ?





Finger morphology when a more viscous intrudes a less viscous material
(Whitehead & Luther, 1975; Olson & Singer, 1985)

. **Hot is more viscous**:

-> grain size (Solomatov, 1996 ; Korenaga, 2005)

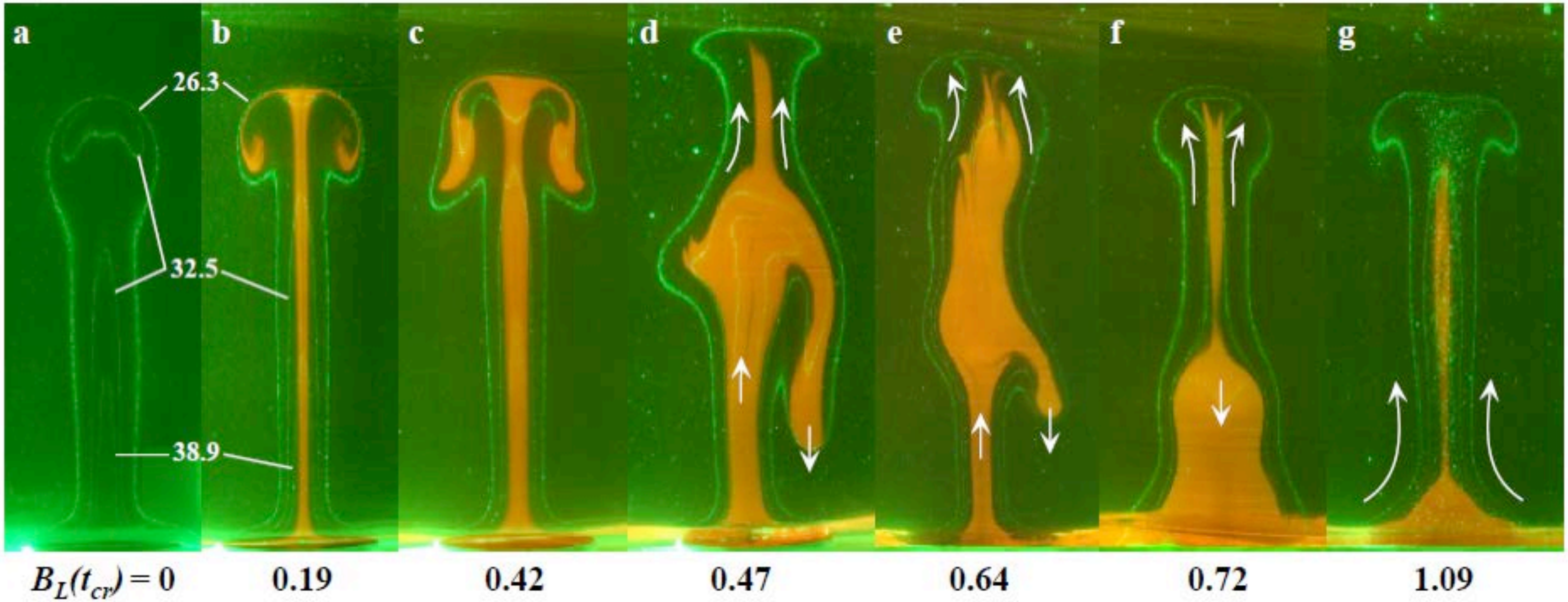
$$\dot{\gamma} = A\,\sigma^{n_E}\,d^{-p}\,f_{H_2O}\,exp\,(\beta\,\Phi)\;exp\left(-\frac{E^* + P\,V^*}{RT}\right)$$

How to create fat plumes in a newtonian mantle ?

. lower mantle is heterogeneous

=>Thermo-chemical plume

Initial buoyancy ratio $B_L=\Delta\rho_x/\rho_0\alpha\Delta T$



(Davaille et al, 2005; Kumagai et al, 2008; Lin & van Keken, 2006; Dannberg & Sobolev, 2015)

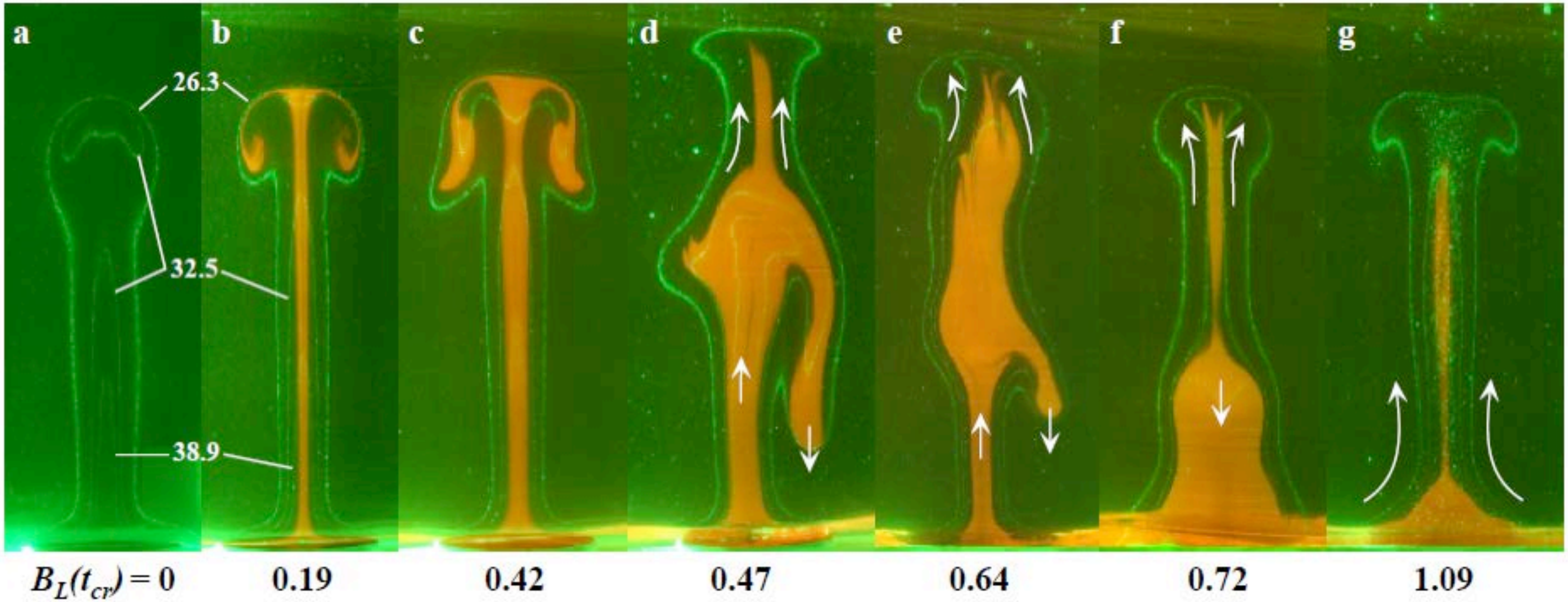
How to create fat plumes in a newtonian mantle ?

. **lower mantle is heterogeneous**

=>Thermo-chemical plume

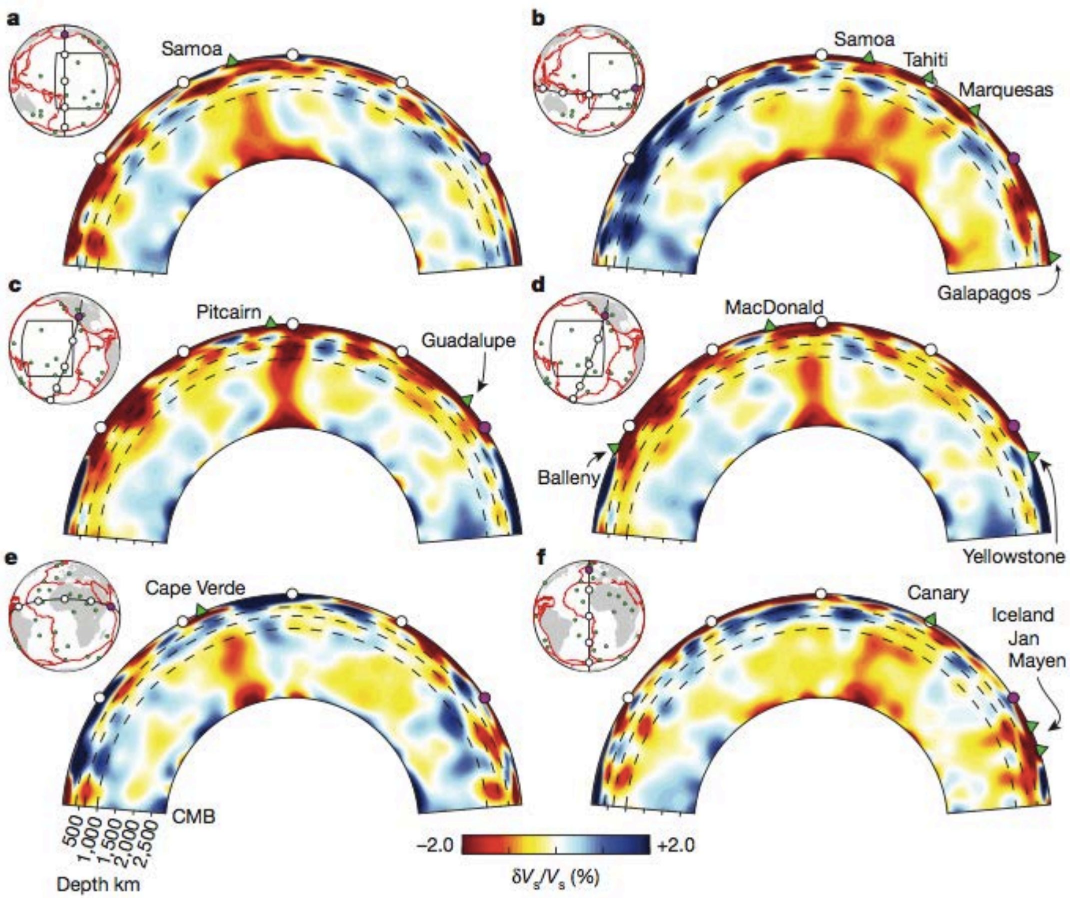
when recirculation within conduit => conduit thicker (x 2-5)

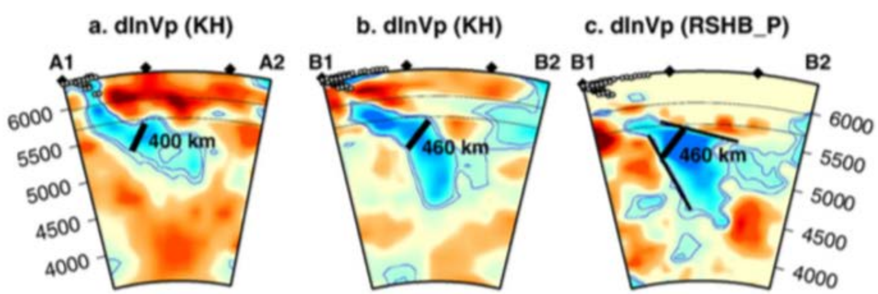
Initial buoyancy ratio $B_L = \Delta\rho_x / \rho_0 \alpha \Delta T$



(Davaille et al, 2005; Kumagai et al, 2008; Lin & van Keken, 2006; Dannberg & Sobolev, 2015)

3- Observations: « Horizon » around 800-1000 km depth





- Viscosity jump (Rudolph et al, 2015)?
- Chemical stratification (Ballmer et al,
- BEAMS (Ballmer et al, 2017)?

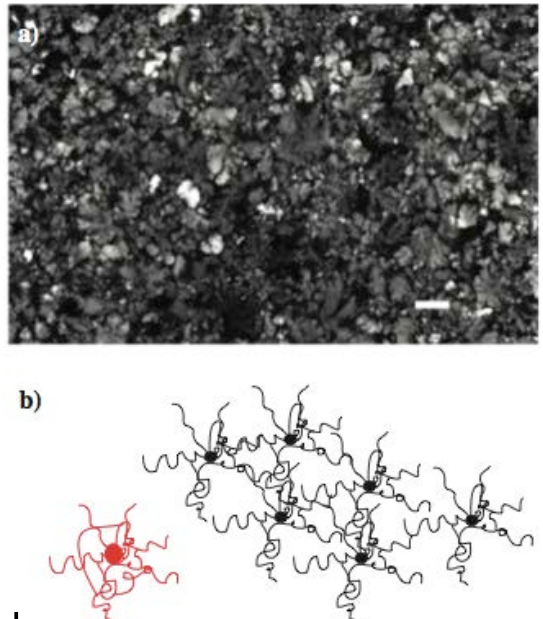
What if :

- fat plumes
- 1000 km-depth horizon
- fat slabs

were due to the complex nature of lower mantle rheology ?

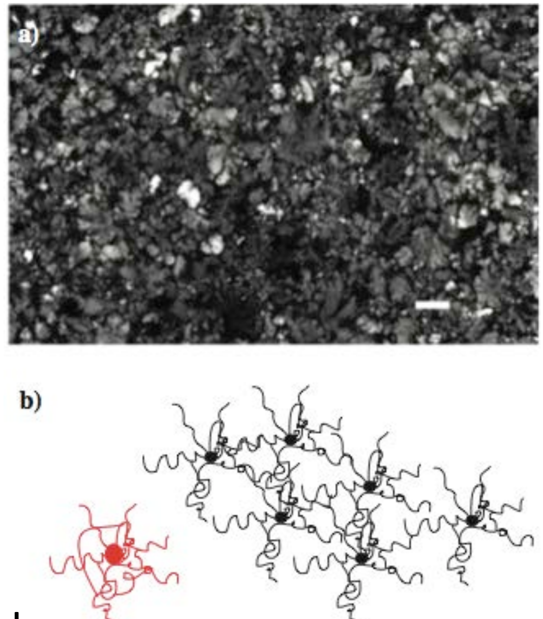
Several phases and compositions, texture

4-Texture and jamming:

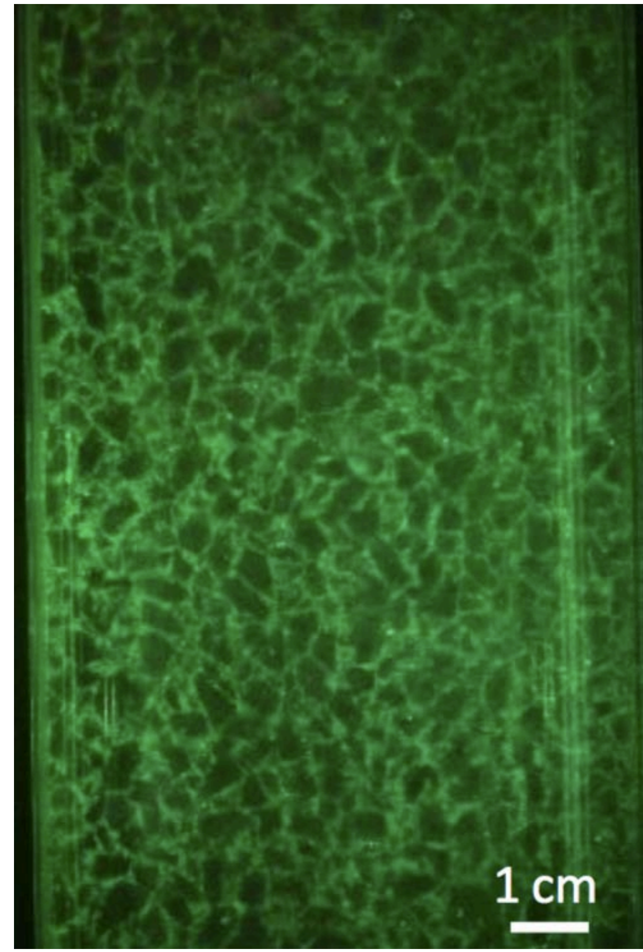


Carbopol

4-Texture and jamming:

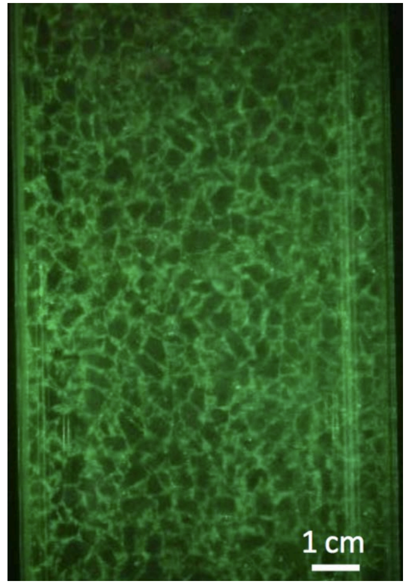


Carbopol



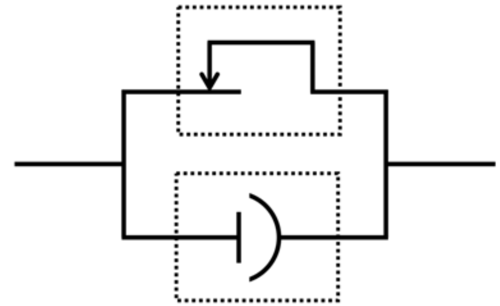
Hydrogels (Sgreva et al, 2020)

4-Texture and jamming:



Carbopol

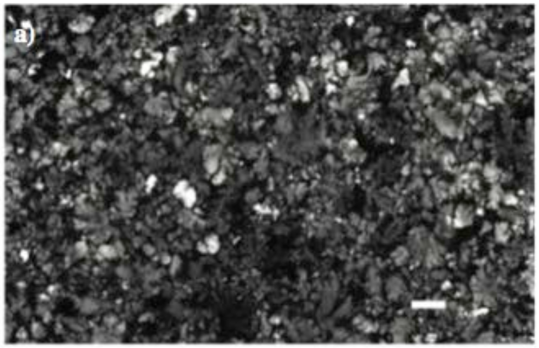
Saint-Venant body: σ_Y



Non linear damper (Norton): K, n

$$\sigma = \sigma_0 + K_v \dot{\gamma}^{n_{\mathrm{HB}}}$$

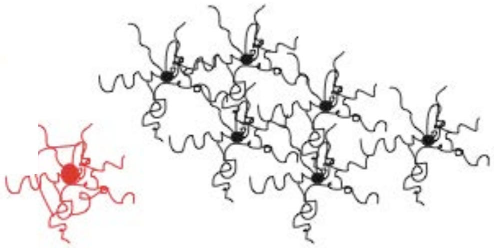
5- FAT plumes in a visco-plastic fluid



. Carbopol ETD 2050 + glycerin + water, pH=5-7

for $\sigma < \sigma_0$, elastic

for $\sigma > \sigma_0$, Herschel-Bulkley:: $$\sigma = \sigma_0 + K_v \dot{\gamma}^{n_{HB}}$$

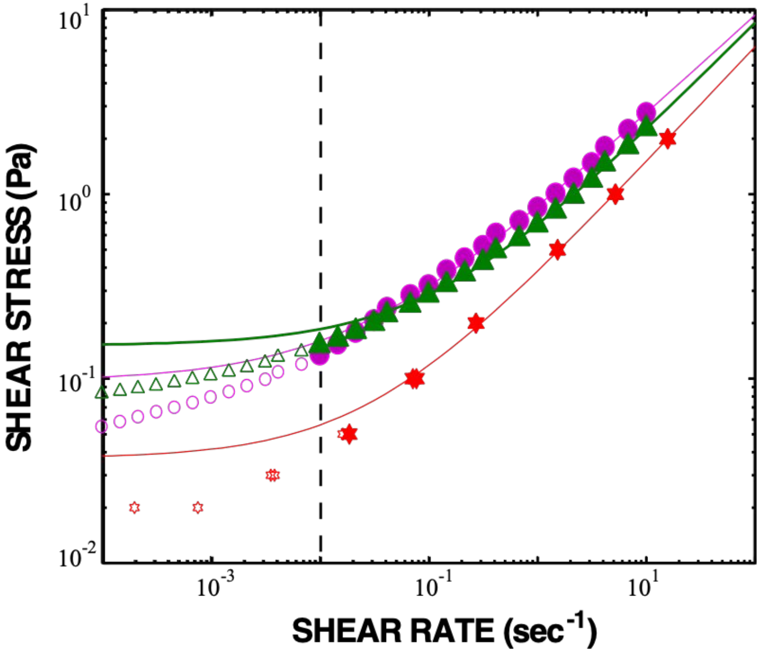


σ_0 = yield stress, comes from structure jamming

n_{HB} = 0.3-0.75;
σ_0 = 0.02-0.4 Pa
K_v = 0.3 - 2.5 (Tp-dependent)

=> $$\eta = \sigma / \dot{\gamma} = \sigma_0 \dot{\gamma}^{-1} + K_v \dot{\gamma}^{n_{HB}-1}$$

NB: Earth => $n_E = 1/n_{HB}$ ~3



(Davaille et al, JNNFM, 2013; Massmeyer et al, 2013; Di Giuseppe et al, 2015)

5- Convection in a visco-plastic fluid

-Homogeneous Temperature on the Cu plates

-Good insulation of the side walls

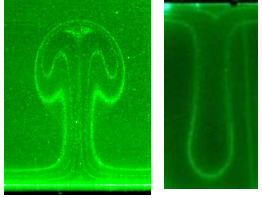
$\Rightarrow$Very nice linear
unstable temperature gradient

For 3 weeks…. NEVER became unstable.

=> NEED of a finite amplitude perturbation
(e.g. Zhang & Frigaard, 2007)

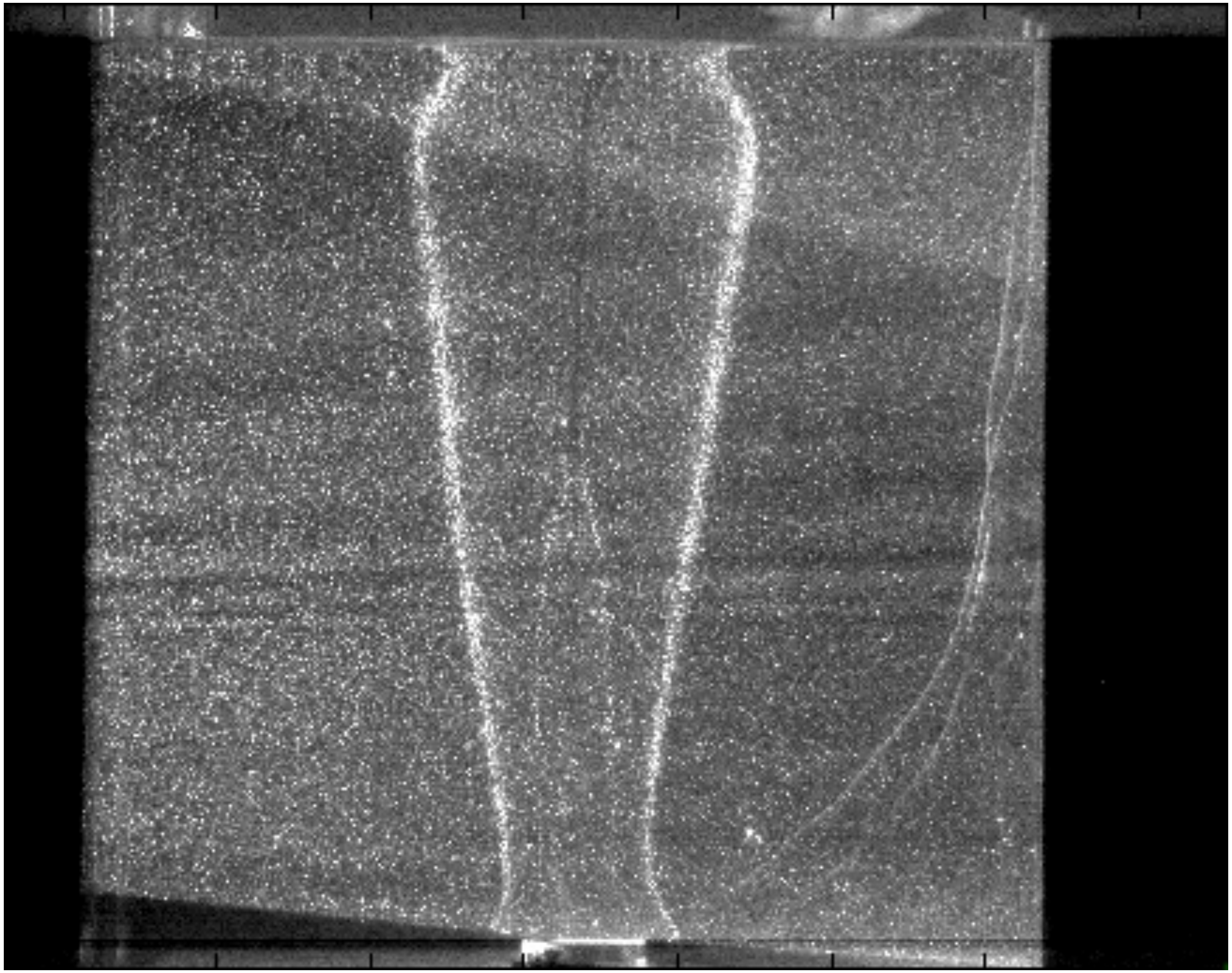
ex: shake the tank !!
Localized heating
Compositional heterogeneities
Impacts, …

5- FAT plumes in a visco-plastic fluid



Less viscous mushroom
More viscous finger

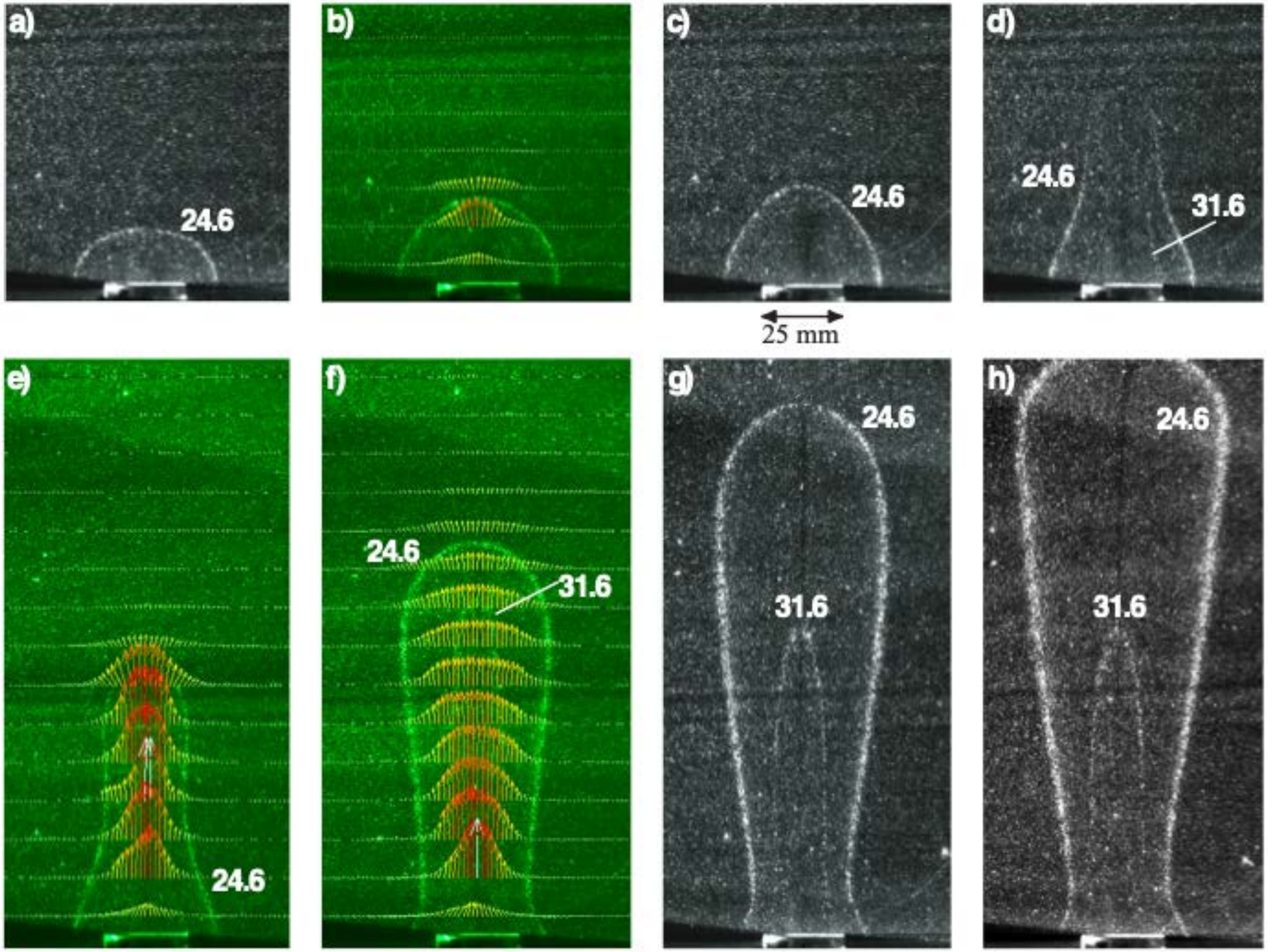
CARBOPOL: P = 4.15 W, Y_0 = 554   (time x 250)



Fat finger

The isotherms are: 23°C, 27°C, 31°C, 35°C, 39°C.

5- FAT plumes in a visco-plastic fluid



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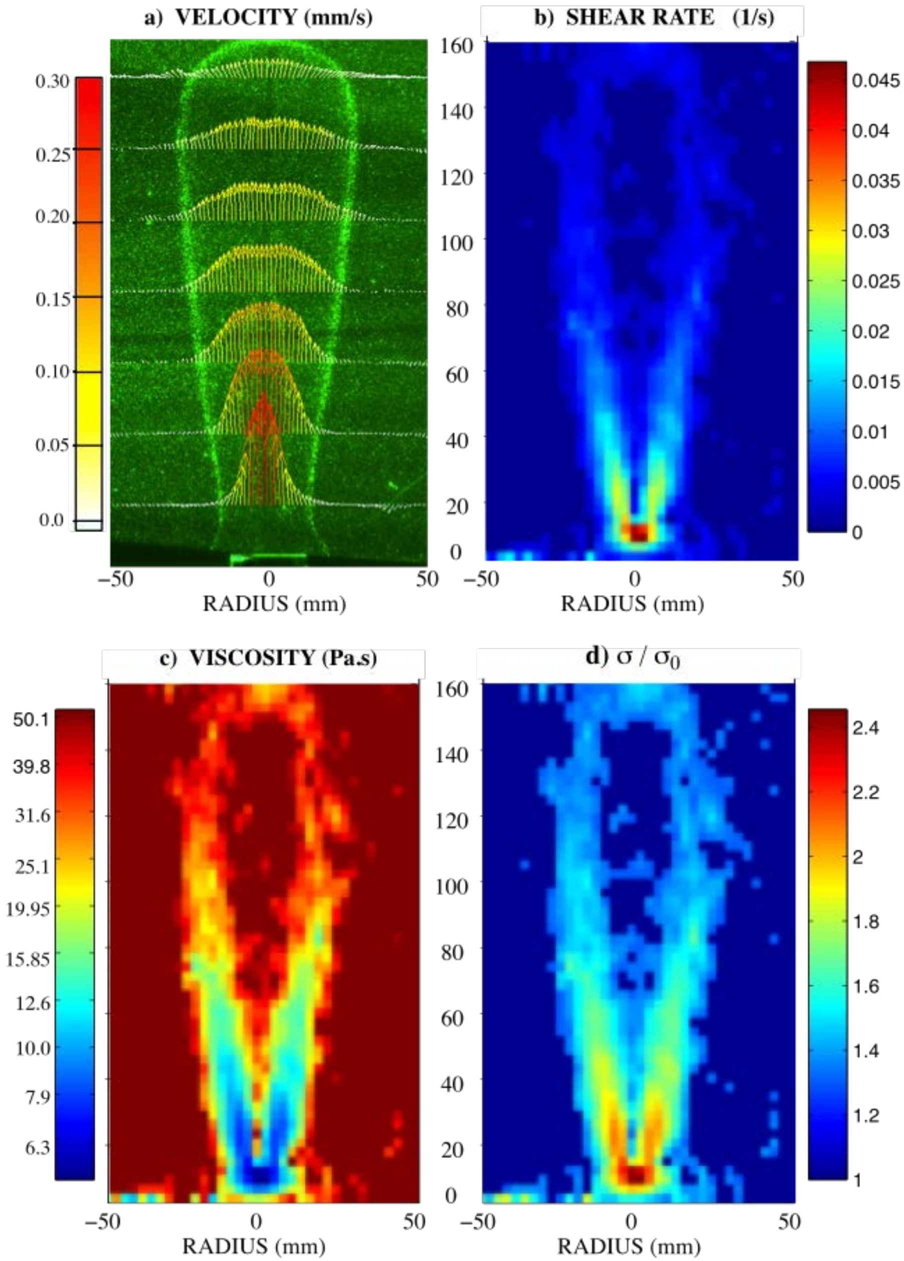
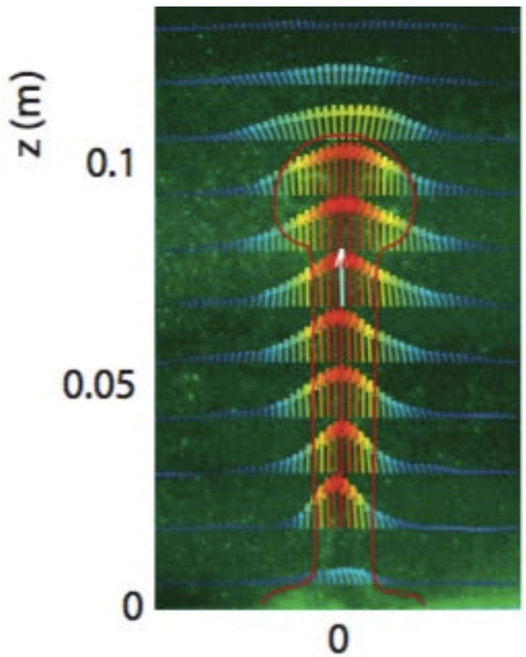


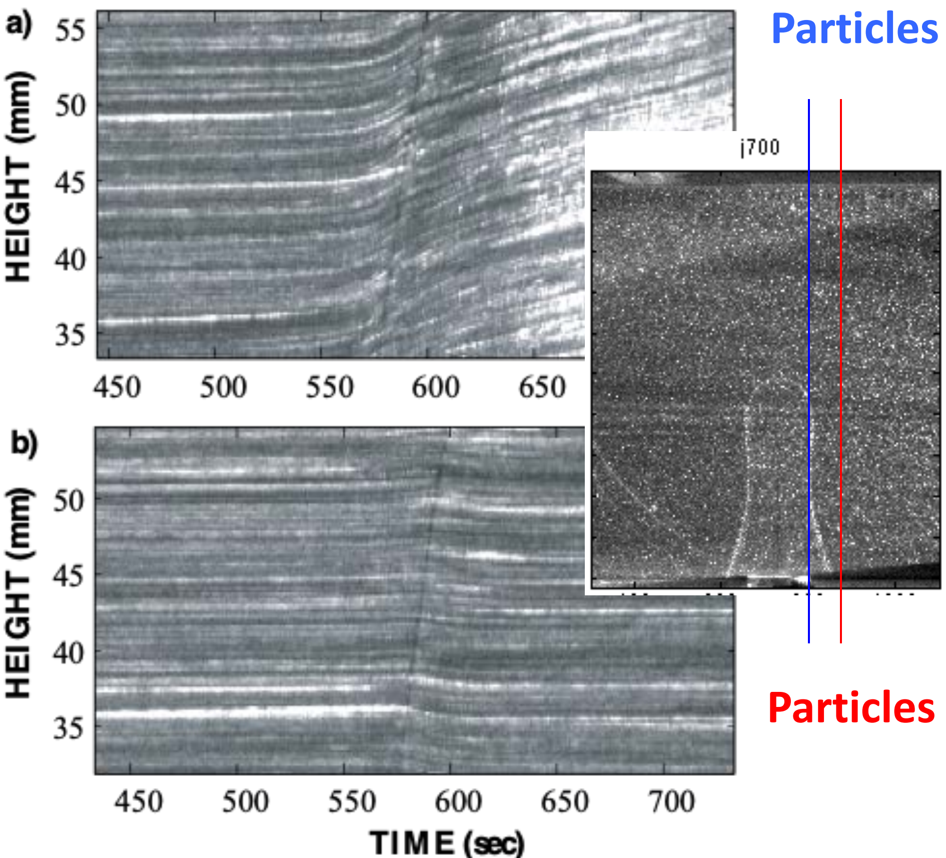
- **Strong shear localization**
- **Pseudo-Plug flow**



Newtonian plume

5- FAT plumes in a visco-plastic fluid

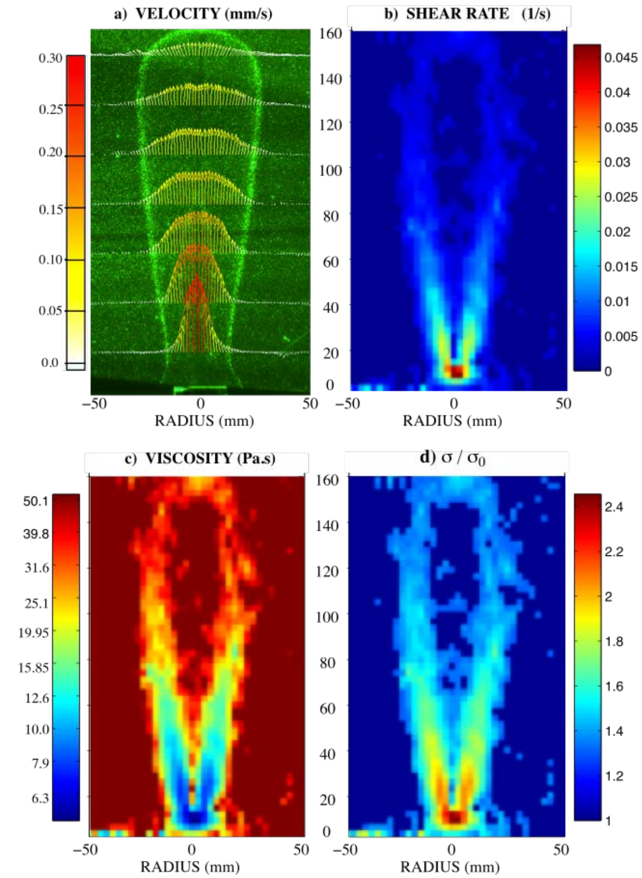
- **Strong shear localization**
- **Pseudo-Plug flow**



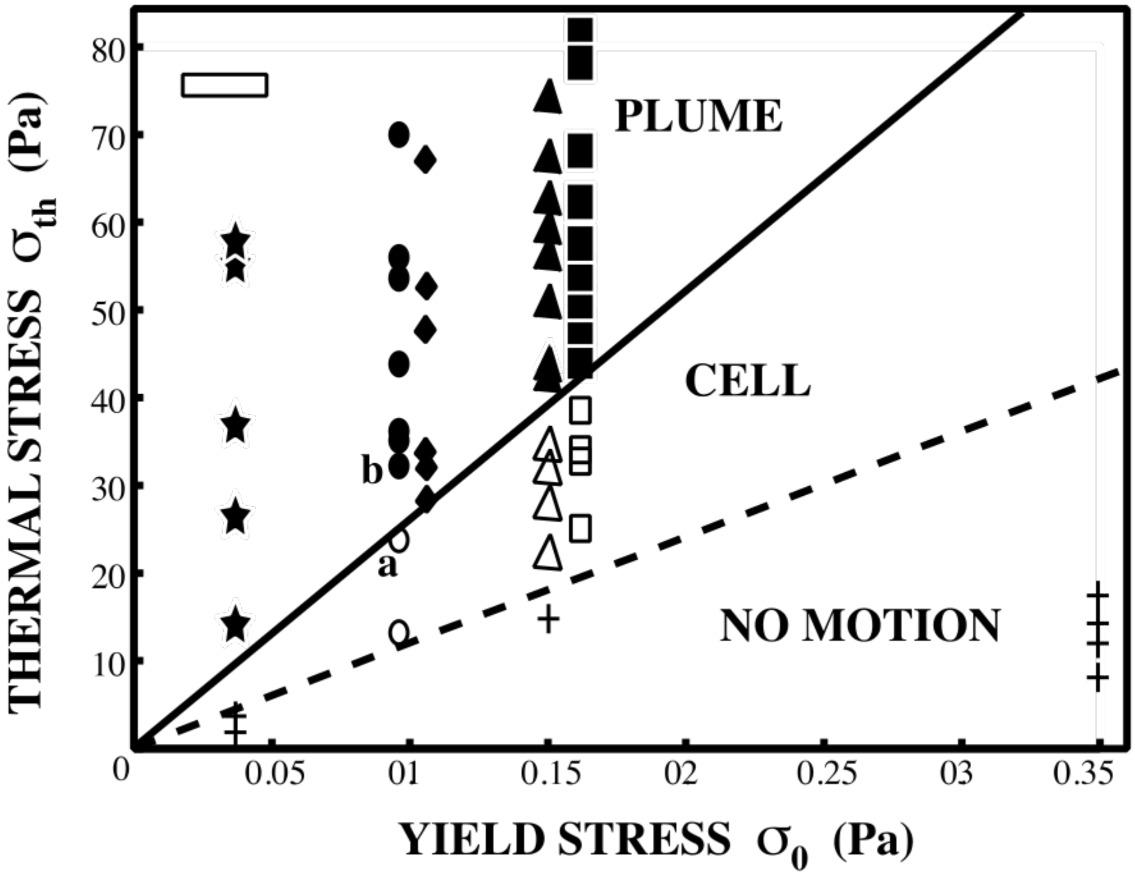
Particles going up

Particles going down

P = 4.15 W, Y_0 = 554



5- FAT plumes in a visco-plastic fluid

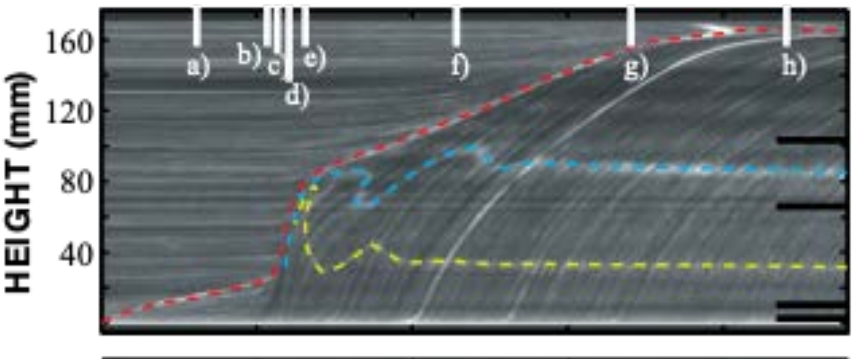


$$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6$$

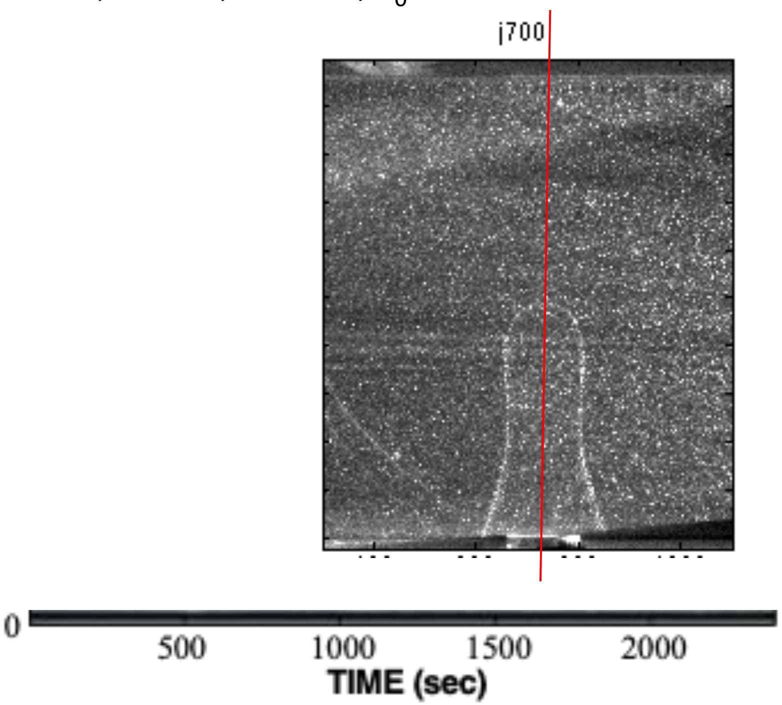
=> Plume

Fat Finger => 10 Y_c > Y_0 > Y_c

5- FAT plumes in a visco-plastic fluid

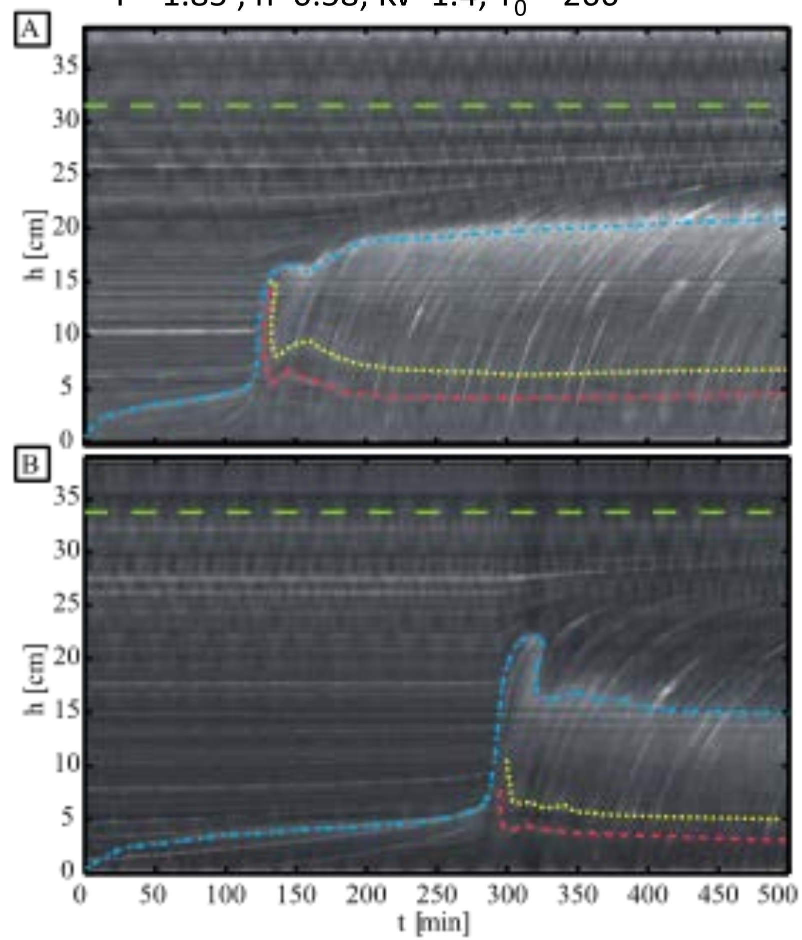


P = 4.15 W; n=0.54; Kv=0.76; Y_0 = 554



Unyielded regions

P =1.85 ; n=0.58; Kv=1.4; Y_0 = 266



The plume can stop before reaching the surface

5- FAT plumes in a visco-plastic fluid

(1) $Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6$ => **Plume**

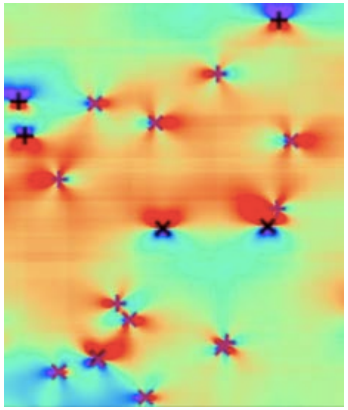
Fat Finger => $10\, Y_c > Y_0 > Y_c$

(2) $Bi = \frac{\sigma_Y}{K_v \dot{\gamma}^{n_{HB}}} < 1.0$ => **rising**

=> Characteristic (minimum) strain rate

$$\dot{\gamma}_c = (\sigma_Y / K_v)^{1/n_{HB}}$$

6- A visco-plastic rheology for a Bridgmanite lower mantle ?

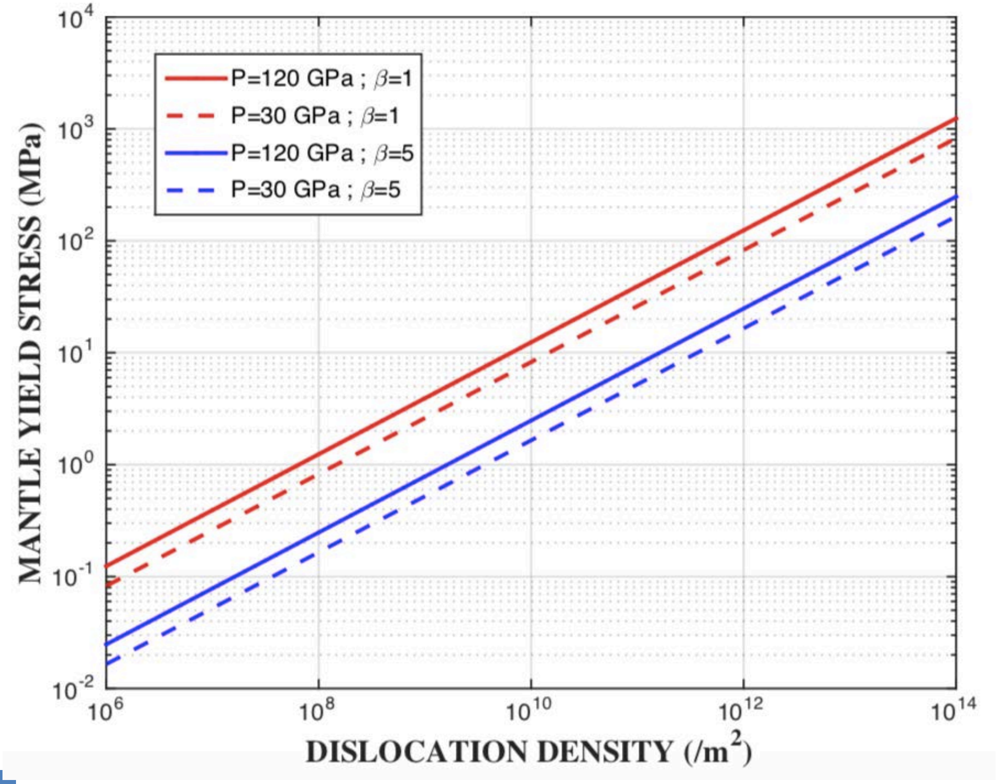


. Each dislocation creates a stress field
. Dislocations interact => **jamming**

dislocation climb

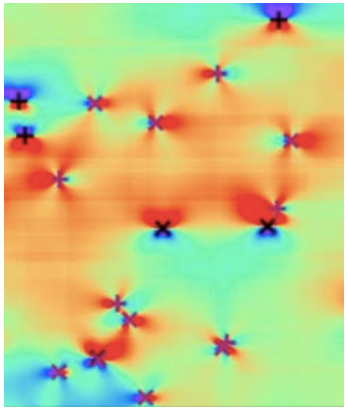
=> **Need to overcome a critical stress to start motion**

$$\sigma_y \propto \frac{Gb}{\beta l} = \frac{1}{\beta} G b \rho_d^{1/2}$$



G=shear modulus
b=Burgers vector
β=1-5
(Friedel, 1964)

6- A visco-plastic rheology for a Bridgmanite lower mantle ?



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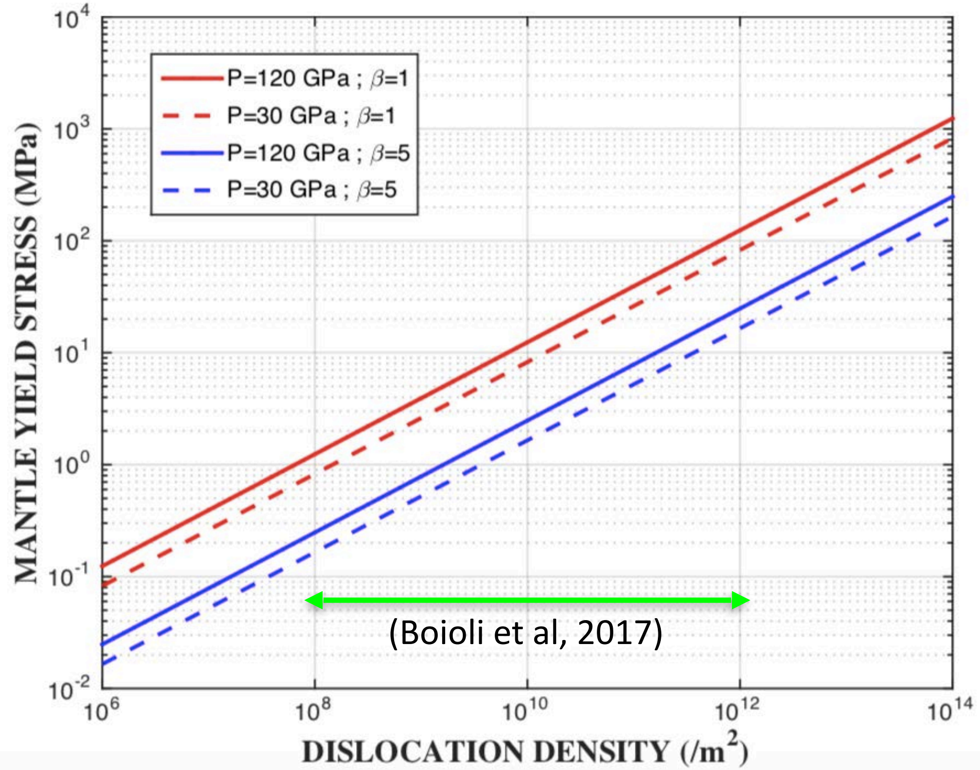

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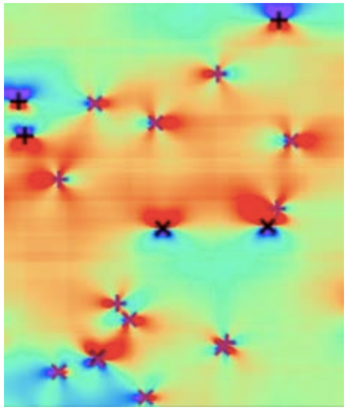


. Each dislocation creates a stress field
. Dislocations interact => jamming
. Once motion starts => **shear-thinning** (Nabarro, 1967; Reali et al, 2019)

dislocation climb

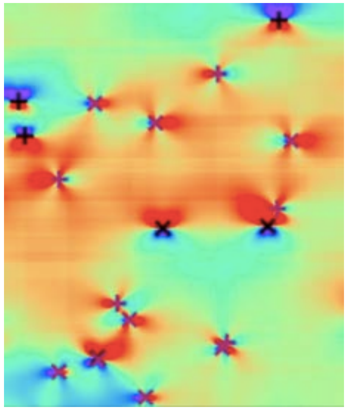
$$\dot{\gamma} = \frac{D^{sd} G b}{\pi k_B T} \left(\frac{\sigma}{G}\right)^3 / ln\left(\frac{4G}{\pi\sigma}\right)$$

with: $$D_{sd} = X_v D_v$$ Self-diffusion coefficient

$$D_v = \frac{Z l^2 \nu}{6} exp\left(\frac{\Delta H_M}{RT}\right)$$ Vacancy diffusion coefficient

X_v vacancy concentration (~ 10^{-6} - 10^{-2})

6- A visco-plastic rheology for a Bridgmanite lower mantle ?



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dislocation climb

So

$$\sigma = \sigma_0 + K_v \dot{\gamma}^{n_{\mathrm{HB}}}$$

with

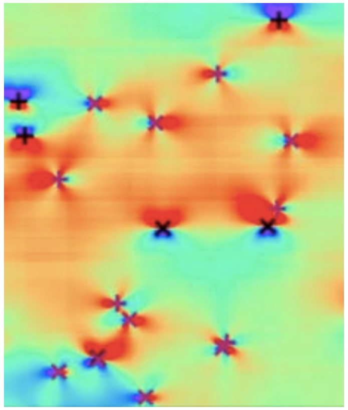
$$\sigma_y \propto \frac{Gb}{\beta l} = \frac{1}{\beta} G b \rho_d^{1/2}$$

$$K_v = \frac{G}{f} \left(\frac{D^{sd} G b}{\pi k_B T}\right)^{-1/3}$$

=> depends on vacancy concentration

$$n_{HB} = 1/3$$

6- A visco-plastic rheology for a Bridgmanite lower mantle ?



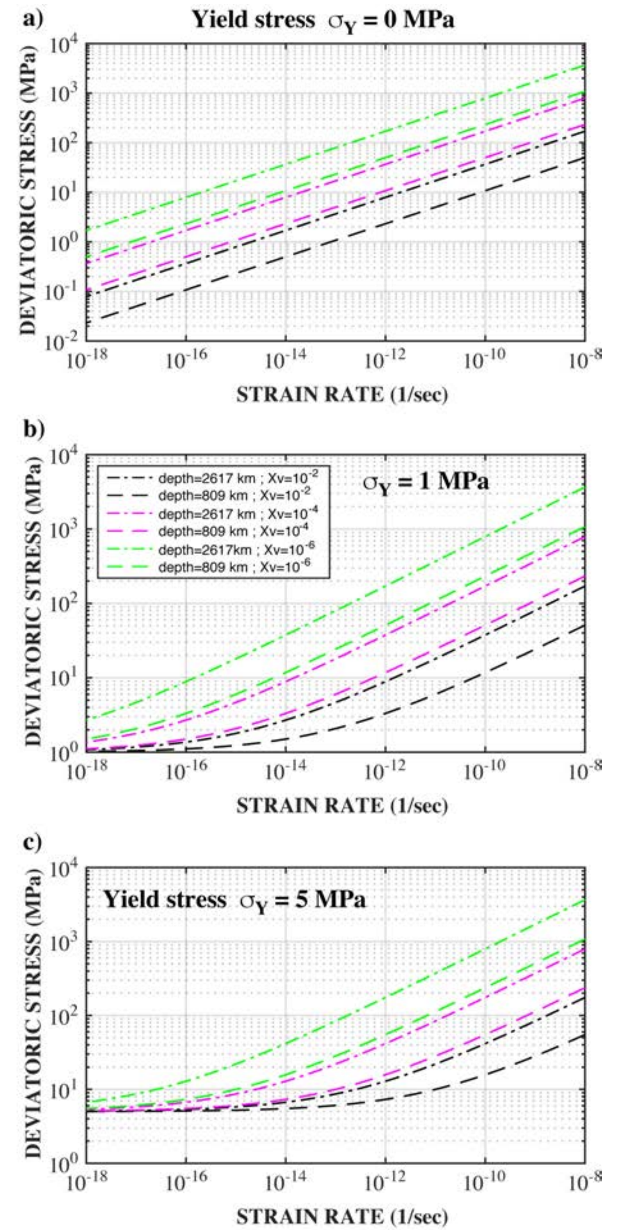
. Each dislocation creates a stress field
. Dislocations interact => jamming
. Once motion starts => **shear-thinning**

So $$\sigma = \sigma_0 + K_v \dot{\gamma}^{n_{\mathrm{HB}}}$$

with $$\sigma_y \propto \frac{Gb}{\beta l} = \frac{1}{\beta} G b \rho_d^{1/2}$$

$$K_v = \frac{G}{f}\left(\frac{D^{sd} G b}{\pi k_B T}\right)^{-1/3}$$

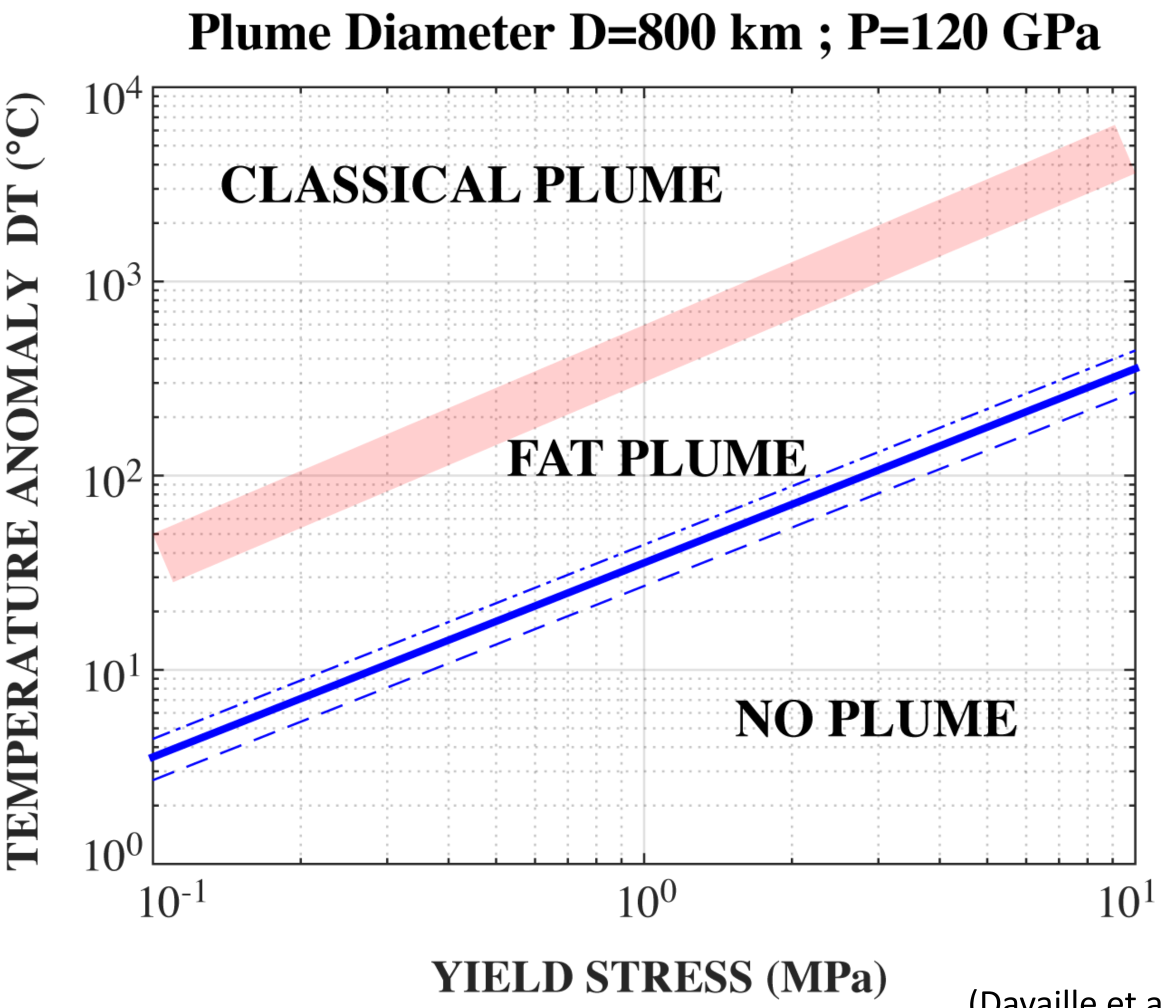
$$n_{HB} = 1/3$$



Lab measurements cannot see the yield stress !

7- FAT plumes in a Bridgmanite mantle

(1) $$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6 \quad ; \quad \Delta\rho = \alpha\rho\Delta T_{av}$$

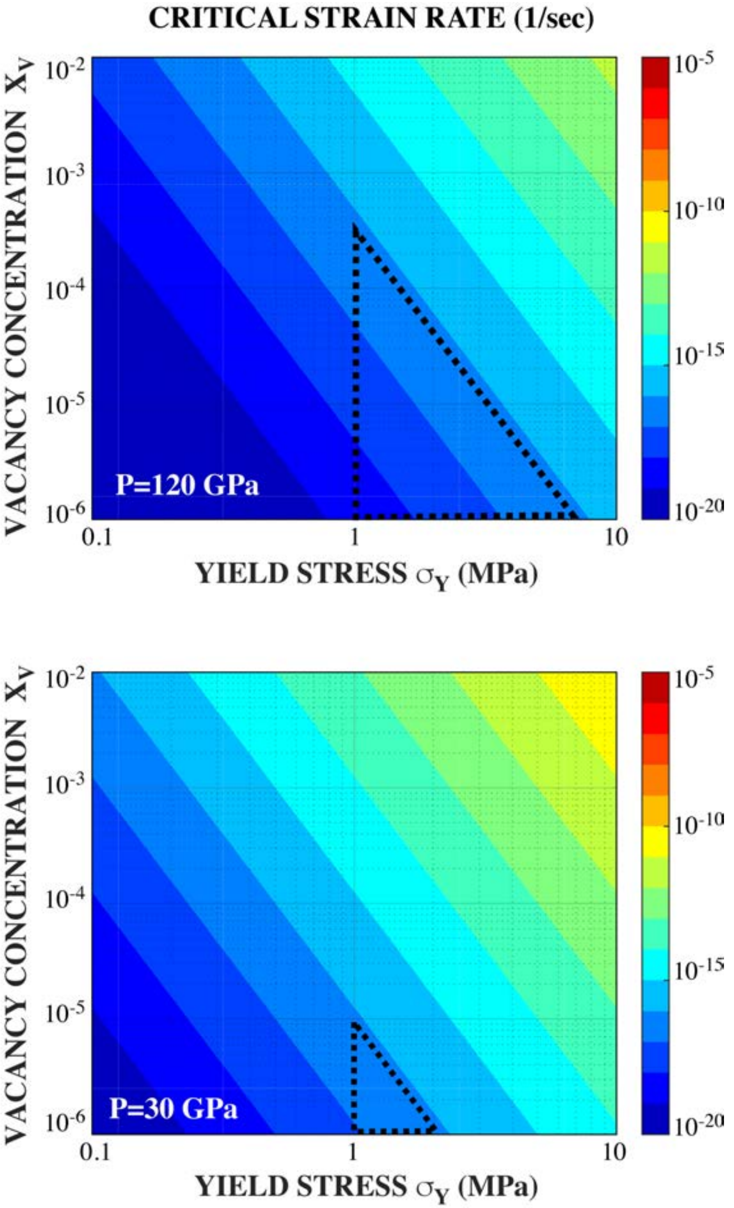


(Davaille et al, 2018)

7- 800 km-depth horizon in a Bridgmanite mantle

(2) $$Bi = \frac{\sigma_Y}{K_v \dot{\gamma}^{n_{HB}}} < 1.0$$

For Xv ~ 10^{-4}, a plume could rise from CMB
But stop around 30 Gpa

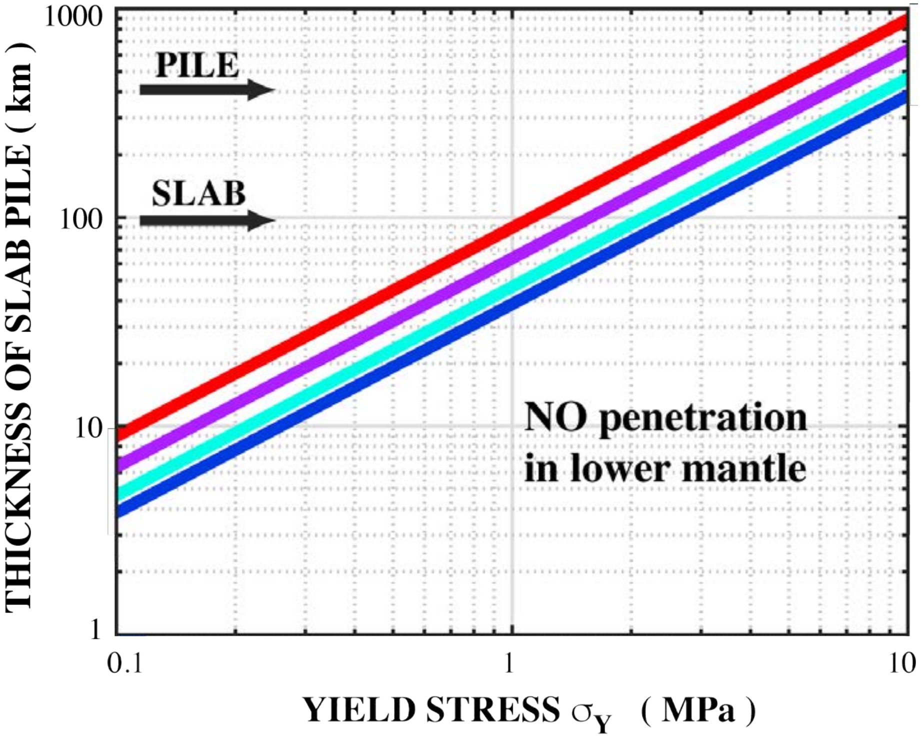


(Davaille et al, in prep.)

7- Filtering thin slabs in a Bridgmanite mantle

(1) $$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6$$

$$\Delta\rho_{slab} = \alpha\rho_m\Delta T_{slab} + \Delta\rho_x\phi_{crust}$$



for different slab averaged temperature and crust density anomalies (ΔT_{slab}, $\Delta\rho_x$). Red: (-200^o, 0.5%); magenta: (-200^o, 3.0%); cyan: (-400^o, 0.5%); blue: (-400^o, 3.0%). The lines thicknesses represent the uncertainty in Y_c.

ΔT (slab) ~ 200-400°C

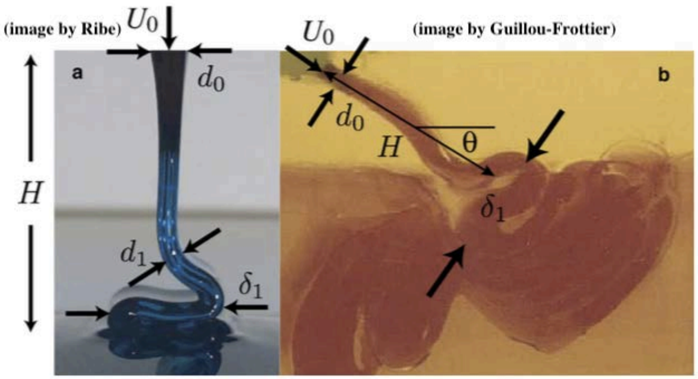
(Billen, 2008; Fukao et al, 2009)

$\Delta\rho_x$ (slab) ~ 0.5-3%

(Hirose, 2005; Fukao et al, 2009; Ricolleau et al, 2010)

7- Filtering thin slabs in a Bridgmanite mantle

$$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6$$

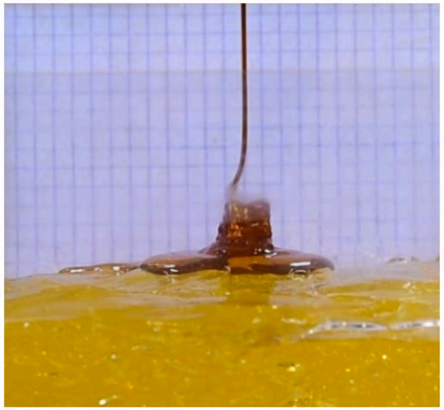


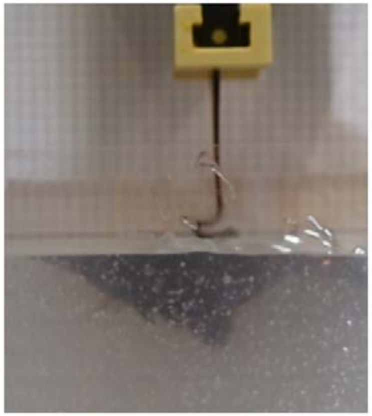
(Ribe et al, 2007)

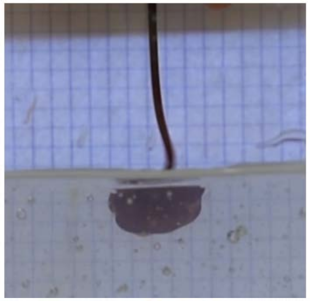
key=slab folding

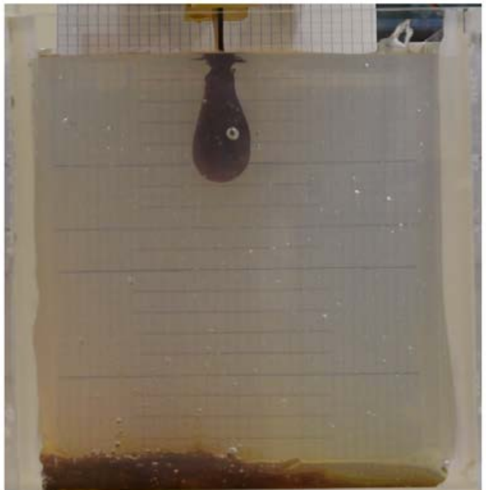
-thin slab => cannot enter LM

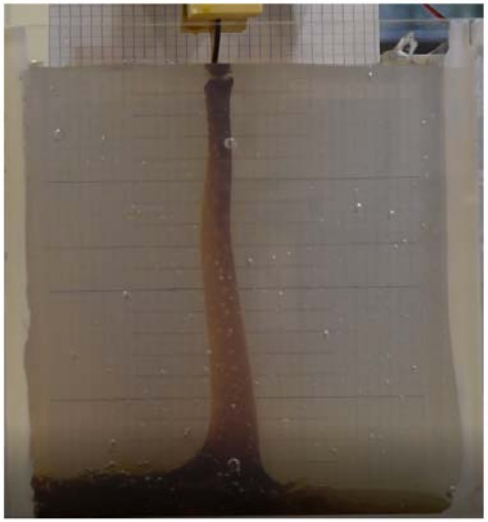
-folded pile => can enter LM







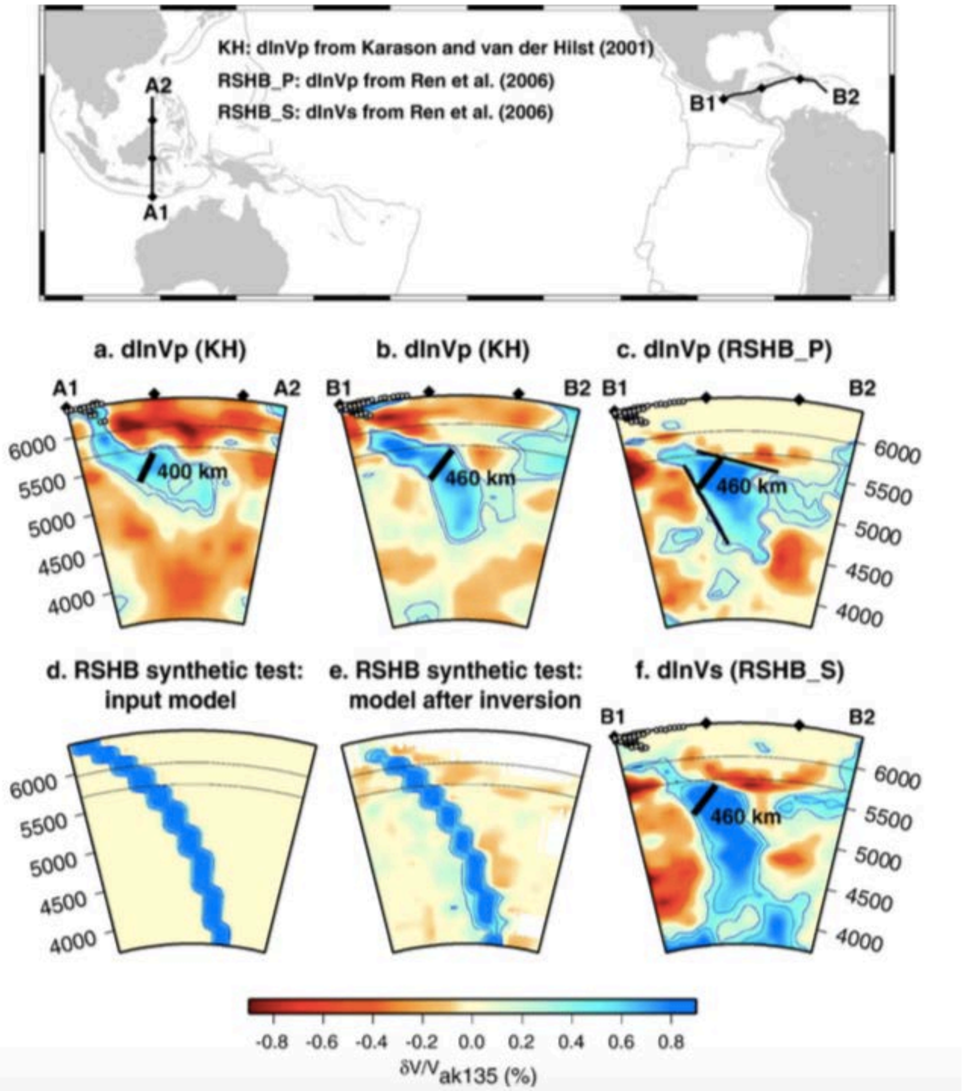




(T. Chasse, 2021)

7- Filtering thin slabs in a Bridgmanite mantle

$$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6$$



key=slab folding

-thin slab => cannot enter LM

-folded pile => can enter LM

CONCLUSIONS: THANK YOU

1- Plume morphology strongly depends on mantle rheology and composition

=> we **need better seismic tomography images, amplitudes, attenuation**,…
=> OBS, MERMAIDS,…

2- The lower mantle might be visco-plastic
because dislocation climb
and also if mixture of two phases

3- Bad news= lab measurements will not see the yield stress because squeeze too quickly and too hard

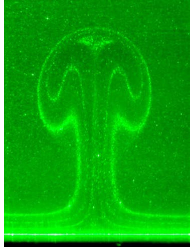
4- Good news: + Subducted pile can penetrate LM;
+ 800-1000 km horizon could be produced

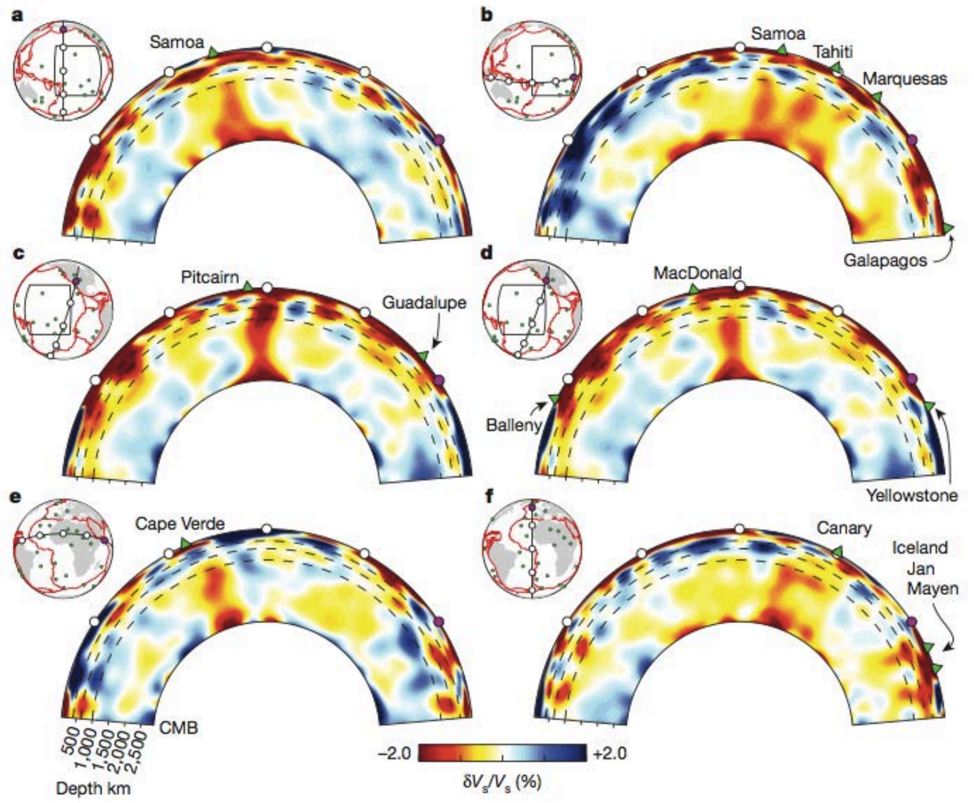
5- Shear should be localized, and large areas may remain isolated
=> **need more modeling to quantify mixing, length- and time- scales**

6- Questions: + mixture of Mg-FeO + Bridgmanite ? (Thielmann et al, 2020)
+ Is Mg-FeO really softer than Bridgmanite ?

F- Implications for Head+Tail?

= Upper mantle filter

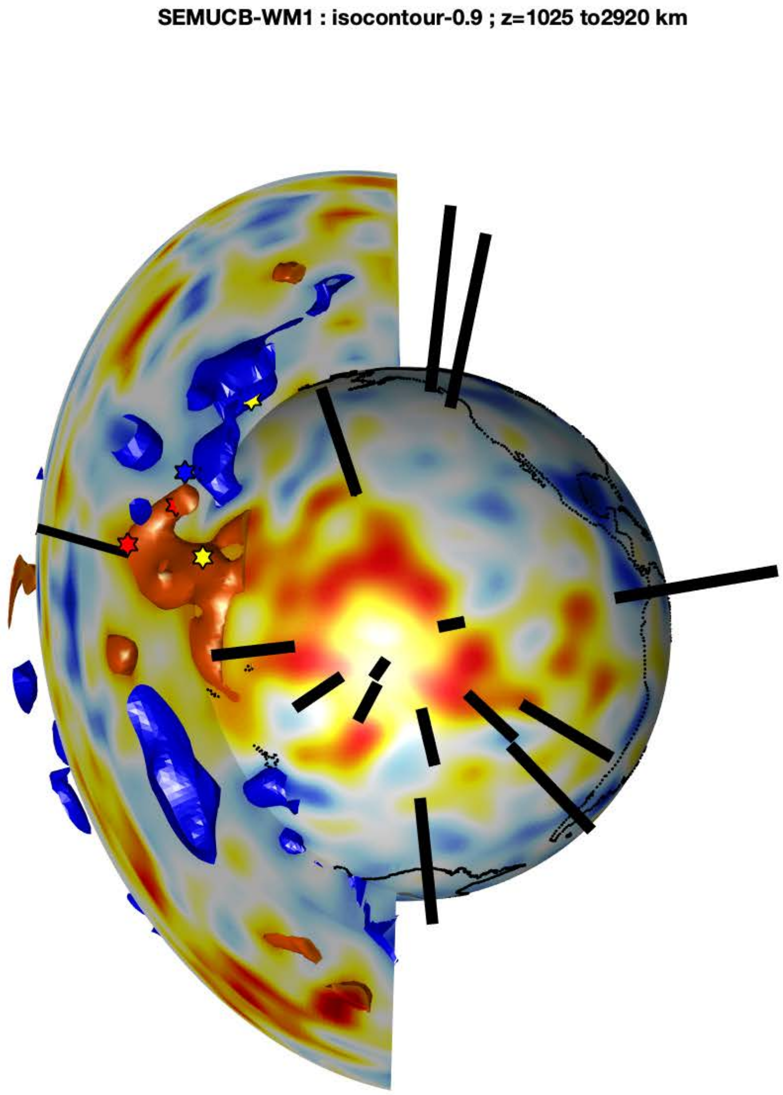




-fat plumes in LM
=> yield stress

-plume existence
=> lateral chemical heterogeneities

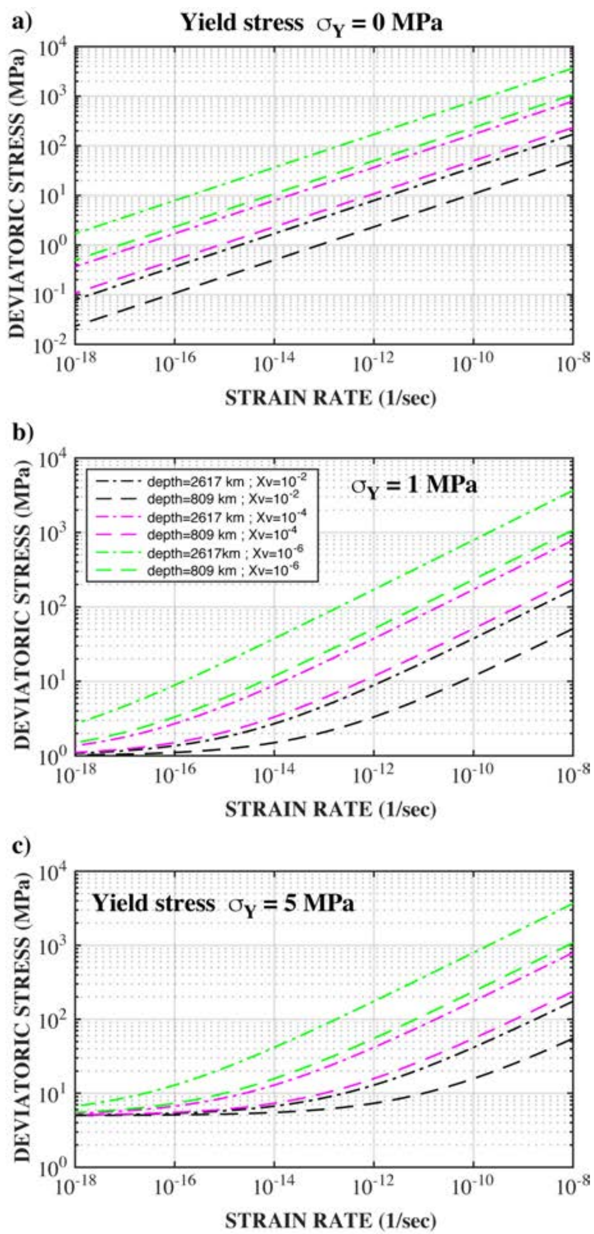
(French & Romanowicz, 2015)

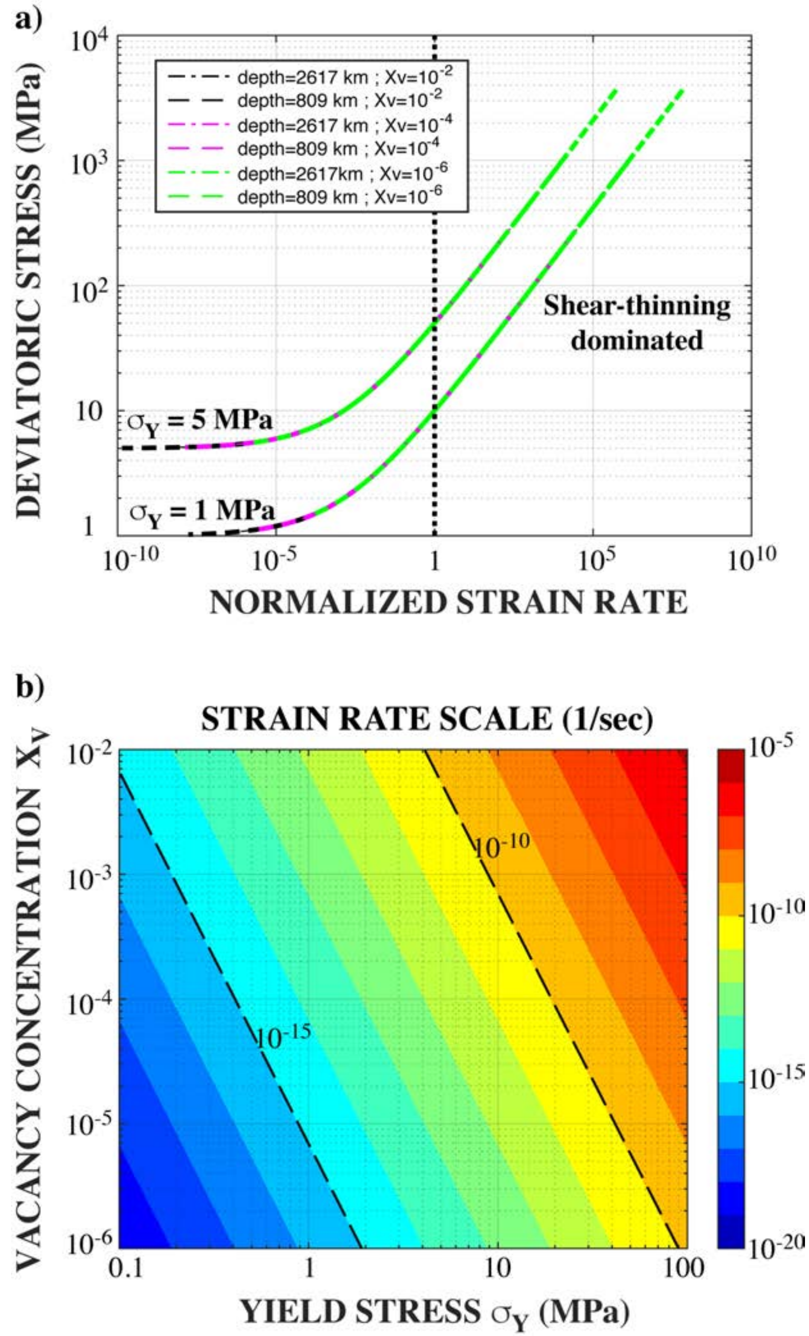


ZOOM under Carolina

SEMUCB-WM1
+ off-plane reflections
Schumacher et al, 2018

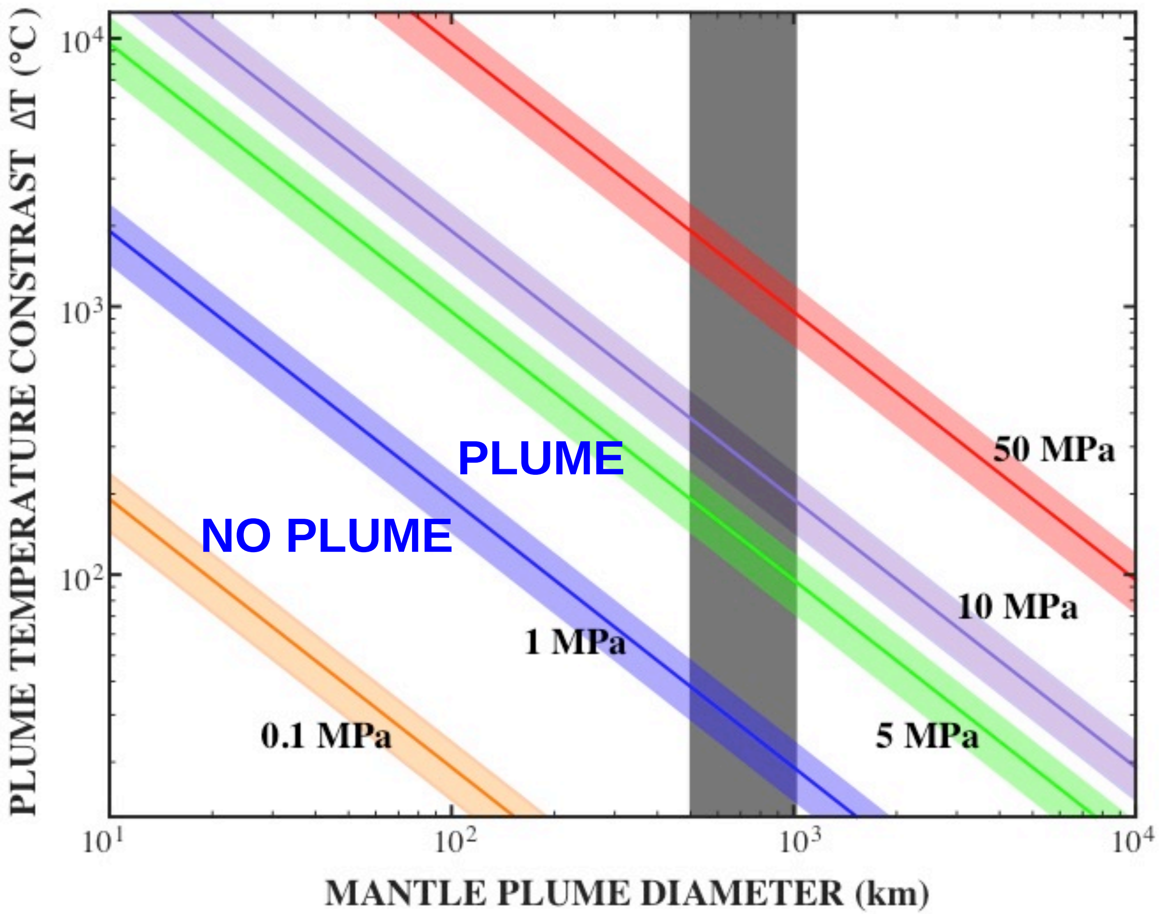
=> evidence for chemical heterogeneities

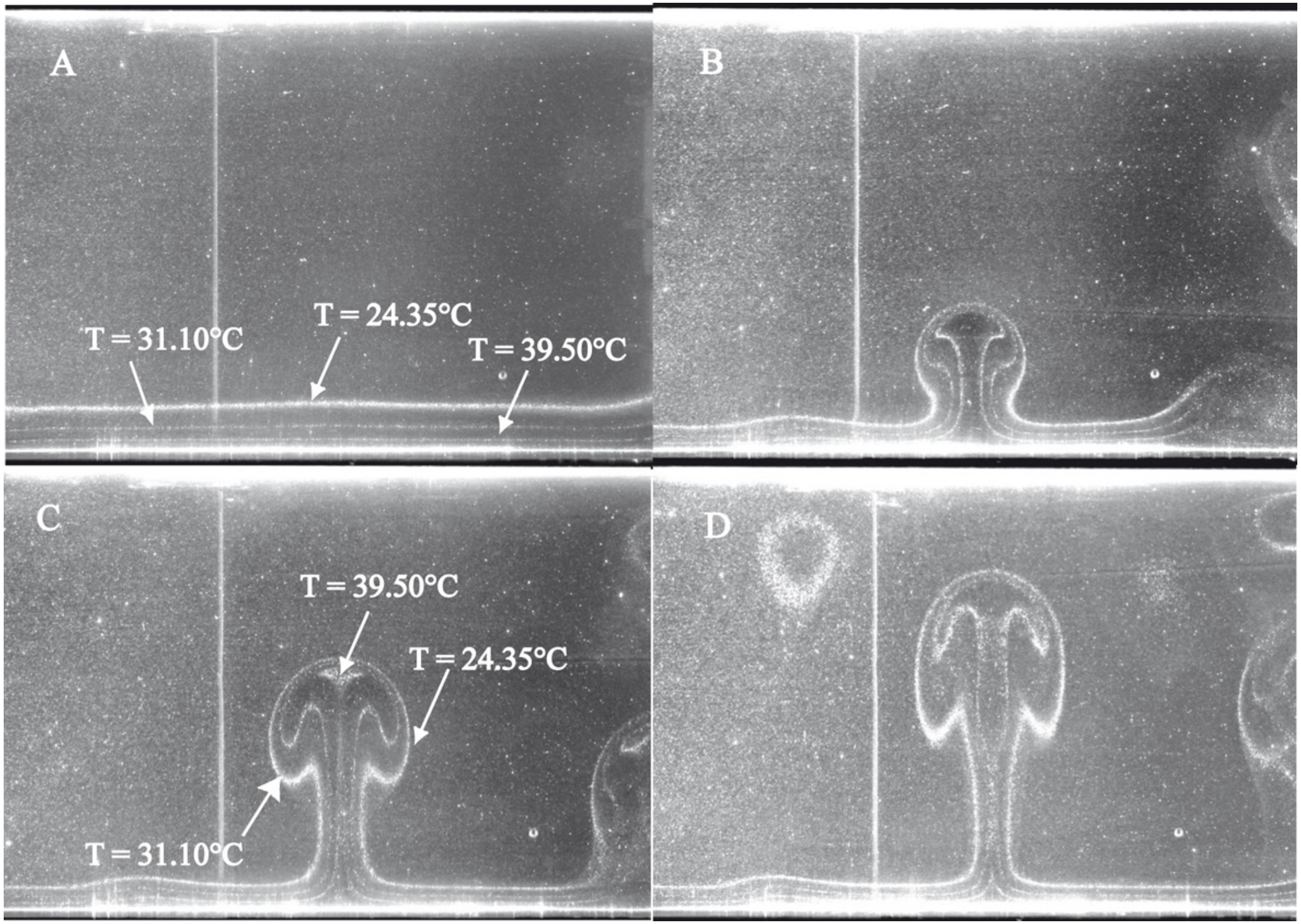

a)
Yield stress σ_Y = 0 MPa
DEVIATORIC STRESS (MPa)
STRAIN RATE (1/sec)
b)
σ_Y = 1 MPa
depth=2617 km ; Xv=10^{-2}
depth=809 km ; Xv=10^{-2}
depth=2617 km ; Xv=10^{-4}
depth=809 km ; Xv=10^{-4}
depth=2617km ; Xv=10^{-6}
depth=809 km ; Xv=10^{-6}
DEVIATORIC STRESS (MPa)
STRAIN RATE (1/sec)
c)
Yield stress σ_Y = 5 MPa
DEVIATORIC STRESS (MPa)
STRAIN RATE (1/sec)


a)
depth=2617 km ; Xv=10^{-2}
depth=809 km ; Xv=10^{-2}
depth=2617 km ; Xv=10^{-4}
depth=809 km ; Xv=10^{-4}
depth=2617km ; Xv=10^{-6}
depth=809 km ; Xv=10^{-6}
Shear-thinning dominated
σ_Y = 5 MPa
σ_Y = 1 MPa
DEVIATORIC STRESS (MPa)
NORMALIZED STRAIN RATE
b)
STRAIN RATE SCALE (1/sec)
10^{-10}
10^{-15}
VACANCY CONCENTRATION X_V
YIELD STRESS σ_Y (MPa)

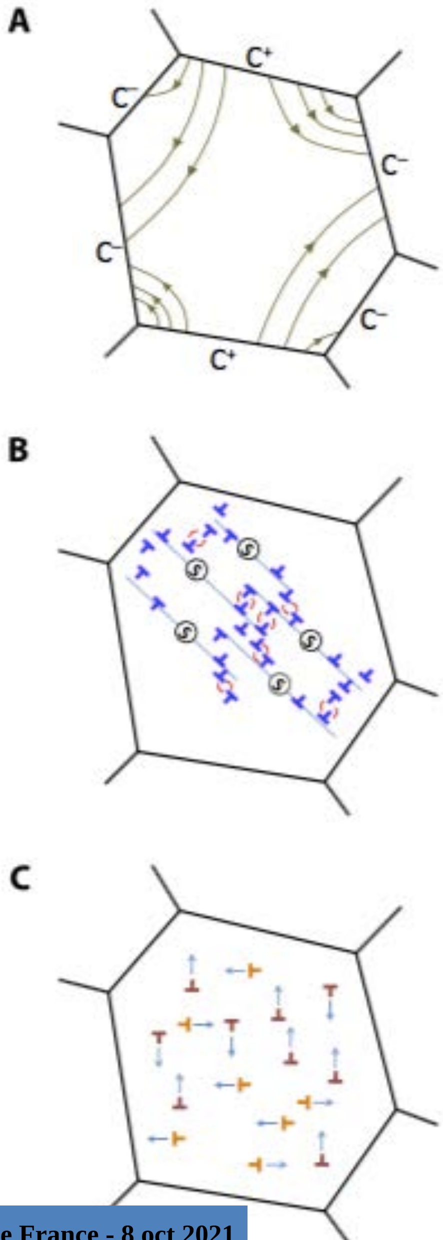
D- FAT plumes in a visco-plastic mantle

$$Y_0 = \frac{gD\Delta\rho}{\sigma_0} > Y_c = 15 \pm 3.6 \quad ; \Delta\rho = \alpha\, .\Delta T$$




A
T = 31.10°C
T = 24.35°C
T = 39.50°C
B
C
T = 39.50°C
T = 24.35°C
T = 31.10°C
D

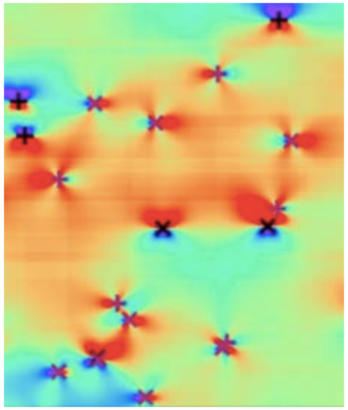
E- A visco-plastic rheology for the lower mantle ?



Diffusion creep :
vacancy flux from one grain boundary to the next
=> .depends on grain size
.no yield stress
.n_E=1

$$\dot{\gamma} = A\,\sigma^{n_E}\,d^{-p}\,f_{H_2O}\,exp\,(\beta\,\Phi)\;exp\left(-\frac{E^* + P\,V^*}{RT}\right)$$

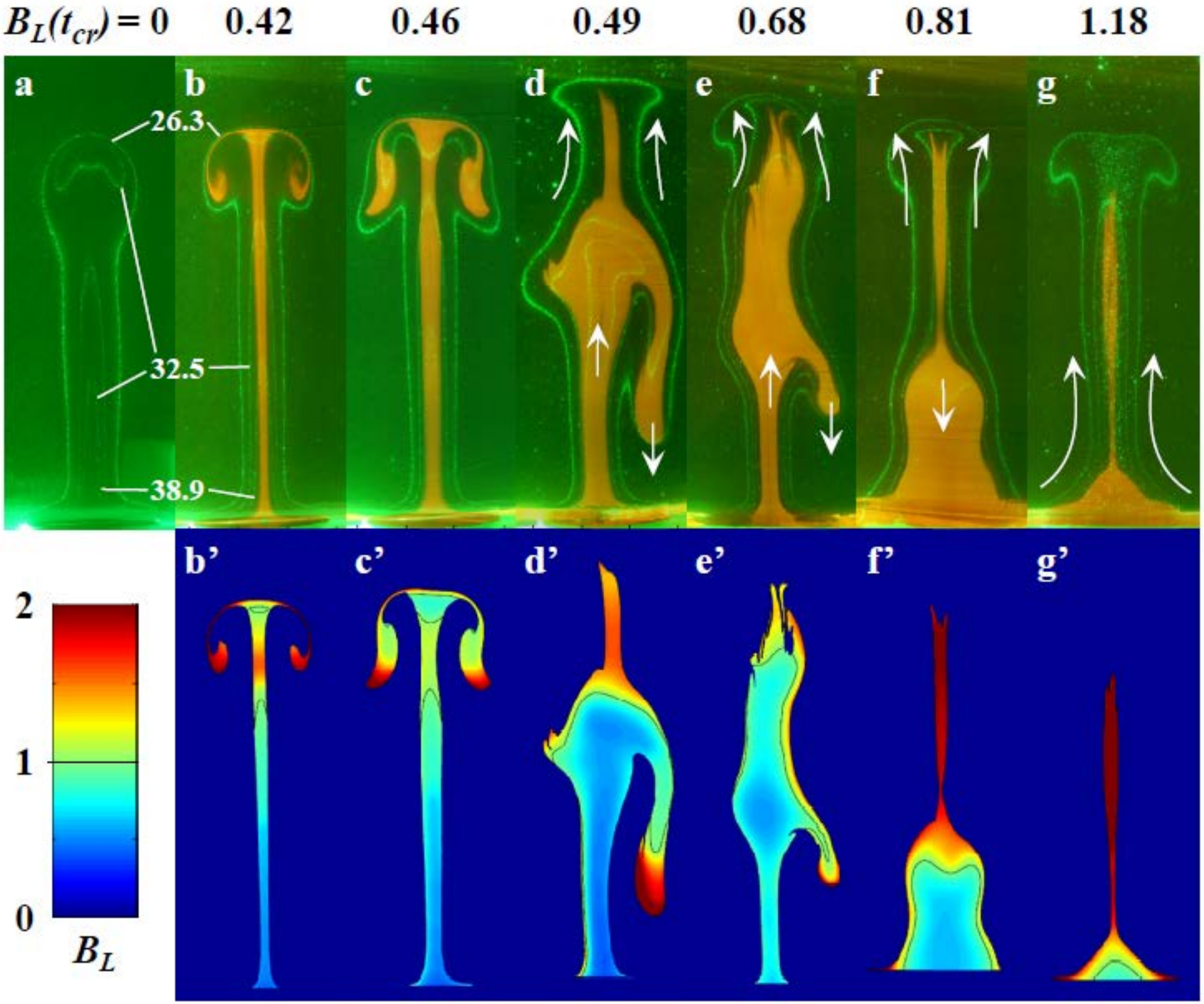
Dislocation: glide and climb
.independent of grain size (p=0)
.n_E=3
.rotation of the grain



Dislocation: glide
.independent of grain size (p=0)
.n_E=3
. NO rotation of the grain

3-Thermo-cher

KEY:
B_l > or < 1



Going DOWN

Going UP

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

(Kumagai & al, 2008)

Table 1

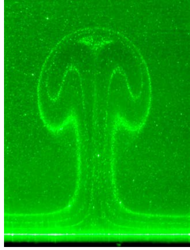
Convective regime and upwellings morphology as a function of B, viscosity ratio γ, layer depth ratio a and internal Rayleigh number of the denser bottom layer Ra_d

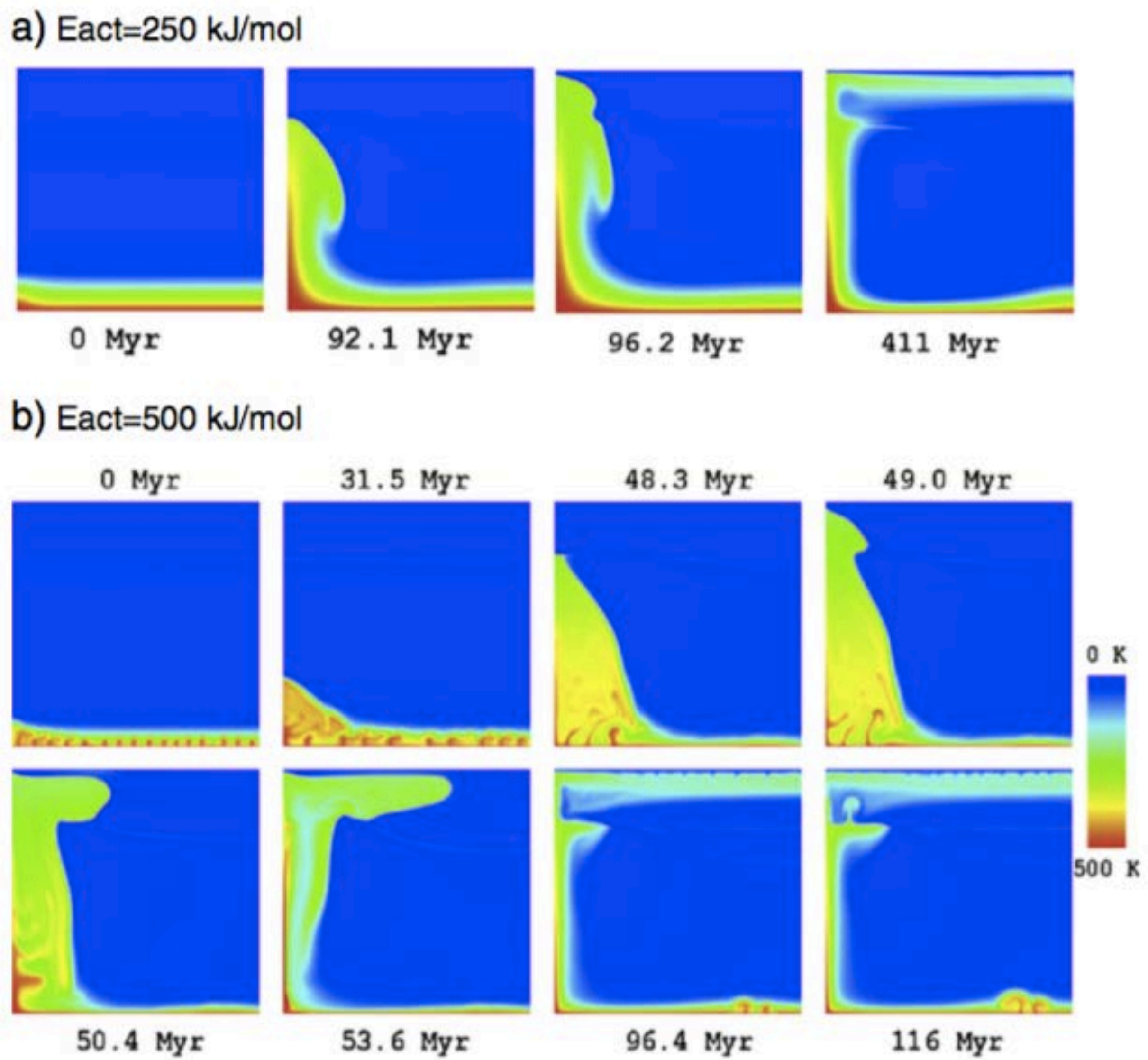
B	Regim	$\gamma = \eta_d / \eta_m$	Ra_d	$a = h_d/H$	Upwellings morphology	Fig.	References
< 0.03	**1-layer**				**Thermal plumes** with no big head	5a	
$0.03<B<B_c$~0.4	**Whole-layer**				Active domes and passive ridges		[86, 61–62]
			$< Ra_c$ ~1000		Passive **ridges** = return flow to downwellings	5c	
		< 1	$>Ra_c$	$a < a_c$ $a_c=1/(1+\gamma^{-1/3})$	Active hot upwellings -**Cavity plumes** (or « mega-plumes ») through collection of small thermal instabilities -detach from hot bottom boundary (HBB)	5e 5g	
			$>Ra_c$	$a > a_c$	Passive **ridges** =return flow to cold more viscous downwellings	5c	
		>1	$> Ra_c$		-Active hot **diapirs** detach from HBB if a<0.3 and B<0.2 continuous fingers from HBB otherwise -**Secondary plumes** on top of domes	5f 5g 5h	
		$1/5<\gamma<5$			**Overturning** = immediate stirring after first instabilities		[86]
		$\gamma<1/5$ or $\gamma>5$			**Pulsations** = two layers retain their identity for several doming cycles	5f+5h	[59, 61–62]
$> B_c$	**2-layers**				-**Stratified** convection above and below interface -**Anchored** hot **thermochemical plumes** arise from TBL at the interface. No big head.	5b–d 5d	[85, 58, 67] [66, 57, 67, 59, 69]
B>1	Nearly flat interface				Thermochemical plumes in upper layer		[58,67]
$B_c<B<1$	**Dynamic topography**				Dynamic topography does not reach the upper boundary	5b–c	[66,61, 92]
		<1			Passive **ridges** (2D) or **piles** (3D) formed in response to cold viscous downwellings	5c	
		>1	$<Ra_c$		Passive **ridges** (2D) or **piles** (3D)	5c	
			$Ra_c<Ra_d<10^4$		Upwelling **ridges**	5b	
			$>10^4$		Upwelling **domes**, or **superplumes**	5b	

For depth- or temperature-dependent properties, the viscosities are taken at the averaged temperature of each layer, and α is taken at the interface [59,62]. We focuss on high global Ra ($>10^6$). Note that if $Ra_d<Ra_c$, the denser layer cannot convect on his own.

(Davaille & al, 2005)

C- How to create fat plumes in a newtonian mantle ?





- **Compressibility**

+

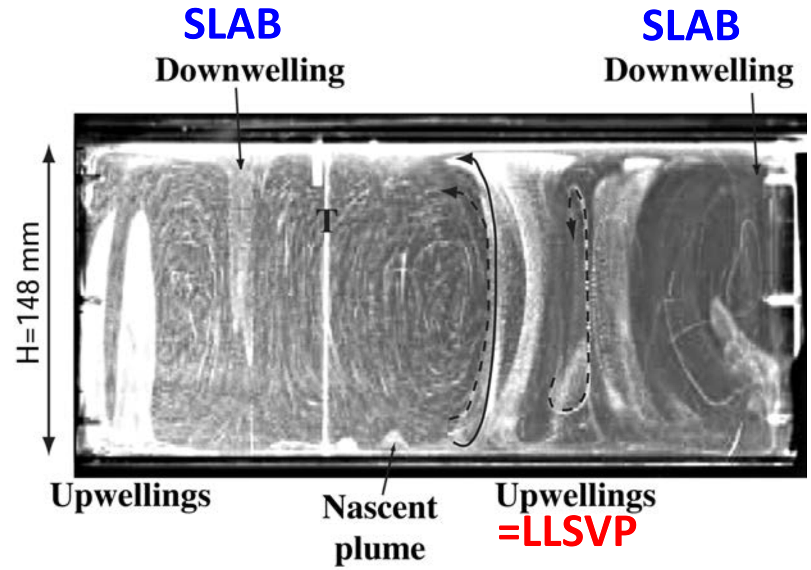
Depth-dependence

(Thompson & Tackley, 1998)

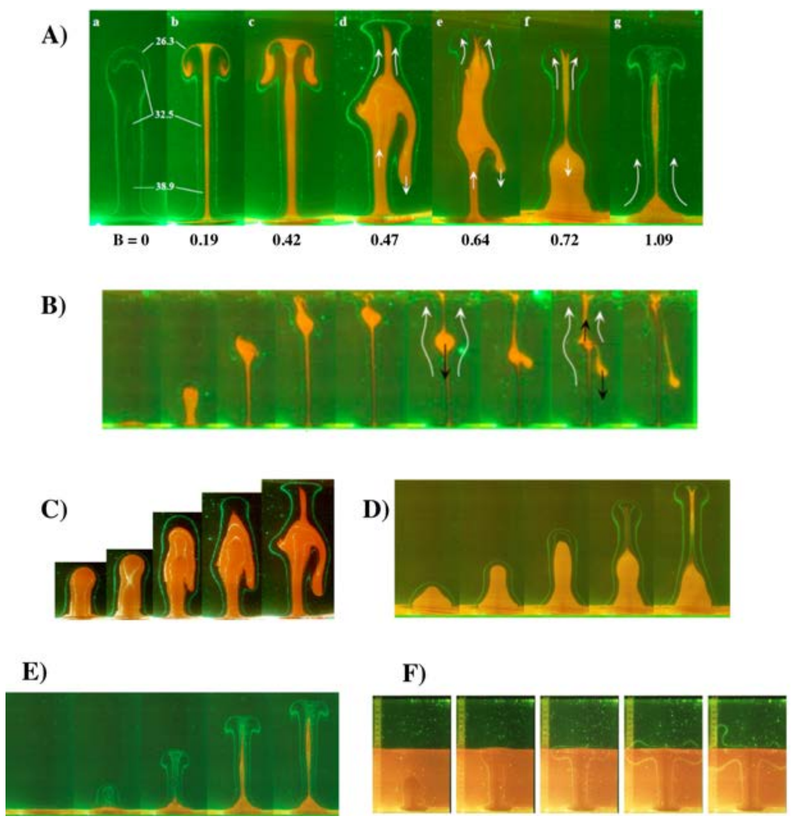
FLUID MECHANICS : convection in an heterogeneous mantle

1- Size of a LLSVP

=> **several** hot instabilities



(Androvandi et al, 2011)



2- Thermochemical instabilities

=> **zoology of shapes**

+ **time-dependence**

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

(Kumagai et al, 2007, 2008)