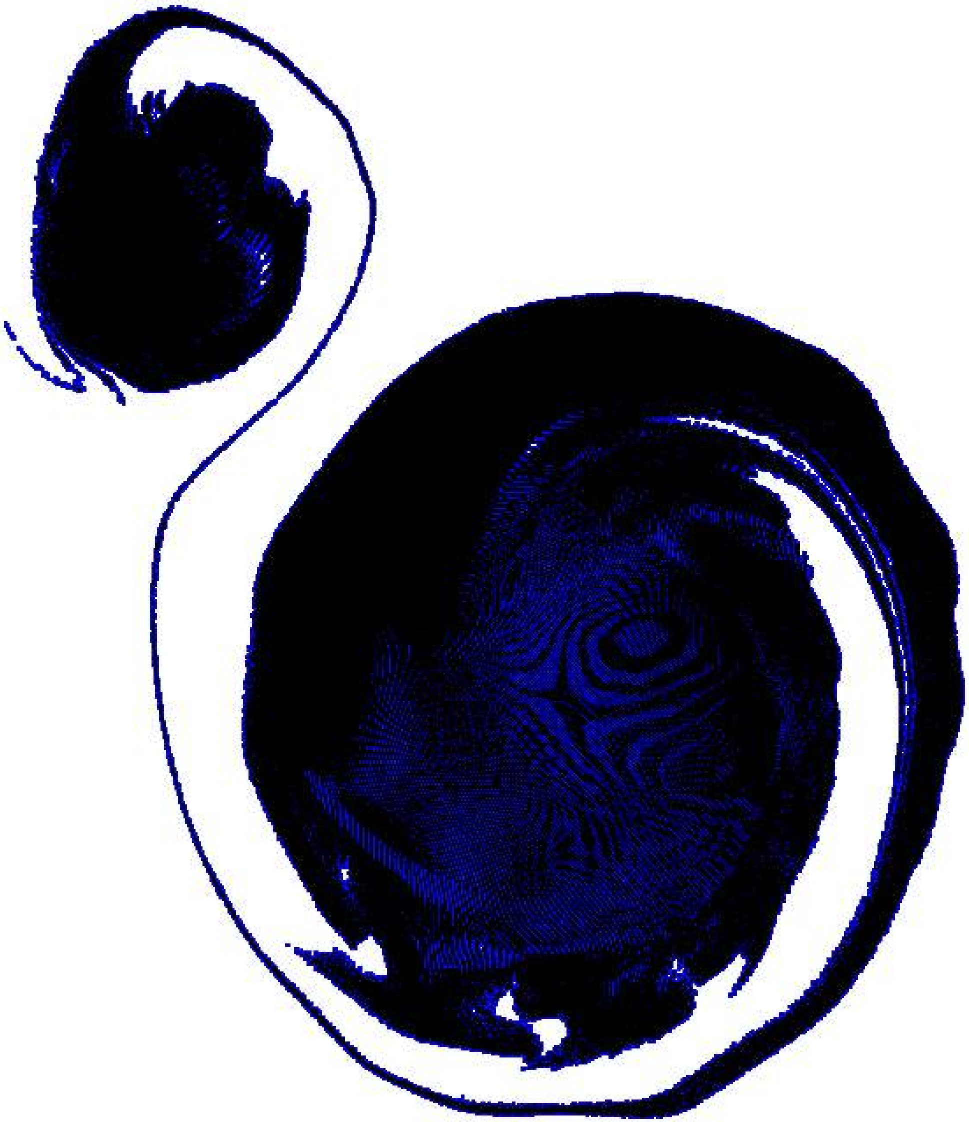
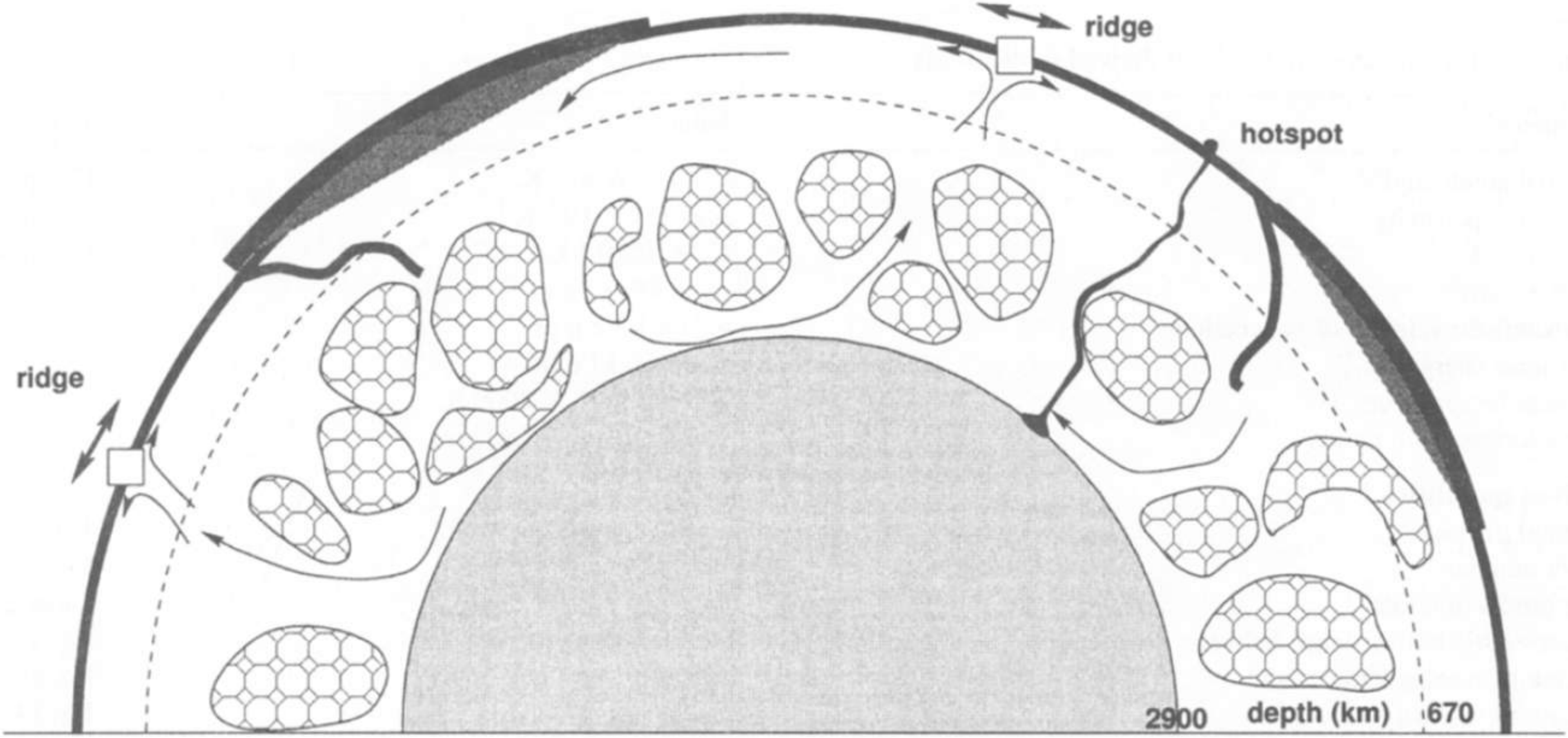


The flow of viscous heterogeneities in mantle plumes

Cinzia G. Farnetani

IPGP et Université Diderot
Paris, France

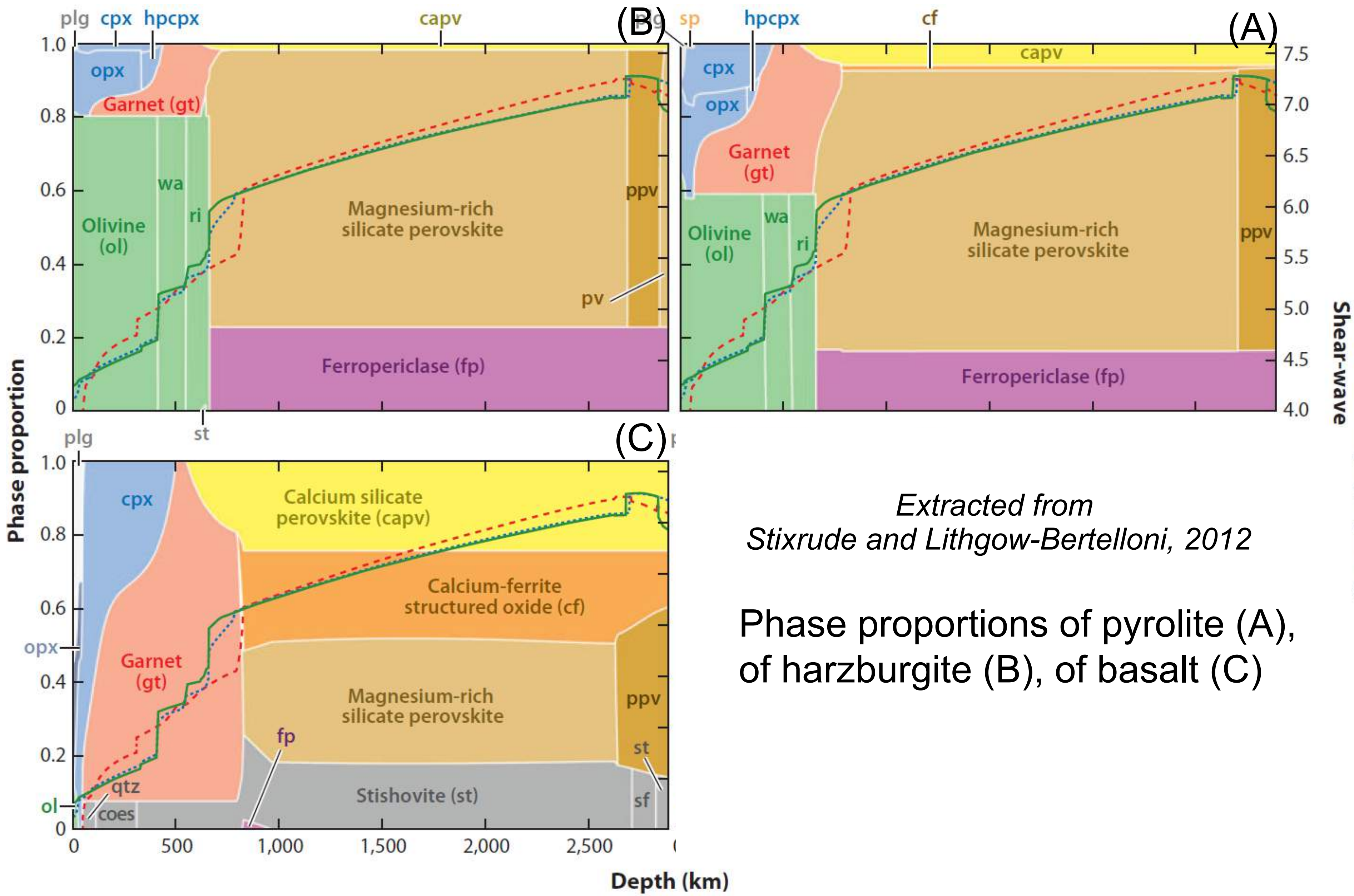
***Viscous heterogeneities**: Conceptual model by Becker et al., 1999*



High-viscosity blobs could persist in the convective mantle for long time without substantial mixing and deformation.

Origin of viscous heterogeneities?

Grain size ($\eta \propto d^2$ for diffusion creep), water content, rock composition

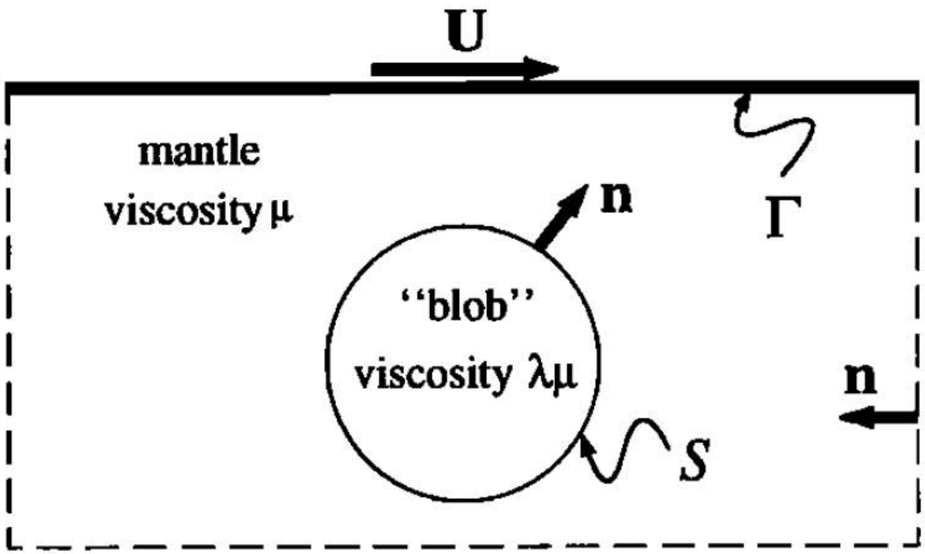


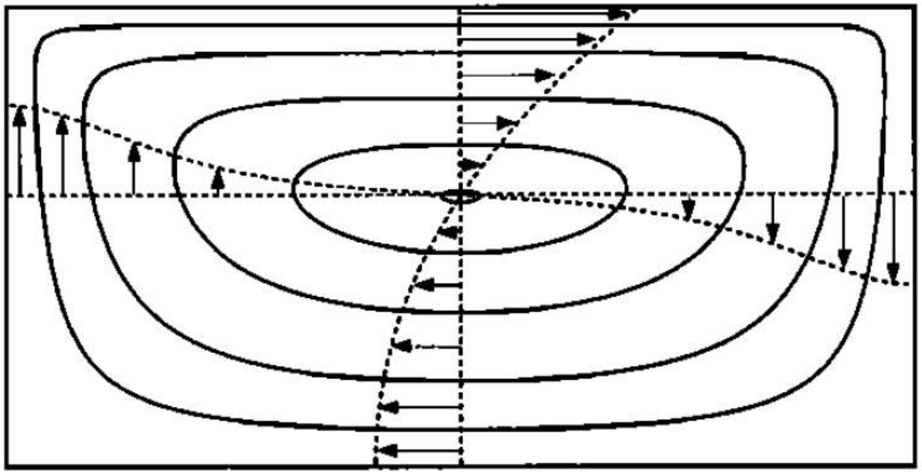
Extracted from
Stixrude and Lithgow-Bertelloni, 2012

Phase proportions of pyrolite (A), of harzburgite (B), of basalt (C)

Viscous heterogeneities are modeled with a "fluid dynamics perspective", rather than with a "mineral physics/compositional" perspective.

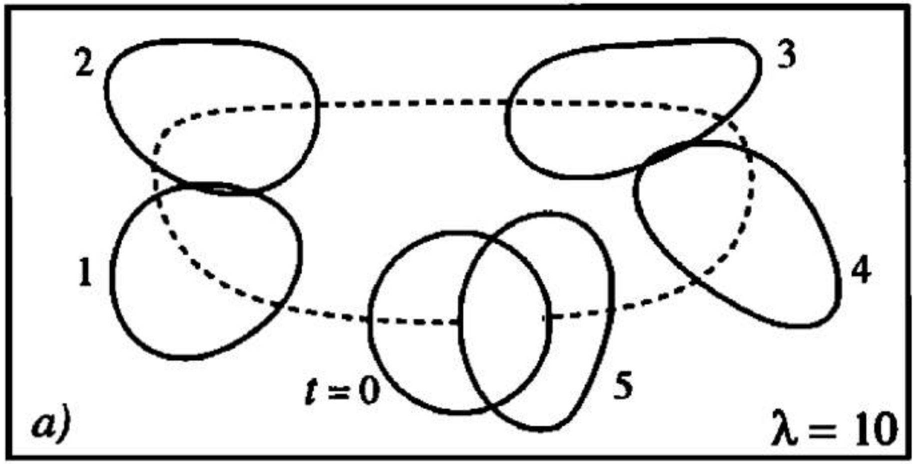
2D flow driven by surface motion





Manga, 1996

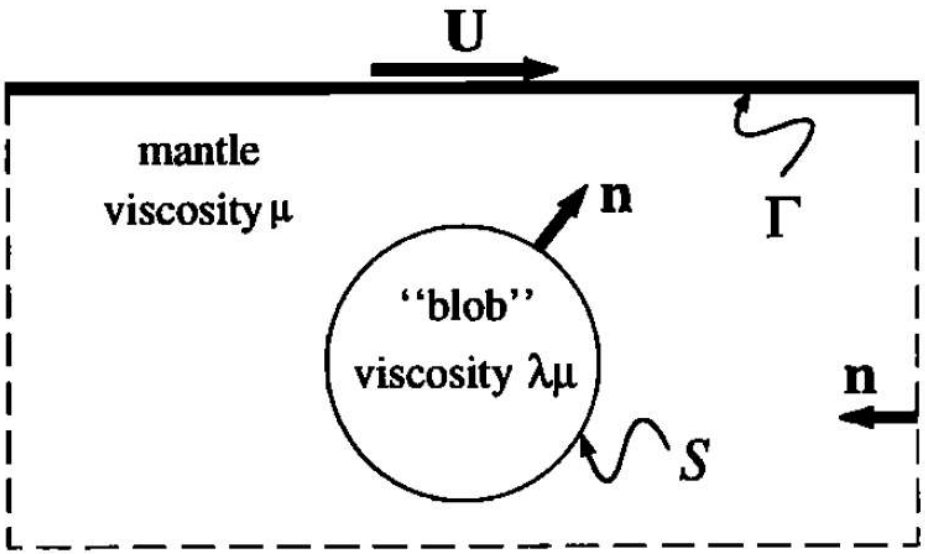
A viscous 'blob' (**λ=10**) experiences little deformation

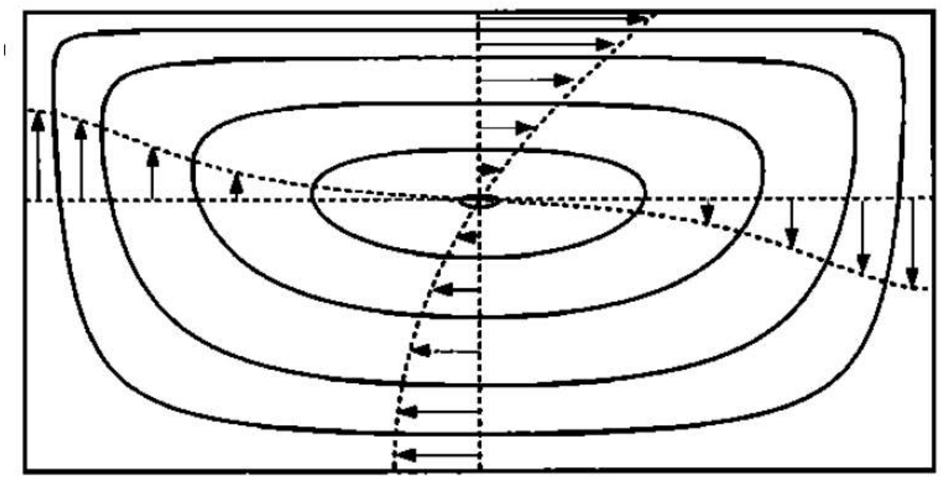


Viscosity ratio

$$\lambda = \eta_{heterogeneity} / \eta_{surrounding\ fluid}$$

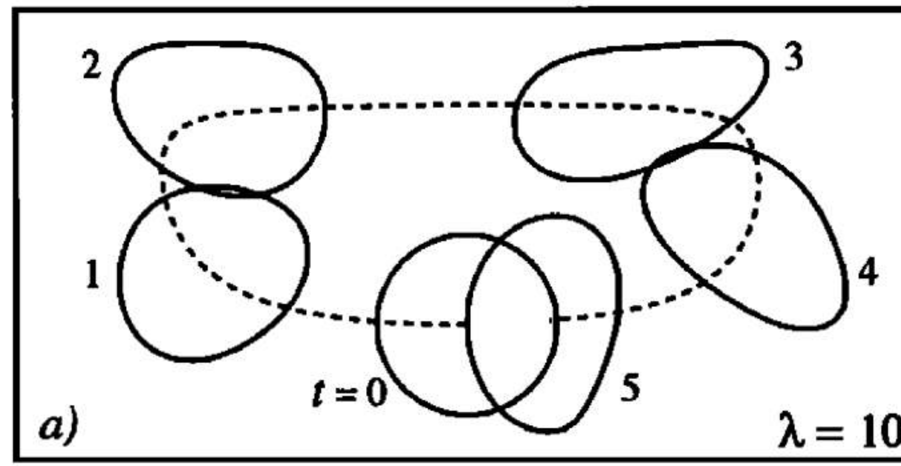
2D flow driven by surface motion

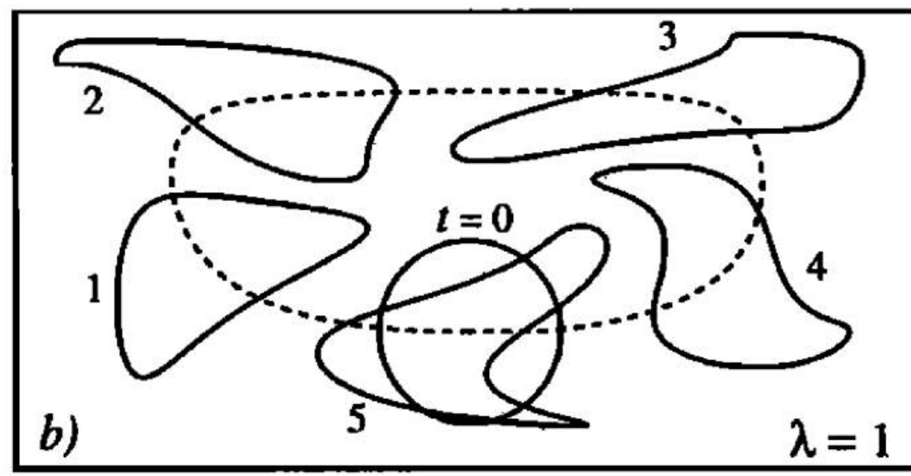




Manga, 1996

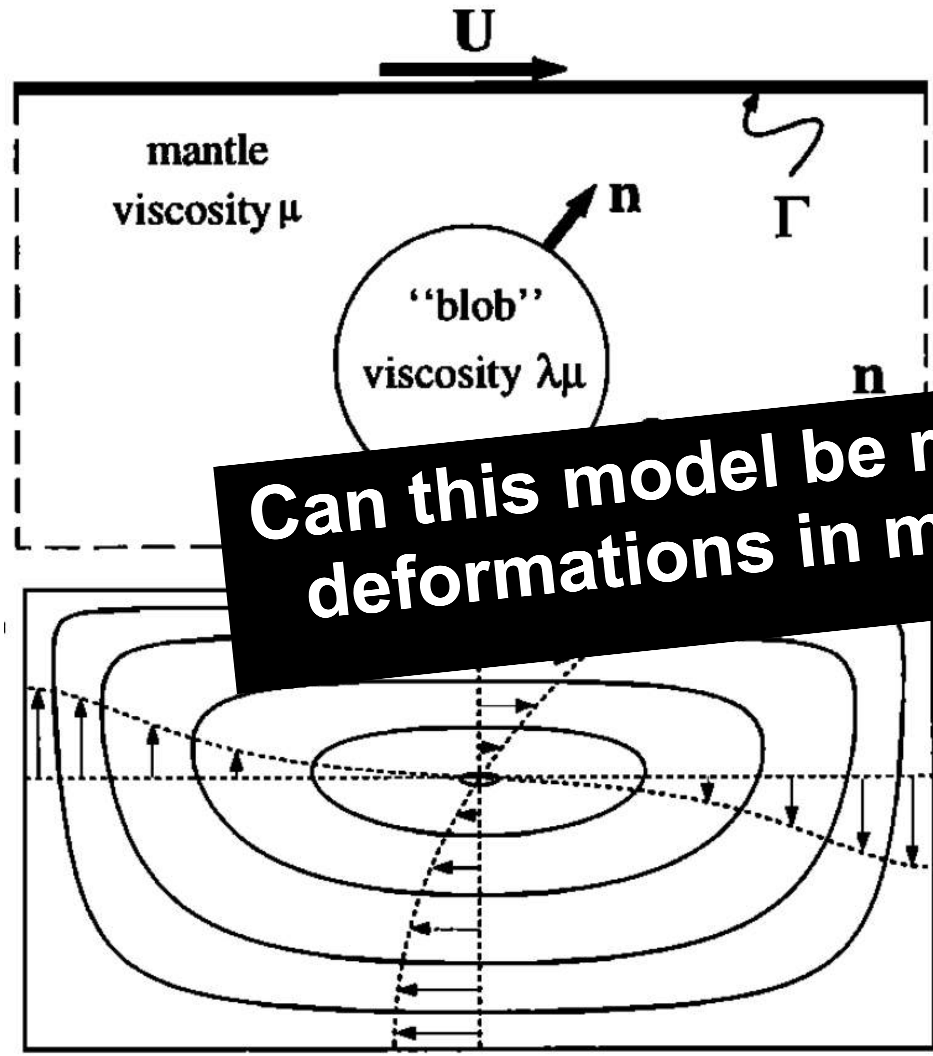
A viscous 'blob' (**λ=10**) experiences little deformation



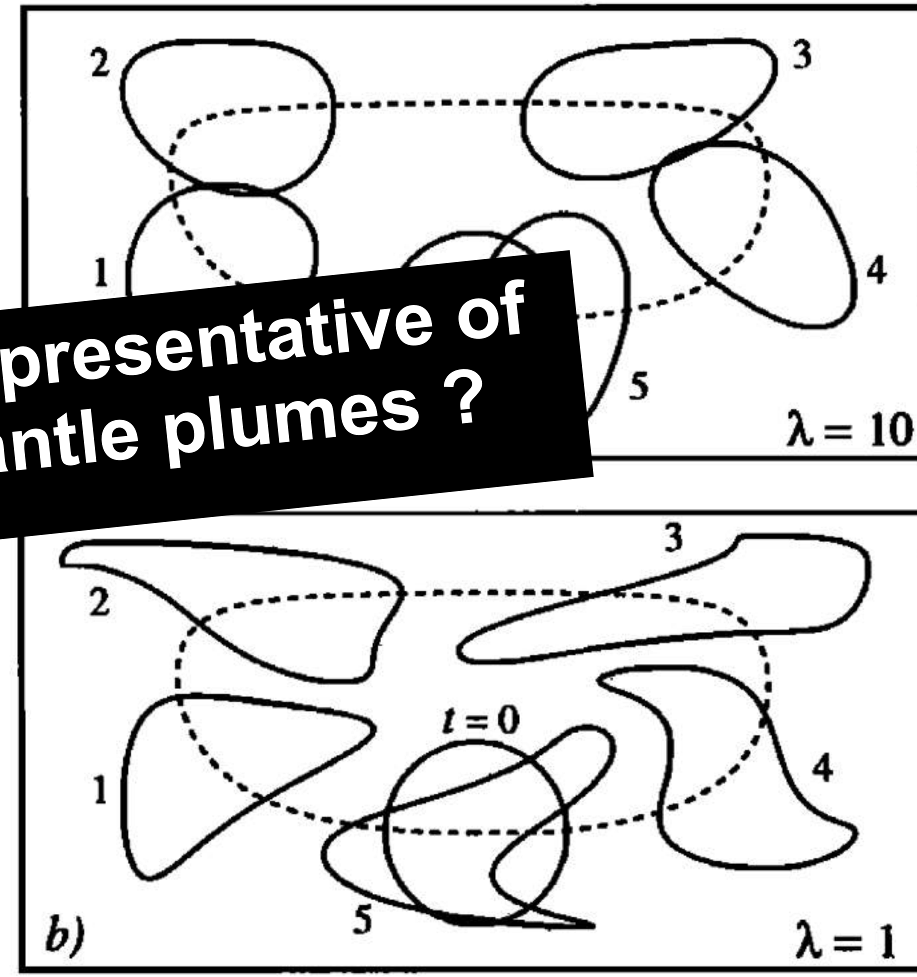


...but also for **λ=1** the deformation is quite modest.

2D flow driven by surface motion



A viscous 'blob' (**λ=10**) experiences little deformation



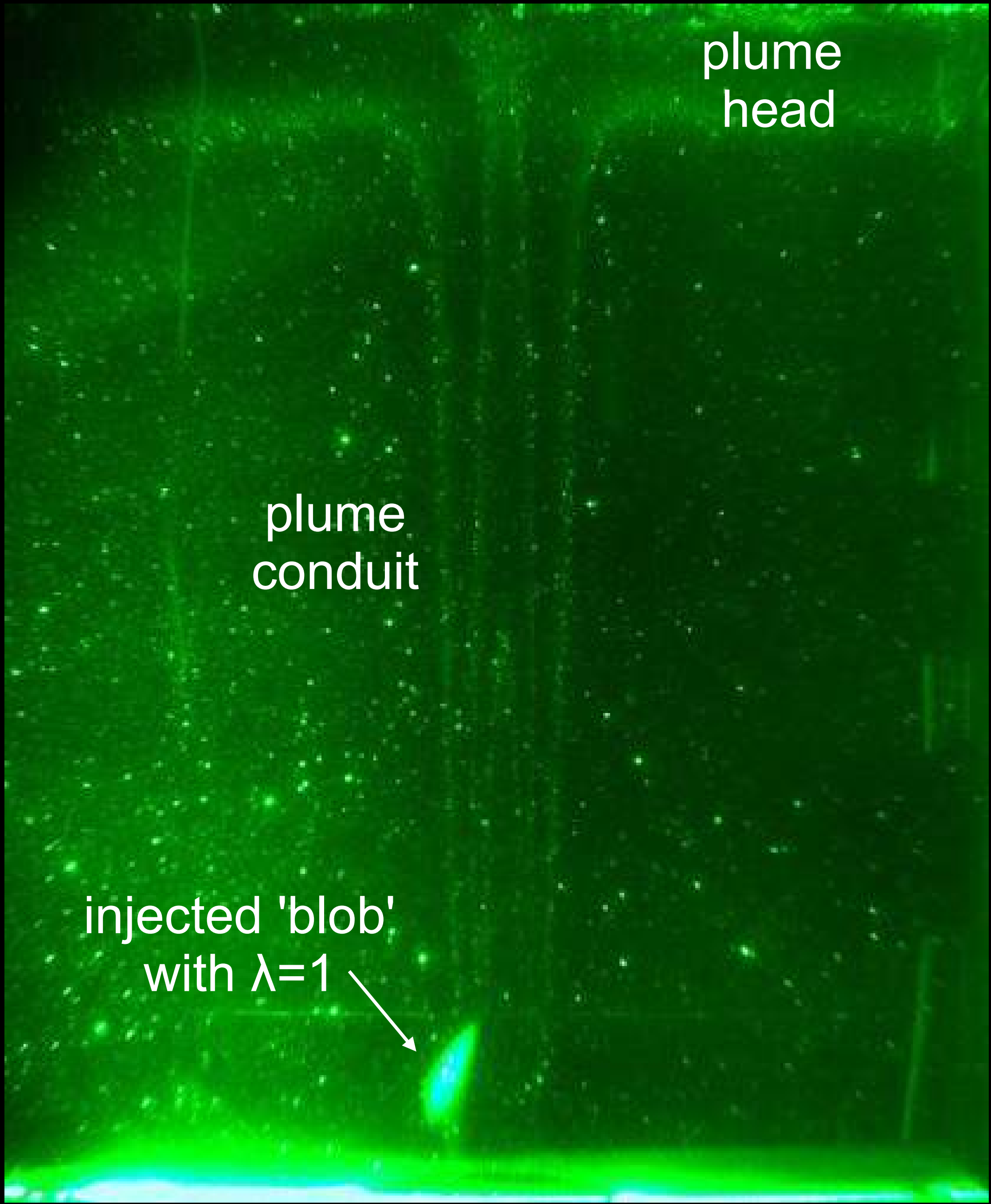
Can this model be representative of deformations in mantle plumes ?

Manga, 1996

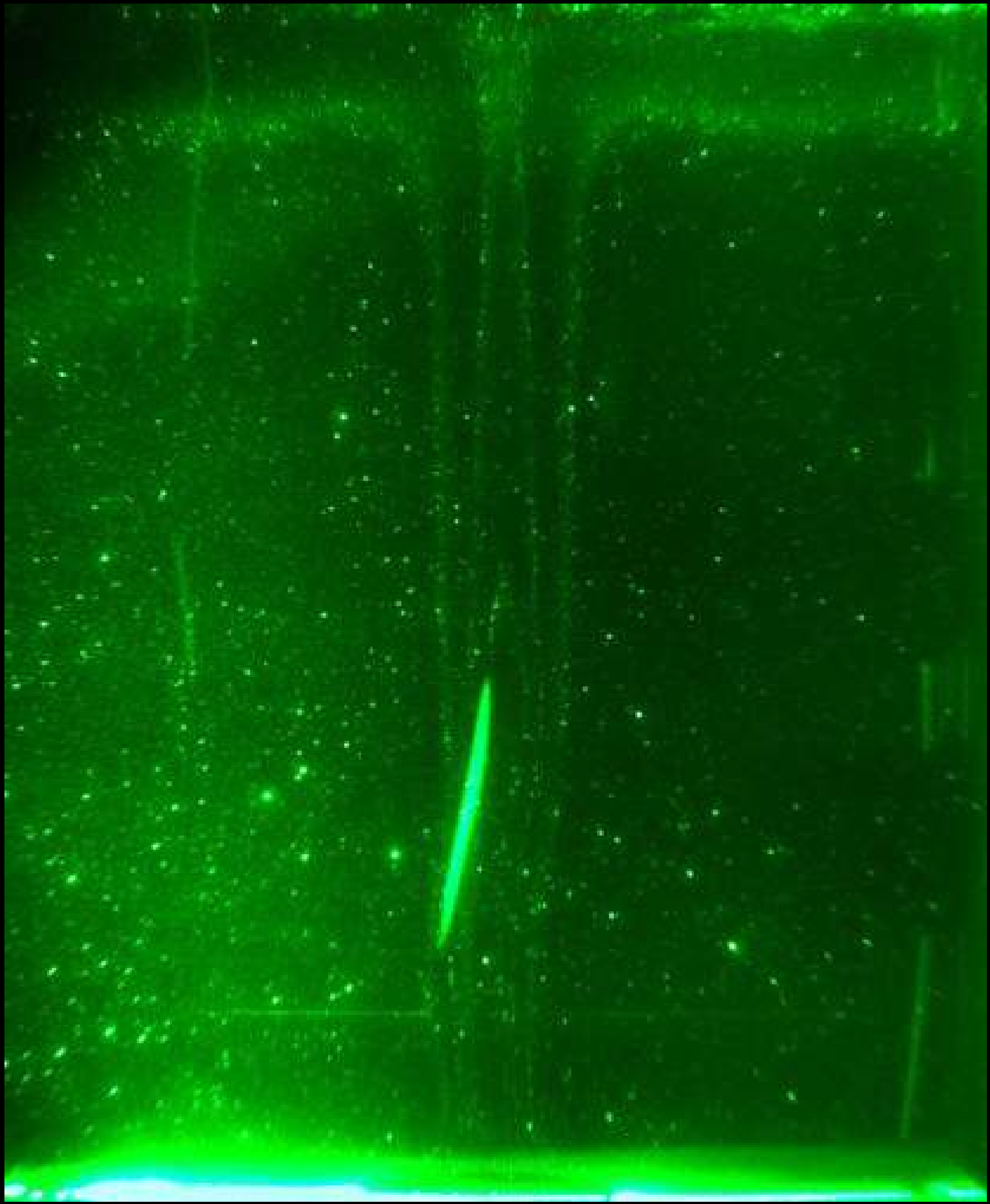
...but also for **λ=1** the deformation is quite modest.

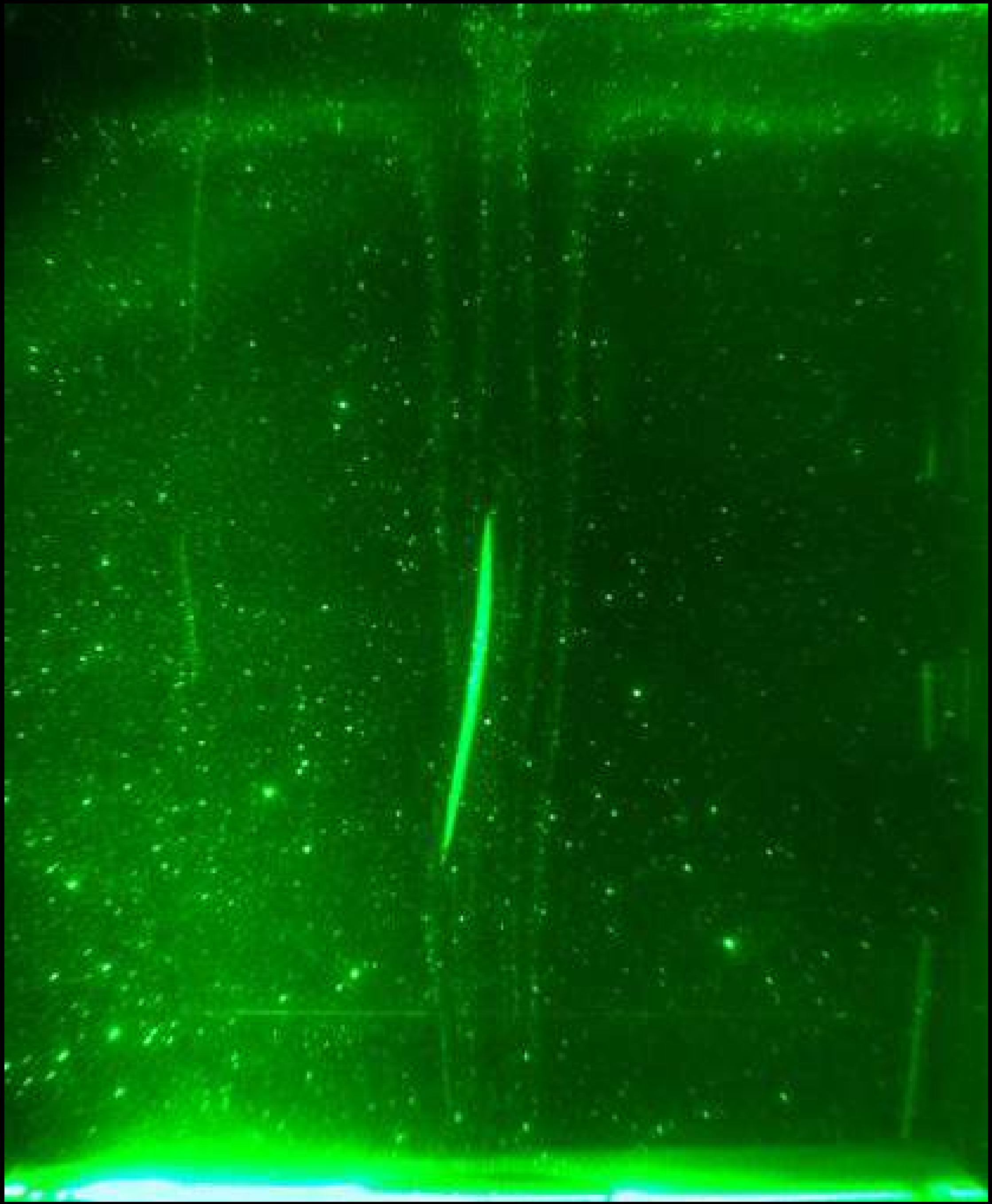
In a plume conduit for λ = 1 we obtain filaments

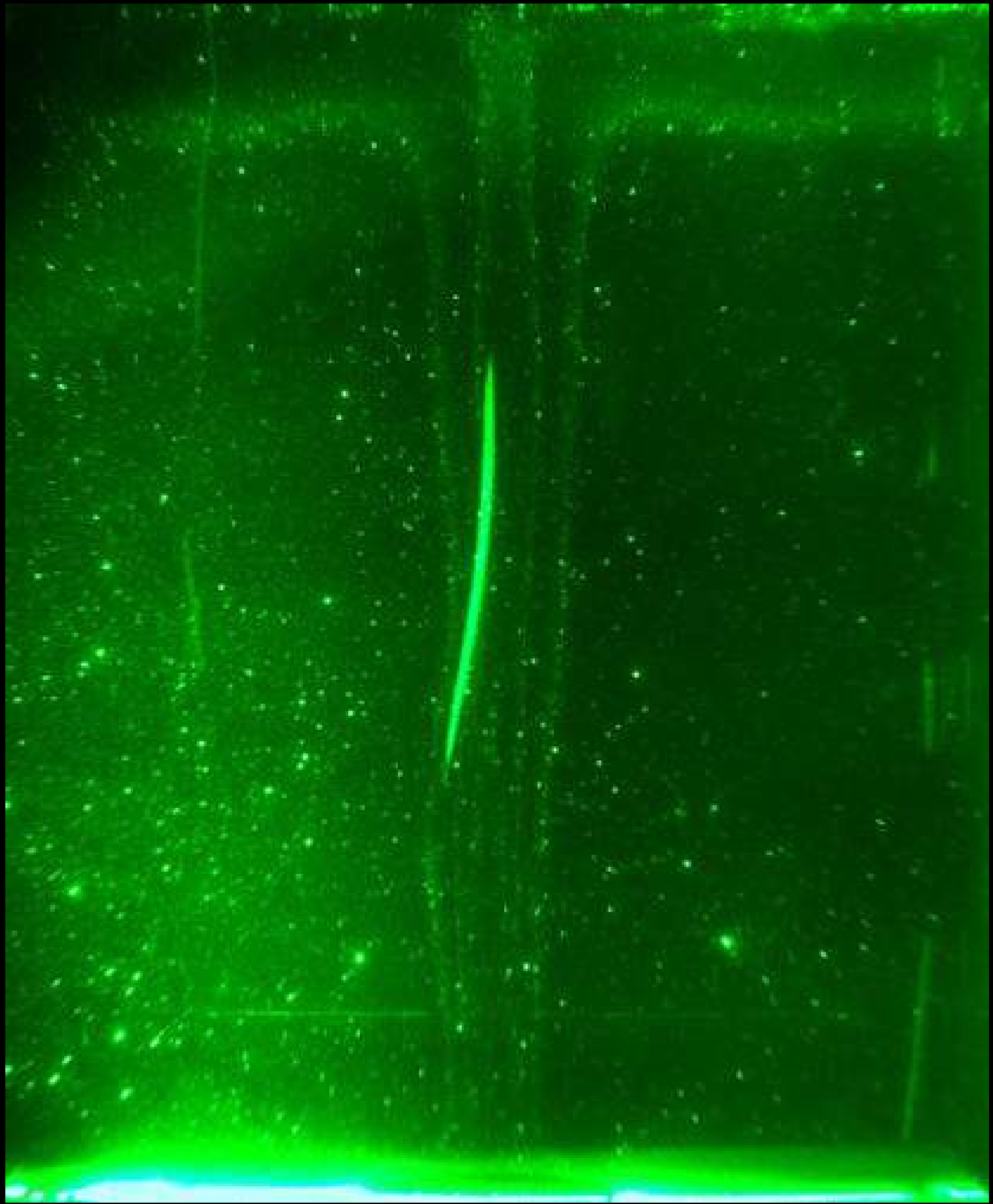
[Farnetani and Hofmann, 2009]

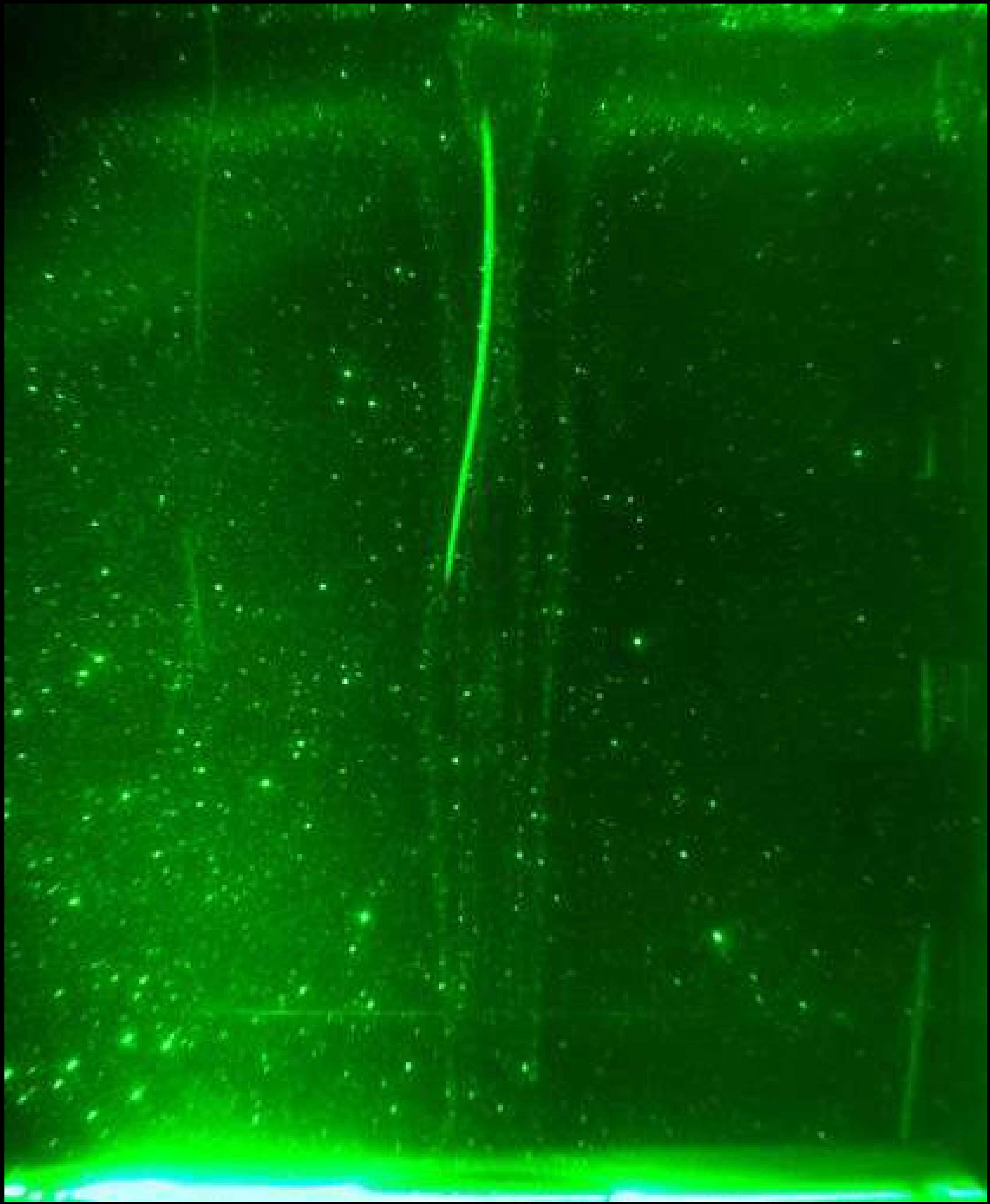


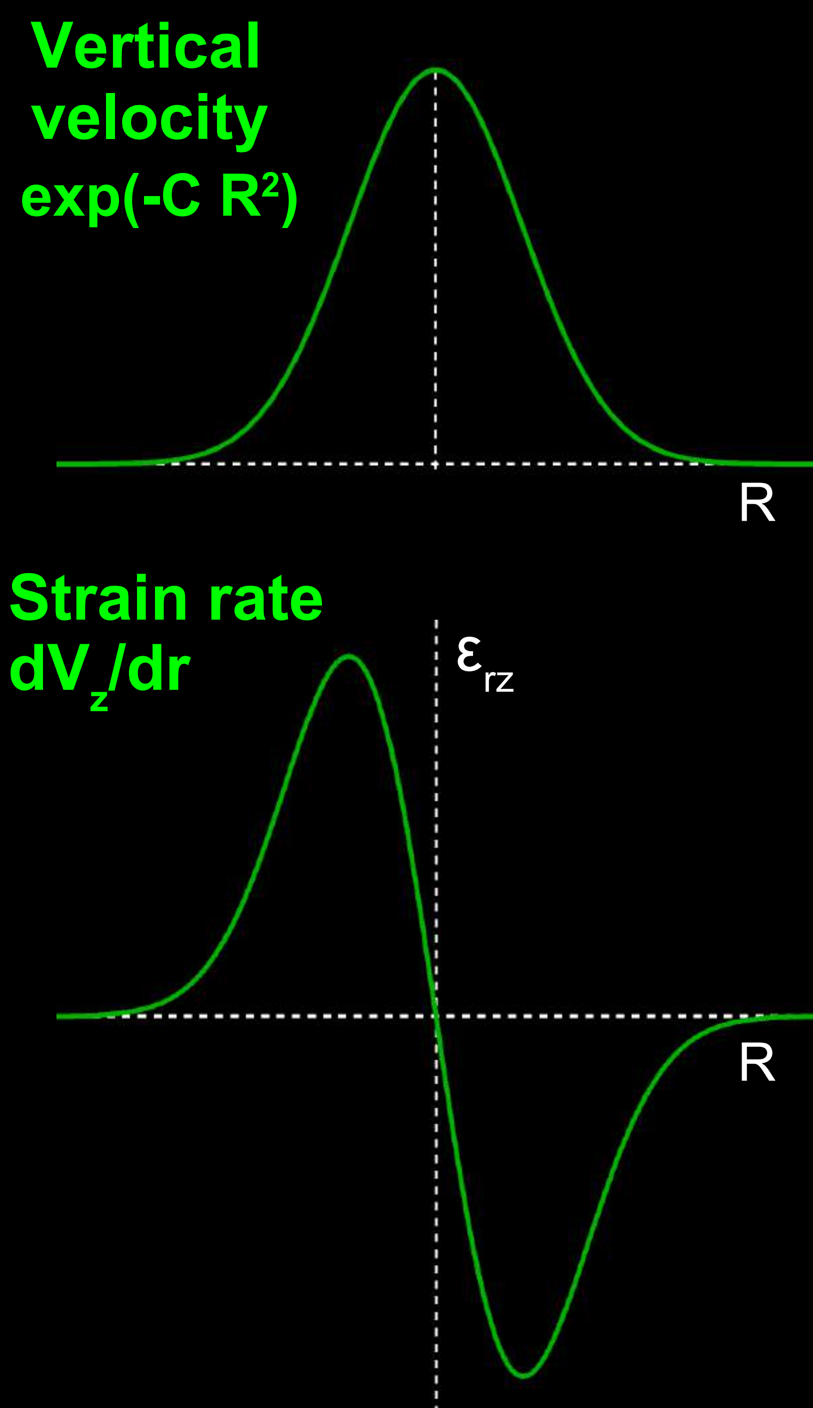
Experiments by A. Limare



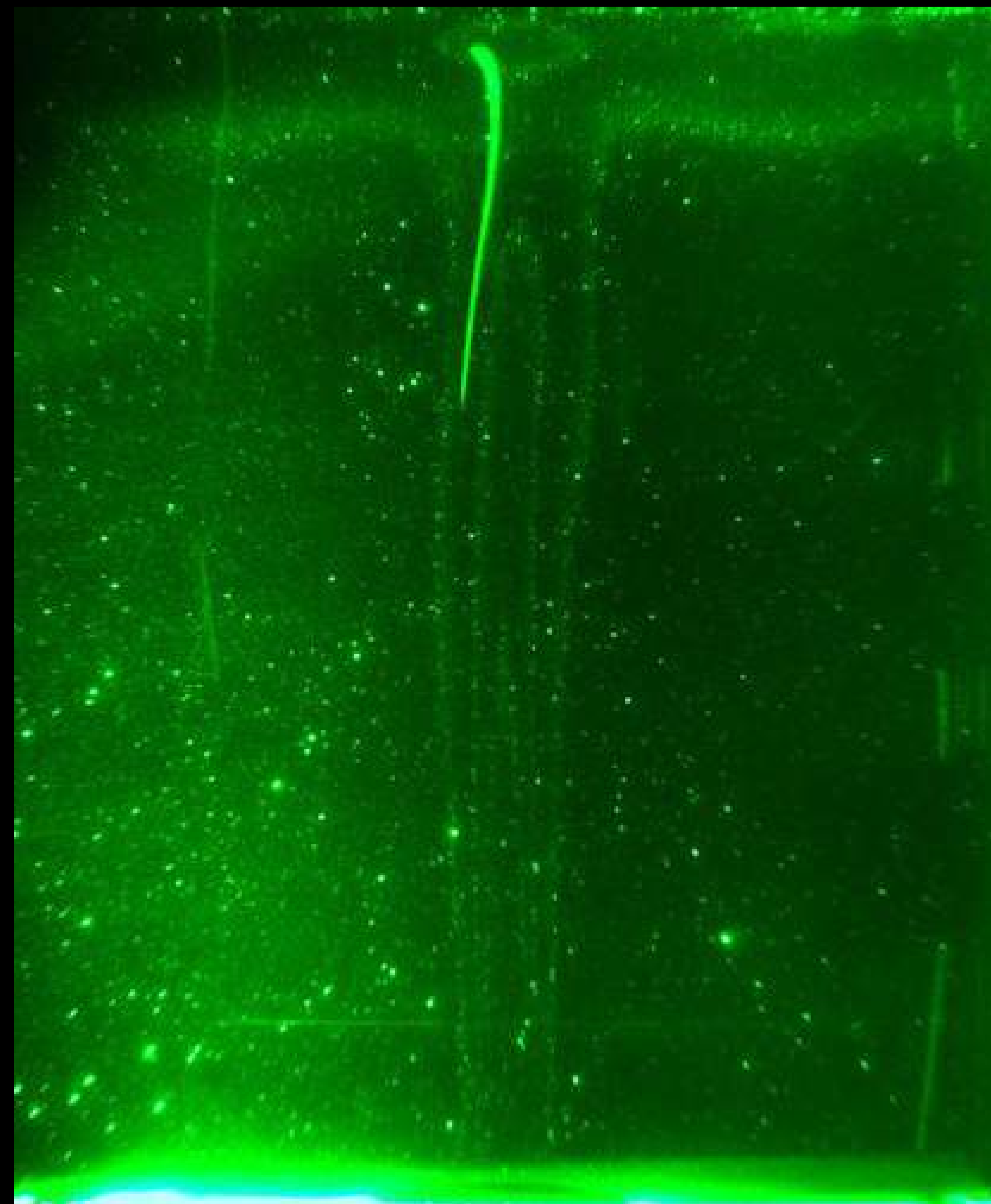








Vertical velocity
exp(-C R²)
R
Strain rate
dV_z/dr
ε_rz
R



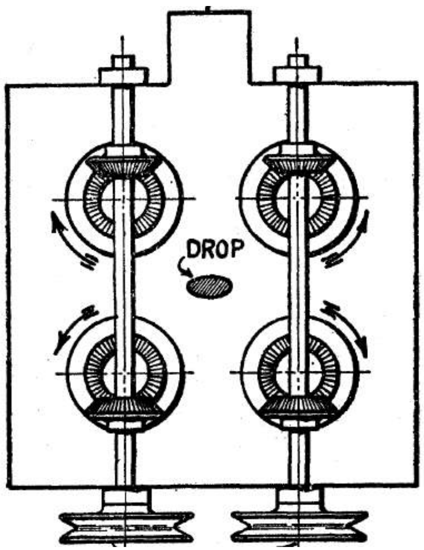
Interesting aspects of the flow within a mantle plume

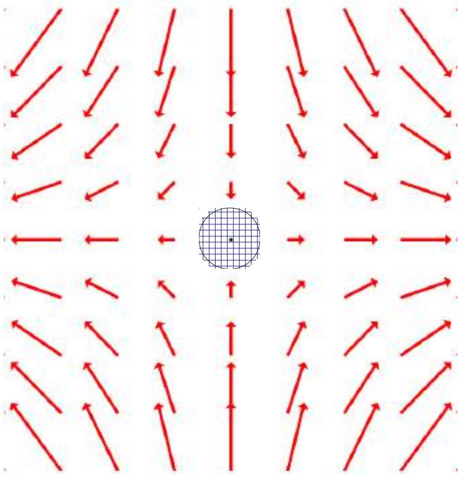
- The flow is often characterized by high strain rates (10^{-13} -10^{-14} s^{-1}) and high deformations

- The deformation history is complex, two types of flow coexist
  Pure shear dominates in the basal part of the plume
  Simple shear dominates in the plume conduit.

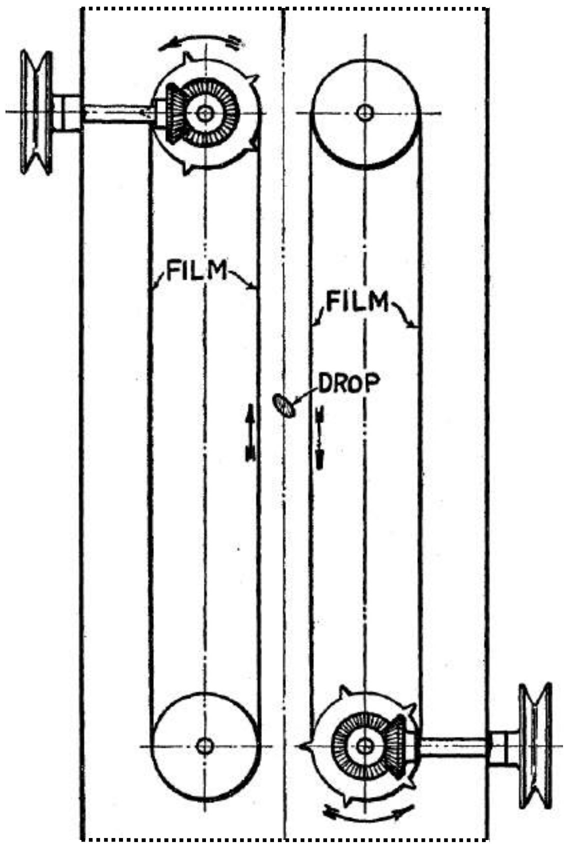
- The "plume flow" rules out commonly used assumptions:
  "Low deformations, Low and linearly varying strain rates, The same type of flow over time....."

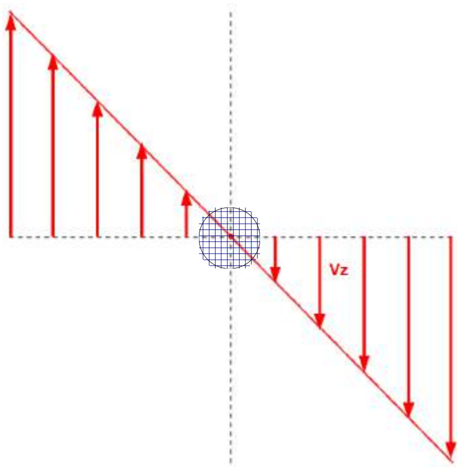
Laboratory experiments by Taylor, 1934





Pure shear flow
a viscous drop λ=20
gets highly deformed



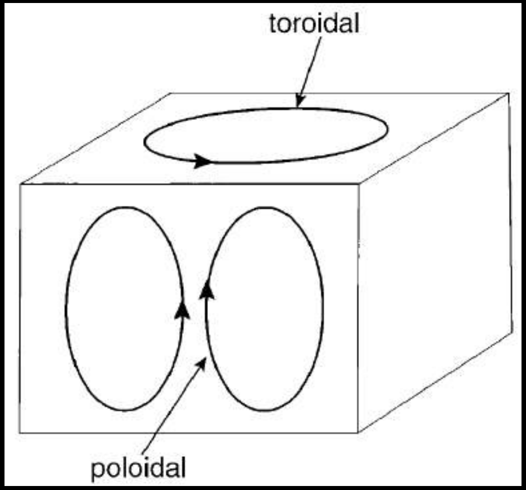


Simple shear flow
a viscous drop λ=20
merely rotates, with
minor deformations

Constant strain rate
throughout the fluid

Key questions about viscous heterogeneities in plumes

- How is a viscous heterogeneity defromed by the plume flow ?
- How is the plume flow perturbed by a viscous heterogeneity ?

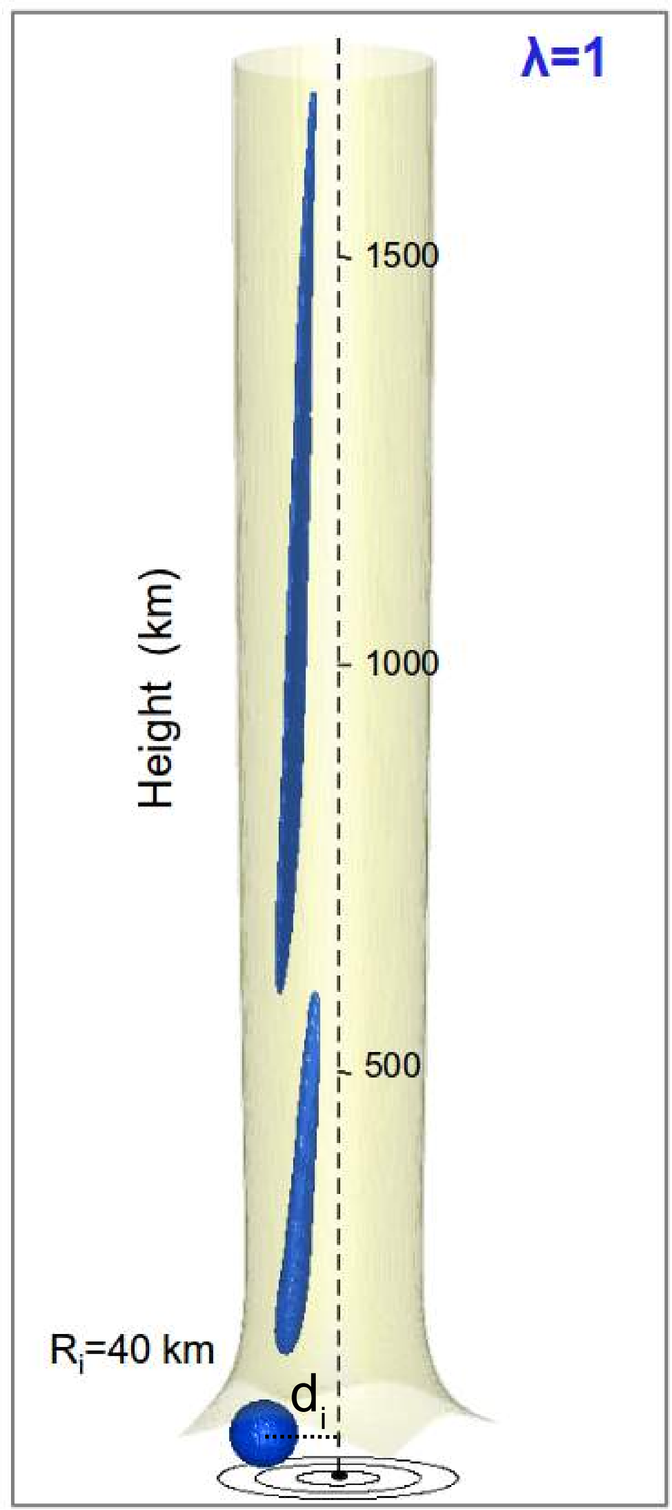


Lateral viscosity variations can induce a toroidal component within a poloidal, buoyancy driven flow

[Ferrachat and Ricard 1998]
[Bercovici et al., 2000]

- If the plume carries viscous heterogeneities, can a toroidal flow component appear ?
- In such a case, are radial mixing and/or azimuthal mixing enhanced ?

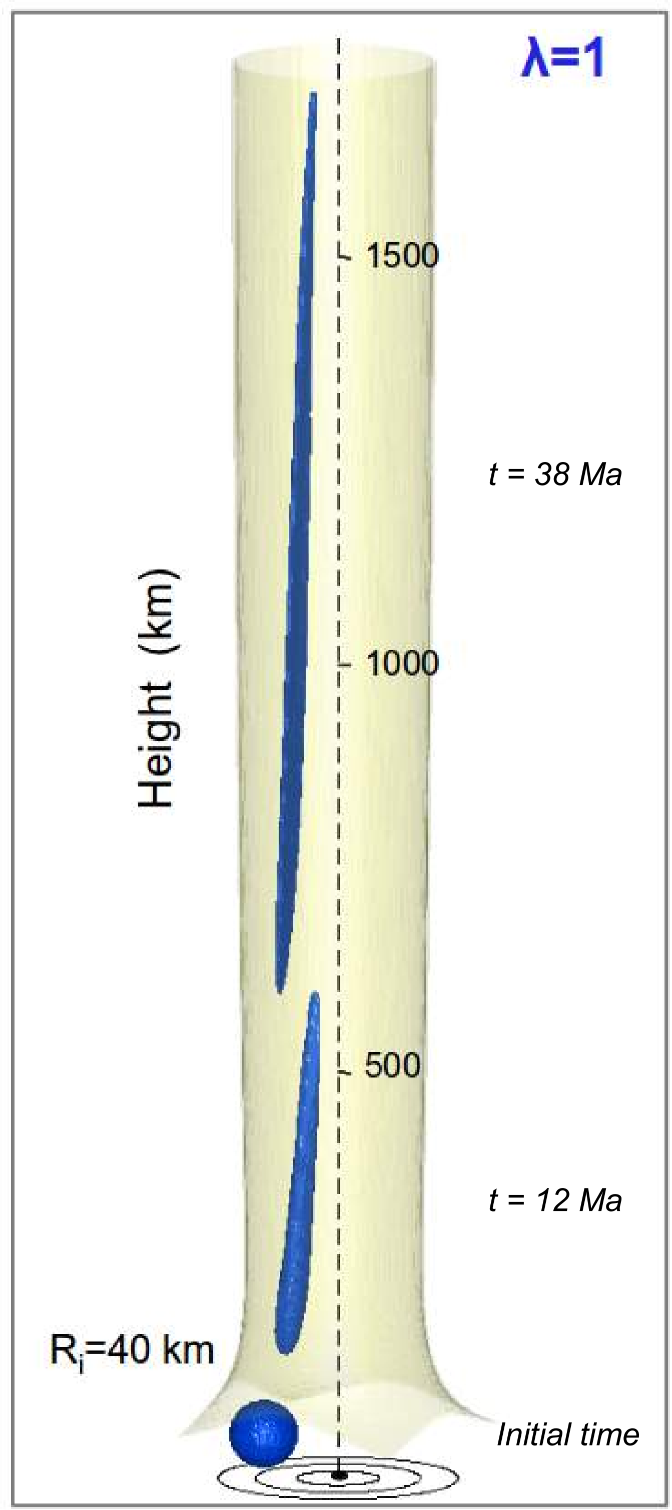
[Blichert-Toft and Albarède, 2009]



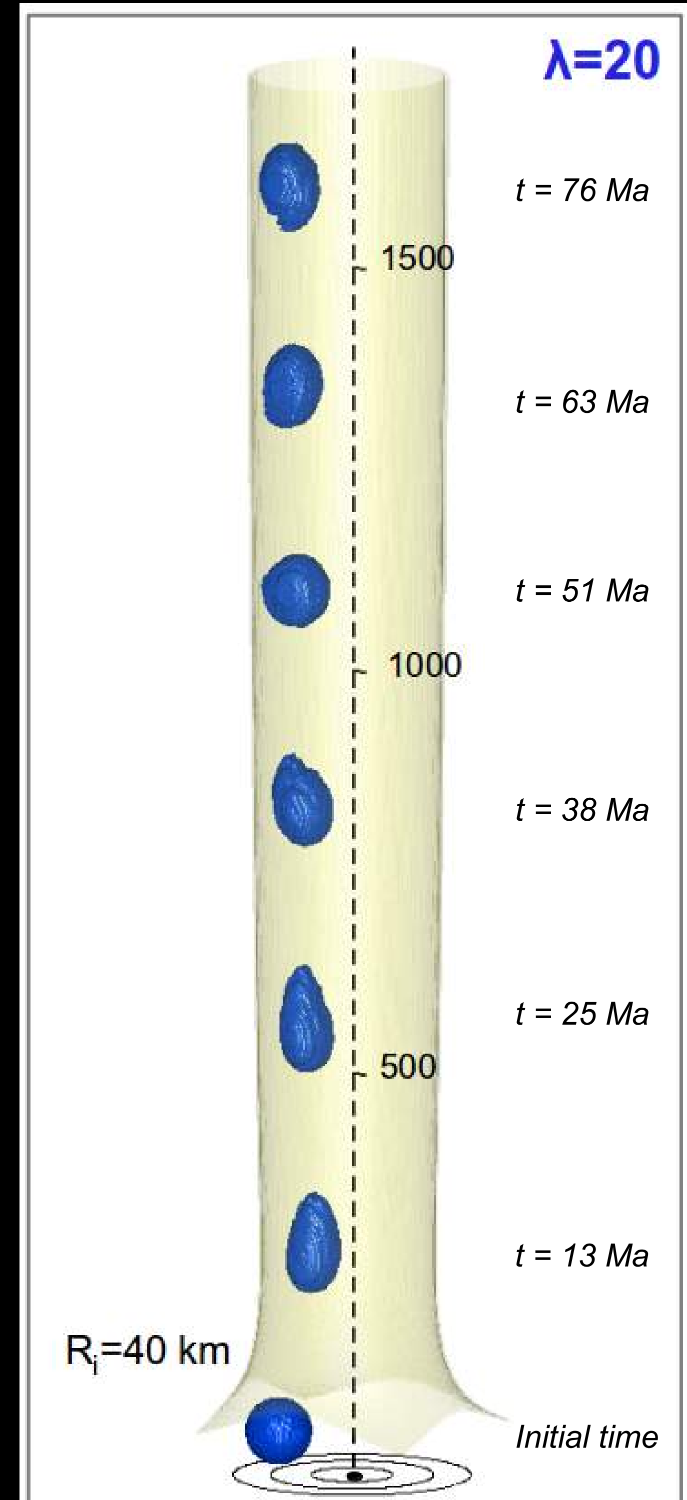
3D simulations of a mantle plume with temperature dependent viscosity

Code Stag3D by *Paul Tackley*

Millions of active tracers model a single more viscous ($1 < \lambda < 20$) heterogeneity with an initial spherical shape of variable radius ($30 < R_i < 50$ km), at initial axial distance d_i =100 km



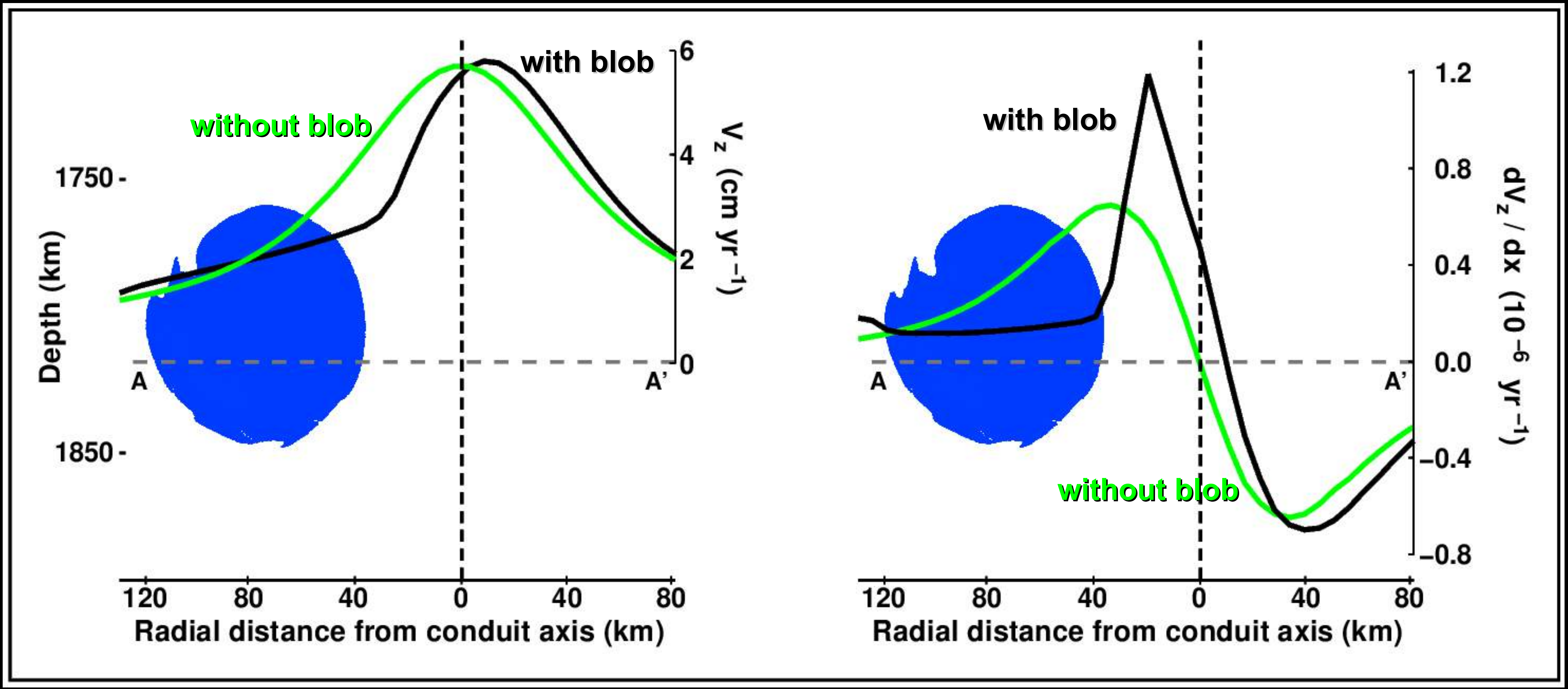
For **λ =20 R_i =40 km** the heterogeneity undergoes a modest deformation

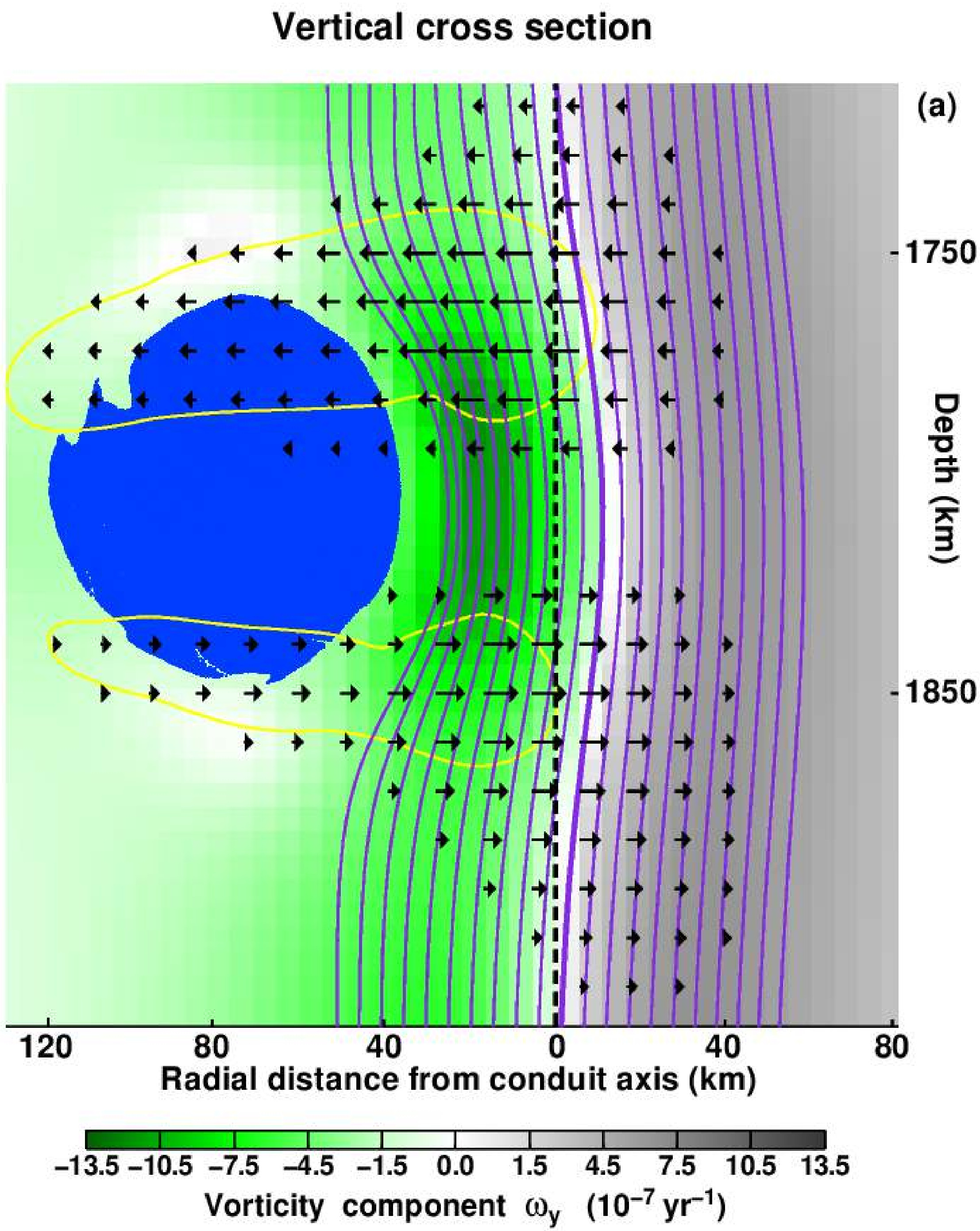


Viscous blob λ = 20

Vertical velocity profile

Strain rate profile





Horizontal velocity v_x (black)

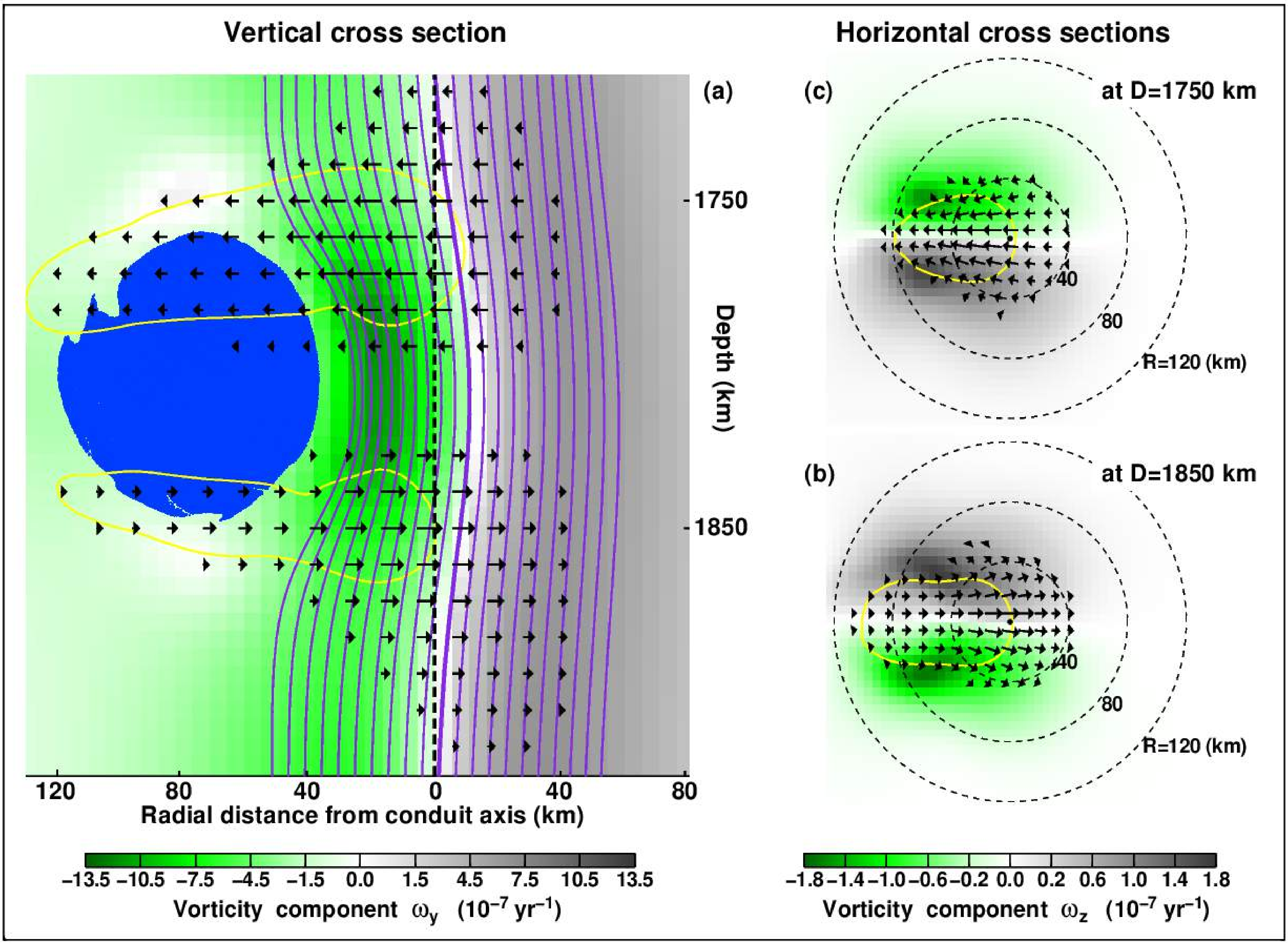
Contour $v_x \geq 0.1\ v_z$ (yellow)

Vorticity component (shades)

$$\omega_y = \left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x} \right)$$

$$\omega_z = \left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right)$$

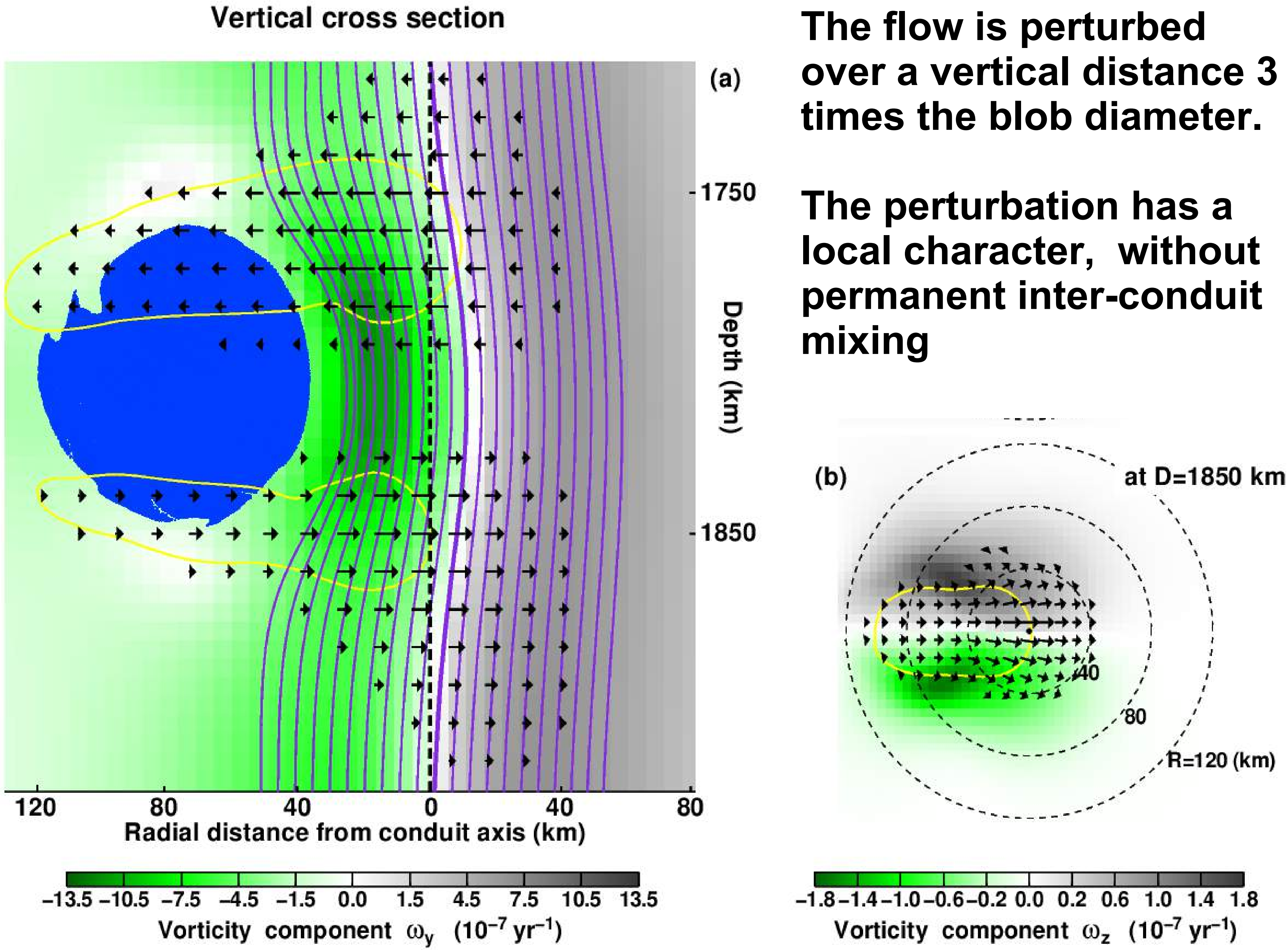
Flow trajectories (violet) are deviated and locally cross the plume axis (dashed line)

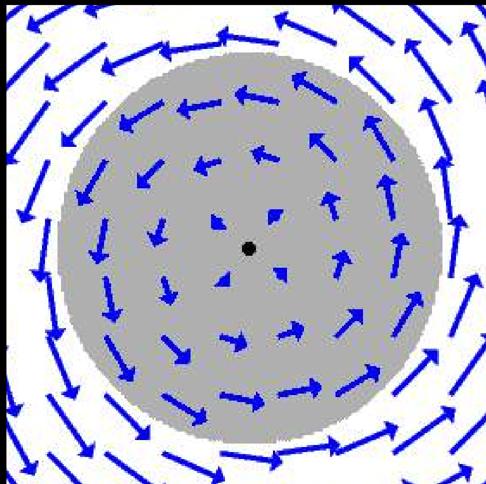


Vertical cross section
Horizontal cross sections
(a)
(c)
at D=1750 km
(b)
at D=1850 km
-1750
-1850
Depth (km)
40
80
R=120 (km)
120
80
40
0
40
80
Radial distance from conduit axis (km)
−13.5 −10.5 −7.5 −4.5 −1.5 0.0 1.5 4.5 7.5 10.5 13.5
Vorticity component ω_y (10^{-7} yr^{-1})
−1.8 −1.4 −1.0 −0.6 −0.2 0.0 0.2 0.6 1.0 1.4 1.8
Vorticity component ω_z (10^{-7} yr^{-1})

The flow is perturbed over a vertical distance 3 times the blob diameter.

The perturbation has a local character, without permanent inter-conduit mixing

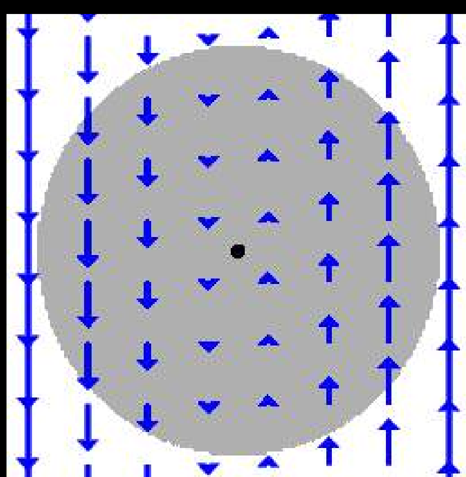




Solid-body rotation

$V_x = -Cz, \quad V_z = Cx$

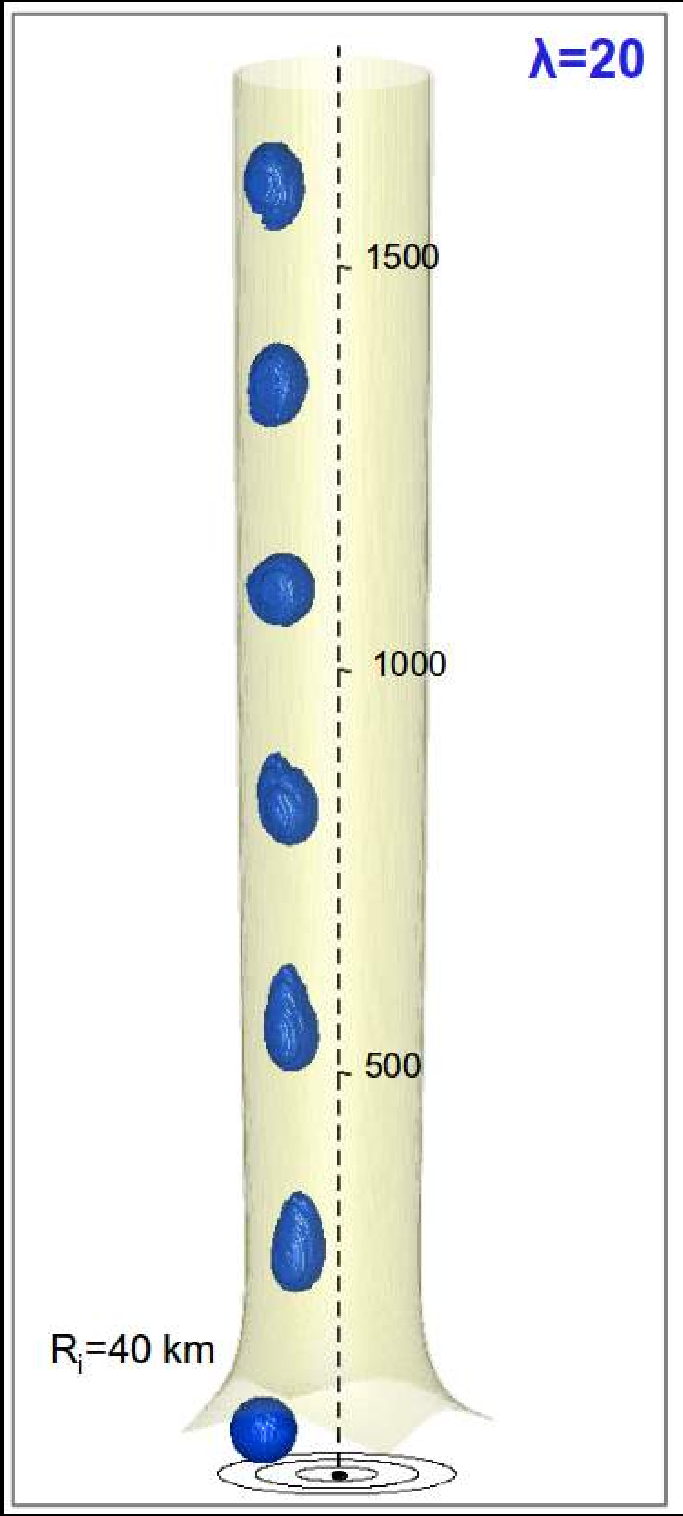
$\omega_y = -2C, \quad \varepsilon_{xz} = 0$

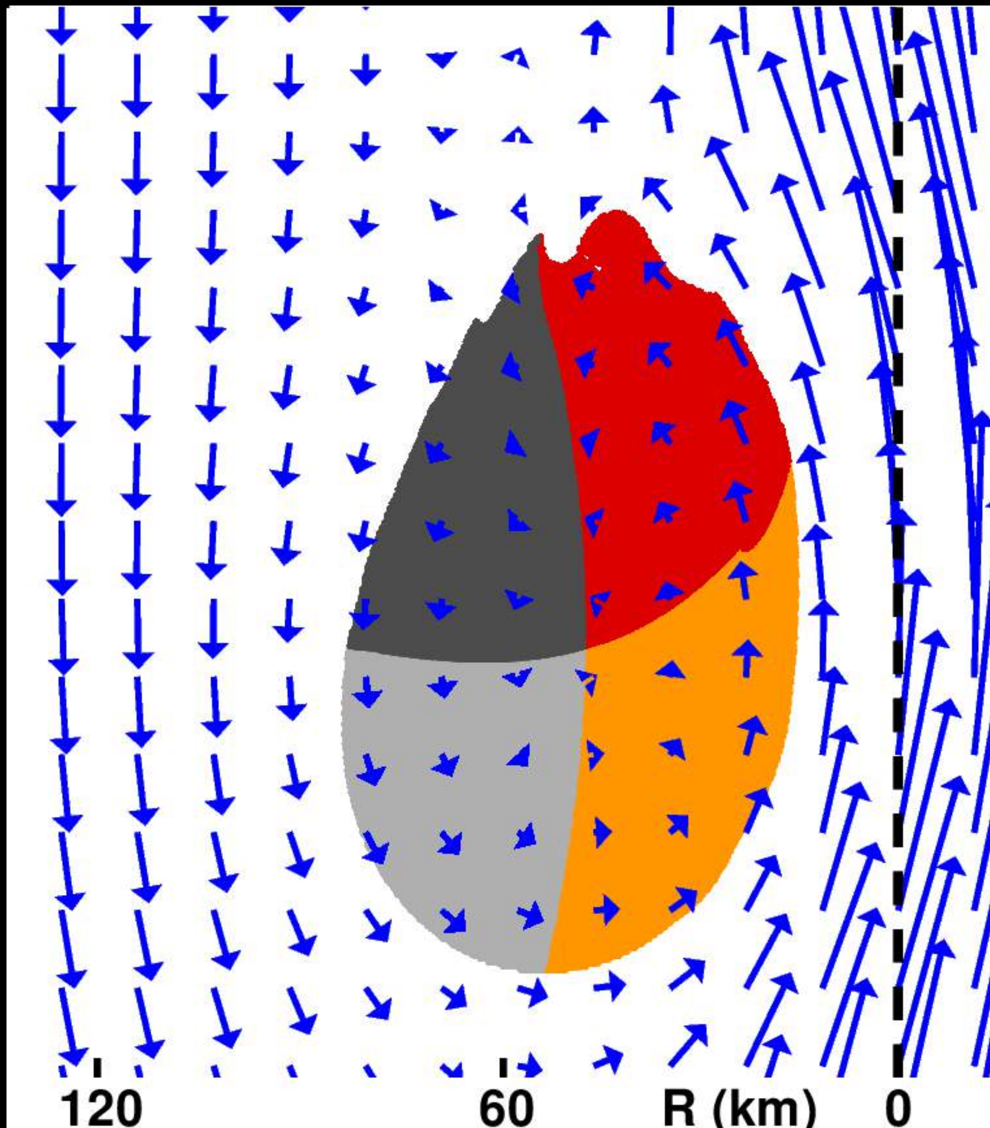


Simple shearing

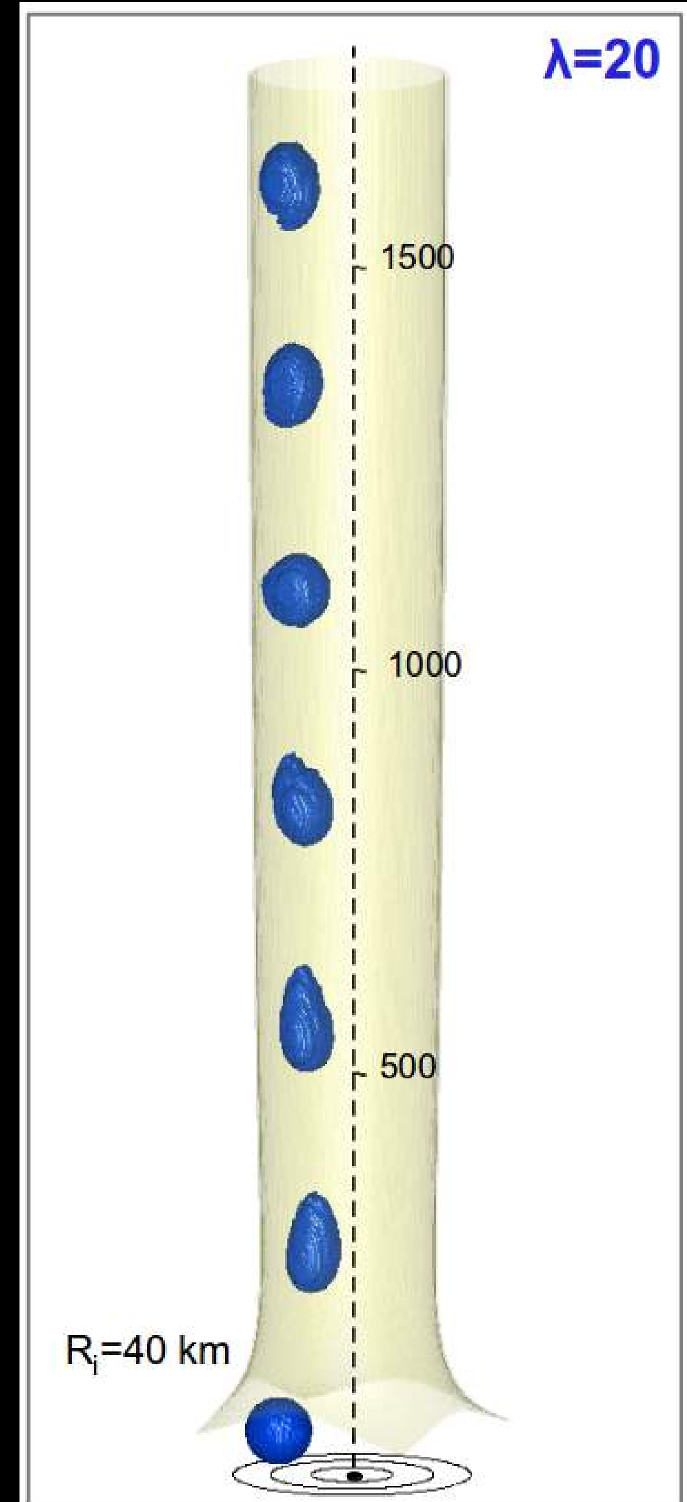
$V_x = 0, \quad V_z = Cx$

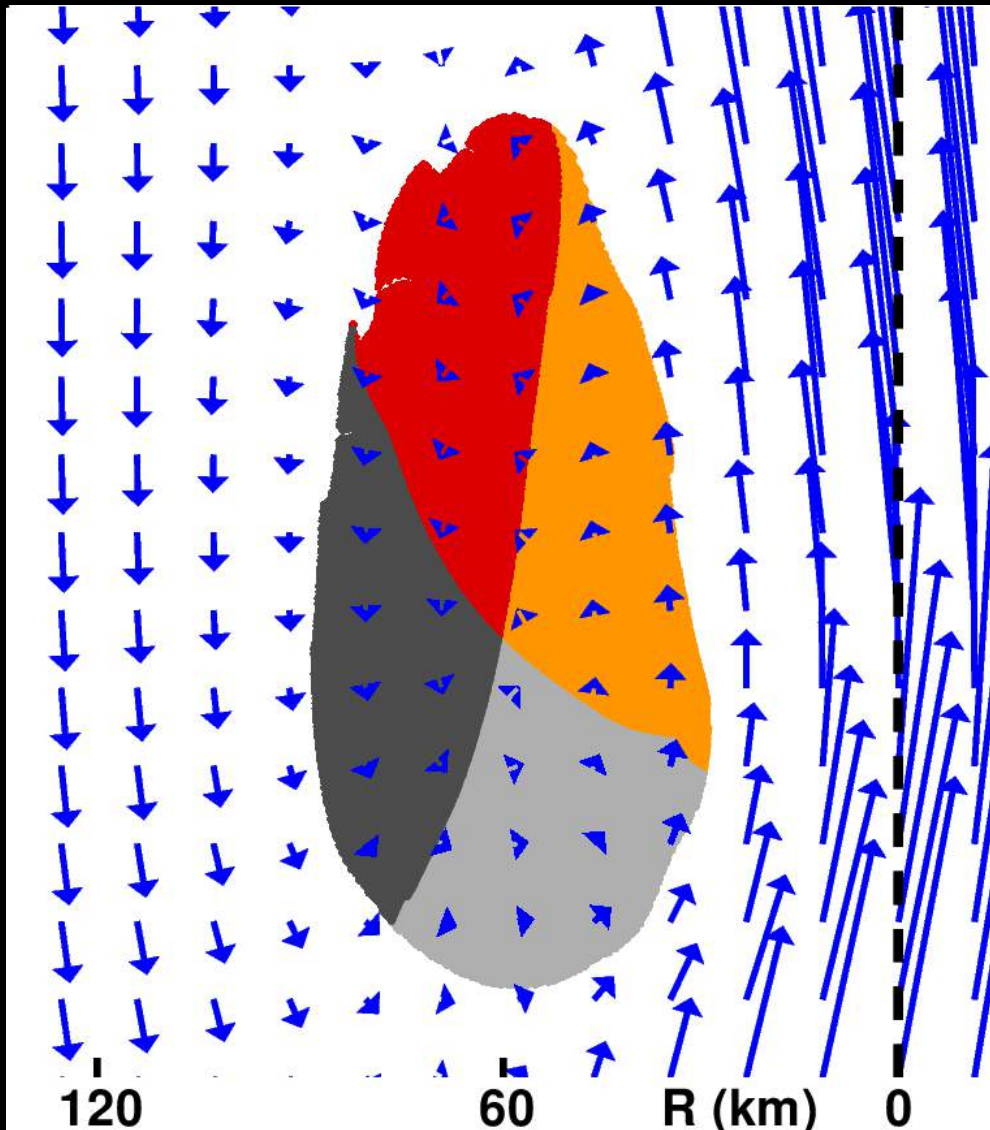
$\omega_y = -C, \quad \varepsilon_{xz} = C/2$

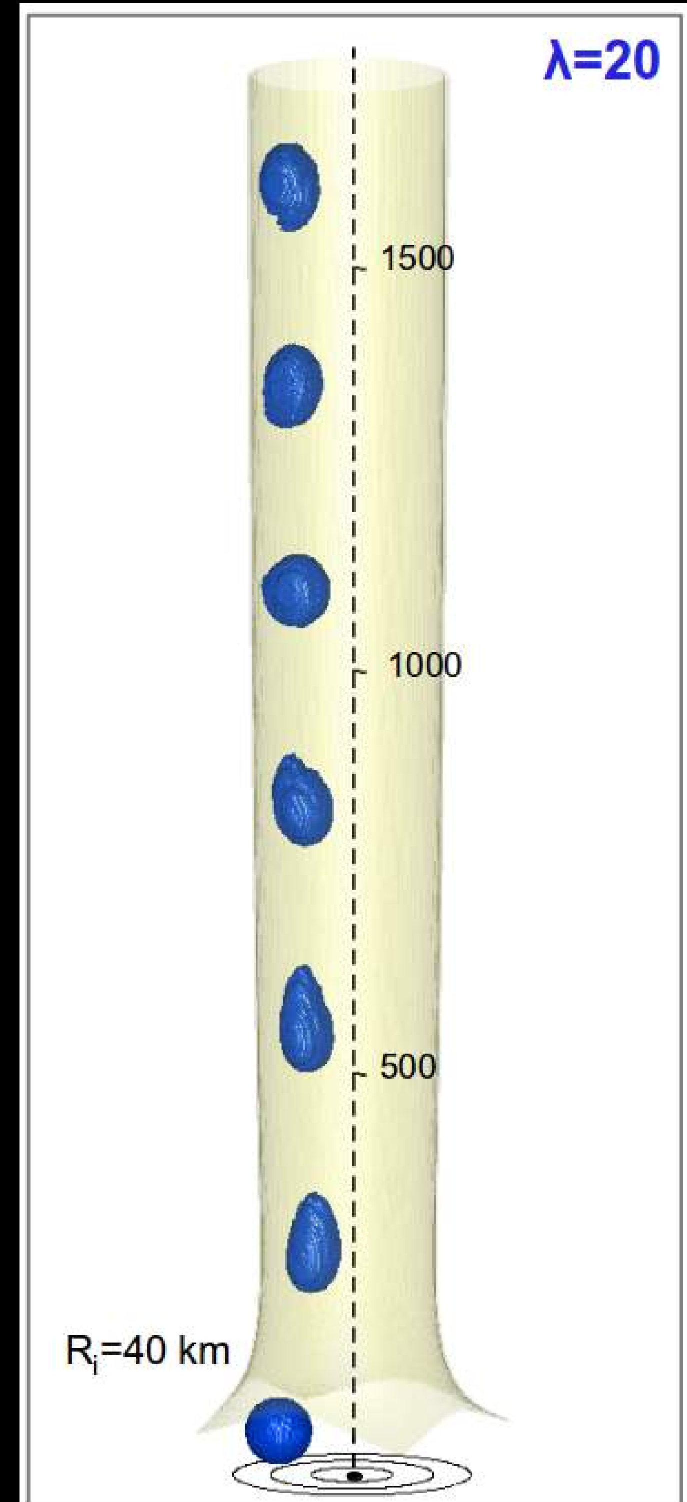


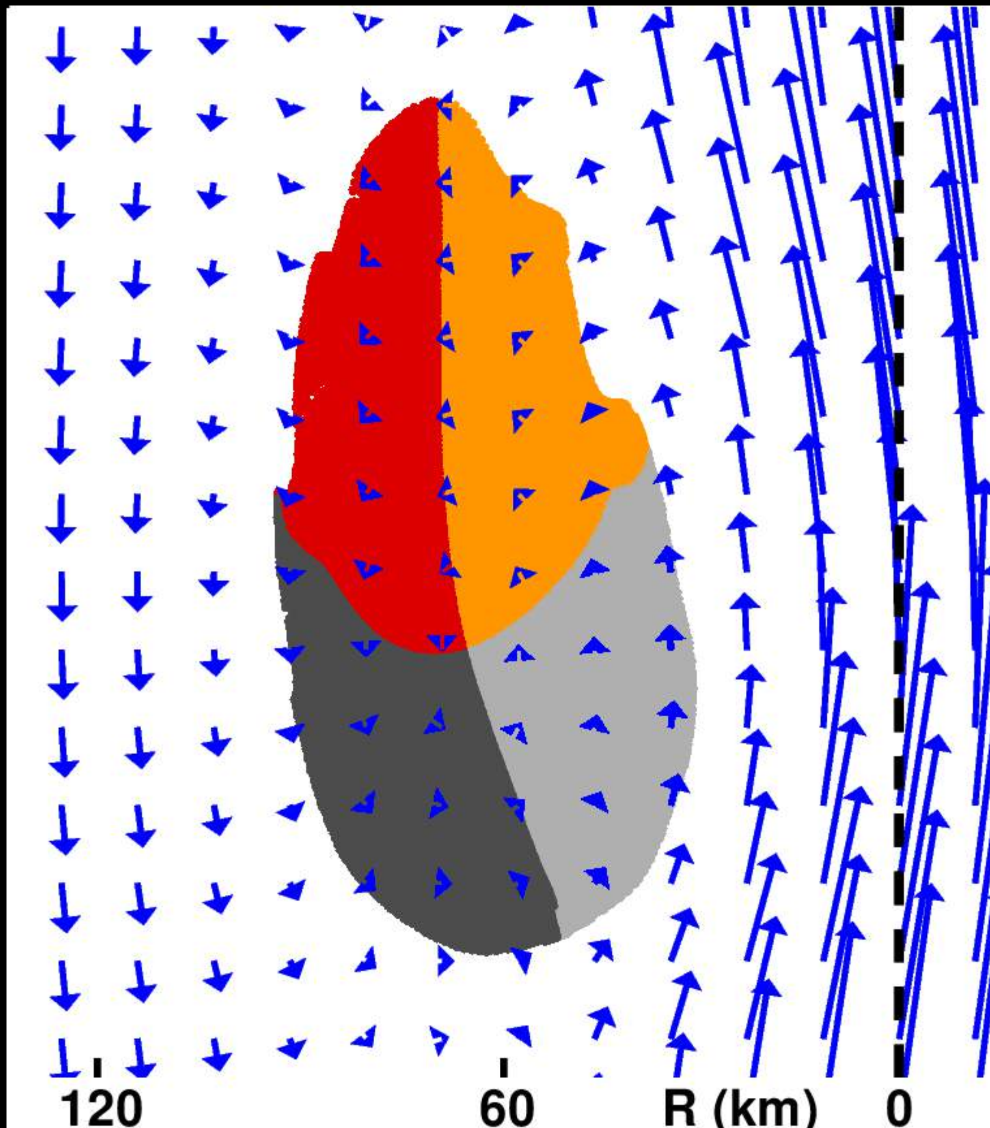


$V_x = V_x - V_x^{\text{center blob}}$ $V_z = V_z - V_z^{\text{center blob}}$

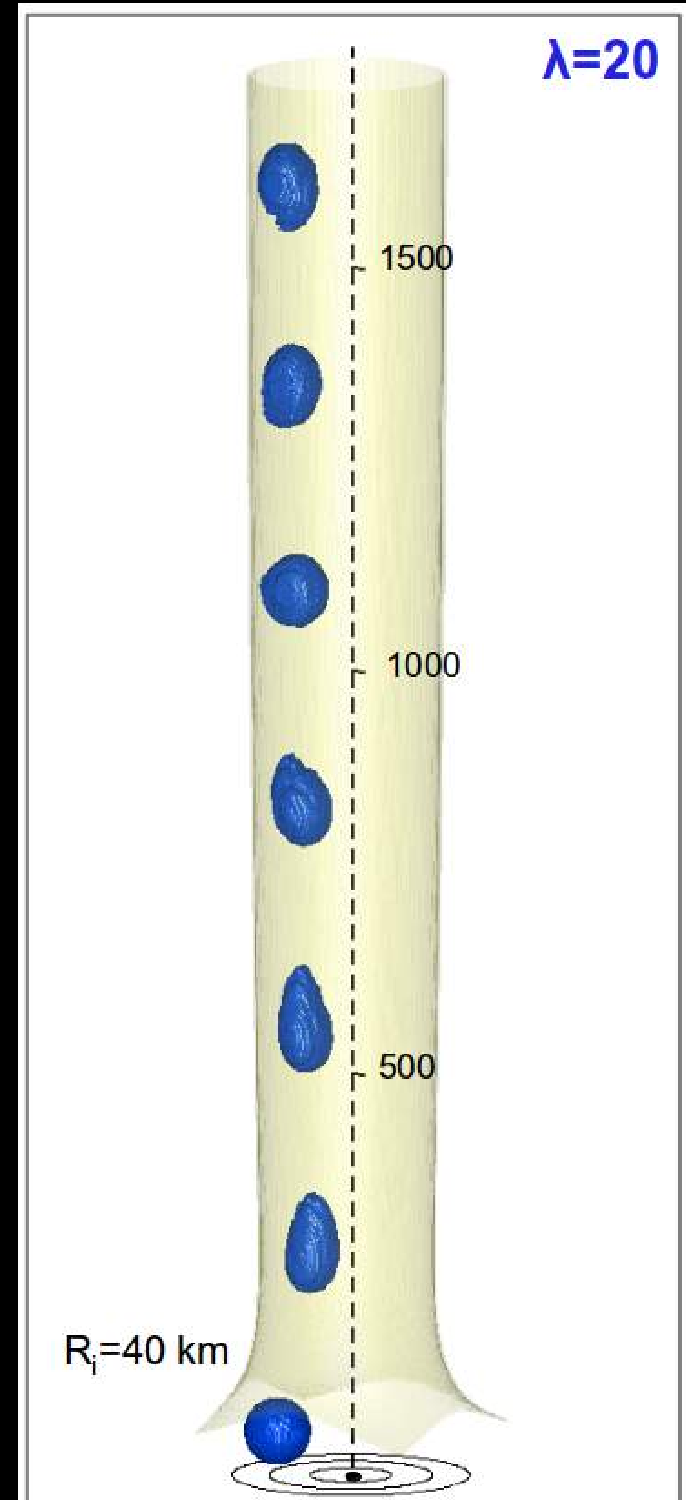



120
60
R (km)
0

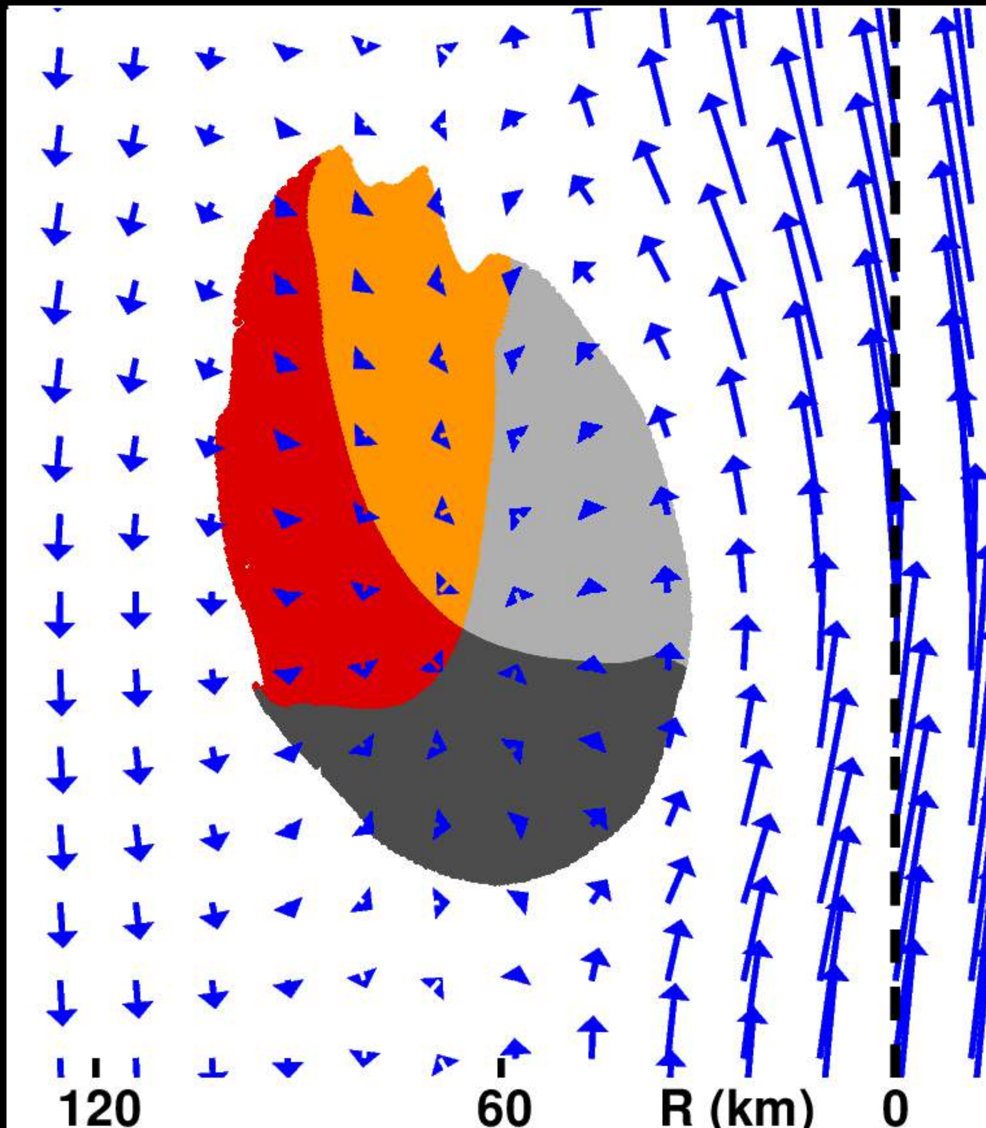

λ=20
1500
1000
500
R$_i$=40 km

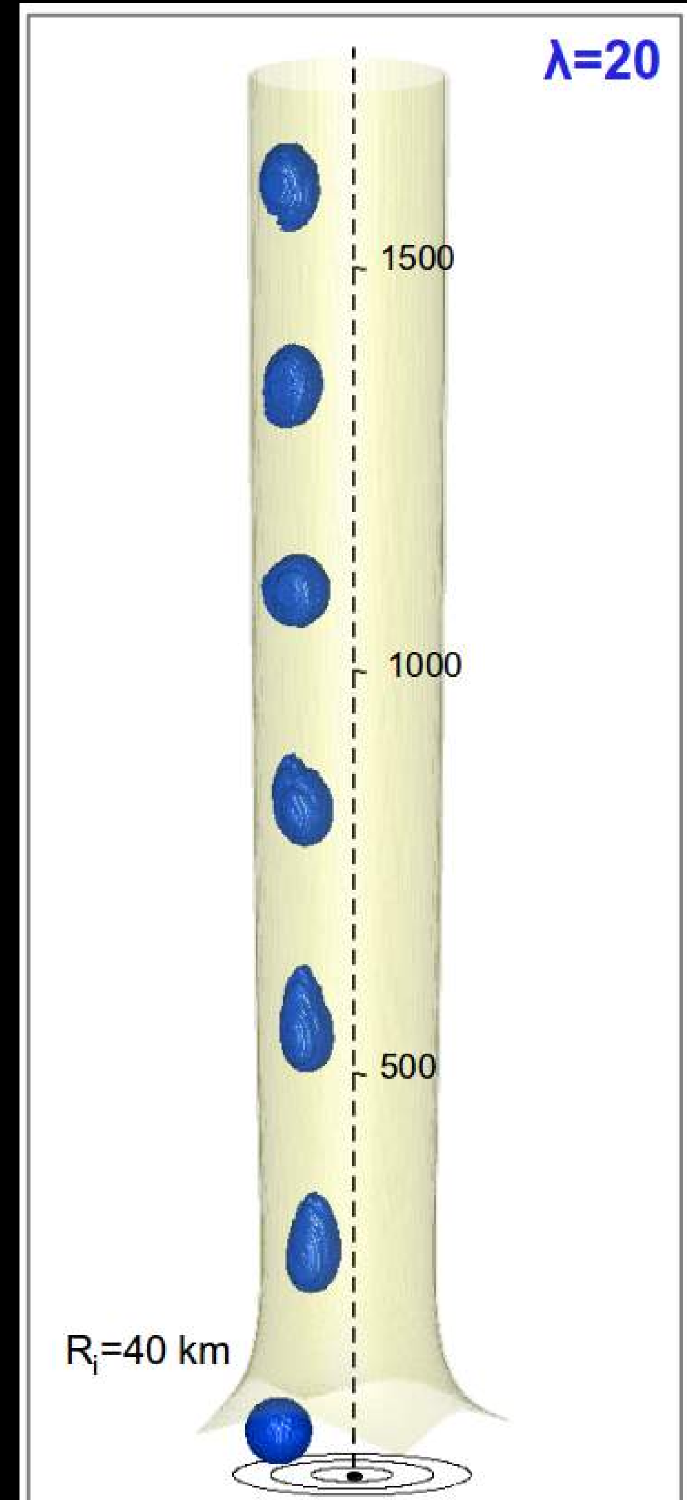


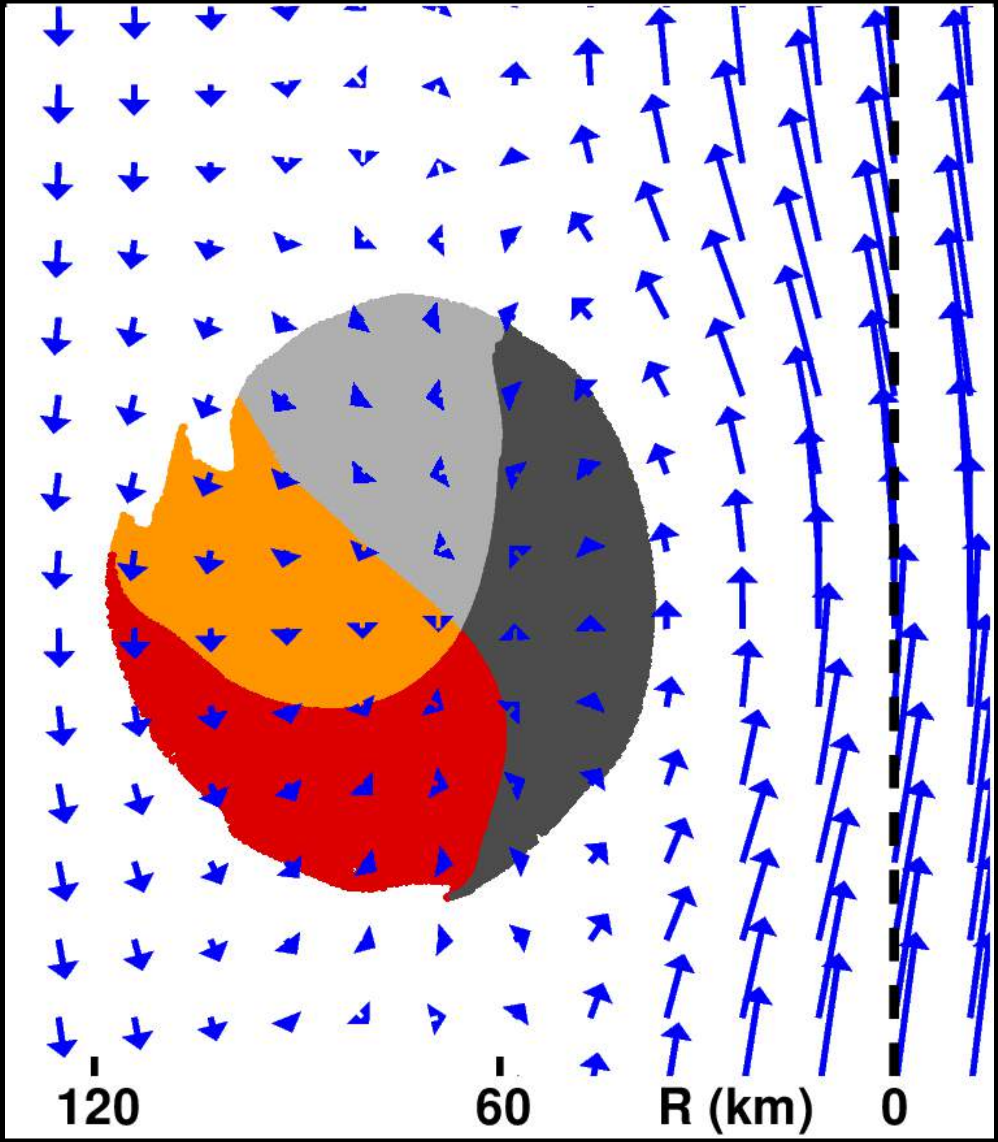
120
60
R (km)
0

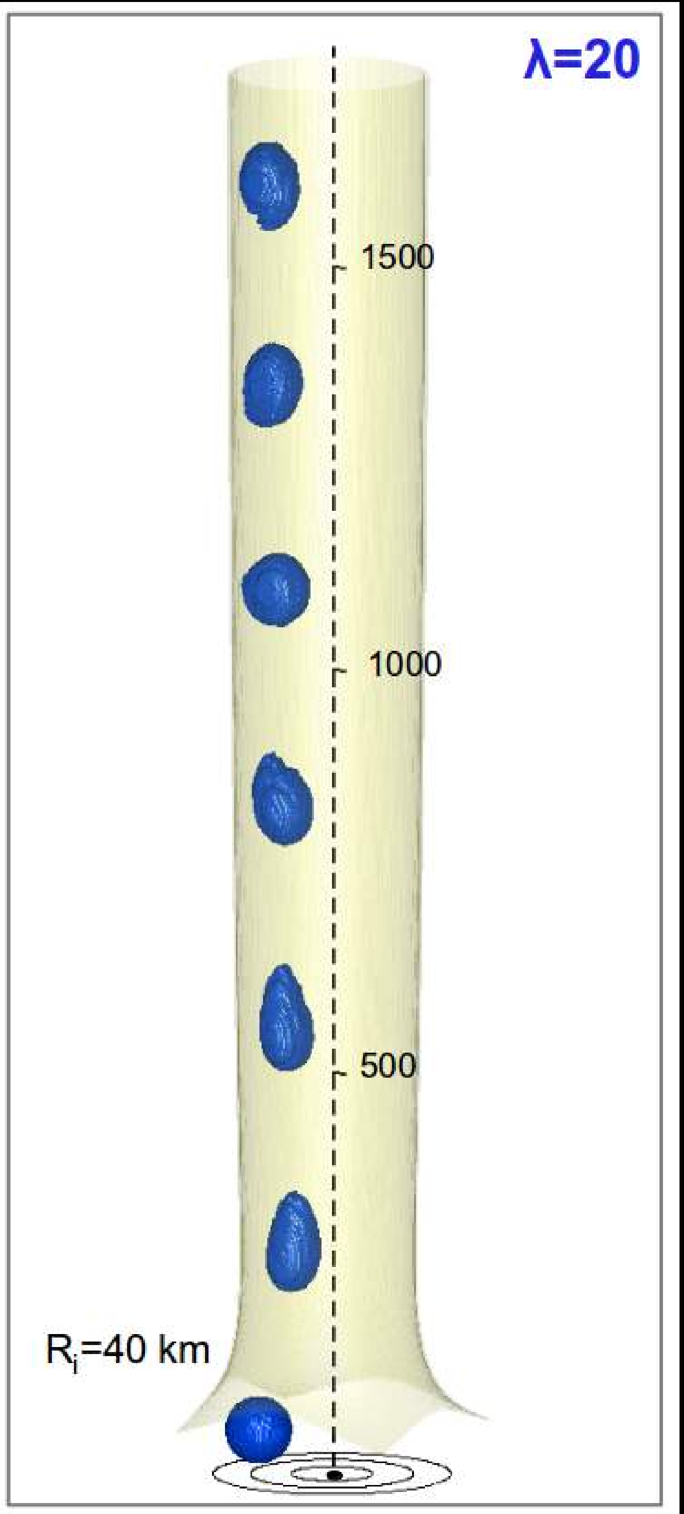


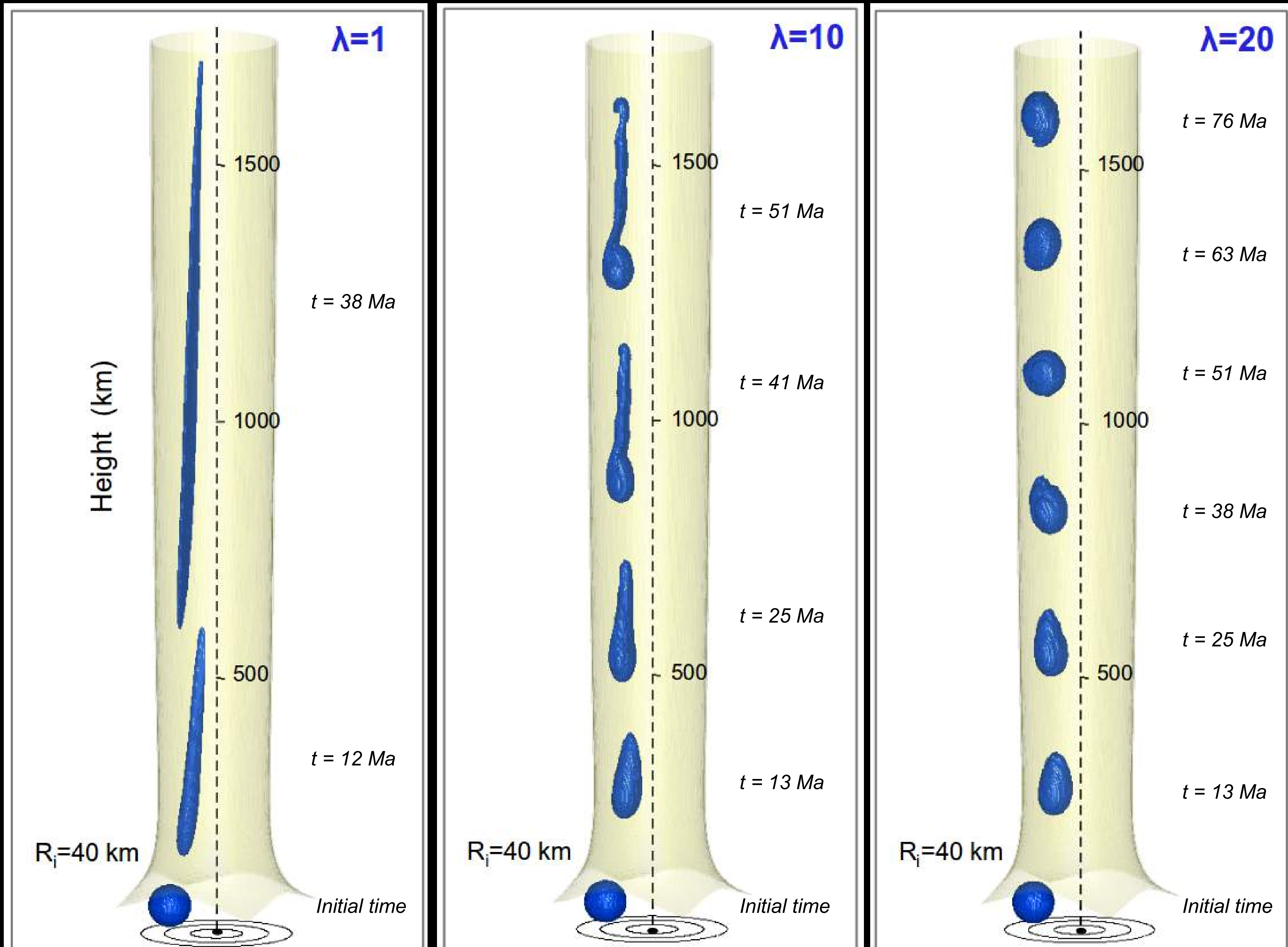
λ=20
1500
1000
500
R_i=40 km


120
60
R (km)
0


λ=20
1500
1000
500
R$_i$=40 km

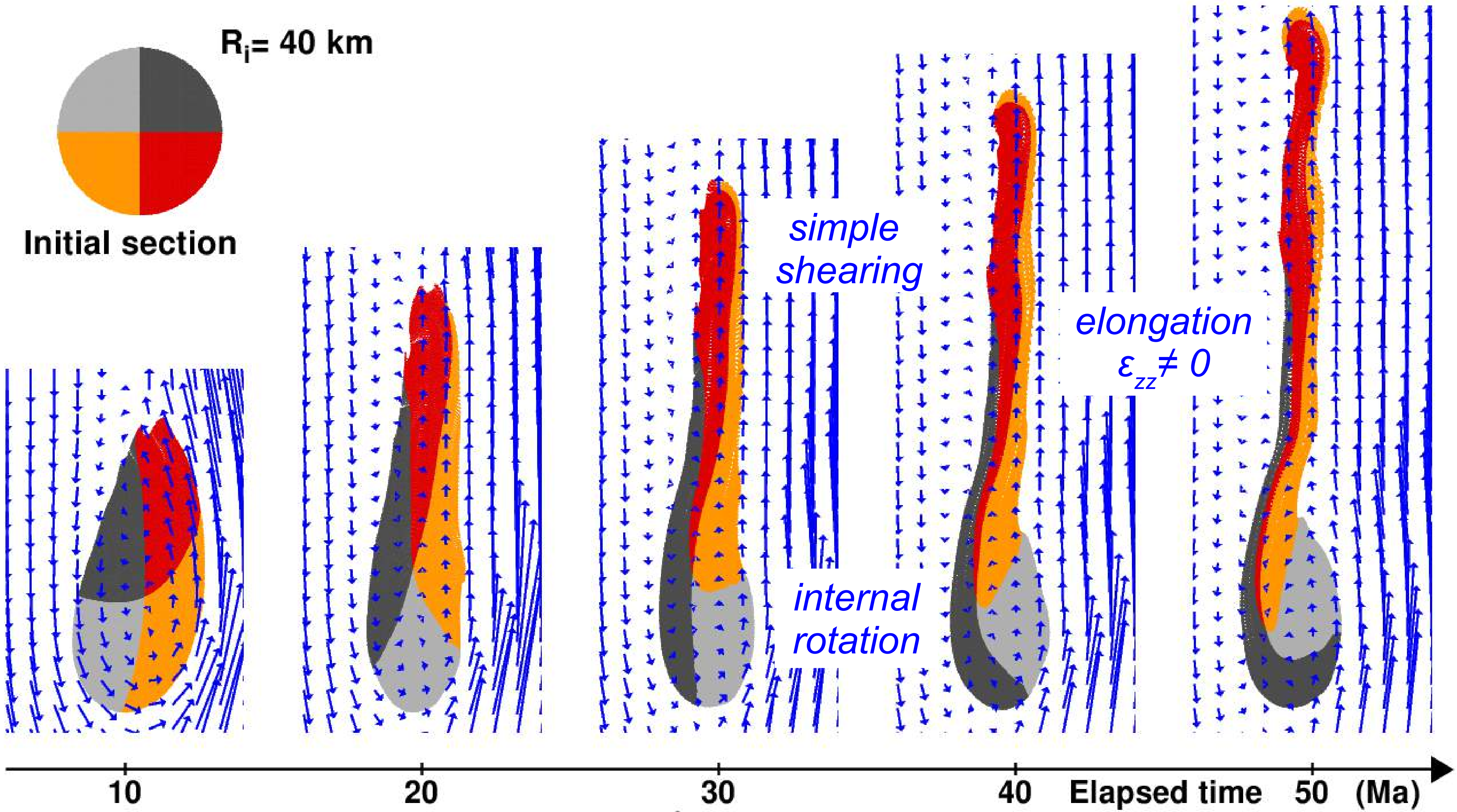

120
60
R (km)
0


λ=20
1500
1000
500
R$_i$=40 km

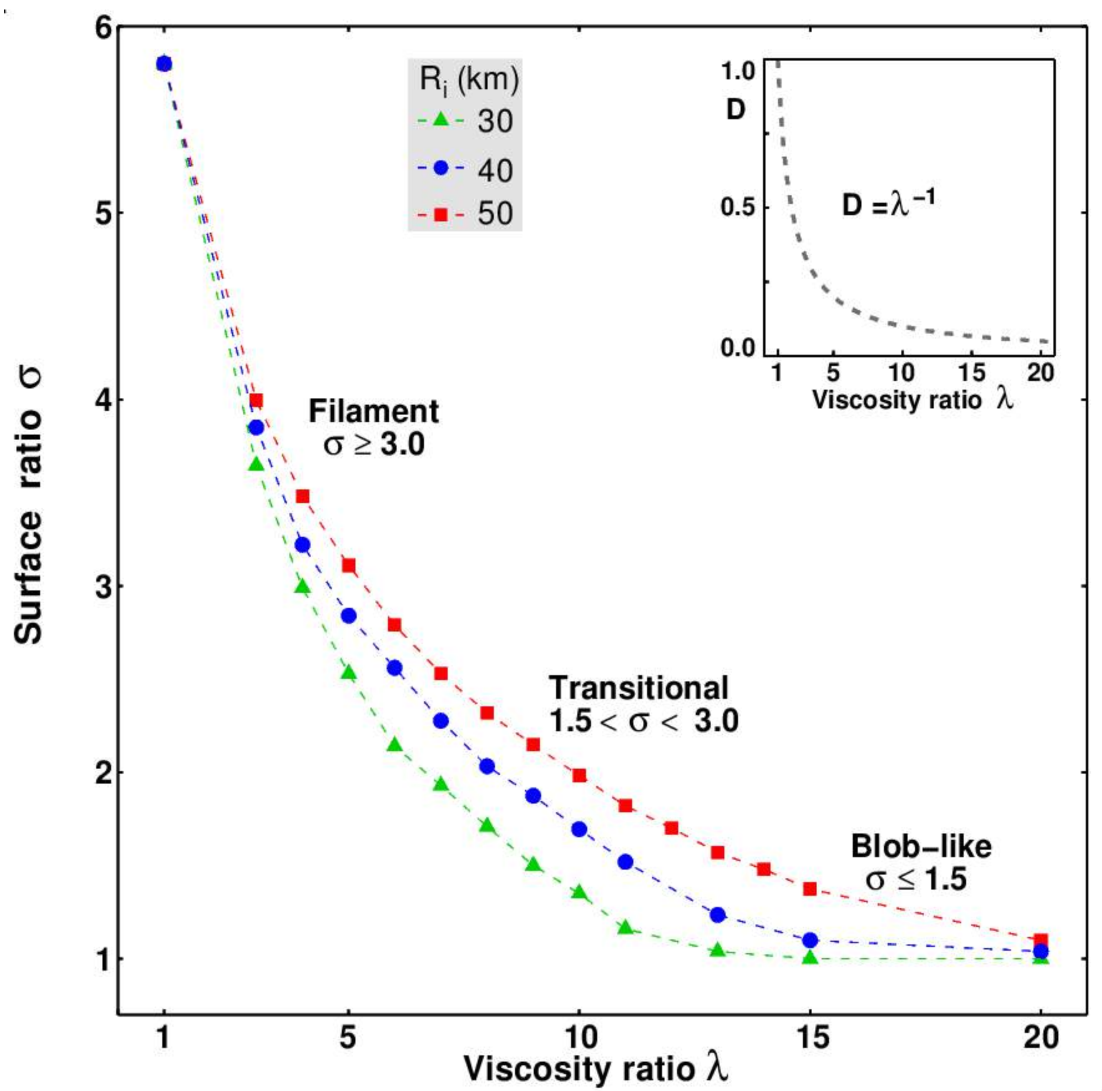


λ=1
λ=10
λ=20
Height (km)
1500
1000
500
t = 38 Ma
t = 12 Ma
t = 51 Ma
t = 41 Ma
t = 25 Ma
t = 13 Ma
t = 76 Ma
t = 63 Ma
t = 51 Ma
t = 38 Ma
t = 25 Ma
t = 13 Ma
R_i=40 km
Initial time

For λ=10 we find a "transitional" shape



Quantifying the deformation of a 3D body with an irregular shape



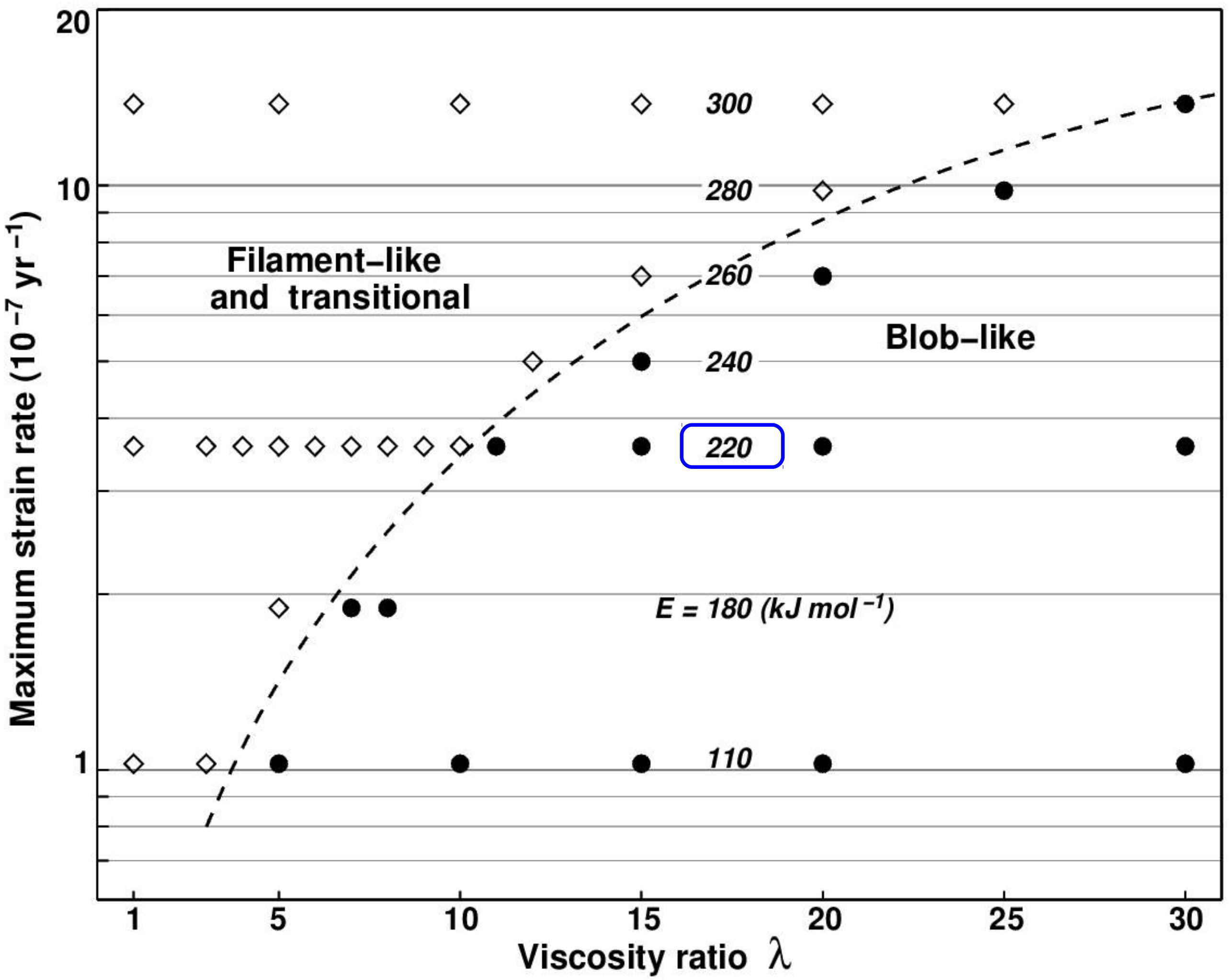
$$\sigma = \frac{\text{Surface}_{\text{heterogeneity at time t}}}{\text{Surface}_{\text{initial sphere}}}$$

σ decreases with increasing λ

For a given λ, a small size (R_i=30 km) heterogeneity is less deformed than a larger (R_i=50 km) one.

Albeit arbitrarily, σ is used to define shapes: filament-like, transitional and blob-like

Effect of the strain rate (ε_{rz}~dV_z/dr) across the conduit



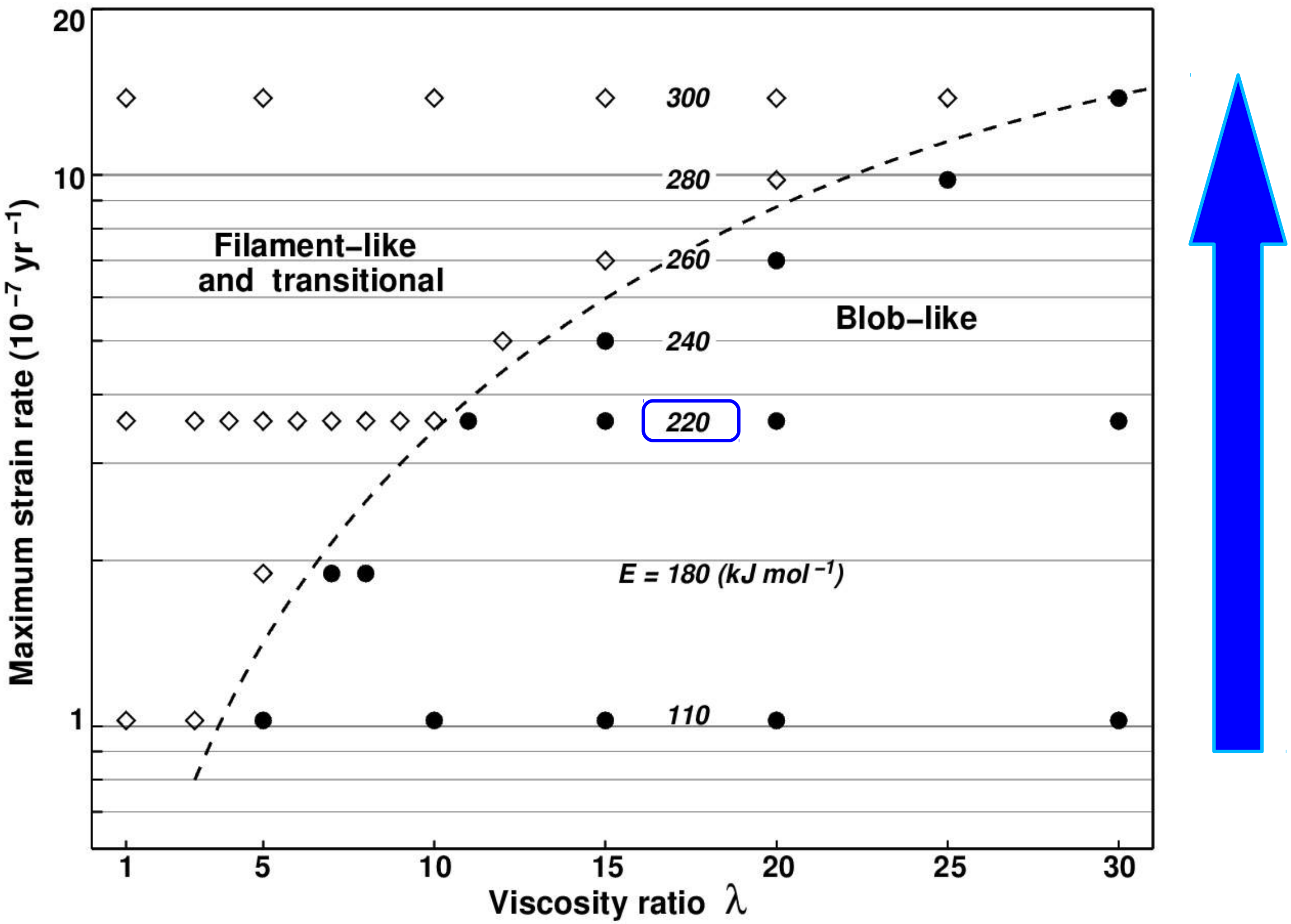
We span a range of ε_{rz} by varying the activation energy E.

$$\eta = \eta_m \exp\left[\frac{E}{R}\left(\frac{T_m - T}{T_m T}\right)\right]$$

At high ε_{rz} the blob-like shape is restricted to high λ (*i.e.*, λ>20).

At low ε_{rz} the blob-like shape is stable at λ=4, as in Manga *[1996].*

Effect of the strain rate ($\varepsilon_{rz} \sim dV_z/dr$) across the conduit

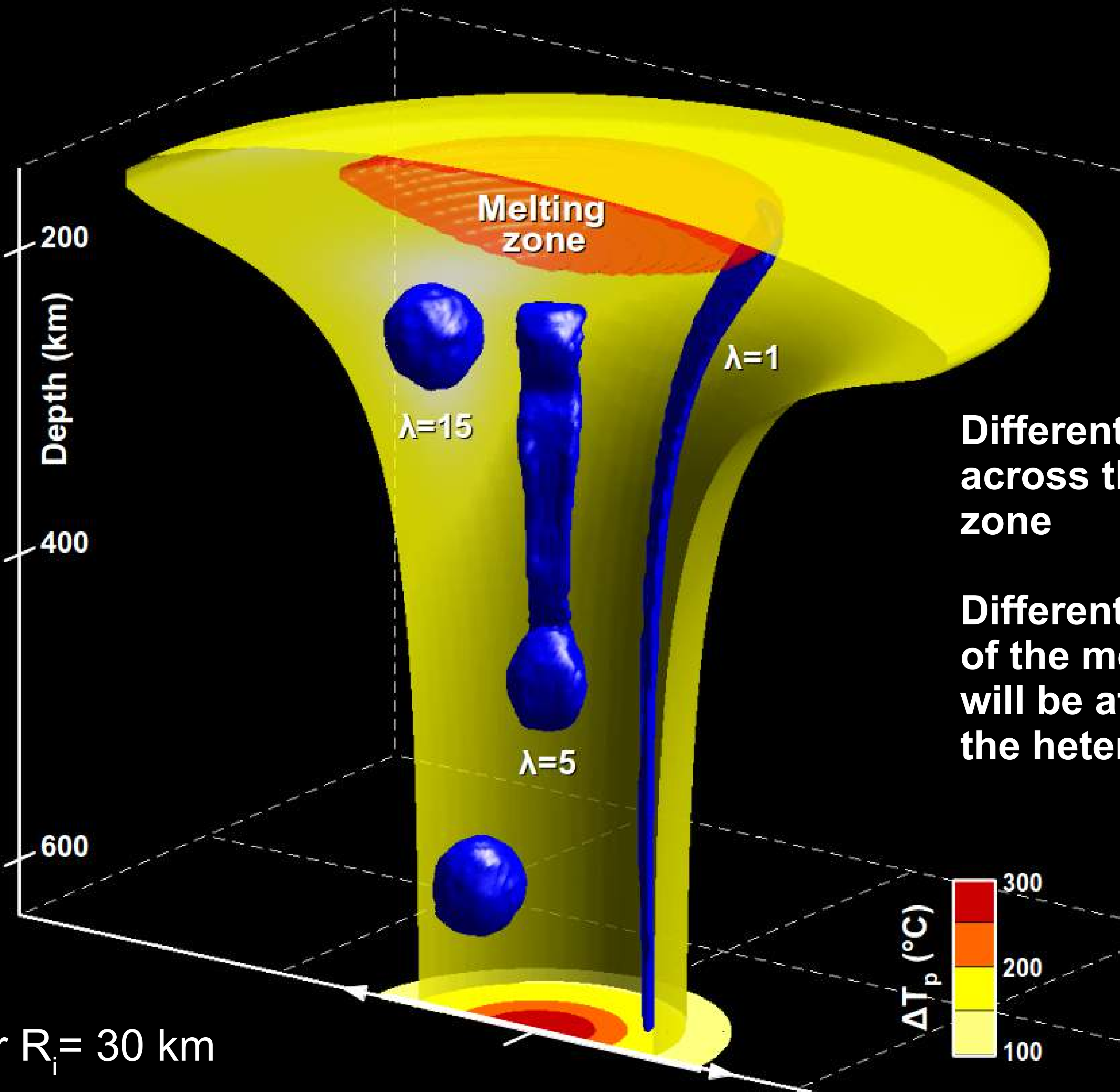


By increasing the activation energy E, the whole plume flow is modified :

- the upwelling velocity increases
- the buoyancy flux B increases

Filament-like heterogeneities will prevail in **vigorous plumes** (B_{Hawaii}= 8700 Kg/s)

Blob-like heterogeneities will be more easily preserved in **weaker plumes** ($B_{Réunion}$= 1900 Kg/s; B_{Samoa}= 1600 Kg/s)

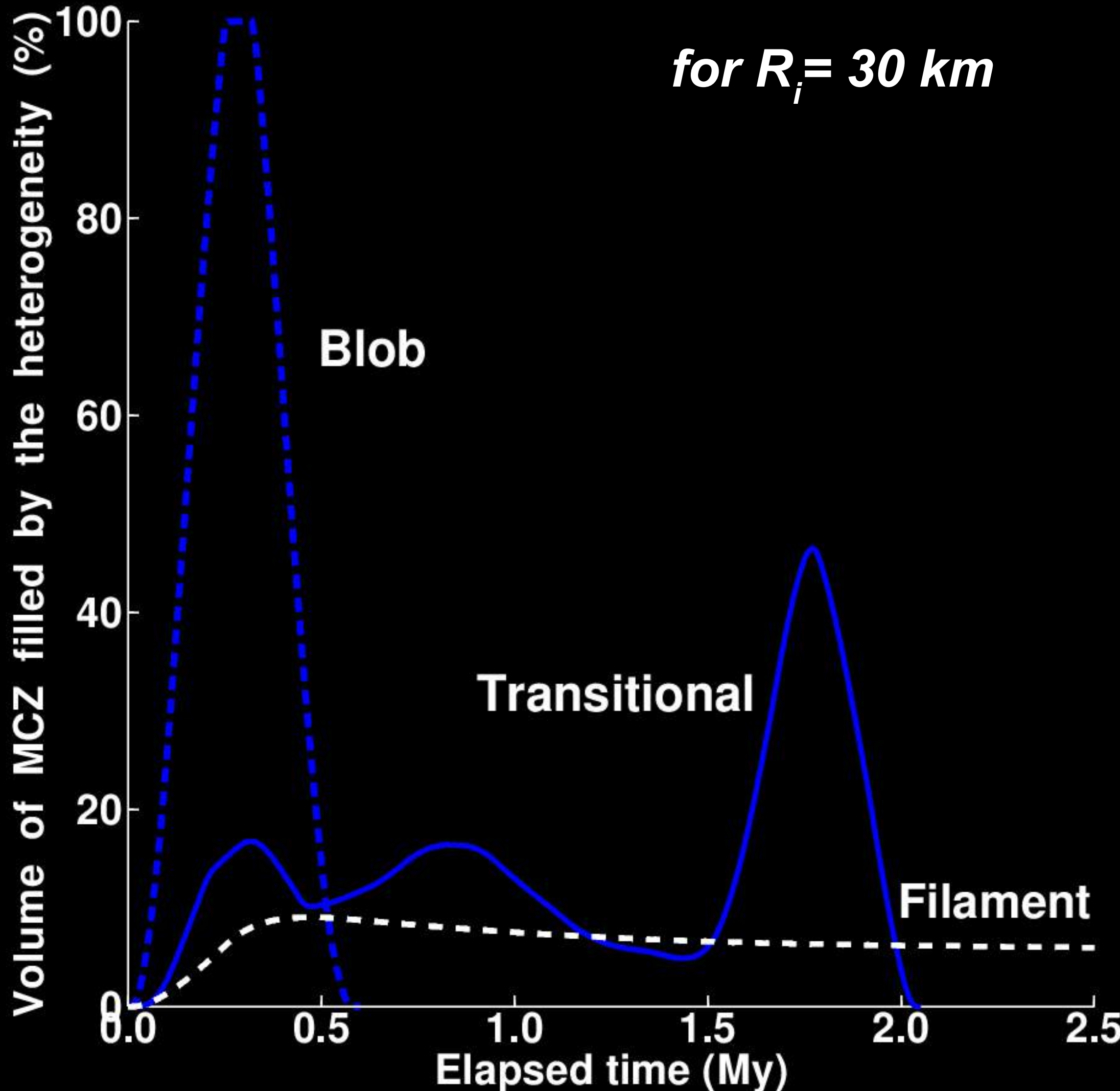


for R_i = 30 km

Different transit time across the melting zone

Different volumes of the melting zone will be affected by the heterogeneity

Are viscous blobs compositionally more (or less) fertile ?



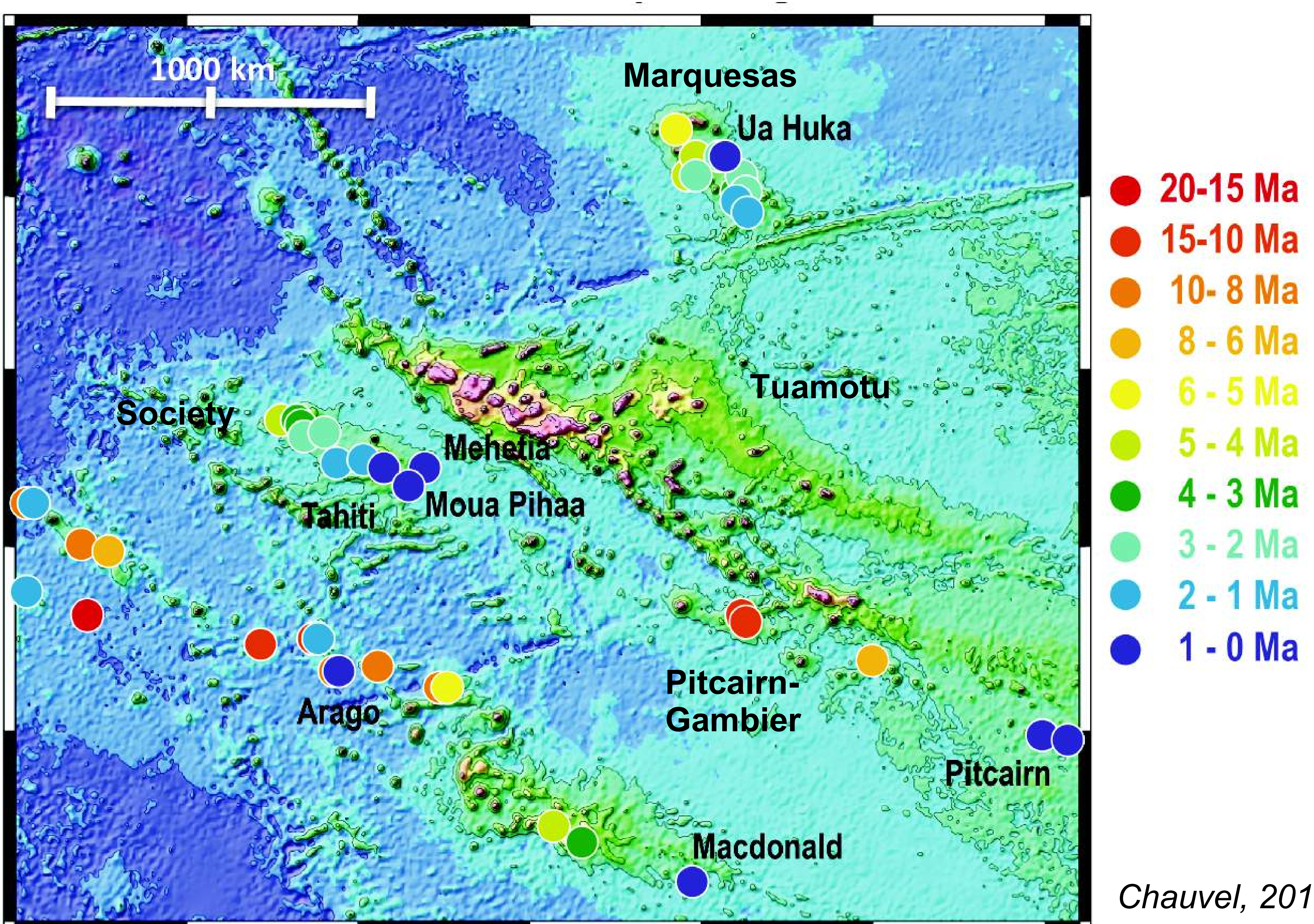
If more fertile

their presence can enhance melting and possibly leave a distinct isotopic fingerprint for time-scales of ~0.5 Ma.

If less fertile

their presence can reduce or shut-off melt production.

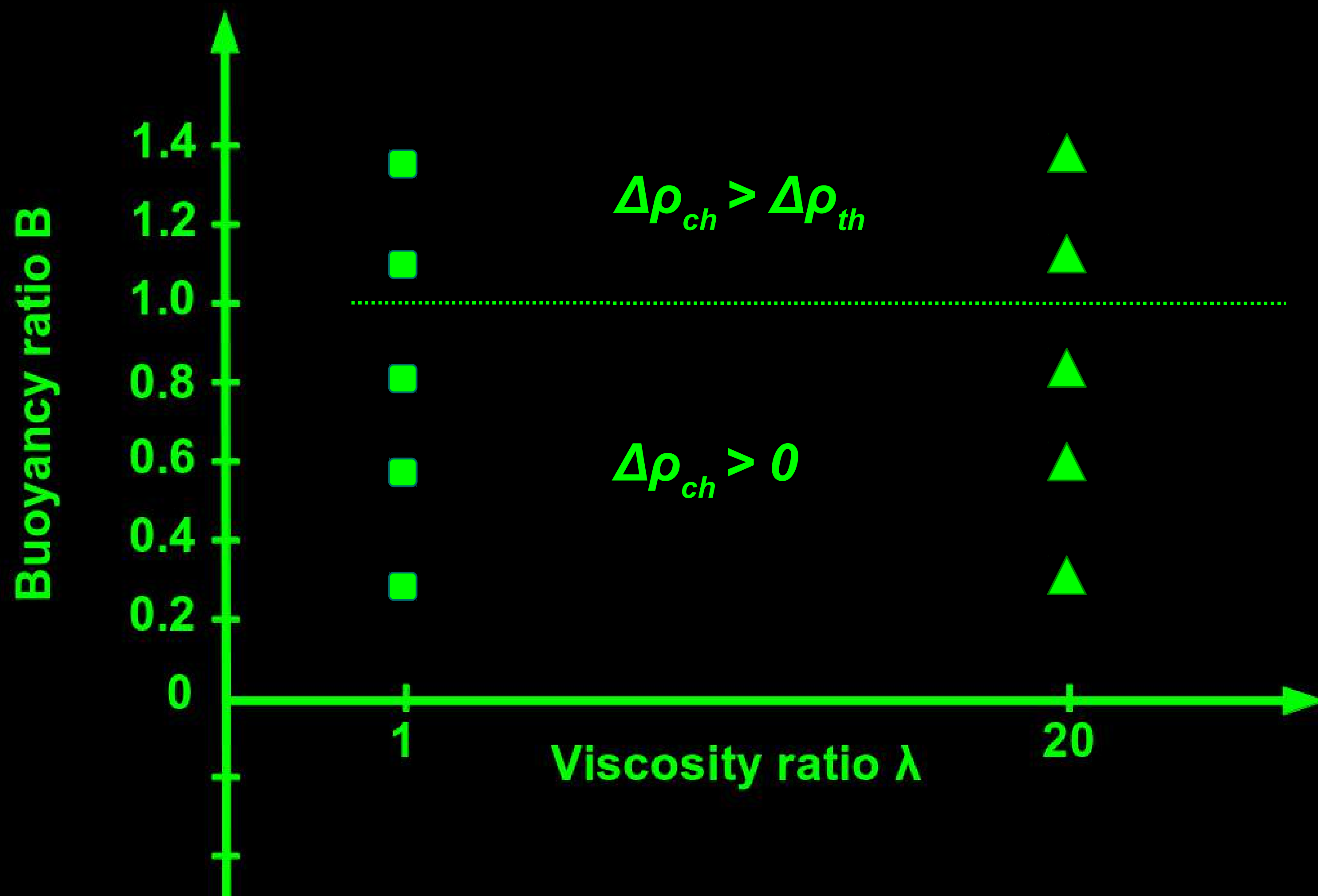
Volcanic activity through time for some Pacific hotspots



Chauvel, 2016

Exploring the effect of compositional buoyancy

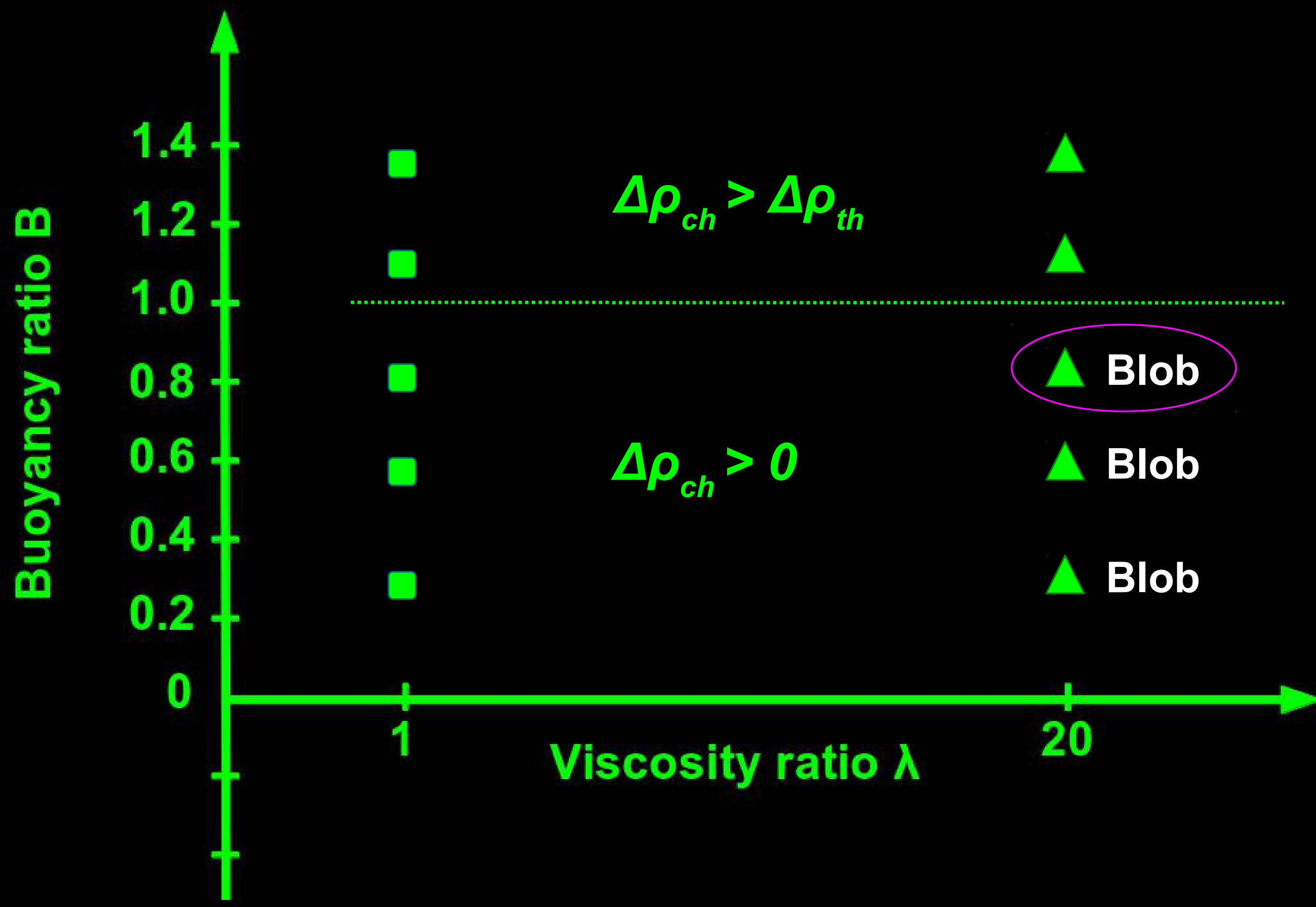
The buoyancy ratio B = $\Delta\rho_{ch} / \Delta\rho_{th}$

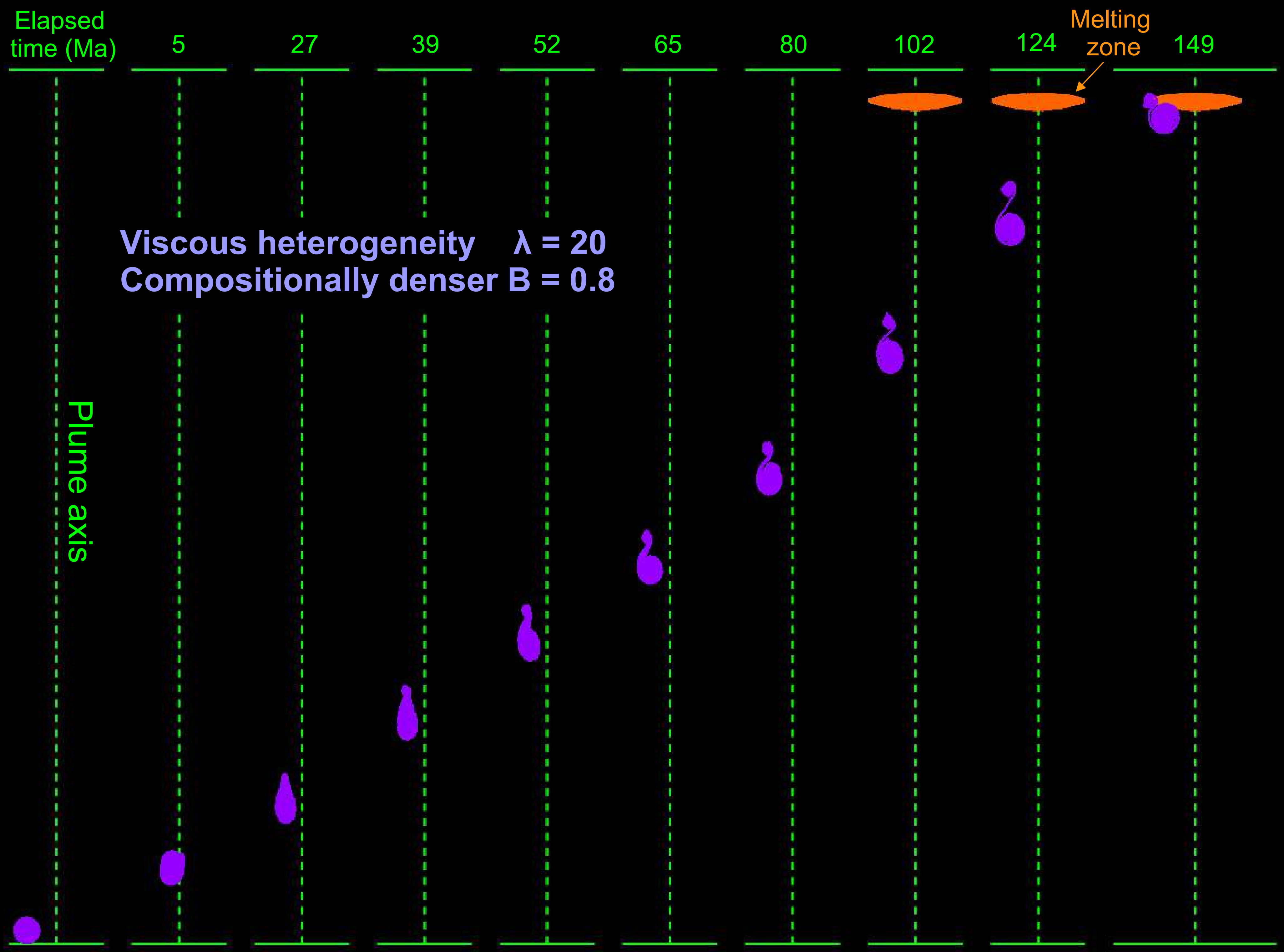


For λ=20 we conducted numerical simulations spanning a range of B values
For λ=1 numerical simulations and laboratory experiments by A. Limare, M. Geissmann

Exploring the effect of compositional buoyancy

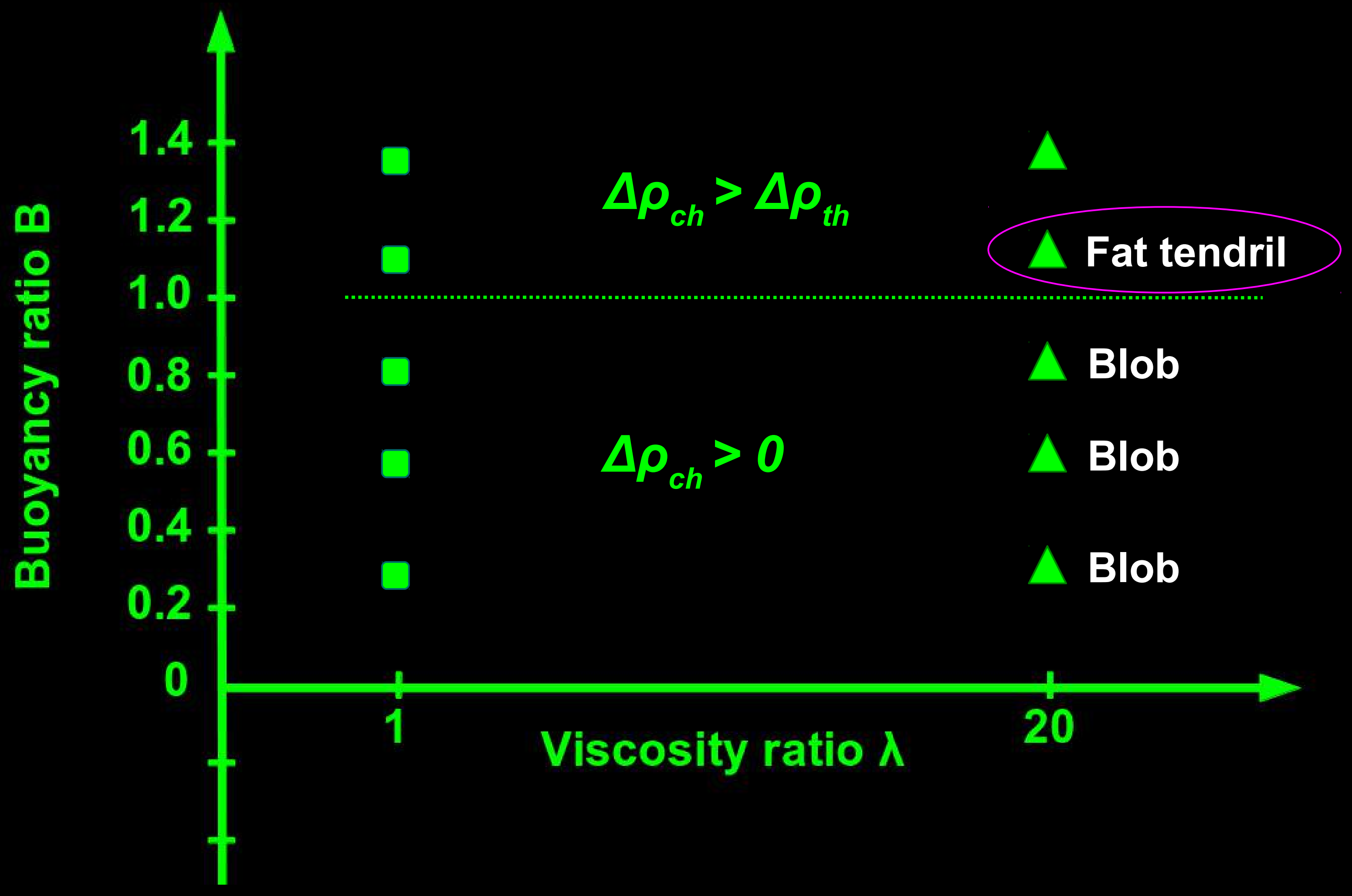
The buoyancy ratio $B = \Delta\rho_{ch} / \Delta\rho_{th}$

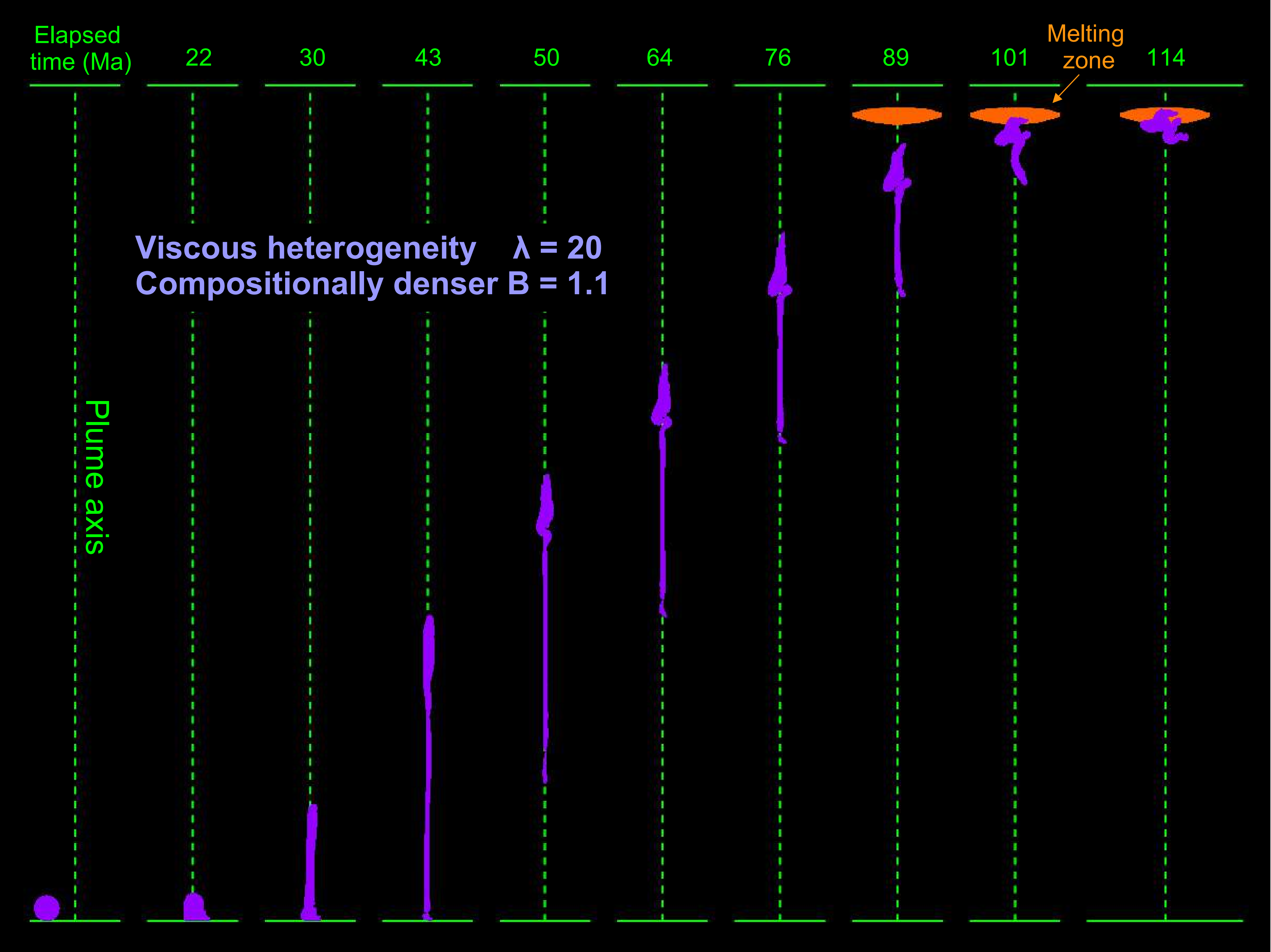



Elapsed time (Ma)
5
27
39
52
65
80
102
124
Melting zone
149
Viscous heterogeneity λ = 20
Compositionally denser B = 0.8
Plume axis

Exploring the effect of compositional buoyancy

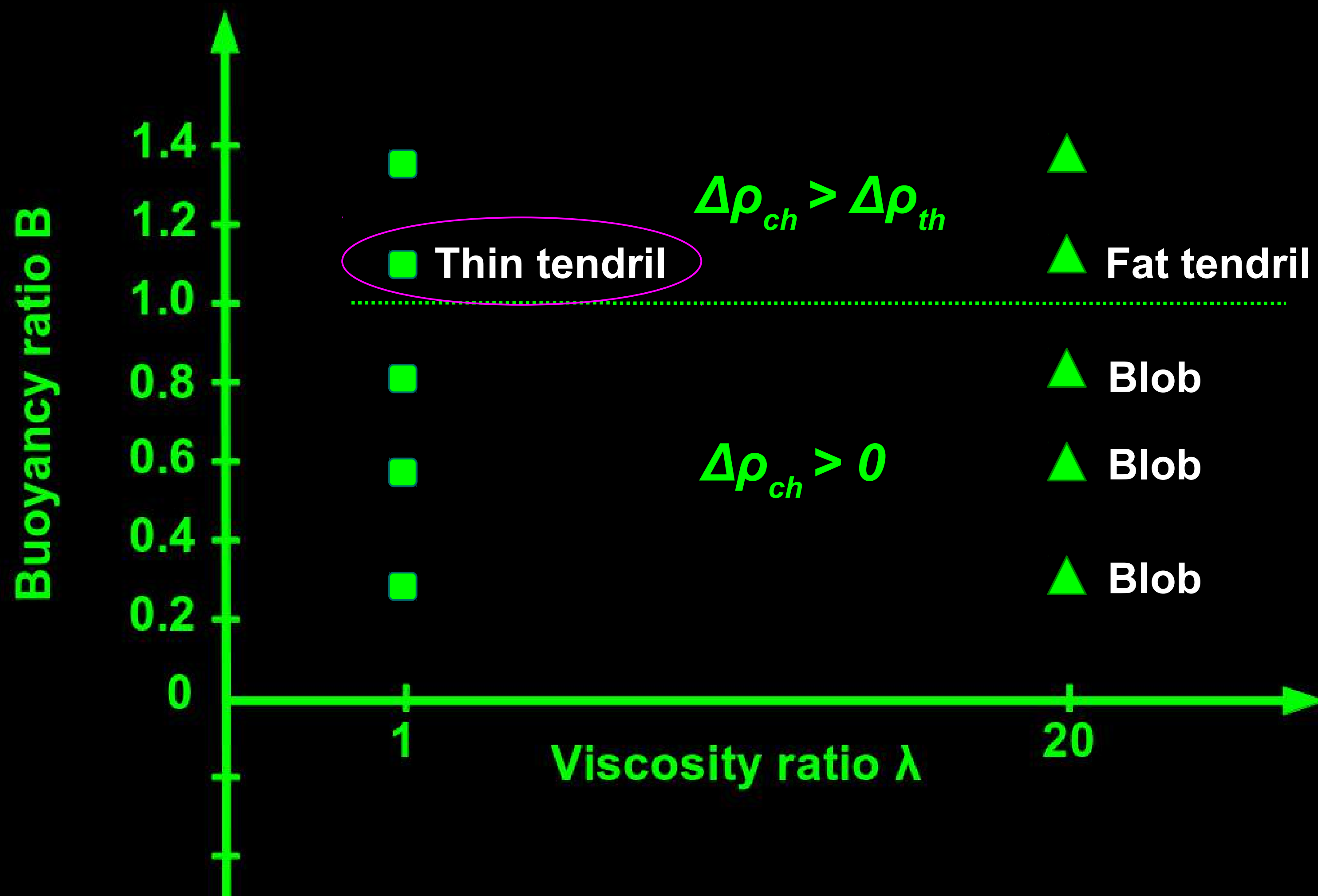
The buoyancy ratio $B = \Delta\rho_{ch} / \Delta\rho_{th}$

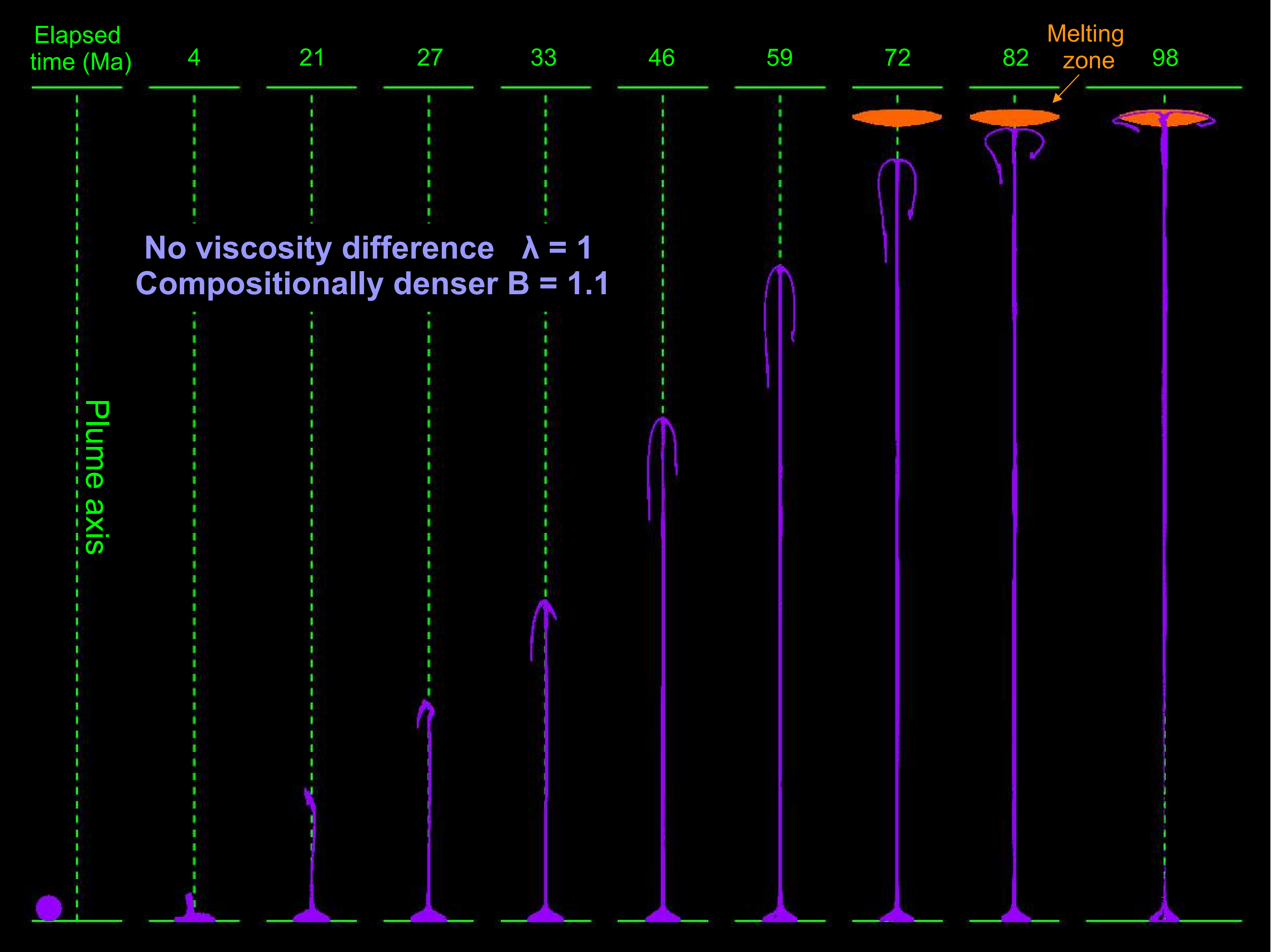



Elapsed time (Ma)
22
30
43
50
64
76
89
101
114
Melting zone
Viscous heterogeneity λ = 20
Compositionally denser B = 1.1
Plume axis

Exploring the effect of compositional buoyancy

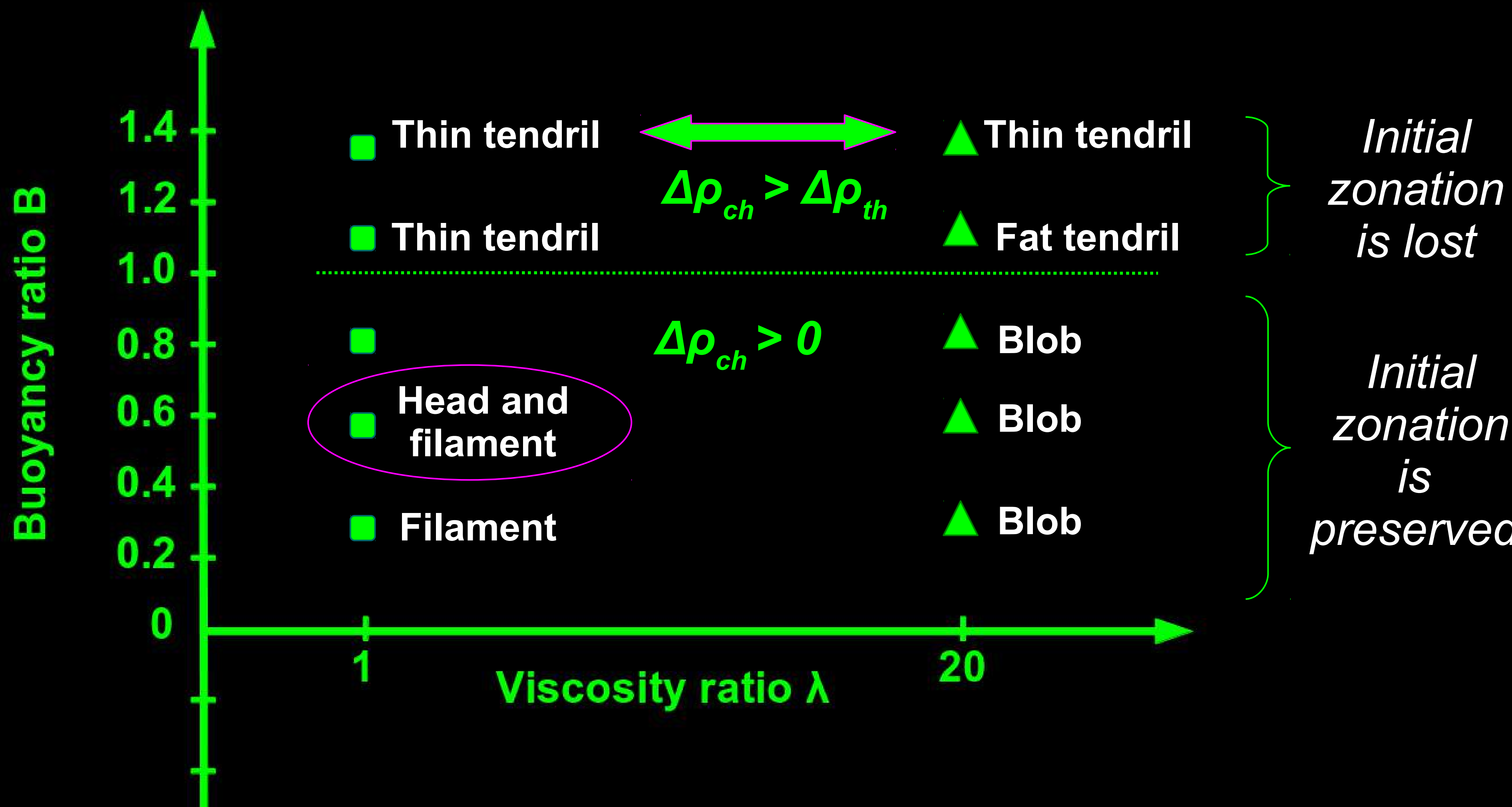
The buoyancy ratio $B = \Delta\rho_{ch} / \Delta\rho_{th}$

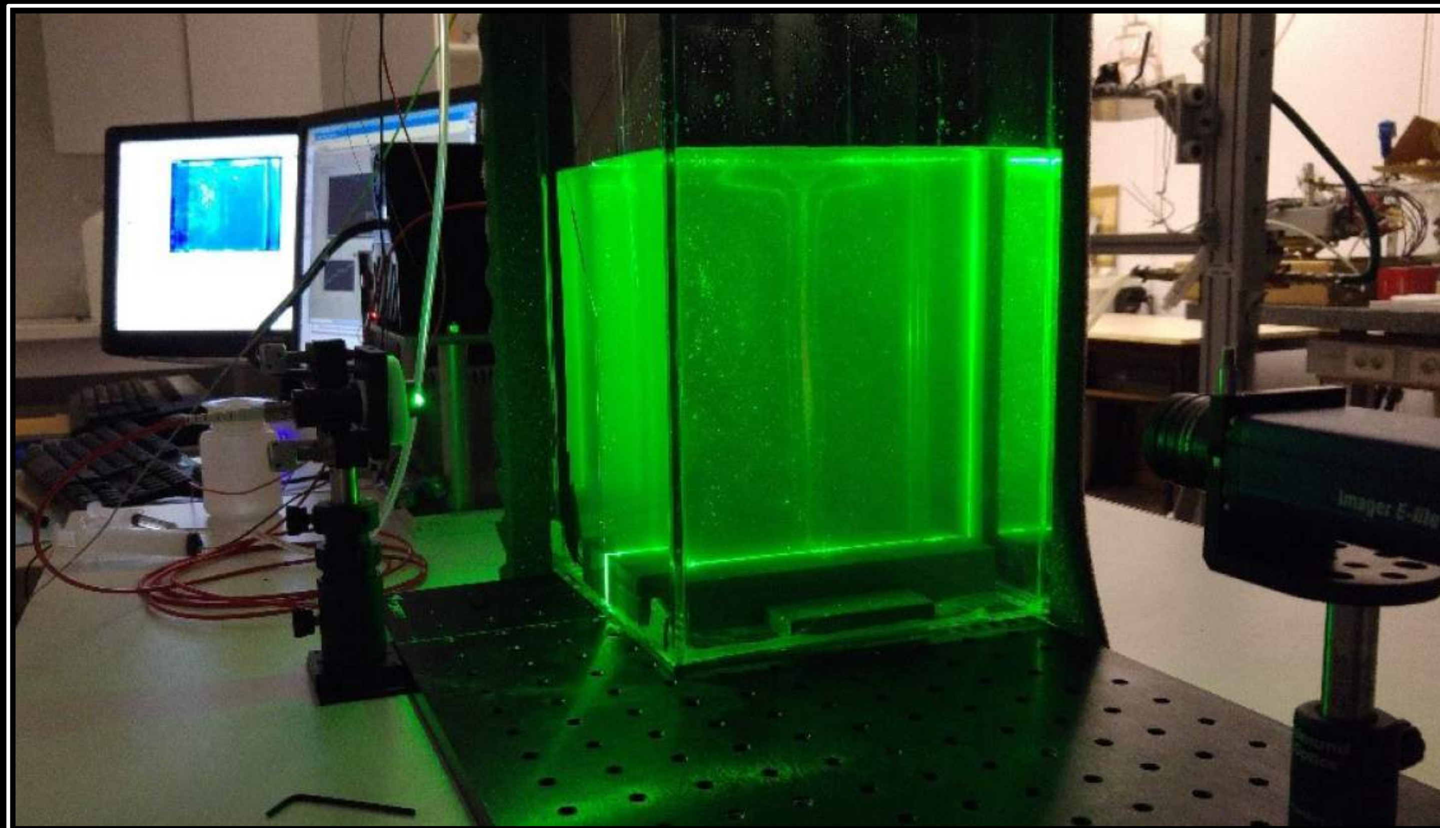



Elapsed time (Ma)
4
21
27
33
46
59
72
82
98
Melting zone
No viscosity difference λ = 1
Compositionally denser B = 1.1
Plume axis

Exploring the effect of compositional buoyancy

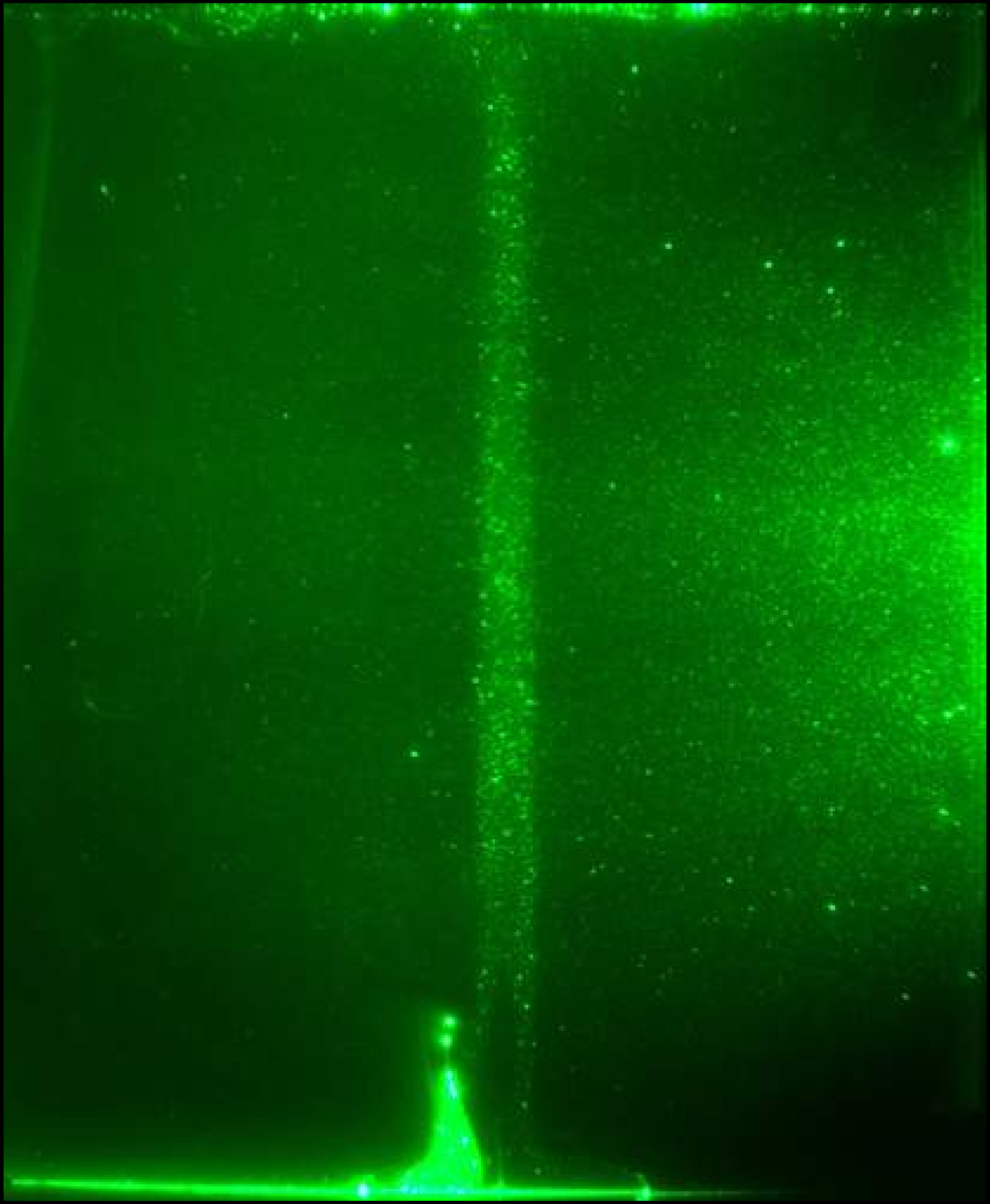
The buoyancy ratio $B = \Delta\rho_{ch} / \Delta\rho_{th}$

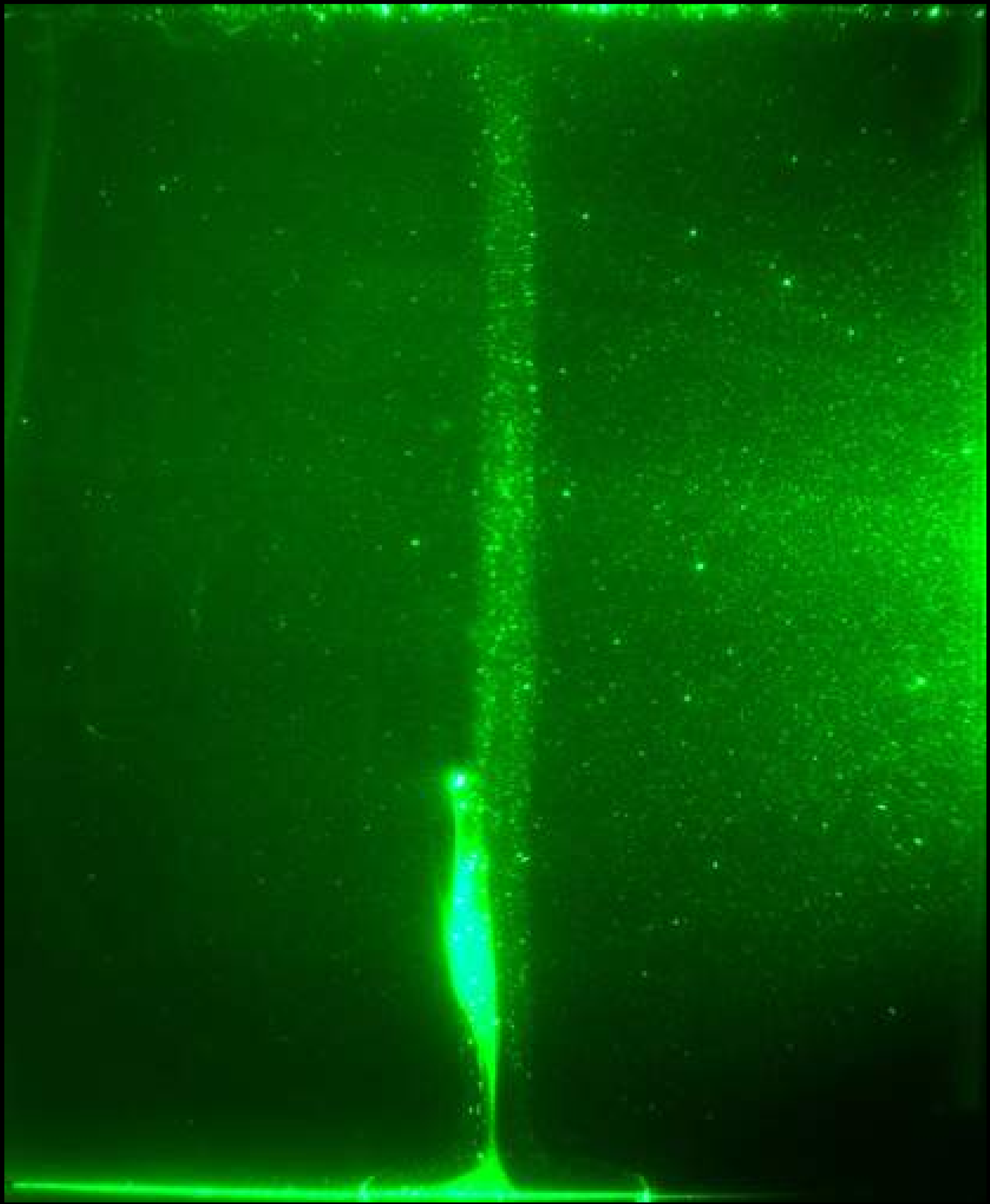


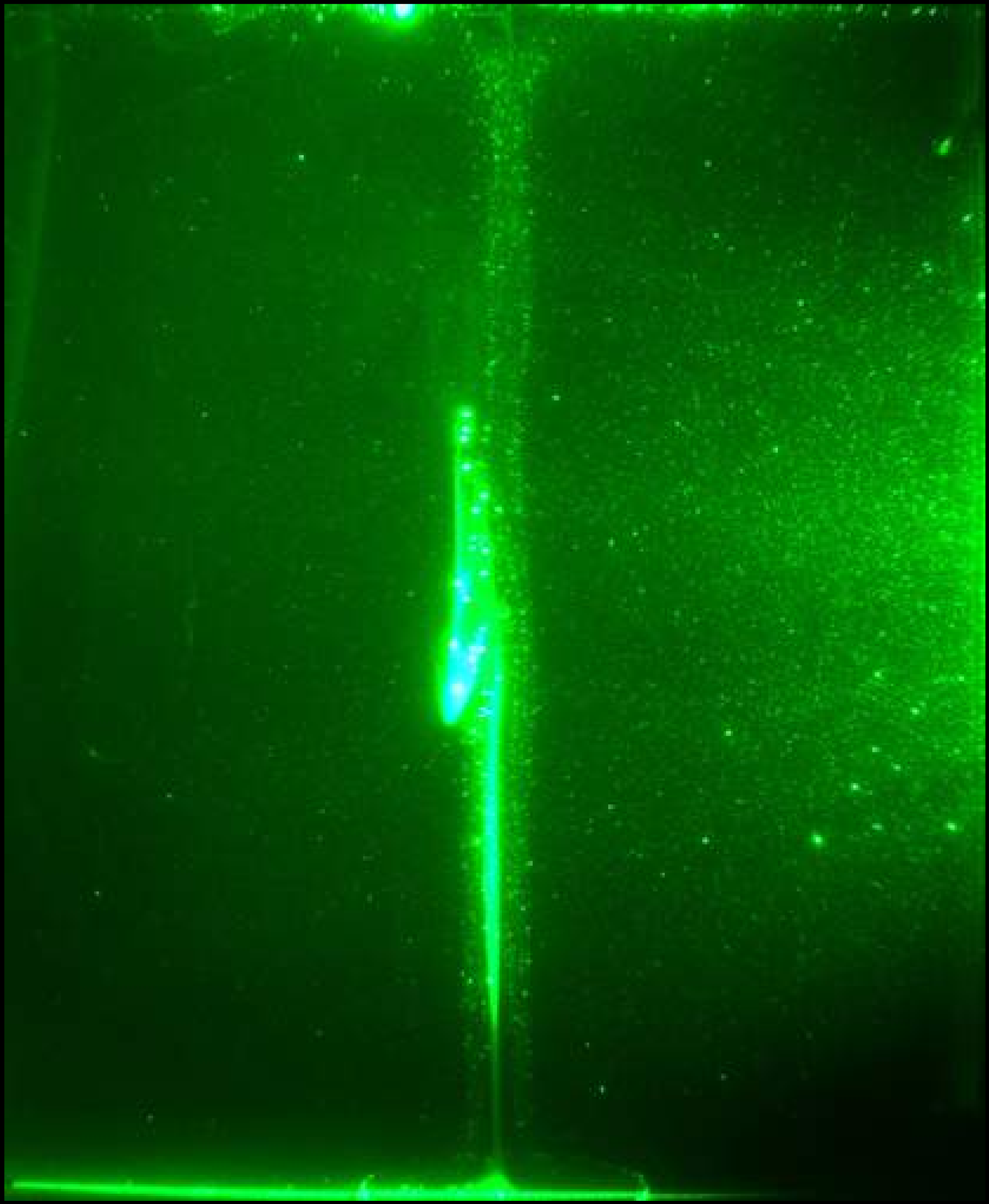


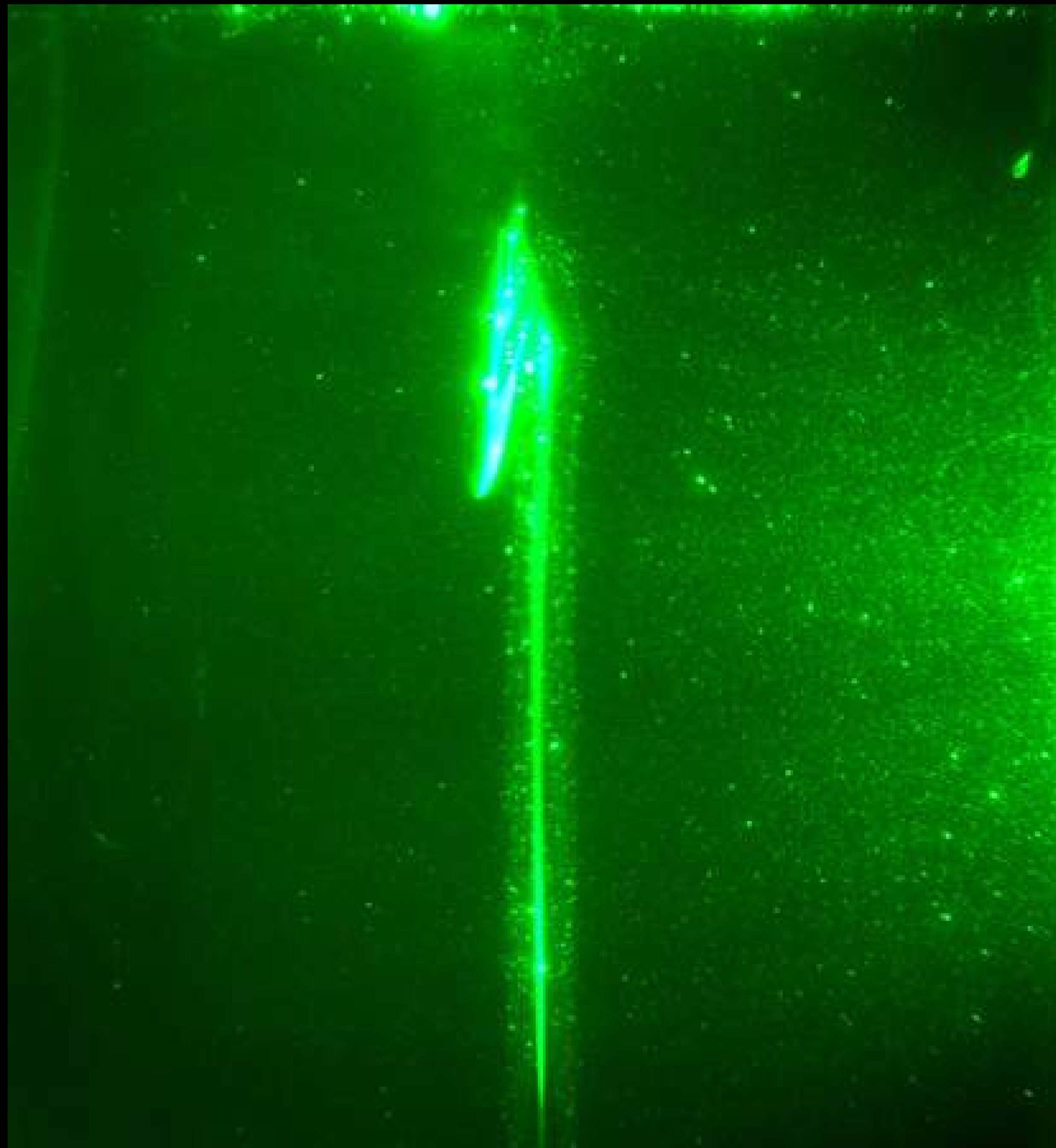
- Experimental tank filled with diluted Glucose syrup. $10^5 < Ra < 10^6$
- We inject chemically denser material at one side of the plume.
- We vary : the injected volume (0.2-0.5 10^{-3} l),
the distances from the plume axis,
the excess compositional density $\Delta\rho_{ch}$ and thus B.
- Thermochromic Liquid Crystals are used to measure temperature, Particle Image Velocimetry to measure flow velocities.

B = 0.6

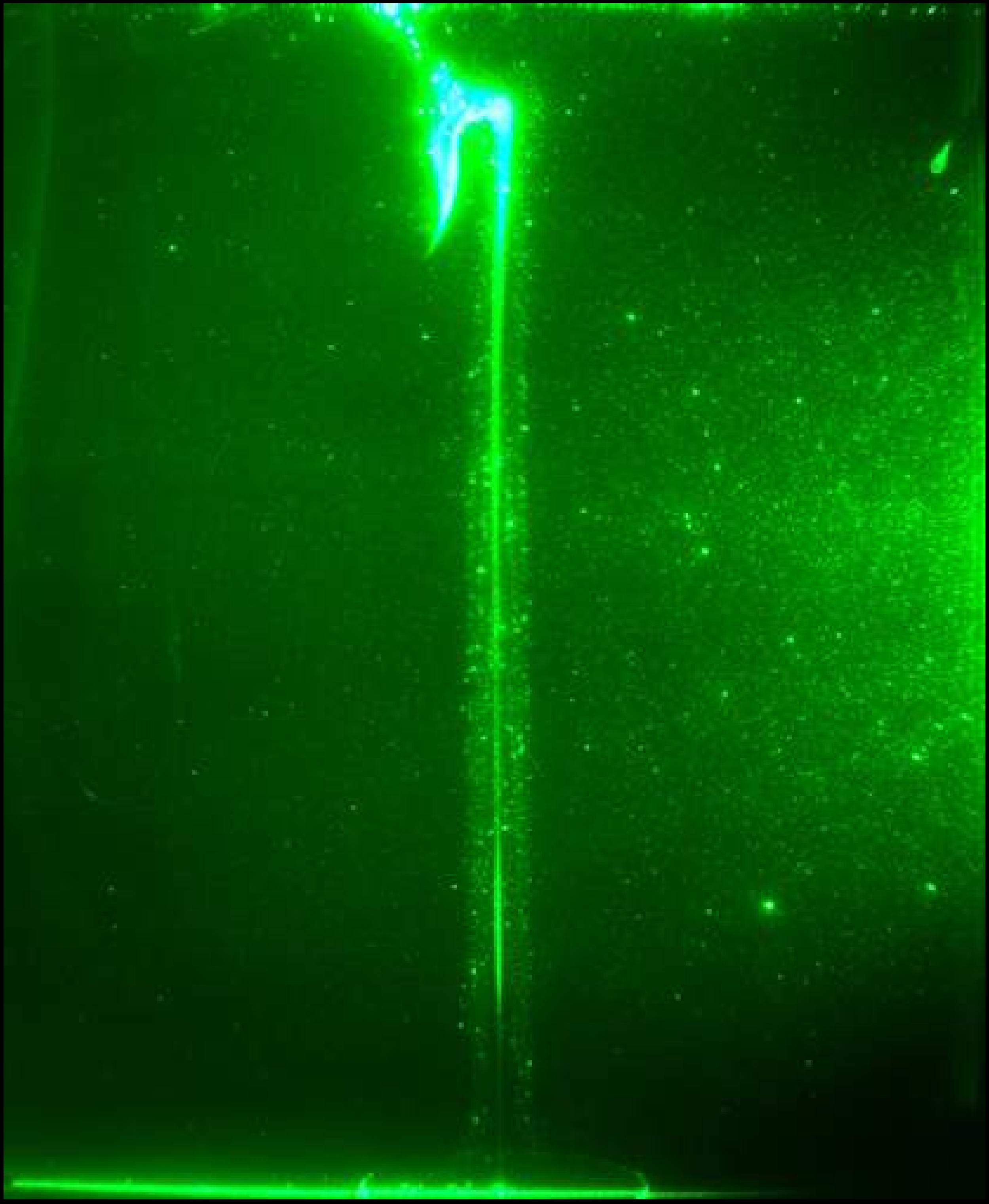


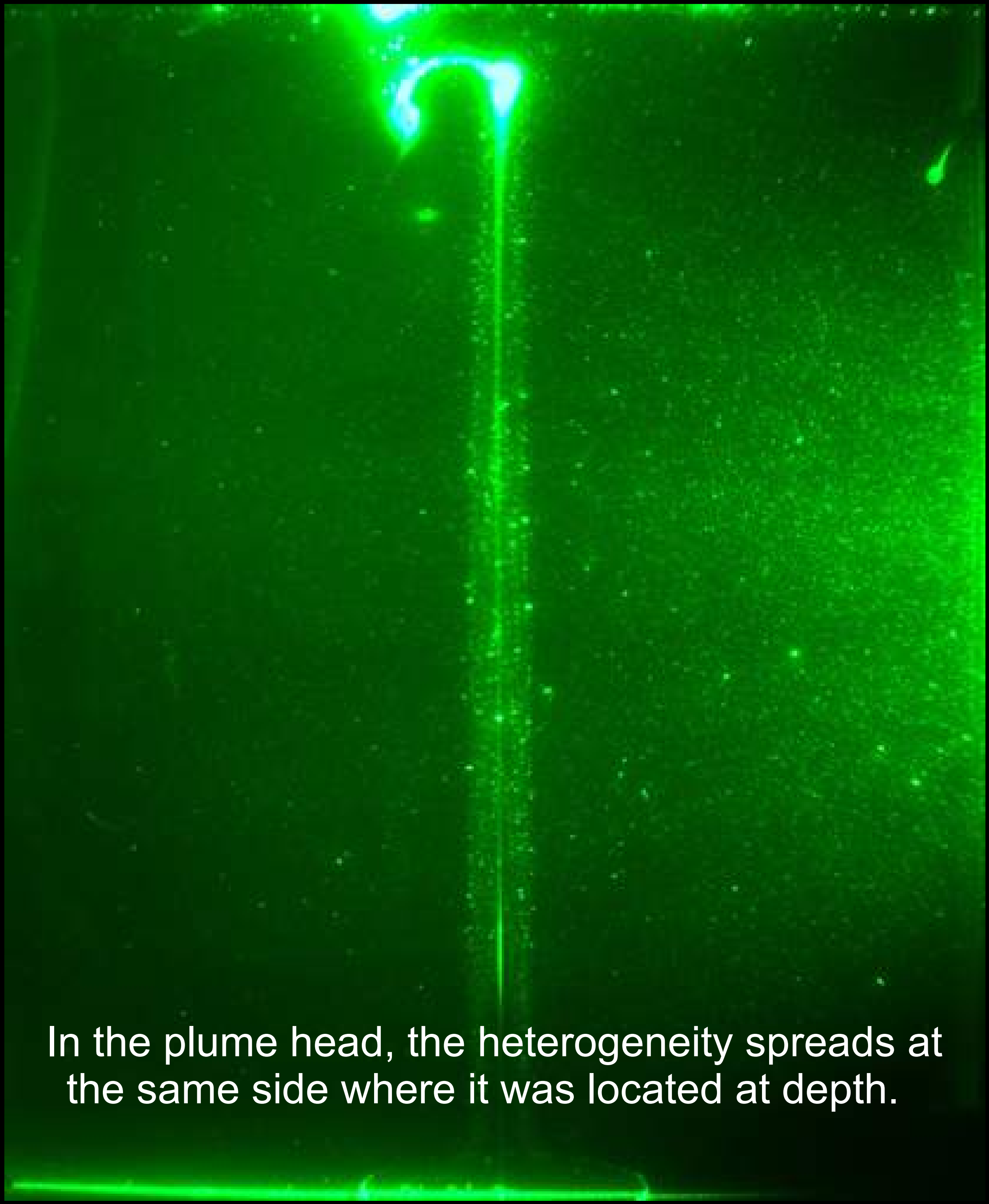




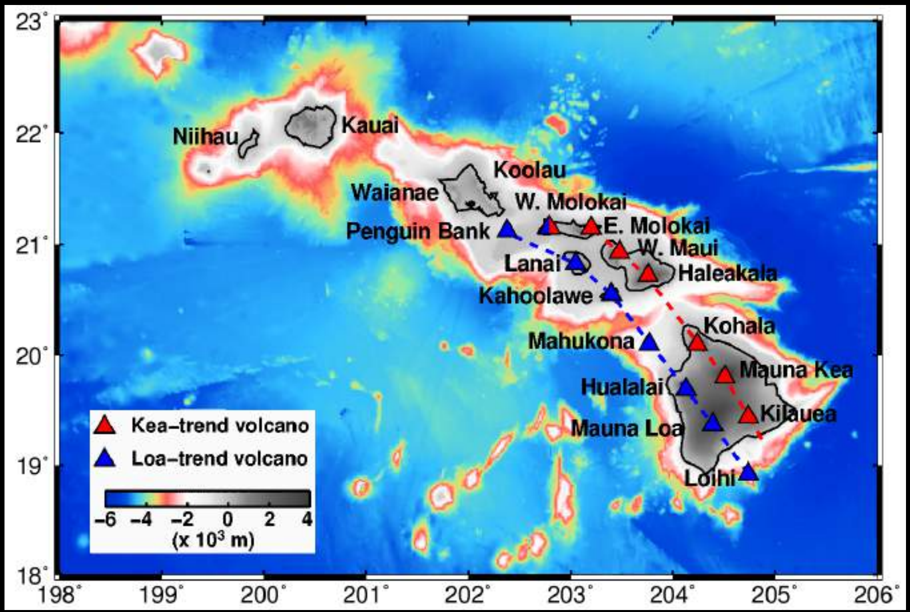


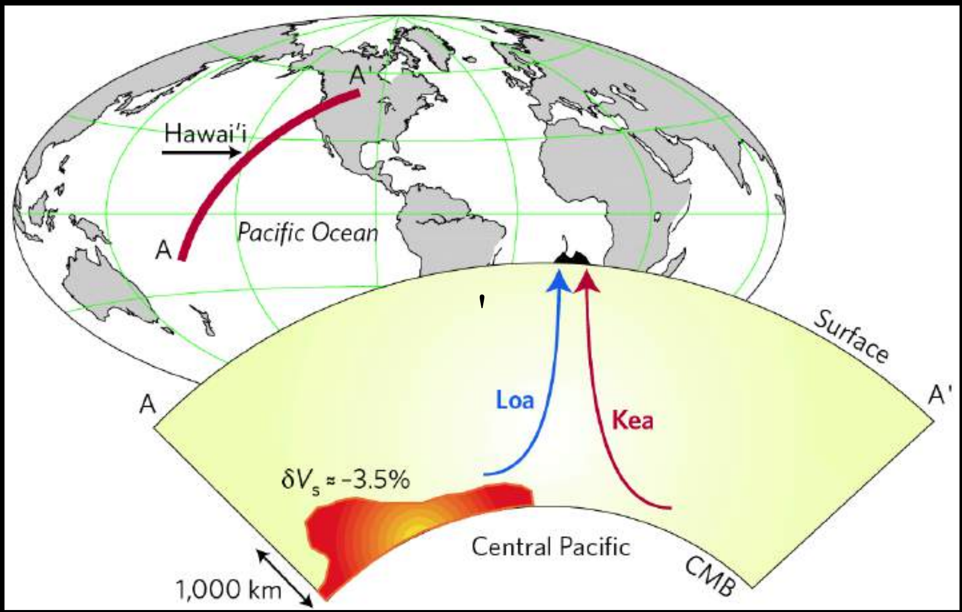
Denser material rises **next** and **at** the plume axis
The presence of the denser material reduces v_z the axis




In the plume head, the heterogeneity spreads at
the same side where it was located at depth.

Why do we care about loosing -or preserving- the initial zonation of deep heterogeneities?



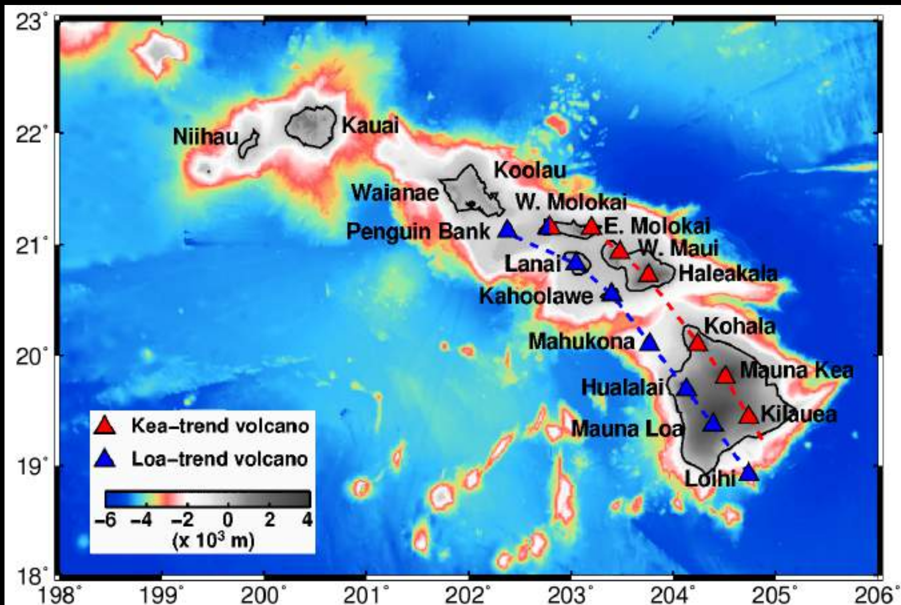


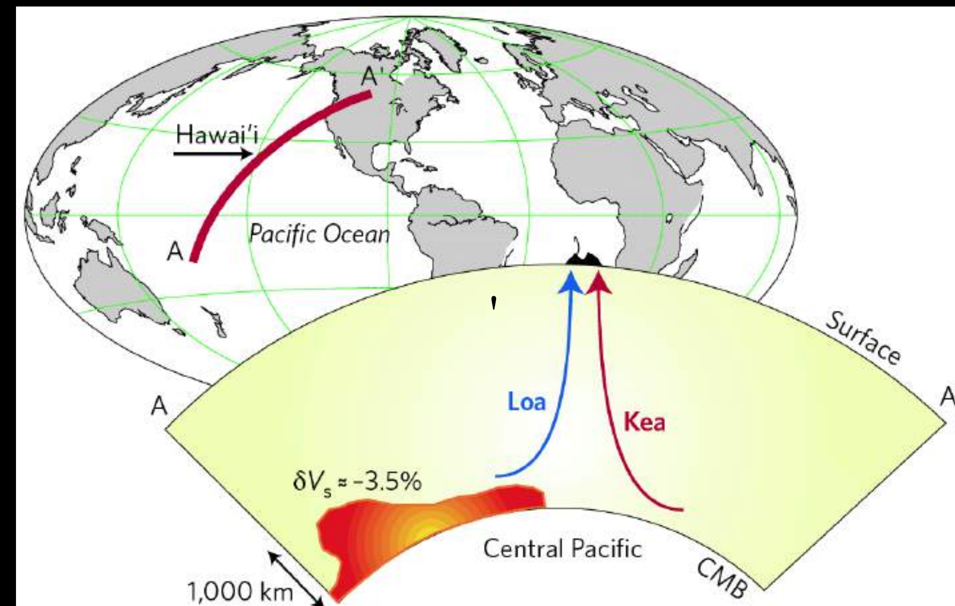
Weis et al., 2011

Spatial variations recorded in the geochemistry of hotspot lavas can reflect the heterogeneous composition of their deep-mantle source.

For passive heterogeneities (i.e., no density or rheological variations) plume flow does preserve the deep zonation.

Why do we care about loosing -or preserving- the initial zonation of deep heterogeneities?

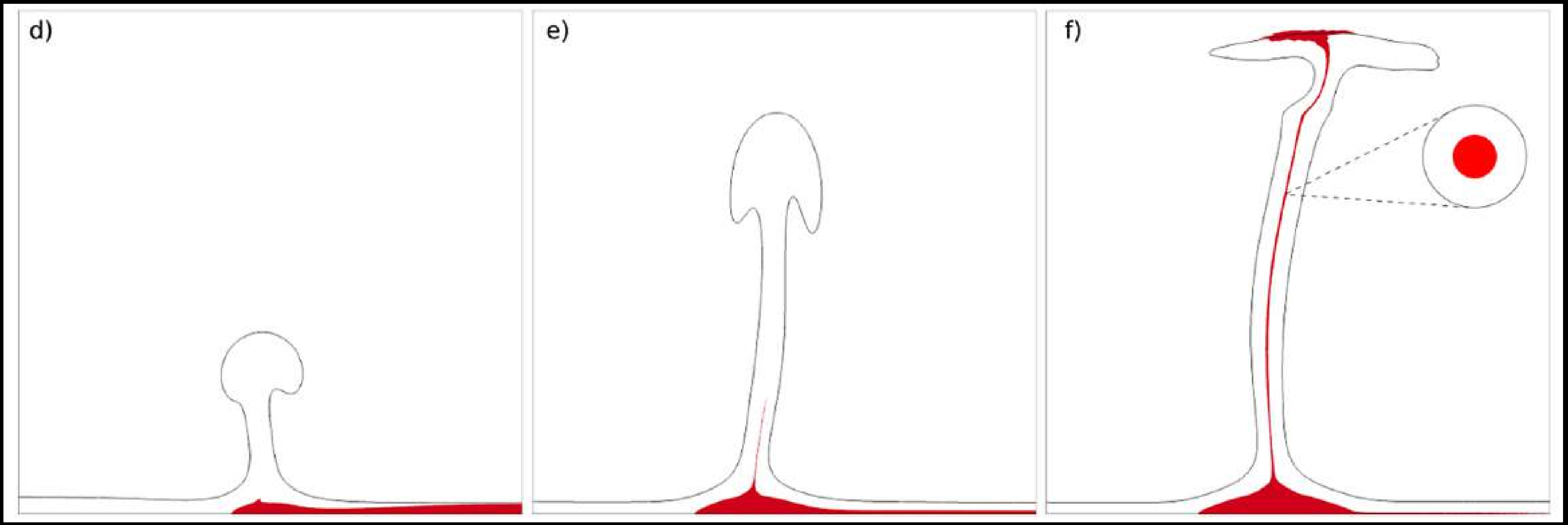




Weis et al., 2011

We find that the <u>initial zonation is preserved</u> if the finite-size heterogeneity is more viscous ($1<\lambda<20$) and with buoyancy ratio up to 0.8

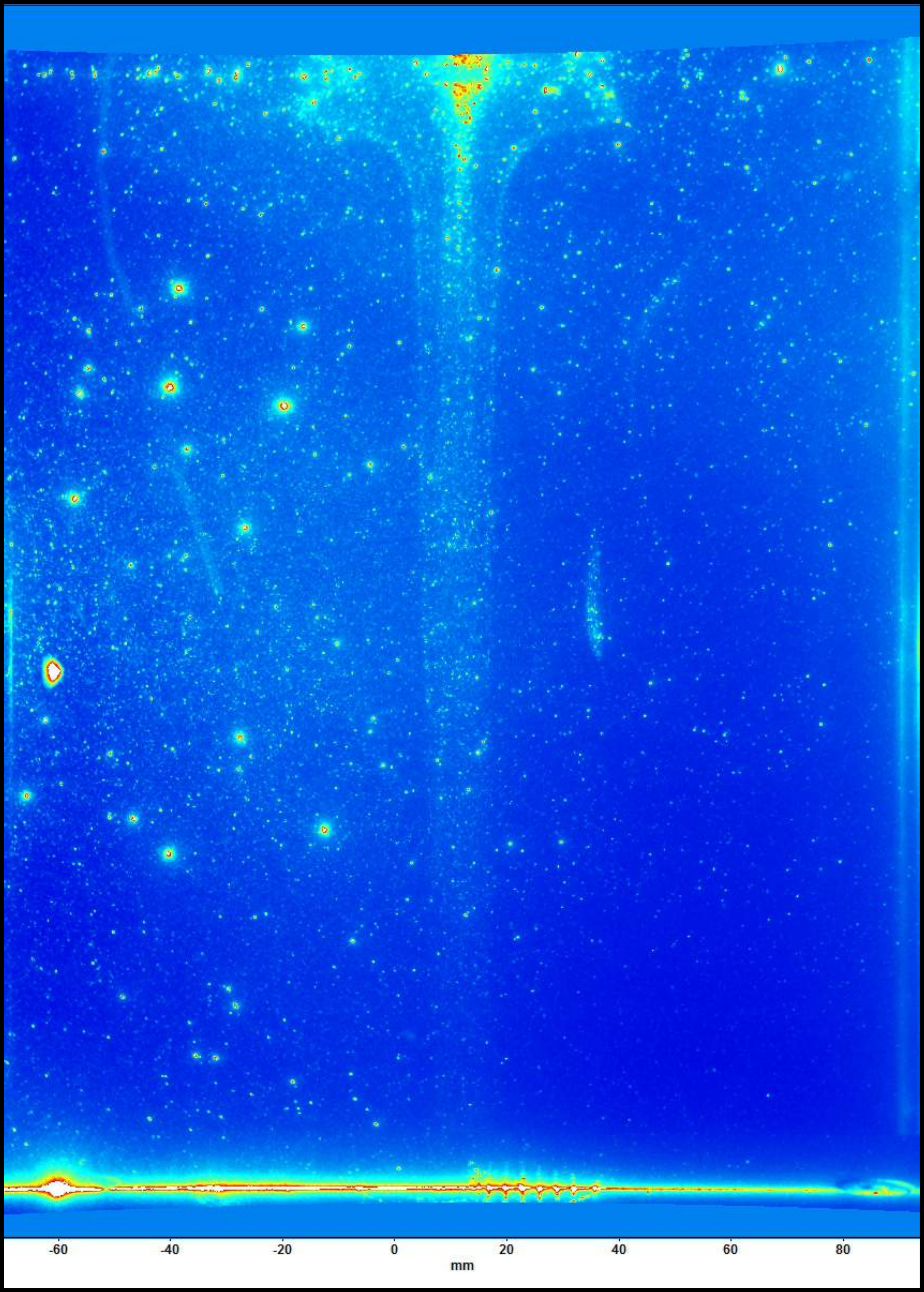
For buoyancy ratio B >1, independently of the viscosity ratio, the heterogeneity spreads at the base of the plume. Only a tendril of denser material rises at the plume axis. The <u>initial zonation is lost</u>.



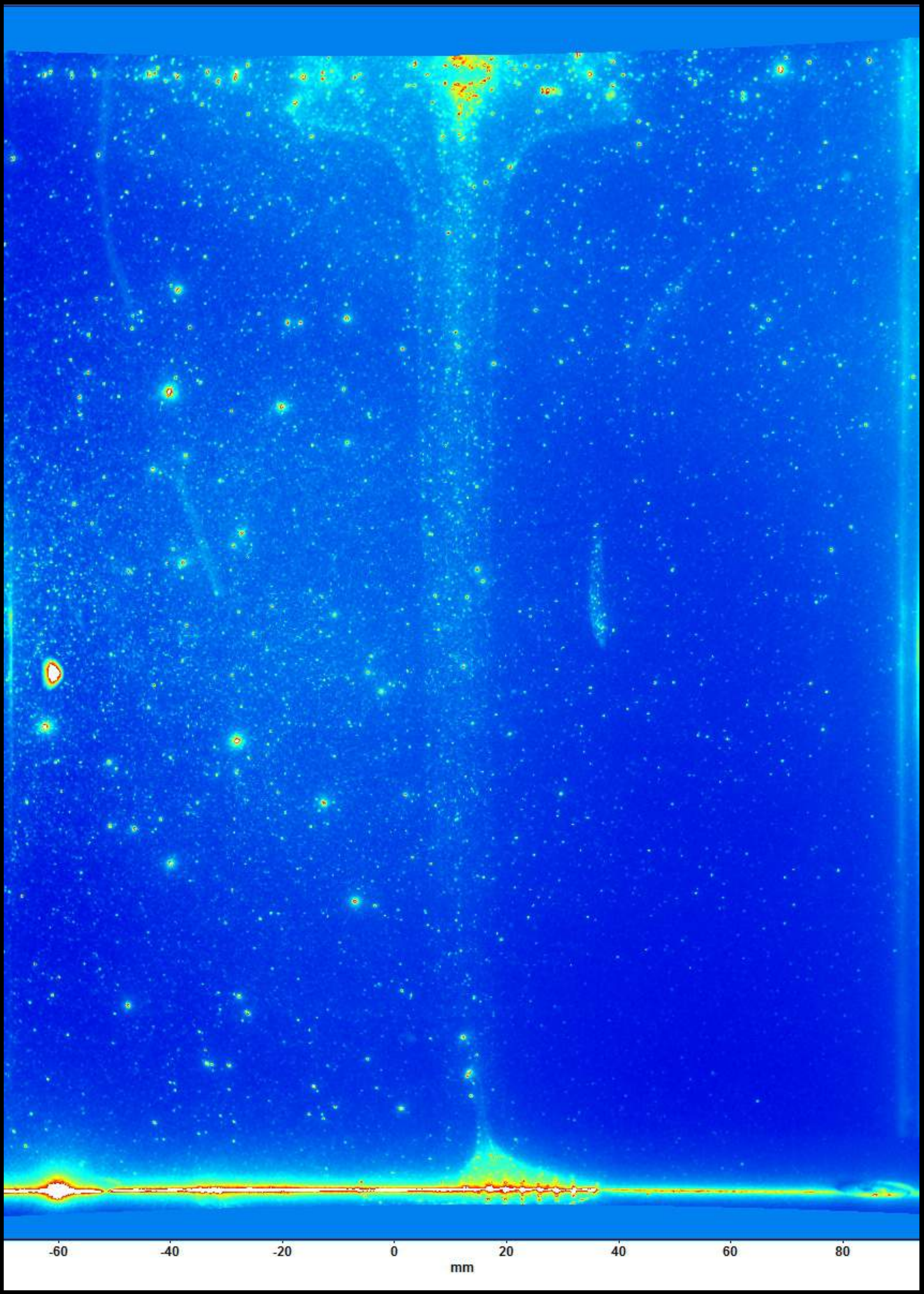
Numerical simulations by Jones et al., 2016 model an asymmetric distribution of denser material (red) at the base of a plume and find that the basal zonation is lost.

Experiments by
A. Limare and
T. Duvernay

0030

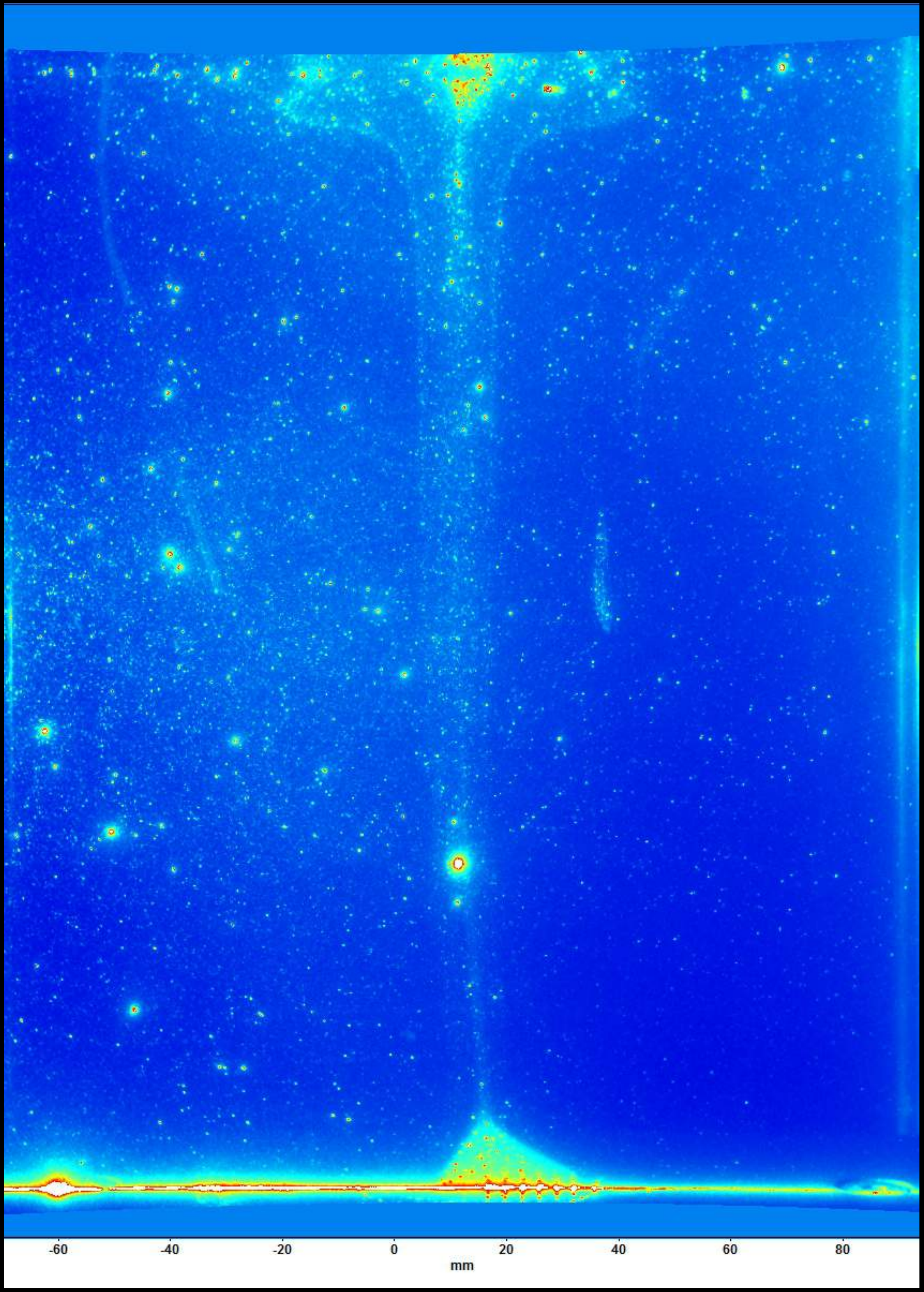


As soon as the thermal plume is established,
we inject (over half of its base) a compositionally denser fluid



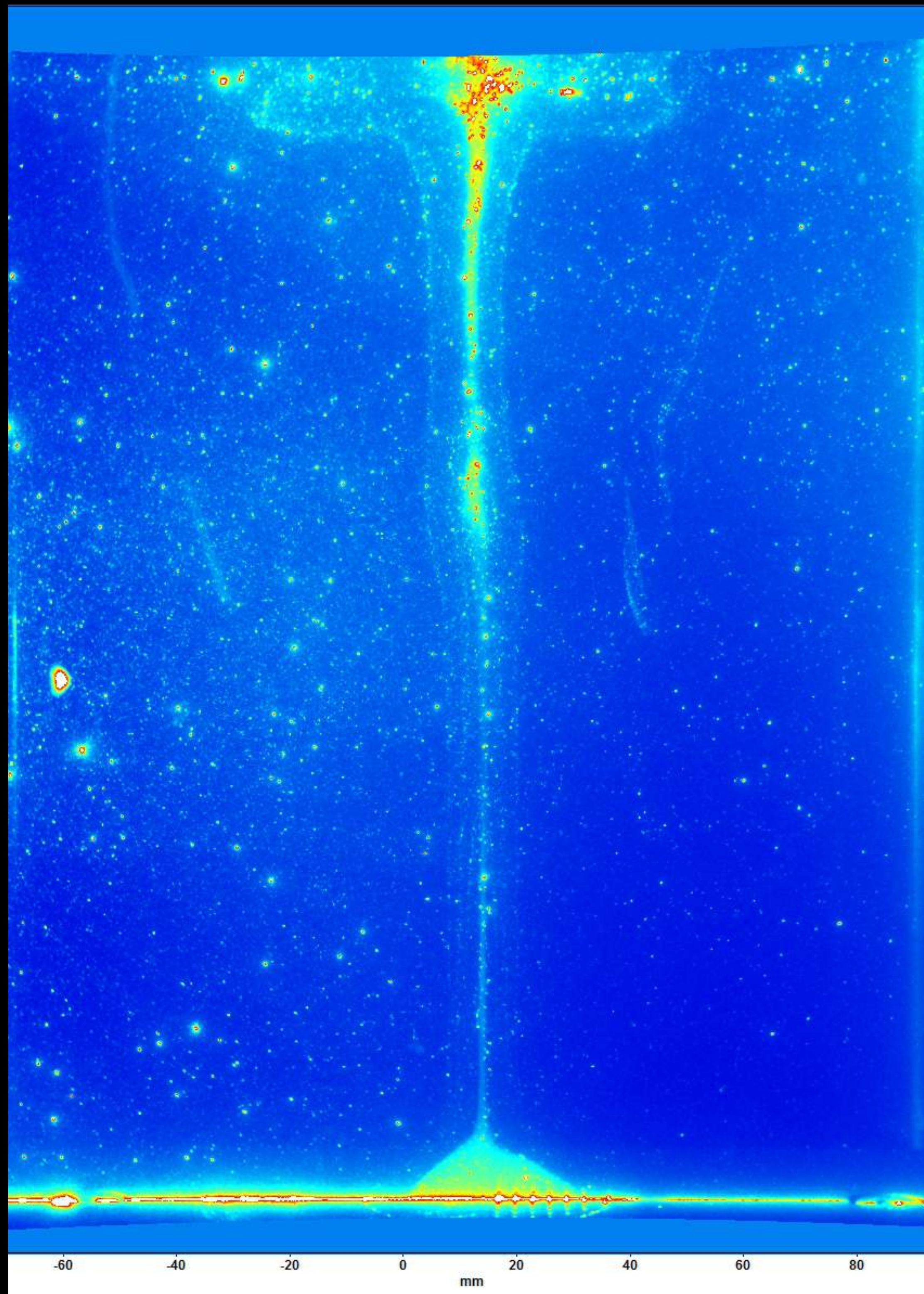
The buoyancy number is B=1.2

$$B = \frac{\Delta\rho_{ch}}{\rho\ \alpha\ \Delta T}$$



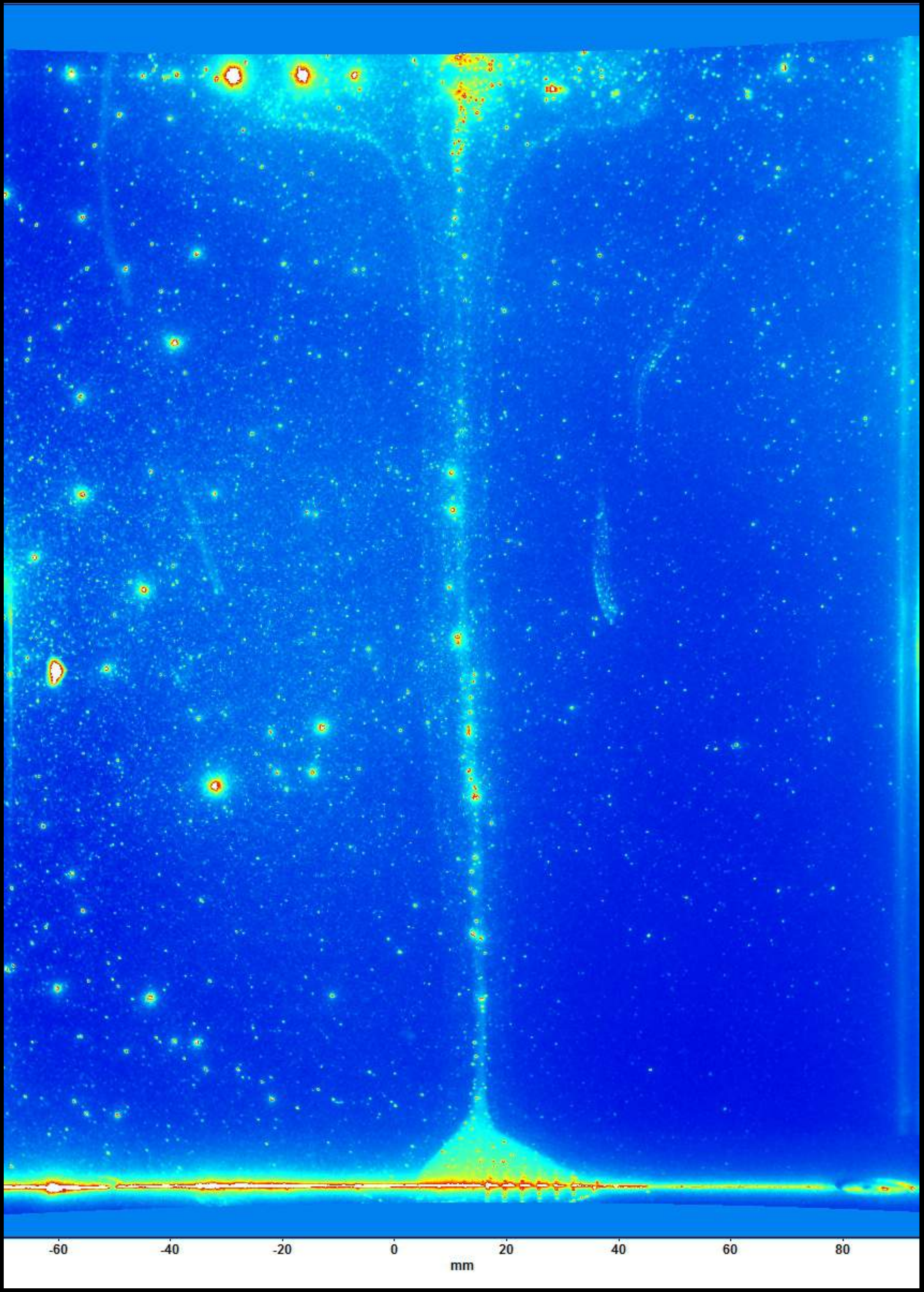
The denser fluid piles up at the base of the plume

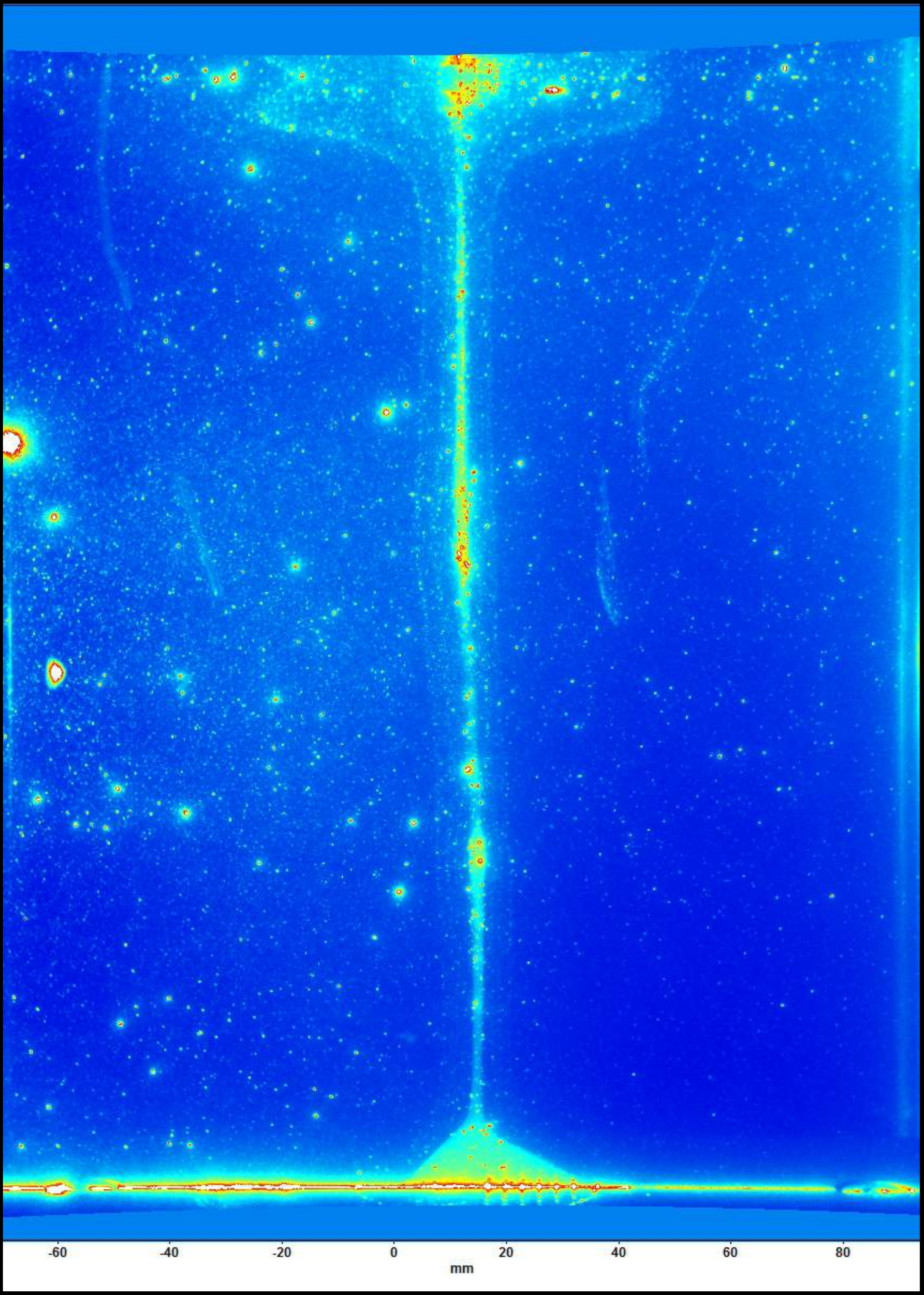
Injected volume: 5ml



The denser fluid rises by viscous coupling at the plume axis

0110

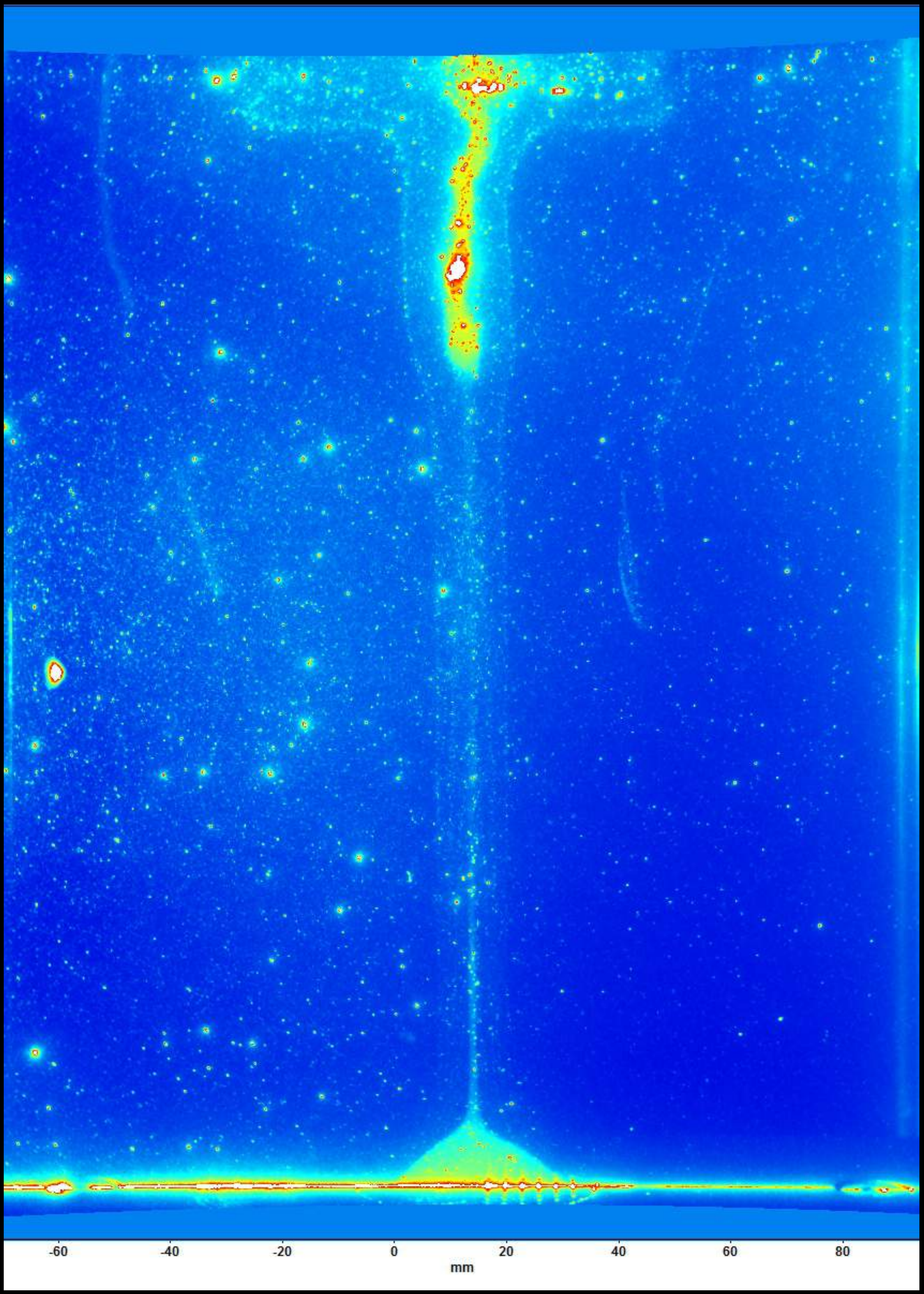




0130

The denser fluid accumulates in the plume head, rather than spreading laterally

0230



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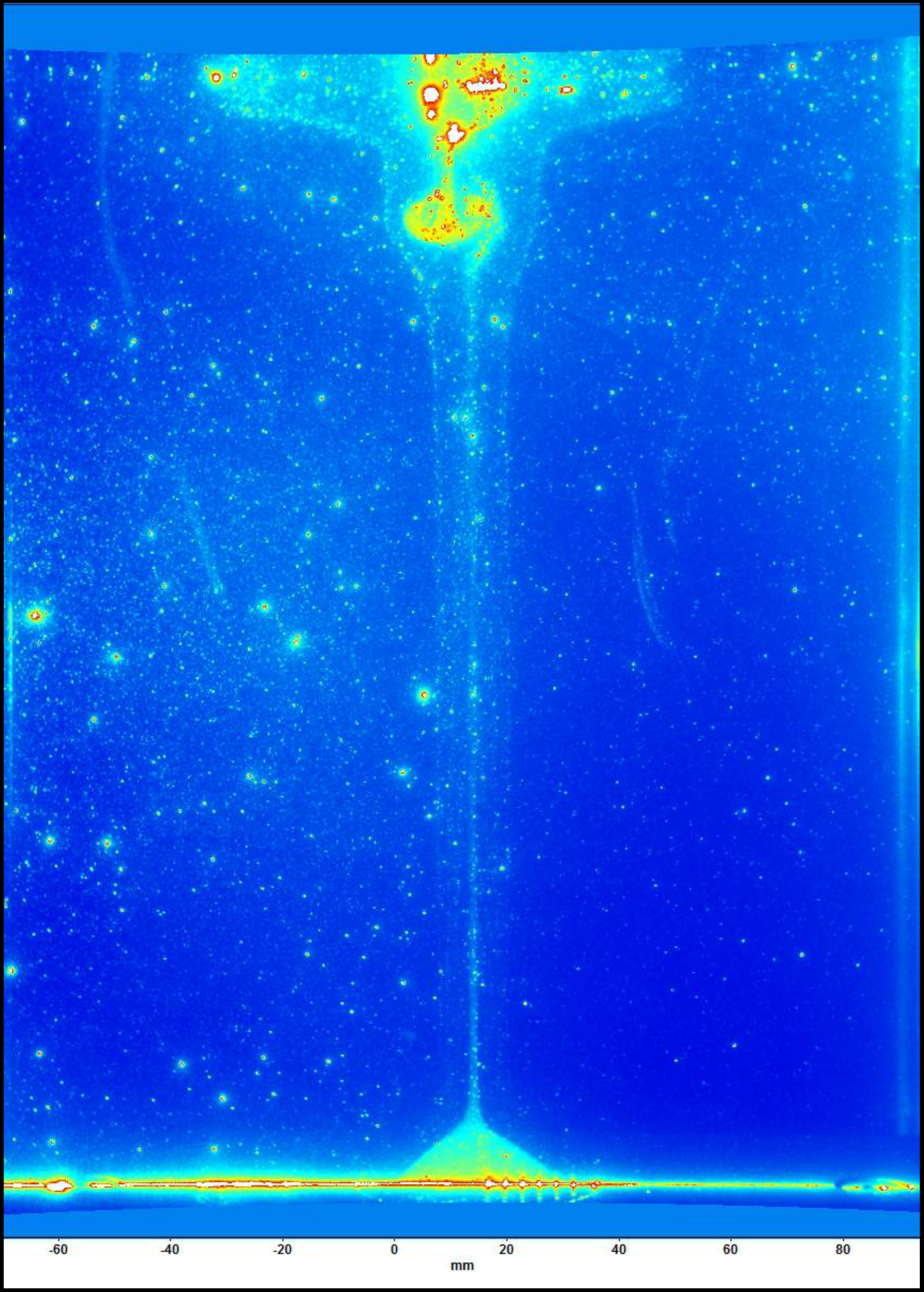

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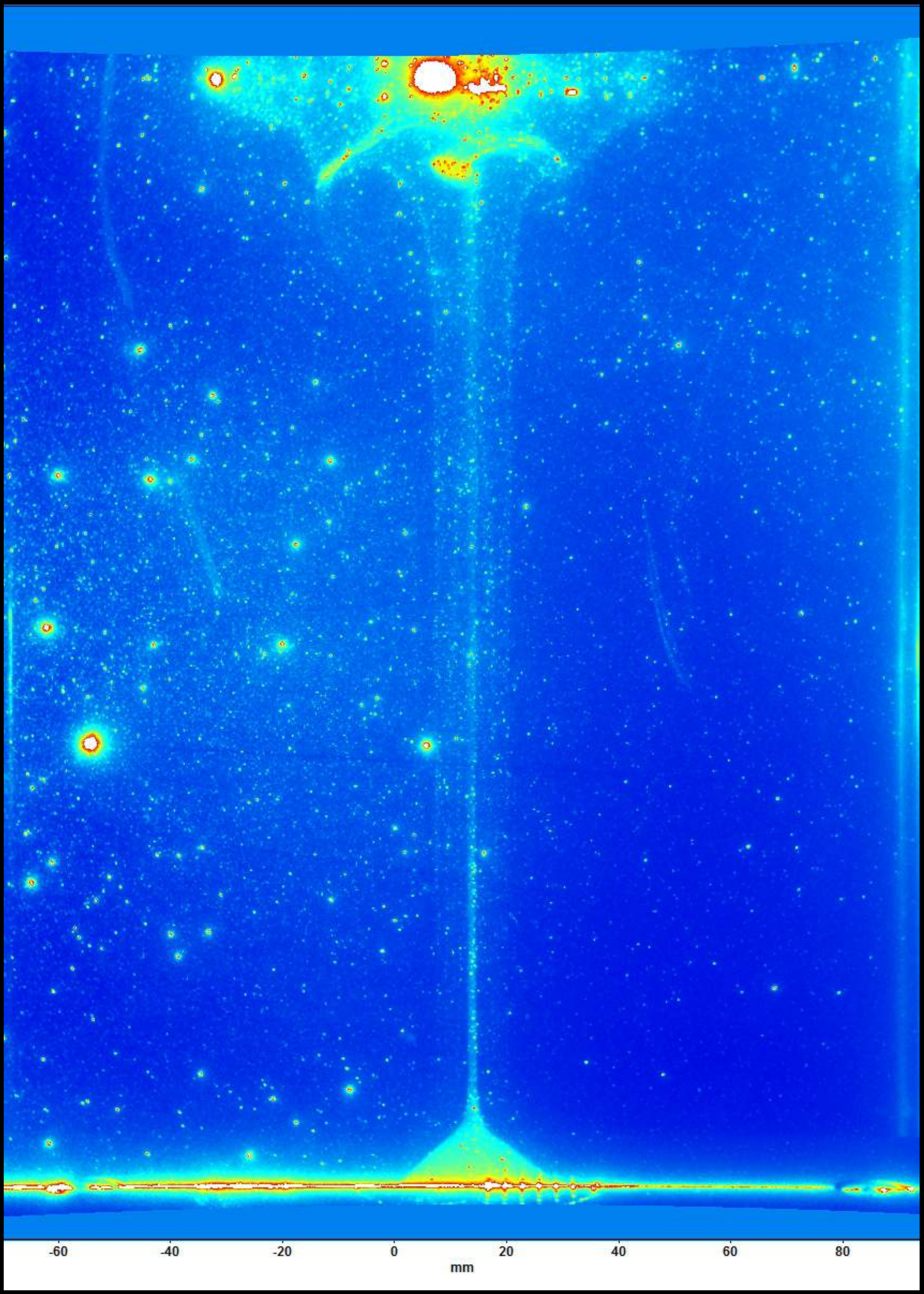
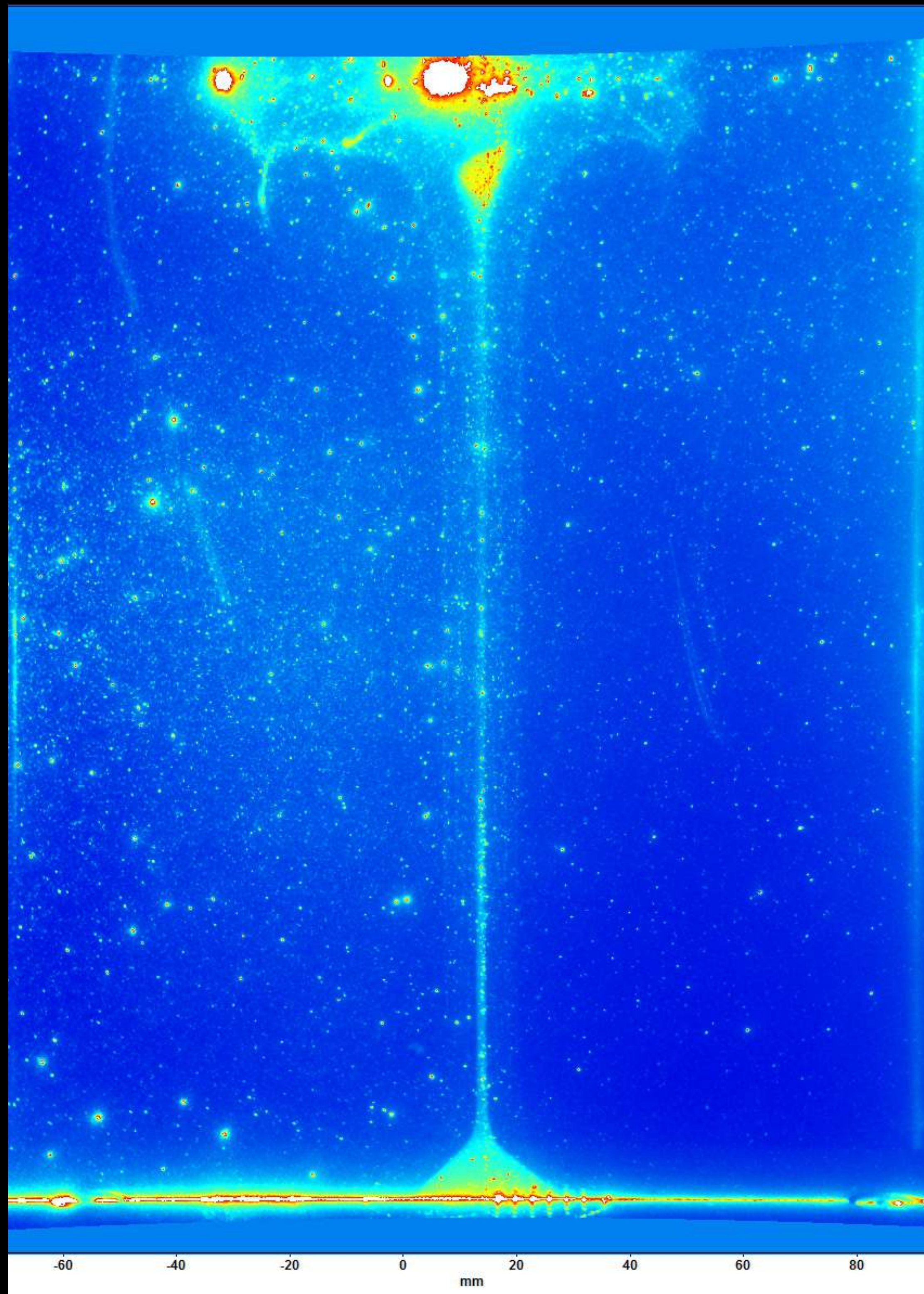
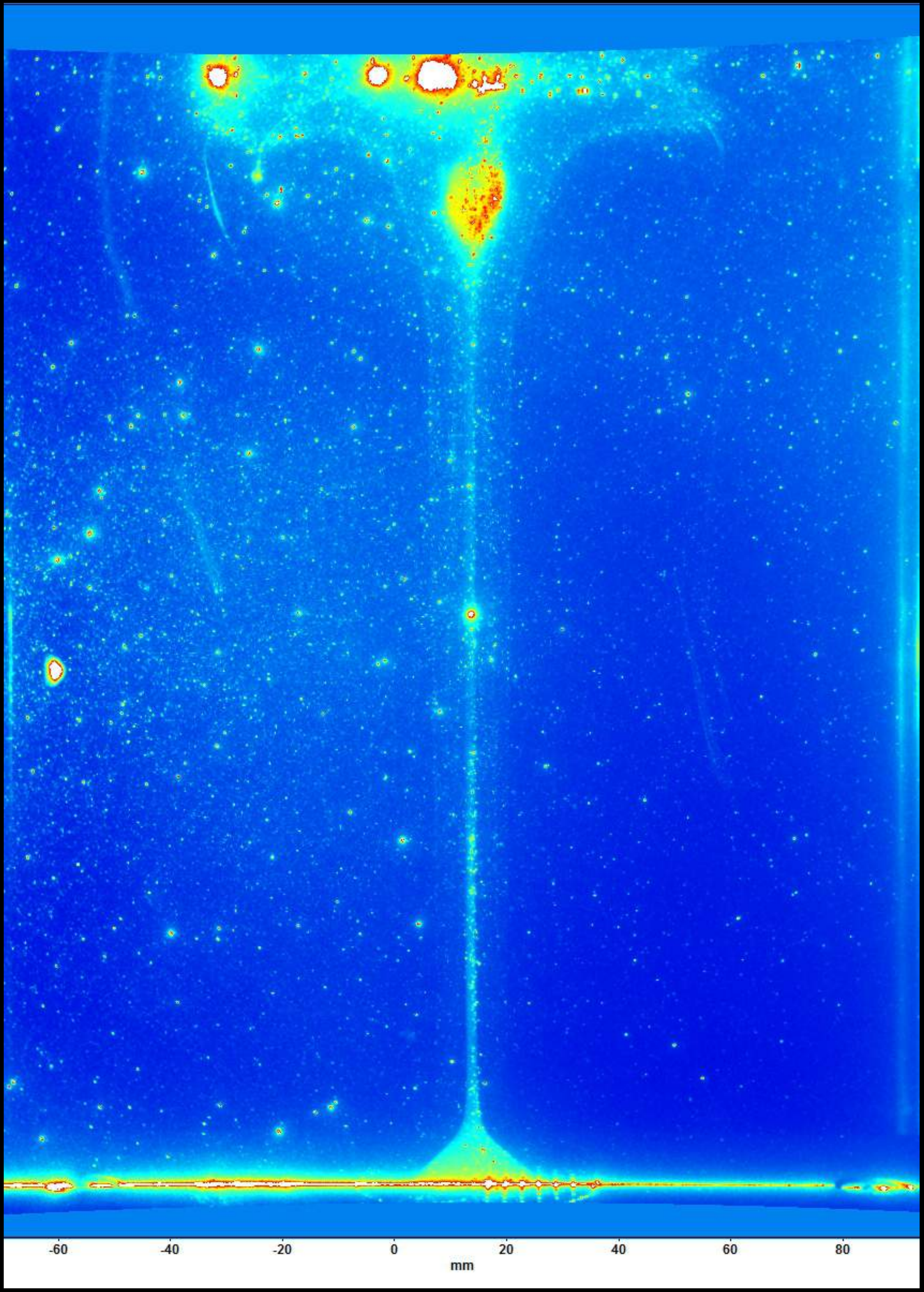




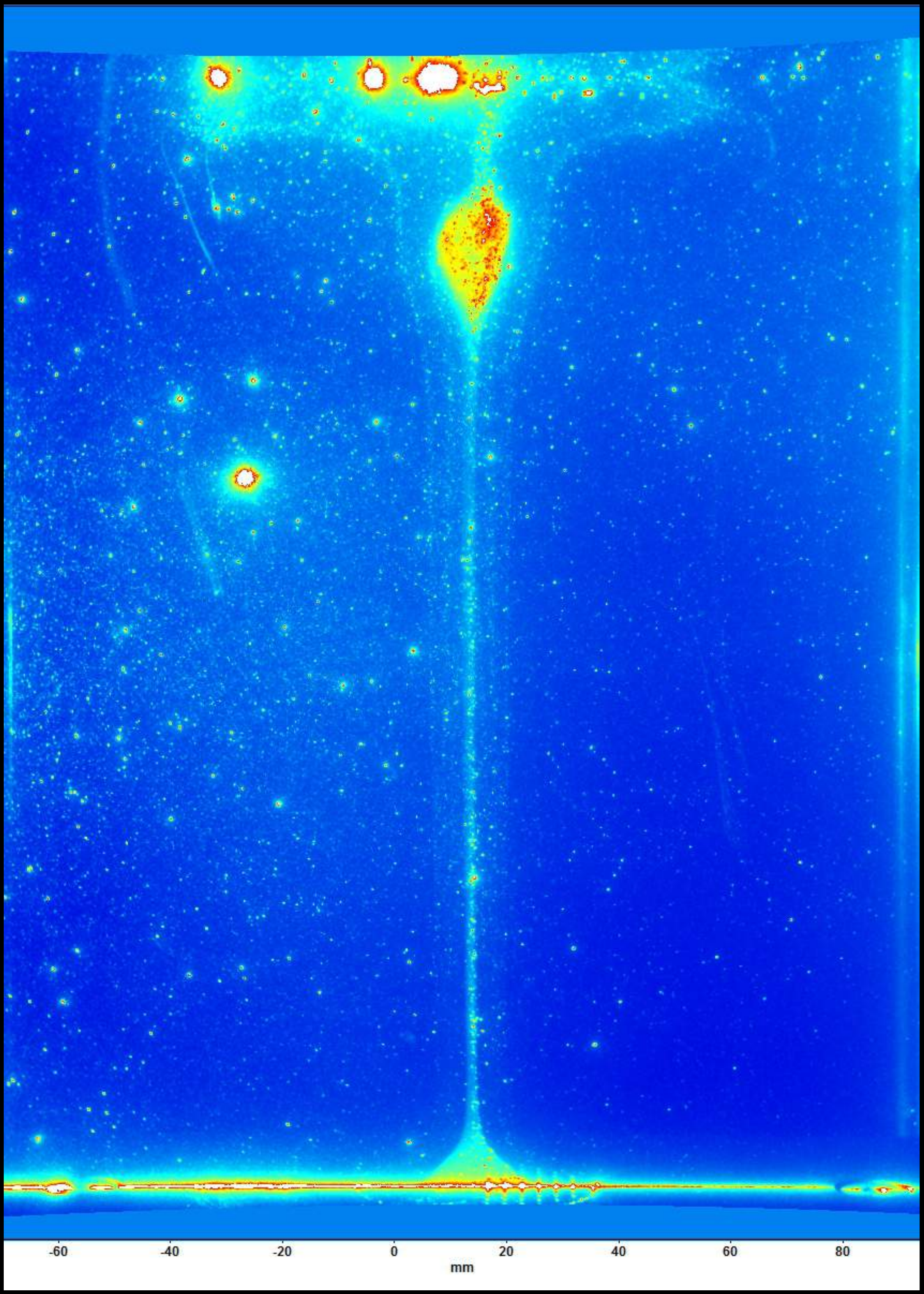
0530

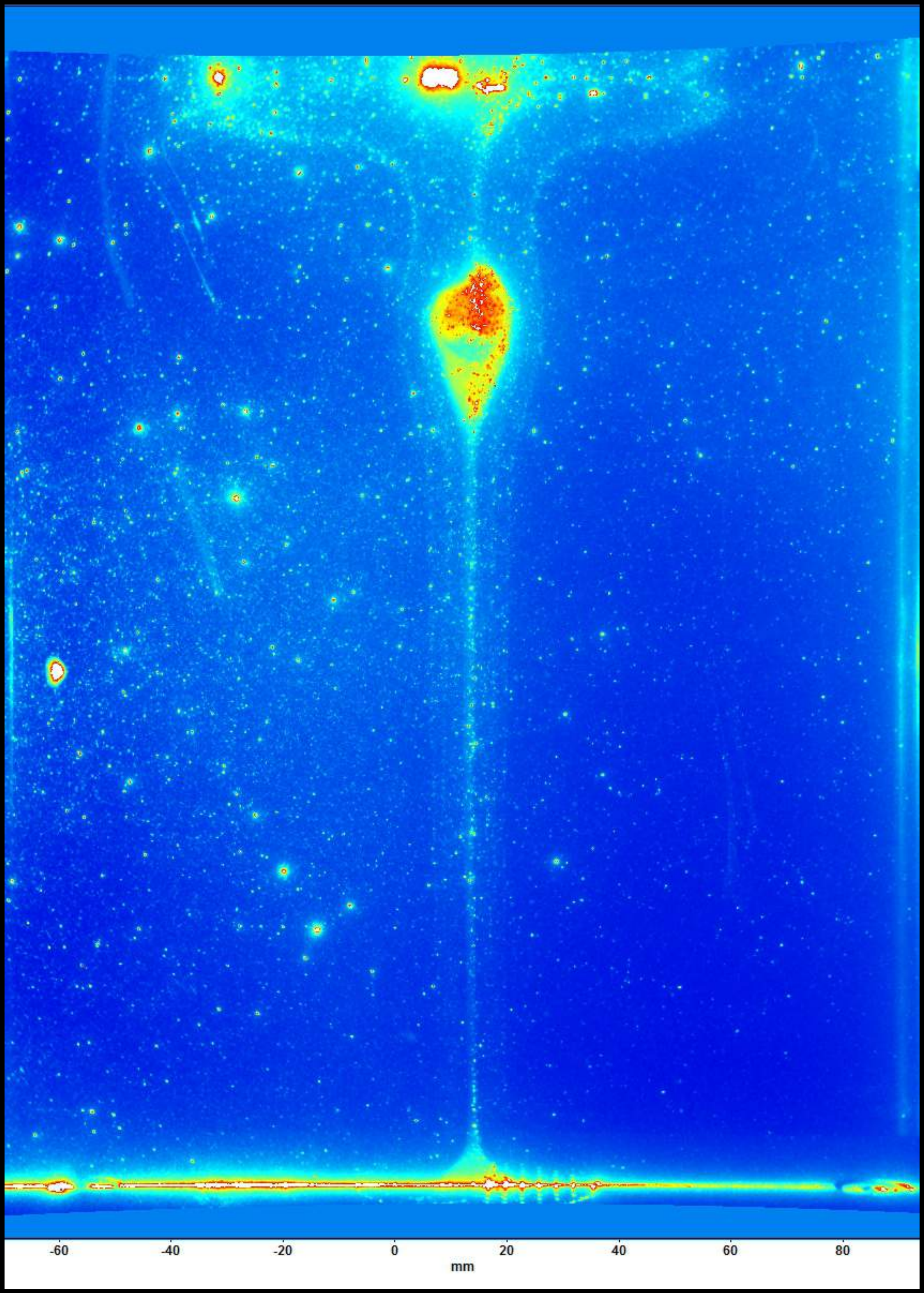
0630



The denser fluid cools and starts to sink at the conduit axis

0730





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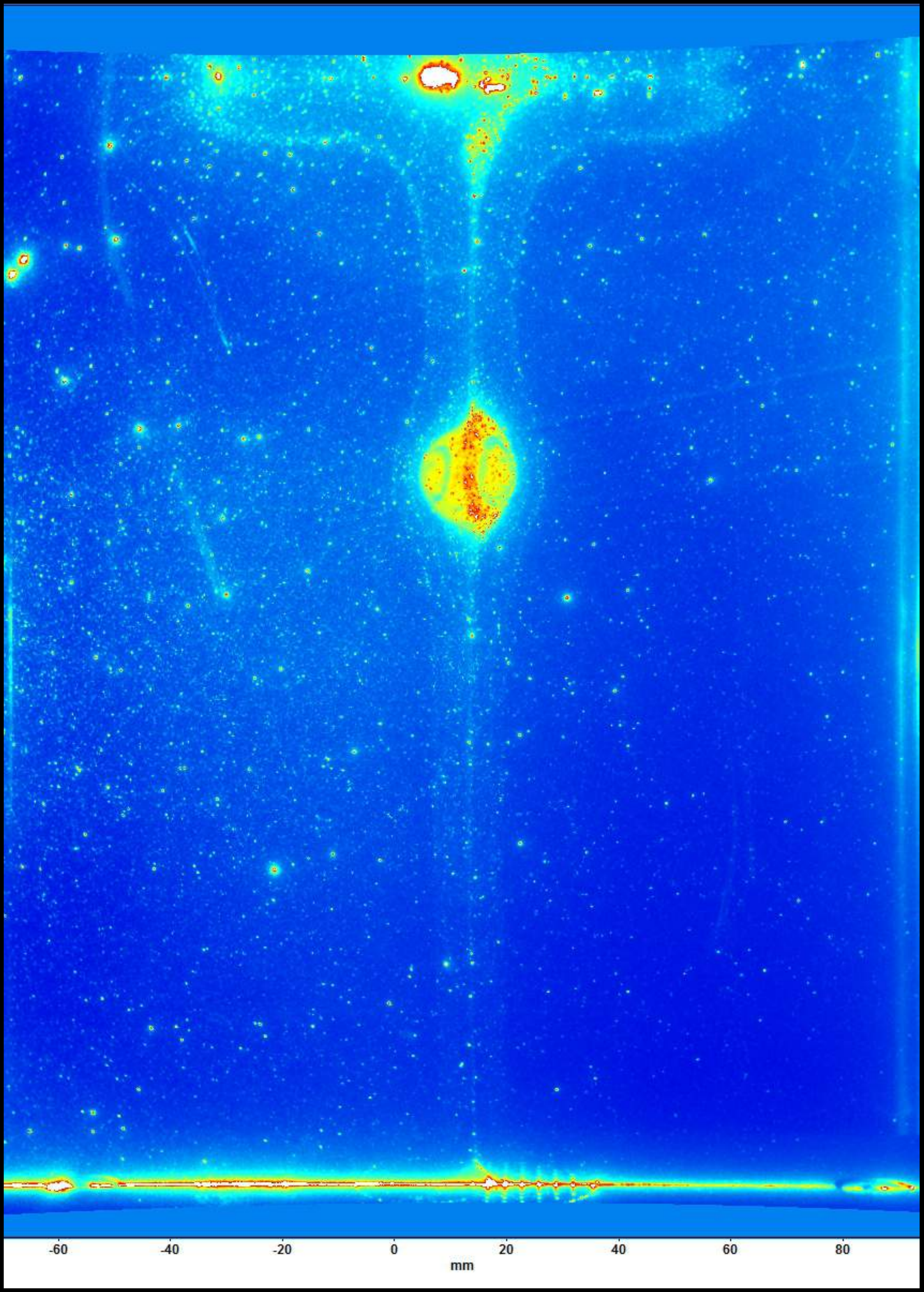
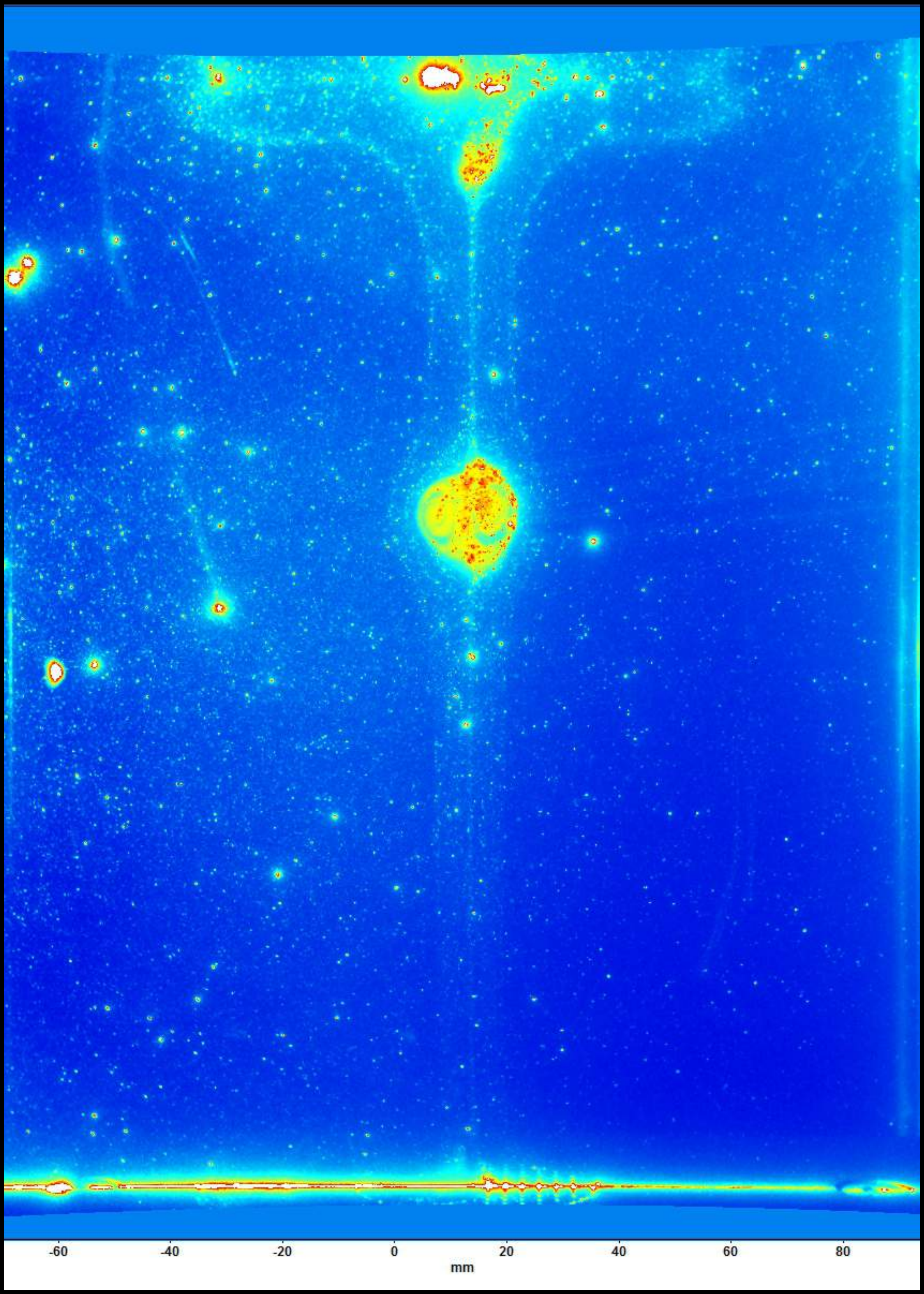
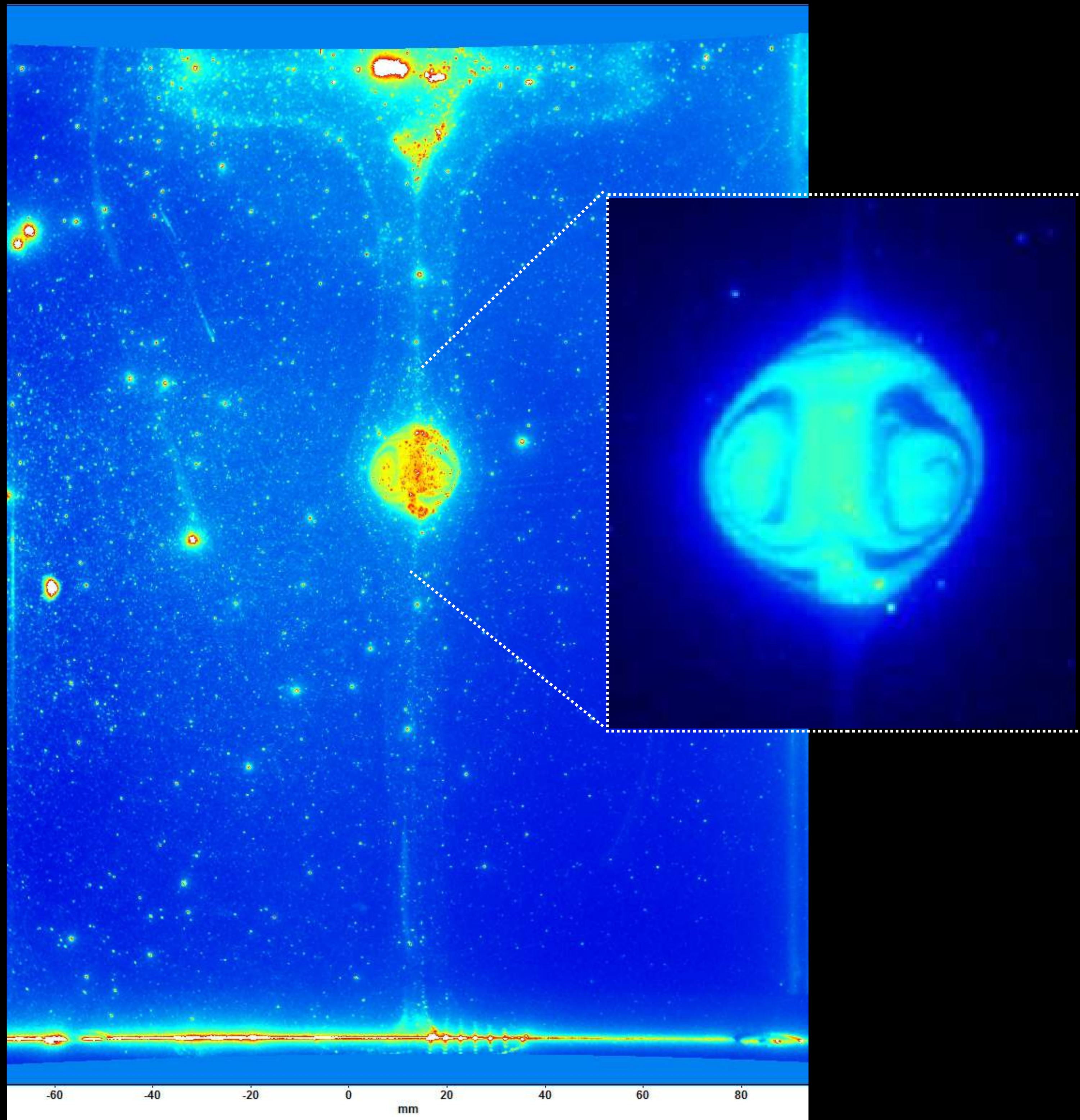


As it falls it grows by entraining surrounding fluid

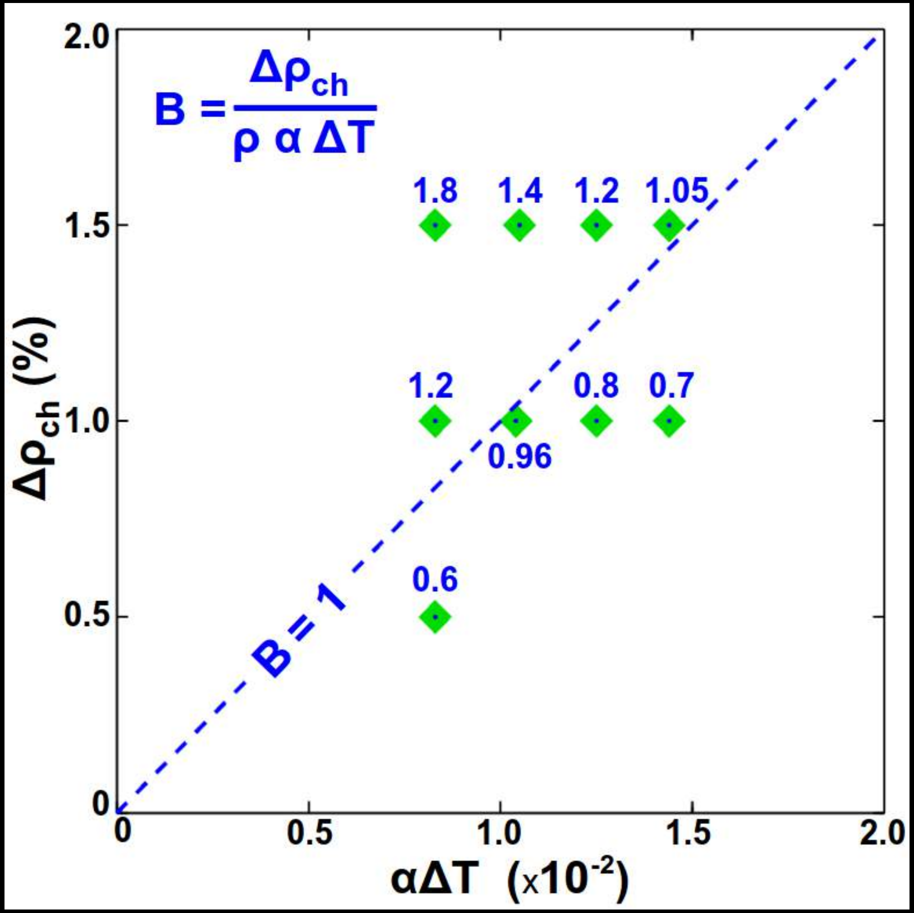


The upwelling plume fluid has to 'circumvent' the sinking denser 'blob'.
The flow lines are perturbed



1000

Laboratory experiments with compositionally denser heterogeneities



How does a denser heterogeneity perturb the plume flow?

What is the evolving shape of an initially spherical denser heterogeneity?