Entrainment Processes during Plume Ascent

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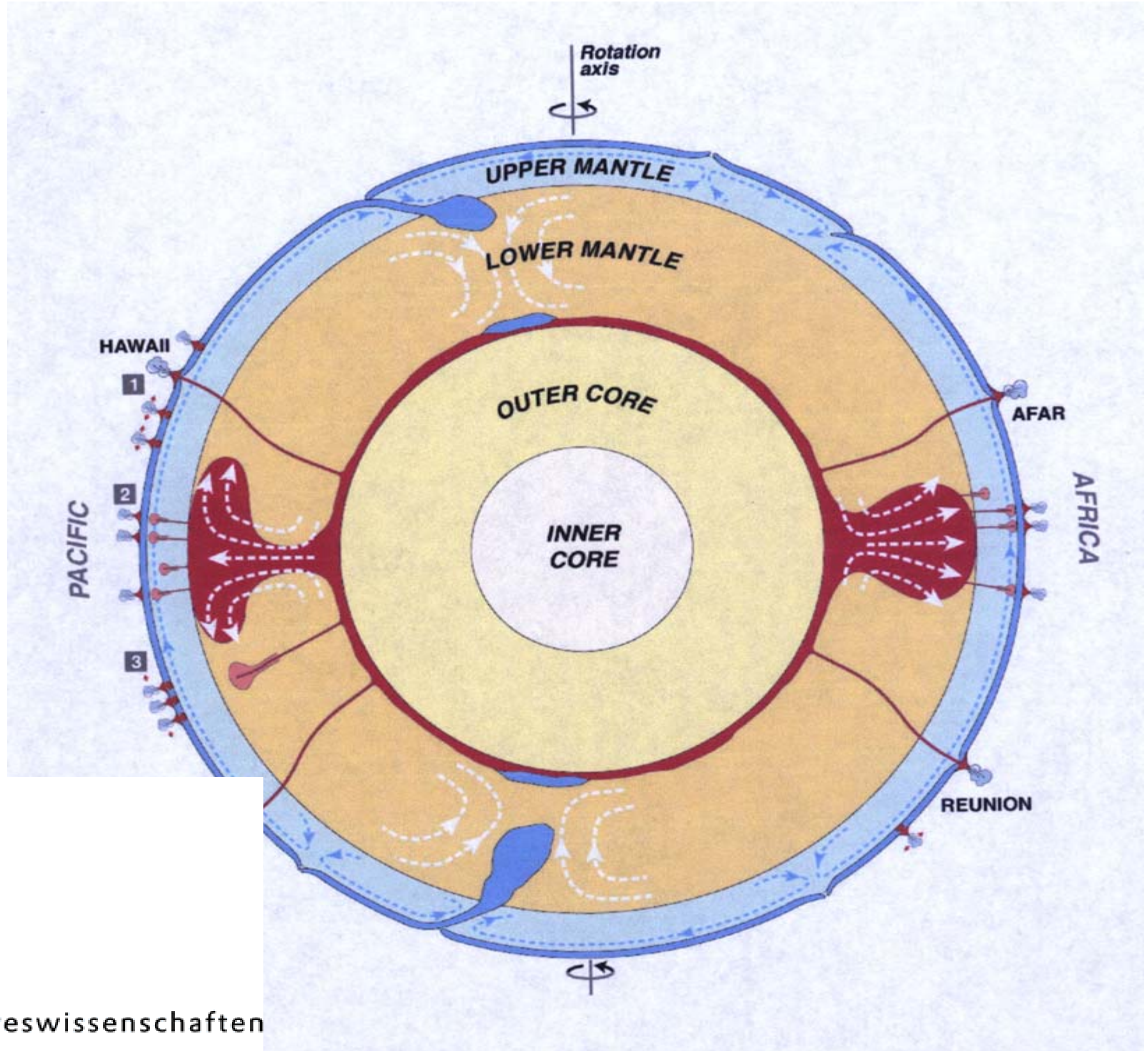

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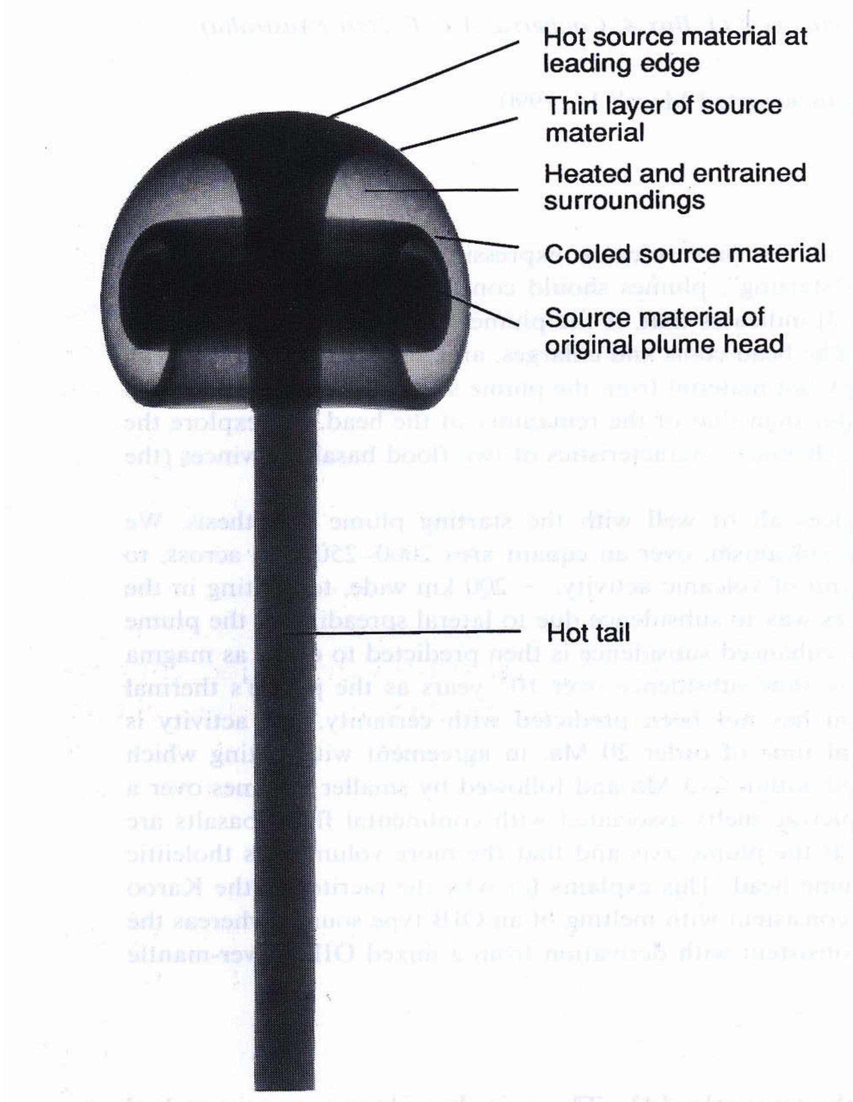
Introduction

- Geochemical analysis of Lavas from Hawaii, Iceland, Galapagos etc. provide compelling evidence on the heterogenious nature of mantle plumes.
- Mantle entrainment is the preferred geochemical explanation for this.
- However: Dynamics of mantle entrainment are poorly known.
- Important questions:
  - Which regions of the mantle are more efficiently sampled by mantle plumes?
  - Is the heterogenious nature of mantle plumes inherited at the source, or does it develop through entrainment during plume ascent?
  - How is the plume affected by mantle discontinuities?

Part 1: Laboratory Experiments

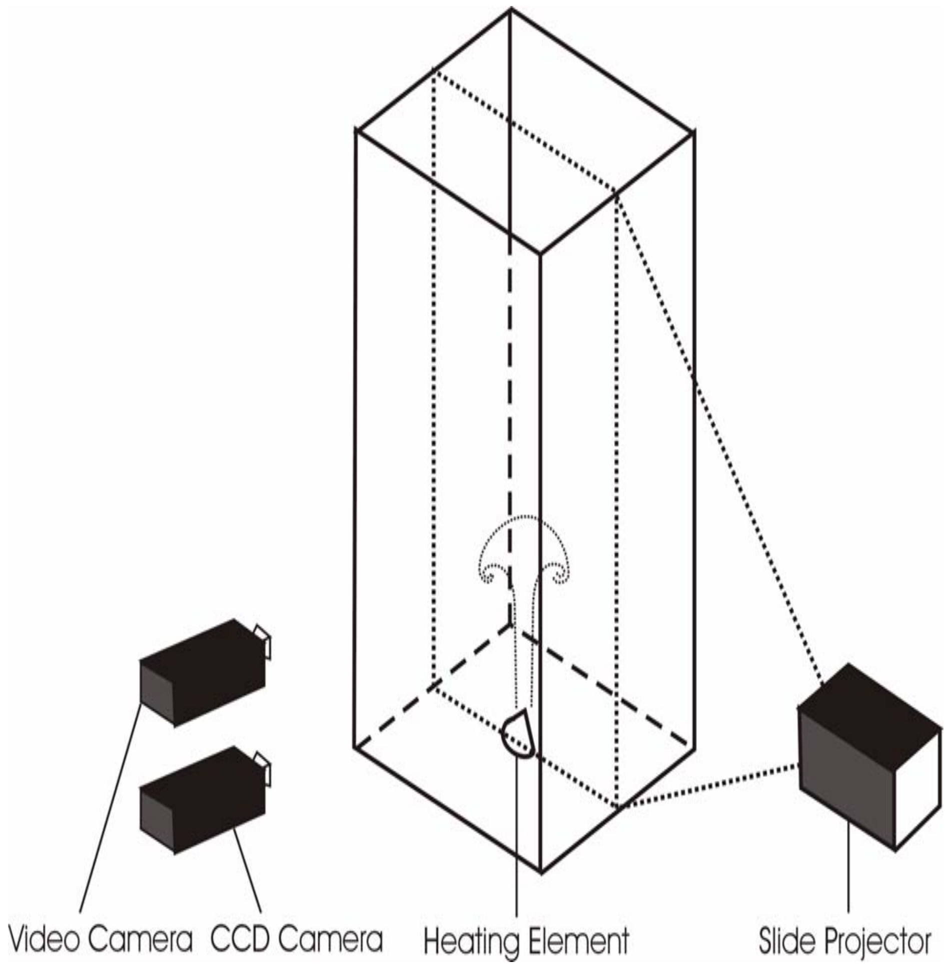
Anatomy of a plume

- Most Laboratory Experiments have used injection of a hot, buoyant fluid into a viscous medium
- "Classic" Plume introduced by Griffith & Campbell (1990):
  - Rapid increase of Plume head size due to enrainment of surounding material into the plume head
  - little mixing between plume source material and surrounding material: Source material gets thinned to filiament-like layers that surround the entrained material, some source material pools in a donut-shaped region around the plume head.
  - no measurable entrainment in the plume tail

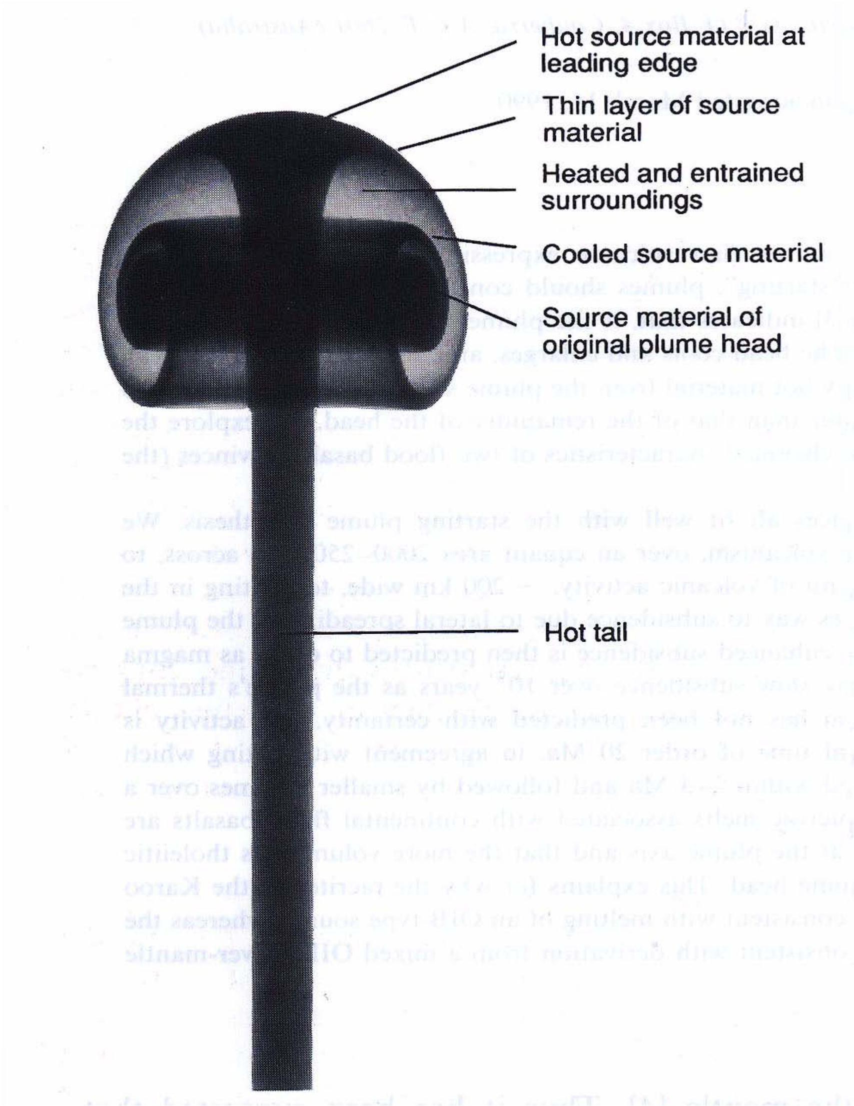


Experimental Setup

- So far, there's been no systematic study where the plume is formed by thermally buoyant material alone.
- Therefore, our setup uses a small (~2cm diam.) heating element to induce a plume in the lab tank
- The syrup is contaminated with small glass particles. The experiment is illuminated by a (roughly) parallel sheet of light, sampling slices of the tank interior
- data aquisition is done by CCD camera and standard Video recording
- The CCD images are processed by a dedicated particle tracking algorithm. Through this, flow speed and entrainment rates are determined.



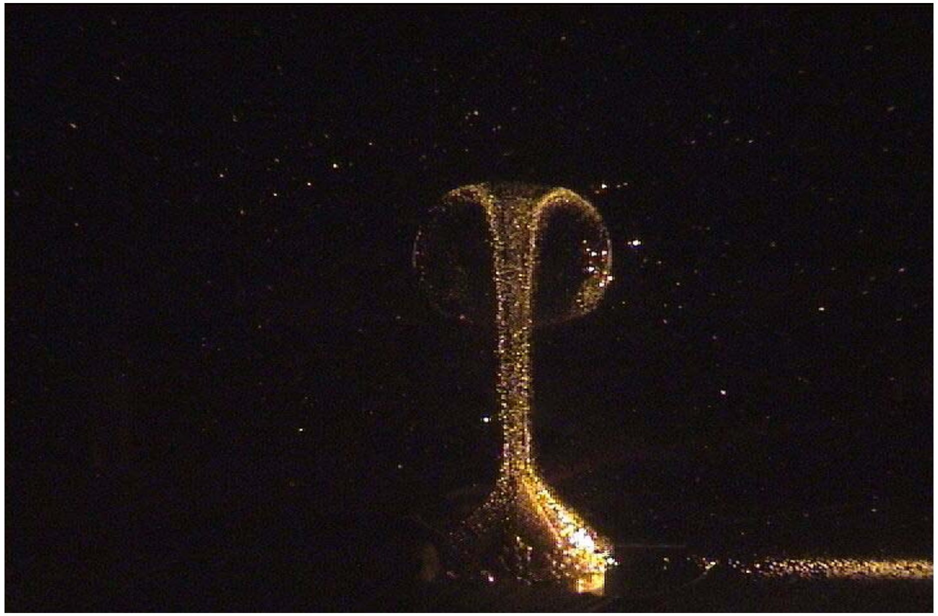
Initial results... don't match!

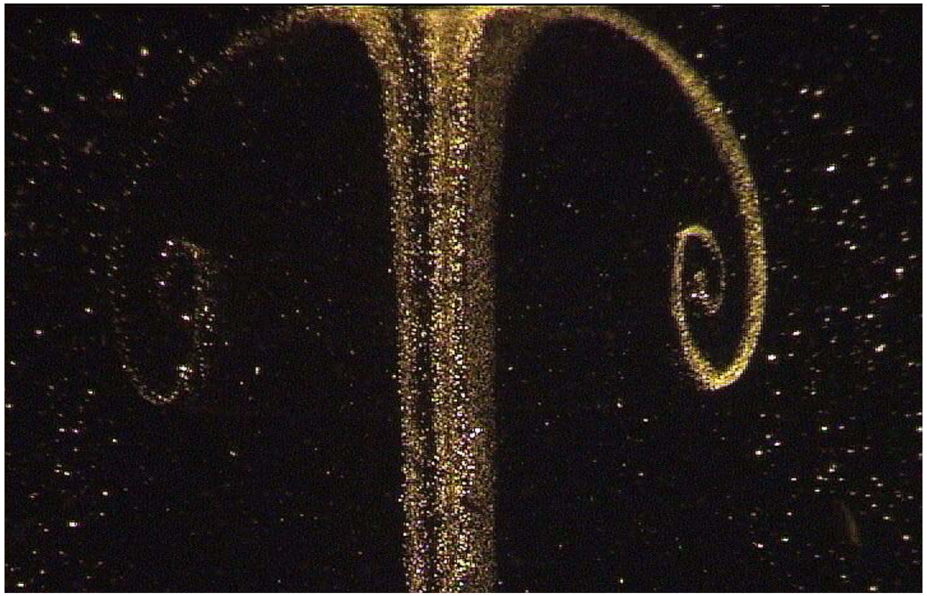


New Model Plume?

- Laboratory work results and Griffith & Campbell could only be reconciled after marking the "plume source" material
- Marking is done by heating up the heating element to 100+°C, thus evaporating the water component in the syrup without caramelising the sugar component.
- This results in tiny bubbles of steam rising up in the plume, and being restricted to the material directly heated by the heating element.
- Resulting shape in agreement with the "classic" plume model.

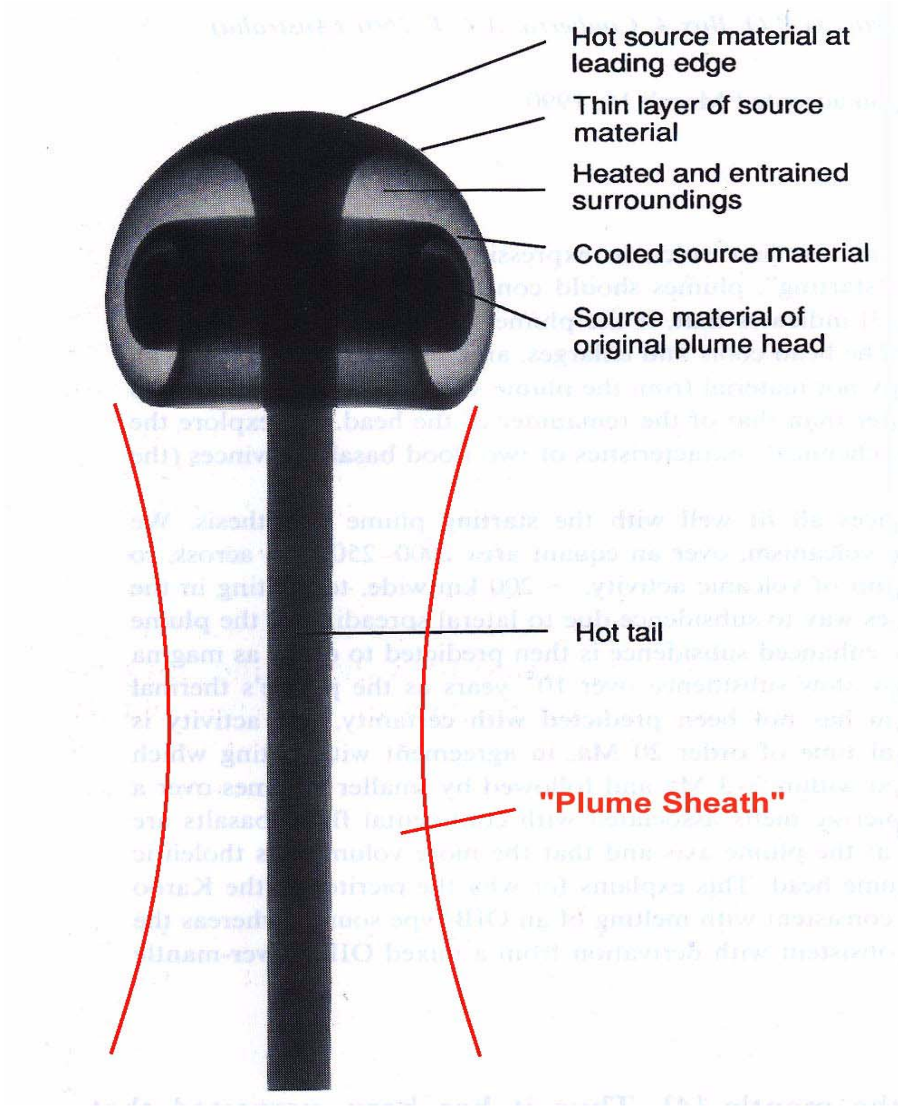
Samples of lab experiments





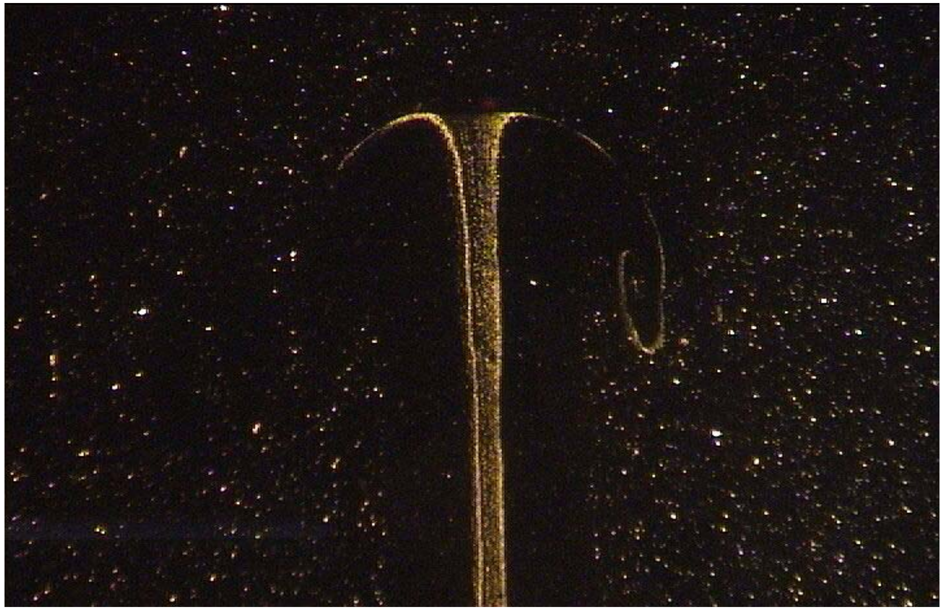
Anatomy of the plume - revised

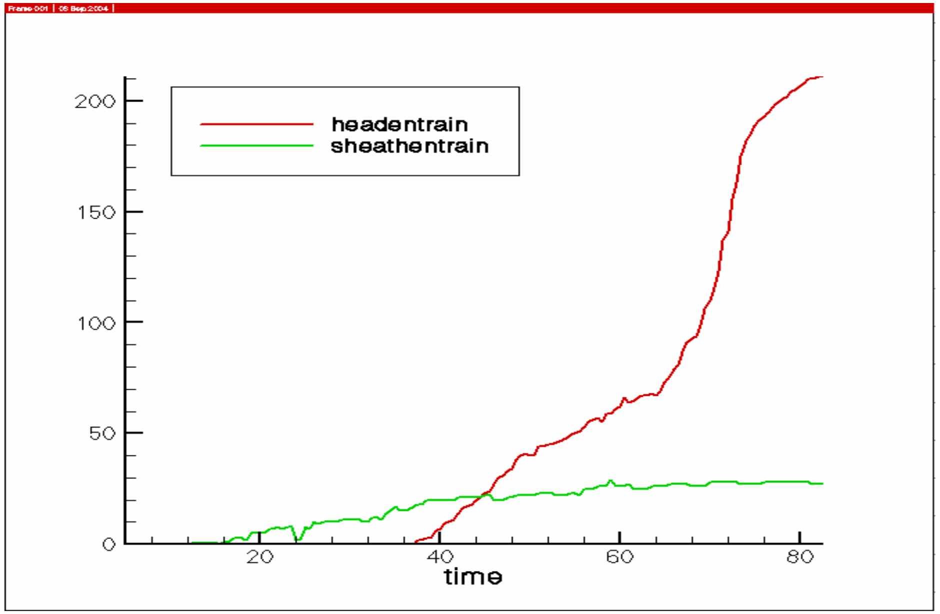
- Lab experiments indicate that there's little entrainment of surrounding material into the plume head (contrary to Griffith & Campbell).
- Also, there's no measurable entrainment into the plume tail
- The rising plume drags a "plume sheath" of source region material in its wake that rises at roughly the same speed as the plume.
- Any entrainment happening during plume ascent is between the plume sheath and the surrounding material.
- Only after the plume head spreads out in reaction to the surface boundary, significant entrainment into the head is observed.



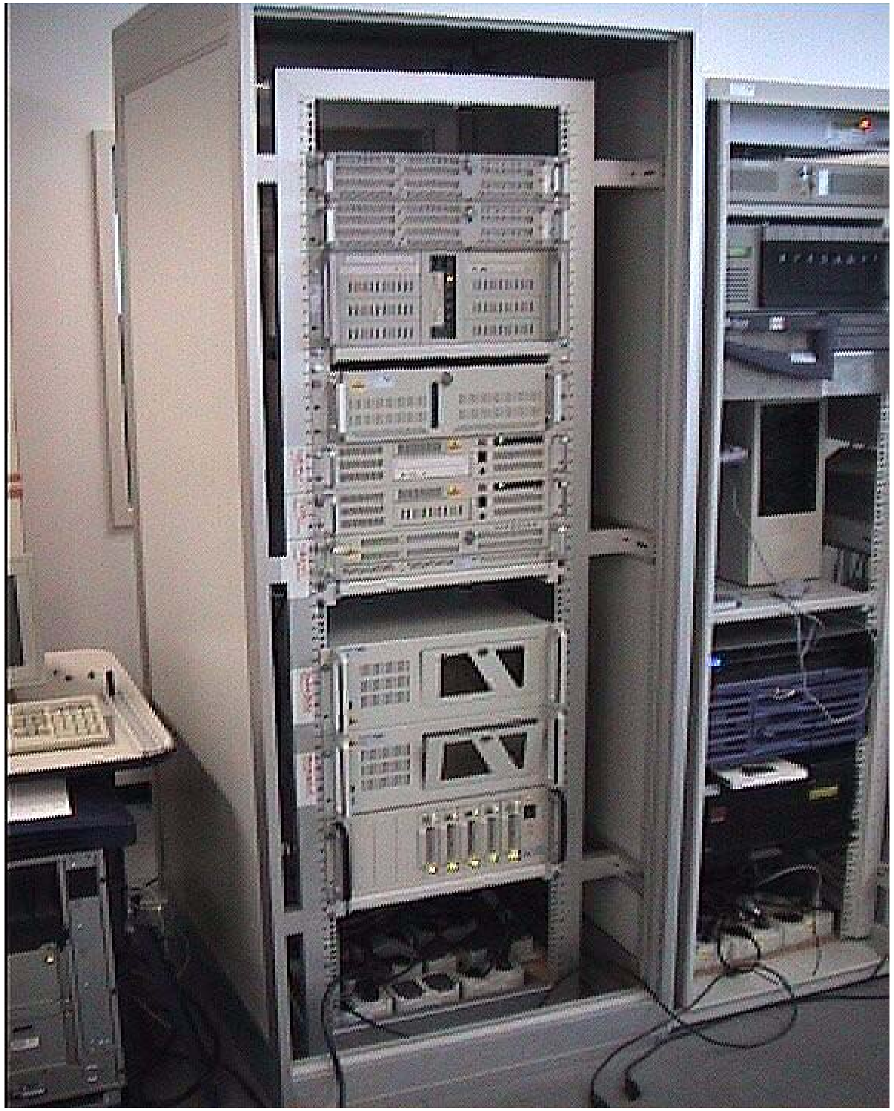
Entrainment in lab experiments

- Entrainment measured through the particle tracking files: where does a particle start, where does it end up.
- Not too precise, since limited by the particle tracking algorithm's performance and the experimental setup
- Chemical way of measuring entrainment too costly and time-intensive

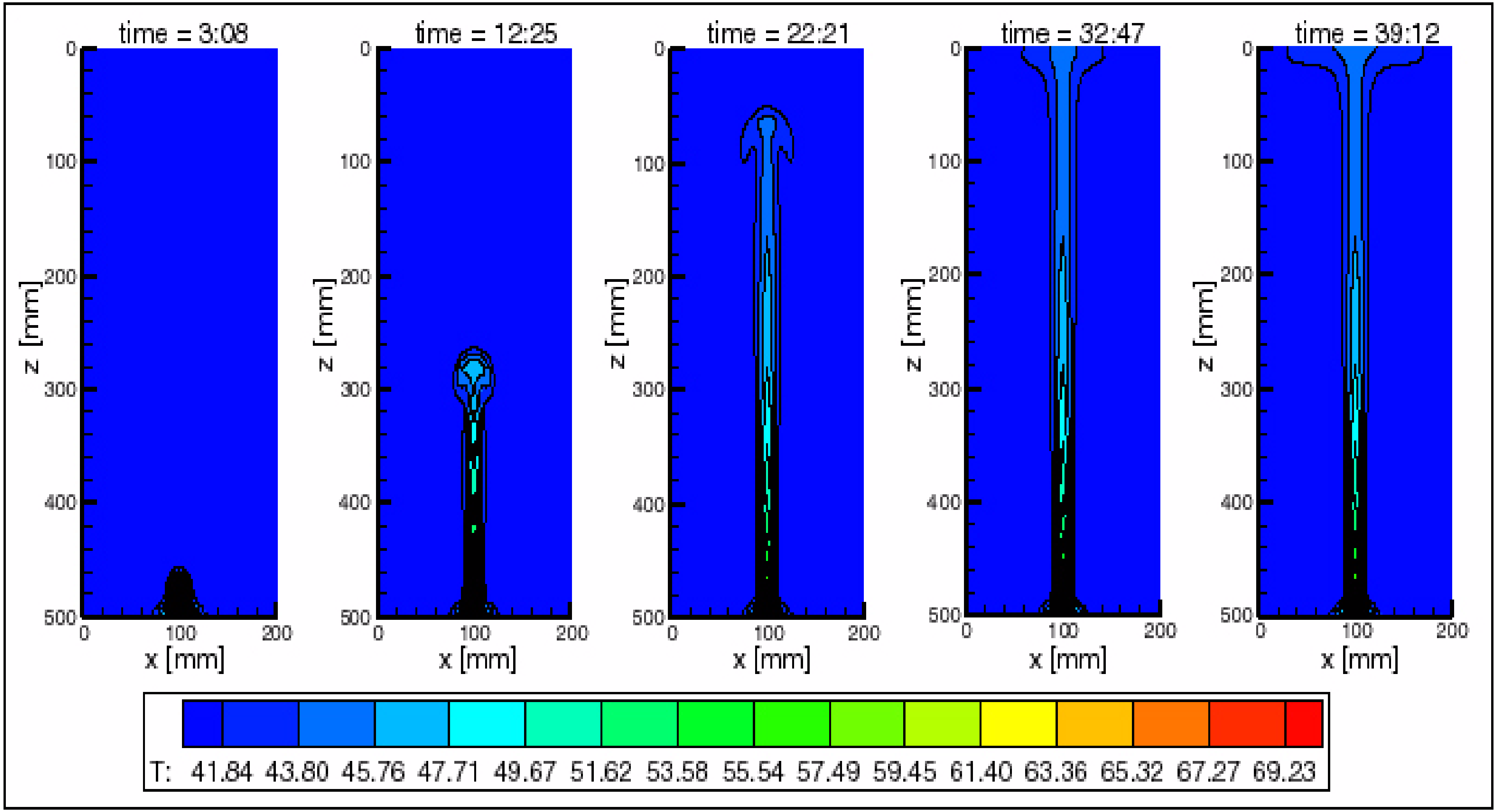




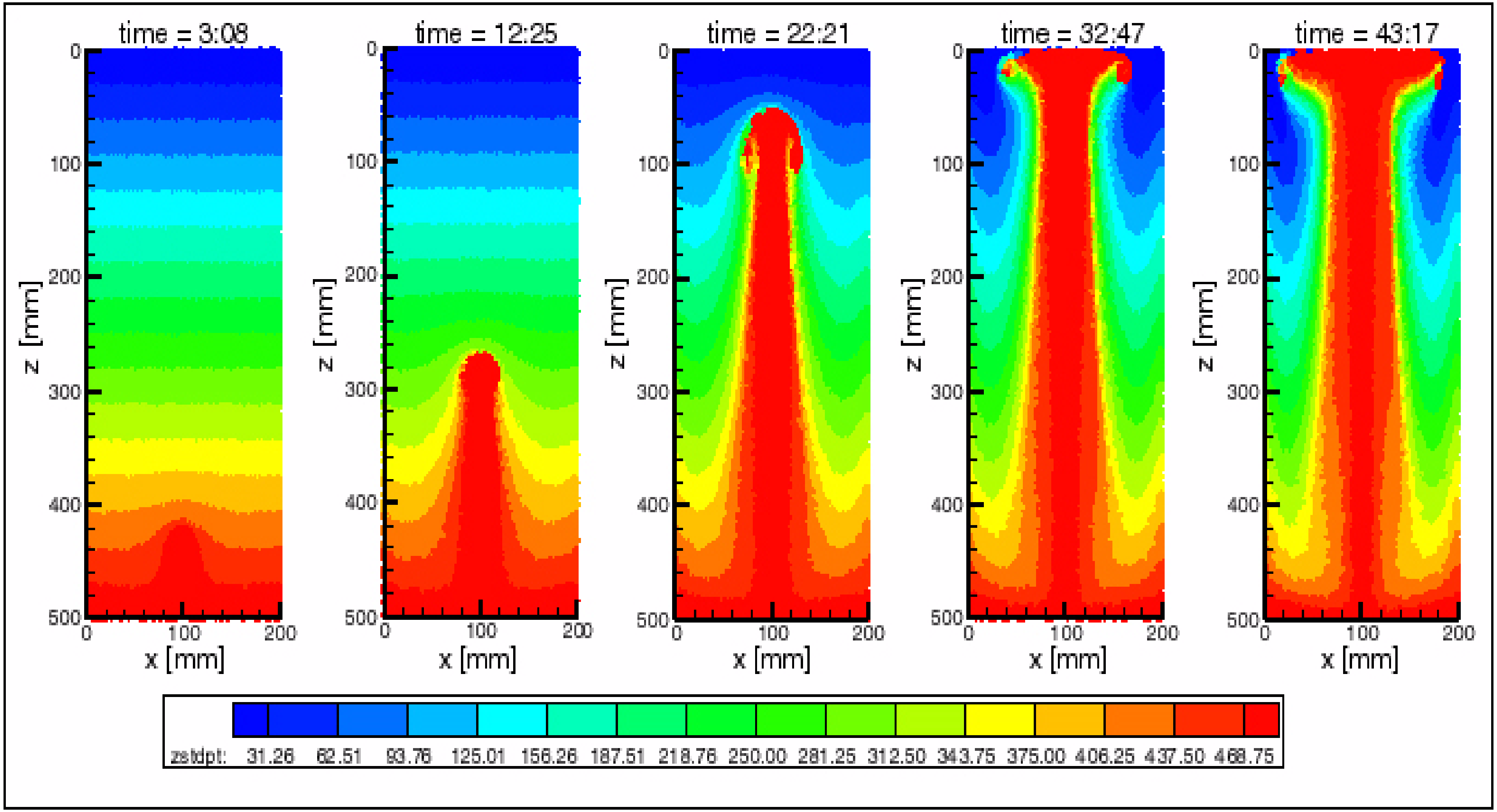
Part 2 - Numerical Modelling



Lab condition modelling - temperature field:



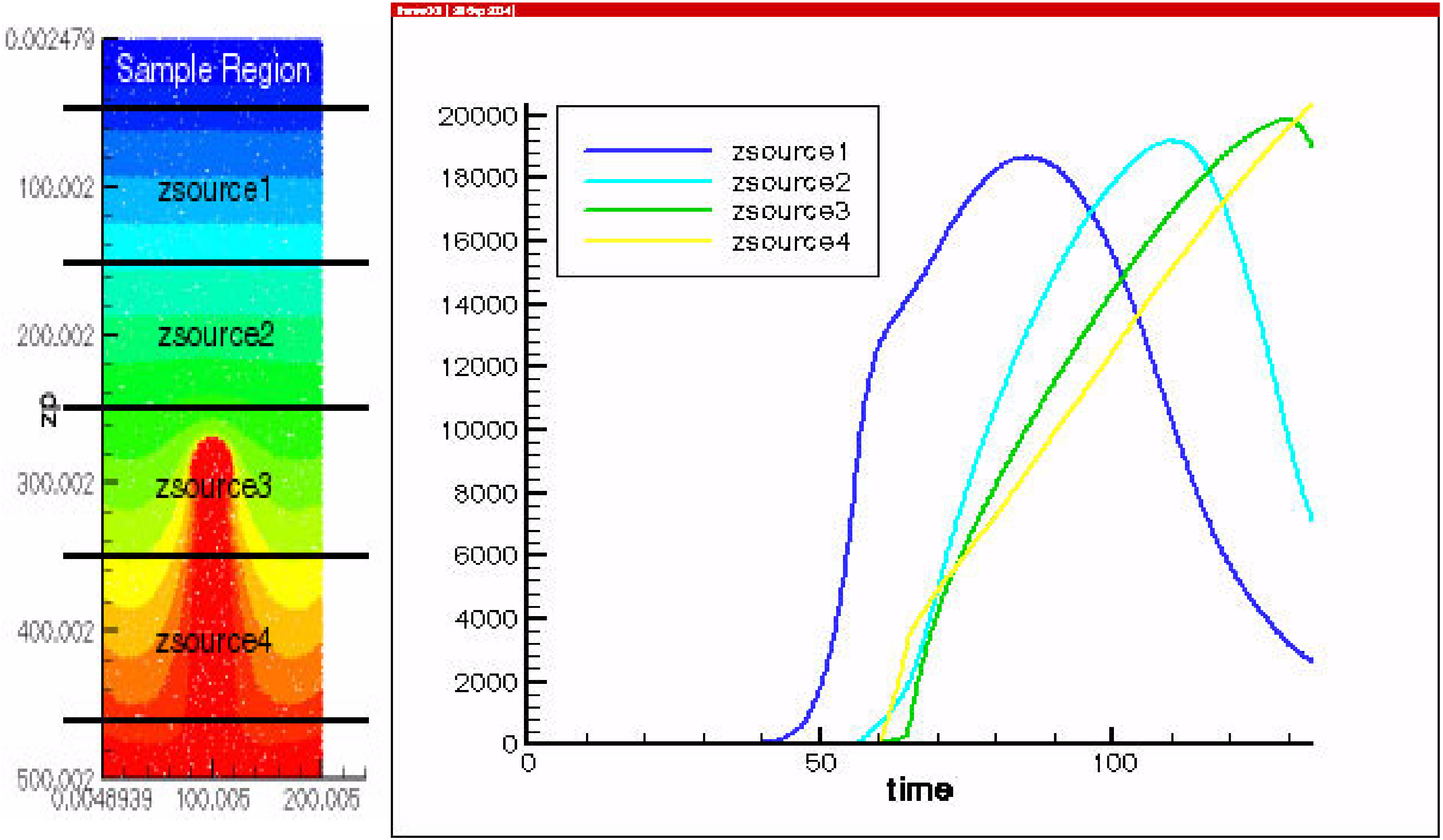
Lab condition modelling - particles:



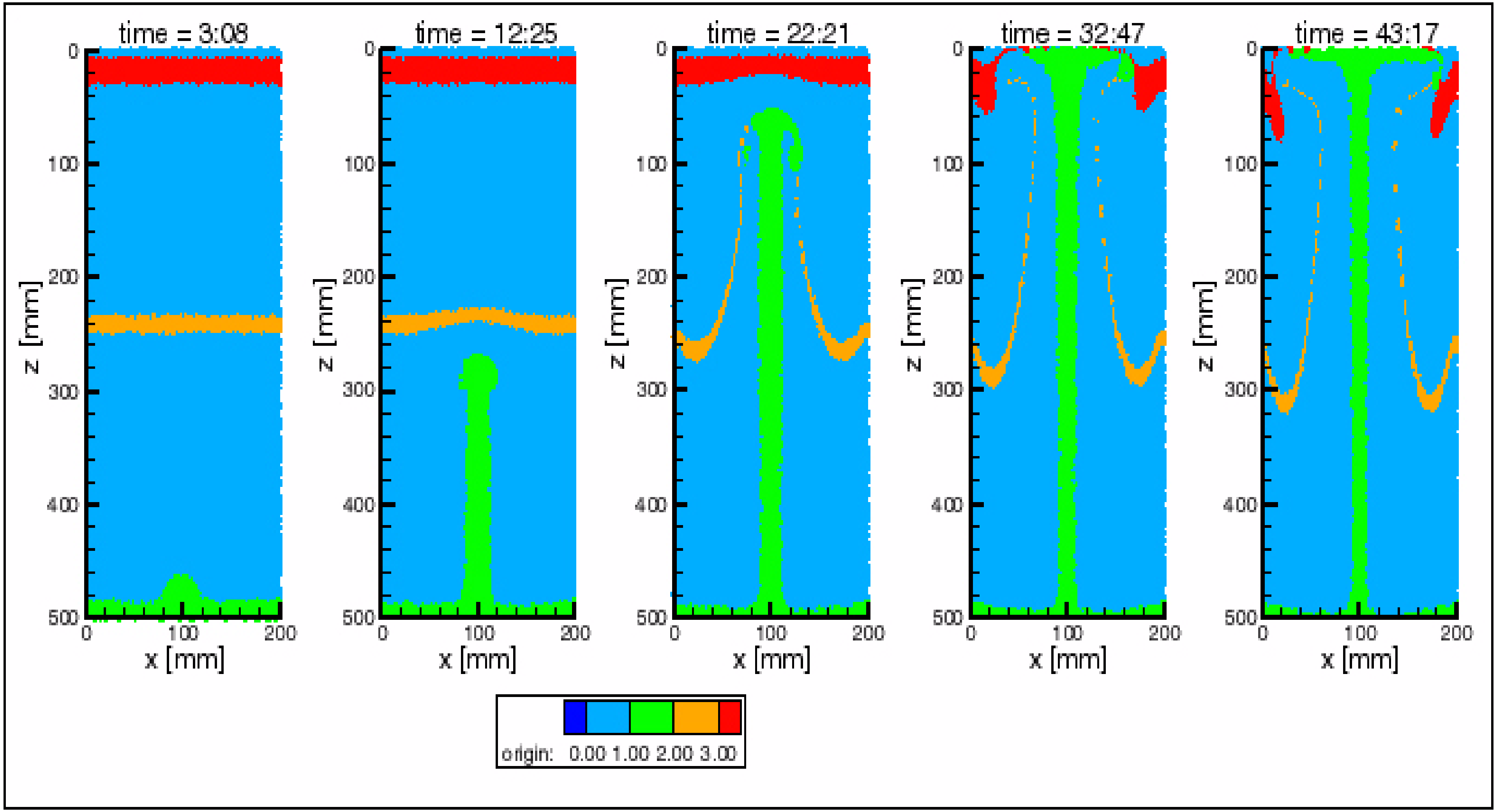
Comparison of lab and numerical experiments:

- Good, almost perfect match between lab and numerical experiments.
- "Plume sheath" as pronounced in the numerical experiments as in the lab experiments
- Both lab and numerical experiments show a remarkably low plume temperature when the plume reaches the upper boundary - 3°C - 7°C above the surrounding non-plume material at most, between 3% and 9% of the original temperature contrast. Thus, heat conduction does seem to play a bigger part than initially thought.
- The plume sheath of the ascending plume contains ~15 times as much material as the plume itself.
- Once the plume is established, the plume sheath thins considerably, but never completely dissolves

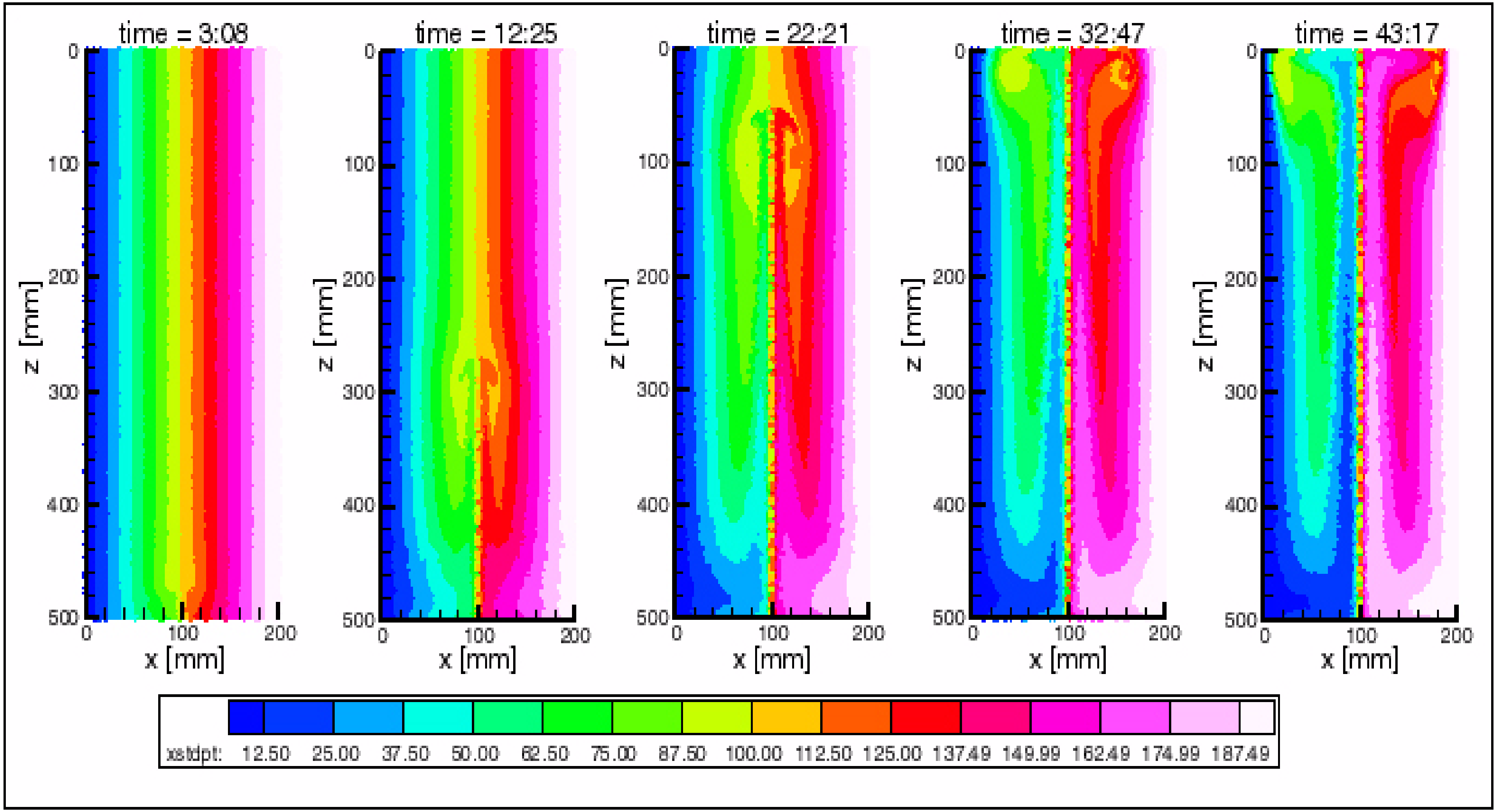
Entrainment in the numerical model



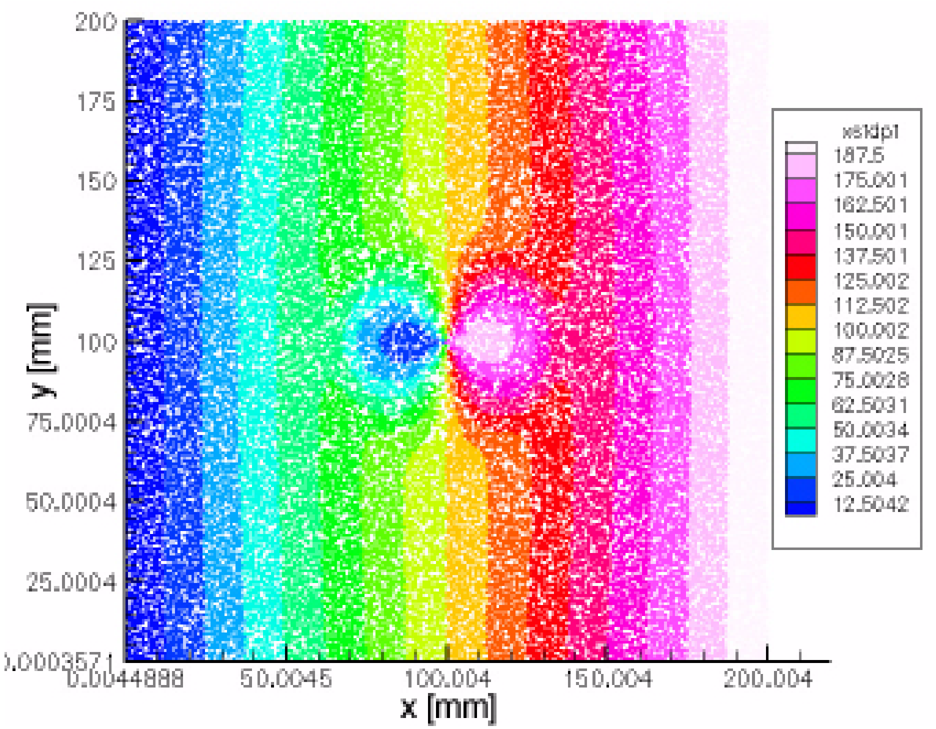
How are distinct reservoirs sampled during plume ascent?

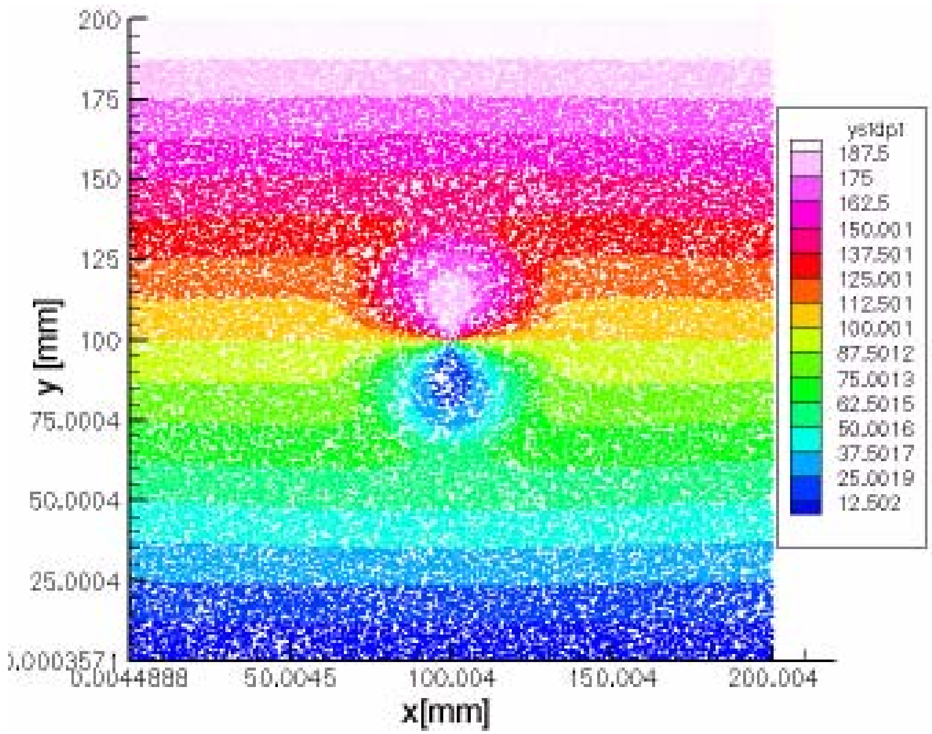


Is there intermixing between the sampled reservoirs?

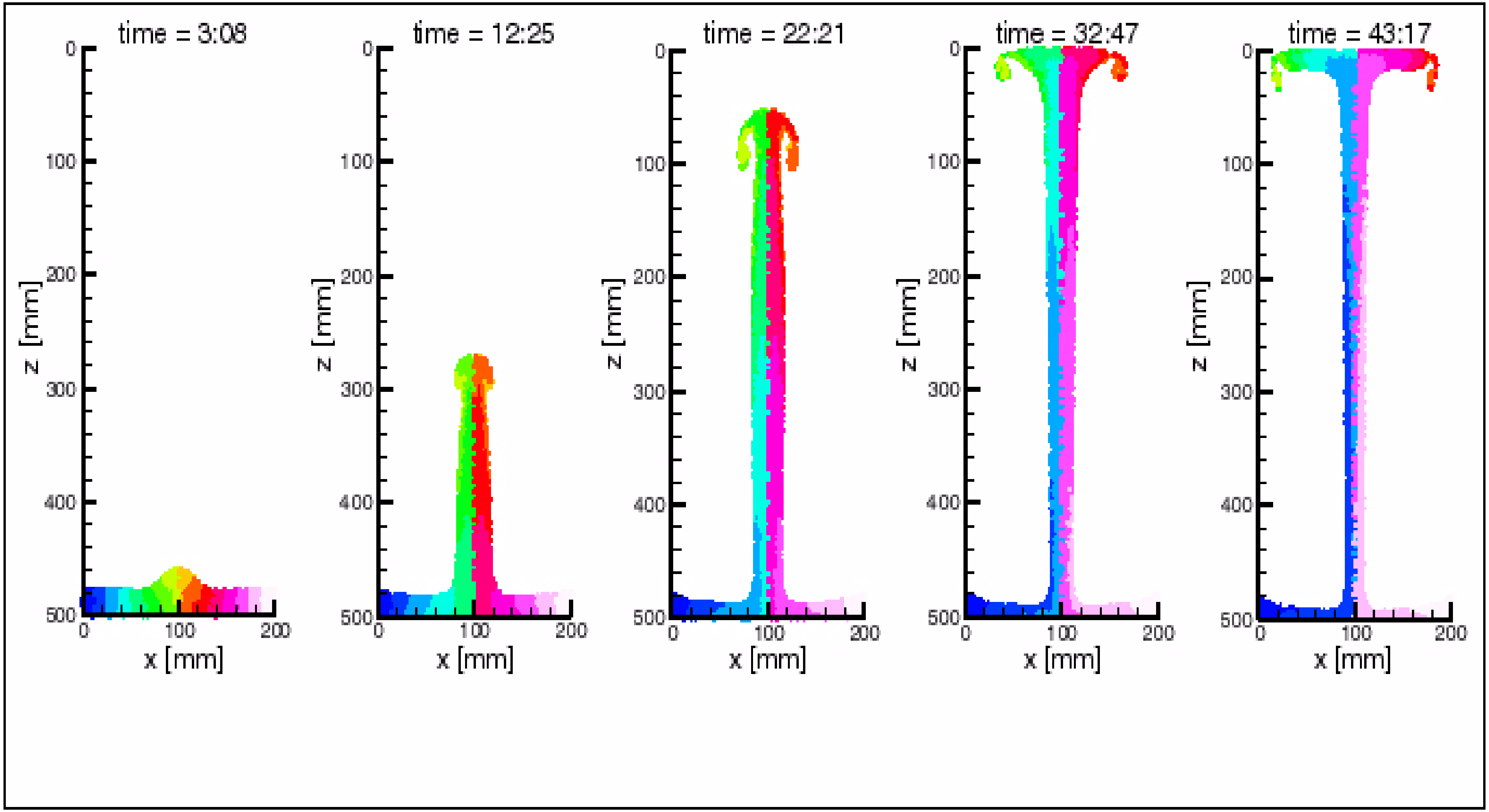


A xy-slice through the plume tail





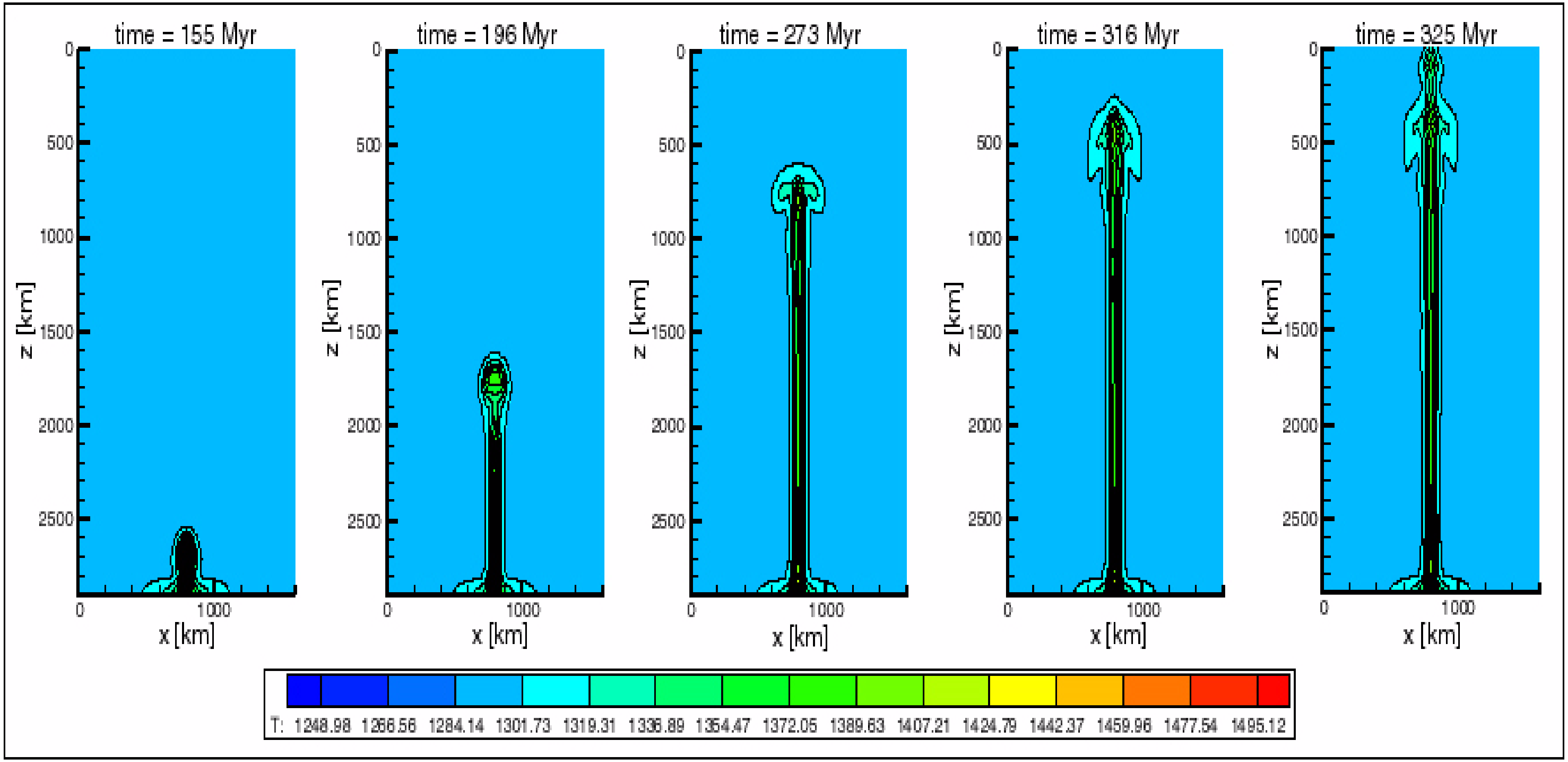
How is the plume source layer sampled?



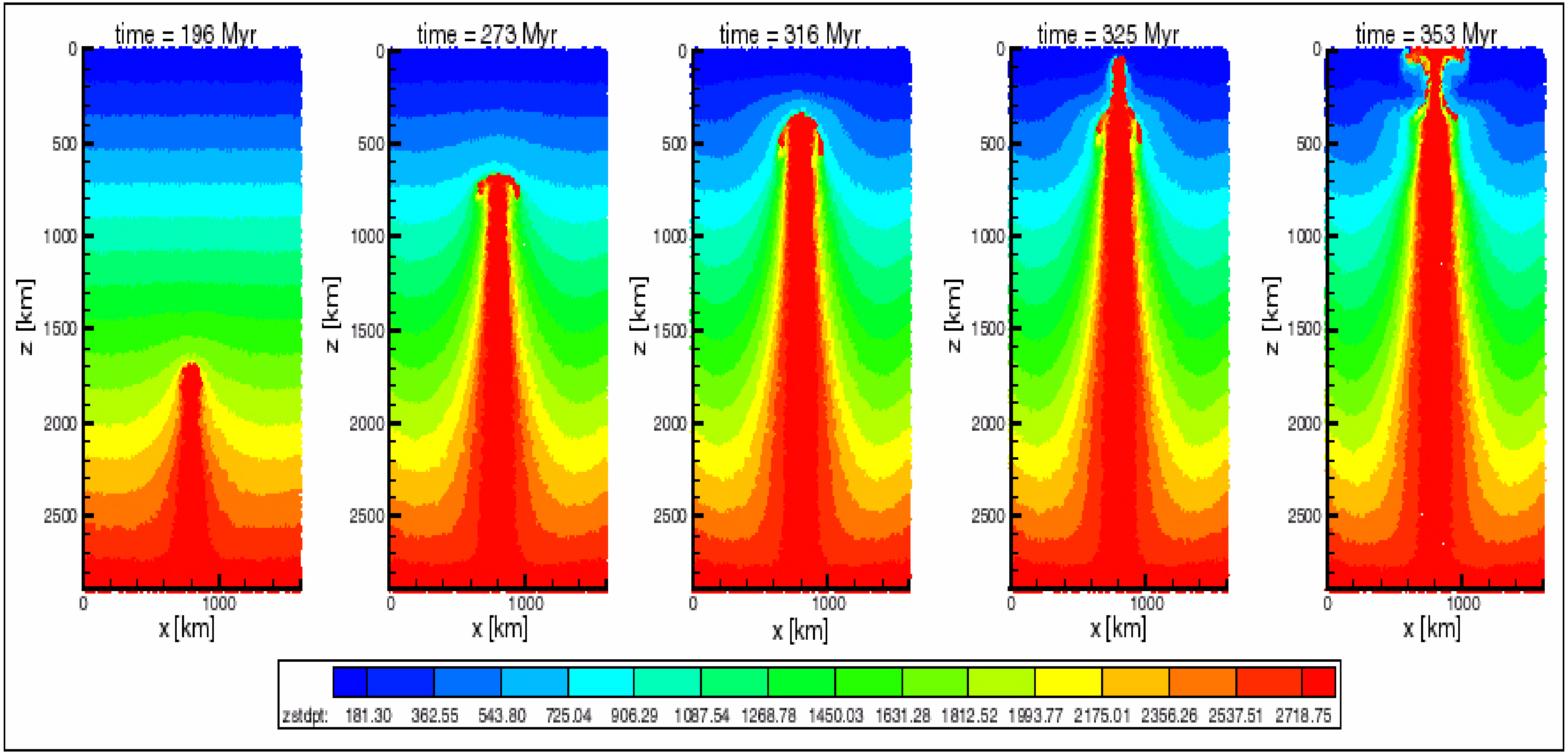
In Summary:

- There is no radial transport of material within the plume - material sampled to the left of the plume axis stays on the left side of the plume axis during entrainment and ascent.
- The source layer is most effectively sampled. Heterogenities in the source layer are most likely to affect the plume composition
- Mantle reservoirs are entrained into the plume sheath and/or dragged along in the wake of the rising plume. Therefore, material from both the upper and the lower mantle can be transported to the surface.

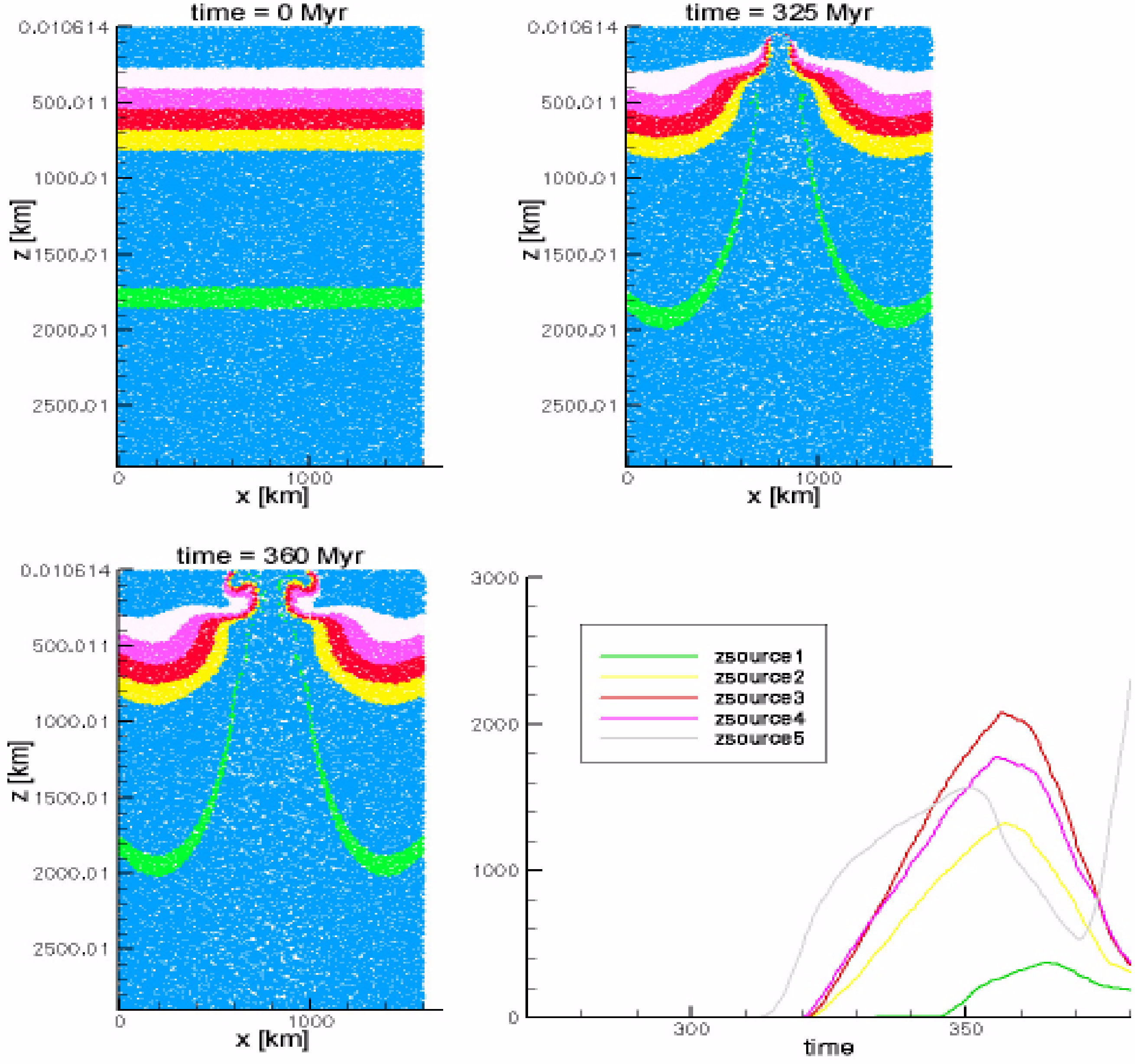
Mantle conditions modelling - temperature field



Mantle condition modelling: particles



Mantle conditions modelling - how are mantle discontinuities sampled?



Summary of mantle plume modelling:

- Good agreement between laboratory experiments, numerical models using lab conditions and numerical models using mantle conditions.
- The thermal boundary layer of the plume source region is the region most effectively sampled by the plume.
- As in the lab models, a plume sheath forms in the wake of the plume head and entrains material all along the plume path.
- Discontinuities in the mantle do not represent a barrier to the rising plume. They can, however, slow down its ascent, causing a significant thickening of the plume and plume sheath.
- The mantle regions most effectively entrained are the regions along the mantle discontinuities (e.g. 660km discontinuity, 410km discontinuity).
- Our melting model shows that only part of the plume head melts, and only a small part of the material entrained in the plume sheath enters the melting region of the hotspot. However, there is significant melting even before the plume head reaches the surface, due to the pressure the rising plume exerts on the mantle above.

Thanks for your time & attention!