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How thermochemical piles initiate plumes at their edges

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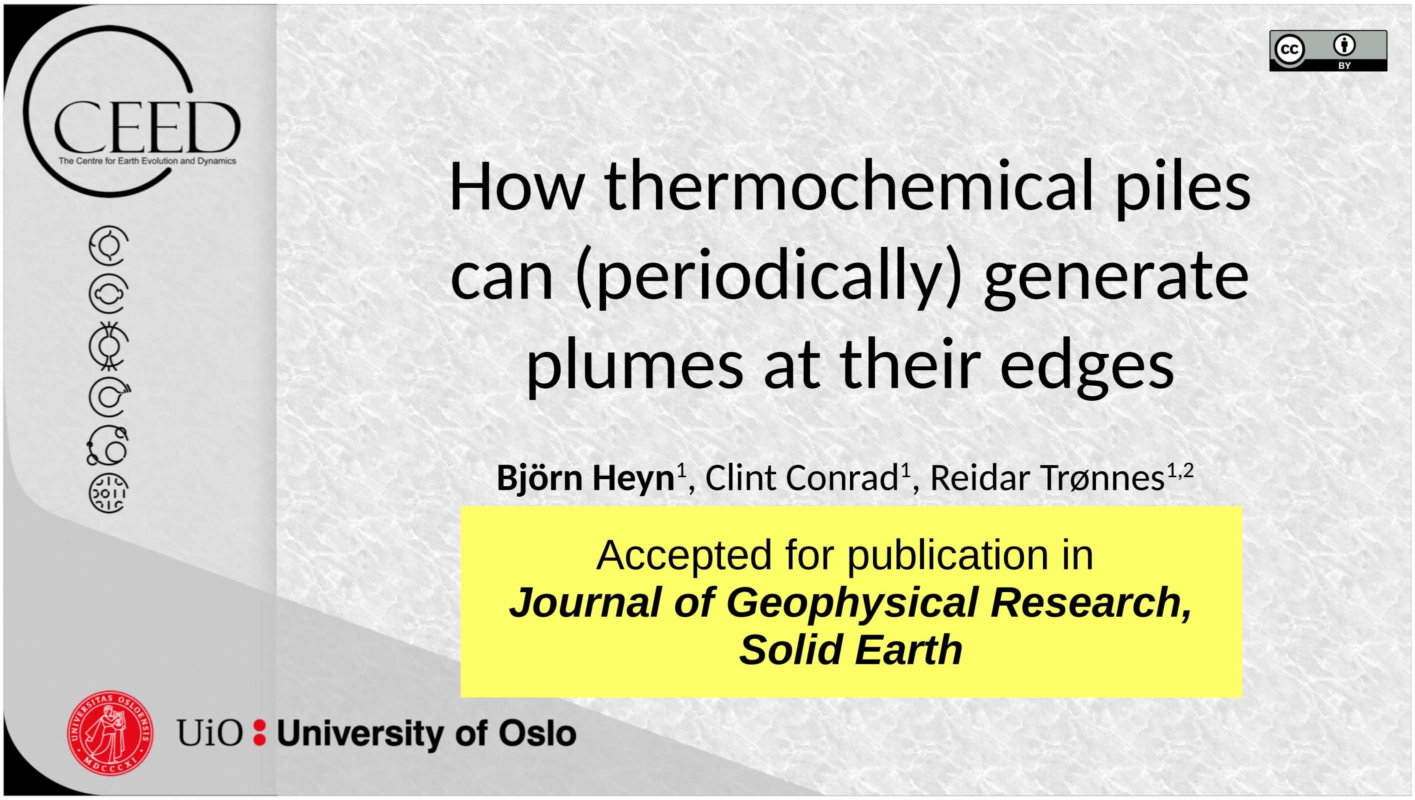
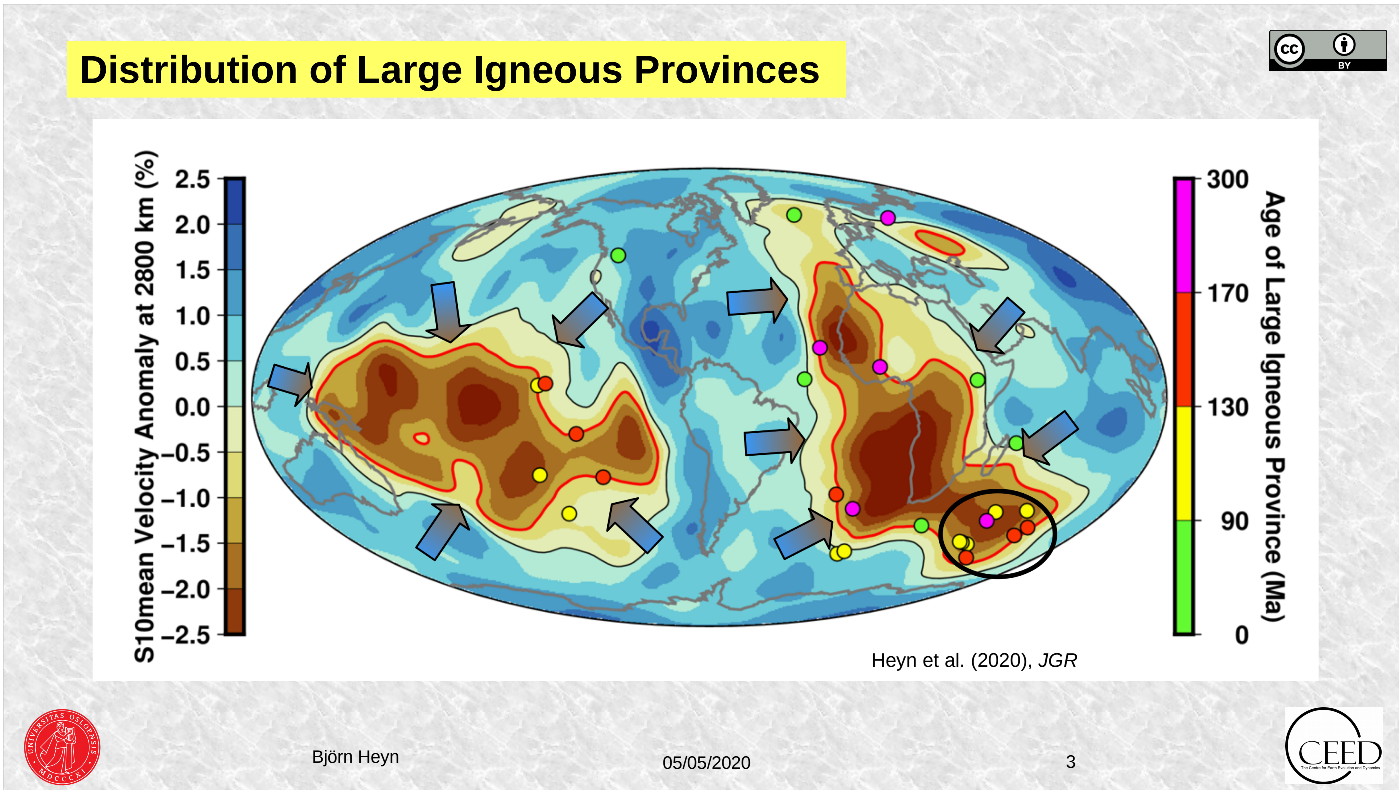
Key points:

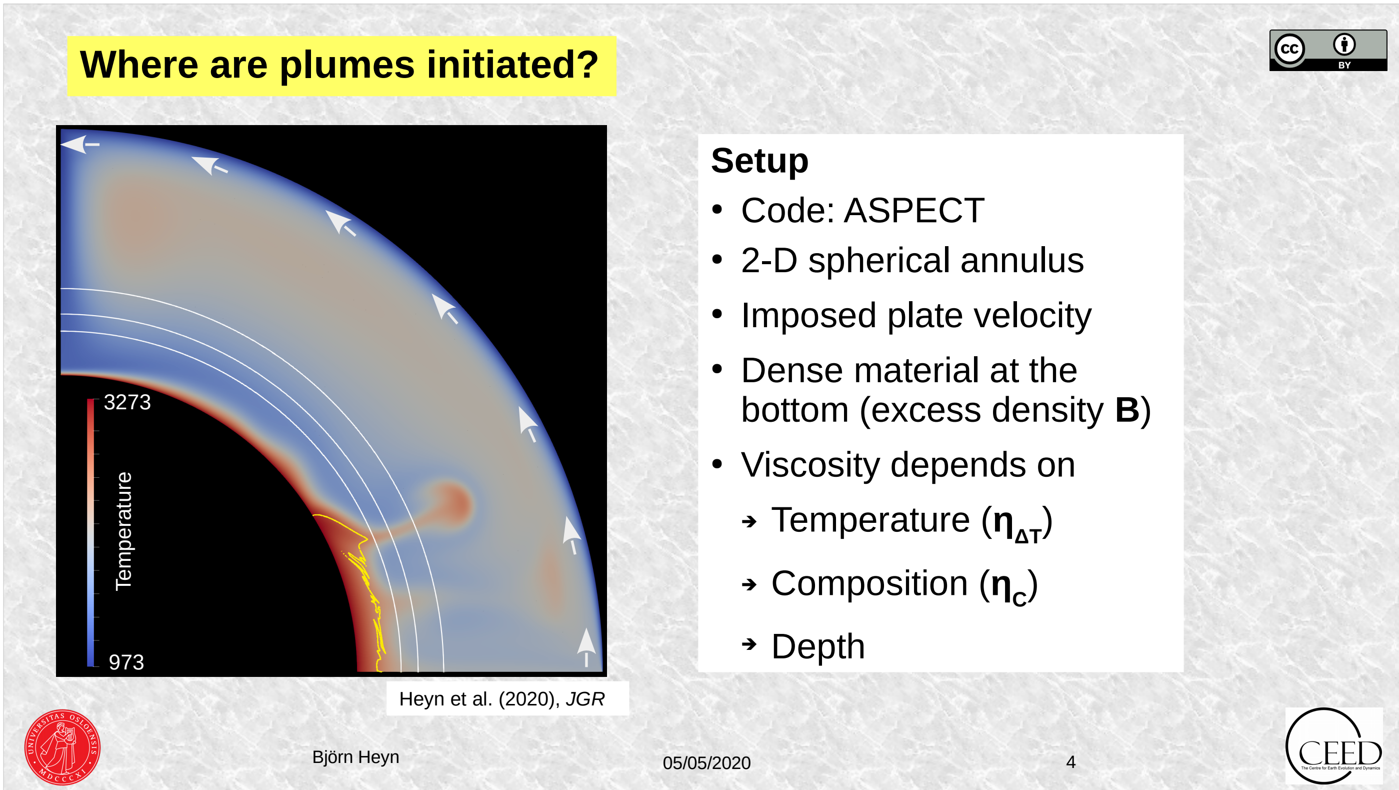
- Plumes can be periodically generated at the margins of thermochemical piles by local pile collapse
- Variations in pile thickness and lateral motion of the pile edge reflect cycles of plume initiation
- The period of plume cycles is controlled by plate velocity and the sinking rate of slabs



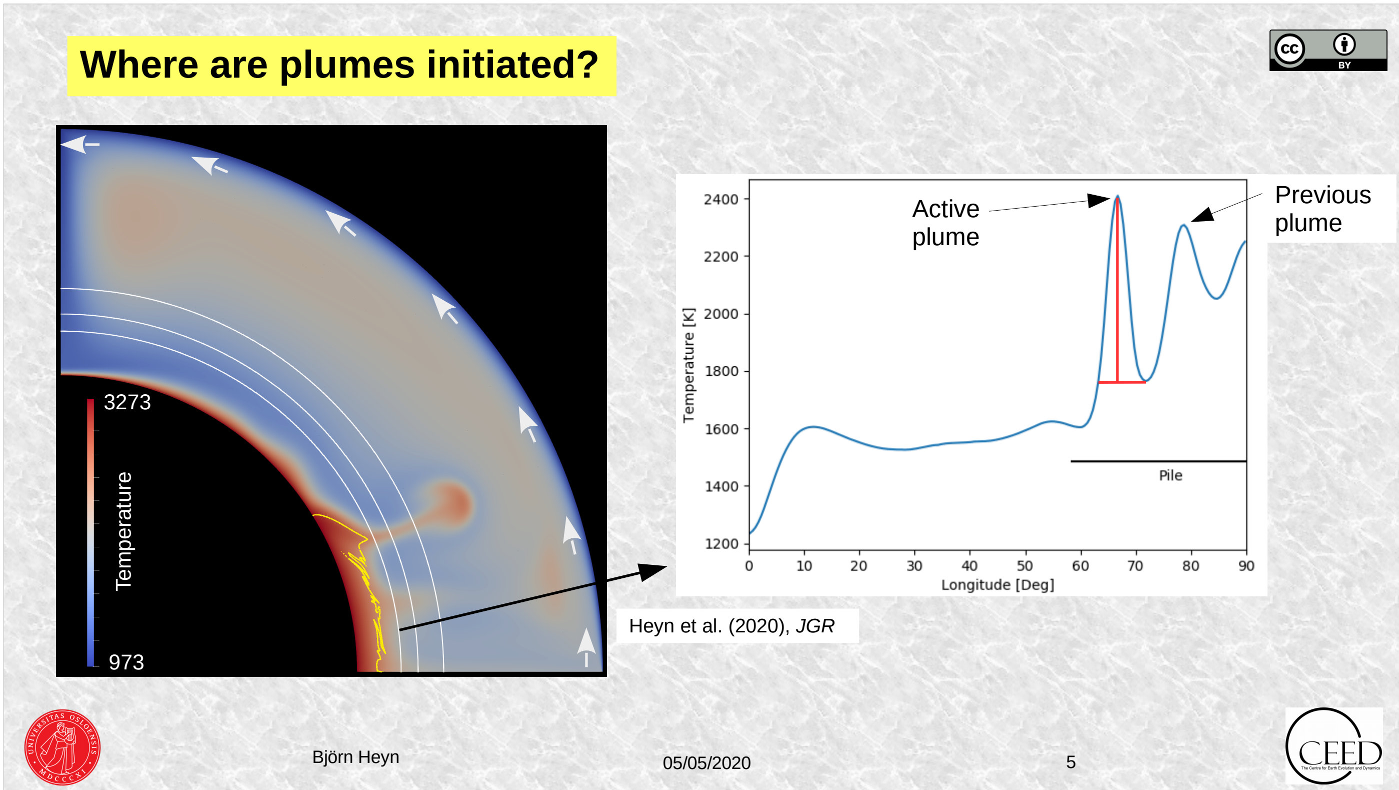
- The work presented here will be published soon in ***JGR Solid Earth*** (Heyn et al., 2020, JGR)



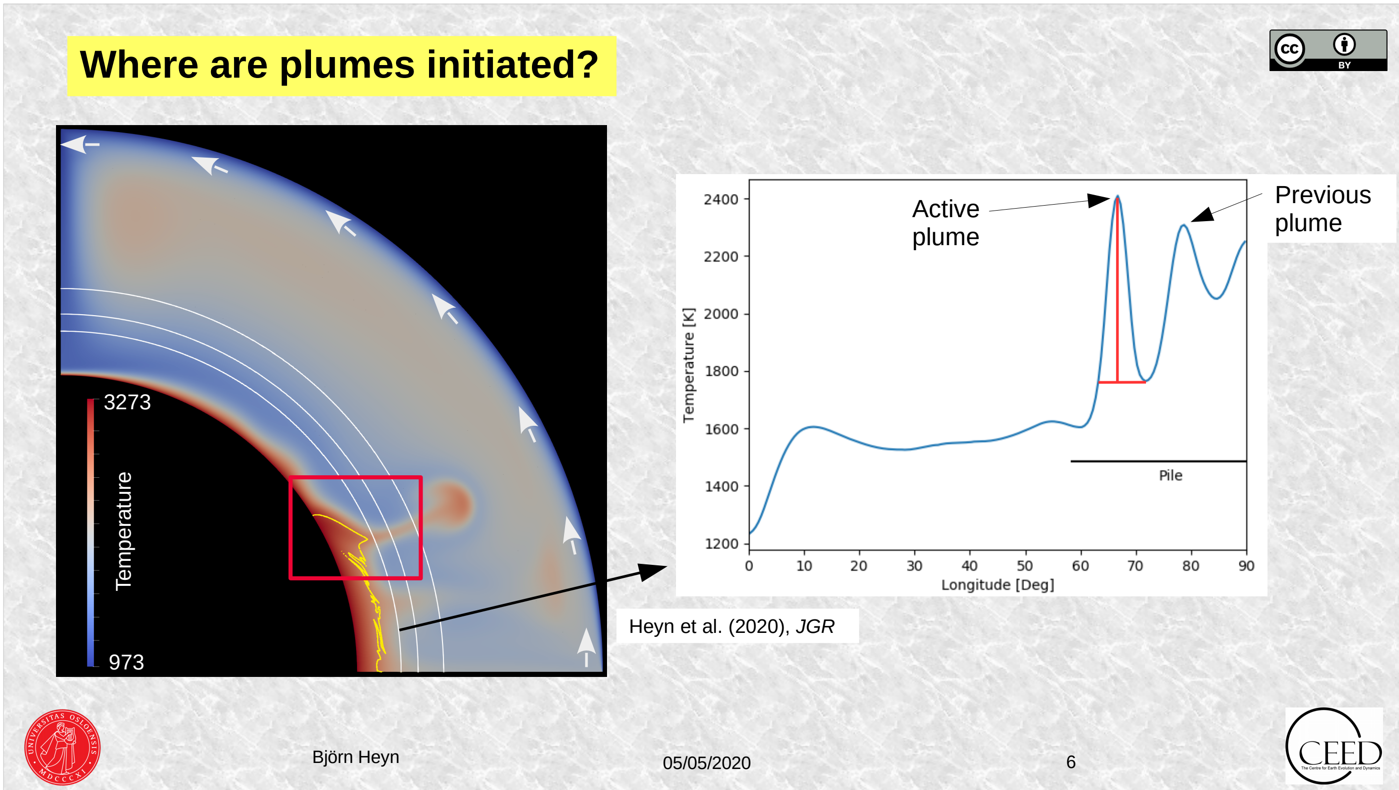
- Reconstructed eruption sites of Large Igneous Provinces (LIPs) correlate with LLSVP, especially with their margins
- Seismic tomography of the lowermost mantle shows a strong degree-2 structure
- This structure has been stable for at least 300 Myr, potentially much longer
- Through the high-viscosity lower mantle, subducted slabs are embedded in cold downwelling mantle flow. A distinct "slab memory" is further erased by strong viscosity reduction due to post-bridgmanite and elevated temperatures in the lowermost mantle.
- Thus, flow in the lowermost mantle is expected to be rather uniform, radially away from the circumpolar subduction belt and towards the LLSVPs (big arrows).



- Our initial condition is a fully developed degree-2 structure with a pile indicated by the yellow outline
- Depth dependence of viscosity is limited to steps for lithosphere, asthenosphere, mantle transition zone and lower mantle (i.e. no depth-dependence within the mentioned layers)
- Surface plate velocity, buoyancy number B, and the thermal and chemical viscosity contrasts $\eta_{\Delta T}$ and η_C are varied systematically
- The compositional viscosity contrast η_C describes the viscosity prefactor for the dense material
- The thermal viscosity contrast $\eta_{\Delta T}$ gives the maximum (theoretical) viscosity variations in the lowermost mantle between material at T=973 K and T=3273 K

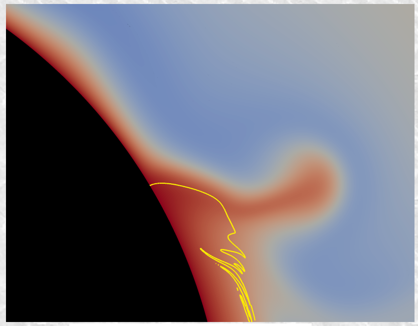


- To investigate plume initiation, we calculate temperature and velocity profiles at specific radii (white lines) of 4000 km, 4200 km and 4500 km, corsresponding to about 519 km, 719 km and 1019 km above the CMB
- Plumes will show up as maxima in these profiles, as indicated by the arrows (the CMB area covered by the pile is indicated the black horizontal line)
- We can measure the excess temperature/ velocity and the width of the plume (indicated by the red lines)



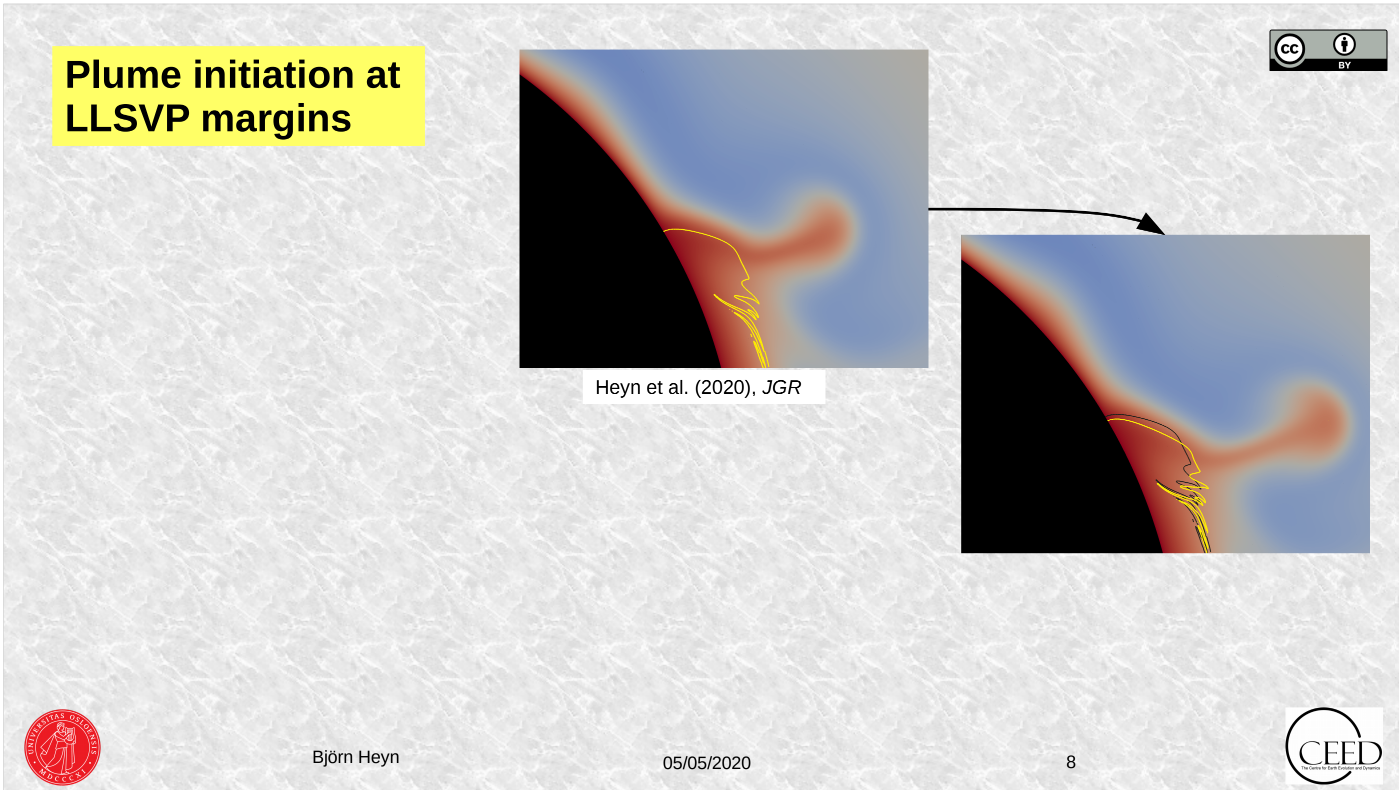
- We are mostly interested in plumes positioned around the pile margin, so we limit our analysis to plumes within the lateral range of 10 degrees outside the pile to 15 degrees inside the pile
- This choice avoids complications of plume detection above the center of the pile, where previous plumes (which are pushed towards the pile center by ambient mantle flow) form a broad upwelling
- Plumes appear in our analysis when they are pushed into the longitude range we investigate, or initiate there, and disappear when they fade away or leave the range
- We track the plume properties (excess temperature or velocity, width) over time and position, and calculate averages for several plumes to even out natural variations in plume properties

Plume initiation at LLSVP margins

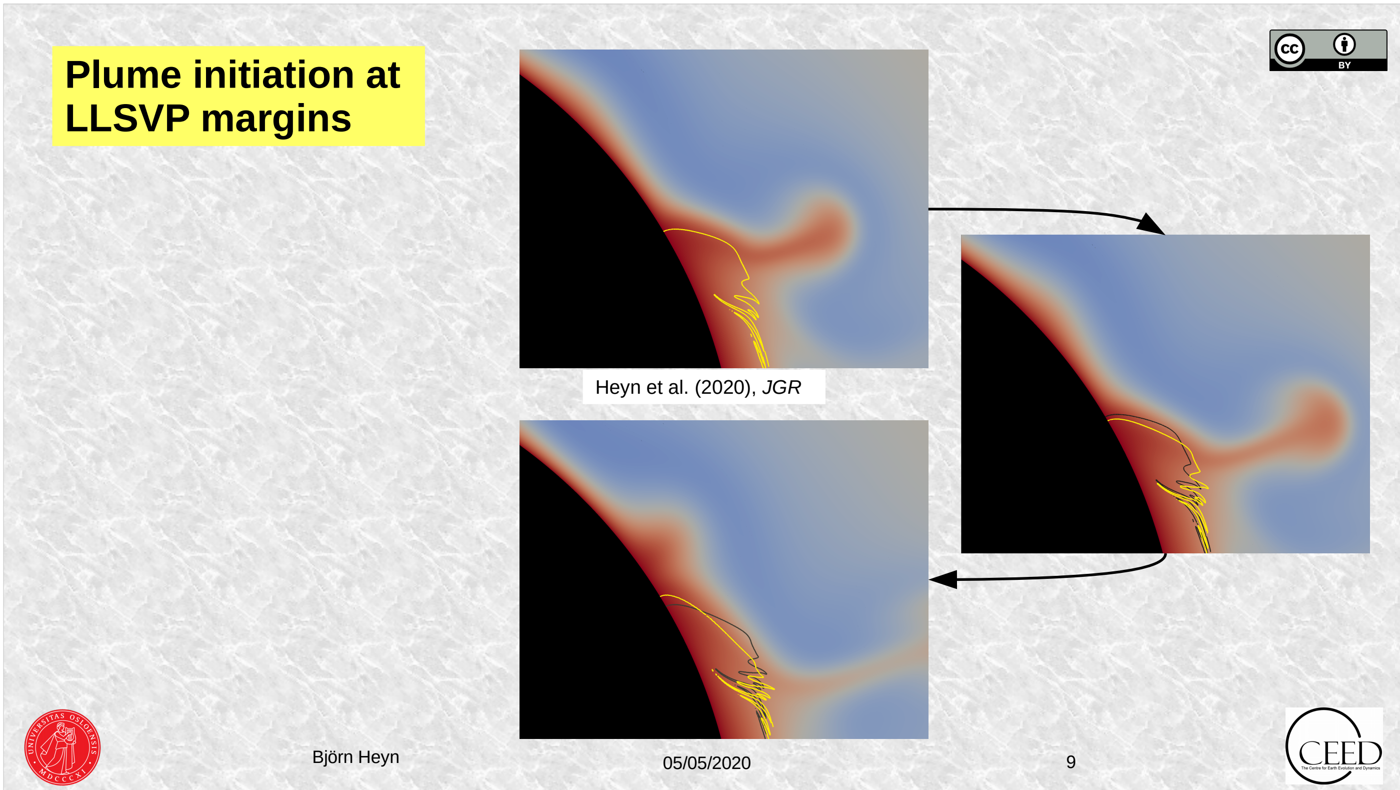


Heyn et al. (2020), *JGR*

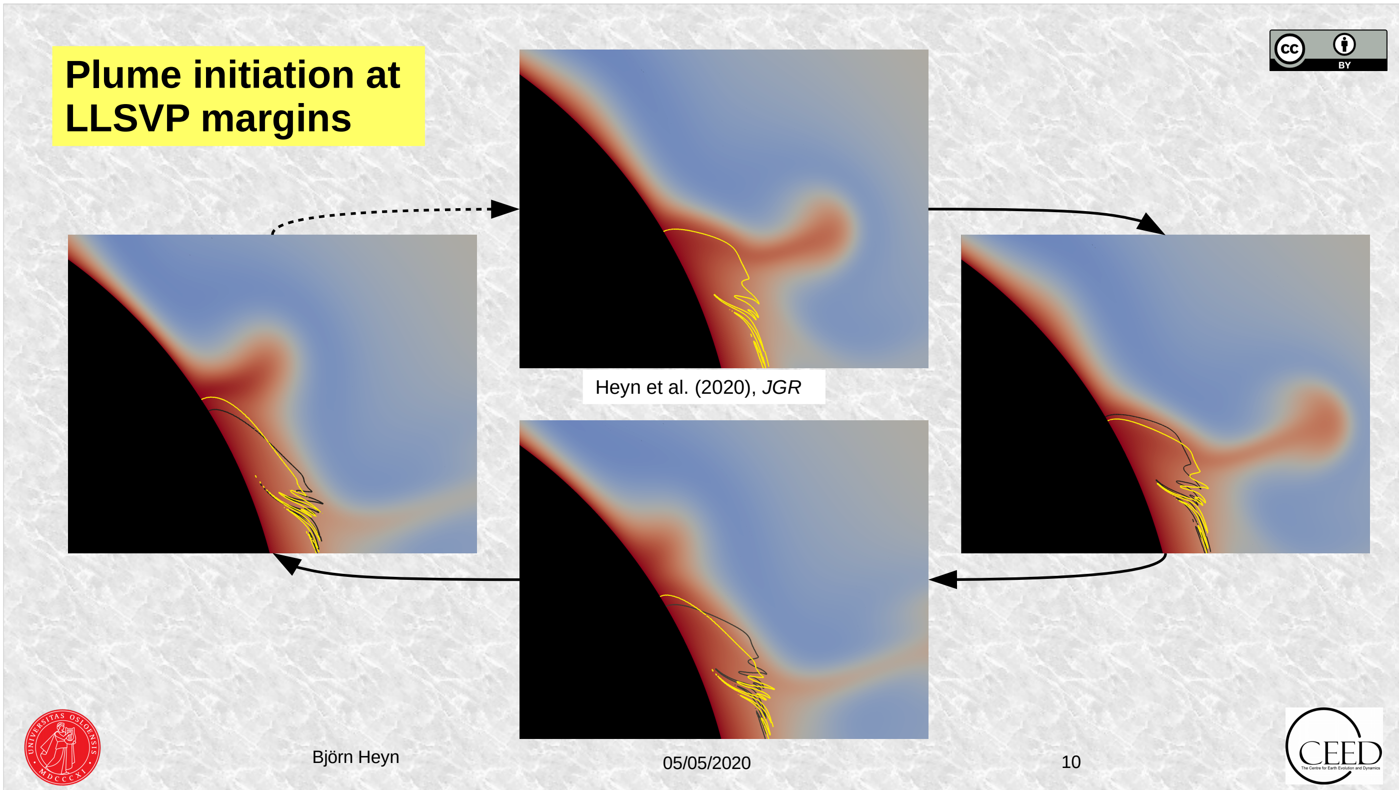
- In our models, most of the plumes are initiated directly at the pile margin
- A plume rising at the pile margin interacts with the pile, pulling some of the dense material upwards and locally thickening the pile margin
- The outline of the pile at the current time step is indicated by the yellow outline, plotted on top of the temperature field



- When the plume moves on, the position of maximum thickness moves towards the pile interior, following the base of the plume
- The gray line indicates the pile outline of the previous snapshot, while the yellow line marks the current pile outline



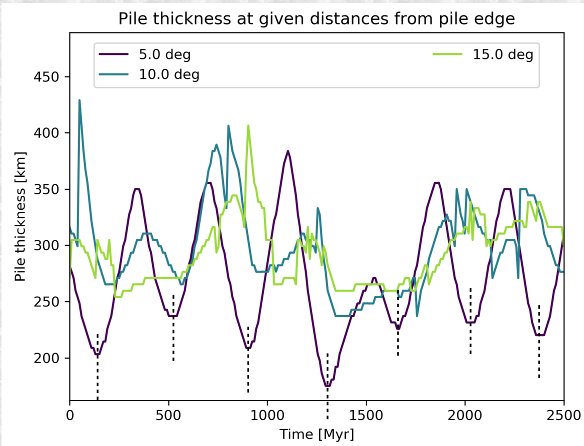
- When the plume is pushed further on top of the thermochemical pile, it loses its connection to the thermal boundary layer (TBL), resulting in a weakening of the plume at the plume root
- Moreover, the rising plume cools down the pile top by extracting heat, locally increasing the density of the pile material
- As a consequence, the thickened pile margin becomes gravitationally unstable and starts to collapse



- The collapsing pile edge spreads along the CMB, pushing hot TBL material against the dominant flow direction (towards the pile)
- This causes a local thickening of the TBL, resulting in plume formation
- The next plumes rises, and the whole cycle of plume-pile interaction starts anew
- Plumes forming this way are triggered earlier than they would be based on condcutive growth of the TBL; the pile collapse provides additional thickening of the TBL
- These “early” plumes are solely triggered at the pile margin

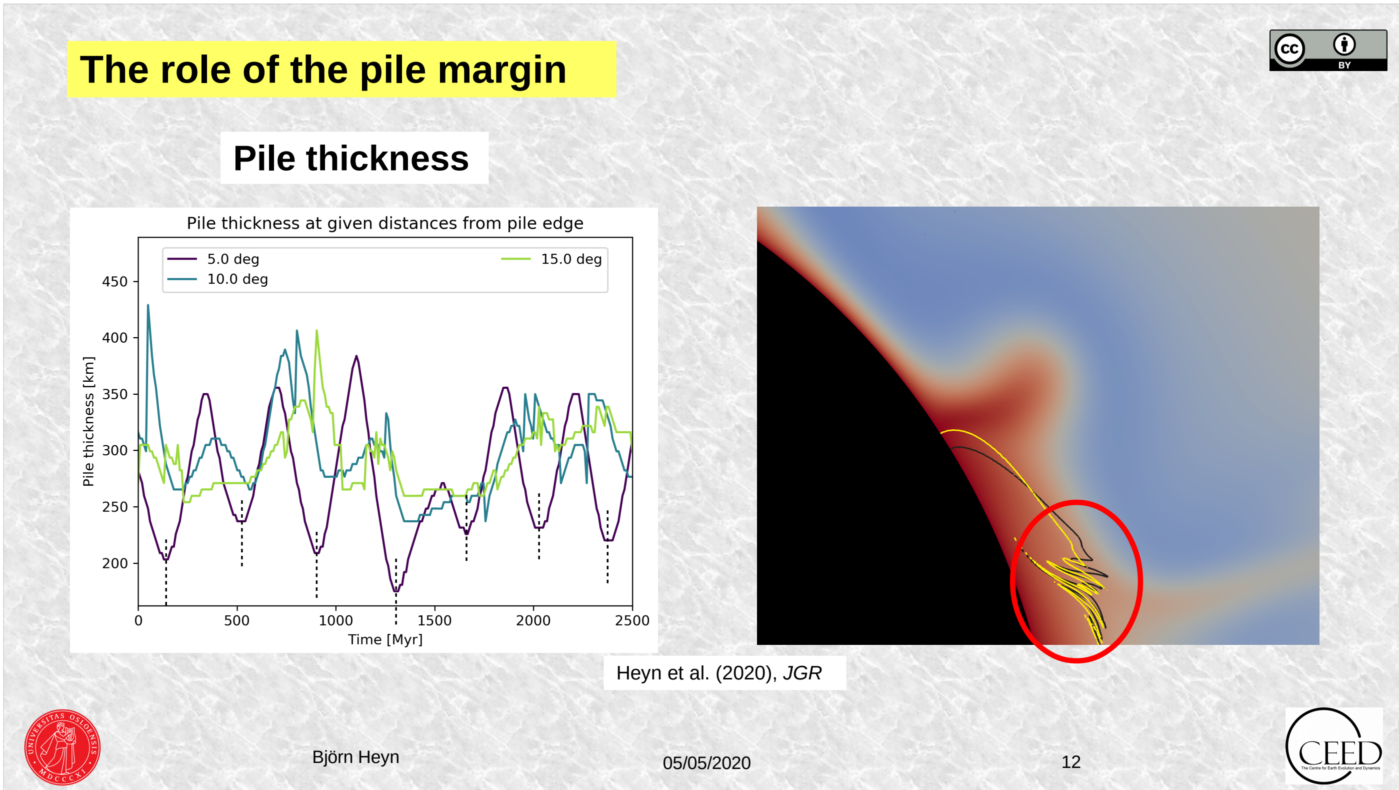
The role of the pile margin

Pile thickness

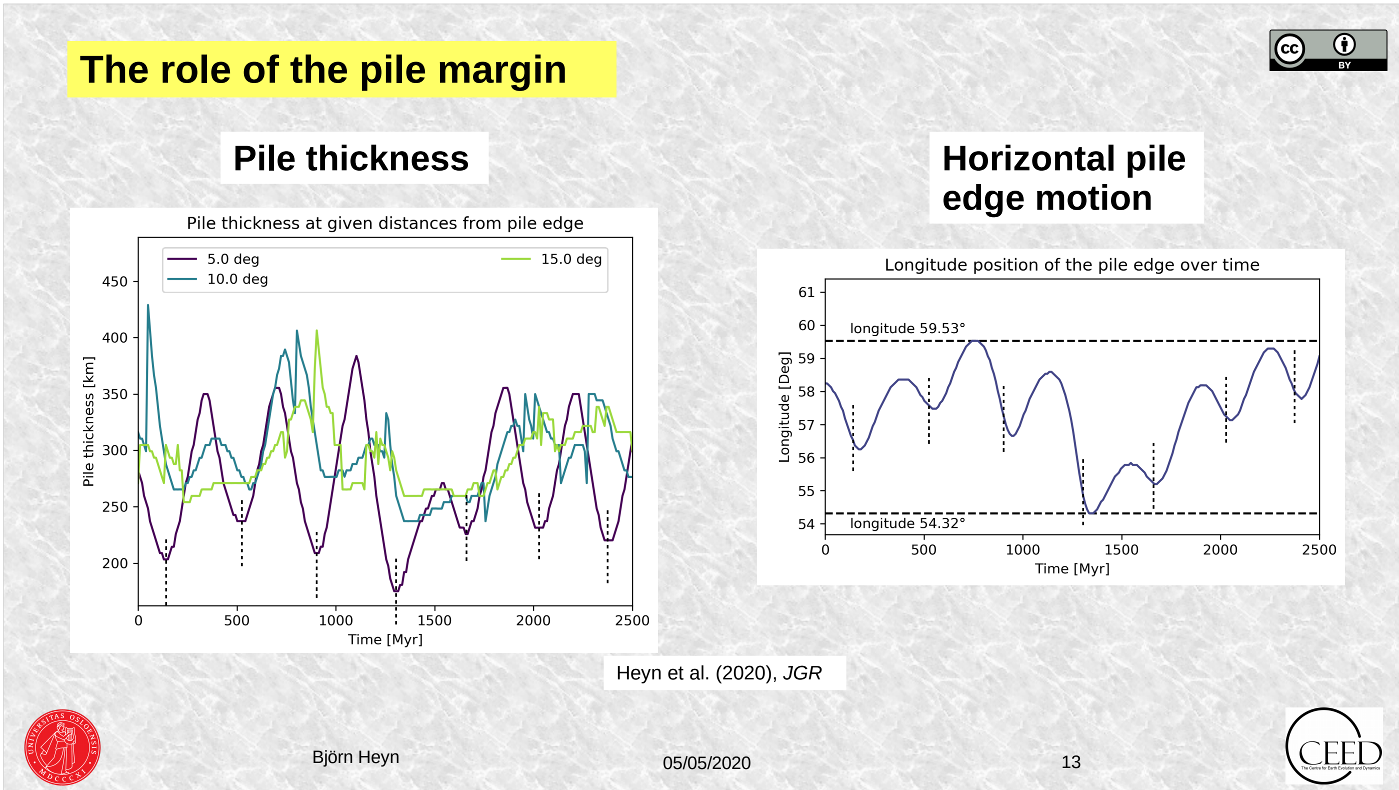


Heyn et al. (2020), *JGR*

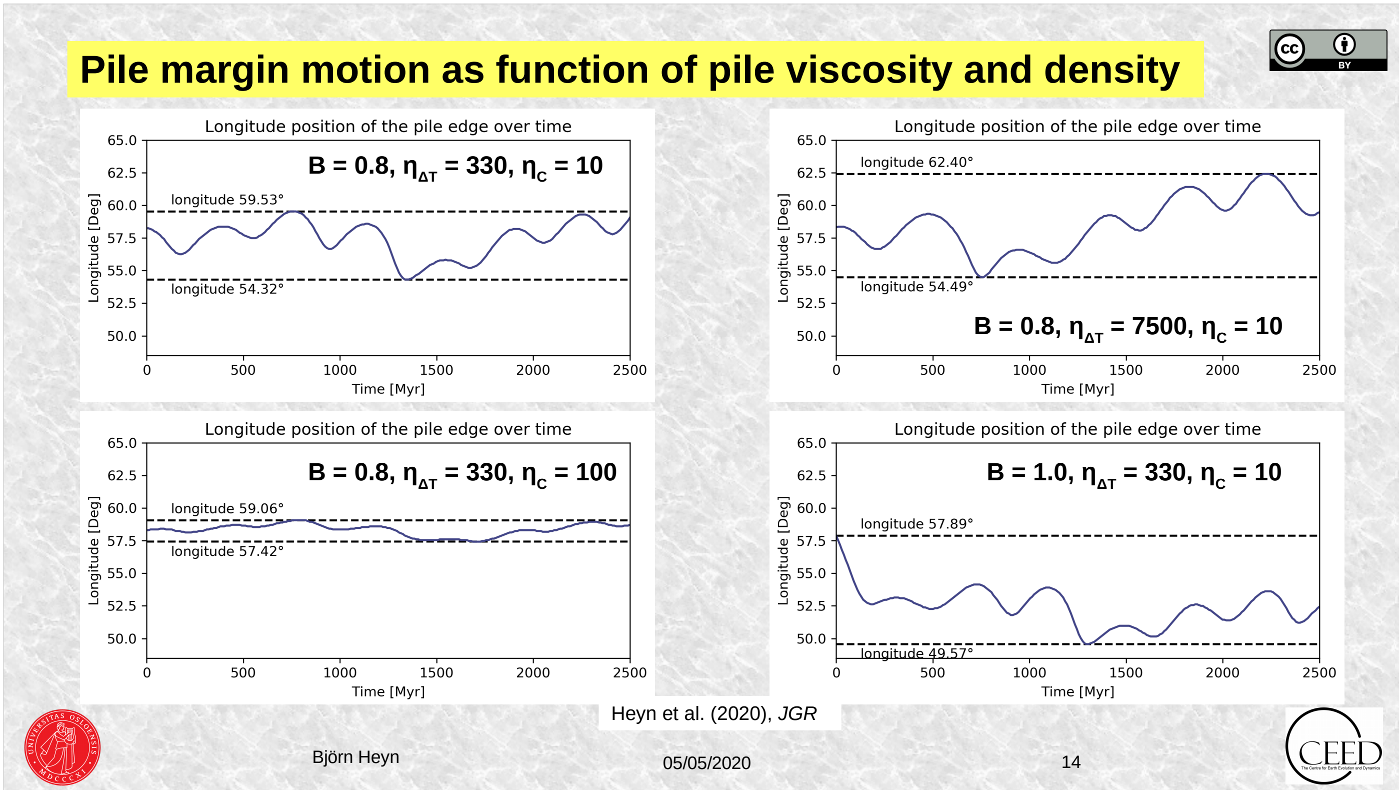
- To investigate the changes in pile morphology, we tracked the thickness of the pile at specific distances from the laterally moving pile edge
- At 5 degrees from the edge, one can clearly see a periodic signal in the thickness
- This periodicity is lost at 10 or 15 degrees distance, indicating that the changes in pile edge thickness are very localized
- When we investigate the thickness of the pile close to the pile center (in our case the domain edge), the pile thickness does not show any sign of the periodicity we see close to the pile margin



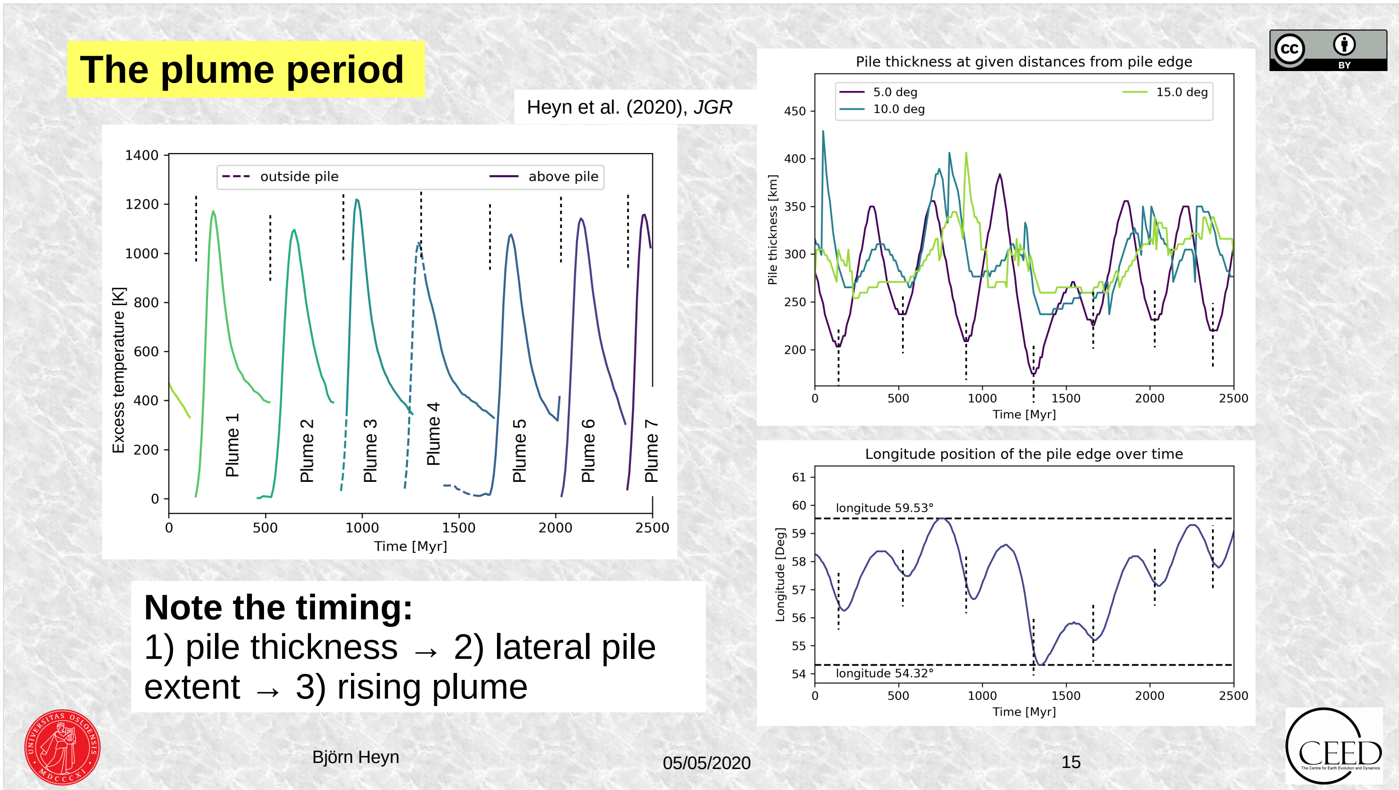
- Changes in pile thickness at 10 and 15 degrees from the pile edge are often quite sharp and abrupt
- This is related to folding of dense material, highlighted by the red circle on the right panel
- Plumes being pushed on top of the pile fold part of the dense material they dragged upwards, causing a ragged top of LLSVPs, and increasing the heterogeneity of piles by mixing ambient mantle into the dense pile
- The ragged structure of the pile top may also explain the absence of seismic observations of LLSVP tops within Earth, since seismic waves would be scattered rather than reflected at this type of structure



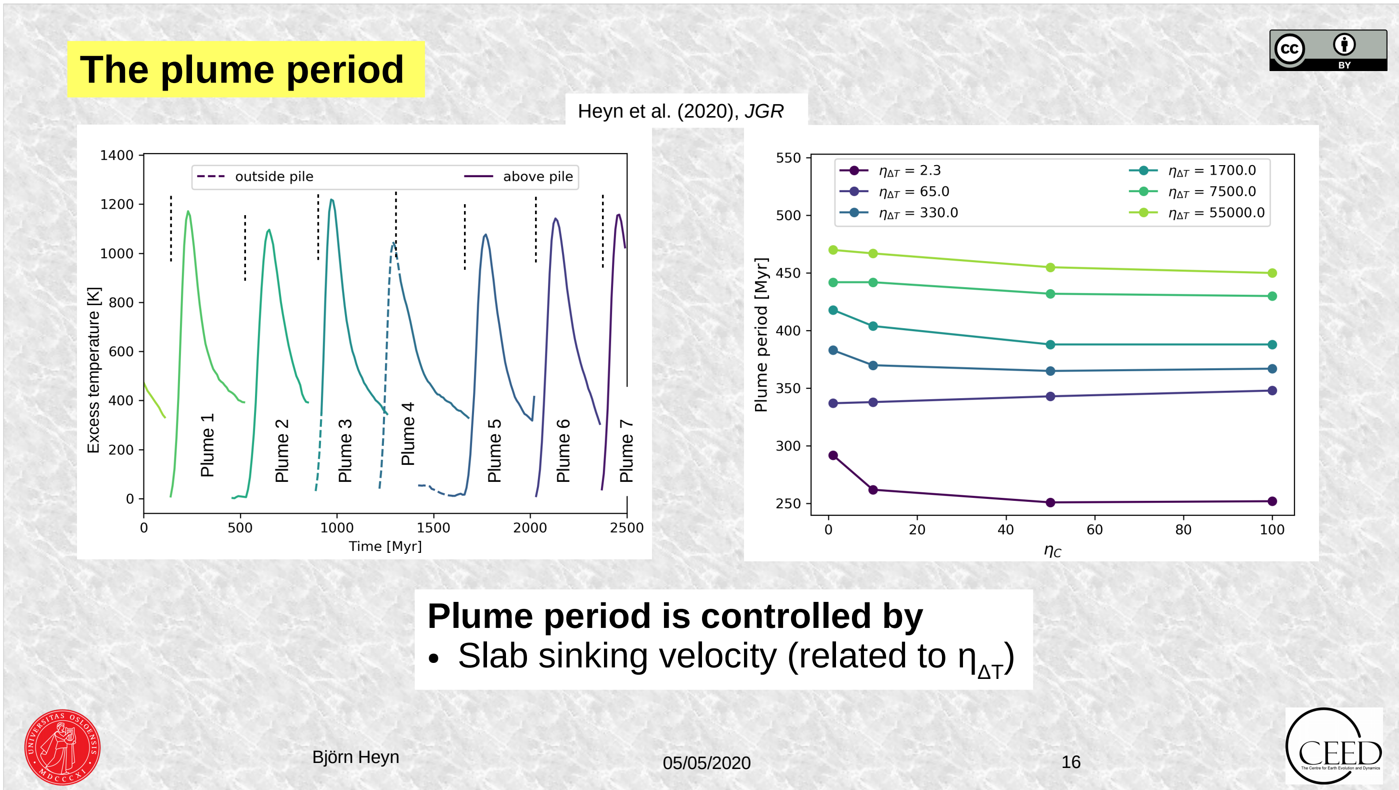
- We also tracked the longitude position of the pile edge, to investigate how the pile edge moves during plume initiation
- As for the pile thickness, one can clearly see a periodicity in pile edge position, varying in a specific range of longitudes
- The dotted lines in the left and right panel give a temporal reference, marking each minimum of pile edge thickness
- As can be seen, the pile edge reaches its minimum ***before*** the the pile has its largest lateral extent (the lowest longitude value)
- Thus, the lateral motion of the pile edge is the response to the changing pile edge thickness



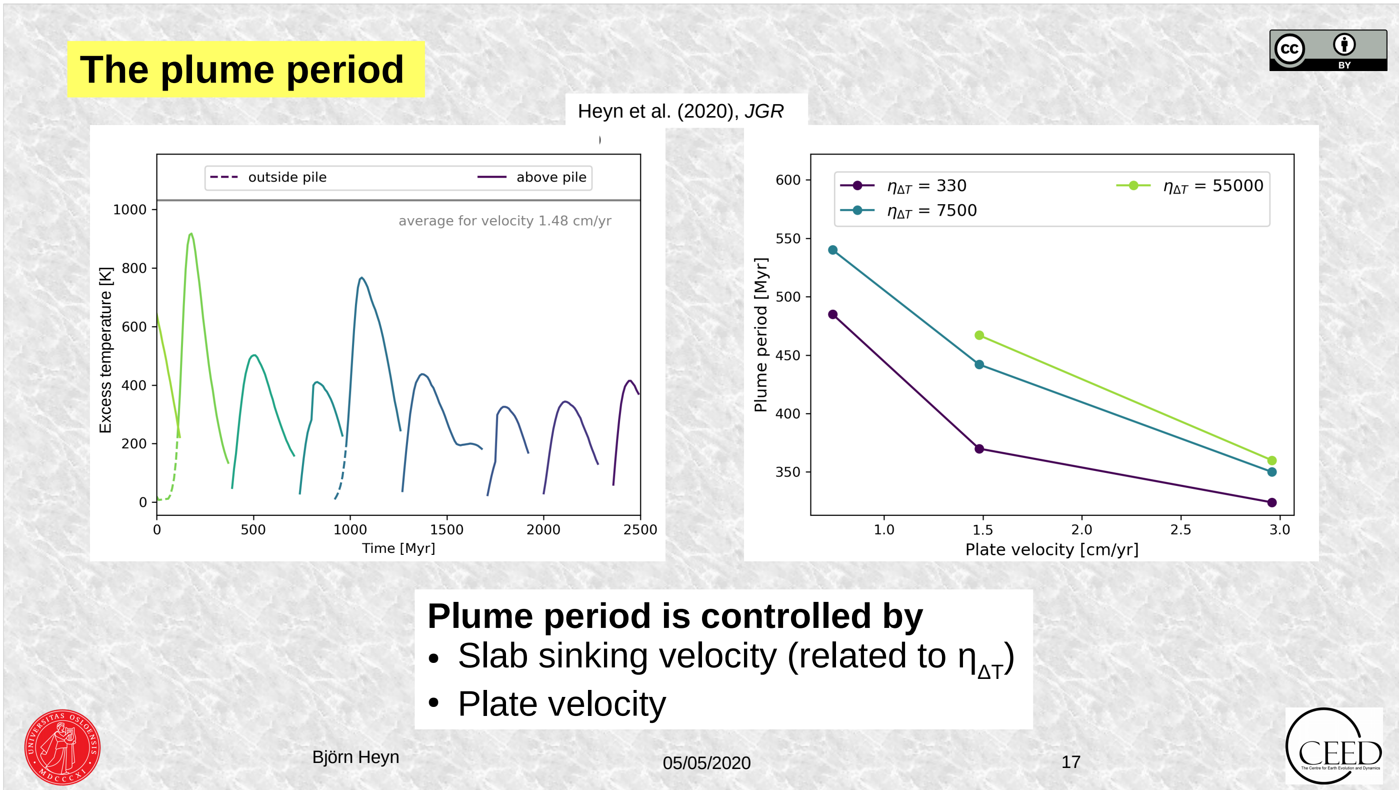
- We can see the same lateral motion (and also the change in pile thickness) for various values of B, $\eta_{\Delta T}$ and η_C
- In every case, the lateral motion is the response of the changing pile thickness
- While the periodicity of the pile edge motion is not changing much with the given parameters (always seven minima, except for the upper right panel with $\eta_{\Delta T}$ = 7500, which has only six minima), the extent of the motion is affected significantly
- A higher density or a higher pile viscosity (lower right and lower left panels) reduce the motion within each plume cycle
- However, we are still able to see the periodic signal even for η_C =10.000



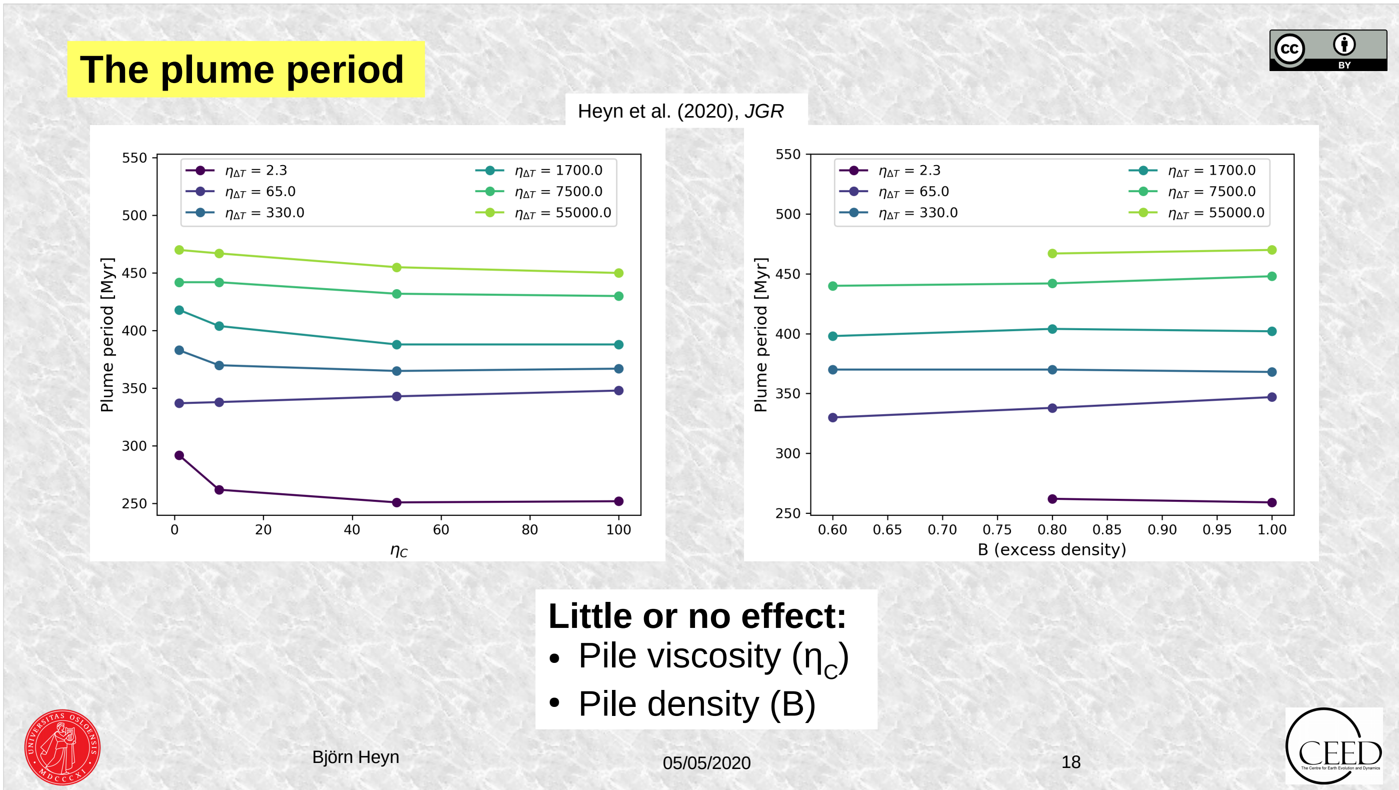
- If we then have a look at the detected plumes, we can see the same periodicity as for the pile edge thickness and motion
- Again, the dotted line indicates the timing of the minima in the pile thickness
- As can be seen, plumes are always delayed compared to the pile edge motion and thickness, indicating that they are indeed triggered by the pile collapse
- The only exception is plume 4, which already starts to rise at a distance from the pile margin. This plume is not triggered by the pile collapse, but is a thermal instability of the growing TBL (stippled lines indicate that the plume we detect is not yet above the pile)



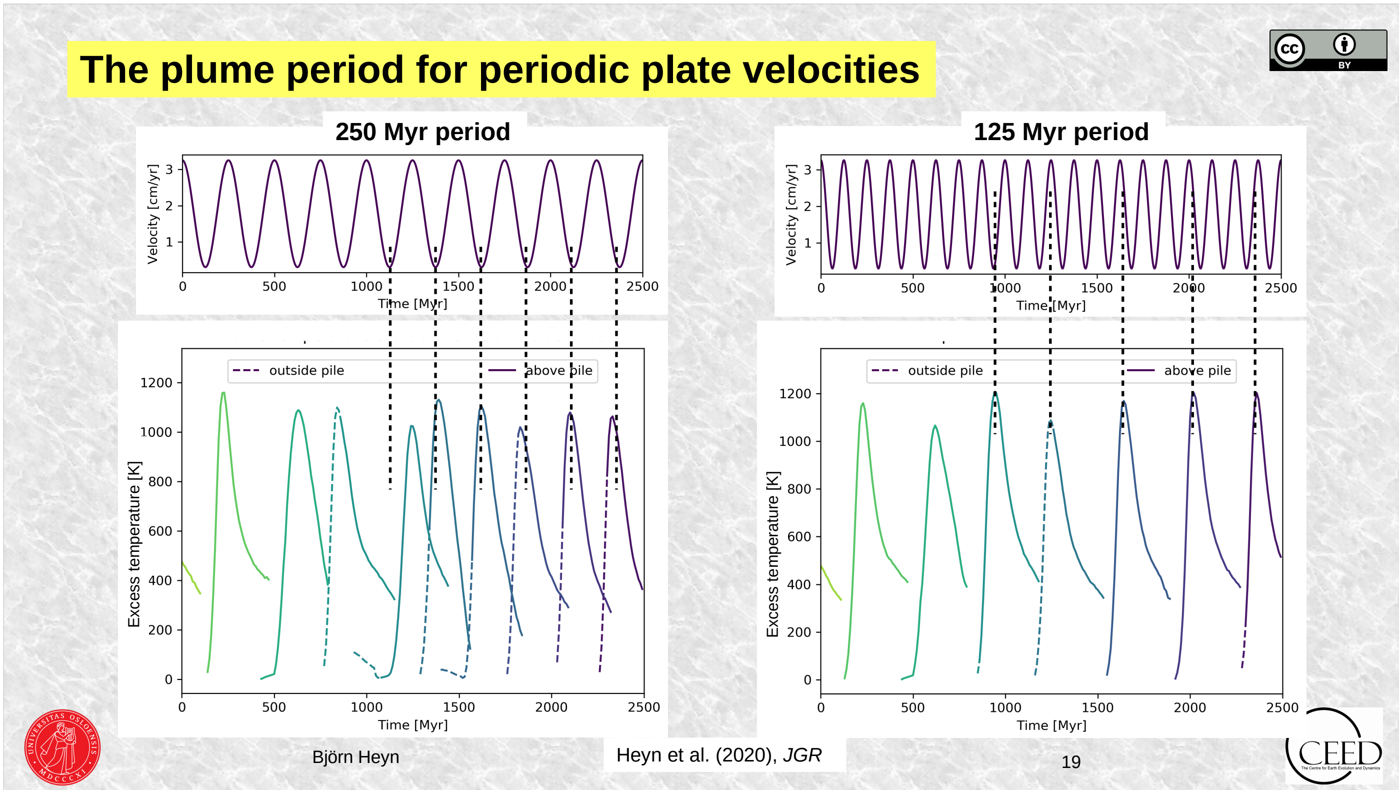
- We then aimed to understand what controls the period of this plume formation process
- We tested a range of values for the parameters buoyancy number B, chemical viscosity contrast η_C, thermal viscosity contrast $\eta_{\Delta T}$, and the imposed surface plate velocity
- For $\eta_{\Delta T}$, the plume period changes significantly. A higher value of $\eta_{\Delta T}$ results in a longer plume period
- This reflects the velocity with which the slab material spreads along the CMB, connected to how fast slabs sink through the lower mantle. A slower sinking rate means less material is brought down to the lowermost mantle, and thus the spreading velocity of cold material decreases
- Slabs sink slower for higher values of $\eta_{\Delta T}$ due to the increased slab viscosity



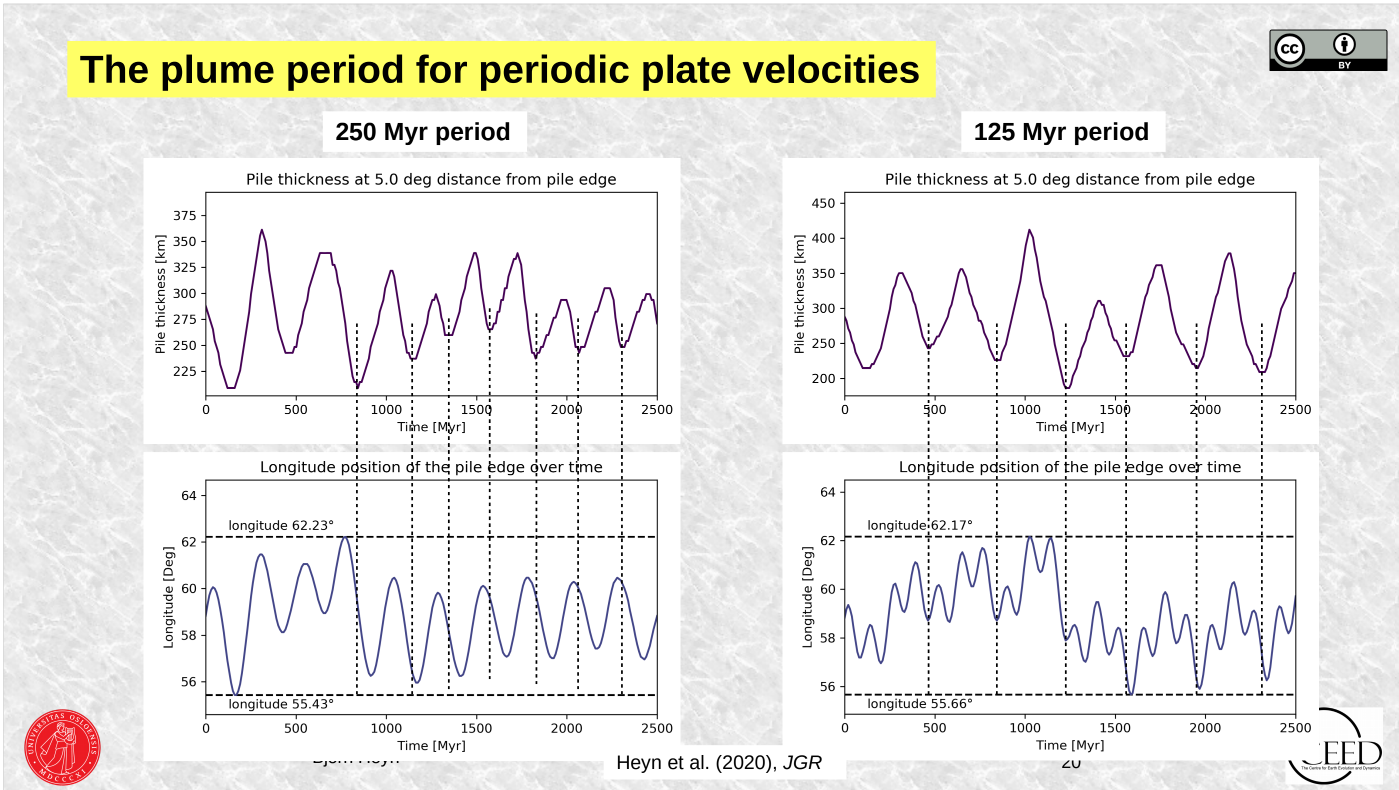
- Another important control is the imposed surface plate velocity, which forces subduction in our models
- The faster we force subduction, the more material is brought down to the lowermost mantle, and the faster the material spreads along the CMB
- This effect can be even stronger than for $\eta_{\Delta T}$



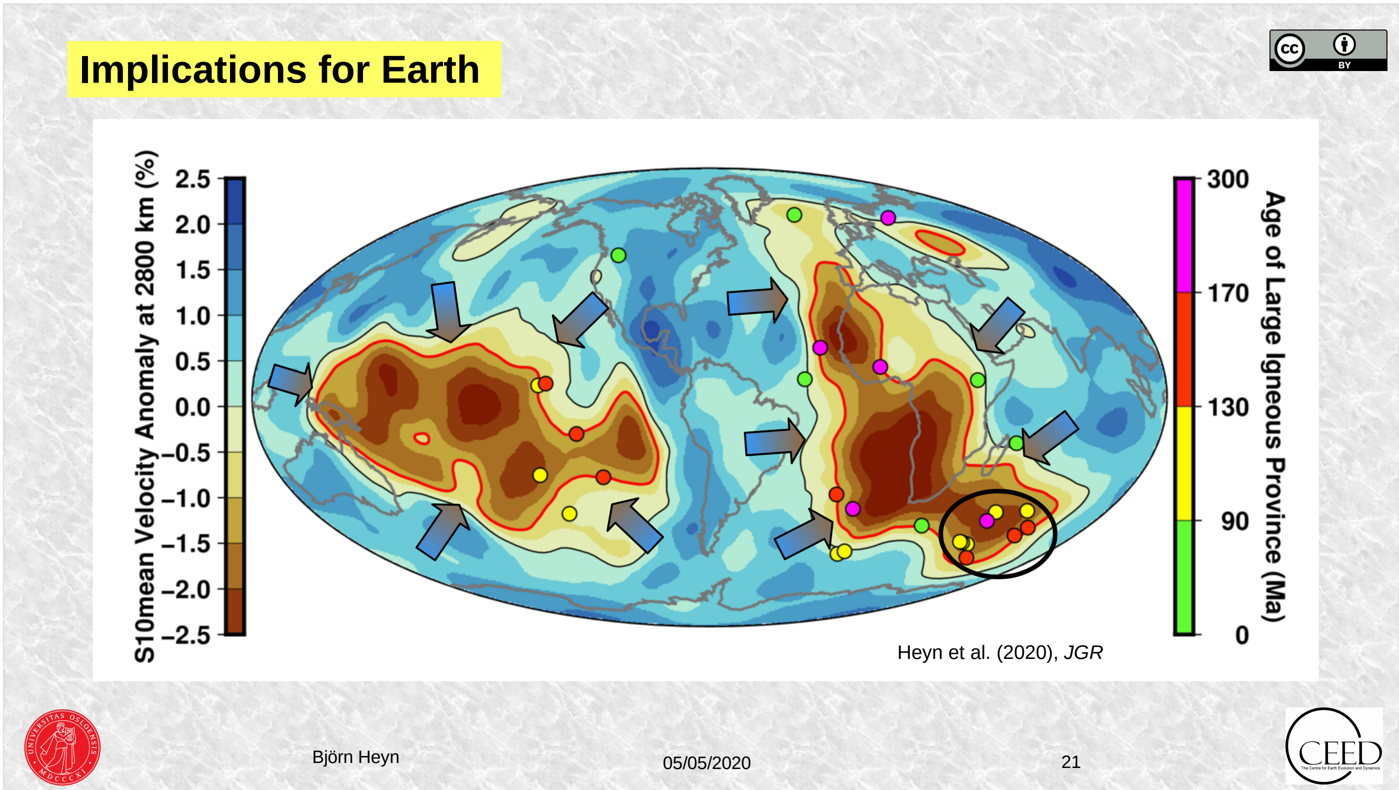
- In contrast, the pile properties B and η_C (x-axis in the right and left panel) have little to no influence on the plume period
- This has also been seen for the pile edge motion (slide 14)
- Missing points in the right panel (and also the right panel of the previous slide) indicate parameter combinations for which plume detection and identification was problematic, causing the average to be very unprecise



- Apart from constant plate velocities, we also tested periodic place velocities, a simplistic model of supercontinent cycles (assuming that the degree-2 structure is maintained, i.e. the position of the subduction zone does not change in our models)
- The plume cycle can adjust to 250 Myr (left panel; plume period for the same model with constant plate velocity would be ~350 Myr), but not to 125 Myr
- The same holds true for longer plate velocity periods of 500 Myr (plume period can adjust) and 1 Gyr (plume period cannot adjust)
- Thus, supercontinent cycles can excite plume initiation within a certain resonance range around the “natural” period of the slab-pile system



- For 250 Myr plate velocity period (left panels), both the pile edge thickness (top) and the lateral motion of the pile edge (bottom) reflect the plume period (i.e. the 250 Myr period)
- For 125 Myr plate velocity period, the pile edge thickness shows a period of ~350 Myr (as for the plume cycle), and only the lateral pile edge position reflects the shorter periodicity (superimposed on the long-wavelength variations of the plume cycle)
- The central period of the resonance range (and thus also the upper and lower limit) shift with $\eta_{\Delta T}$
- Plate velocity periods shorter than the resonance range are damped in the plume initiation process
- Plate velocity periods larger than the resonance range result in thermal instabilities from the growing TBL, independent of the pile collapse



- Within Earth, the effect of changes in subduction velocity, positions and duration of subduction zones, plate configuration etc. on large-scale mantle flow will probably be damped within the lowermost mantle (see explanation for slide 3)
- Even though we cannot expect the plume formation in Earth's lowermost mantle to be globally periodic, we may get locally periodic plume initiation for periods of time (also related to the stability of the degree-2 structure of the lowermost mantle)
- The currently available LIP data is insufficient to reconstruct plume periods of 350 Myr or more, since most oceanic crust of that age is subducted
- A local collapse of a pile corner may cause several plumes rising in close proximity with respect to time and space
- The southeastern corner of the African LLSVP shows a LIP cluster of 8 LIPs erupted between 95 and 155 Ma (black circle), potentially related to such a pile corner collapse

Conclusions

- A **rising plume locally increases the thickness** of thermochemical **piles at their margins**
- The **pile margin gravitationally collapses** when plume becomes weaker and/or gets pushed towards pile center
- The collapsing pile margin thickens the thermal boundary layer next to the pile, and **triggers a new plume**

- **Plume initiation can be periodic** for stable lower mantle conditions (e.g. stable degree-2 structure)
- Plume periodicity is **mainly controlled by slab sinking rate and surface plate velocity**
- Periodic plate velocities (i.e. "super-continent cycles") can force plume periodicity within a resonance range

=> Collapsing pile margin may explain LIP clustering