Plume-induced heat flux anomalies and the associated thinning of the continental lithosphere

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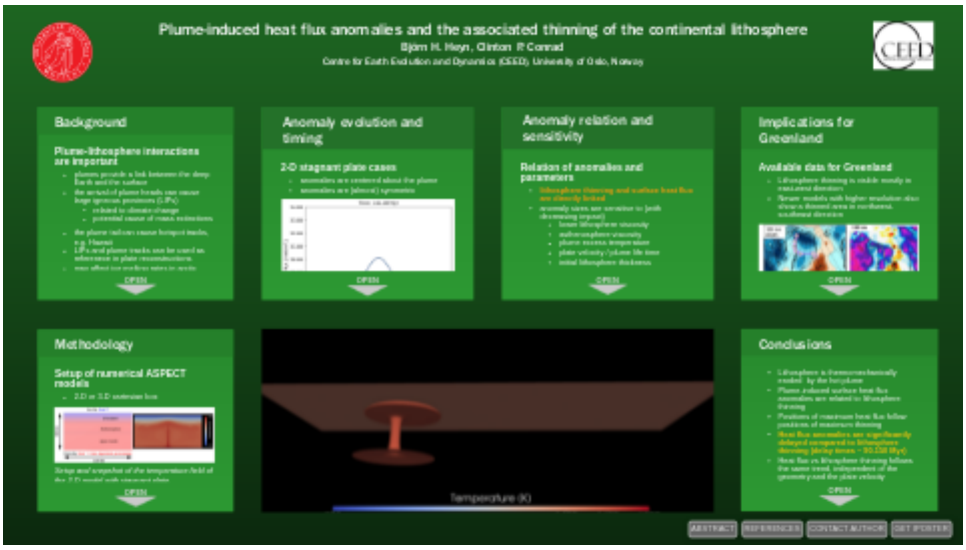
Abstract

While the passage of a plume beneath a thin oceanic lithosphere is usually connected to a hot spot track, and thus can easily be traced back in time, the interaction between a plume and thick continental or cratonic lithosphere is less obvious. Although volcanic eruptions are a common feature for plumes reaching the surface beneath continents, especially in the form of large igneous provinces associated with the arrival of a plume head, it is unlikely that the entire plume track is marked by extrusive volcanism. The thickness of continental lithosphere, and especially cratonic lithosphere, may prohibit the eruption of magma in many places, and can re-focus extrusive volcanism towards places where the lithosphere is thinner or more permeable due to preexisting fault structures. However, even though no magma might be erupted, the passage of a continent over a hot mantle upwelling will be visible in the surface heat flux, even millions of years after the plume passage. In this study, we use numerical models to investigate how a plume passing beneath continental or cratonic lithosphere affects surface heat flux over time, and which parameters of the plume and subsurface structure are the most relevant for determining the size of the respective heat flux anomaly. We show that any kind of surface heat flux anomaly is associated with an erosional thinning of the base of the lithosphere, and greater thinning leads to larger heat flux anomalies. While the maximum of lithosphere thinning is observed at a position and time a few million years after the plate passes over the plume, heat flux anomalies related to conduction continue to increase, reaching a maximum about 80-150 Myr after passage over the plume. In the case of stagnant (stationary) plates, the delays between lithosphere thinning and heat flux anomaly are smaller and the observed anomalies are larger. Amplitudes of both thinning and heat flux anomalies are most sensitive to the viscosity of the asthenosphere and the lower lithosphere, because a lower viscosity facilitates basal erosion and thus increases heat fluxes. Also important are the interaction time between plume and plate, i.e. plate velocity or plume life time, and the plume strength / excess temperature. These results have important implications for understanding plume-lithosphere interactions in polar settings, e.g. Greenland and Antartica, and for various places in Africa, North America and China.

Plume-induced heat flux anomalies and the associated thinning of the continental lithosphere



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BACKGROUND

Plume-lithosphere interactions are important

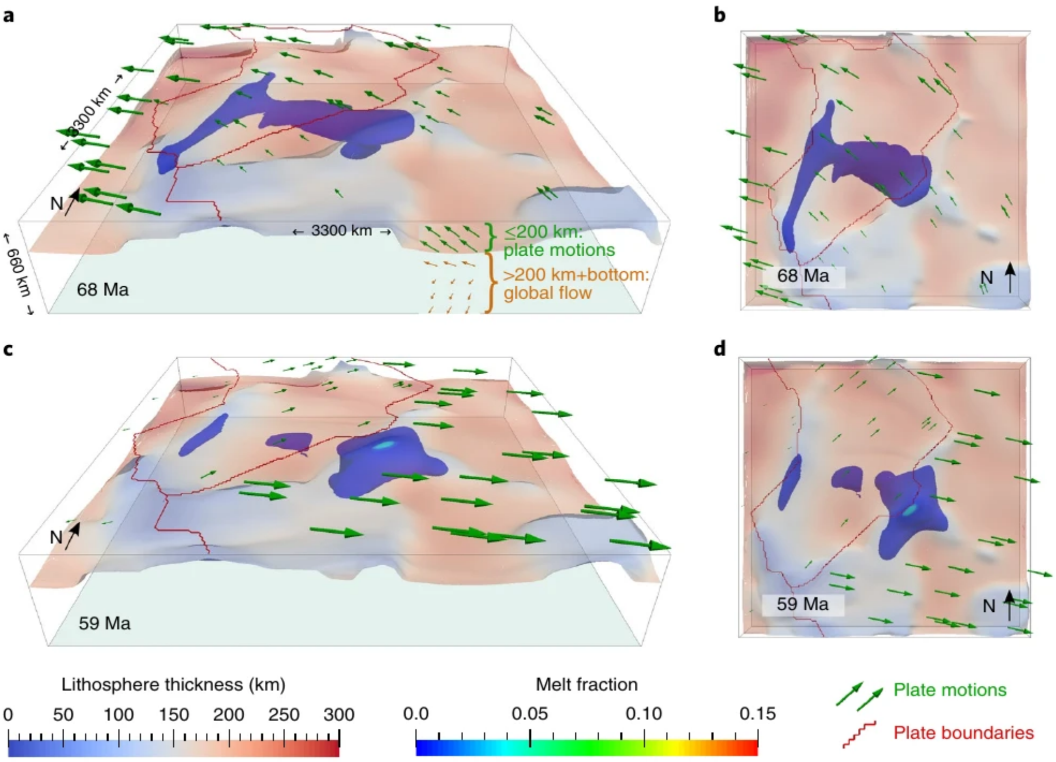
- plumes provide a link between the deep Earth and the surface
- the arrival of plume heads can cause large igneous provinces (LIPs)
  - related to climate change
  - potential cause of mass extinctions
- the plume tail can cause hotspot tracks, e.g. Hawaii
- LIPs and plume tracks can be used as referenece in plate reconstructions
- may affect ice melting rates in arctic settings, e.g. Greenland and Antarctica (Marie Byrd Land)

Most continents experienced plume-lithosphere interaction

- North China craton / China
- Yellowstone / US
- Marie Byrd Land / Antarctica
- Indian Craton / India
- Slave Craton / Canada
- **Tanzania and other places in Africa**
- **Greenland**

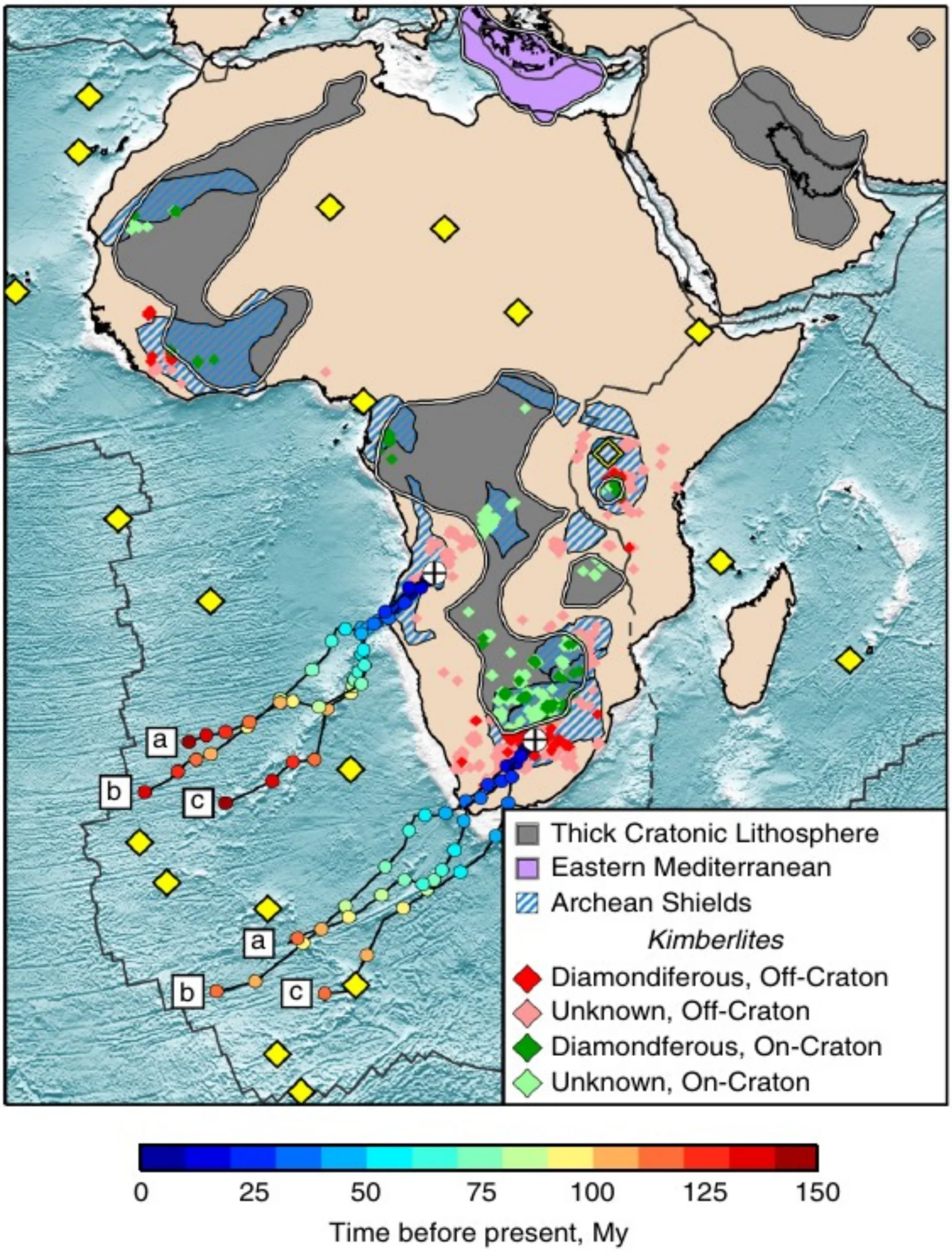
Focus of previous work

- **Volcanism for**
  - Yellowstone
  - Africa
  - Noth China
  - Slave craton
  - Antarctica
  - Greenland
  - ...



Melt distribution for the passage of the Iceland plume beneath Greenland from Steinberger et al. (2019)

- **Lithosphere thinning for**
  - Yellowstone
  - Africa
  - Slave Craton
  - Antarctica
  - Greenland



Cratons (grey) and kimberlite eruptions indicating thick cratonic lithosphere at the time of emplacement from Celli et al. (2020). Hotspot tracks are shown as connected dots with age as color scale. Kimberlites above a non-cratonic area indicate loss of cratonic root, thus lithosphere thinning.

- **Dynamic uplift for**
  - Yellowstone
- **Heat flux for**
  - Yellowstone
  - Antartica
  - Greenland

=> We still lack a systematic understanding of the impact of plumes on lithosphere thinning and surface heat flux

ANOMALY EVOLUTION AND TIMING

2-D stagnant plate cases

- anomalies are centered about the plume
- anomalies are (almost) symmetric

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638810480/agu-fm2021/2F-EB-F9-27-BF-C7-A0-30-03-F3-08-A7-F8-33-A3-D0/Video/2Dsimple_Reference_heat_flux_mahzxj.mp4

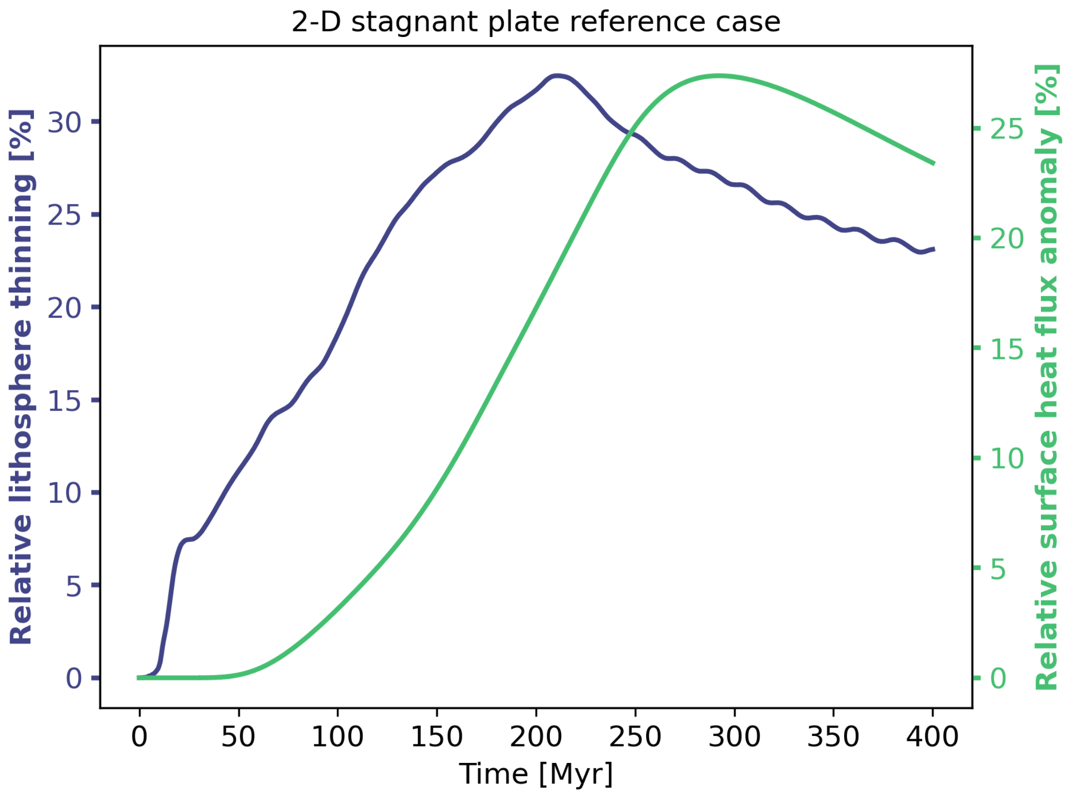
Evolution of the heat flux of our reference case over time. The plume is centered at x=600 km.

- cold lithospheric drips form next to the plume

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638810567/agu-fm2021/2F-EB-F9-27-BF-C7-A0-30-03-F3-08-A7-F8-33-A3-D0/Video/2Dsimple_NoLAB_PlumeTest_Tvideo_gvjidy.mp4

Temperature field of our reference case over time.

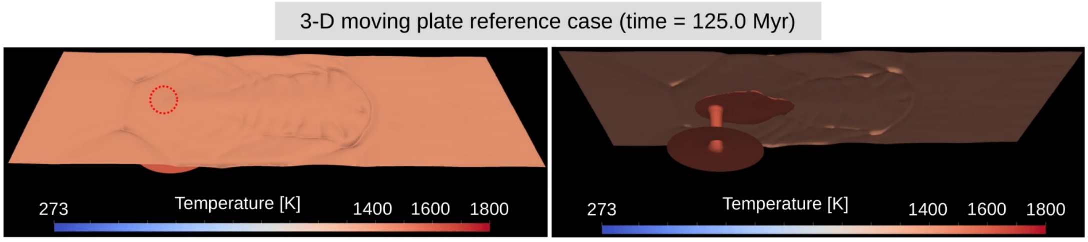
- evolution of surface heat flux is delayed compared to lithosphere thinning
- maximum heat flux observed **after** the plume is faded
- maximum heat flux observed **after** the lithosphere started to heal



Relative lithosphere thinning and relative surface heat flux anomaly versus time.

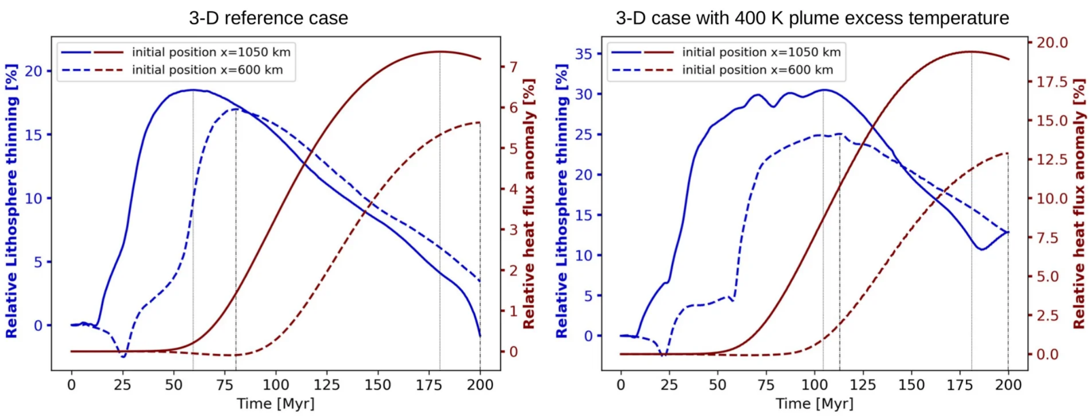
2-D and 3-D moving plate cases

- anomalies are assymetric due to moving plate



1400K and 1600K isotherms from our 3-D reference case. The red circle marks the position of the plume

- maximum lithosphere thinning close to the plume position
- maximum surface heat flux significantly later, and downstream of the plume
- Maximum heat flux follows position /pattern of maximum lithosphere thinning



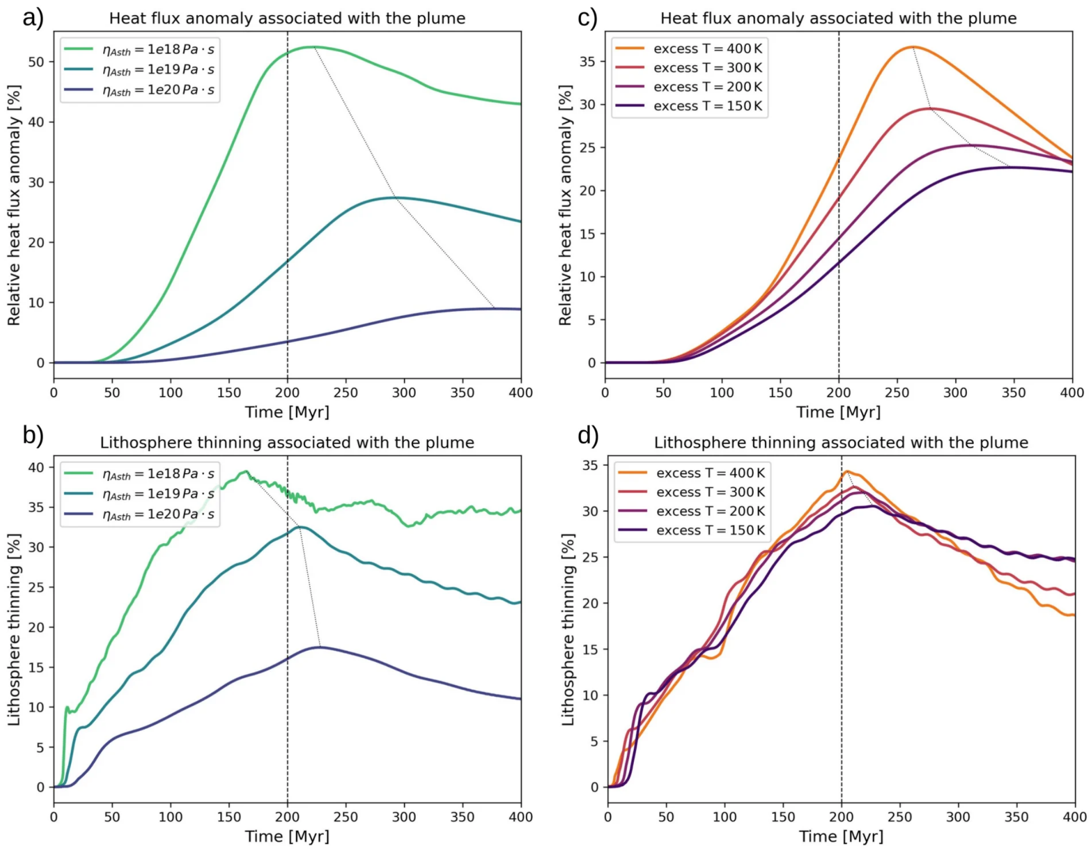
Heat flux and lithosphere thinning vs. time tracked for two positions that move along with the plate.

=> maximum surface heat flux is significantly (~90-150 Myr) delayed compared to lithosphere thinning

ANOMALY RELATION AND SENSITIVITY

Relation of anomalies and parameters

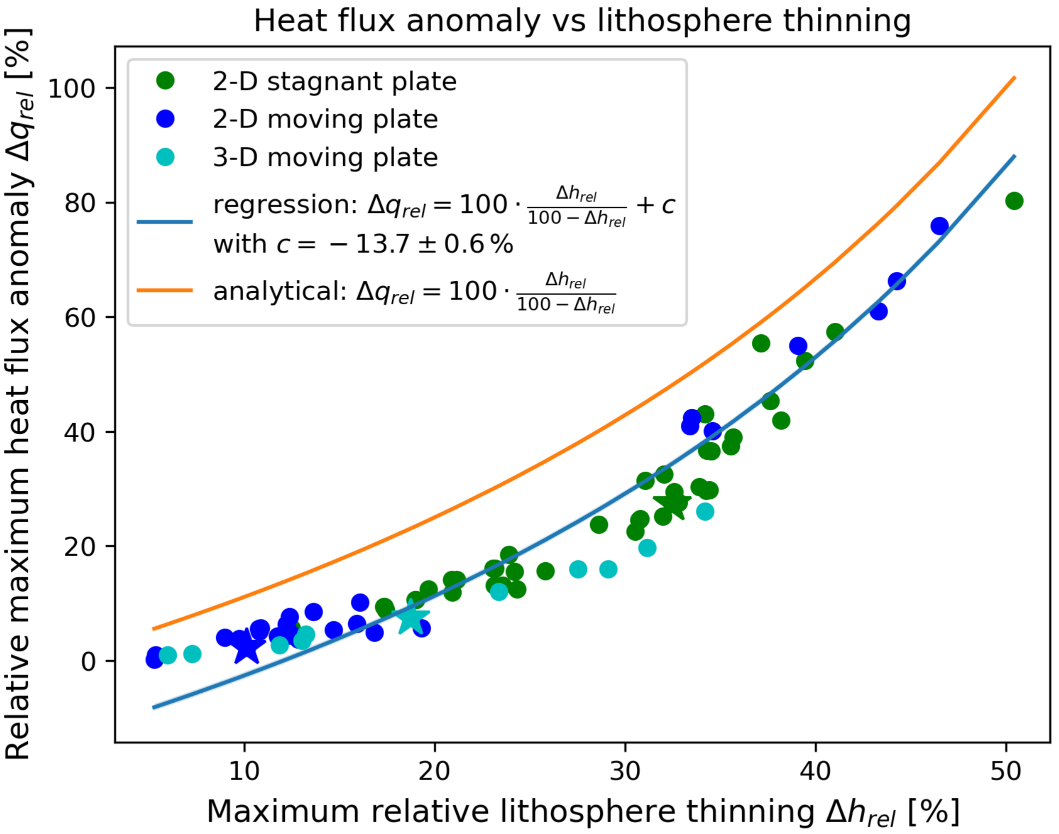
- **lithosphere thinning and surface heat flux are directly linked**
- anomaly sizes are sensitive to (with decreasing impact)
  - lower lithosphere viscosity
  - asthenosphere viscosity
  - plume excess temperature
  - plate velocity / plume life time
  - initial lithosphere thickness



Heat flux (top) and lithosphere thinning (bottom) for models with different asthenosphere viscosity (left) or plume excess temperature (right) for 2-D stagnant plate cases.

- **effect of parameters smaller when plate is moving**

Overview over all models



Heat flux versus lithosphere thinning for all models, together with the analytical solution (orange) and a regression curve (blue).

- all models fall along the same trend, independent of geometry and plate velocity
- **In general, models with moving plate feature smaller anomalies**
- analytical solution describes expected anomaly for stationary model in equilibrium
  - can be derived from heat flux equation

$$\Delta q = q_1 - q_0 = -k \cdot \left(\frac{\Delta T}{L - \Delta h} - \frac{\Delta T}{L} \right)$$

$$\Delta q = k \cdot \left(\frac{\Delta h \cdot \Delta T}{L^2 + L \cdot \Delta h} \right)$$

  - expressed in relative anomalies

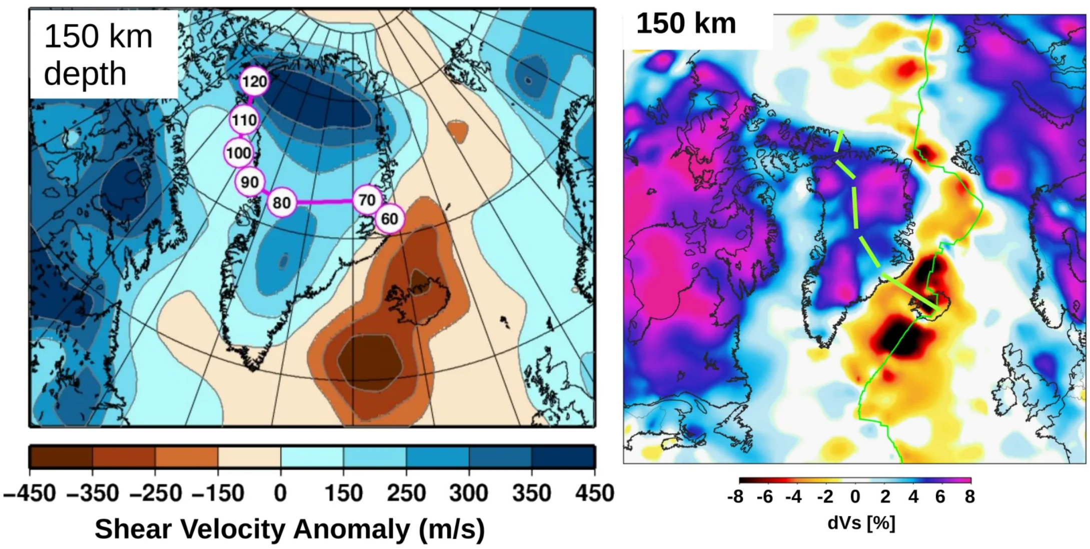
$$\Delta q_{rel} = 100 \cdot \frac{\Delta h_{rel}}{100 - \Delta h_{rel}}$$

- **All models fall below the analyical solution, which gives a maximum heat flux anomaly**
- on average, models result in 13.7% smaller anomalies than the theoretical maximum

IMPLICATIONS FOR GREENLAND

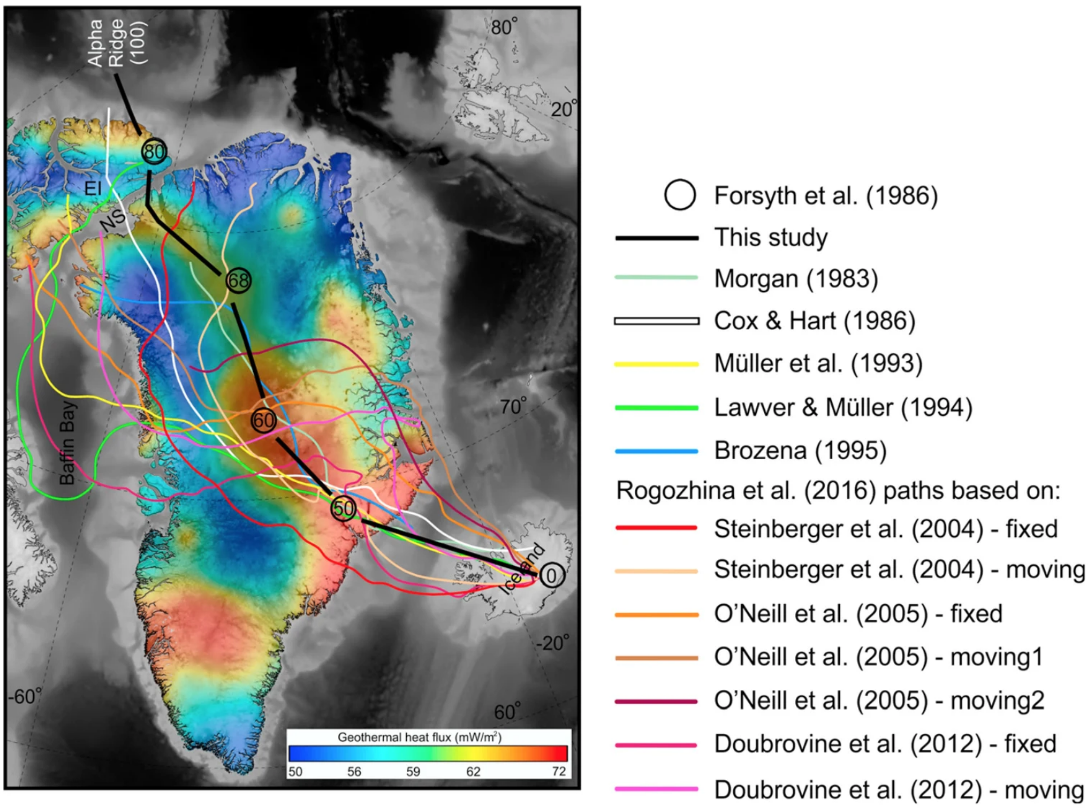
Available data for Greenland

- Lithosphere thinning is visible mostly in east-west direction
- Newer models with higher resolution also show a thinned area in northwest-southeast direction



Left: Seismic tomography of Schaeffer and Lebedev (2013), with the plume track of Doubrovine et al. (2012). Right: tomography of Celli et al. (2021). The thick dashed green line indicates a potential northwest-southeast trend of the plume track, as suggested e.g. by Martos et al. (2018) based on heat flux anomalies.

- Heat flux anomalies have not been well constrained
  - Martos et al. (2018) showed anomaly in northwest-southeast direction
  - Other studies show no clear anomaly

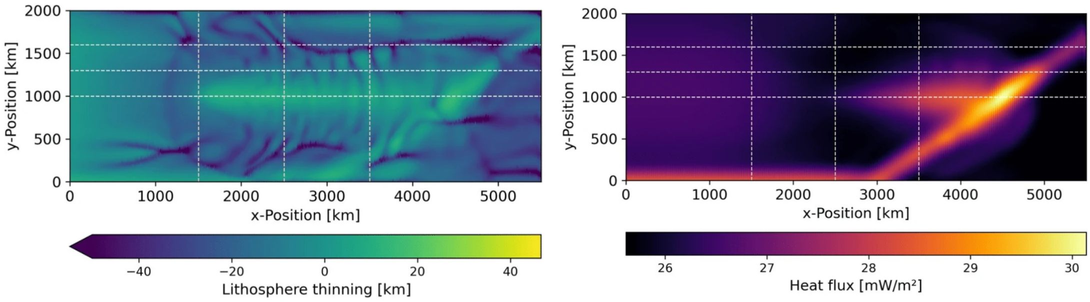


The heat flux anomaly of Martos et al. (2018), including various potential hostspot tracks.

=> heat flux anomaly and lithosphere thinning are not aligned, so are they both from the plume?

Can heat flux and lithosphere thinning from plume deviate in direction?

- If lithosphere has uniform thickness before interacting with the plume, **both anomalies are aligned**
- Initial lithosphere-asthenosphere boundary topography can change this
  - topography parallel to plate motion affects anomaly patterns within to-plume distances of about 500 km
  - initial LAB topography diagonal to plate motion results in non-aligned heat flux and lithosphere thinning anomalies
  - **But**: this effect is temporal, as the thinning along the plume track will be visible as heat flux anomaly later



Lithosphere thinning and surface heat flux for a model with an initial LAB topography in form of a thinned channel diagonal to the plate motion. At the time step shown, the dominant llithosphere thinning anomaly is aligned with the plume track, while the dominant heat flux anomaly still represents the originally thinned channel.

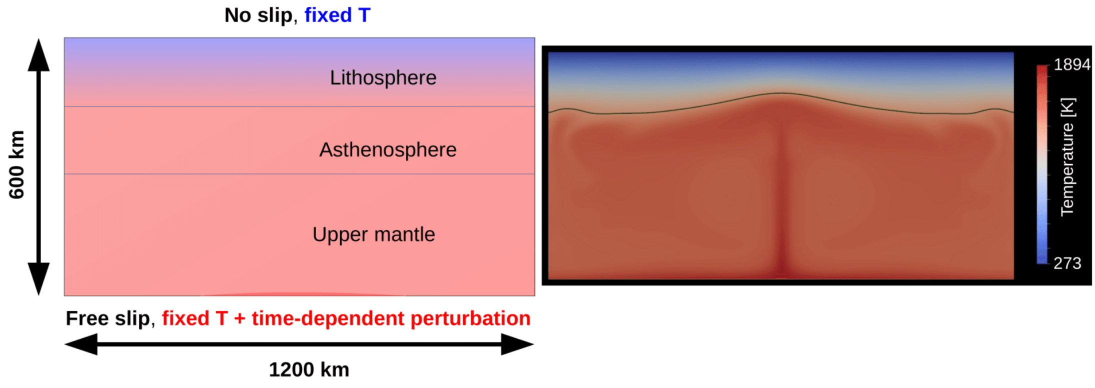
=> Lithosphere thinning and surface heat flux may temporarily not be aligned if there is lithosphere-asthenosphere boundary topography prior to plume-lithosphere interaction

=> For Greenland, an initial LAB topography in northwest-southeast direction and a plume track in west-east direction may be reconciled with observations

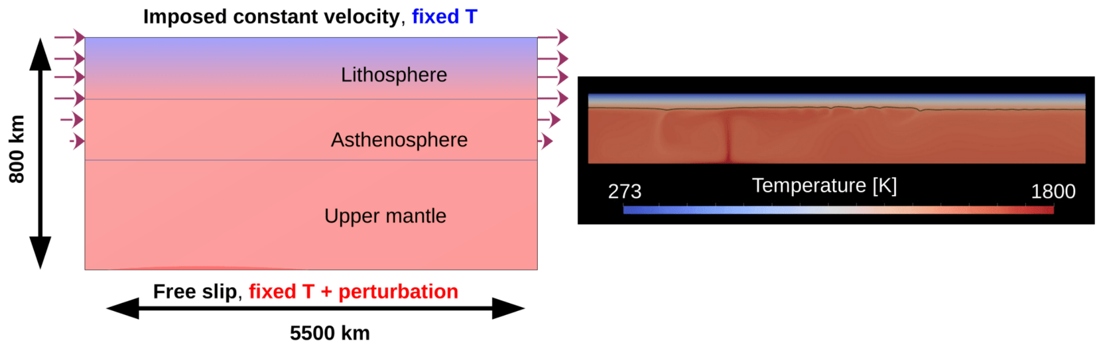
METHODOLOGY

Setup of numerical ASPECT models

- 2-D or 3-D cartesian box



Setup and snapshot of the temperature field of the 2-D model with stagnant plate.



Setup and snapshot of the temperature field of the 2-D model with moving plate. The arrows indicate the imposed boundary velocity, which decreases to zero within the asthenosphere.

- top boundary no-slip (stagnant plate) or imposed velocity (moving plate)
- initial temperature field
  - linear temperature gradient within the lithosphere (~ 7.5 K/km)
  - linear temperature gradient within (upper) mantle (~1 K/km)
  - temperature perturbation at bottom acting as plume seed
- viscosity law

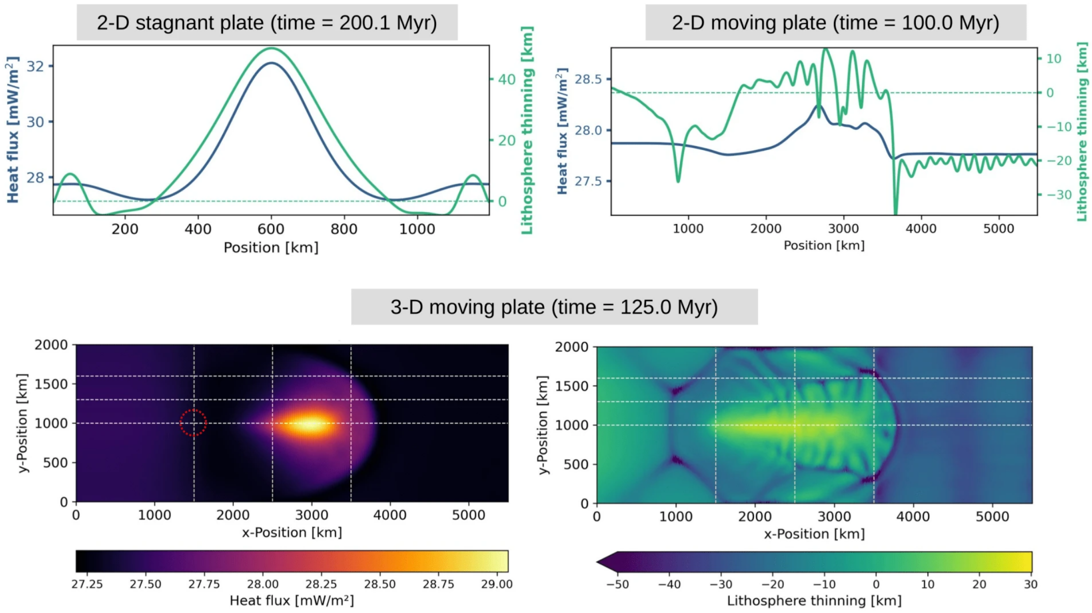
$$\eta_{eff} = \left(\frac{1}{\eta_{eff}^{diff}} + \frac{1}{\eta_{eff}^{disl}}\right)^{-1}, with$$

$$\eta_{eff}^{i} = \frac{1}{2} A^{-\frac{1}{n_i}} d^{\frac{m_i}{n_i}} \dot{\epsilon}_i^{\frac{1-ni}{ni}} exp\left(\frac{E_i+PV_i}{n_i RT}\right)$$

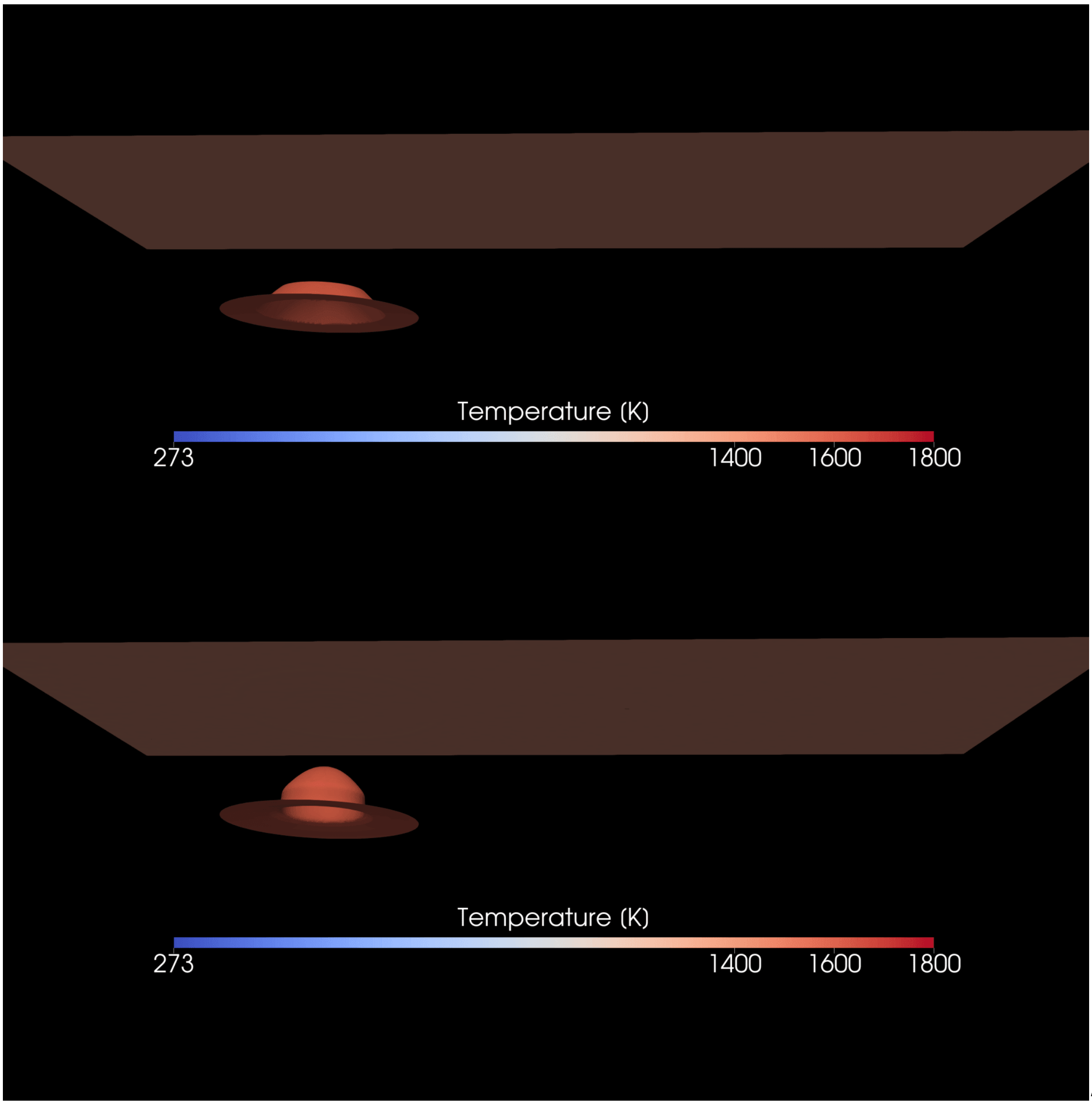
  - depends on strain rate ϵ, temperature T, grain size d, activation energy E, activation volume V and pressure P
  - in most cases, simplified to temperature-dependence only (n=1, m=0, V=0)
- simulation time
  - 400 Myr for stagnant plate cases (plume seed removed at 200 Myr)
  - 200 Myr for moving plate cases

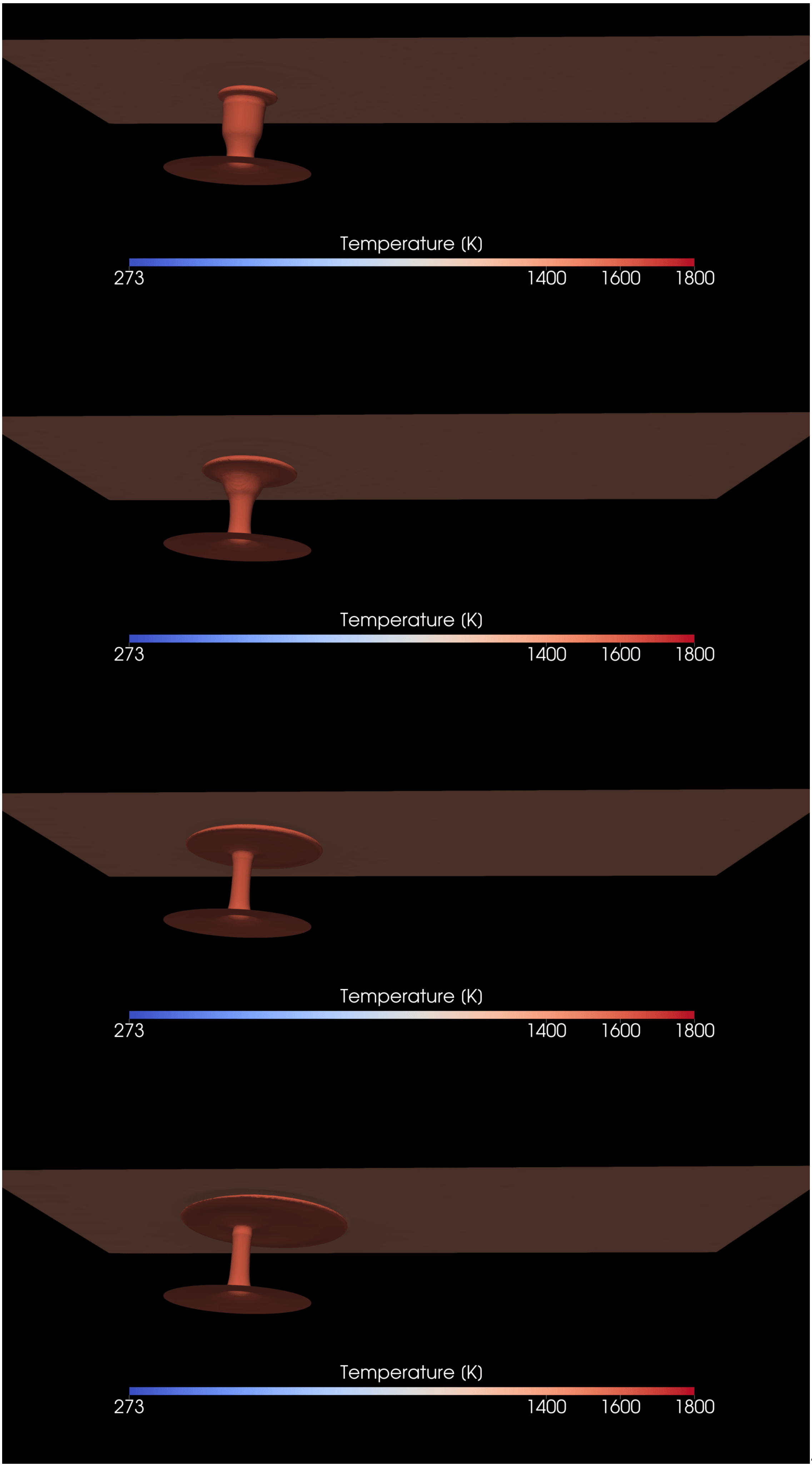
Analysis of anomalies

- average for x<=300 km is used as reference to obtain anomalies
- anomalies are expressed in percent of the reference value
- anomalies are tracked over time and space



Examples of lithosphere thinning and heat flux taken at specified times for our 2-D stagnant, 2-D and 3-D moving plate reference cases. The red circle in the lower left panel marks the position of the plume.

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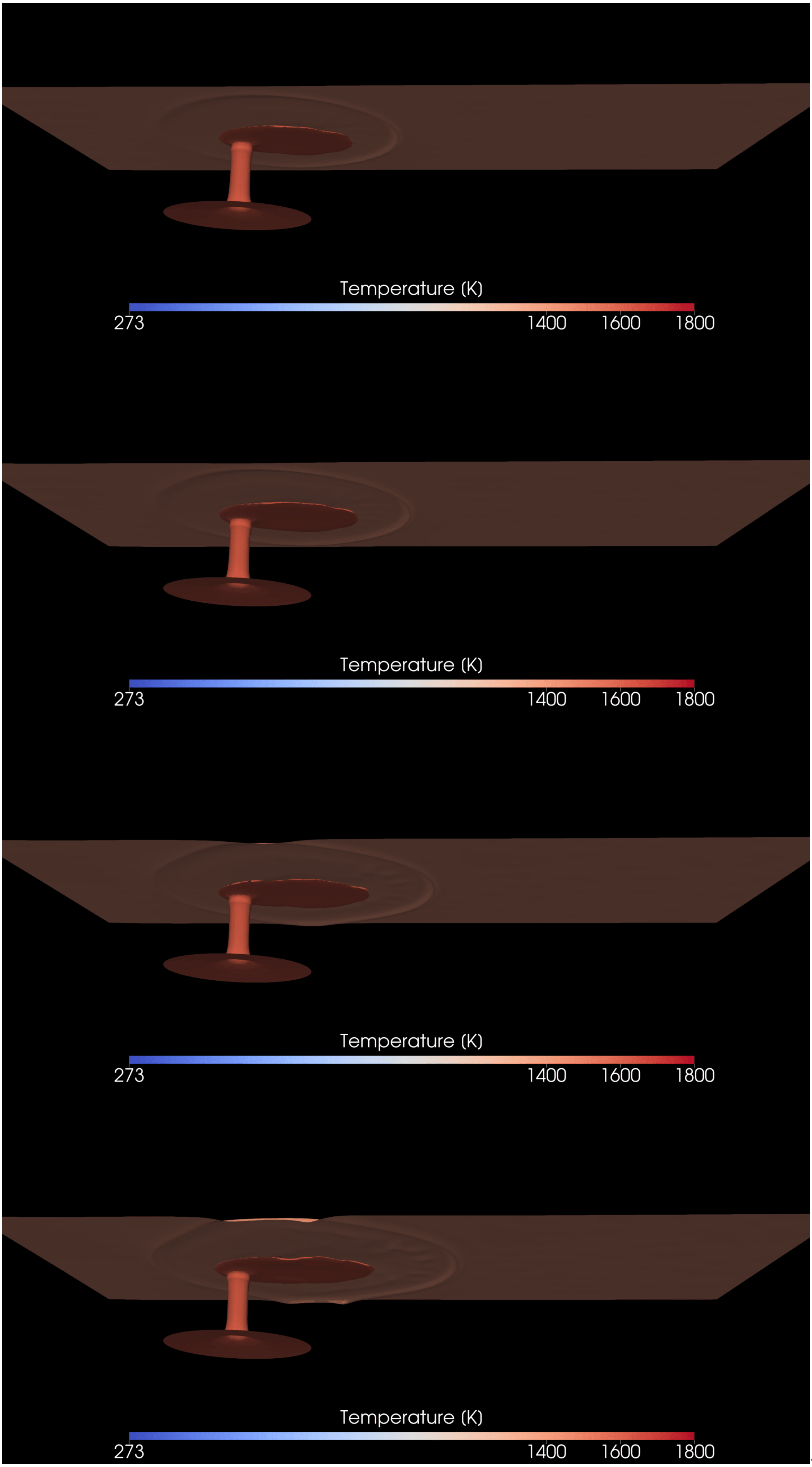
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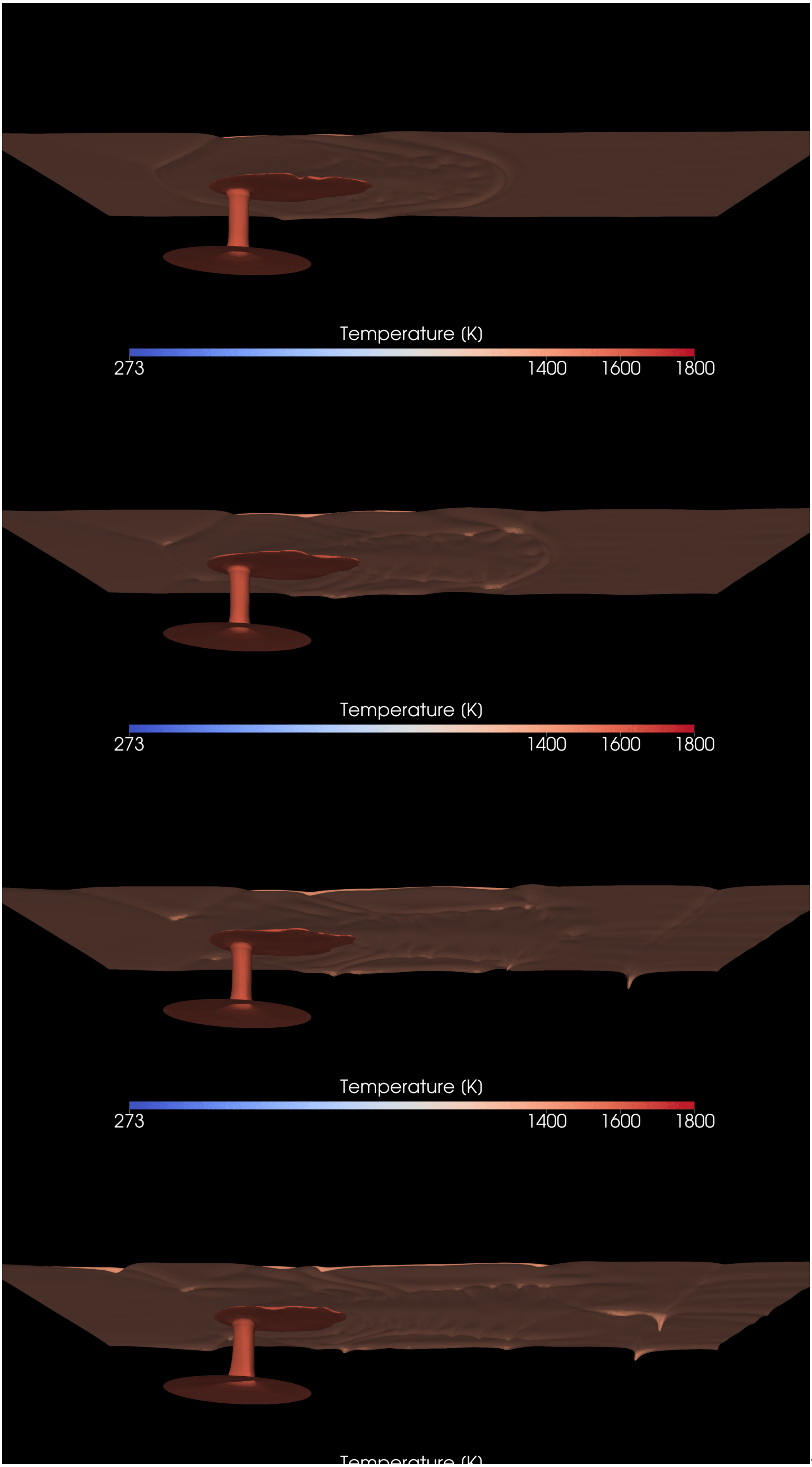
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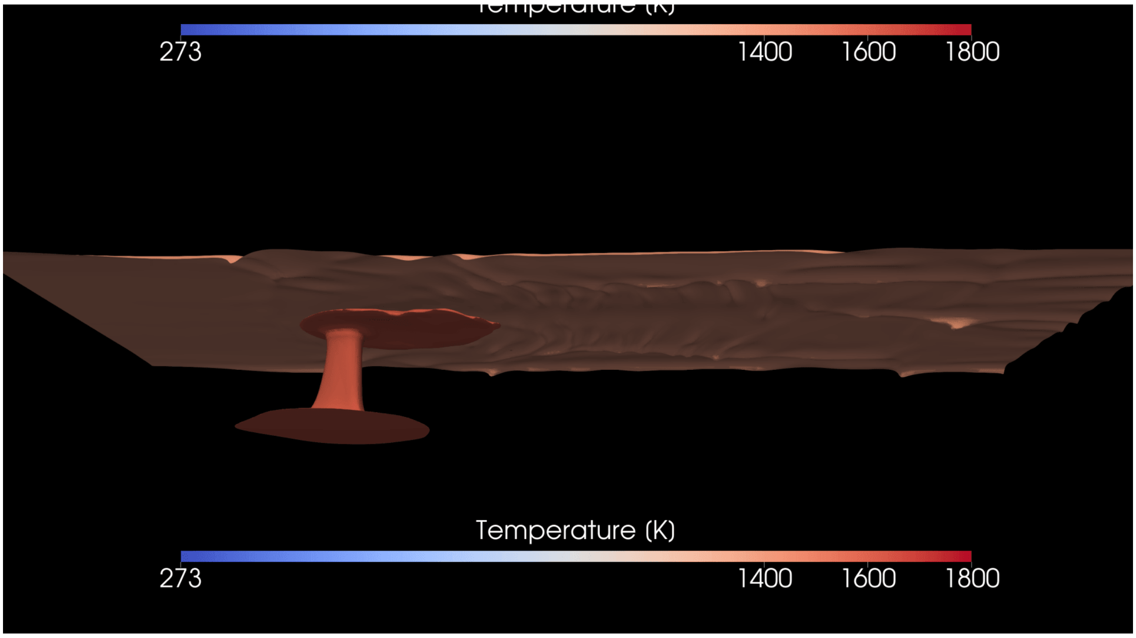
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CONCLUSIONS

- Lithosphere is thermomechanically eroded by the hot plume
- Plume-induced surface heat flux anomalies are related to lithosphere thinning
- Positions of maximum heat flux follow positions of maximum thinning
- **Heat flux anomalies are significantly delayed compared to lithosphere thinning (delay times ~ 90-150 Myr)**
- Heat flux vs lithosphere thinning follows the same trend, independent of the geometry and the plate velocity
- **None of the models has time to equilibrate to the plume, i.e. the heat flux anomaly is smaller than the analytical solution for the respective lithosphere thinning**
- **The most important parameters that controll anomaly amplitudes are lower lithosphere and asthenosphere viscosity, followed by plume excess temperature**
- **Lithosphere thinning and heat flux anomalies are aligned, except for cases with initial LAB topography prior to plume-lithosphere interaction**

ABSTRACT

While the passage of a plume beneath a thin oceanic lithosphere is usually connected to a hot spot track, and thus can easily be traced back in time, the interaction between a plume and thick continental or cratonic lithosphere is less obvious. Although volcanic eruptions are a common feature for plumes reaching the surface beneath continents, especially in the form of large igneous provinces associated with the arrival of a plume head, it is unlikely that the entire plume track is marked by extrusive volcanism. The thickness of continental lithosphere, and especially cratonic lithosphere, may prohibit the eruption of magma in many places, and can re-focus extrusive volcanism towards places where the lithosphere is thinner or more permeable due to preexisting fault structures. However, even though no magma might be erupted, the passage of a continent over a hot mantle upwelling will be visible in the surface heat flux, even millions of years after the plume passage. In this study, we use numerical models to investigate how a plume passing beneath continental or cratonic lithosphere affects surface heat flux over time, and which parameters of the plume and subsurface structure are the most relevant for determining the size of the respective heat flux anomaly. We show that any kind of surface heat flux anomaly is associated with an erosional thinning of the base of the lithosphere, and greater thinning leads to larger heat flux anomalies. While the maximum of lithosphere thinning is observed at a position and time a few million years after the plate passes over the plume, heat flux anomalies related to conduction continue to increase, reaching a maximum about 80-150 Myr after passage over the plume. In the case of stagnant (stationary) plates, the delays between lithosphere thinning and heat flux anomaly are smaller and the observed anomalies are larger. Amplitudes of both thinning and heat flux anomalies are most sensitive to the viscosity of the asthenosphere and the lower lithosphere, because a lower viscosity facilitates basal erosion and thus increases heat fluxes. Also important are the interaction time between plume and plate, i.e. plate velocity or plume life time, and the plume strength / excess temperature. These results have important implications for understanding plume-lithosphere interactions in polar settings, e.g. Greenland and Antartica, and for various places in Africa, North America and China.

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