Lithospheric processes: From oceanic lithosphere accretion to hydrothermal cooling

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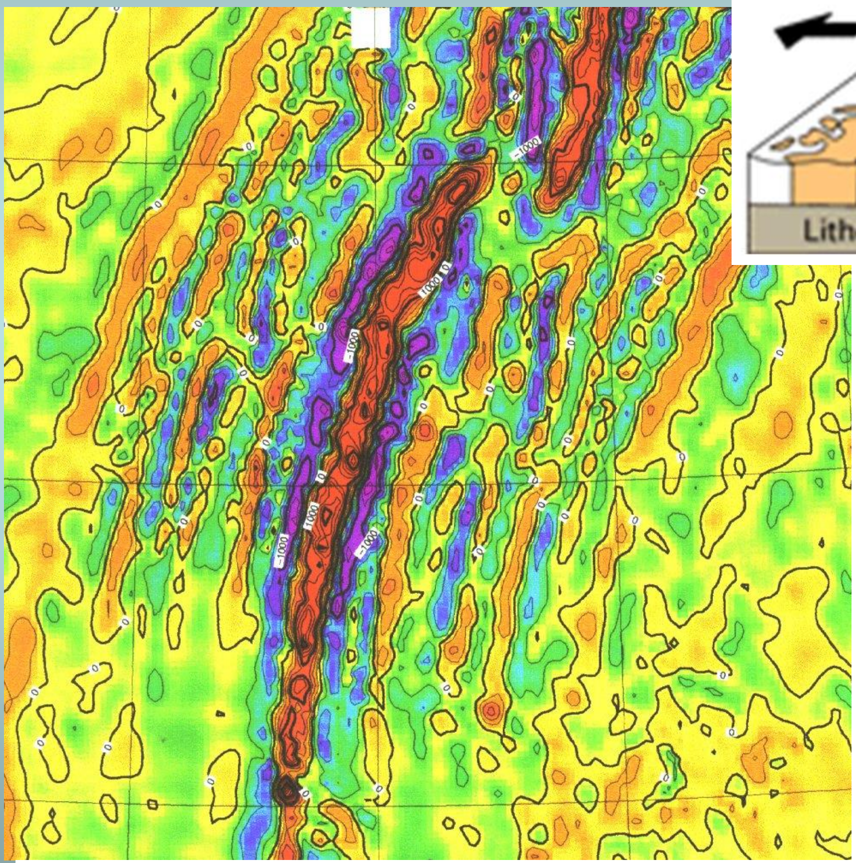
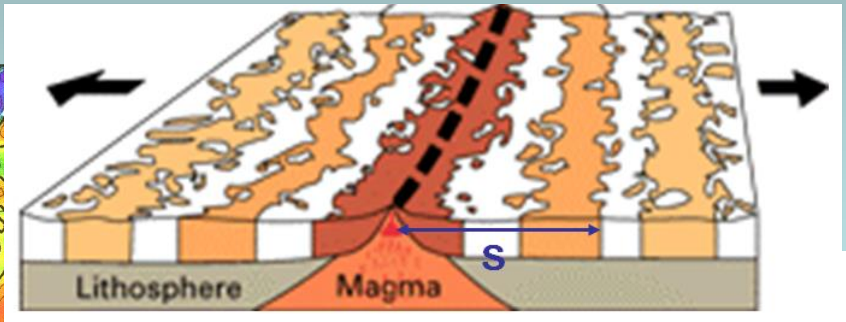
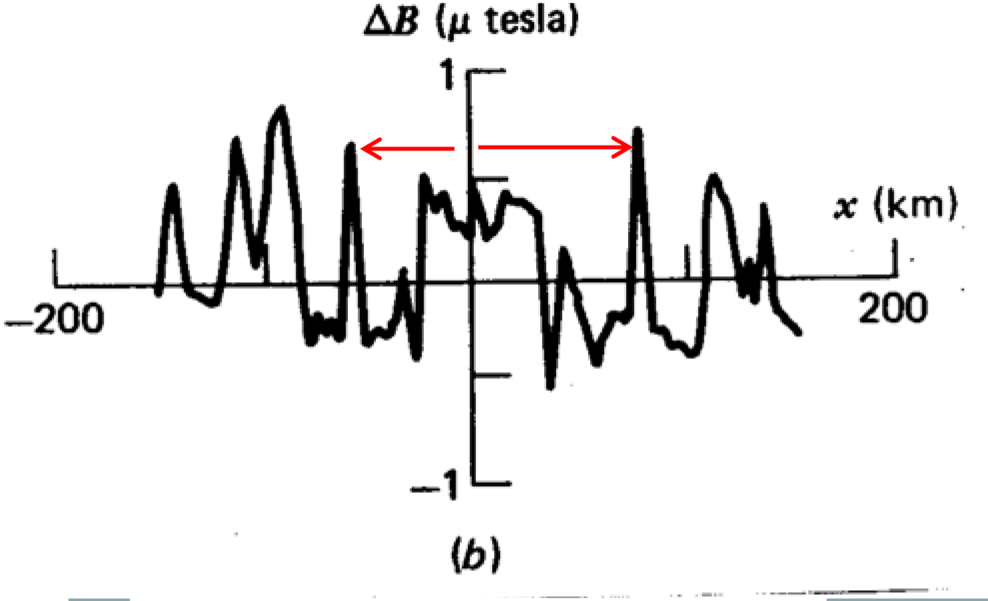
Outline

- Why do MORs spread symmetrically and how is this related to ridge mirgation?
  - Relation MOR symmetry – ridge migration
  - Modelling migrating ridges → symmetric spreading
  - Symmetric even when overriding plumes?
  - Comparison to lava lakes (thermal boundary condition)
- Square root cooling away from the MOR
  - Deviations due to hydrothermal convection
  - Fitting to observations
- Modelling crust generation at MOR
  - Focussing melt towards the ridge (Katz 2008)
  - Asymmetric mantle potential temperature (Katz 2010)

Examples symmetric and asymmetric spreading



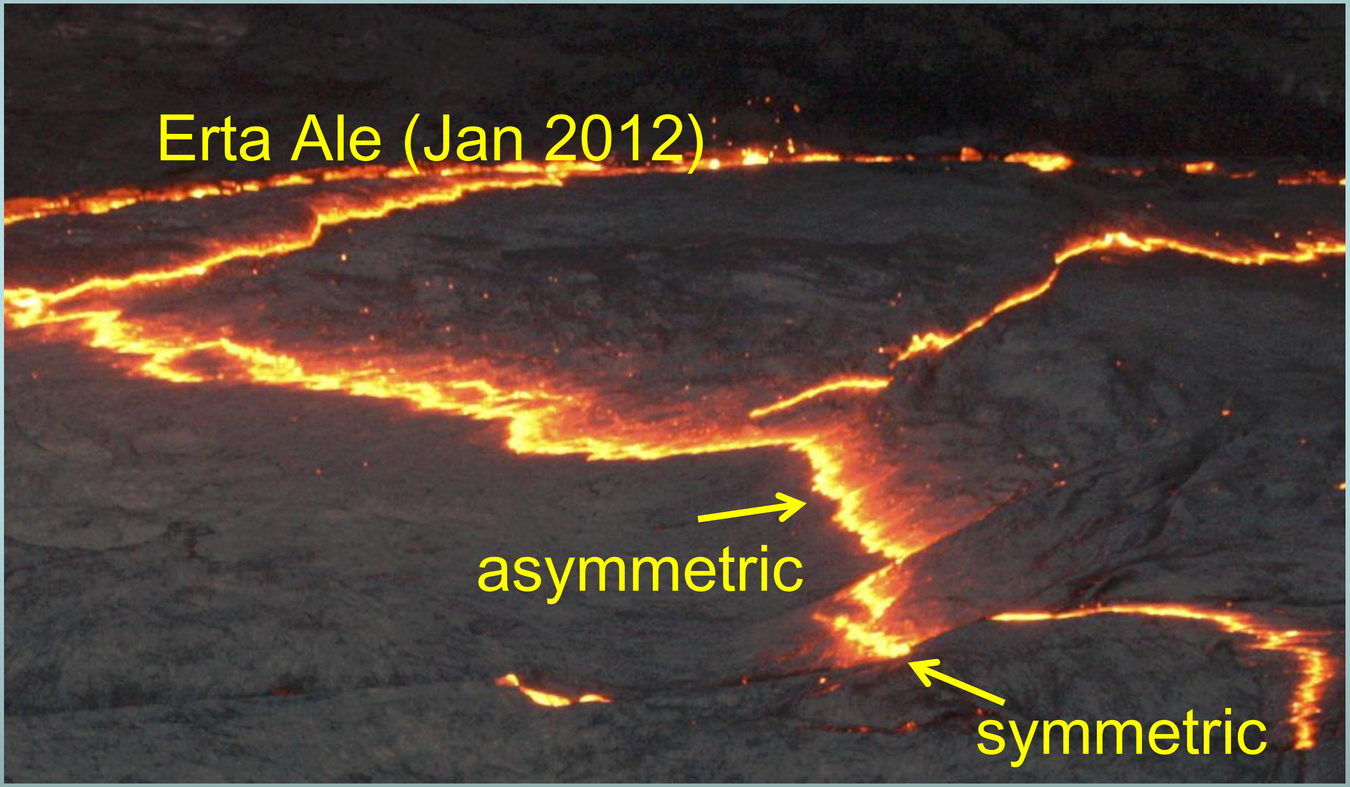




Magnetic anomalies, Kolbeinsey ridge (symmetric)

South East Indian Rise (asymmetric)

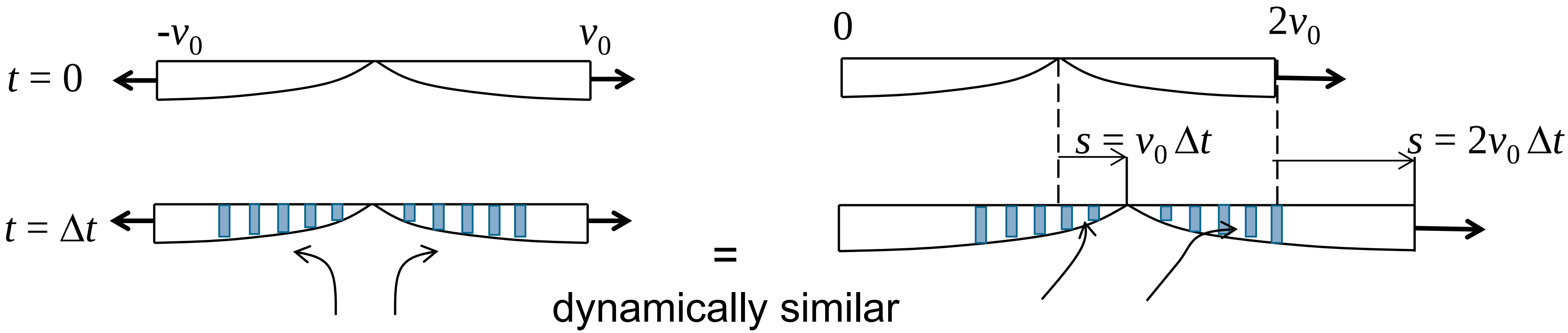
Examples symmetric and asymmetric spreading



Some kinematics

Symmetric spreading (Assume: passive mantle)

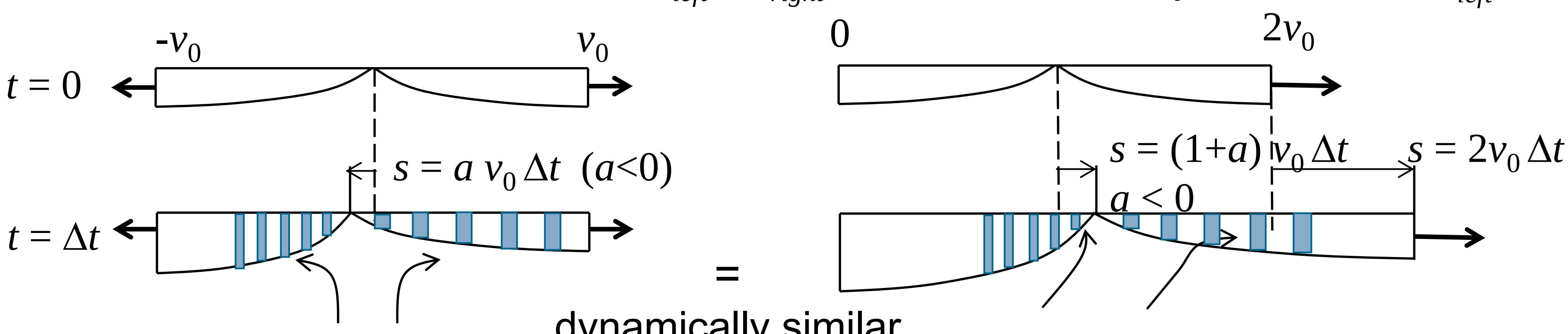
Coordinate system fixed at ridge | Coordinate system fixed at one plate



No ridge migration, $v_{ridge} = 0$ | $v_{ridge} = v_0$

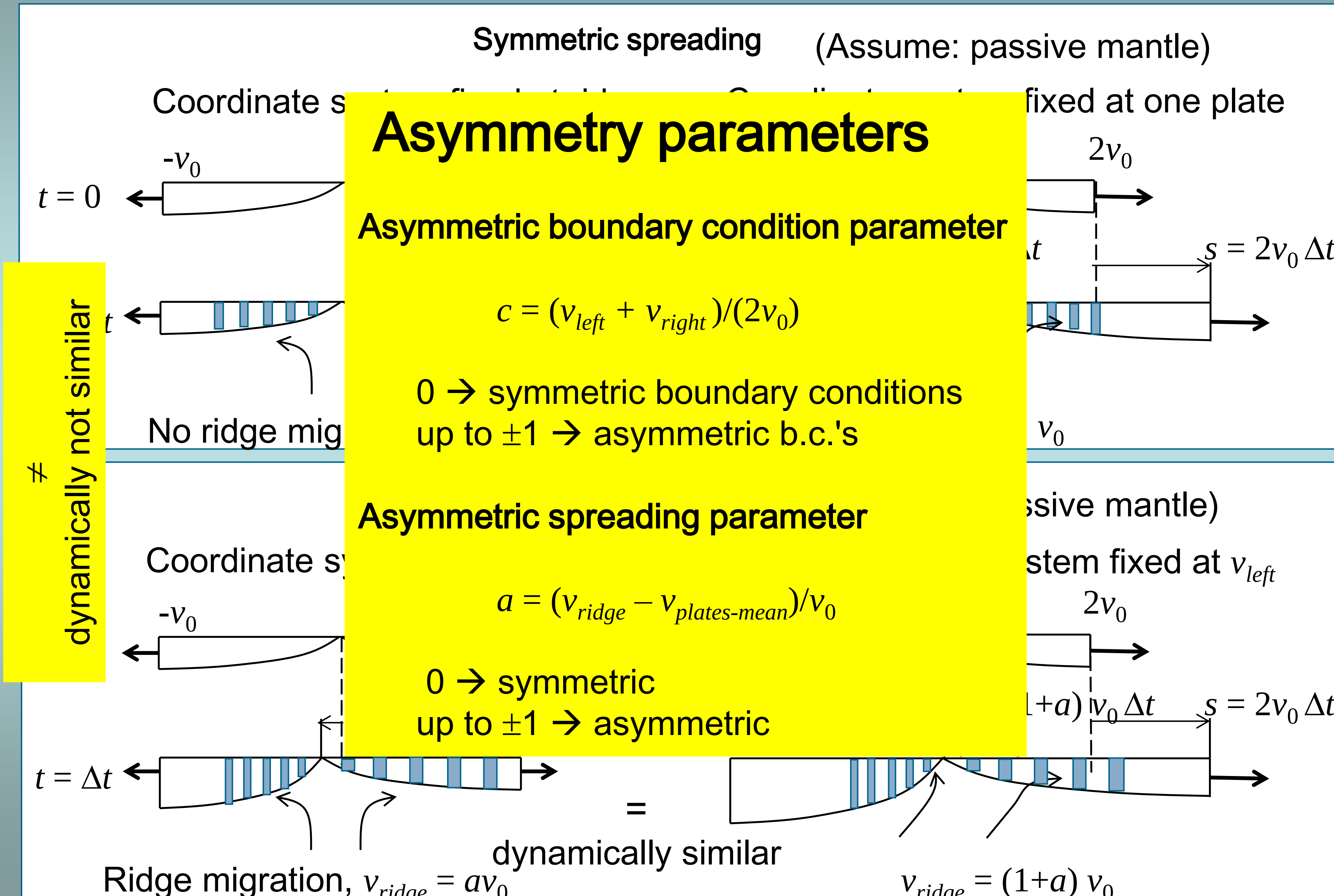
Asymmetric spreading (Assume: passive mantle)

Coordinate system fixed at $(v_{left} + v_{right})/2$ | Coordinate system fixed at v_{left}



Ridge migration, $v_{ridge} = av_0$ | $v_{ridge} = (1+a)\, v_0$

Some kinematics



Asymmetry parameters

Asymmetric boundary condition parameter

$$c = (v_{left} + v_{right})/(2v_0)$$

0 → symmetric boundary conditions
up to ±1 → asymmetric b.c.'s

Asymmetric spreading parameter

$$a = (v_{ridge} - v_{plates\text{-}mean})/v_0$$

0 → symmetric
up to ±1 → asymmetric

Governing equations

$$-\vec{\nabla} P + \frac{\partial}{\partial x_j}\left[\eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\right] - \rho g \vec{e}_3 = 0$$

Navier Stokes

$$\dot{e}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right),$$

$$\tau_{ij} = 2\eta \dot{e}_{ij}$$

$$\vec{\nabla} \cdot \vec{v} = 0$$

Mass conservation

$$\rho c_p\left(\frac{\partial T}{\partial t} + \vec{v} \cdot \vec{\nabla} T\right) = \vec{\nabla} \cdot (k \vec{\nabla} T) + \rho H$$

Energy conservation

"Pore pressure" factor

Mohr Coulomb (Byerlee) plasticity:

$$\dot{e}_{ij}^{MC} = \begin{cases} 0 & \tau_{II} < \tau_{\max} \\ arbitrary & \tau_{II} = \tau_{\max} \end{cases} \qquad \dot{e}_{ij}^{MC} = \frac{1}{2\eta^{MC}} \tau_{ij} \quad with \quad \eta^{MC} = \frac{\tau_{\max}}{2\dot{e}_{II}} \qquad \tau_{\max} = \left(a_{By} z + b_{By}\right)\lambda_p$$

Dislocation creep

$$\dot{e}_{ij}^{duc} = B \exp\left(\frac{-E}{RT}\right) \tau_{II}^{\,n-1} \tau_{ij}$$

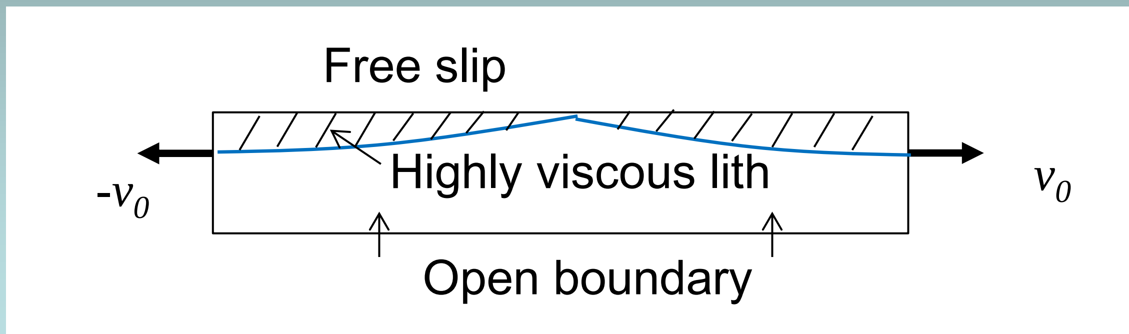
$$\eta^{duc} = \frac{1}{2B^{1/n}} \exp\left(\frac{E}{nRT}\right) \dot{e}_{II}^{duc\left(\frac{1}{n}-1\right)}$$

Composite viscosity

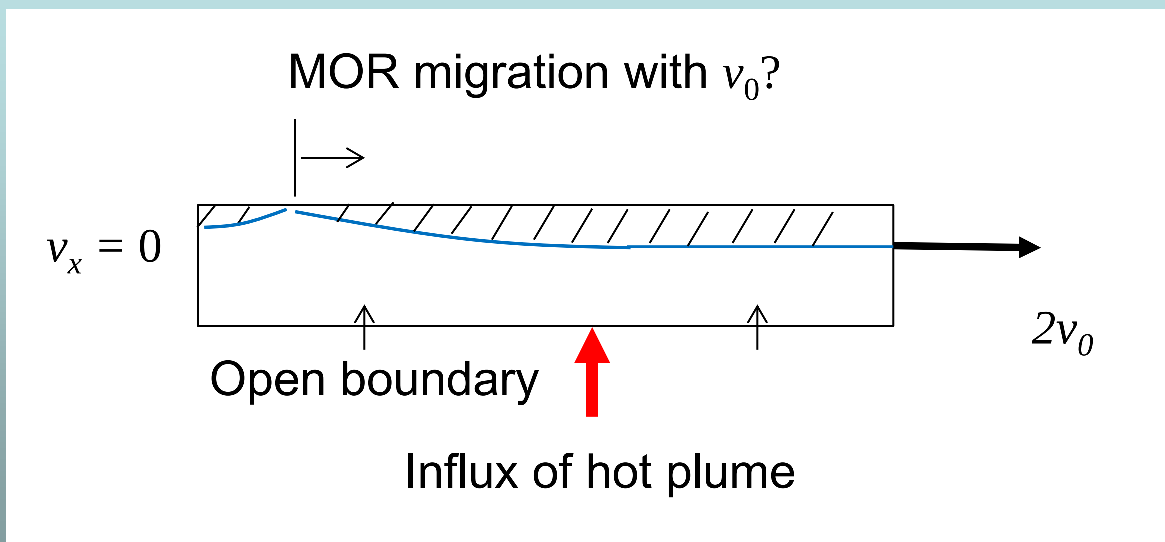
$$\dot{e}_{ij} = \dot{e}_{ij}^{MC} + \dot{e}_{ij}^{duc} = \left(\frac{1}{2\eta^{MC}} + \frac{1}{2\eta^{duc}}\right)\tau_{ij}$$

$$\frac{1}{\eta_{eff}} = \frac{1}{\eta^{MC}} + \frac{1}{\eta^{duc}}$$

Model setup



or:

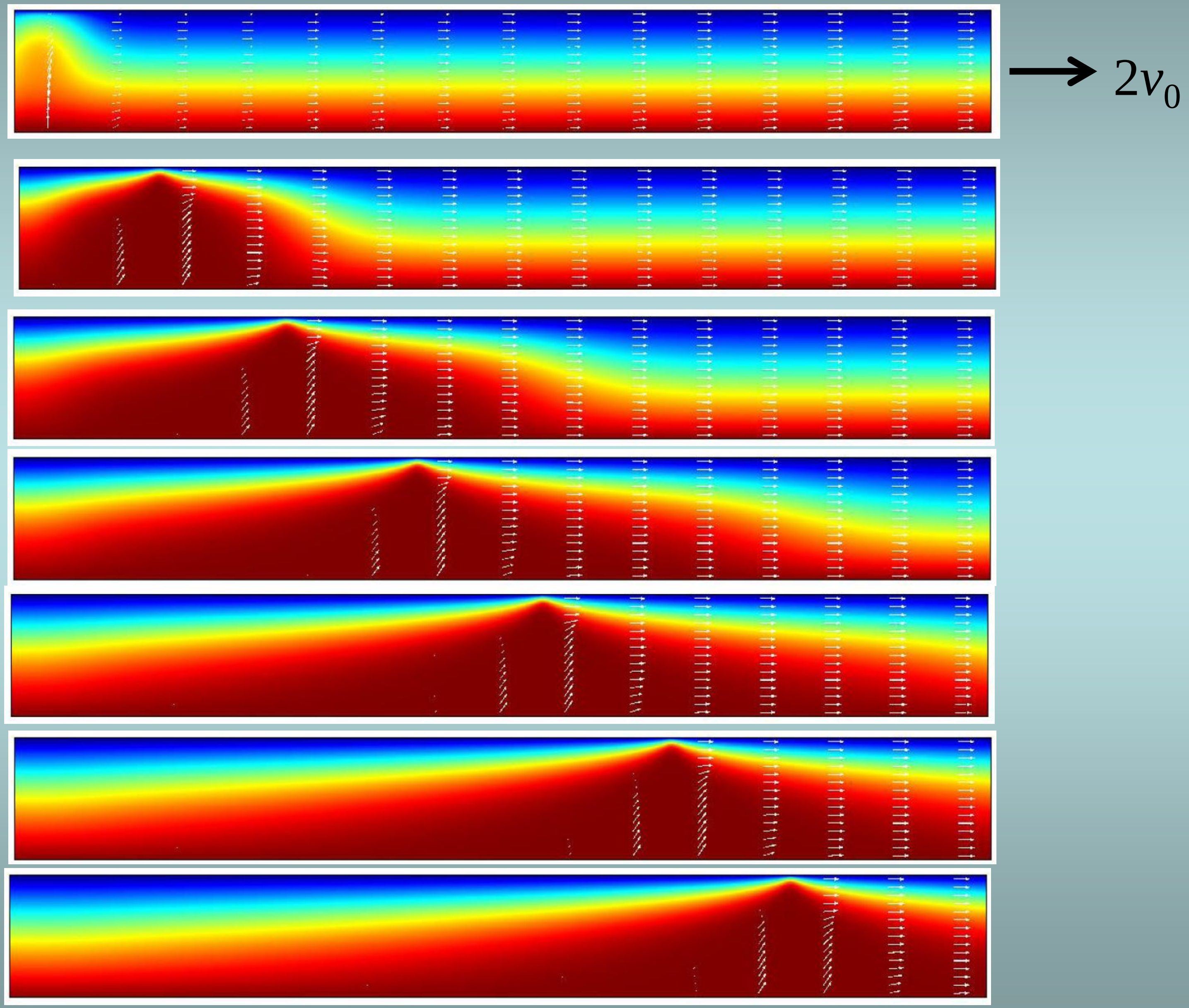


Variation:

- Spreading velocity
- "Pore pressure factor λ_p
- Plume temperature

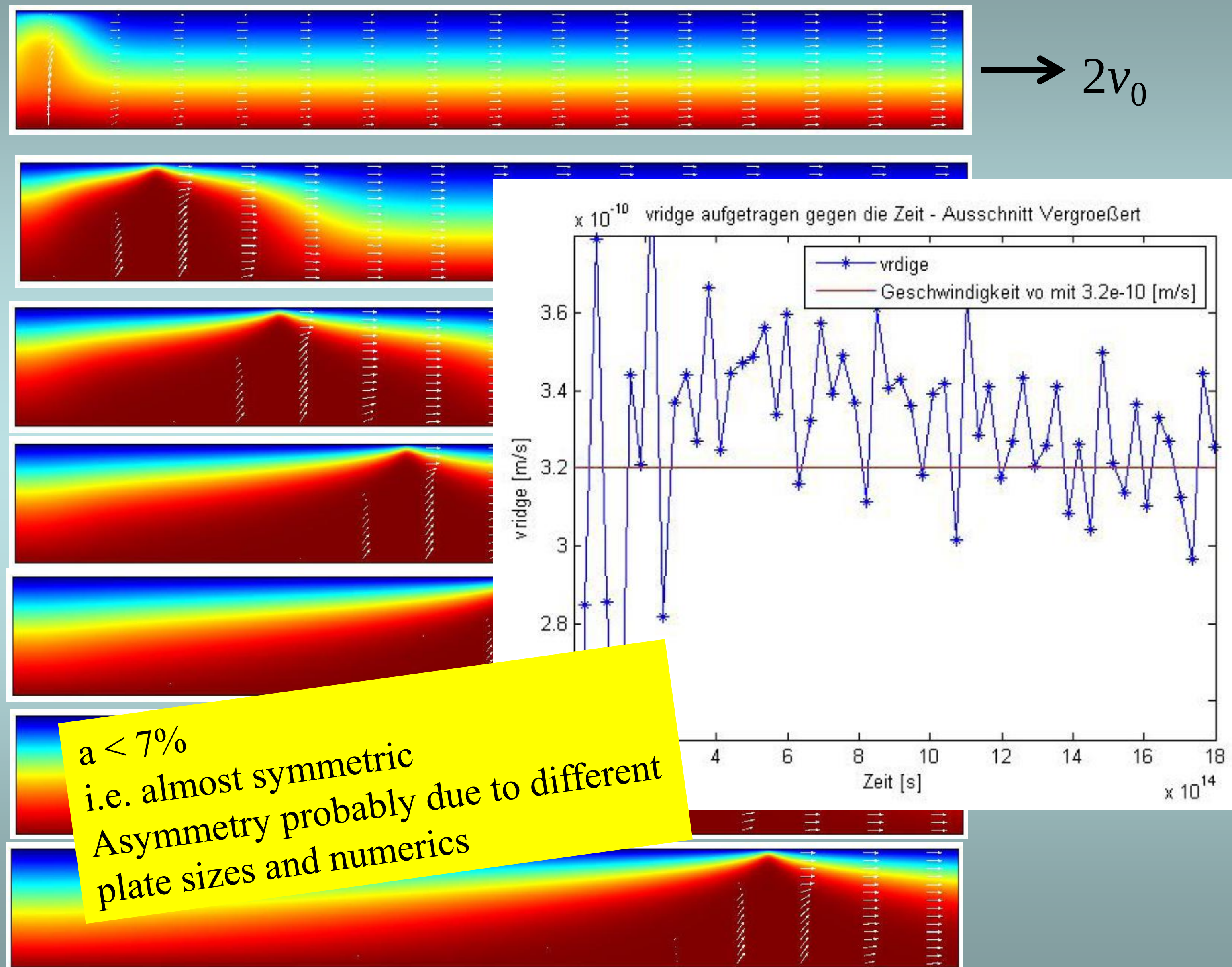
Asymmetry spreading parameter a?

Fixed
Free slip



Fixed
Free slip

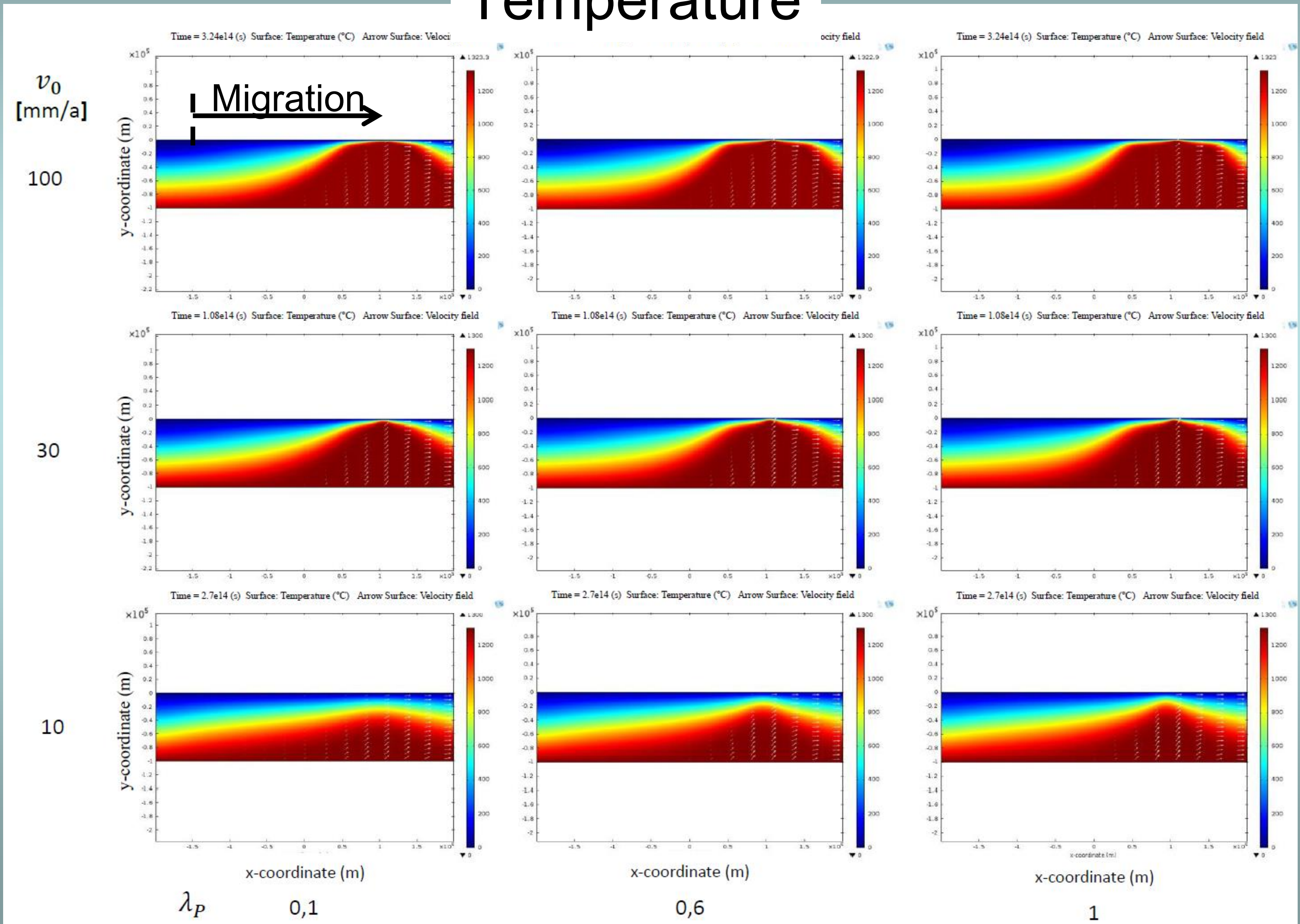
→ $2v_0$



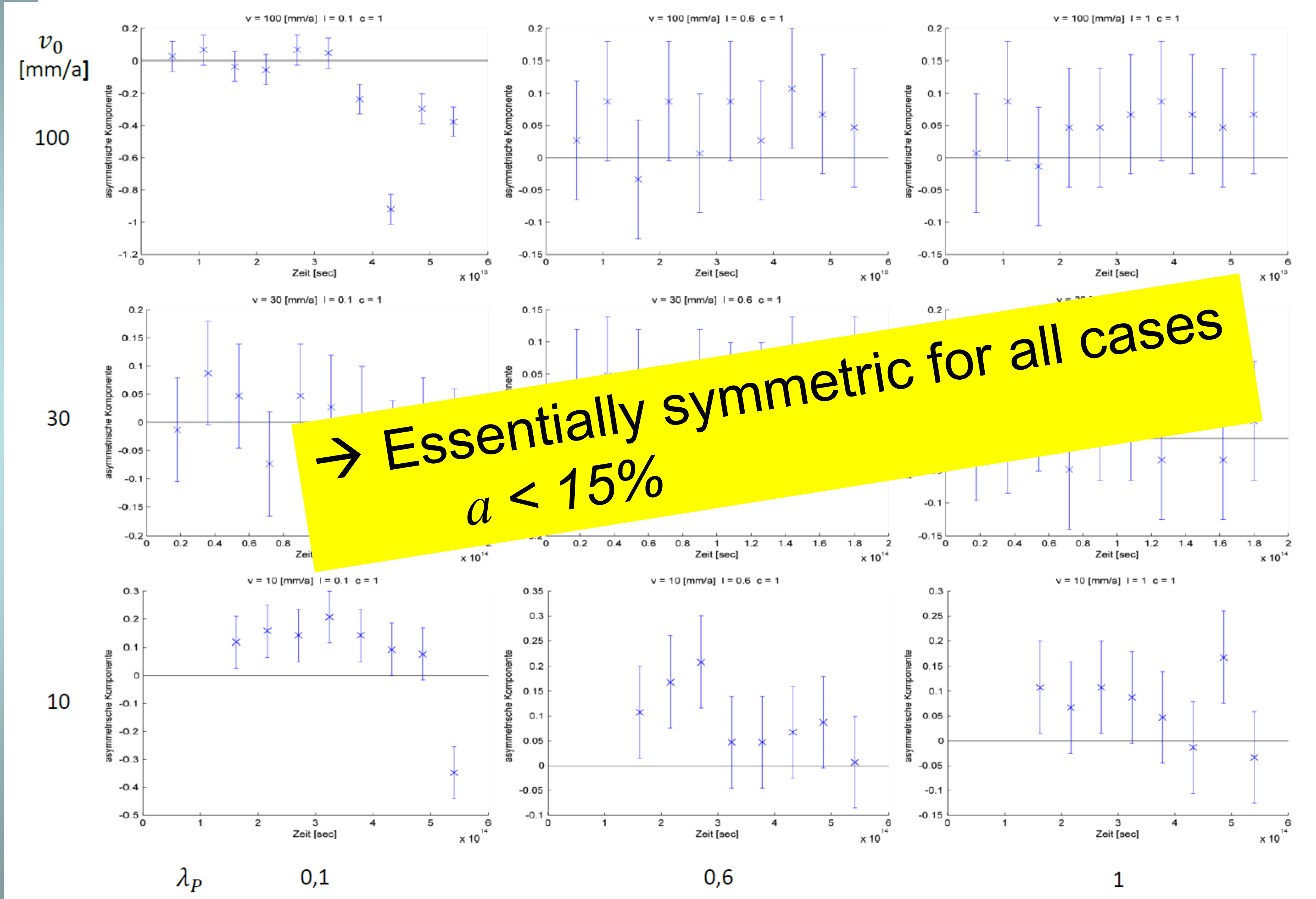
a < 7%
i.e. almost symmetric
Asymmetry probably due to different plate sizes and numerics

Variation of spreading velocity and "pore pressure" parameter

Temperature



Asymmetry spreading parameter a (=0 if symmetric)



→ Essentially symmetric for all cases $a < 15\%$

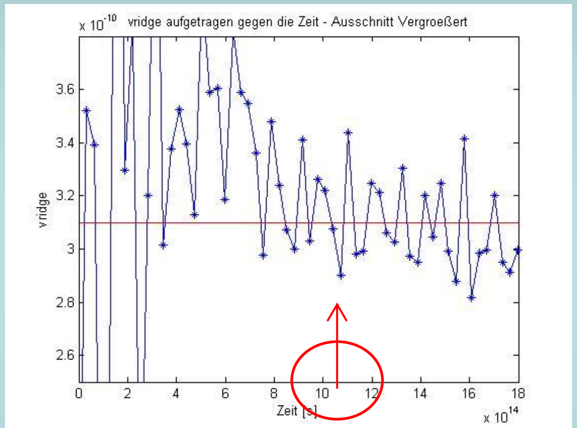
MOR overriding a plume

MOR migration velocity for different plume excess temperatures

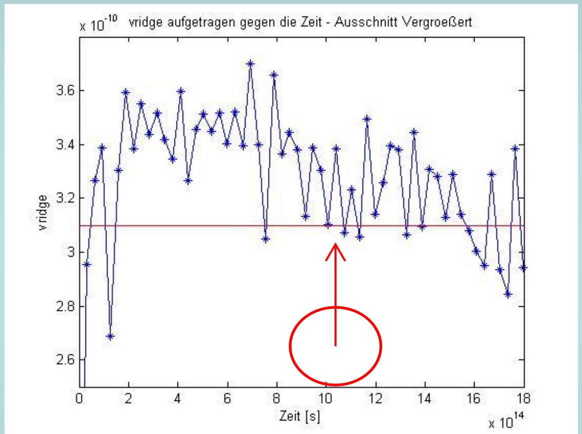
150 K

250 K

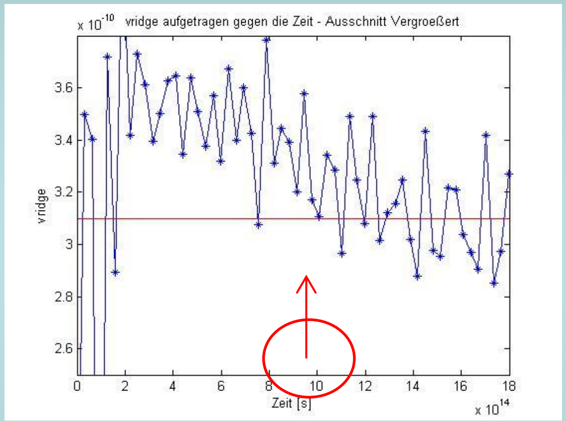
350 K



260420 dof's

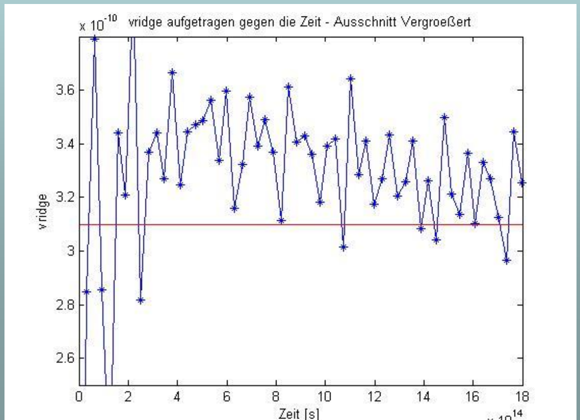


260420 dof's



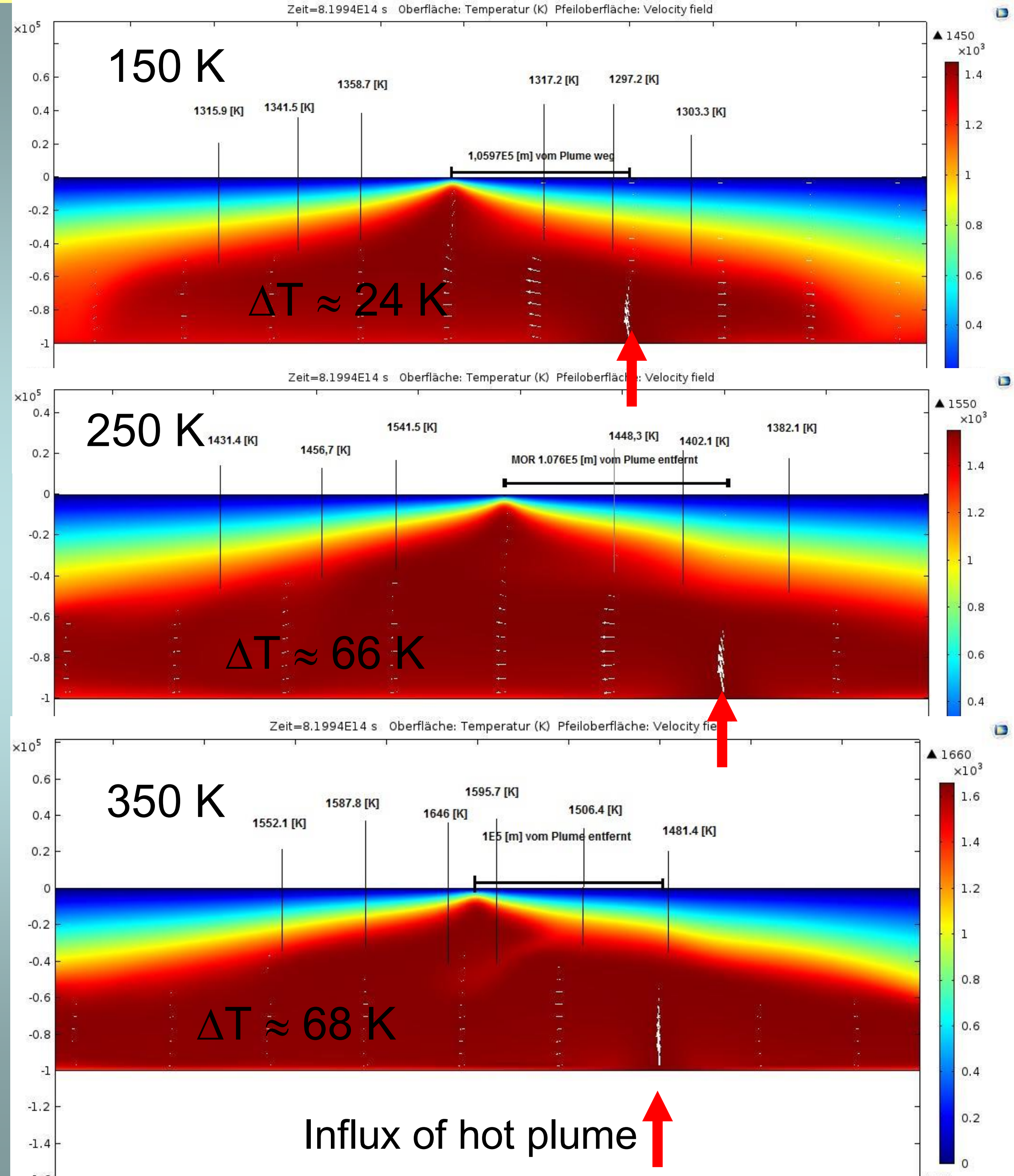
34420 dof's

- MOR slows down when approaching and overriding the plume
- For comparison, without plume →

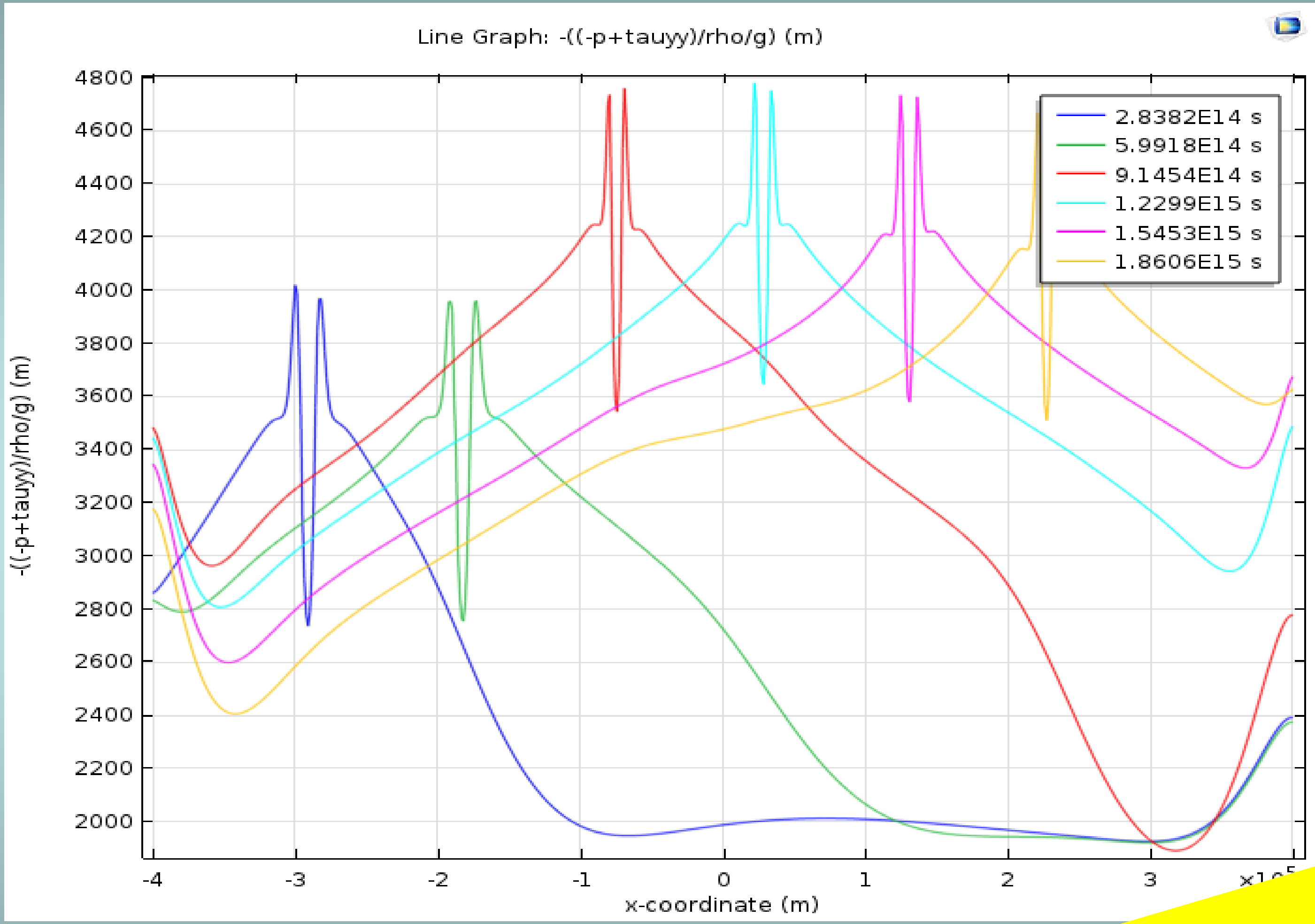


Snapshots at times before MOR will override plume

- LAB cooler (!) on plume side
- Weak, cooler part of thermal boundary layer is swepted towards MOR
- Cooler accretion more effective than hot accretion (?) → MOR migration slightly slows down



Plume effect on topography



- Topography remains essentially symmetric
- Hot plume material lifts up the whole ridge

Conclusion:
Both observed and modelled asymmetries < 15%

What is the difference to lava lake plate tectonics?

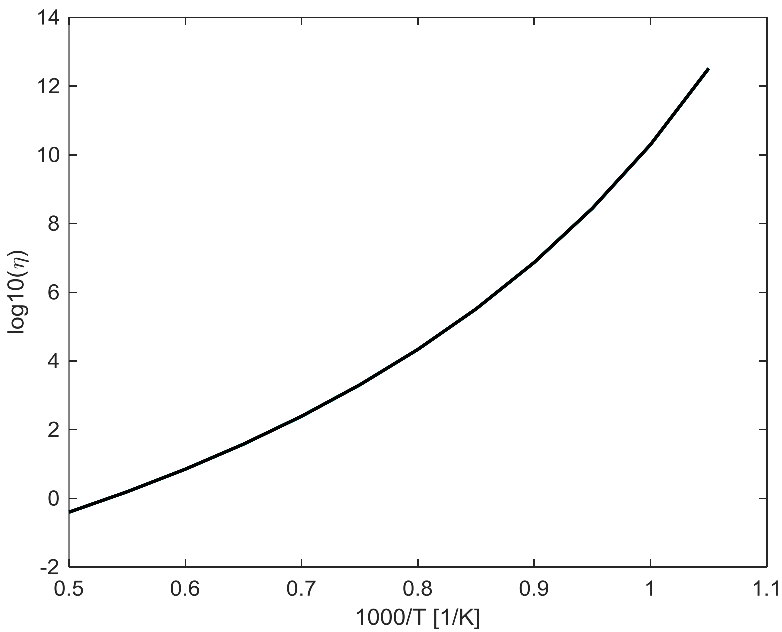
Rheology

$$\eta^{duc} = \eta_0 \exp\left(\frac{A_v}{T - T_v}\right)$$

Vogel-Fulcher-Tammann equation, empirical

$$\dot{e}_{ij}^{MC} = \frac{1}{2\eta^{MC}} \tau_{ij} \quad with \quad \eta^{MC} = \frac{\tau_{\max}}{2\dot{e}_{II}}$$

- Stronger T-dependence (more than Arhenius)
- Linear



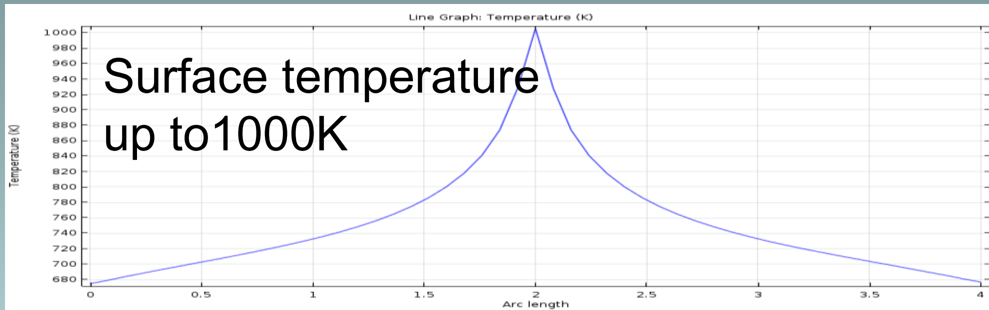
Thermal boundary condition: Radiation

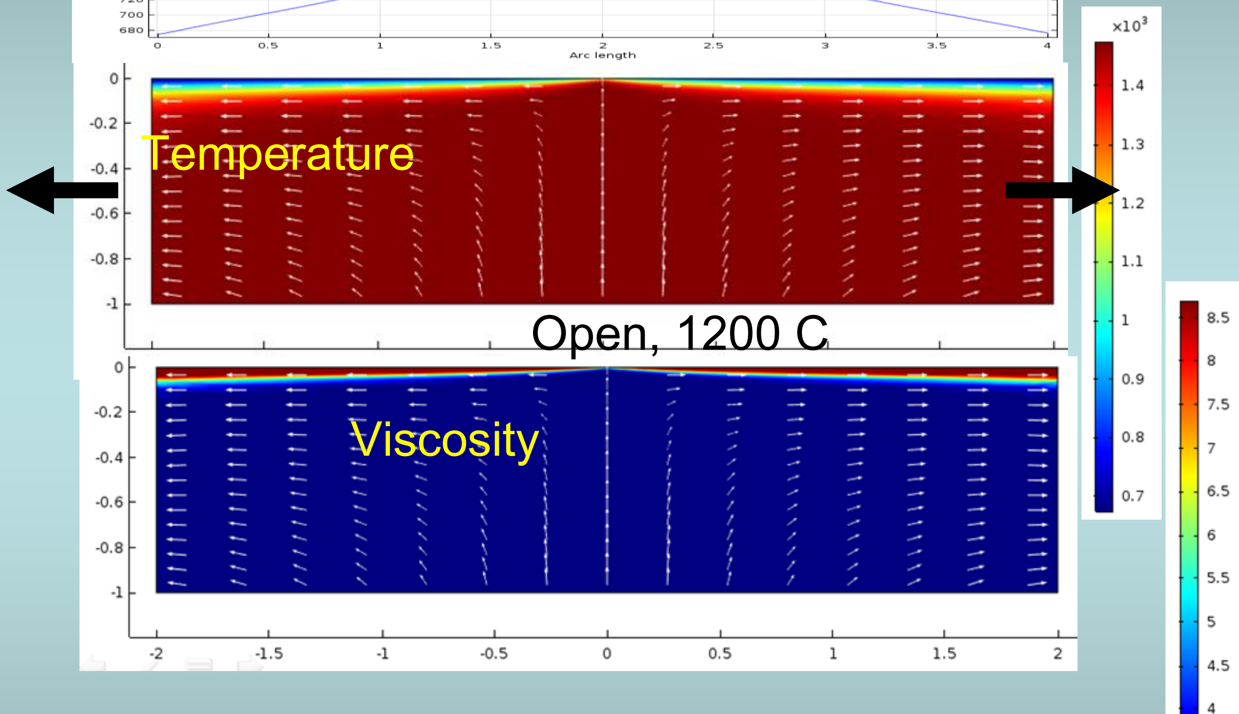
$$q = \varepsilon\sigma\left(T^4 - T_{amb}^4\right)$$

ε - surface emissivity (0.9)

σ - Stefan-Boltzmann constant

Spreading on lava lake

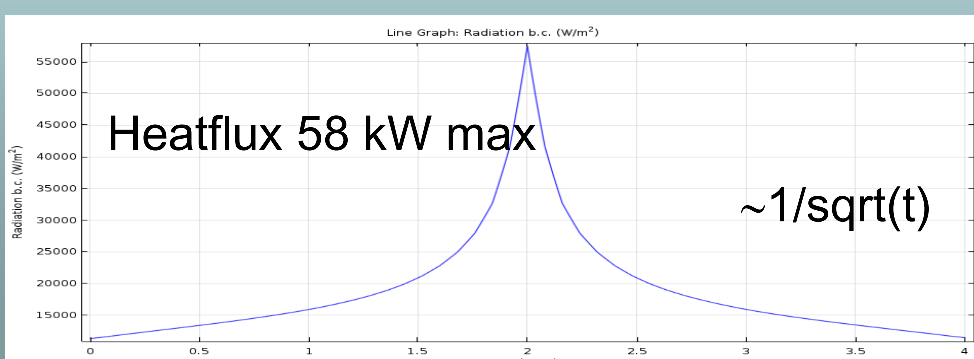


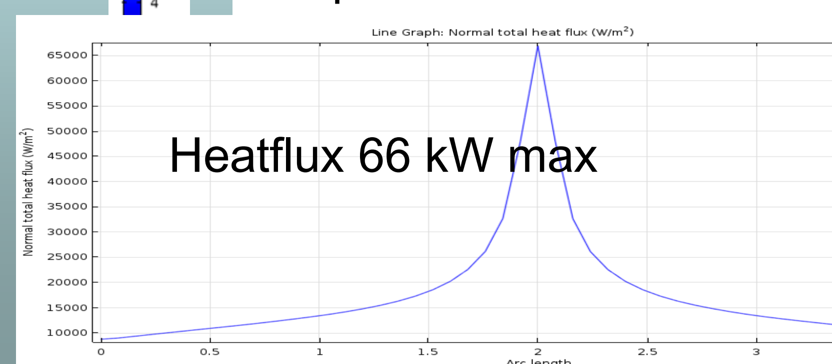


Results:

- Similar behavior as with const T boundary condition
- Symmetric spreading

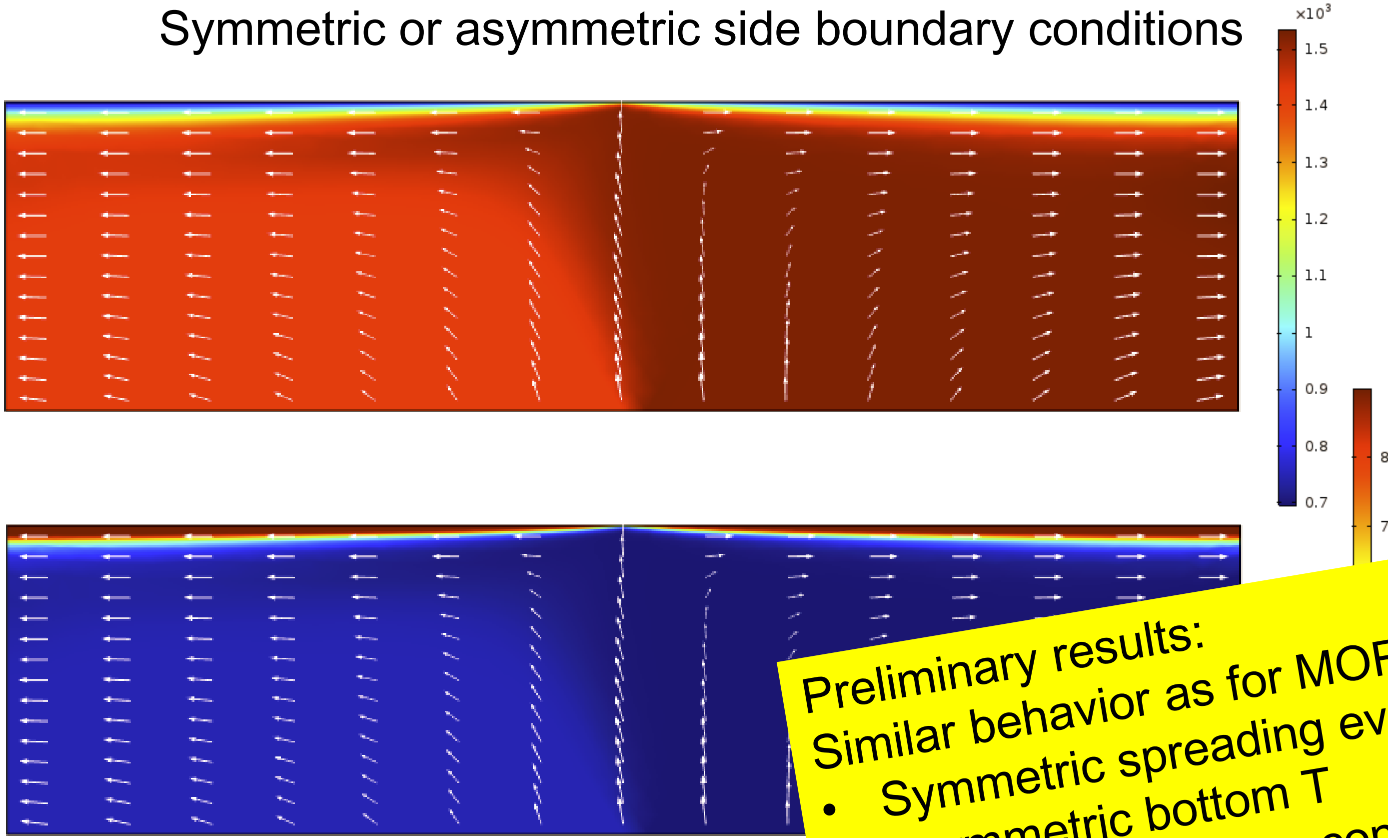
Compare: constant surface temperature 773 K





Attempts to obtain asymmetric spreading….

Asymmetric bottom temperature
Symmetric or asymmetric side boundary conditions



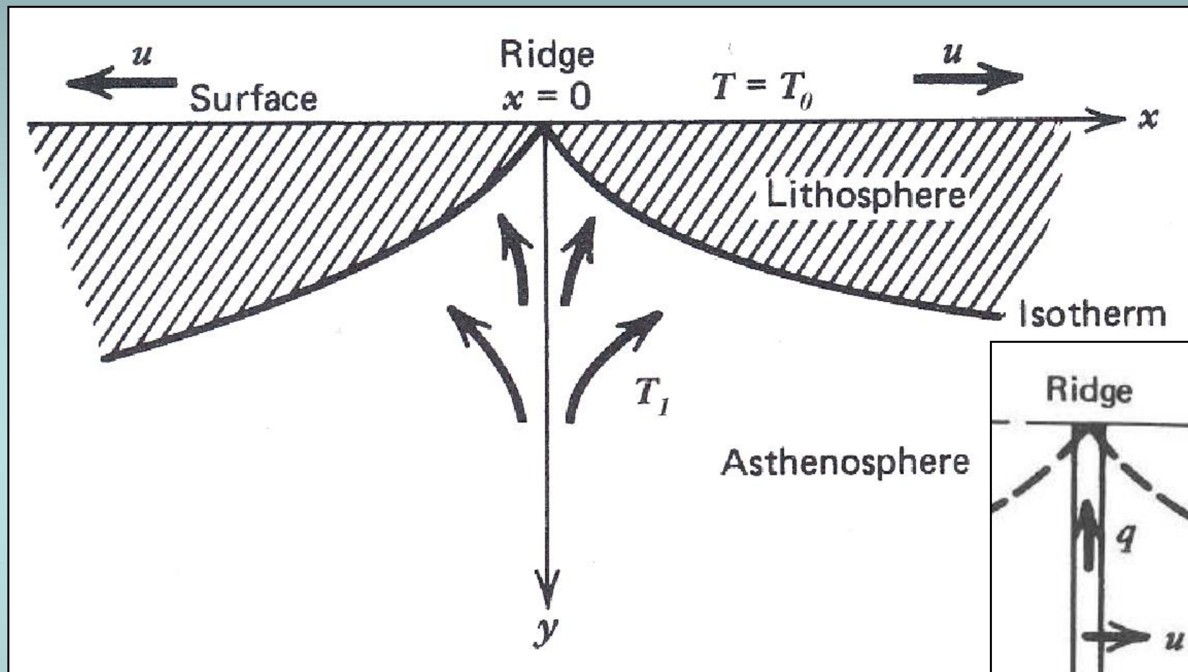
Preliminary results:
Similar behavior as for MOR:

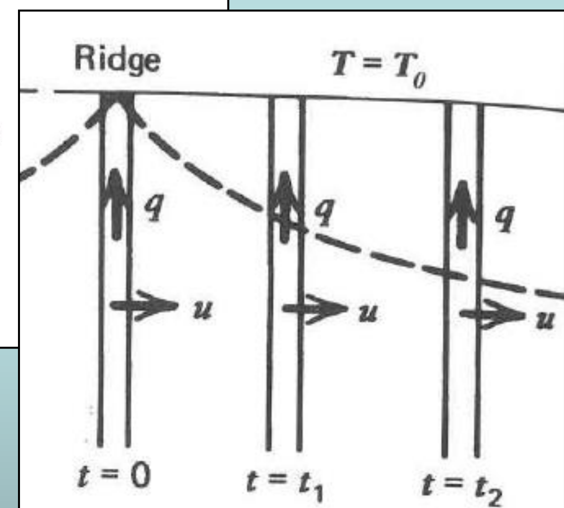
- Symmetric spreading even for asymmetric bottom T
- Radiative boundary condition similar to const T b.c.
- Observed asymmetries: to be explored

Cooling of oceanic lithosphere with hydrothermal convection

Inversion of observed heatflow and bathymetry

Cooling lithosphere, $\sqrt{t}$ - law

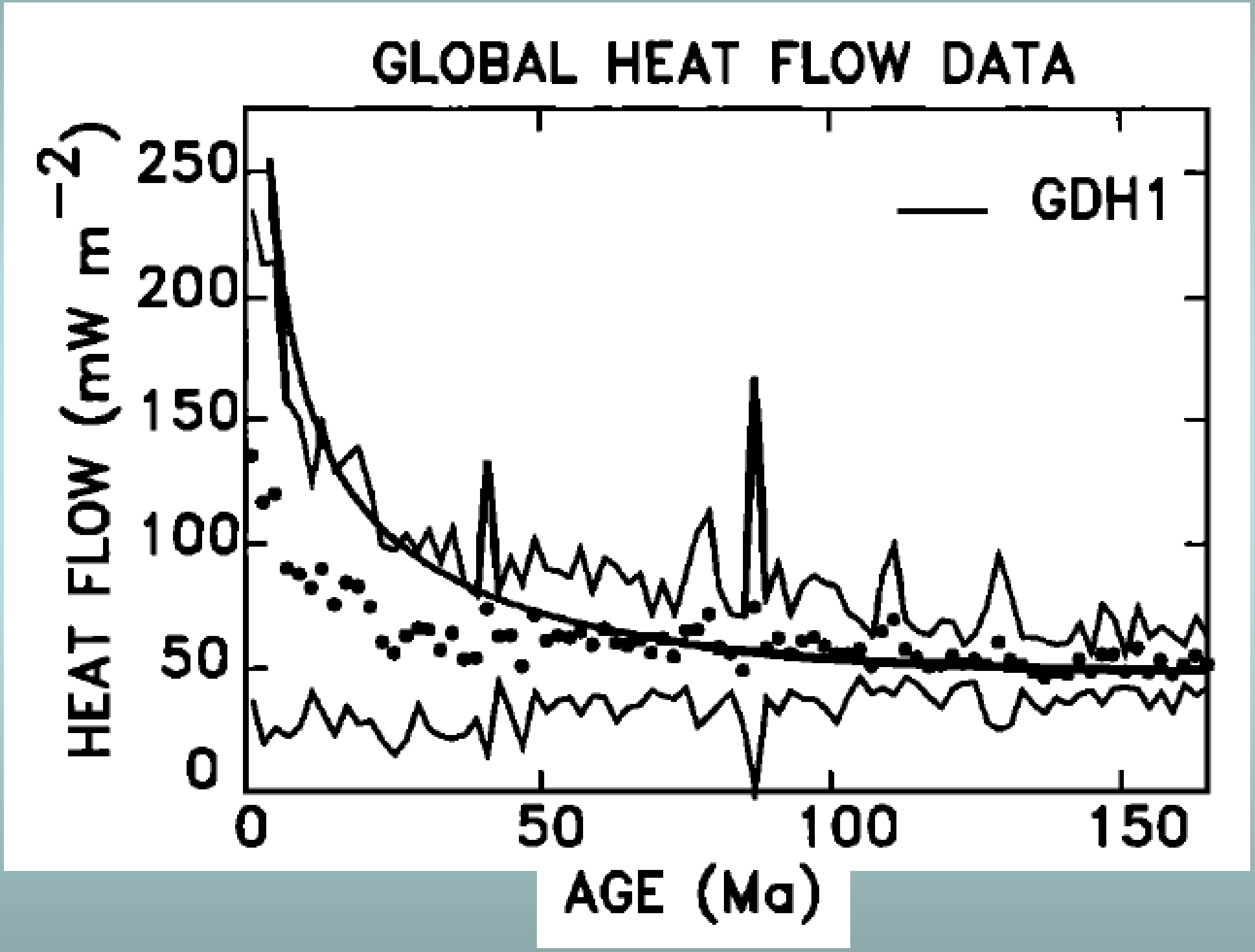




Turcotte & Schubert:

$$q_0(t) = \lambda \cdot \left.\frac{dT}{dz}\right|_{z=0} = -\frac{\lambda \cdot \Delta T}{\sqrt{\pi}\sqrt{\kappa \cdot t}}$$

Cooling lithosphere, $\sqrt{t}$ - law



Stein and Stein, 1994

Cooling lithosphere, $\sqrt{t}$ - law

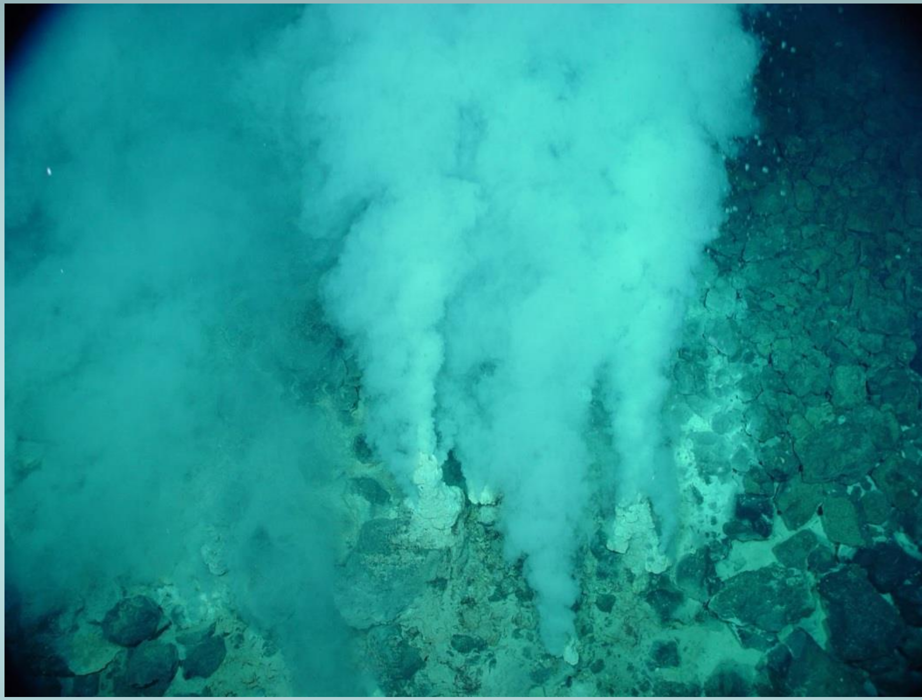
Discrepancy: hydrothermal cooling

Fraction of hydrothermally removed heat**: 20 - 40%** of total heat flow of the earth (Sclater et al., 1980; Stein and Stein, 1992; Lowel et al., 2008; Spinelli and Harris, 2011)

But… no cooling plate model exists which consistently includes hydrothermal convection

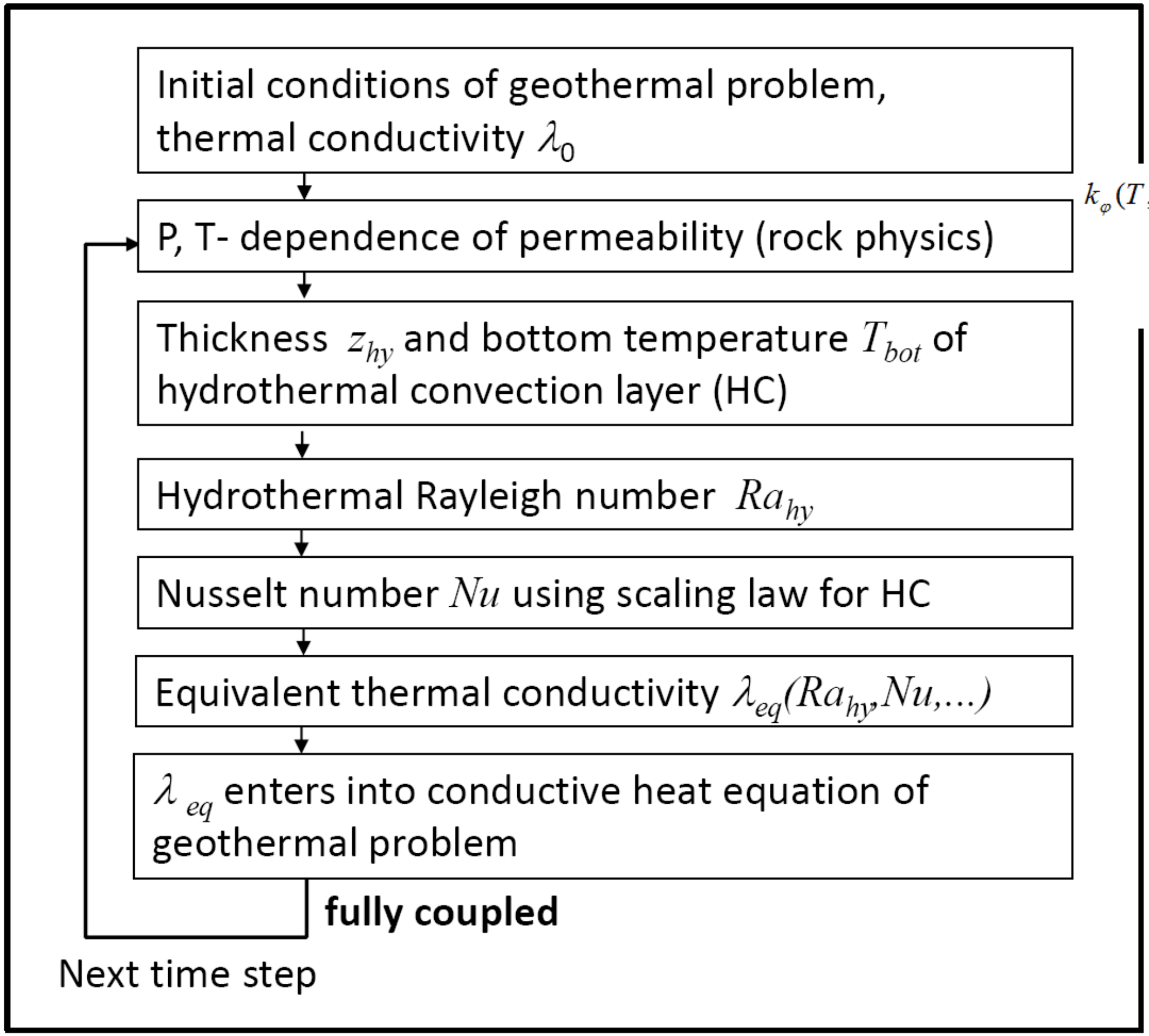
Effect on $\sqrt{t}$ - law?

Fitting observations?

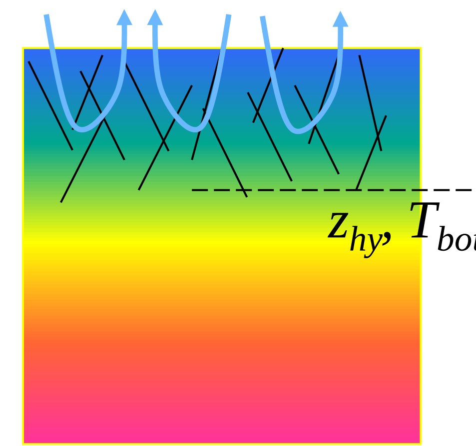


Our approach: Parameterized hydrothermal convection and equivalent conductivity

Schmeling, H, and G. Marquart, 2014: A scaling law for approximating porous hydrothermal convection by an equivalent thermal conductivity: theory and application to the cooling oceanic lithosphere. Geophys. J. Int., 197 (2): 645-664



$$k_\varphi(T,z) = k_{\varphi 0} \cdot [1-\gamma \cdot (T-T_0)]^n \cdot H(1-\gamma \cdot (T-T_0)) \cdot H(T_{duc}-T) \cdot \exp\left(-n \cdot \frac{z}{z_{ch}}\right)$$

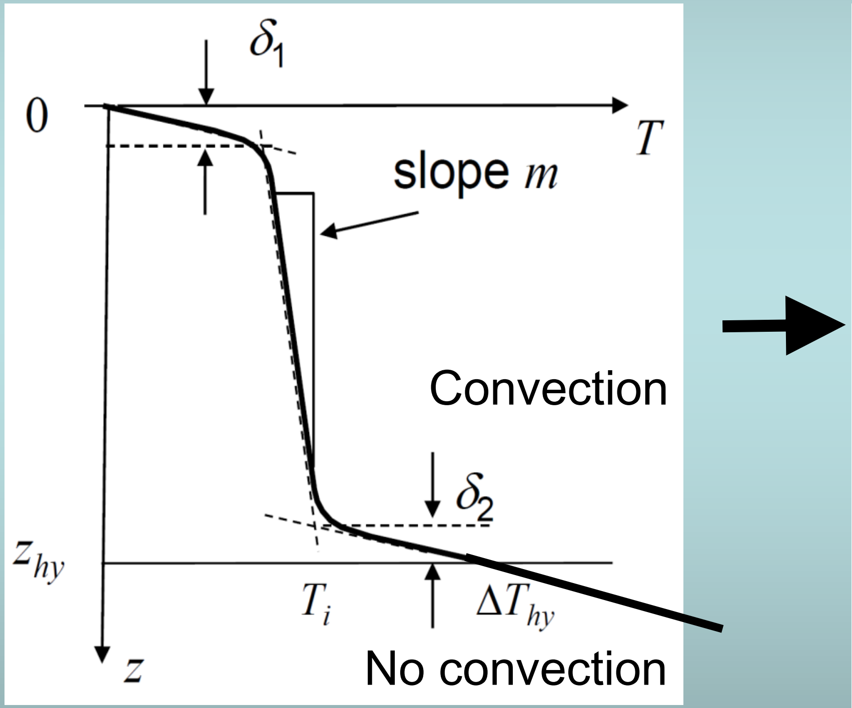


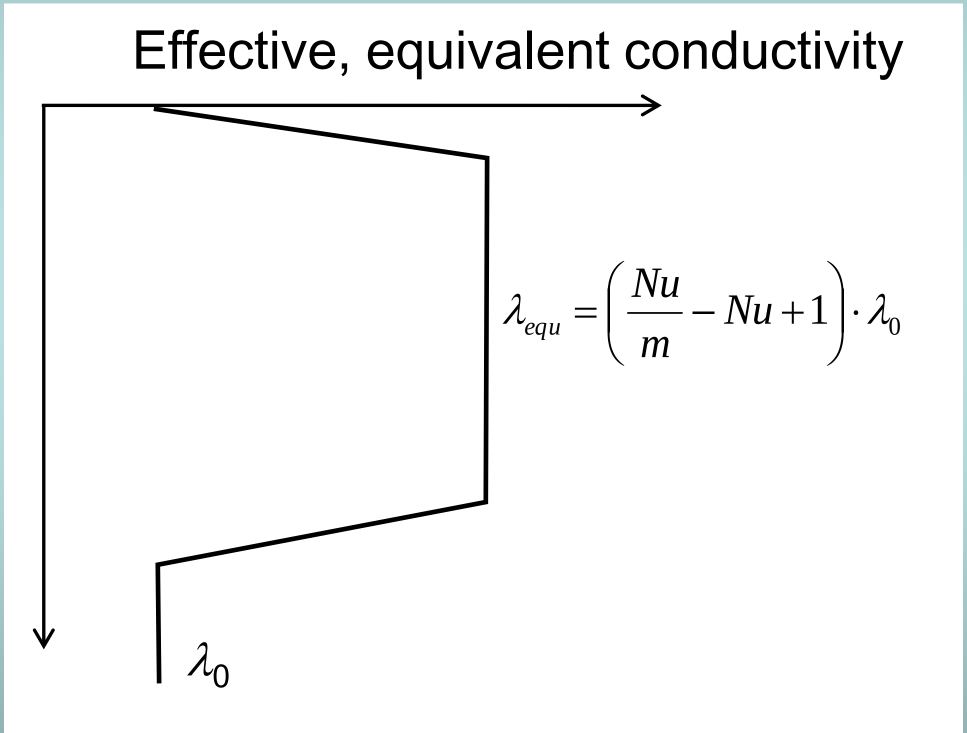
$$Ra_{hy} = \frac{\alpha_f g \rho_f^2 c_{pf} k_{\varphi 0} \Delta T_{hy} z_{hy}}{\lambda_m}$$

$$Nu = \frac{q_{top} z_{hy}}{\lambda_0 \Delta T_{hy}}$$

Equivalent thermal conductivity

Approximate convective layer by conductive layer with an effective, higher thermal conductivity





Solve 1D equation for cooling plate with simulated hydrothermal convection

Conductive 1D heat equation with $\lambda_{eq}(z,t)$ based on Nu, z_{hy} etc from paramaterized hydrothermal convection:

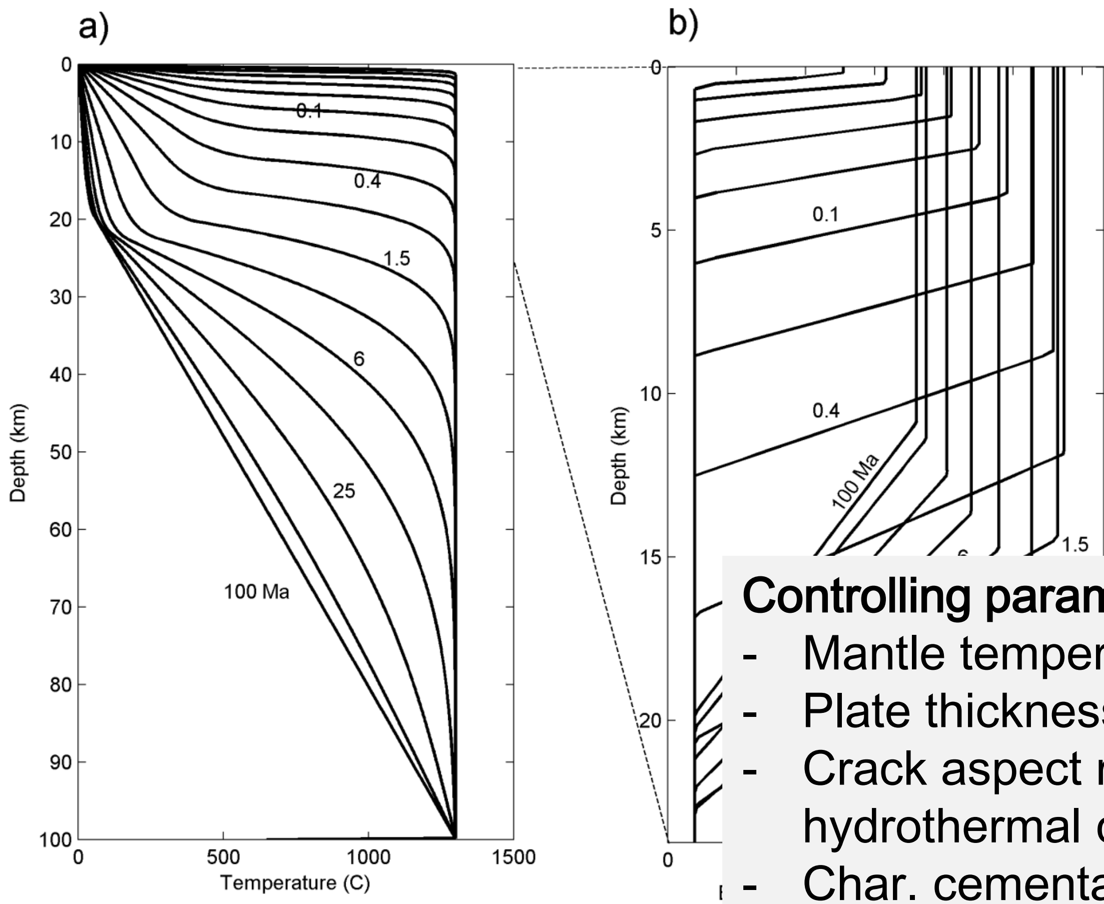
$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_p(T)} \frac{\partial}{\partial z}\left(\lambda_{eq}(Nu,T,z)\frac{\partial T}{\partial z}\right) - \frac{T}{c_p(T)}\frac{\partial c_p(T)}{\partial t}$$

Hydrothermal convection

Time-dependent c_p
→ Few iterations per time step

- Solved with 4th order FD-scheme, foreward in time
- Reduced diffusive time steps due to increased λ_{eq}

Example of cooling plate with simulated hydrothermal convection

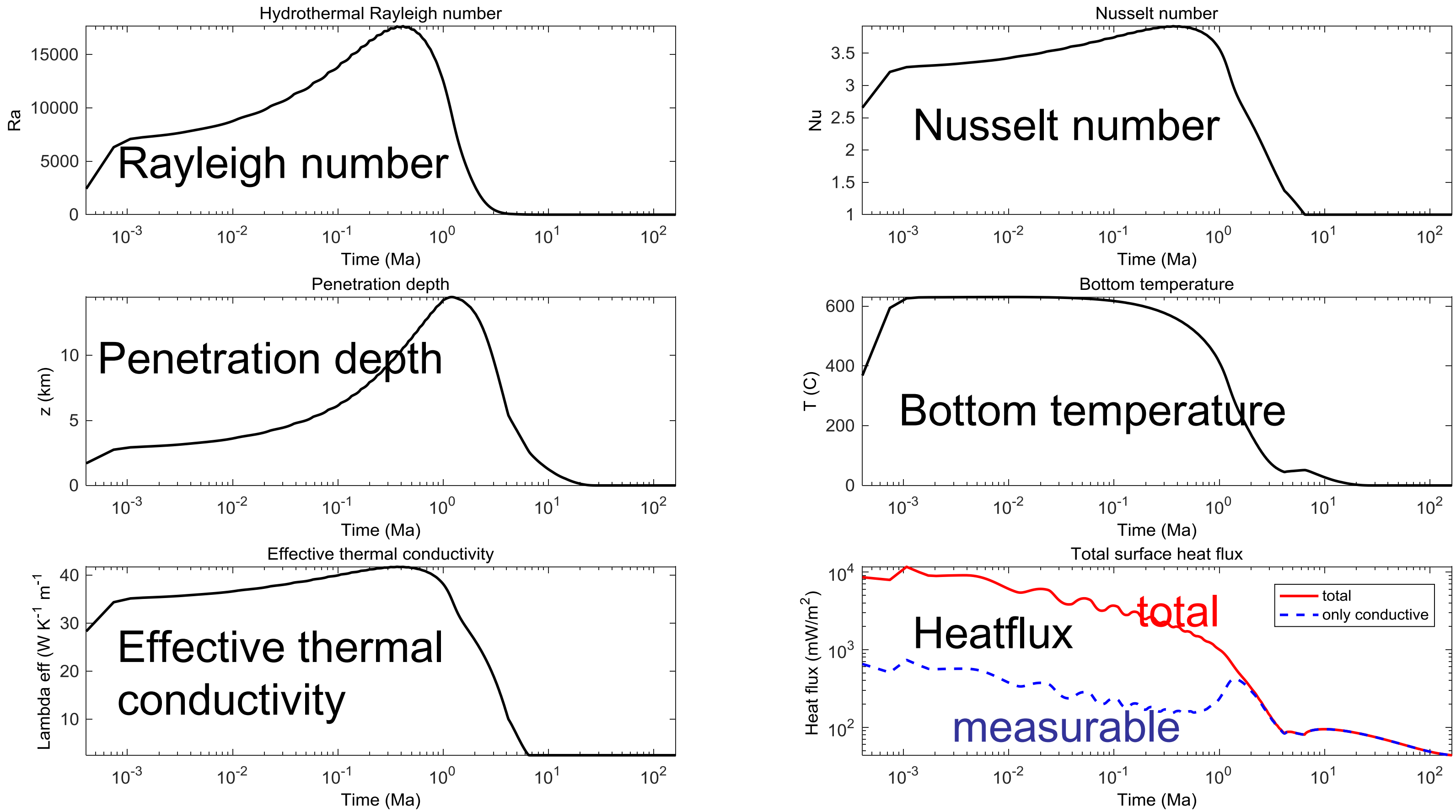


Solving the conductive 1D heat equation with $\lambda_{eff}(z,t)$ based on Nu, z_{hy} etc from paramaterized hydrothermal convection

Controlling parameters:

- Mantle temperature
- Plate thickness
- Crack aspect ratio (controls permeability → hydrothermal convection penetration)
- Char. cementation time ar_{decay}
- Sealing time (open → covered convection)

Time evolution of a typical model



3 Phases:

0 – 1 Ma increasing vigor of hydrothermal convection

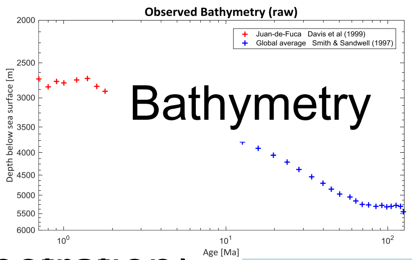
1 – 10 Ma declining convective vigor due to cooling and sealing

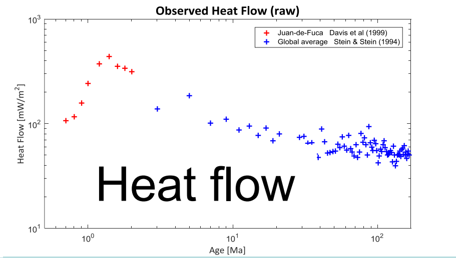
> 10 Ma no convection, only conductive cooling and cementation

Optimizing parameters by downhill simplex inversion

Parameters to be optimized:

Data to be inverted





With hydrothermal convection:

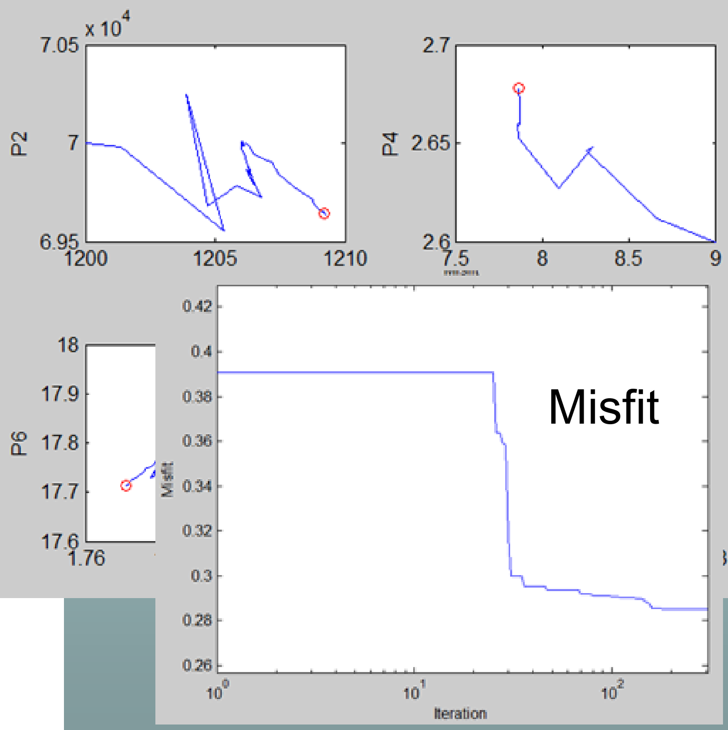
- Mantle temperature
- Plate thickness
- Crack aspect ratio (controls permeability → hydrothermal convection penetration)
- Char. cementation time ar_{decay}
- Sealing time (open → covered convection)
- Prefactor thermal expansivity of lithosphere

Without hydrothermal convection:

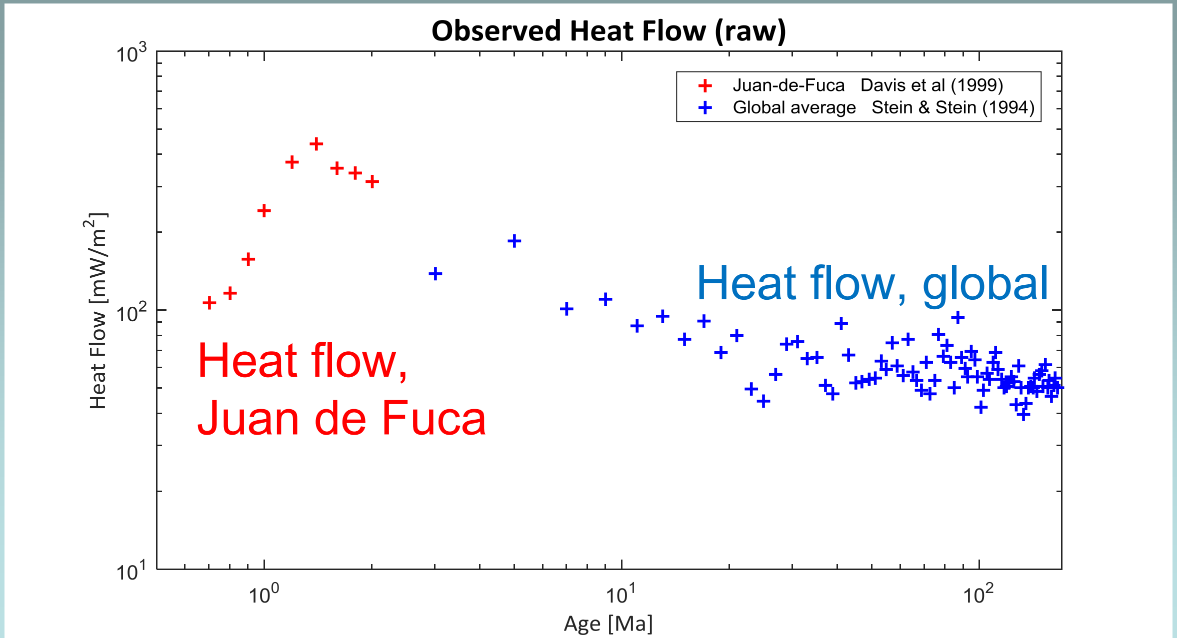
- Mantle temperature
- Plate thickness
- Thermal expansivity of lith

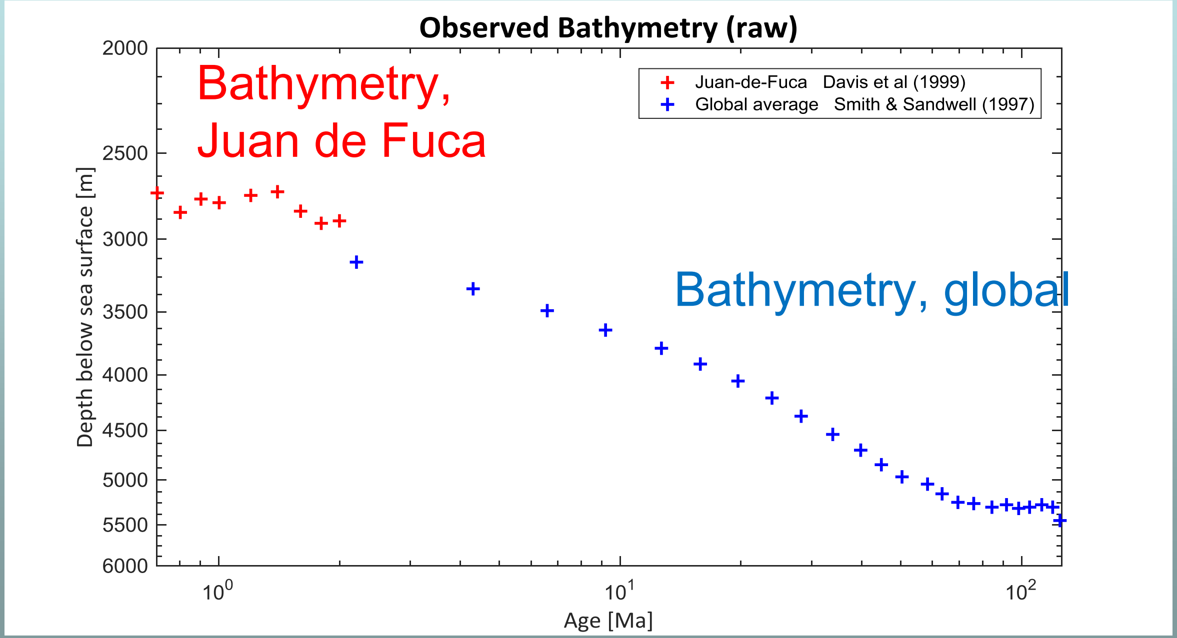
- Downhill simplex inversion run: typically 400 models
- Depends on choice of starting parameters → 200 rur → O(80 000) cooling models

Stronger weight (factor 5) for young lithosph

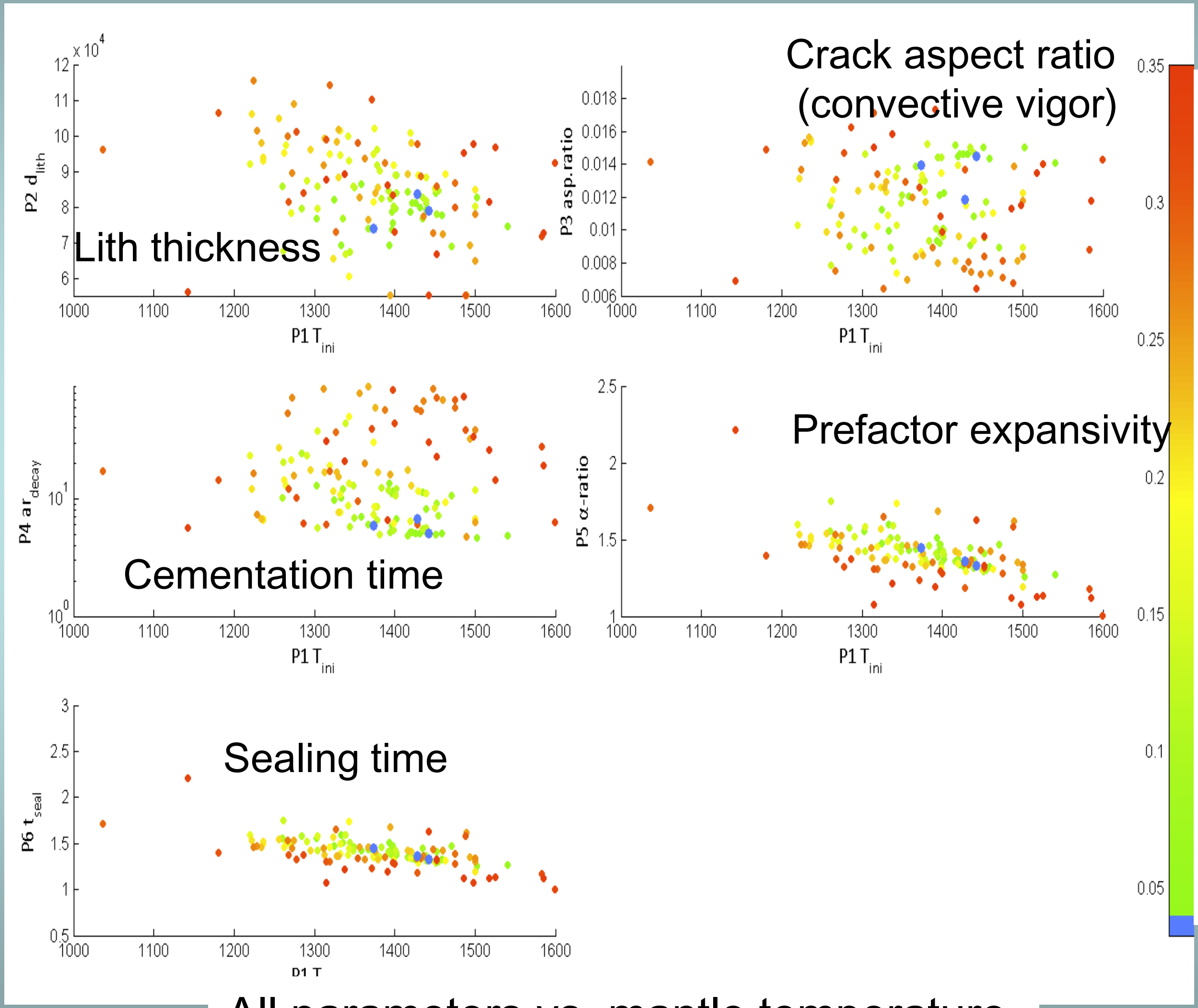


Data to be inverted





Different projections of best models within parameter space



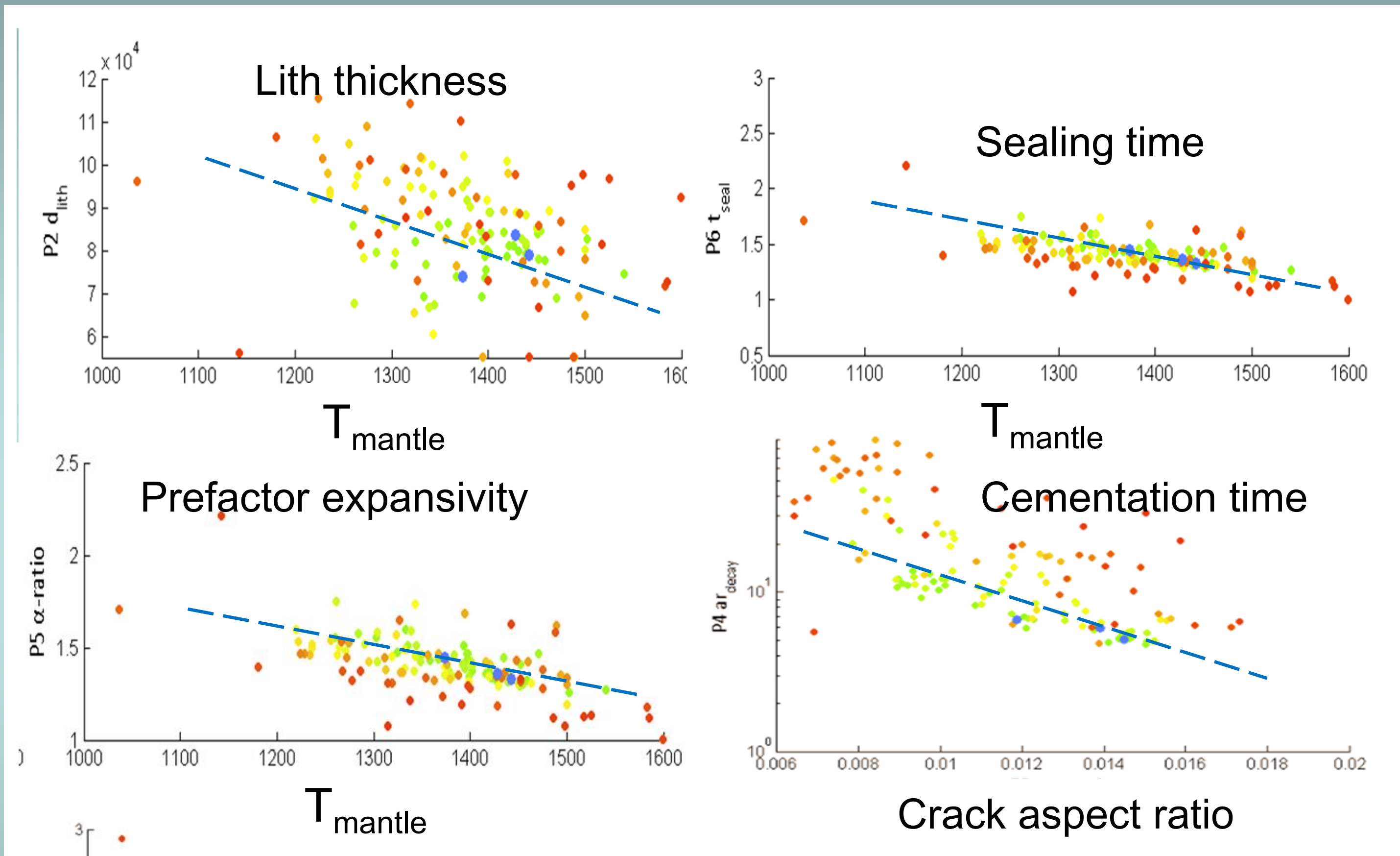
All parameters vs. mantle temperature

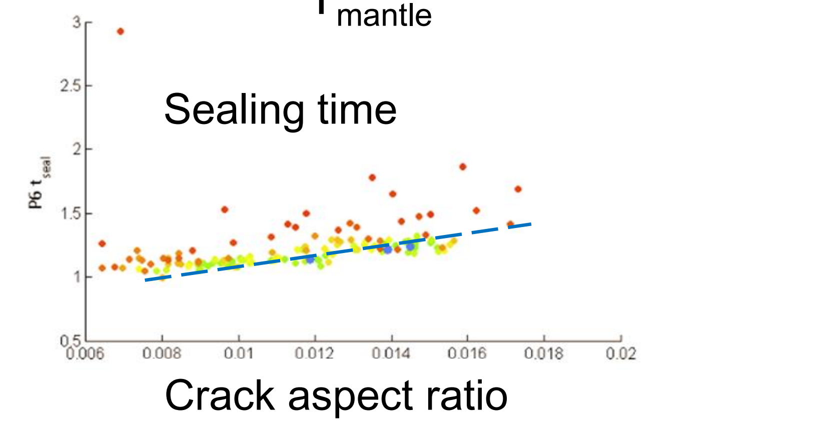
→ **Many local minima in 6D parameter space**

Best parameters

- 1350 – 1450 °C mantle
- 70 – 90 km lithosphere
- 0.01 – 0.015 aspect ratio, i.e. a narrow range of convective vigor
- 5 – 10 Ma cementation time
- Narrow range sealing time 1.3 – 1.6 Ma
- 1.3 – 1.5 prefactor lith expansivity

Tradoffs for different projections

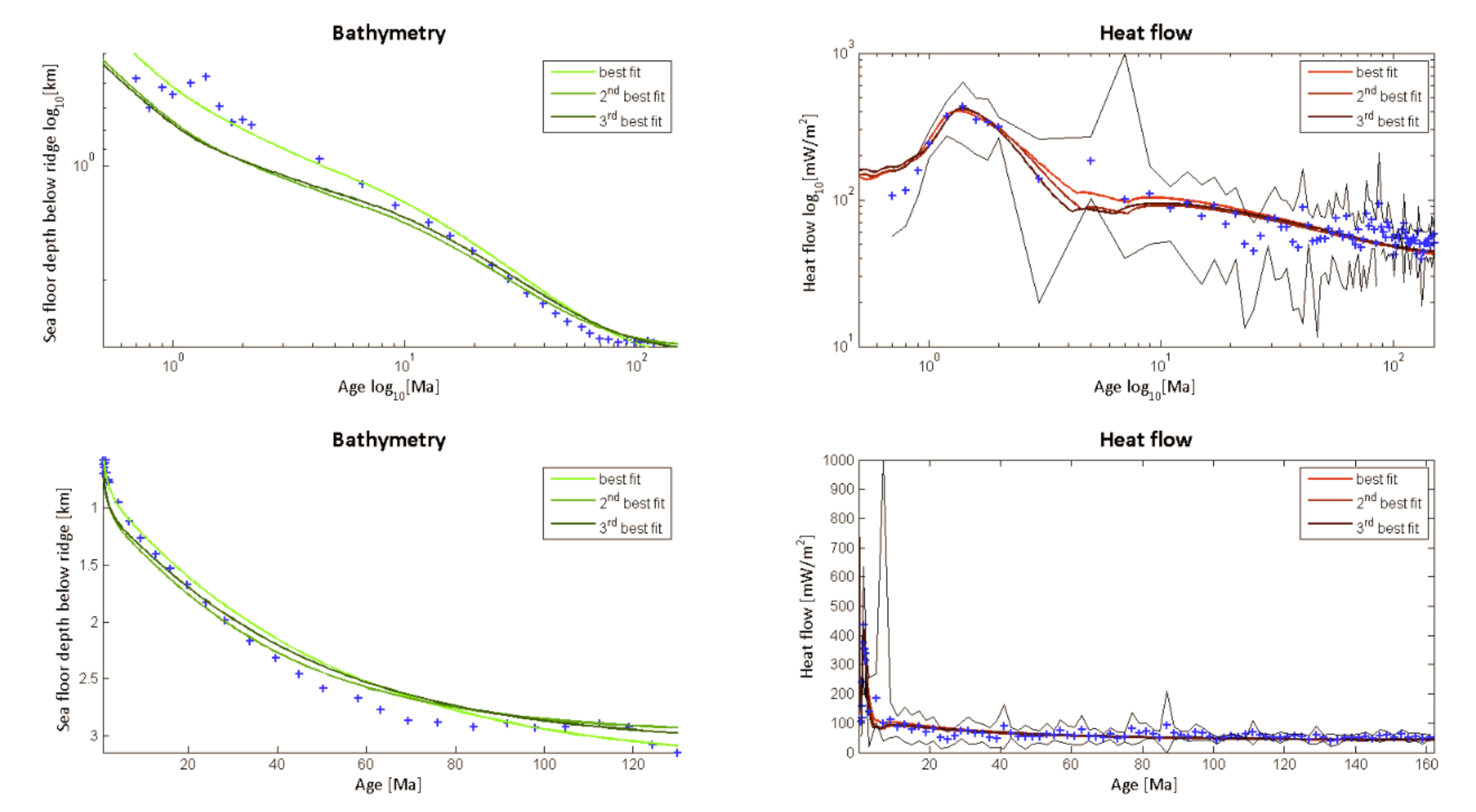




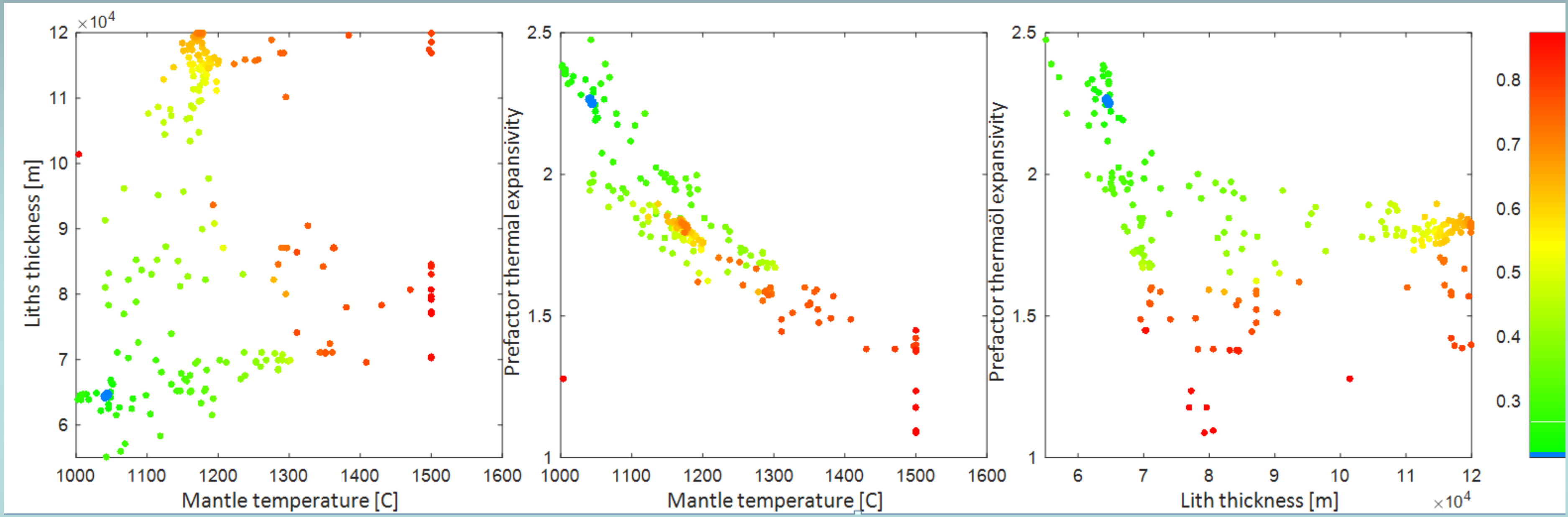
Tradeoffs:

- d_{lith} – T_{mantle} (?)
- Thermal expansivity – T_{mantle}
- Sealing time – T_{mantle}
- Crack aspect ratio - sealing time
- Cementation time – aspect ratio

3 best models and the observations



Inversion without allowing for hydrothermal convection



Without hydrothermal convection

- T_{mantle} 1000 – 1200C
- Lith thickness 60 – 85 km
- Prefactor expansivity 1.6 – 2.4
- Misfit never below 0.2

With hydrothermal convection

- T_{mantle} 1350 – 1450 C
- Lith thickness 70 – 90 km
- Prefactor expansivity1.3 – 1.5
- Misfit down to 0.03

Conclusions

- Self-consistent modelling: Mostly symmetric spreading with and without ridge migration for many spreading velocities, plasticity factors, even asymmetric temperatures
- Both MOR and models show asymmetric spreading up to 15%
- MOR slighty slows down when approaching and overriding the plume
- Physics of observed asymmetric spreading (lava lakes) not clear

- Lithospheric cooling with hydrothermal convection → significantly better fit of bathymetry and heatflux for young plates
- T_{mantle} 1350 – 1450 °C, Lith thickness 70 – 90 km
- Prefactor expansivity 1.3 – 1.5 (i.e. higher than from lab experiments)
- Sealing time 1.3 – 1.6 Ma, cementation time 5 – 10 Ma

Thank you for your attention