Hydrothermal cooling of the oceanic lithosphere and the square root age law

using parameterized porous convection

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

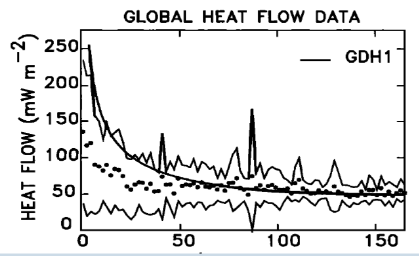
see also:

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 doi:10.1093/gji/ggu022

Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

Overview:
Cooling of the oceanic lithosphere follows approximately the $\sqrt{t} - \text{law}$, but significant deviations imply the importance of hydrothermal convection. Here we include hydrothermal convection into models of lithospheric plate cooling using a new approach.



1/3

Introduction
- Heatflow of the earth
- The $\sqrt{t} - law$

New approach
Approximating hydrothermal convection by an equivalent thermal conductivity based on parameterized convection

Result
Cooling plate with hydrothermal convection

Deviation from $\sqrt{t} - law$:
→ Measurable heat flow
→ Increased total heat loss

Sedimentary sealing of the ocean floor at a given age

Effect on Bathymetry

see also:
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 doi:10.1093/gji/ggu022

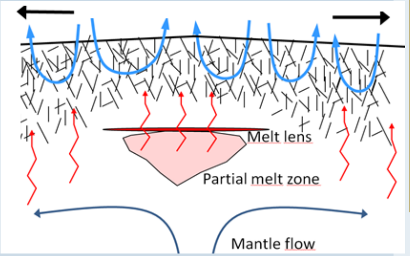
Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Introduction
- Heatflow of the earth
- The $\sqrt{t} - law$

Overview:
2D porous convection models with depth-dependent permeability are used to derive **parameterized convection** scaling laws. From these laws an equivalent thermal conductivity is employed in conductive cooling models of the lithosphere mimicking hydrothermal cooling.



2/3

New approach
Approximating hydrothermal convection by an equivalent thermal conductivity based on parameterized convection

Result
Cooling plate with hydrothermal convection

Sedimentary sealing of the ocean floor at a given age

Deviation from $\sqrt{t} - law$:
→ Measurable heat flow
→ Increased total heat loss

Effect on Bathymetry

see also:
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 doi:10.1093/gji/ggu022

Hydrothermal cooling of the oceanic lithosphere and the square root age law

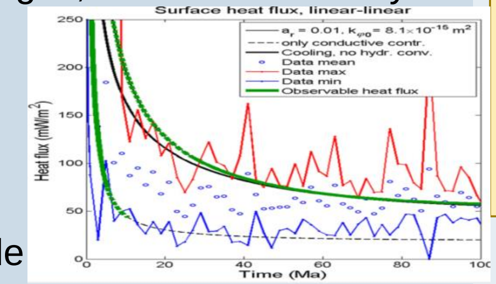
H. Schmeling[1] and G. Marquart[2],
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Introduction

- Heatflow of the earth
- The $\sqrt{t} - law$

Overview:
Hydrothermal convection **increases the total heat flux and loss** with respect to the classical $\sqrt{t} - \mathrm{law}$. At young ages, heat flow data may miss the hydrothermal contribution, at high ages sediment cover most likely changes the hydrothermal cooling mode



3/3

New approach

Approximating hydrothermal convection by an equivalent thermal conductivity based on parameterized convection

Clicking on the boxes gives details and figures

Result

Cooling plate with hydrothermal convection

Clicking on the boxes gives details and figures

Sedimentary sealing of the ocean floor at a given age

Deviation from $\sqrt{t} - law$:
→ Measurable heat flow
→ Increased total heat loss

Effect on Bathymetry

see also:
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 doi:10.1093/gji/ggu022

Hydrothermal cooling of the oceanic lithosphere and the square root age law

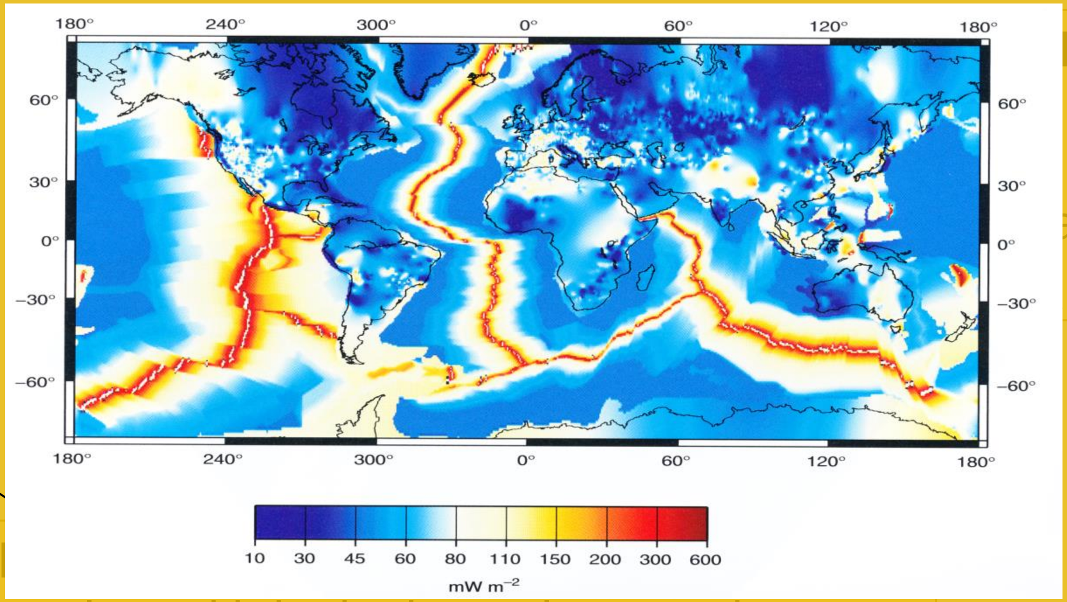
H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

www.goethe-universitaet.de

X

Introduction
- Heatflow of the earth
- The $\sqrt{t} - law$



This map shows the global heat flow data (Jaupart & Mareshal, 2011)
- Continents: heat flow measurements
- Oceanic lithosphere: plate cooling model assumed, thus hydrothermal cooling is not included

h
hydrothermal
an equivalent thermal
ased on parameterized

Resul
Cooling plate with hydrothermal convection

Sedimentary sealing of the ocean floor at a given age

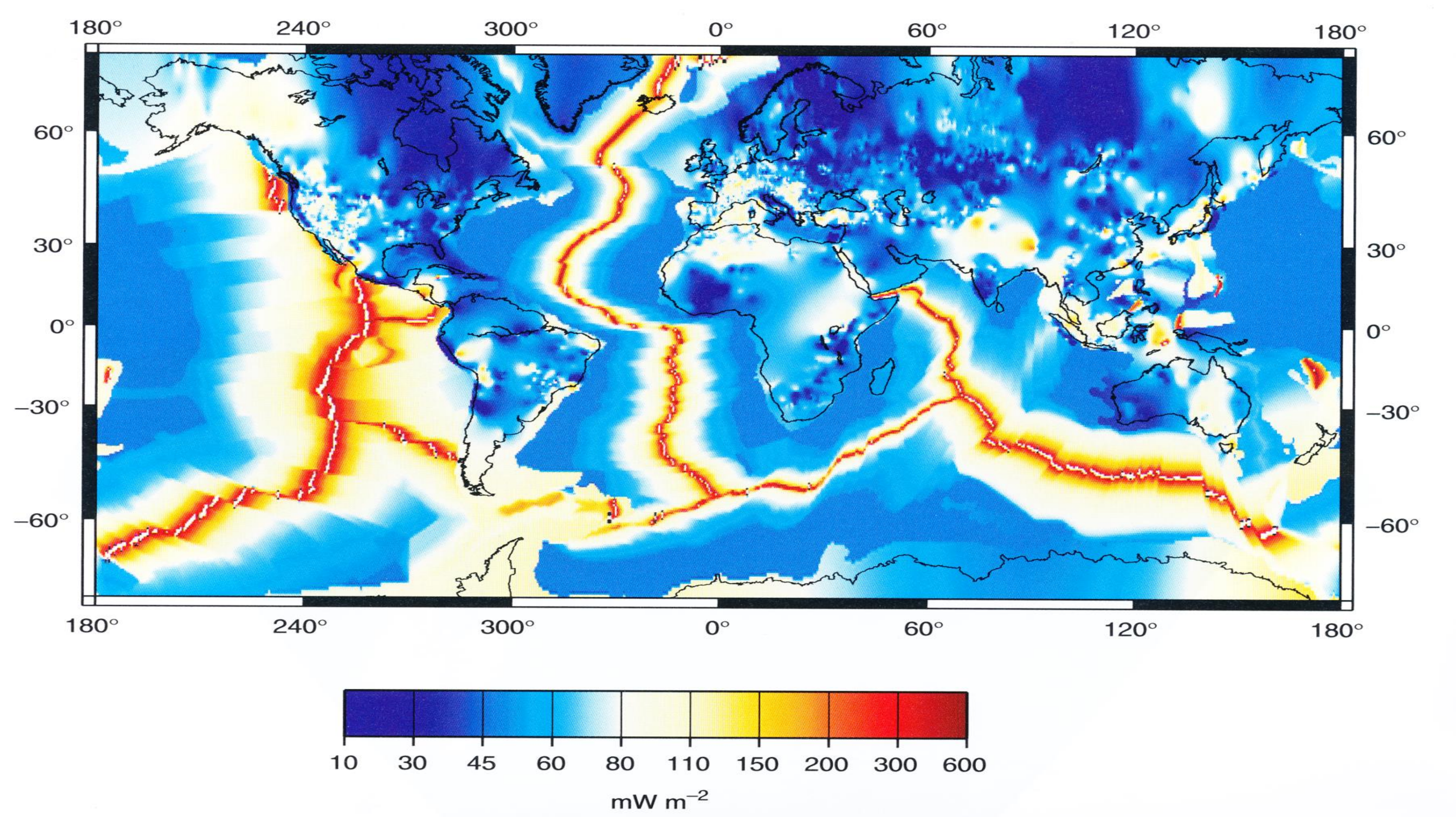
Deviation from
→ Measurable
→ Increased total heat loss

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Global heat flow data

X



Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

www.goethe-universitaet.de

Introduction

- Heatflow of the earth
- The $\sqrt{t} - law$

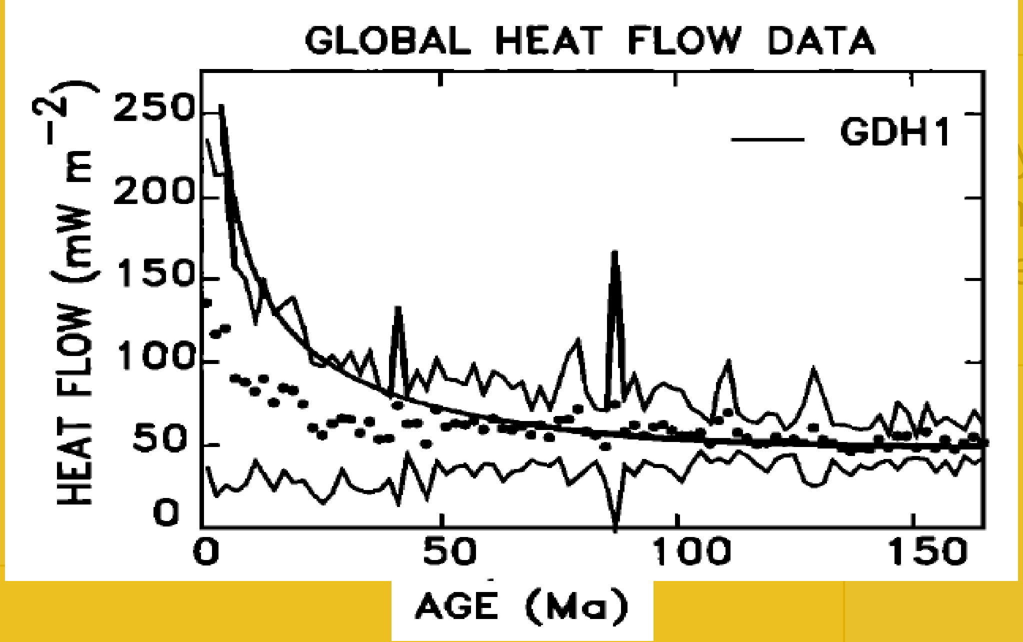
Result
Cooling plate with hydrothermal convection

Sedimentary sealing of the ocean floor at a given age

Deviat…
→ Mea…
→ Incr…

…ydrothermal
… equivalent thermal
…ed on parameterized

X



From Stein and Stein, 1994
Global heat flow measurements have been compiled and plotted as a function of age (dots) with their upper and lower bounds.
The conductive plate cooling model GDH1 is shown for comparison. At ages less than 40 Ma the observations are below the cooling model, indicating that the hydrothermal contrinution may have been missed

Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

Introduction

- Heatflow of the earth
- The $\sqrt{t} - law$

Result
Cooling

Sedimentary sealing of the ocean floor at a given age

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)

→ the conductive $\sqrt{t}$ - law needs to be modified

→ no cooling plate model exists which consistently includes hydrothermal convection

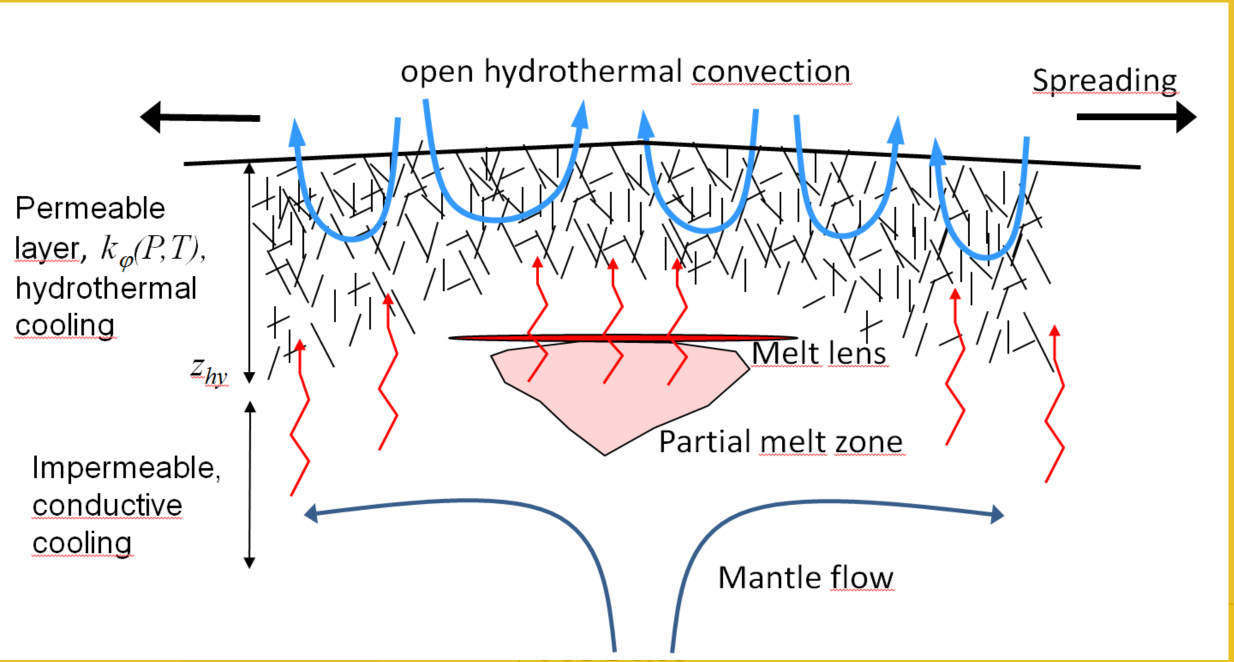
Effect on $\sqrt{t}$ - law?

Right: Black or white smokers at the bottom of mid oceanic ridged impressively demonstra... how much heat may be lost b... hydrothermal convection

X

Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2]
[1]Goethe University Frankfurt, [2]RWTH Aachen



X

New approach
Approximating hydrothermal convection by an equivalent thermal conductivity based on parameterized convection

Cooling plate with hydrothermal convection

- Thermal contraction due to cooling from above produces cracks → permeable layer
- Penetration of hydrothermal fluids amplify cooling
- Permeability is a function of temperature (thermal contraction) and pressure (compaction)
- Total penetration depth, z_{hy}, is a function of cooling history

→ Consistent cooling model should include feedback between cooling – P-T-dependent permeability and porous convection

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

Flow chart of approach

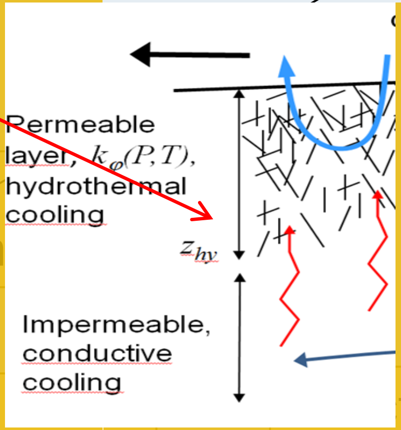
X

- Initial conditions of geothermal problem, thermal conductivity λ_0
- P, T- dependence of permeability (rock physics) — Details
- Thickness z_{hy} and bottom temperature T_{bot} of hydrothermal convection layer (HC) — Details
- Hydrothermal Rayleigh number Ra_{hy}
- Nusselt number Nu using scaling law for HC — Details
- Equivalent thermal conductivity $\lambda_{eq}(Ra_{hy}, Nu, \ldots)$ — Details
- λ_{eq} enters into conductive heat equation of geothermal problem

fully coupled

Next time step

New approach
Approximating hydrothermal convection by an equivalent thermal conductivity based on parameterized convection

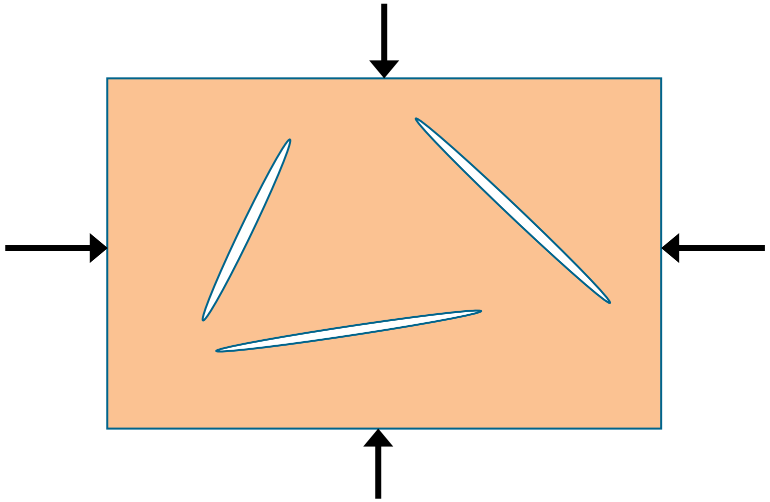


$$Ra_{hy} = \frac{\alpha_f g \rho_f^2 c_{pf} k_{\varphi 0} \Delta T_{hy} z_{hy}}{\eta_f \lambda_m}$$

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

Details of approach: P – T – dependent porosity and permeability

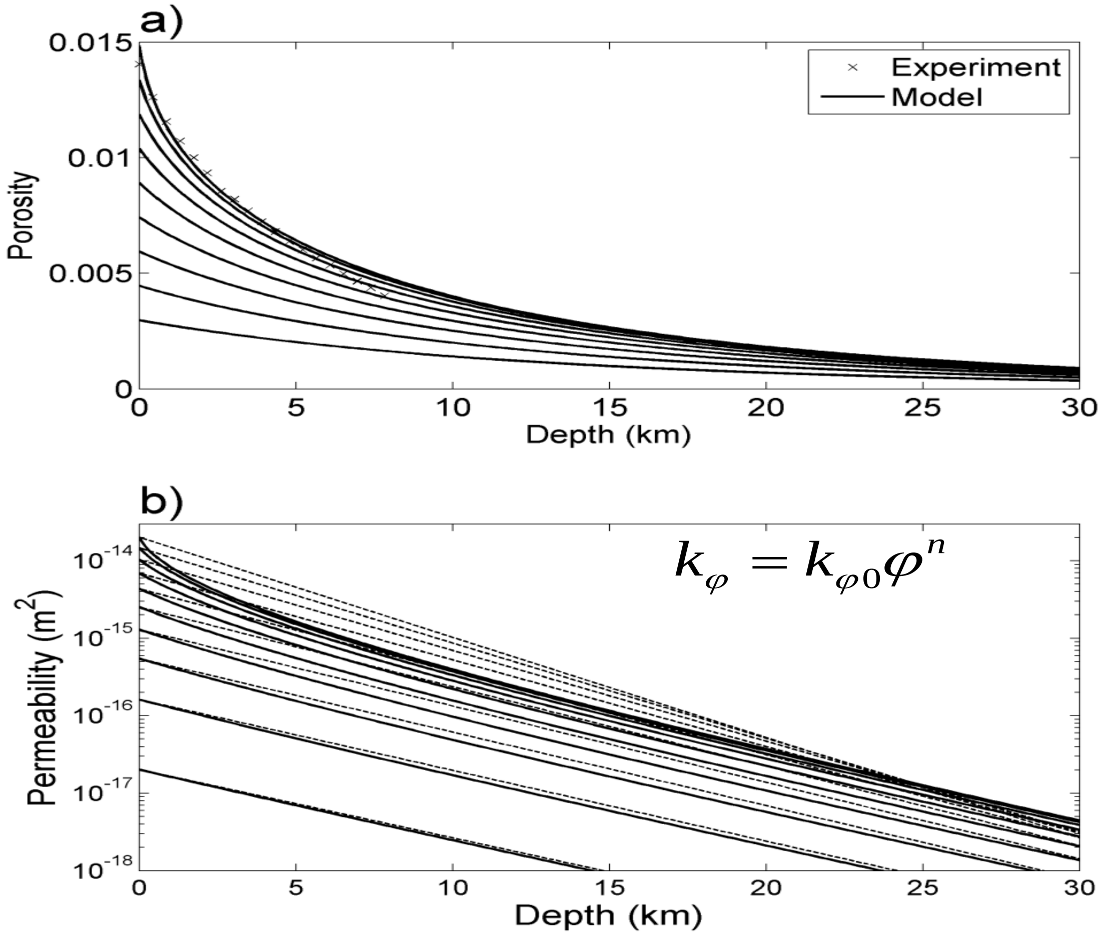
Effect of pressure from elastic crack model (based on Schmeling(1986))



Crack porosity

$$\varphi(z) = \varphi_0 \cdot \exp\left(-\frac{z}{z_{ch}}\right)$$

$$z_{ch} = \frac{\tilde{a}_{r0} K_0}{(\bar{\rho} - \rho_f) g} \cdot \left(1 - c_{fit} \frac{1 - c_v}{\tilde{a}_{r0}} \cdot \varphi_0 \cdot \left(1 - \frac{1}{e}\right)\right)$$



Details of approach: P – T – dependent porosity and permeability

Pore closure by thermal expansion at const volume and relaxed thermal stress

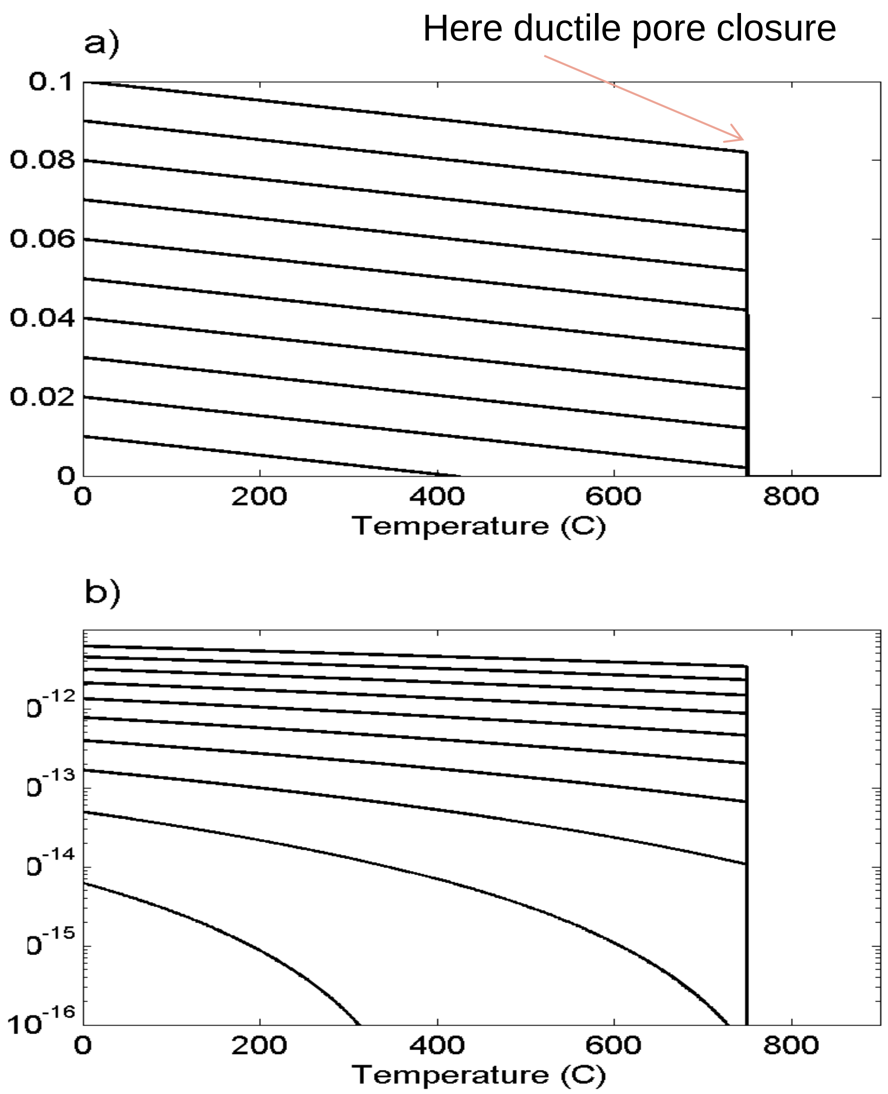
Germanovich et al. (2000)

and ductile creep

The final permeability law

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

$\gamma = \alpha_r/\varphi_0$ thermal expansivity / surface porosity
n = permeabilty – porosity law power exponent
H – Heaviside function



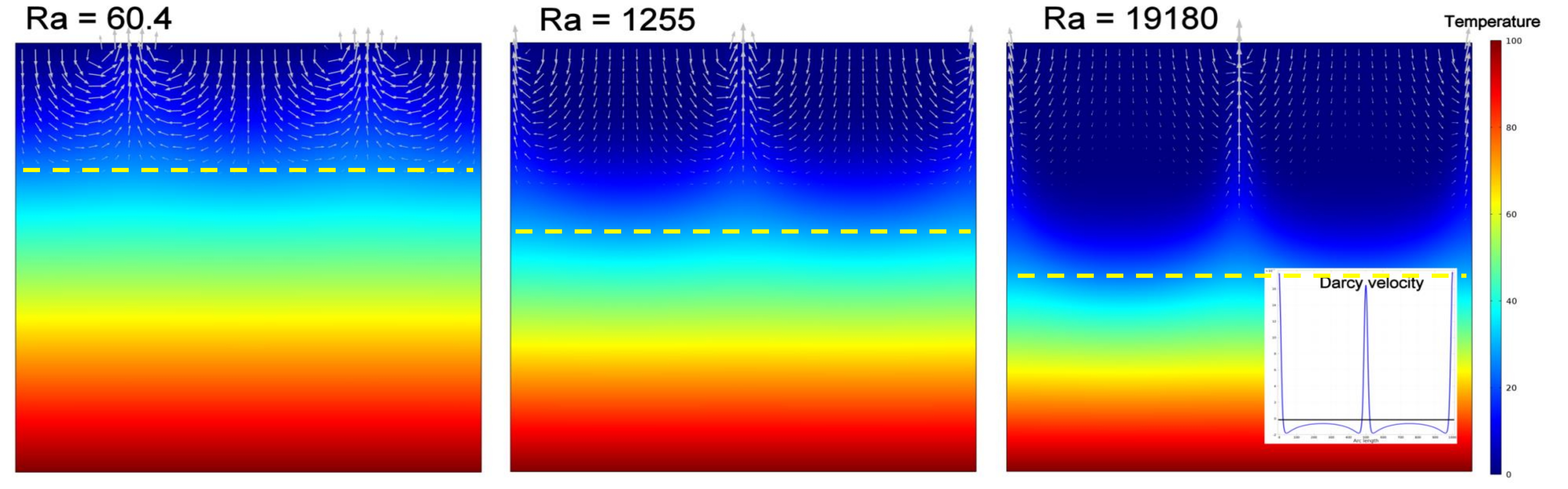
X

Details approach: Deriving a scaling law $Nu - Ra$ and c_{kthr}

Convection experiments with permeable surface, representing regions near the ridge axis

- 2-D hydrothermal convection experiments using the FEM code COMSOL
- Depth-dependent permeability
- Dashed lines show penetration depth of porous convection → determine z_{hy}, T_{bot}, $k_{\varphi bot}$
- Heat flow at surface → $Nu(Ra)$

$$k_{\varphi}(z) = k_{\varphi 0} \cdot \exp\left(-n \cdot \frac{z}{z_{ch}}\right)$$



Details to determine penetration depth, bottom temperature

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

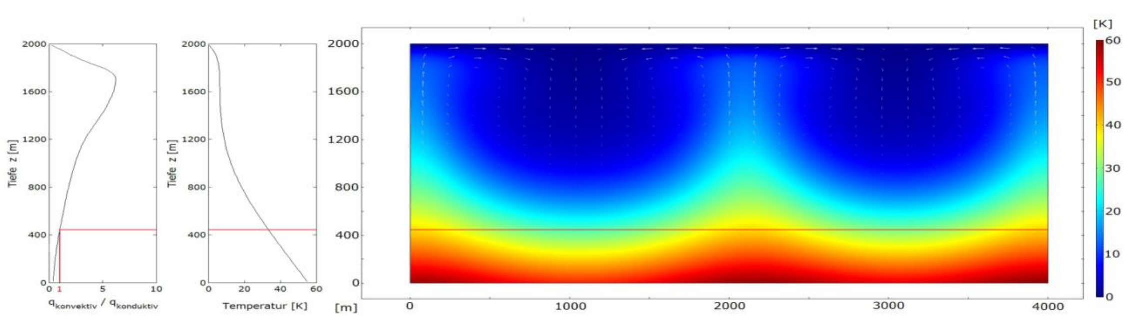
X

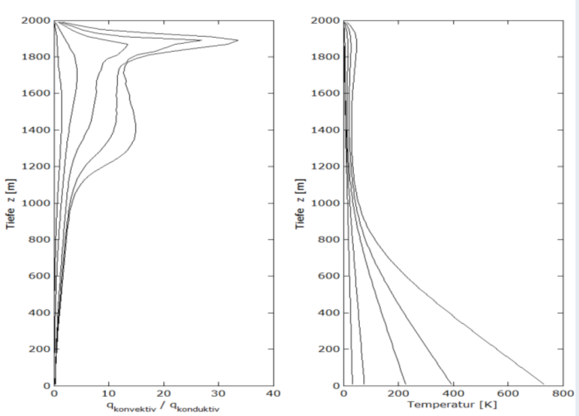
Convection experiments with impermeable surface, representing regions far from the ridge axis

- 2-D hydrothermal convection experiments using the FEM code COMSOL
- Depth-dependent permeability
- Red lines show penetration depth of porous convection → determine z_{hy} , T_{bot}, $k_{\varphi bot}$
- Heat flow at surface → $Nu(Ra)$

$$k_\varphi(z) = k_{\varphi 0} \cdot \exp\left(-n \cdot \frac{z}{z_{ch}}\right)$$

Click on images to enlarge





Details to determine penetration depth, bottom temperature

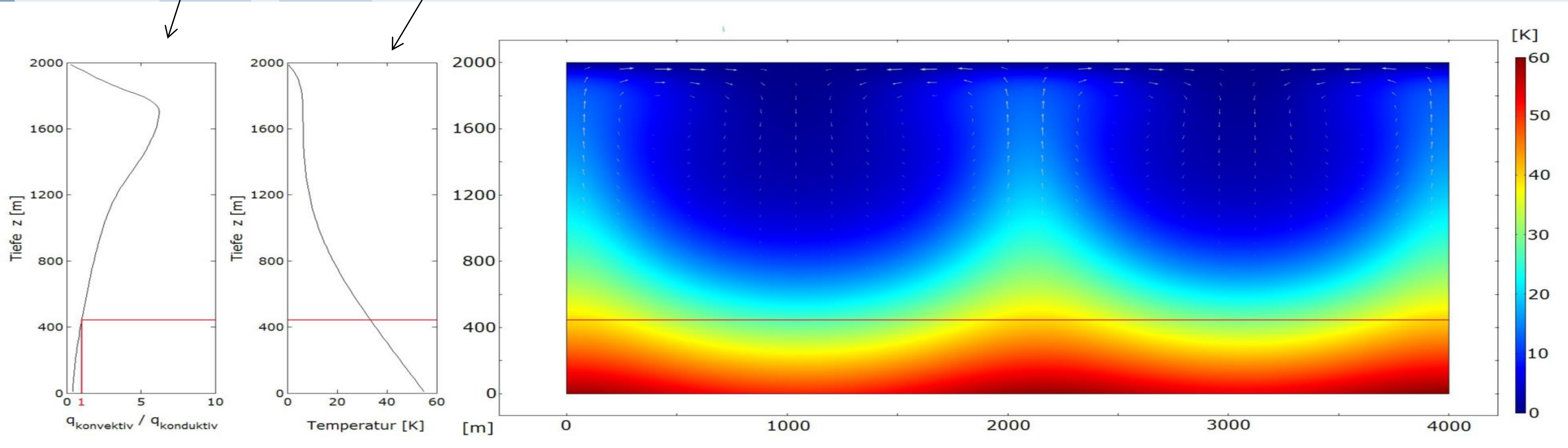
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

X

Horizontally averaged advective / conductive heat flow. Convective penetration depth is defined by the depth at which this ratio equals 1

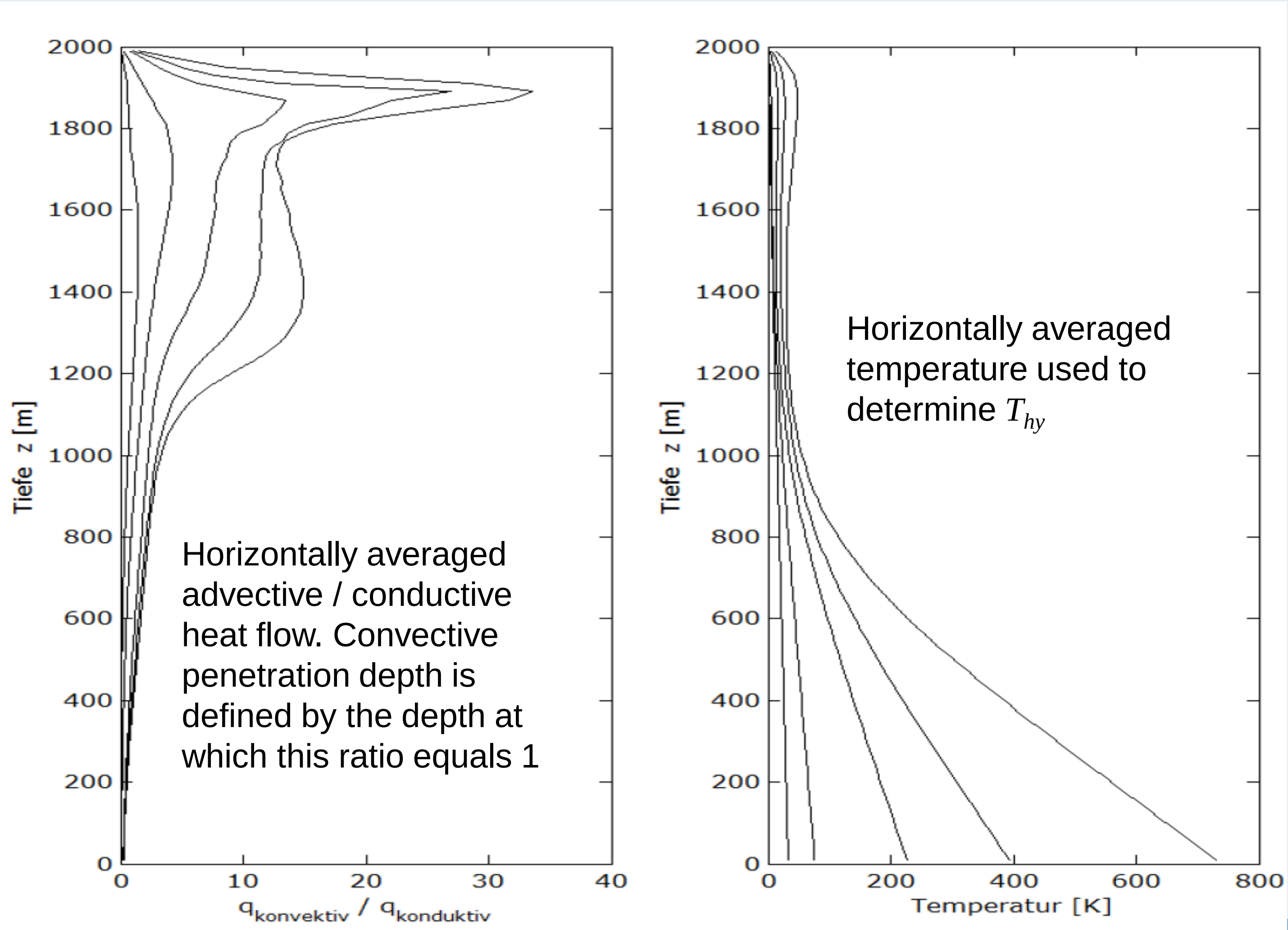
Horizontally averaged temperature used to determine T_{hy}

Example of a 2D model with impermeable top boundary and heat flux bottom boundary condition



Details to determine penetration depth, bottom temperature

Compilation of profiles for different Rayleigh numbers



Derived scaling laws

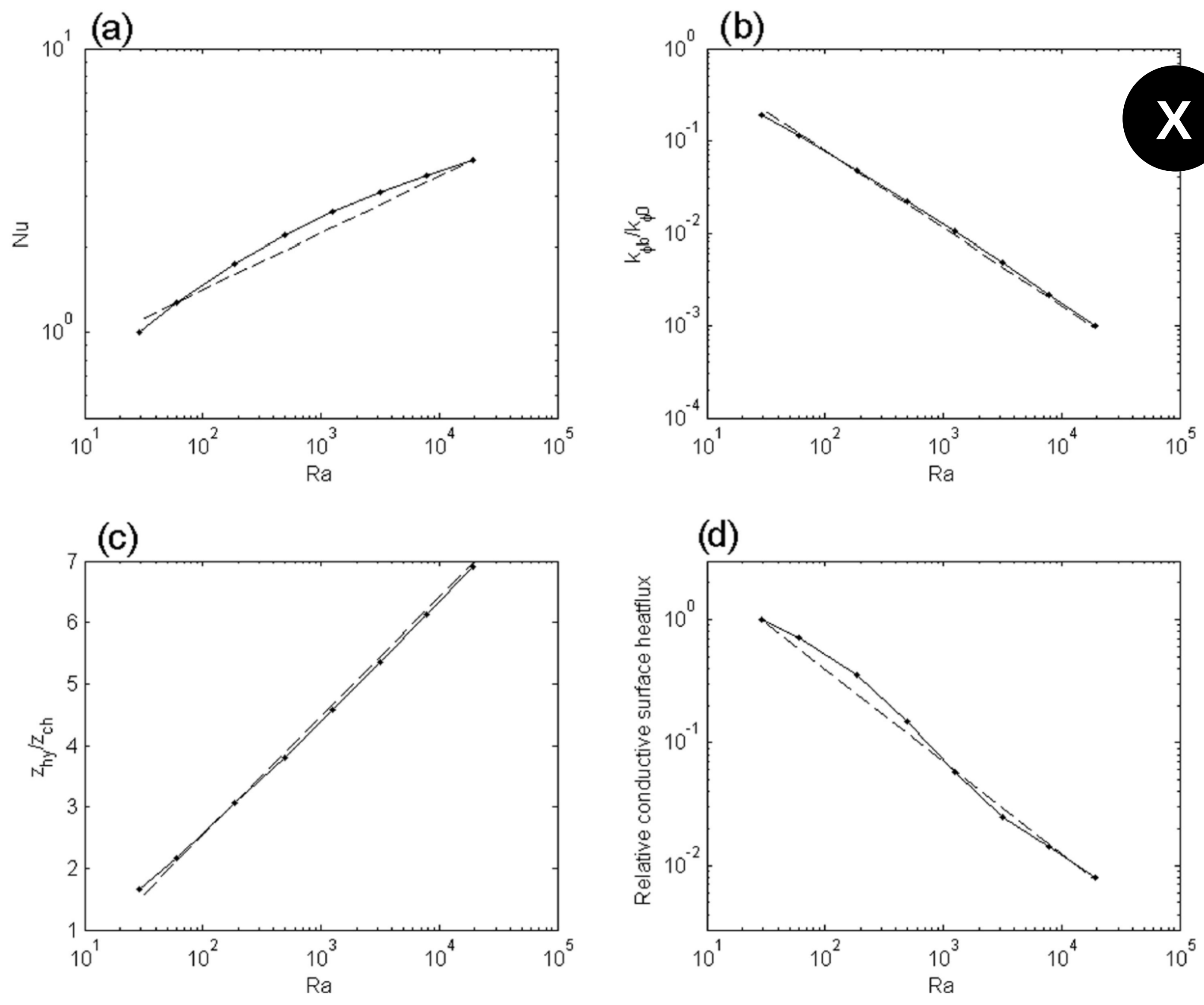
$$k_{\varphi}(z) = k_{\varphi 0} \cdot \exp\left(- n \cdot \frac{z}{z_{ch}} \right)$$

From the numerical experiments scaling laws for hydrothermal convection with depth-dependent permeability are derived.

- They show a surprisingly low exponent of 0.2 for the Nu – Ra relationship
- With increasing Ra the penetration depth increases
- With increasing Ra the conductive (measurable) contri bution to the total heat flux decreases

$$Nu = c_{Nu} \, Ra_{hy}^{\beta_{Nu}}, \quad \beta_{Nu} = 0.2$$

$$k_{\varphi b} / k_{\varphi 0} = c_k \, Ra_{hy}^{\beta_k}$$



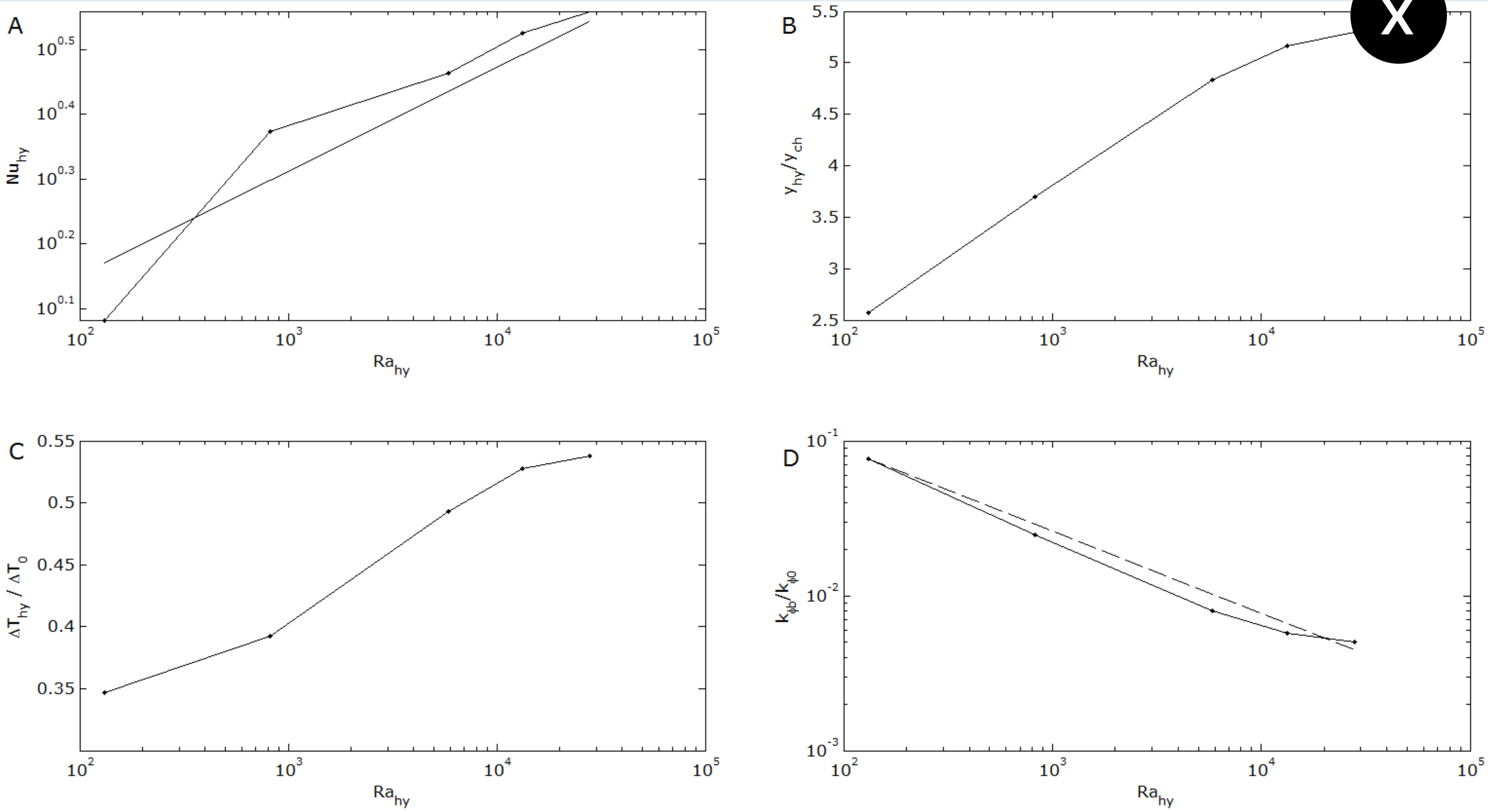
X

Click here for the impermeable case

GOETHE

Derived scaling laws

Similar scaling laws are derived for experiments with impermeable upper boundary. They show a somewhat weaker magnitude of convection.



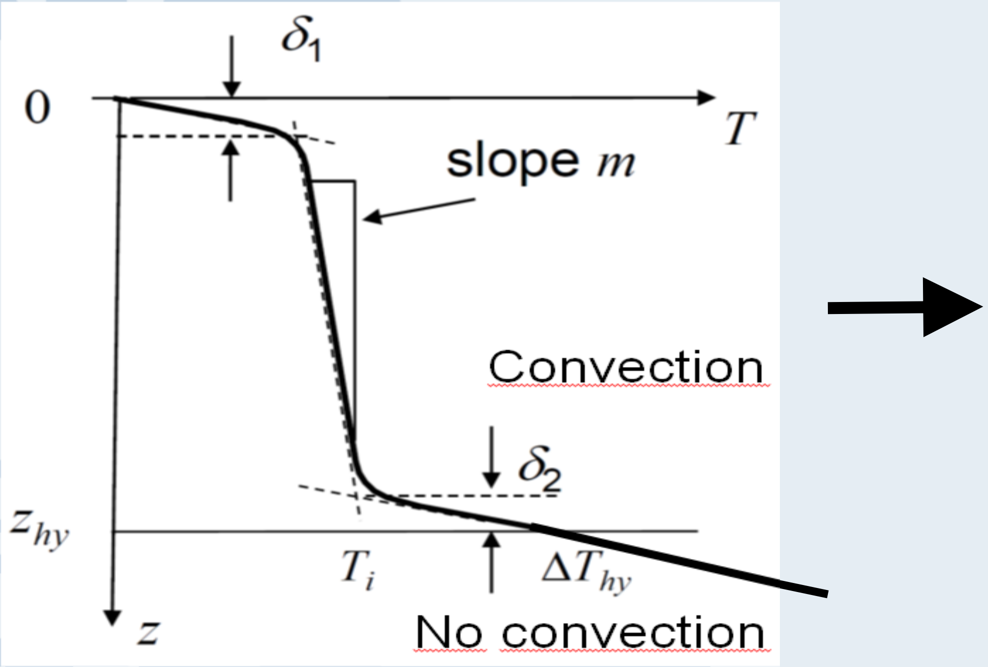
Equivalent thermal conductivity

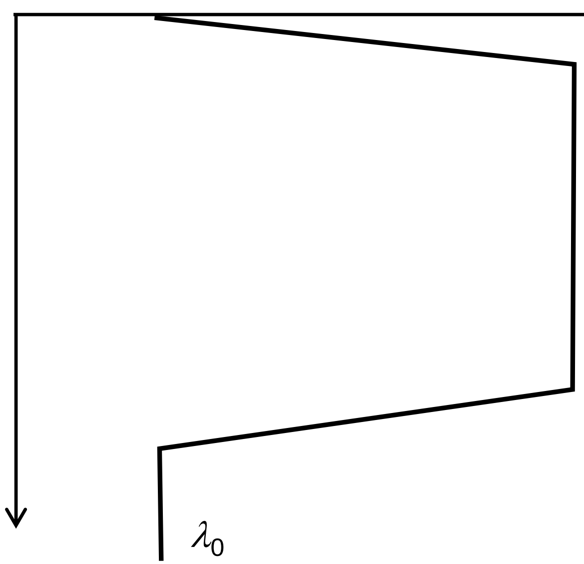
X

Given the Rayleigh number, z_{hy} and Nu are obtained from the scaling laws and are used to detemine an equivalent thermal conductivity within the depth interval down to z_{hy}.

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

The thermal boundary layers are correctly included by the transitition regions between λ_0 and λ_{equ} .
A finite slope m is assumed avoiding numerical problems in case of high Rayleigh number.





$$\lambda_{equ} = \left(\frac{Nu}{m} - Nu + 1 \right) \cdot \lambda_0$$

Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

X

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

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

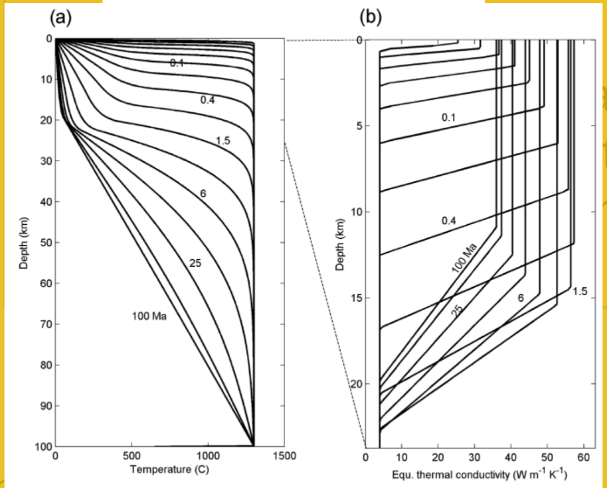
Intro

- He
- Th

Controlling parameters:
$k_{\varphi 0}$ surface permeability (8 10^{-14} m^2 (2.4 %))
a_r Crack aspect ratio (0.01)
Initial temperature 1300°C
Surface temperature 0°C

Results: click on figures

Temperatur profiles



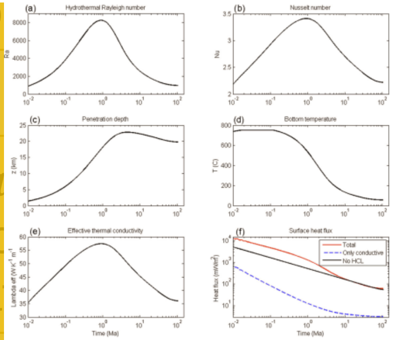
al
t thermal
meterized

Result
Cooling plate with hydrothermal convectio

Sedimentary sealing of the ocean floor at a given age

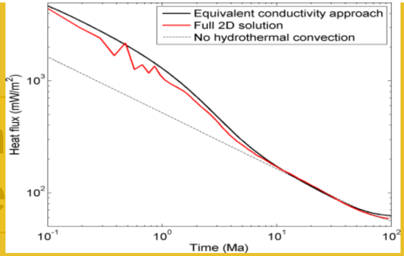
Deviation from $\sqrt{t}$ – la
→ Measurable heat flo
→ Increased total hea

Evolution of parameters



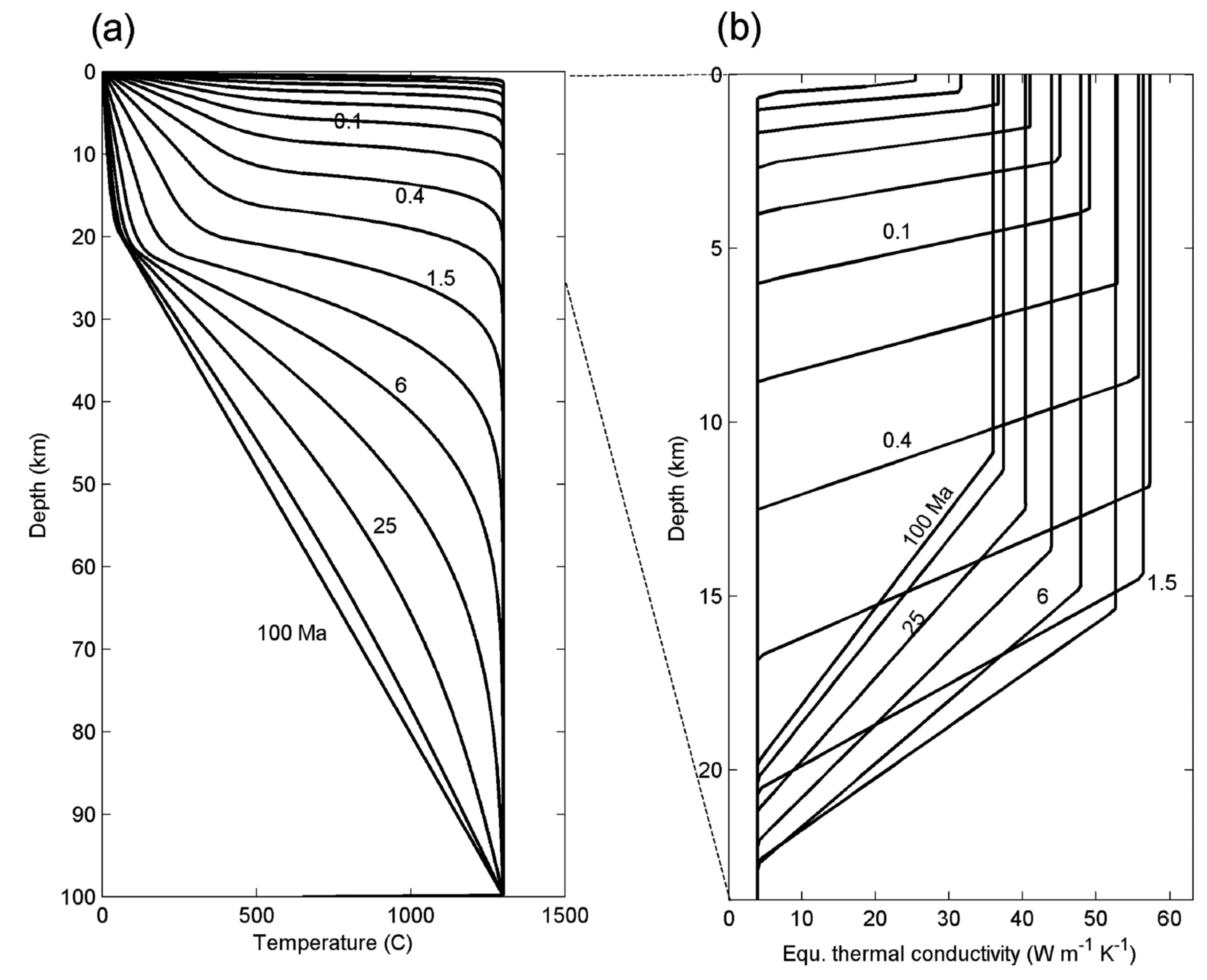
Effect on
Bathyme

Comparison with full 2D solution



www.goethe-universitaet.de

Example of cooling plate with simulated hydrothermal convection



X

Phase 1 (0 Ma)
Plate is hot, no hydrothermal convection

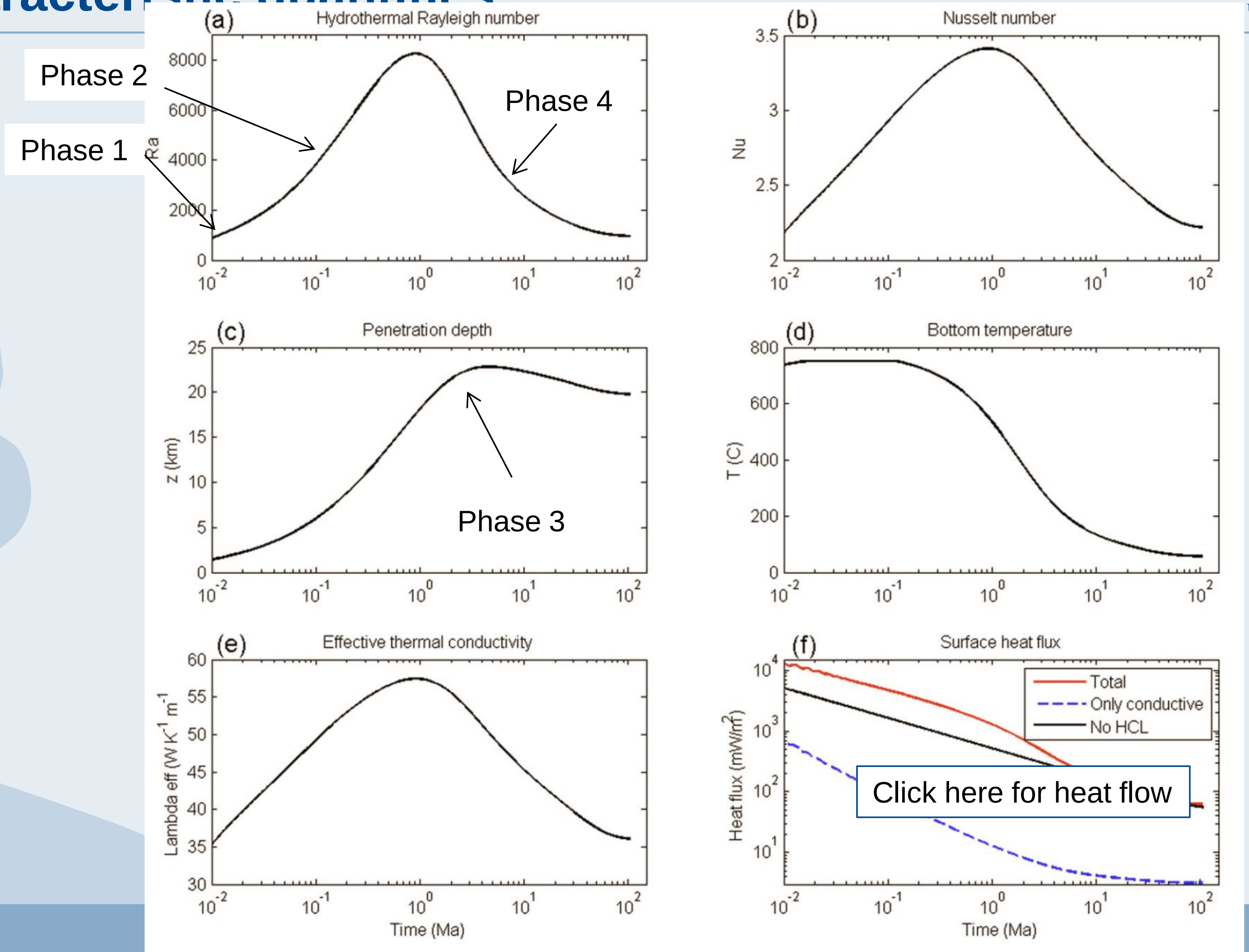
Phase 2 (0.02 – 1.5 Ma)
Cooling opens pore space → convection layer thickens → *Ra* increases → effective conductivity increases → shallow cooling increases
Maximum effective conductivity is reached

Phase 3 (2 Ma)
Maximum penetration depth is reached due to pressure effect on permeability

Phase 4 (> 2Ma)
Bottom temperature of convection layer cools → Ra drops → hydrothermal convection slows down, but remains active even at late ages

Evolution of characteristic quantities

Evolution of hydrothermal Rayleigh number, penetration depth, Nusselt number and bottom temperature shows the 4 phases.



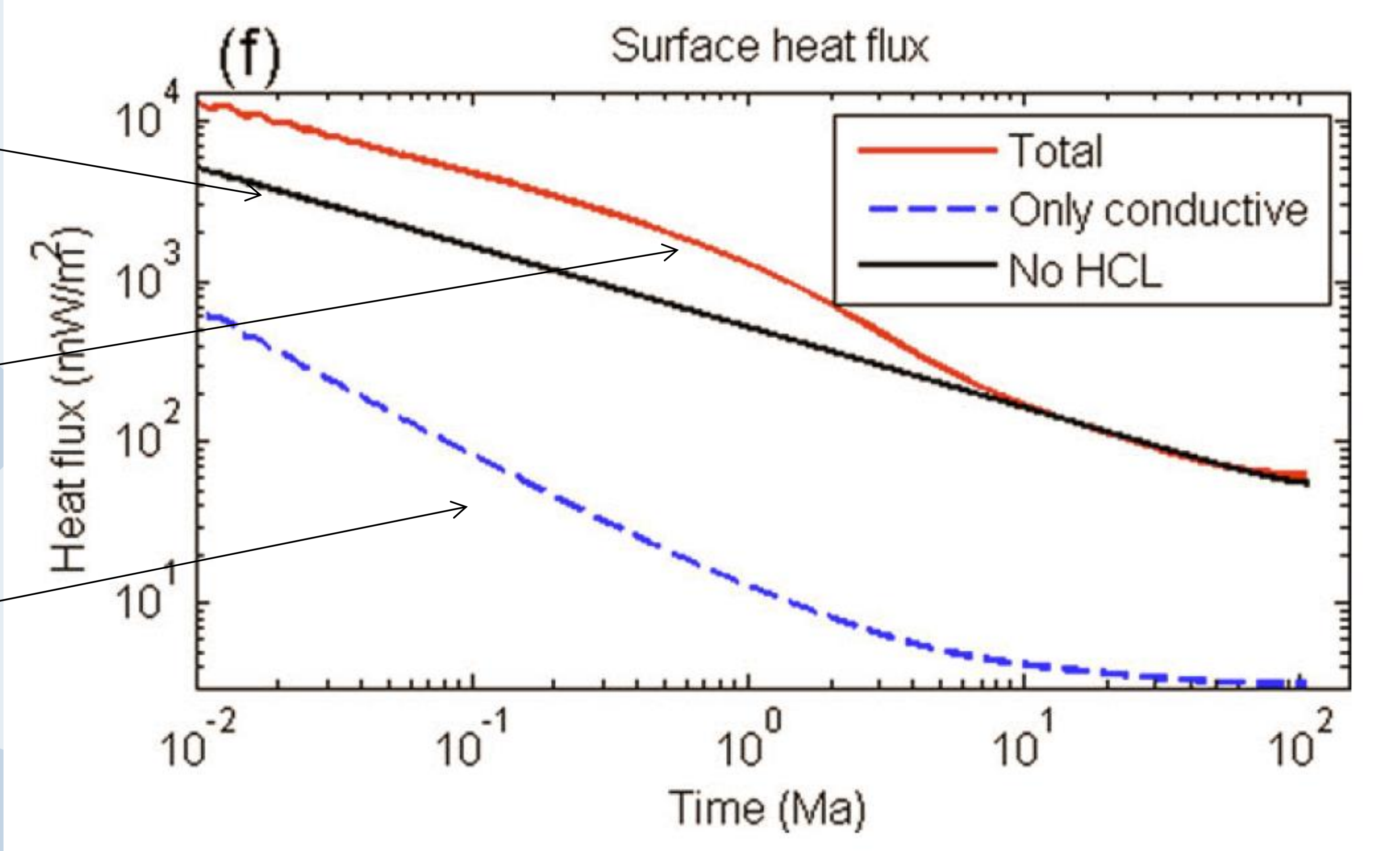
X

Evolution of characteristic quantities

Black curve shows the surface heat flux in the absence of hydrothermal convection. It follow the square root t law. At 100 Ma lettle flattening due to finite plate thickness

Red curve show the total heat flux, which is increased due to hydrothermal convection. Between 1 – 10 Ma a clear deviation from the square toot t law is evident

Blue dashed curve shows the conductive contribution of the heat flux, i.e. most of the heat is lost by advection. Through the top boundary. This is the heat flux measurable by thermal gradients



Comparison with full 2D solution

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The red curve shows the full 2D solution obtained with the FEM code COMSOL for a cooling plate including the porous convection equations:

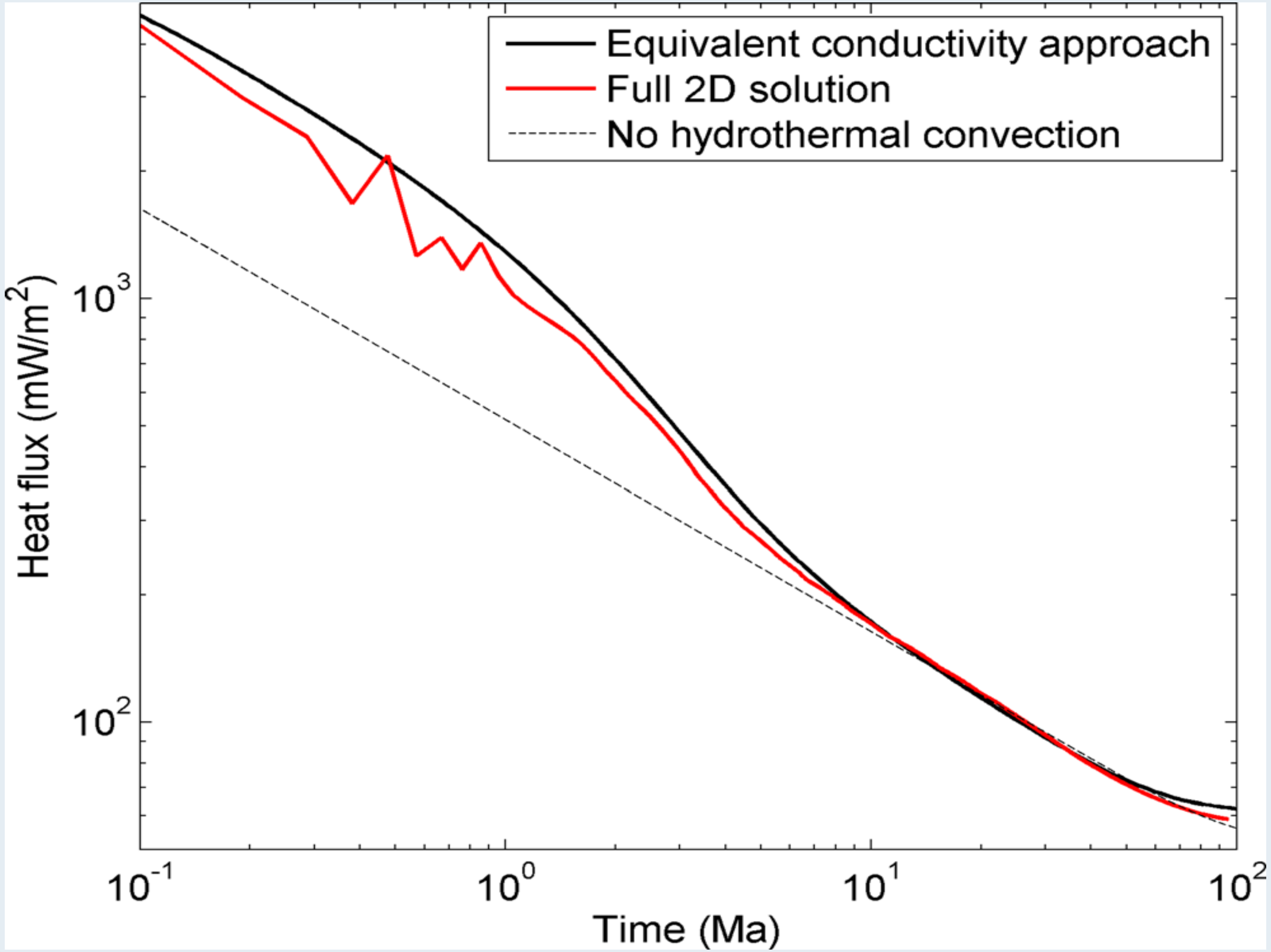
$$\rho_0 c_p \frac{\partial T}{\partial t} + \tilde{\rho}_f c_{pf} \vec{u} \cdot \vec{\nabla} T = \lambda_m \nabla^2 T,$$

$$\vec{\nabla} \cdot \tilde{\rho}_f \vec{u} = 0,$$

$$\vec{u} = -\frac{k_\varphi}{\eta_f} \left(\vec{\nabla} P_f - \tilde{\rho}_f g \vec{e}_z \right),$$

$$\tilde{\rho}_f = \rho_f \left[1 - \alpha_f (T - T_0) \right],$$

The agreement with the approximate solution using the equivalent thermal conductivity is satisfactory



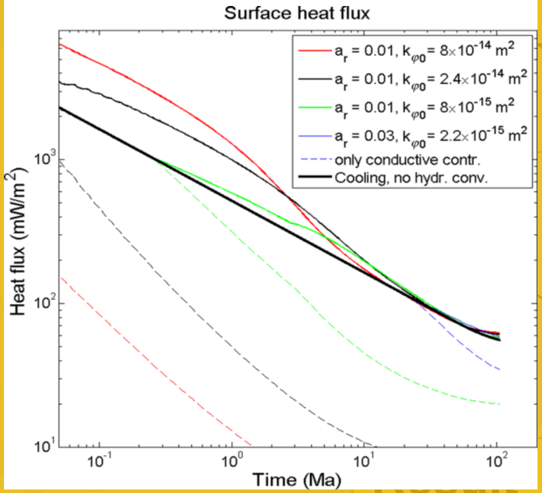
Hydrothermal cooling of the oceanic lithosphere and the square root age law

H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

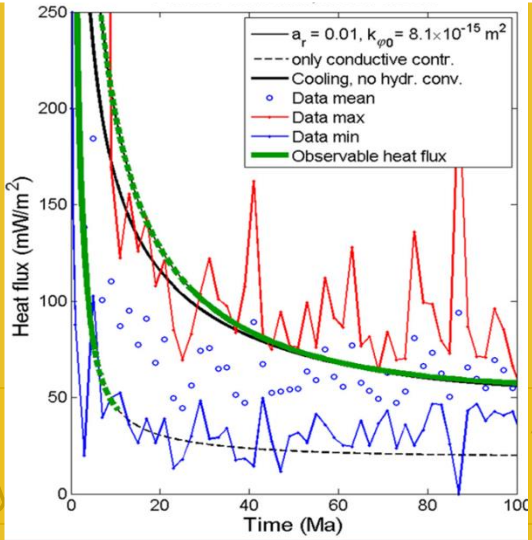
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

X

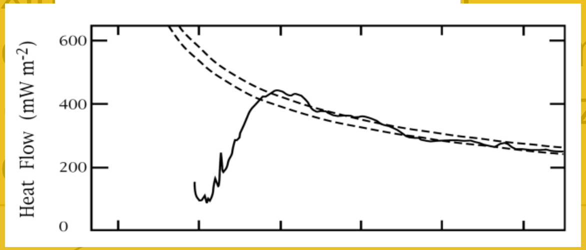
Strong deviation from $\sqrt{t} - law$ for various porosity parameters



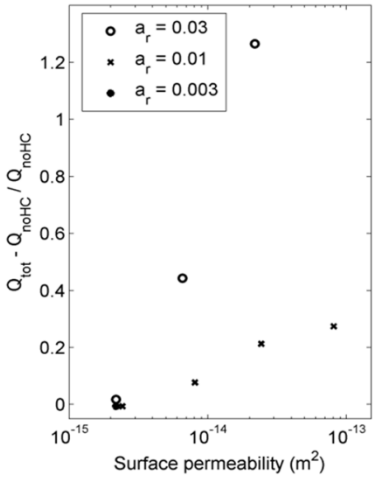
Comparison with heat flow data suggests importance of hydrothermal convection with a transition from permeable to impermeable surface conditions



A local comparison



Total heat loss is significantly increased compared to the conductive $\sqrt{t} - law$

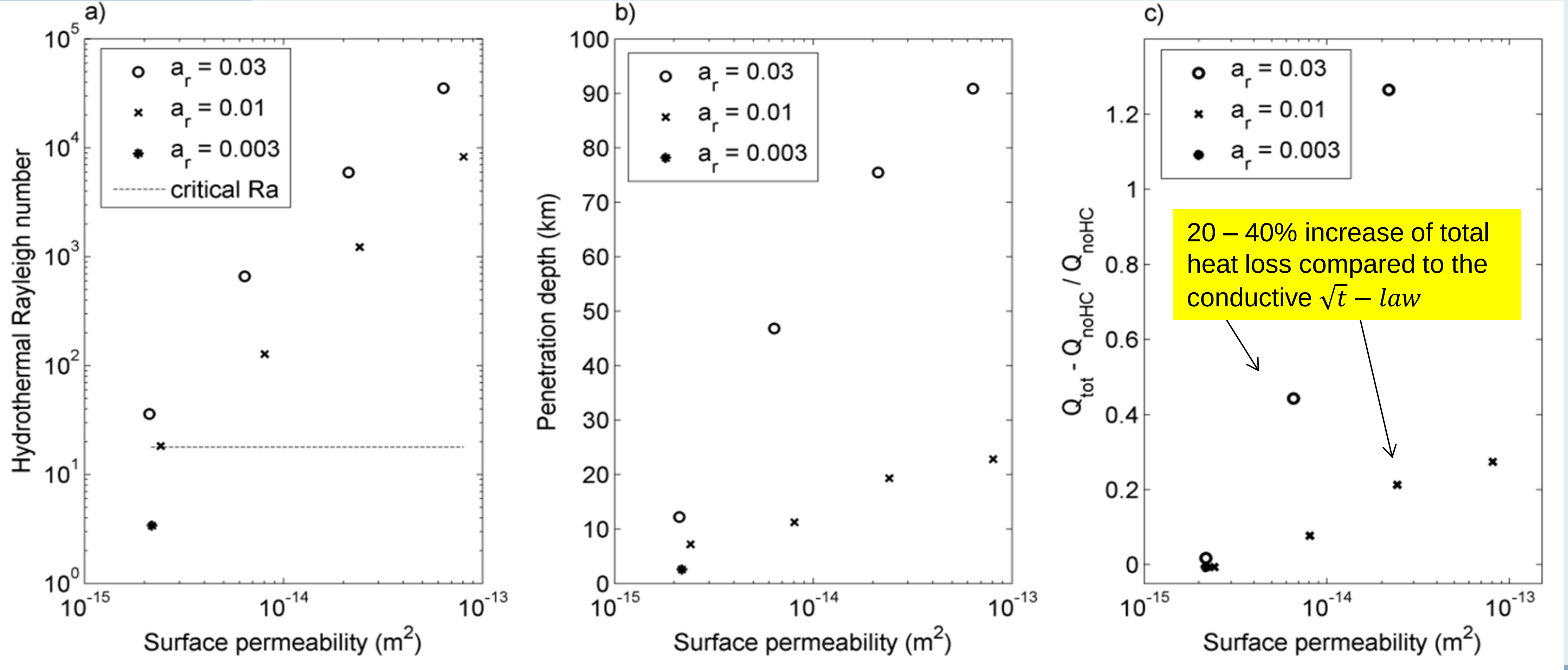


Sedimentary sealing of the ocean floor at a given age

Deviation from $\sqrt{t} - law$:
→ Measurable heat flow
→ Increased total heat loss

Varying porosity parameters

Here the effect of varying porosity parameters on the hydrothermal rayleigh number, penetration depth and excess heat loss is shown



20 – 40% increase of total heat loss compared to the conductive $\sqrt{t} - law$

$\sqrt{t}$ – law ?

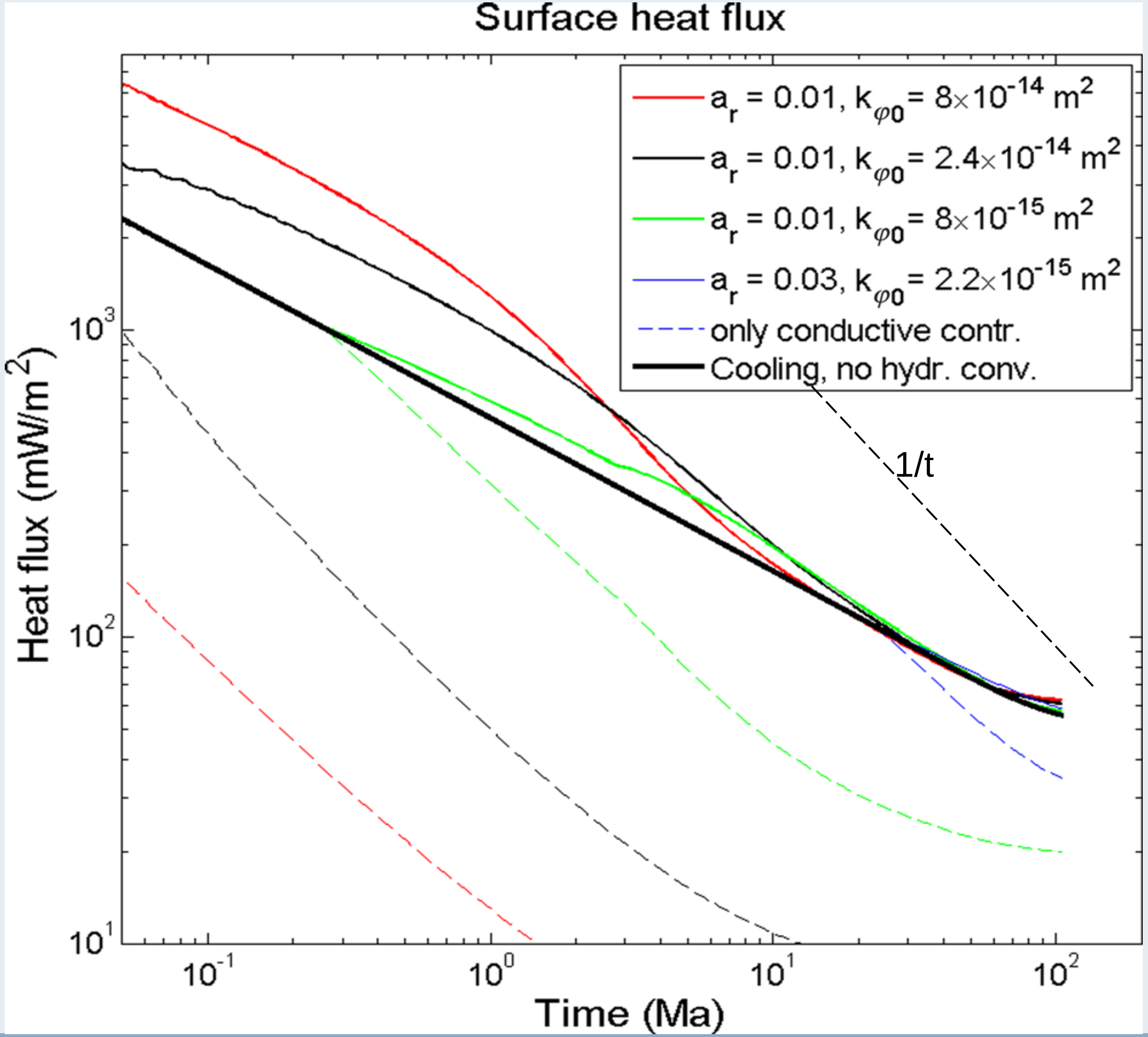
Strong deviation from $\sqrt{t} - law$ for various porosity parameters:

The crack aspect ratio a_r and the surface permeability $k_{\varphi 0}$ are varied. They influence the magnitude of the deviation from the $\sqrt{t} - law$ as well as the timing.

Compare the slopes with the 1/t slope

Effective cooling due to hydrothermal convection reduces the total cooling time, which leads to an earlier onset of flattening due to a finite plate thickness at already 60 Ma.

Dashed colored curves give the measurable condictive contribution



X

$\sqrt{t}$ – law , comparison with data

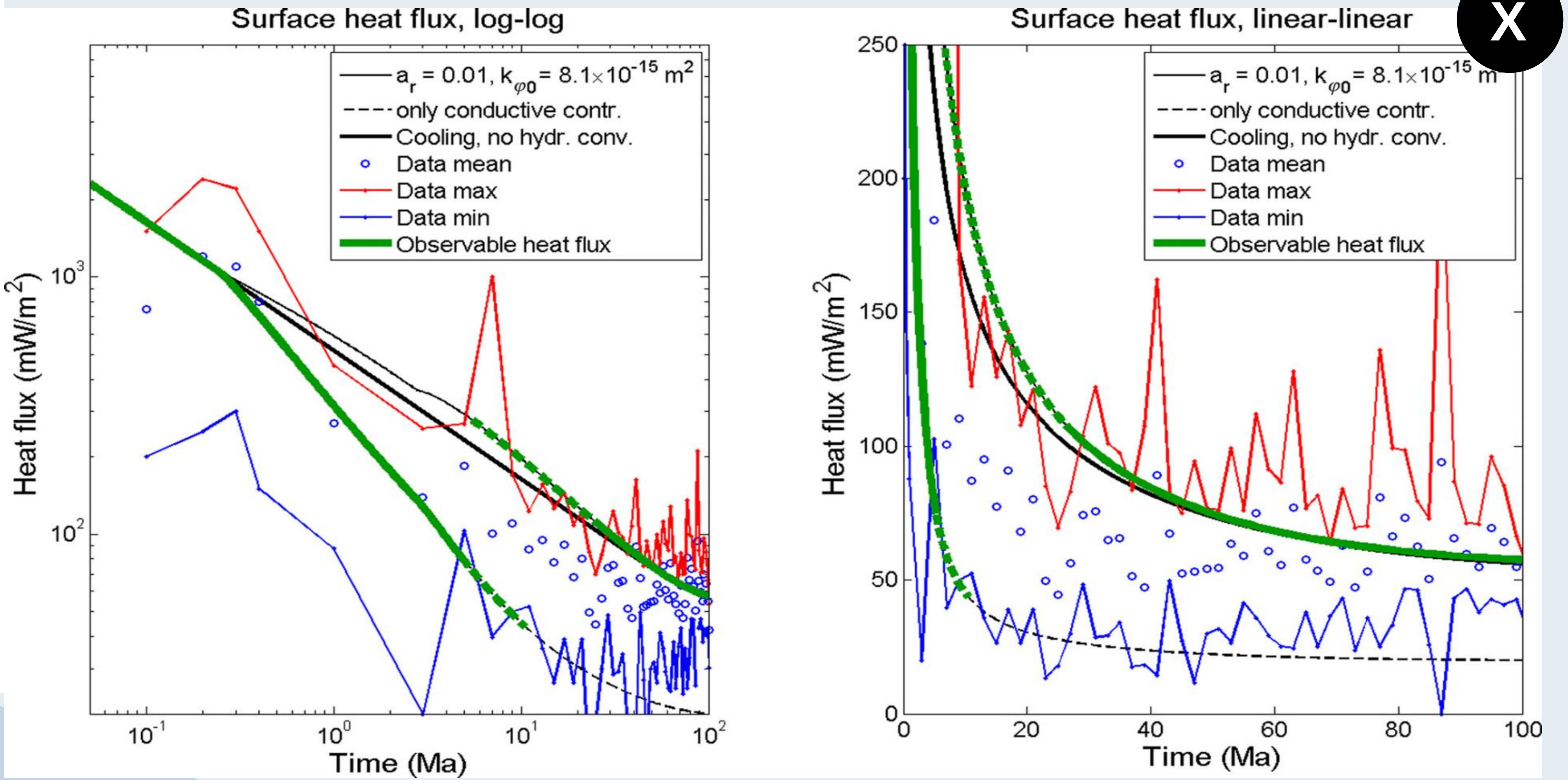
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Global heat flow measurements plotted as a function of age (dots) with their upper (red) and lower (blue) bounds.

Black (thin) curve shows the total heat flux of a model with hydrothermal cooling, dashed (thin) is its measurable, conductive contrinution.

The green thick curves indicated the curve sections which are observable in case of a permeable surface at young plates, and an impermable surface at older ages in case of a sealing sediment layer

Model and observational data from Stein and Stein (1994) shown in a log-log and a linear – linear plot



Comparison with a heat flow profile near the Juan de Fuca ridge

Typical model

Observations (Davies et al. 1999)

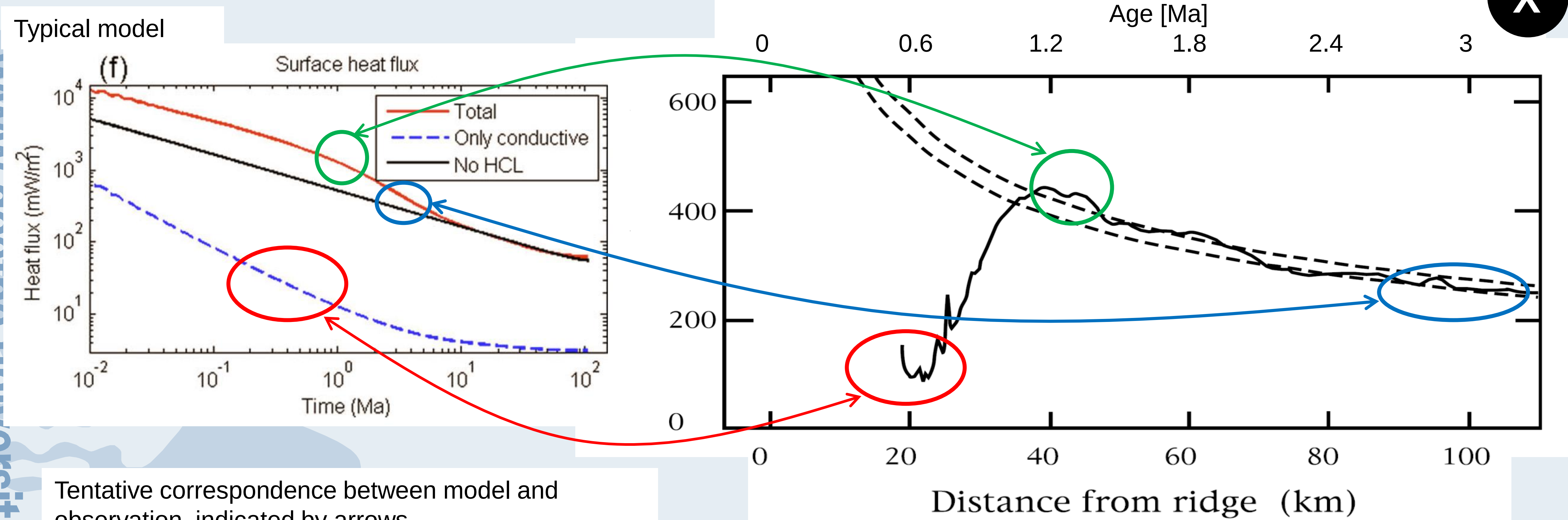


Fig. 4. High resolution heat flow profile near the Juan de Fuca ridge. From *Davis et al.* [1999]. Dashed lines stand for two predictions of the half–space cooling model with constant C_Q in the $\tau^{-1/2}$ heat flux–age relationship equal to 470 and 510 (with heat flux in mW/m^2 and age in Ma).

Tentative correspondence between model and observation indicated by arrows

→ At 0.6 Ma convective contrinution not measurable

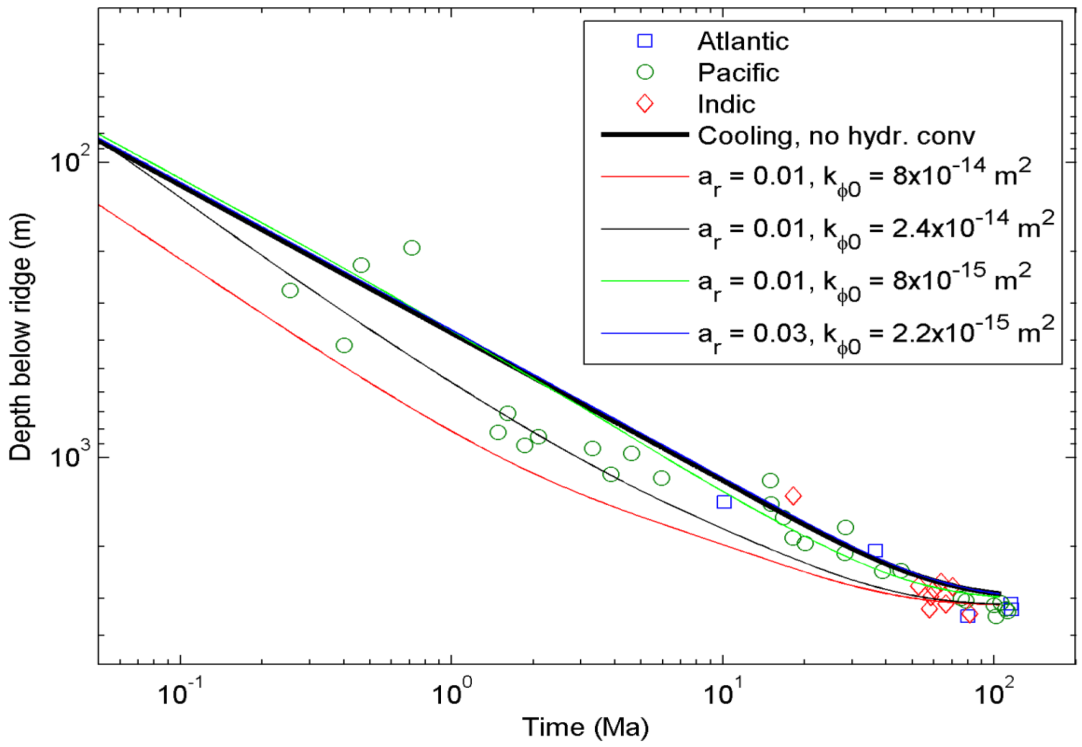
→ At 1.2 Ma sedimentary sealing allows the total convective + conductive heat become measurable

→ At 3 Ma hydrothermal contribution decreases

H. Schmeling[1] and G. Marquart[2,]

[1]Goethe University Frankfurt, [2]RWTH Aachen

Comparison of global bathymetry as a function of age with cooling models with hydrothermal convection for various parameters



The subsidence equation including the effect of porosity

$$w = \frac{\rho_m \alpha_l}{\rho_m - \rho_f}\left(T_m h - \int_0^h T dz \right) - \int_0^h \varphi \, dz$$

Bathymetry of the Atlantic, Pacific and Indic show significant deviations from the $\sqrt{t} - law$ Between 0.3 – 1Ma the bathymetry seems to subside faster, between 1 – 15 Ma it seems to subside slower than with the $\sqrt{t} - law$. Models with hydrothermal cooling show a faster qualitatively a similar behavior.

Effect on Bathymetry

given age

→ Increased total heat loss

X

Hydrothermal cooling of the oceanic lithosphere and the square root age law

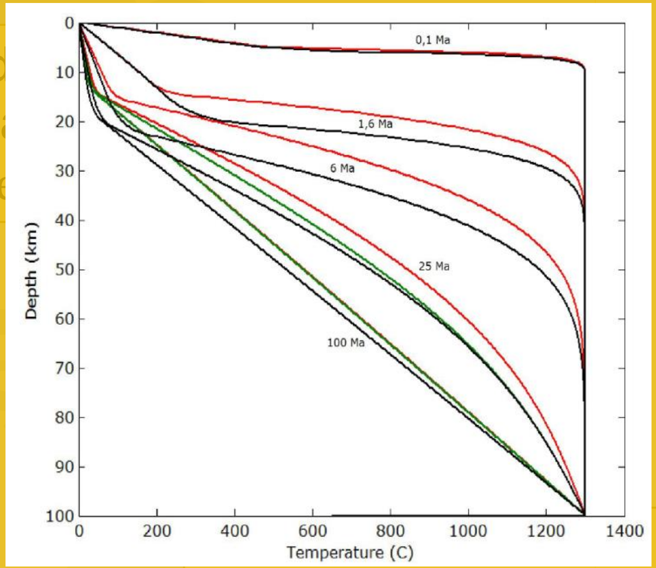
H. Schmeling[1] and G. Marquart[2,]
[1]Goethe University Frankfurt, [2]RWTH Aachen

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

X

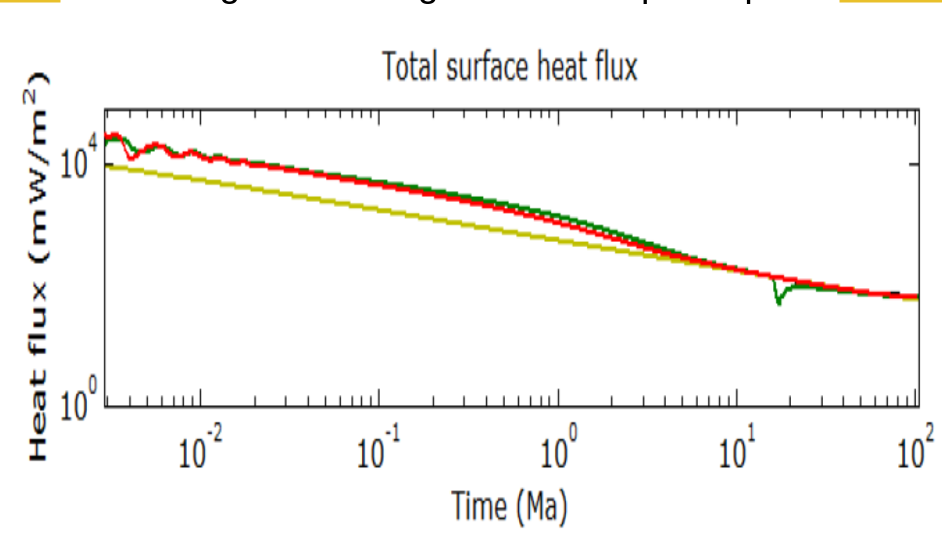
Introd
- Hea
- The

New approach
...imating hydrothermal
...tion by an equivalent thermal
conductivity based on parameterized



Two scaling laws are used: one with open surface boundary, one with impermeable boundary

The effect is not very strong compared to assuming one scaling law for an open top

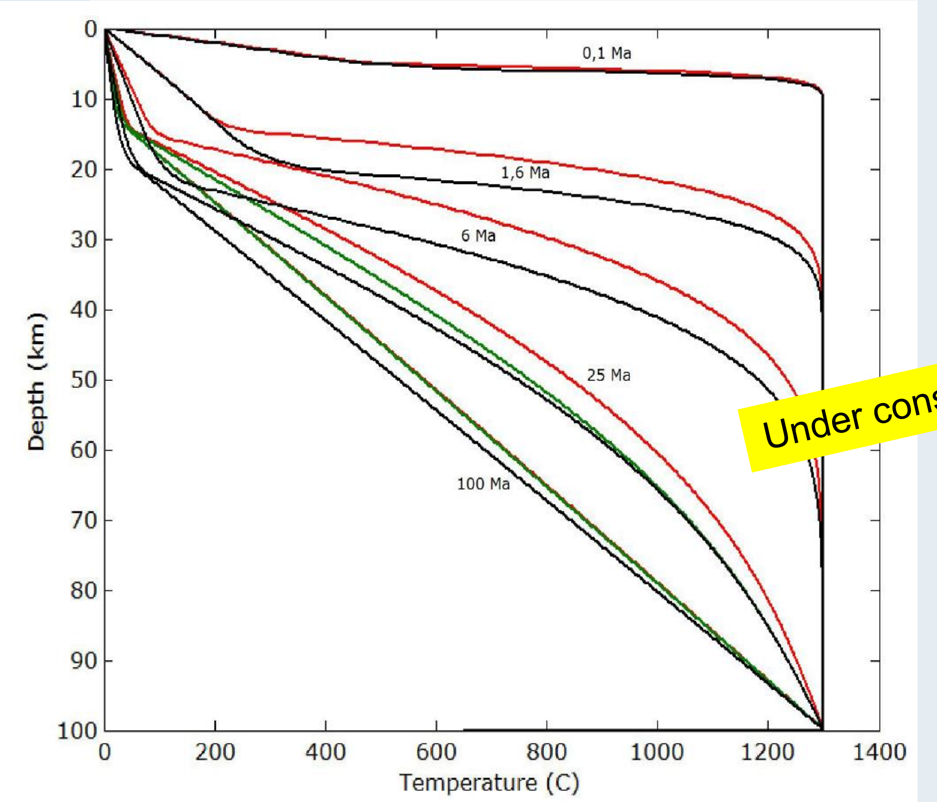


Cooling plate with hydrotherm...

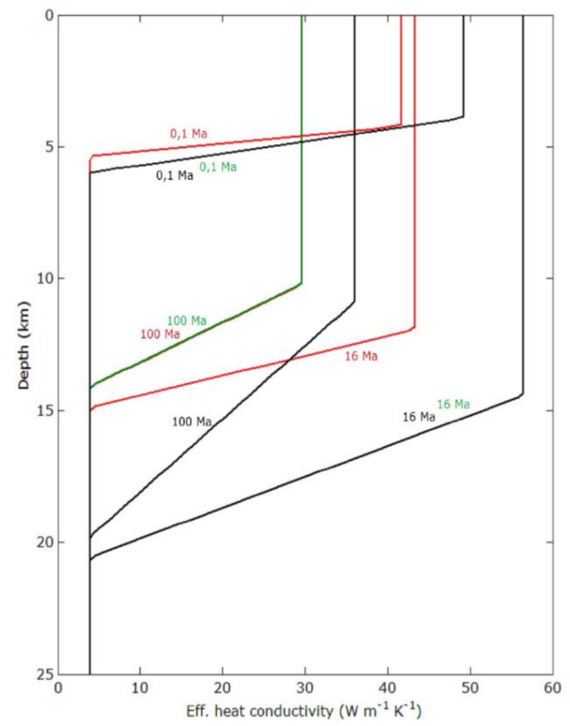
Sedimentary sealing of the ocean floor at a given age

Deviation
→ Measur...
→ Increased total heat loss

Changing cooling due to sediment cover at 15 Ma

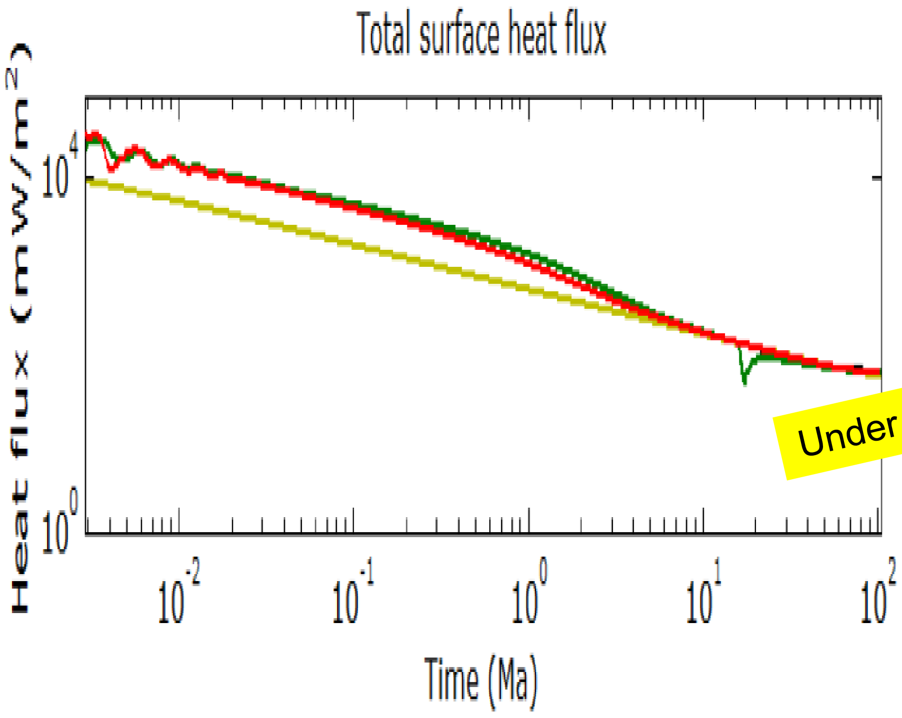


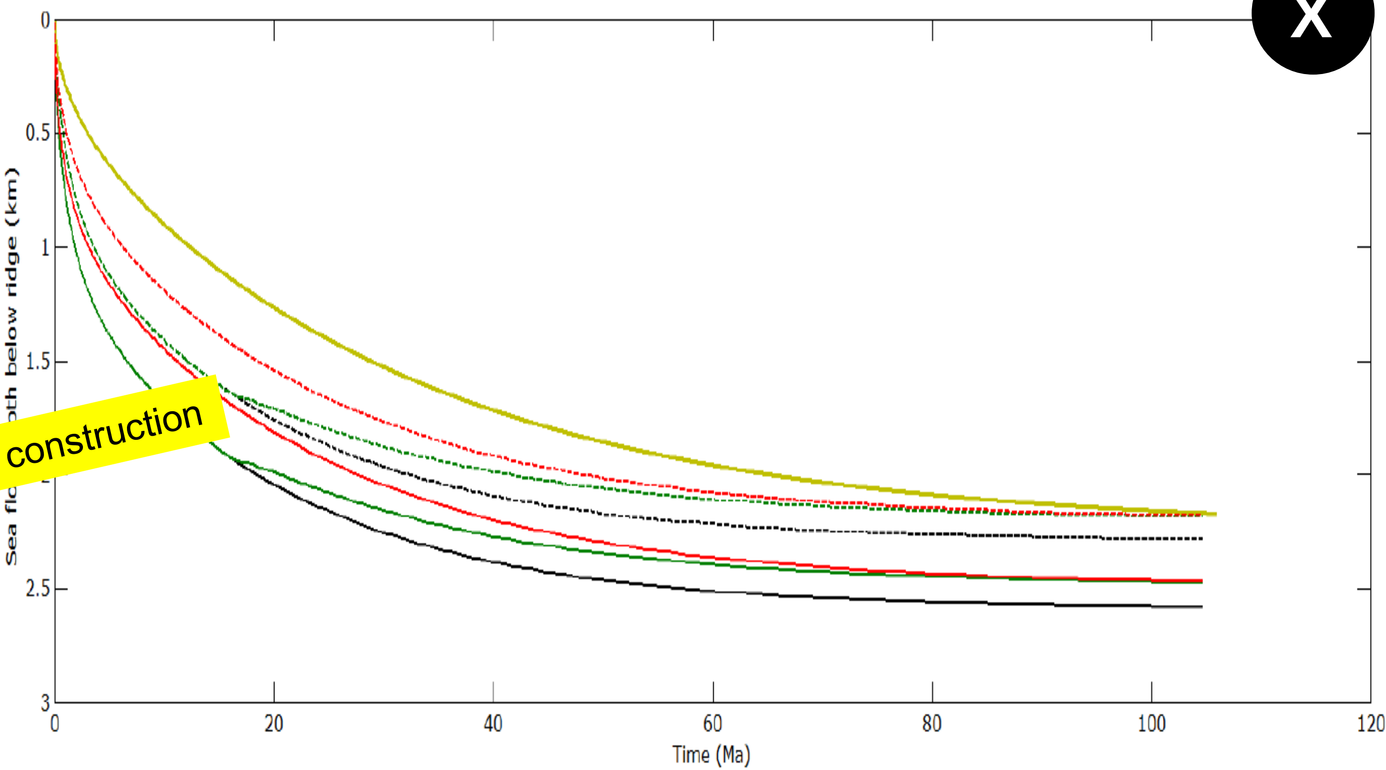
Under construction



X

Changing cooling due to sediment cover at 15 Ma





Conclusion

- …for the first time: Cooling plate model with self-consistent cooling due to parameterized hydrothermal convection (HC)
- HC strongly affects $\sqrt{t}$– law:

  - Total heat loss higher than without HC

  - Heat flux vs. age: steeper than $1/\sqrt{t}$ slope (up to 1/t) for young lithosphere,

  - Flatter slope for older lithosphere
- HC also important for old parts of plates
- Scaling law with depth-dependent permeability: $Nu \propto {Ra_{hy}}^{0.2}$
- Future improvements:

  - crack closure due to plastic deformation

  - sediment cover

  - crack closure due to cementation

Comparison

For comparison:
Constant permeability,
constant T at bottom

Ra = 29

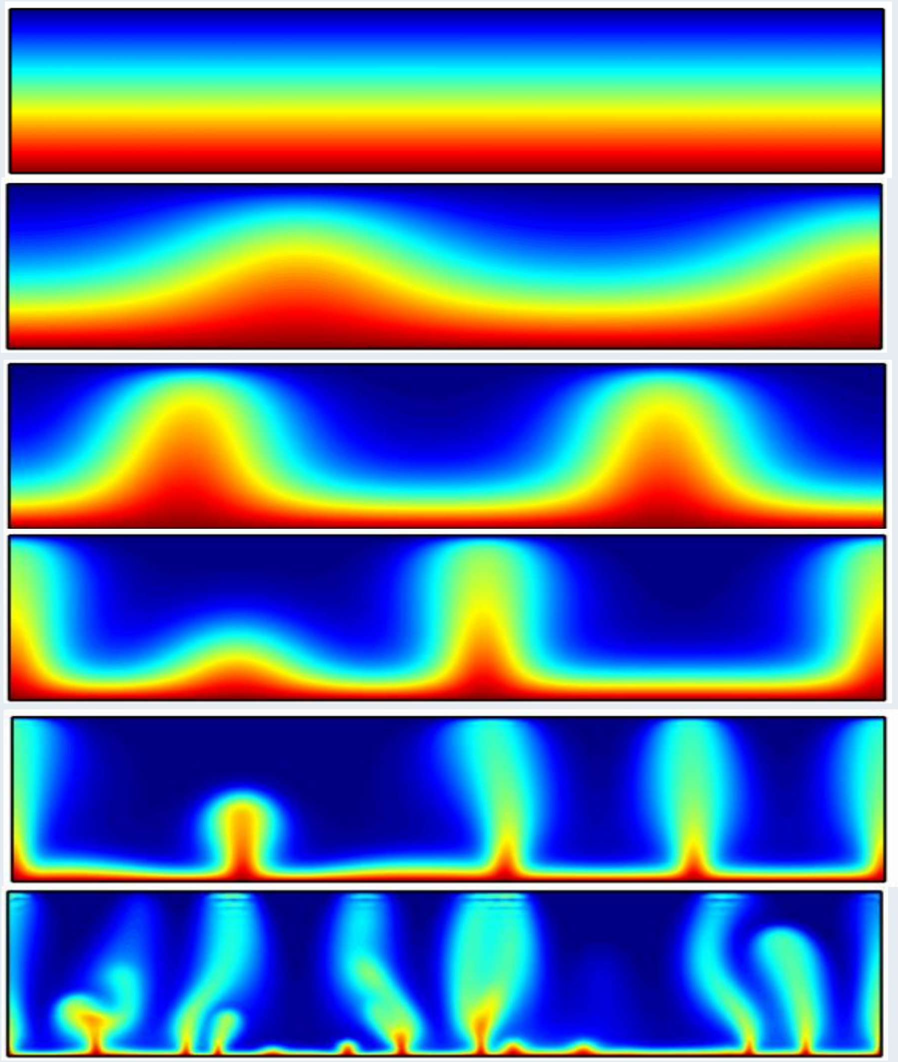
Ra = 30

Ra = 50

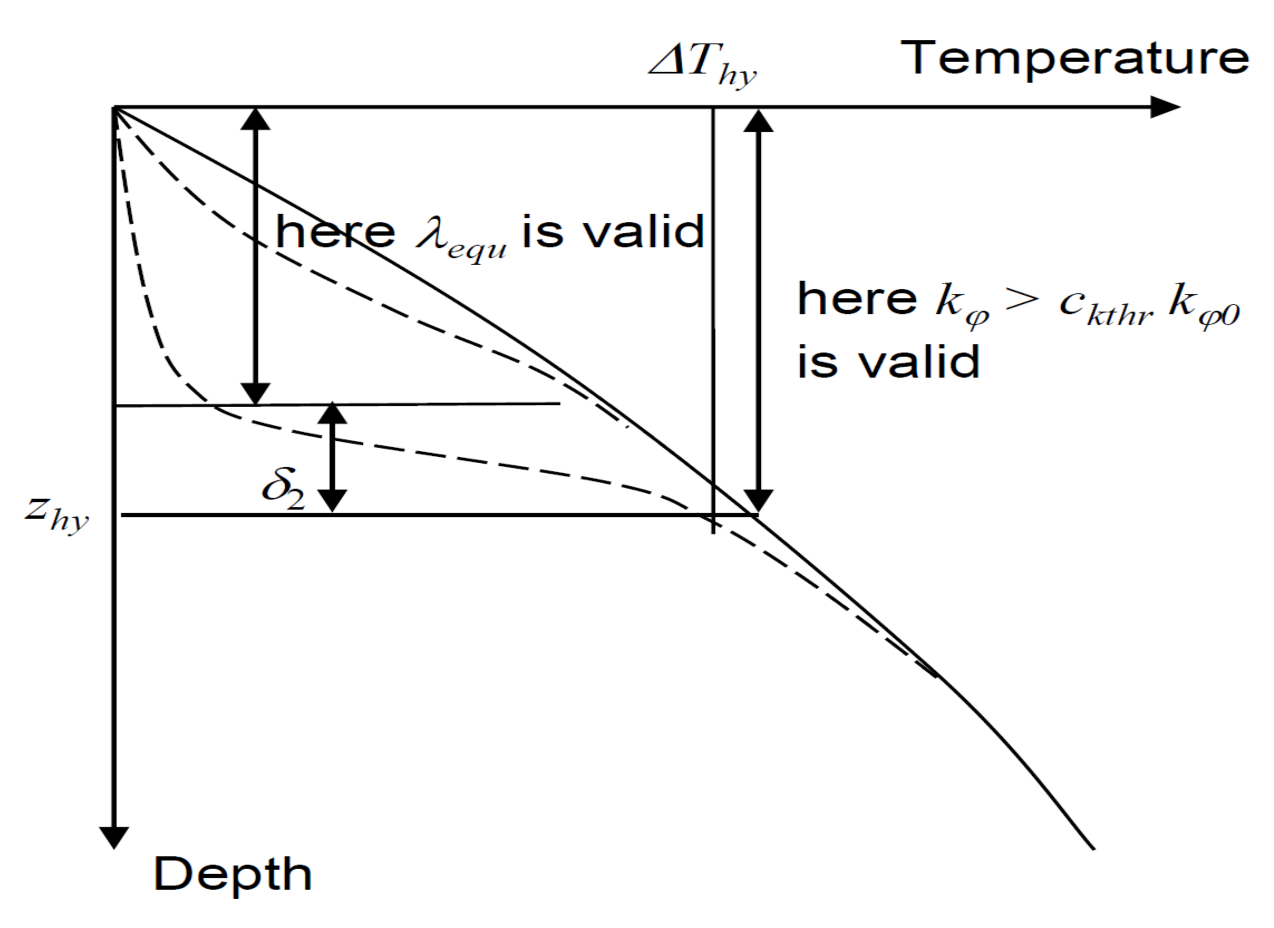
Ra = 100

Ra = 300

Ra = 1000

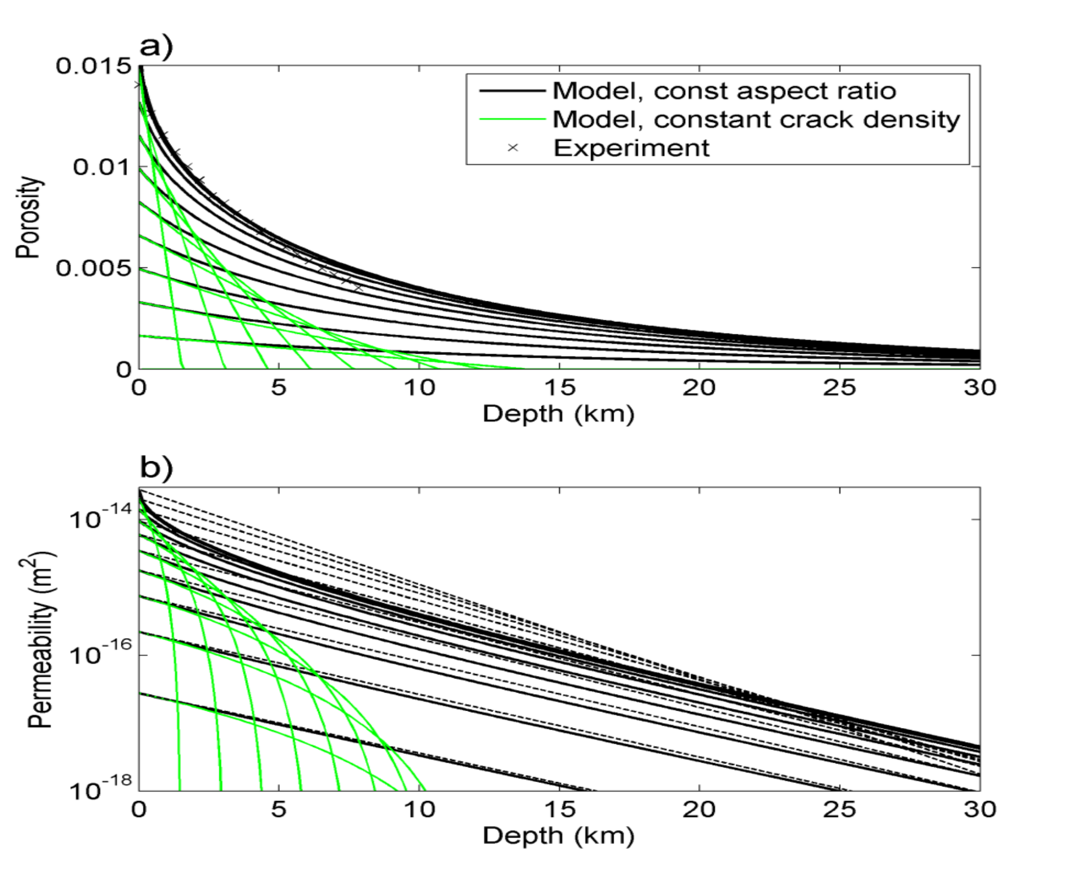


Applying the concept of equivalent thermal conductivity



c_{kthr} allowing for hydrothermal convection (HC)?

→ Scaling law from numerical models of HC



a)
0.015
0.01
0.005
0
Porosity
Model, const aspect ratio
Model, constant crack density
Experiment
0
5
10
15
20
25
30
Depth (km)
b)
10^{-14}
10^{-16}
10^{-18}
Permeability (m^2)
0
5
10
15
20
25
30
Depth (km)