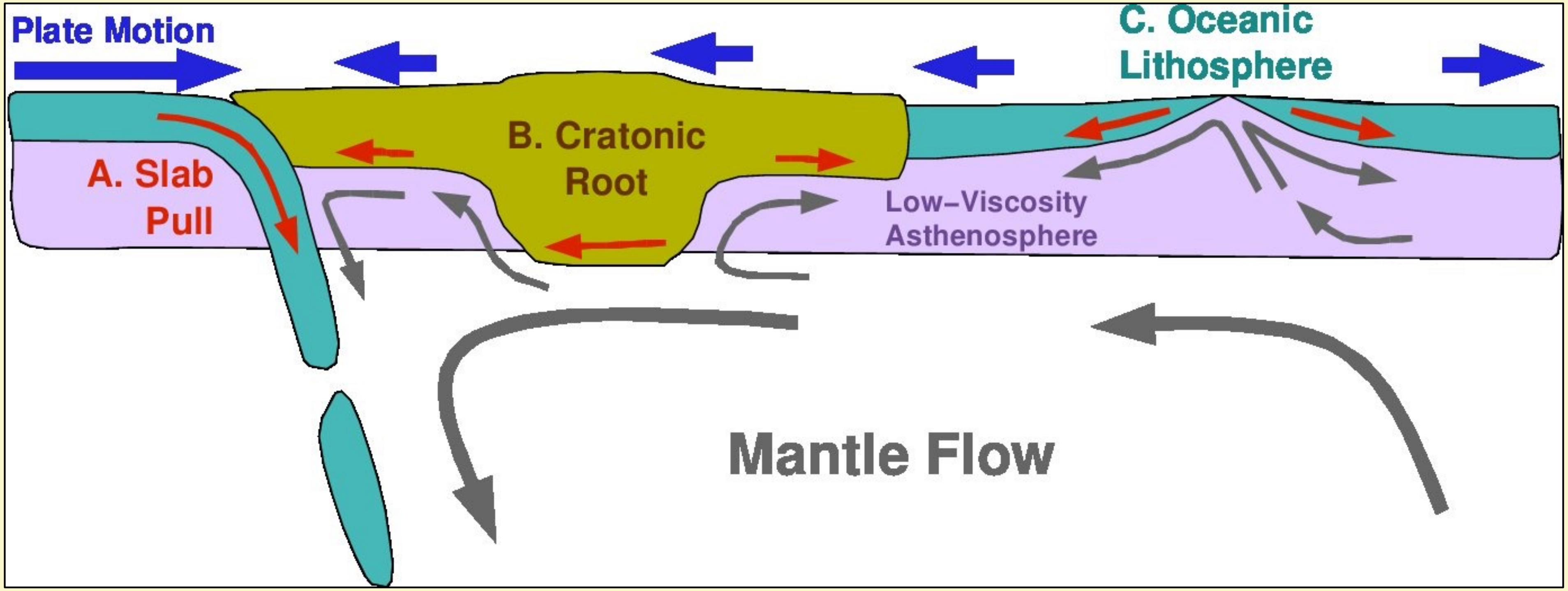
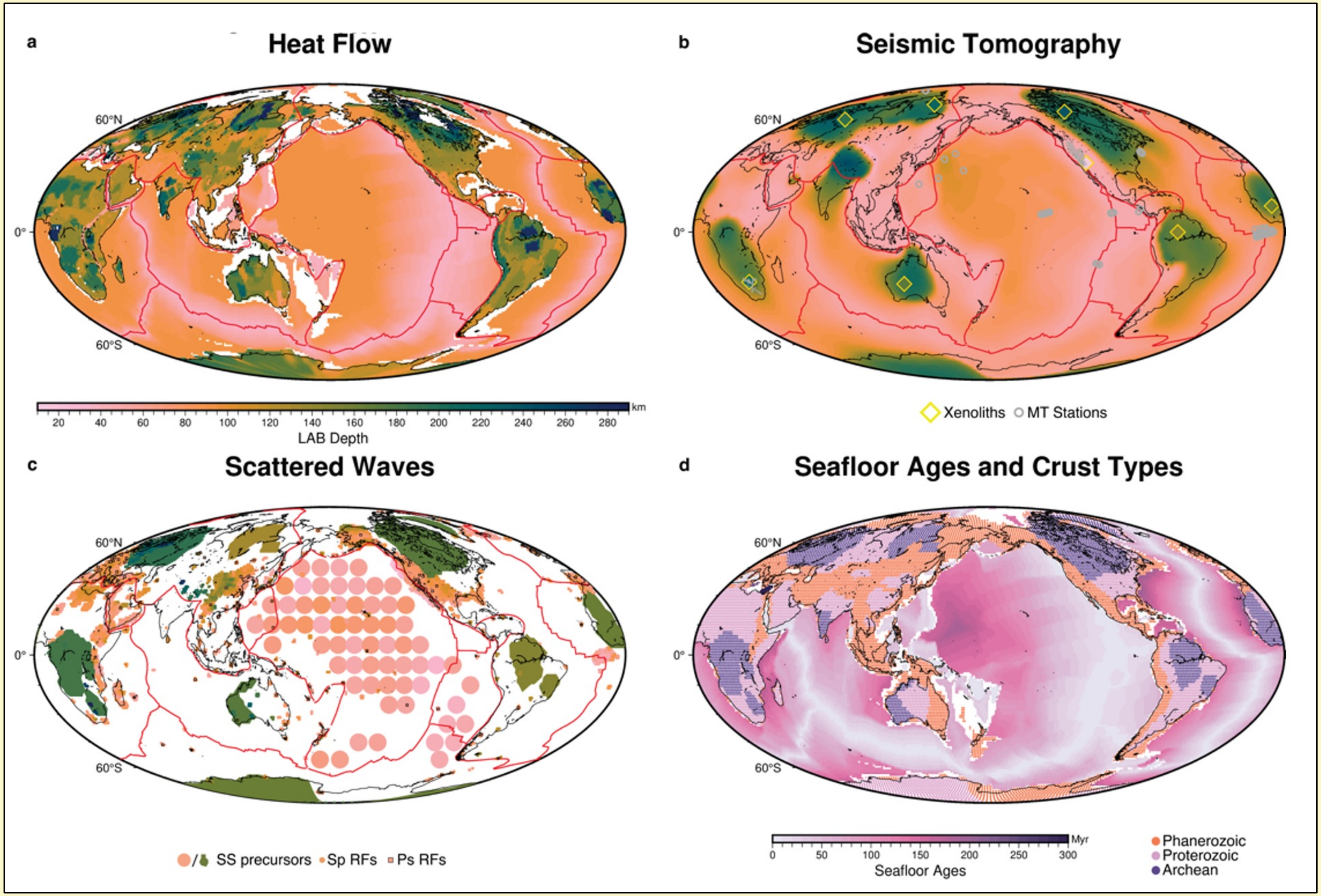
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

Valerie Maupin
Clint Conrad

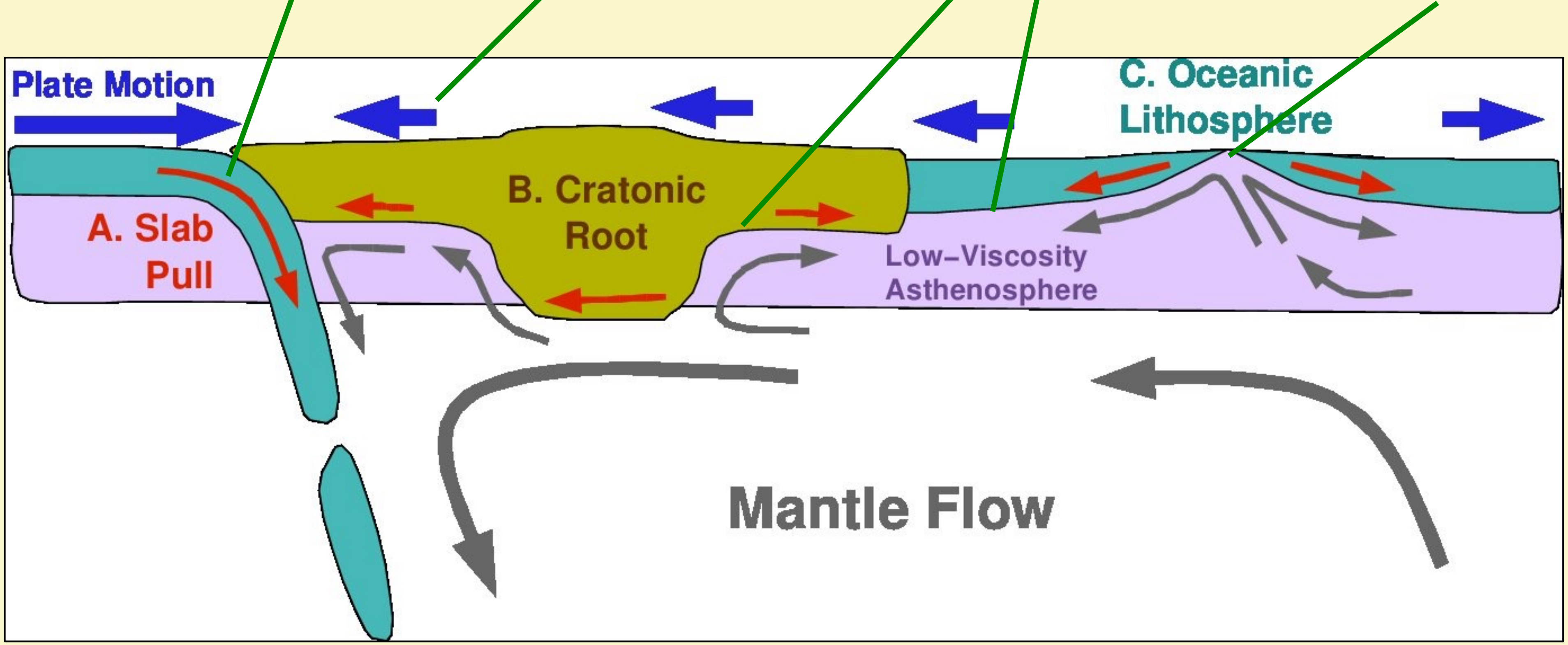


Different Views of the Lithosphere-Asthenosphere Boundary



Rychert et al. [*in review*, 2024]

Geodynamic Processes of the Lithosphere & Asthenosphere



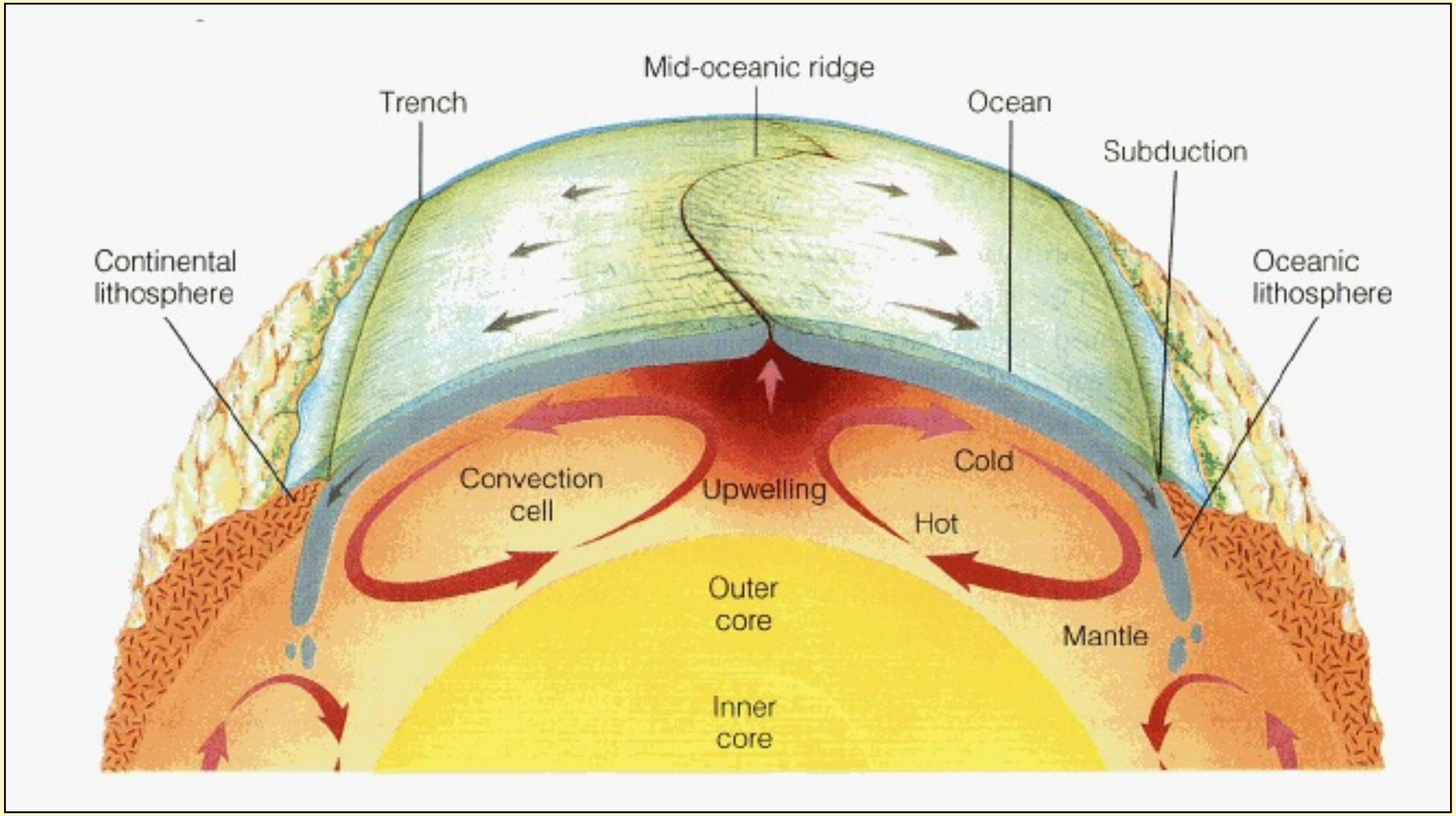
Tectonic Lithosphere:
Plate Motions

Thermal Lithosphere:
Convection

Elastic Lithosphere:
Plate Flexure

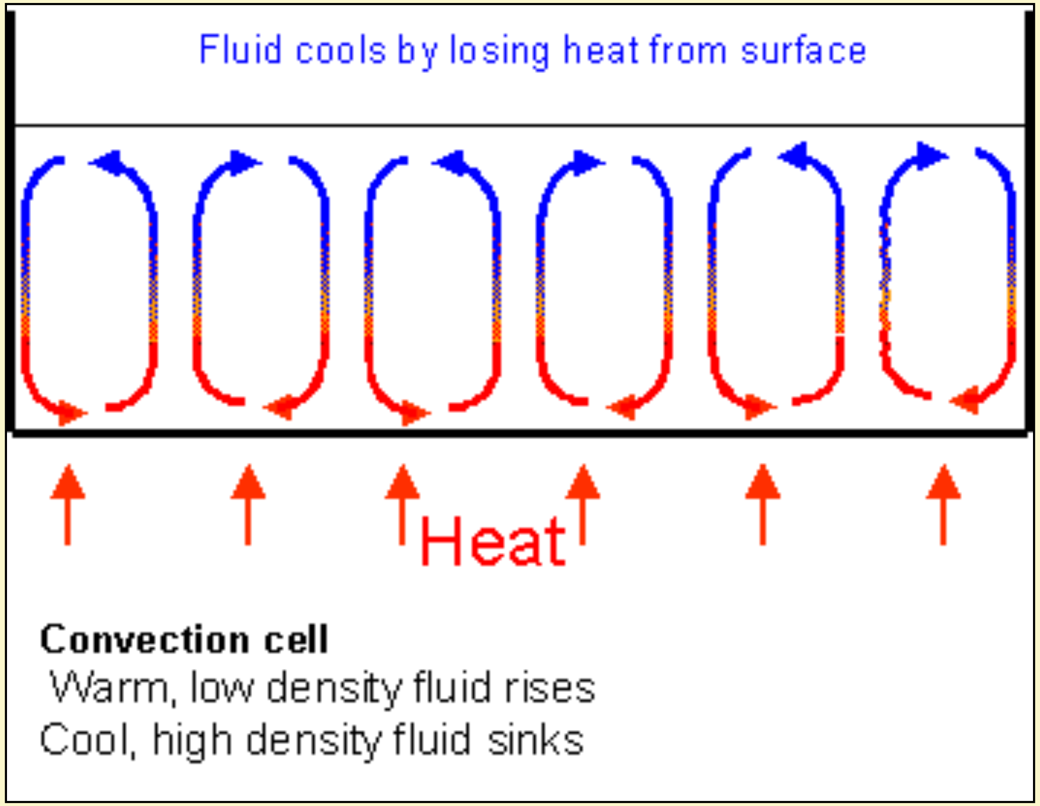
Volcanism

Mantle Convection in the Earth



UPWELLING	beneath spreading ridges
DOWNWELLING	beneath subduction zones
THE PLATES	surface expression of mantle convection
NOT EXPLAINED	intraplate volcanism, continental uplift, …

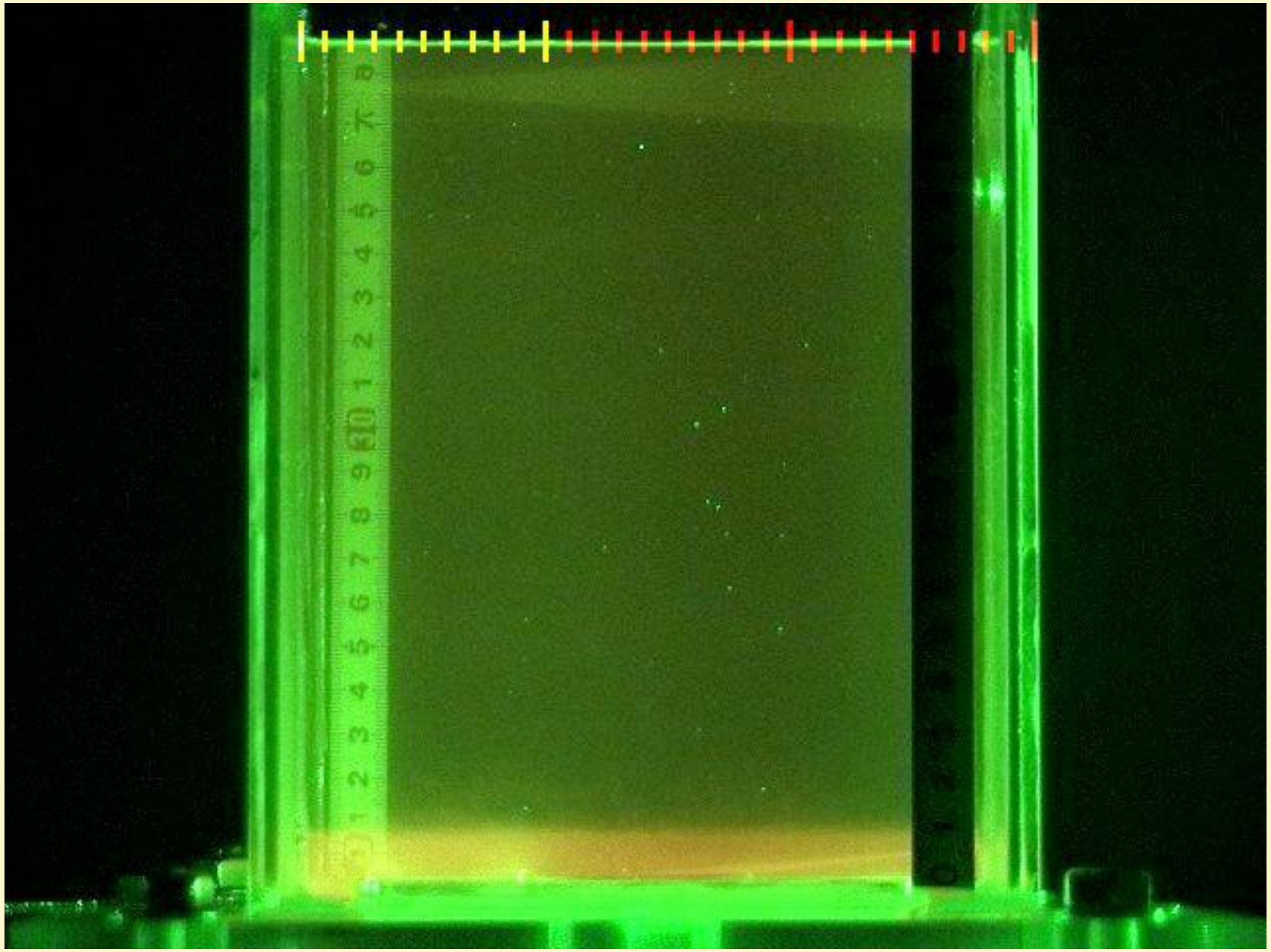
How Convection Works



Convection cell
Warm, low density fluid rises
Cool, high density fluid sinks

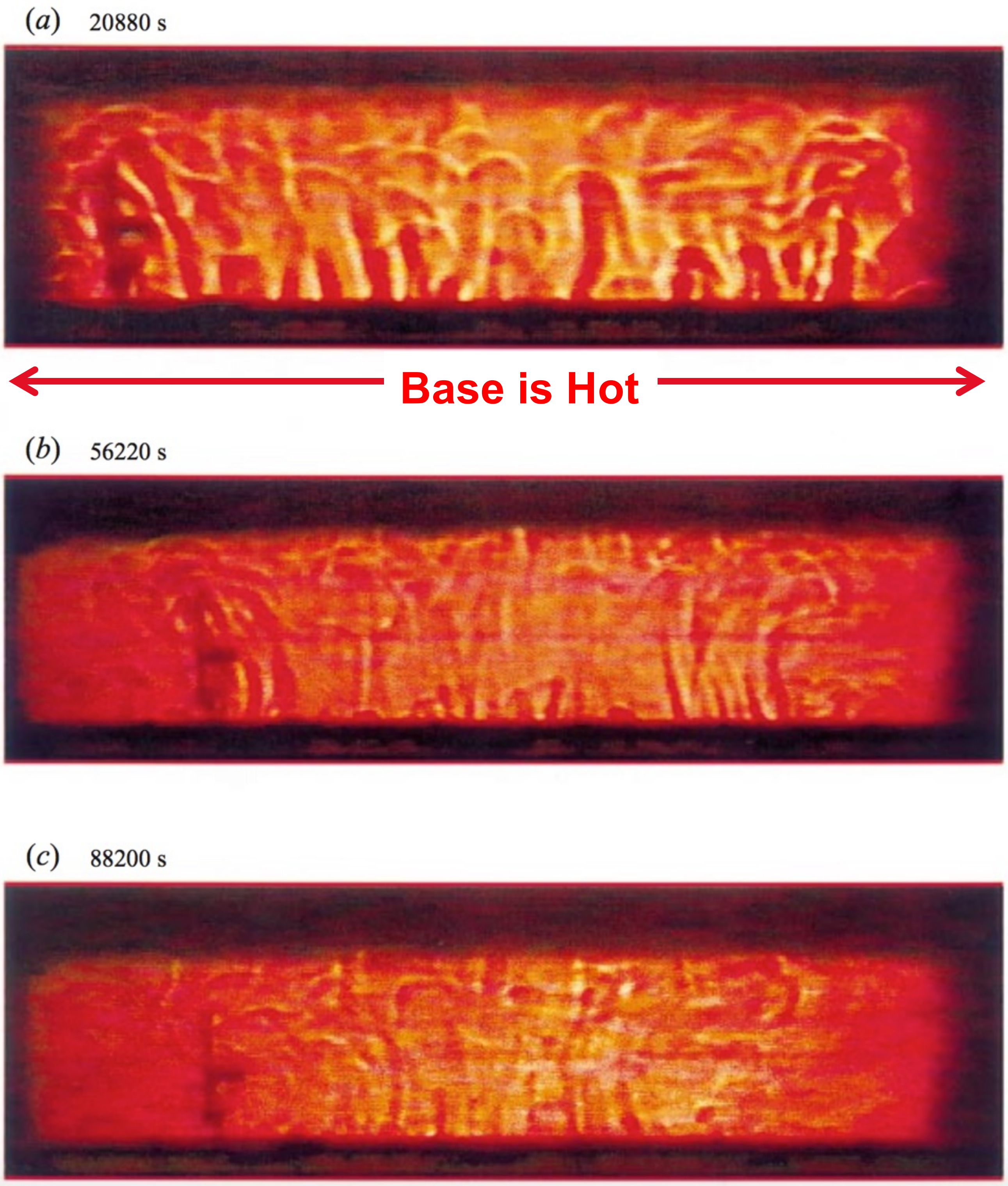
Cold Fluid Sinks

Hot Fluid Rises



Heat source
at the base

Convection:
A Plume
Experiment in
Corn Syrup



Base is Hot

Tank is getting hotter with time

Laboratory experiment of convection in a tank of corn syrup.

Lithgow-Bertelloni et al. [2001]

The **Rayleigh Number** is a dimensionless parameter that measures the **vigor of convection**:

$$Ra = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta}$$

$\rho =$ density (3300 kg/m^3)

$g =$ gravity (10 m/s^2)

$\alpha =$ thermal expansivity (3×10^{-5} K^{-1})

$\Delta T =$ Temperature contrast across mantle (3000 K)

$D =$ Depth of Mantle (2860 km)

$\kappa =$ Thermal diffusivity (10^{-6} m^2/s)

$\eta =$ Mantle viscosity (10^{21} Pa s)

Convection occurs if Ra > Ra_{cr}

For convection in a layer, $Ra_{cr} \sim 657$

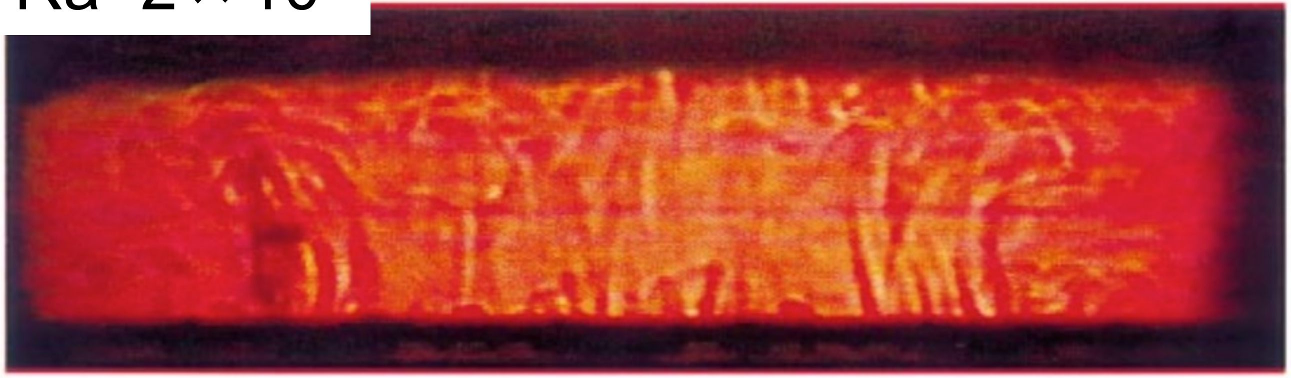
Using these parameters for the mantle: **$Ra_m \sim 7 \times 10^7$**

→ This “model” of the mantle implies vigorous convection

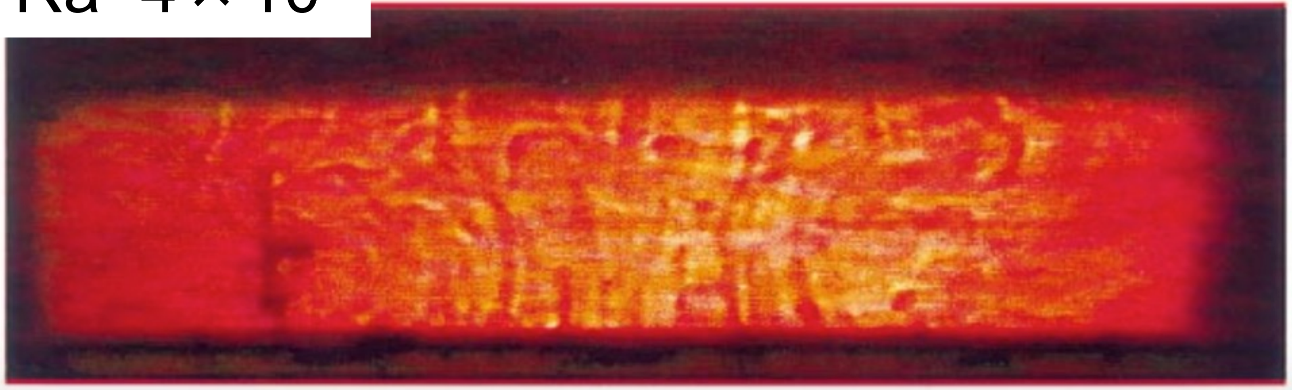
$Ra \sim 4 \times 10^6$

Base is Hot

$Ra \sim 2 \times 10^7$



$Ra \sim 4 \times 10^7$

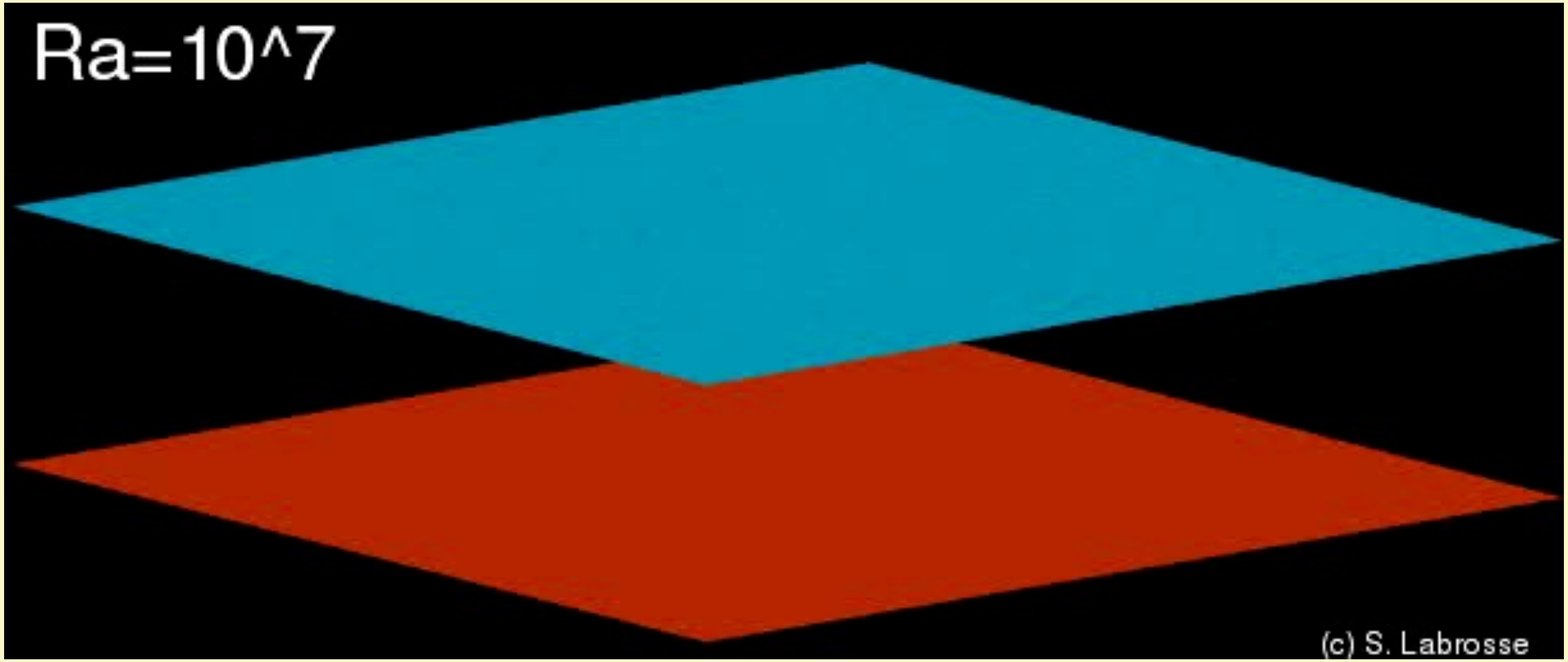


Laboratory experiment of convection in a tank of corn syrup.

Lithgow-Bertelloni et al. [2001]

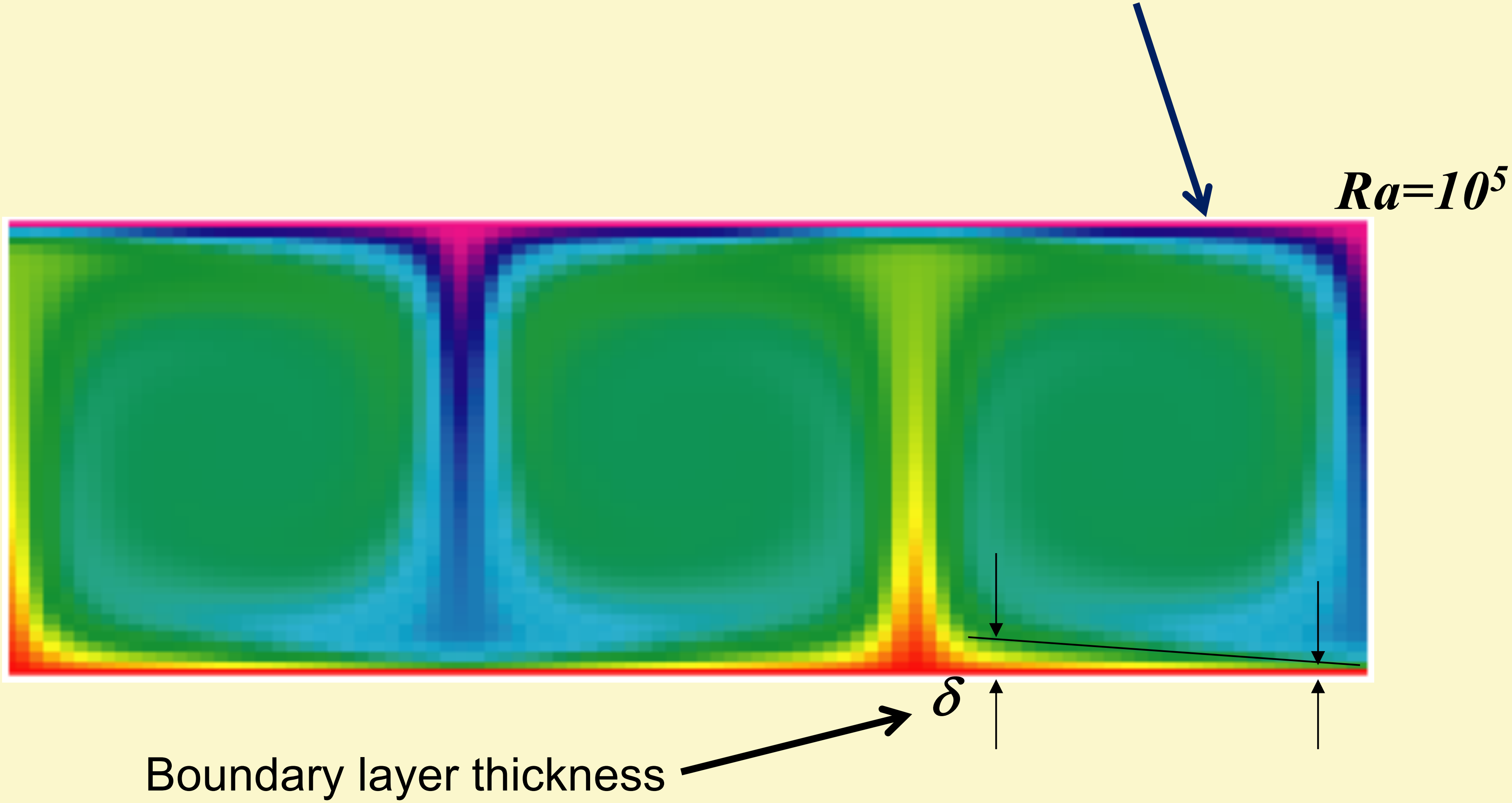
Tank is getting hotter with time

Let's use a computer instead of corn syrup:



Vigorous Convection:

- Thermal conduction across two **thermal boundary layers**
- The upper thermal boundary layer is the **thermal lithosphere**



Boundary layer thickness

Mantle Convection: Effect of Rayleigh Number

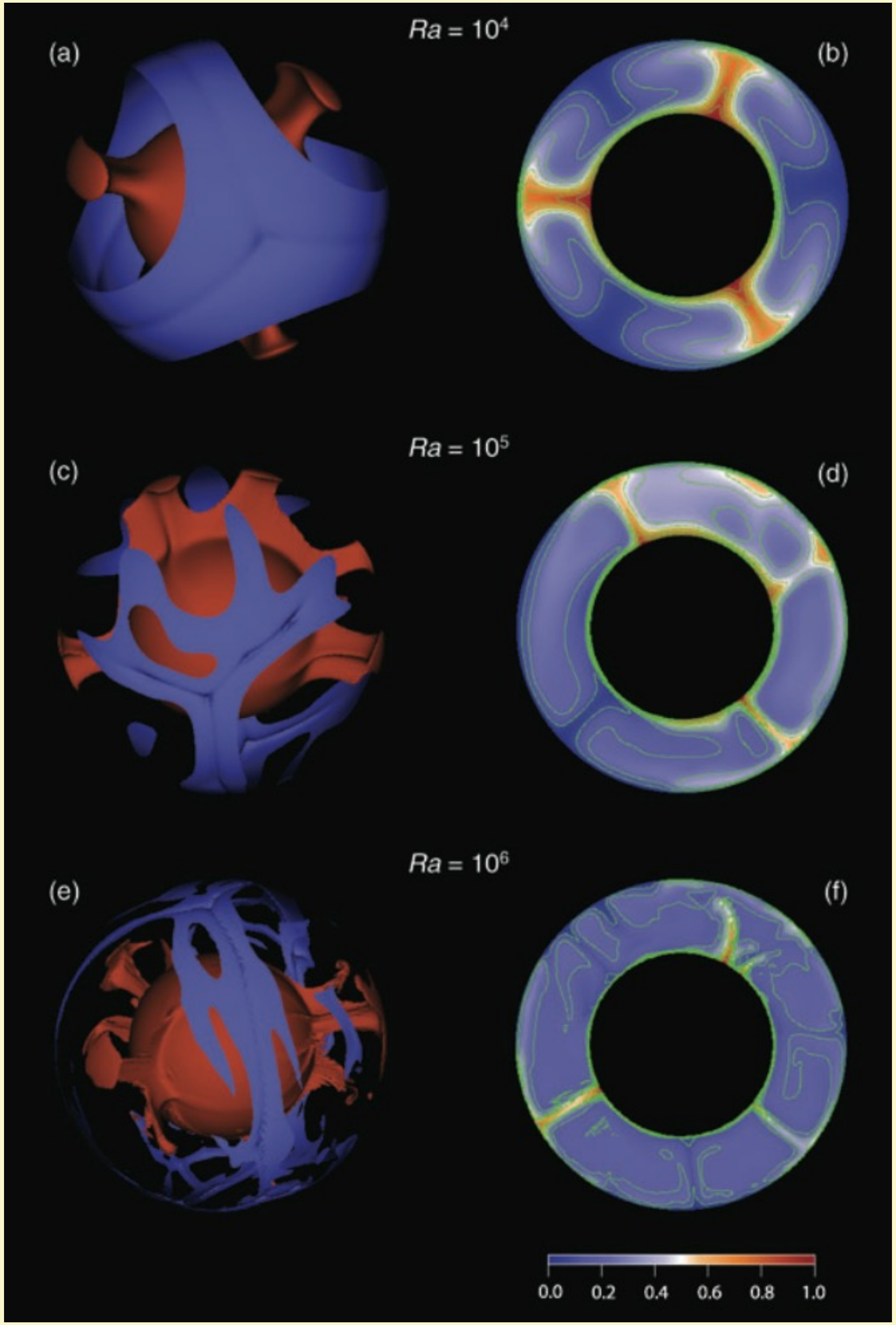
Deschamps et al., 2010

Style and vigor of convection changes with Ra

Boundary layer thickness $h \sim Ra^{-\frac{1}{3}}$

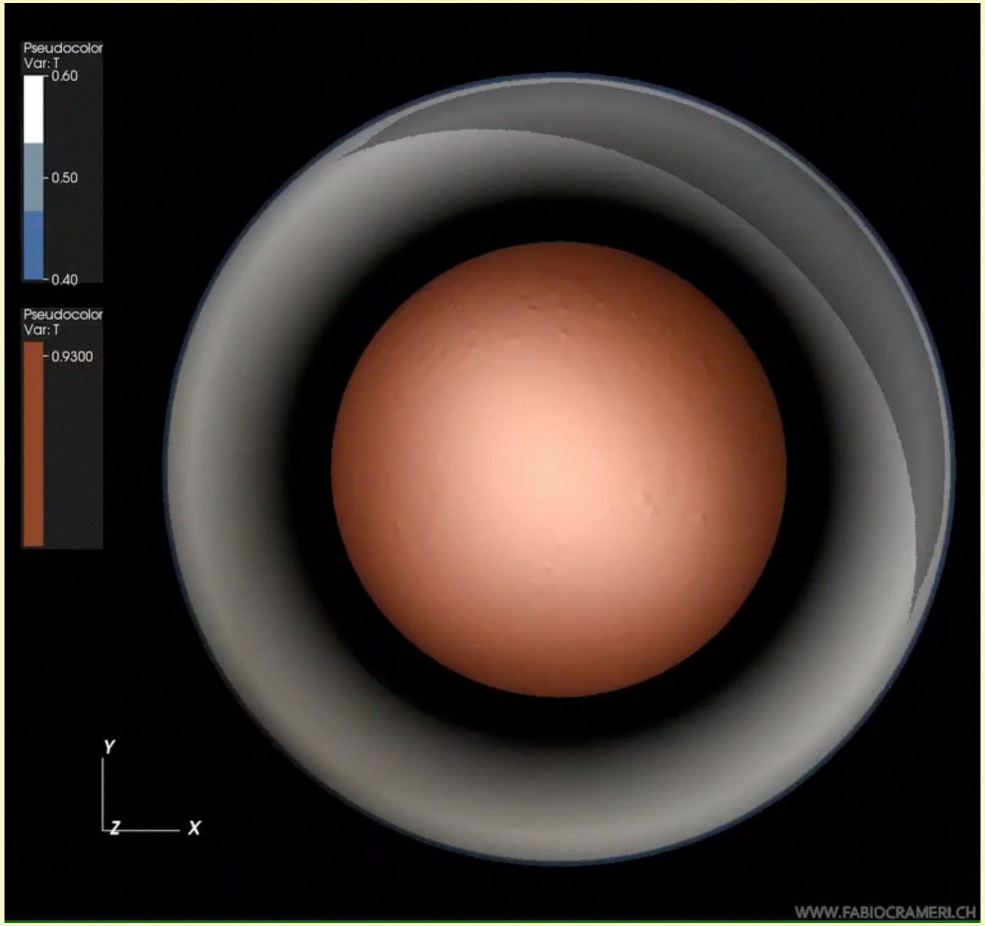
Plate velocity $v_p \sim Ra^{\frac{2}{3}}$

Mantle heat flow $Q \sim Ra^{\frac{1}{3}}$

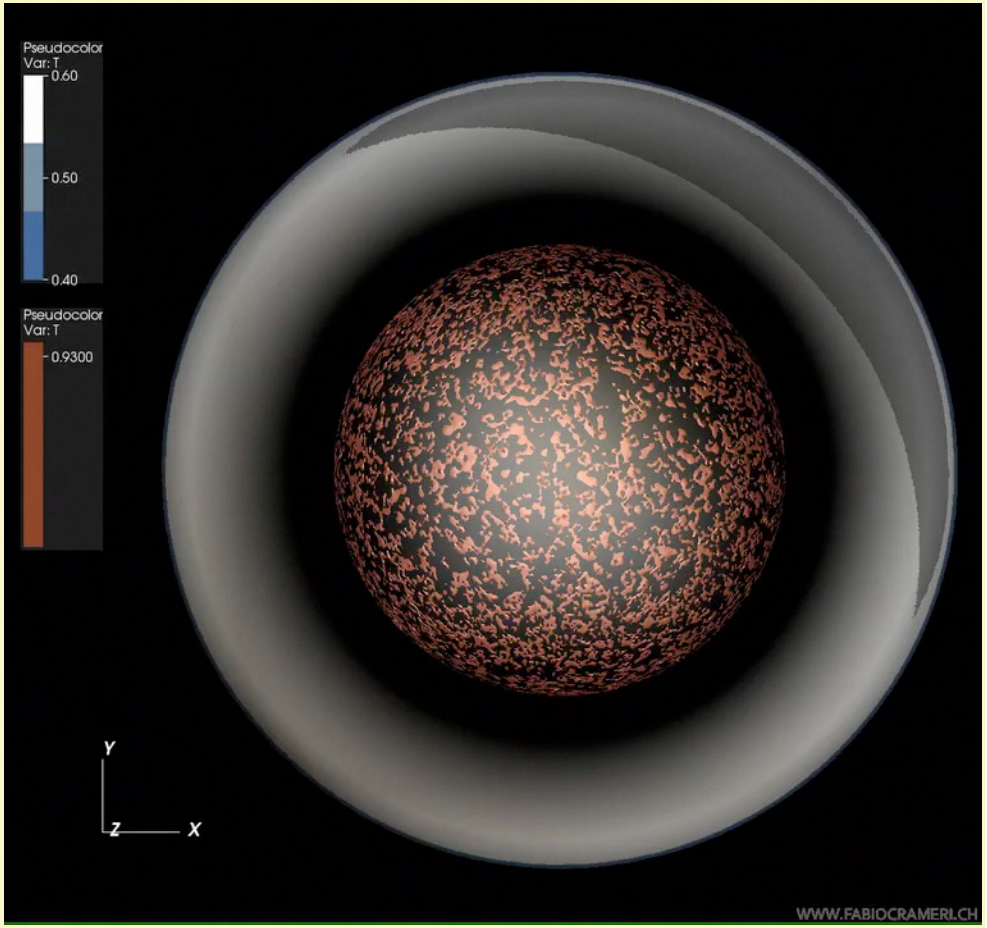


Mantle Convection: Impact of the Lithosphere

Crameri & Tackley [2016]



Lithosphere cannot break (Mars)
→ ”stagnant lid” convection
→ Mantle remains hot



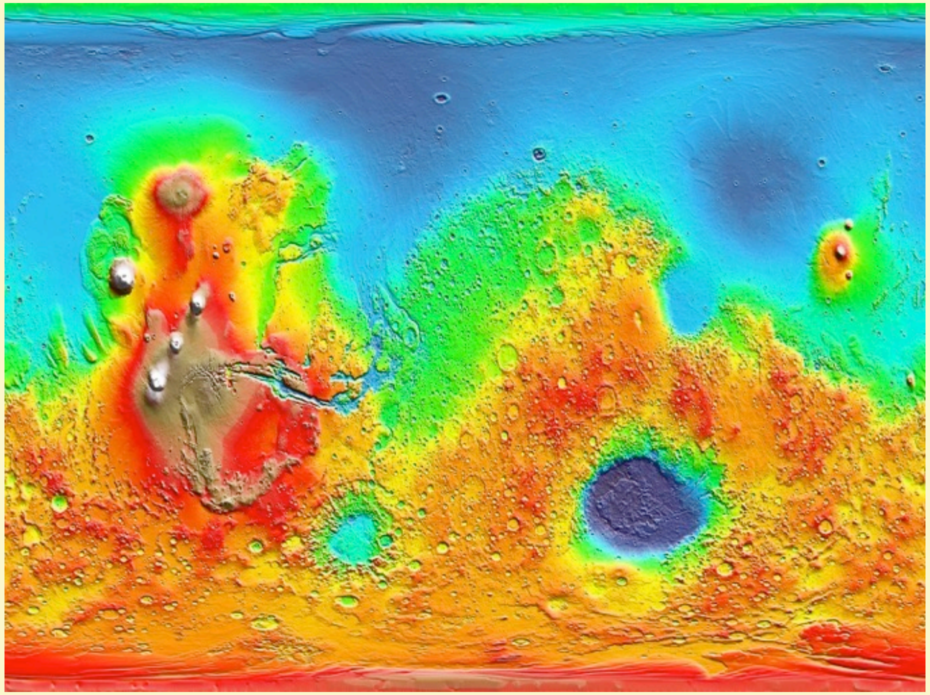
Lithosphere can break (Earth)
→ Subduction forms
→ Plate tectonics

The Lithosphere and Convection on other Planets:

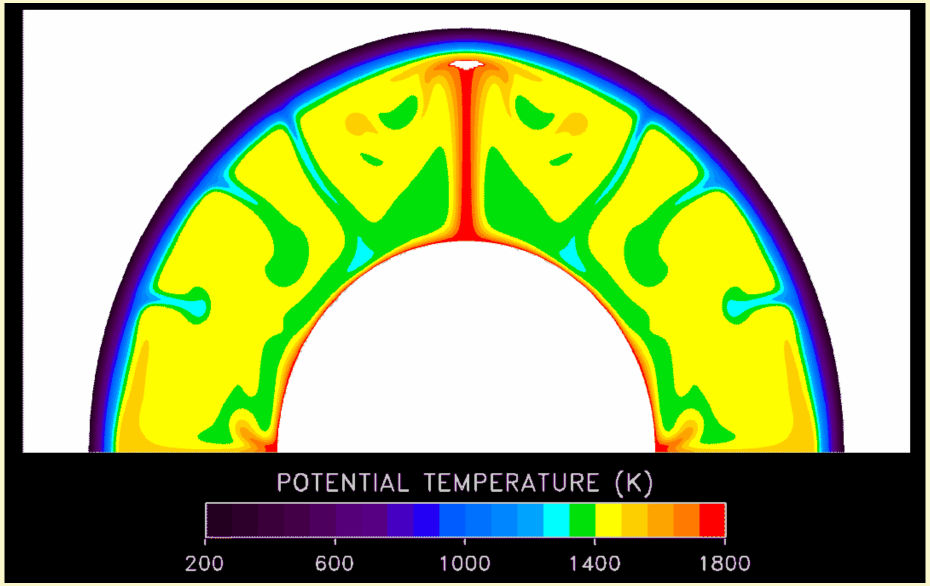
Moon, Mars, Venus, Mercury: Surfaces are much older than Earth's: Probably no plate tectonics

Instead, mantle convection beneath a “stagnant lid”

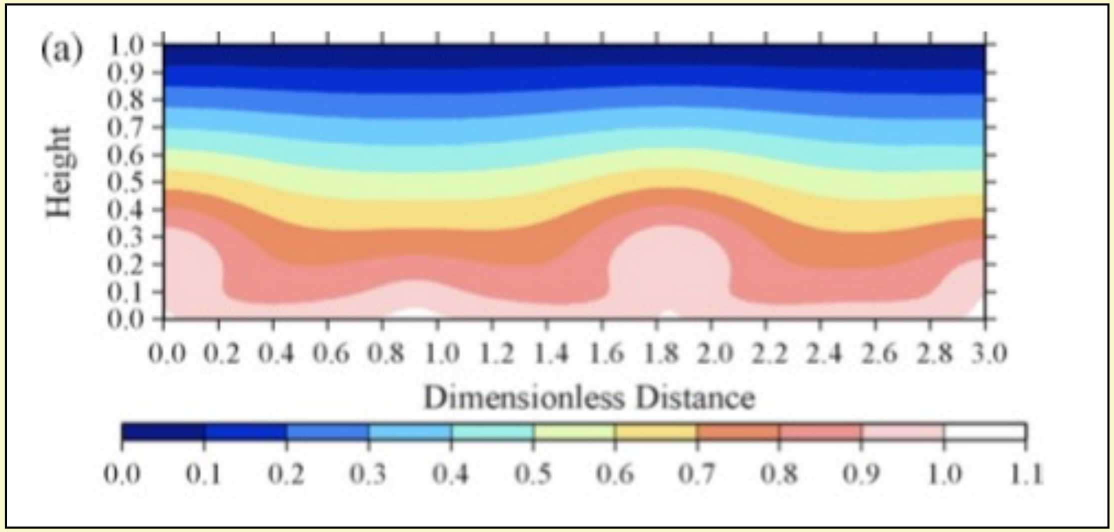
Mars Topography



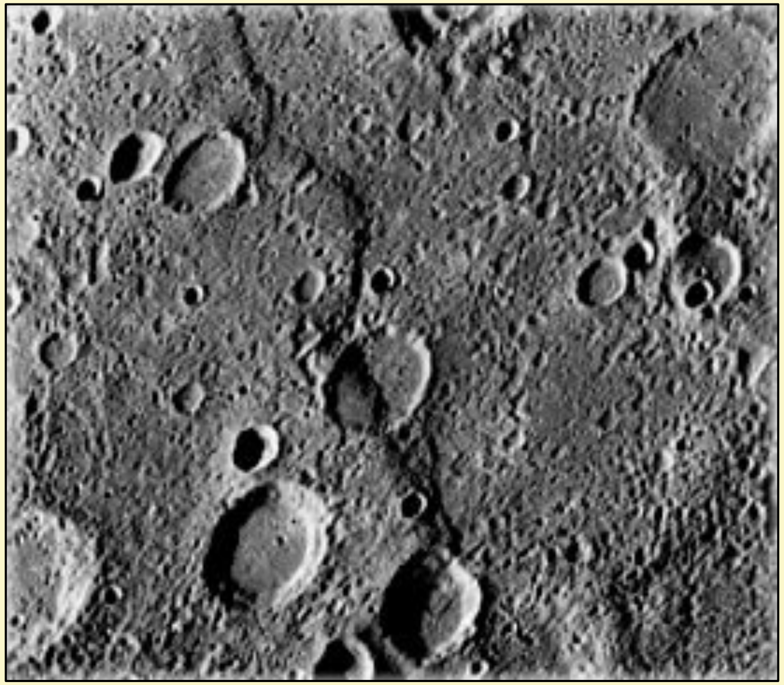
Model of Mars Convection



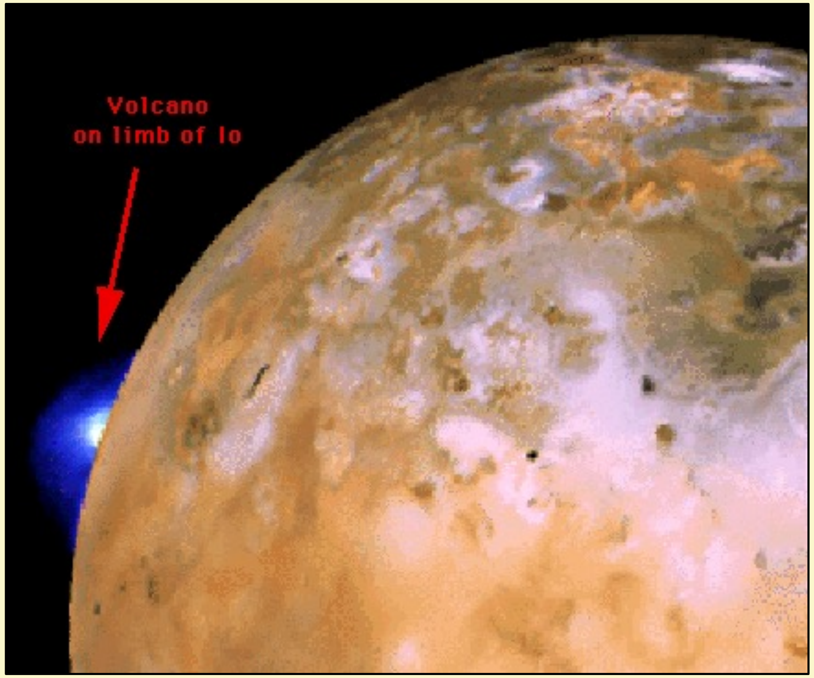
Mercury: Low Ra



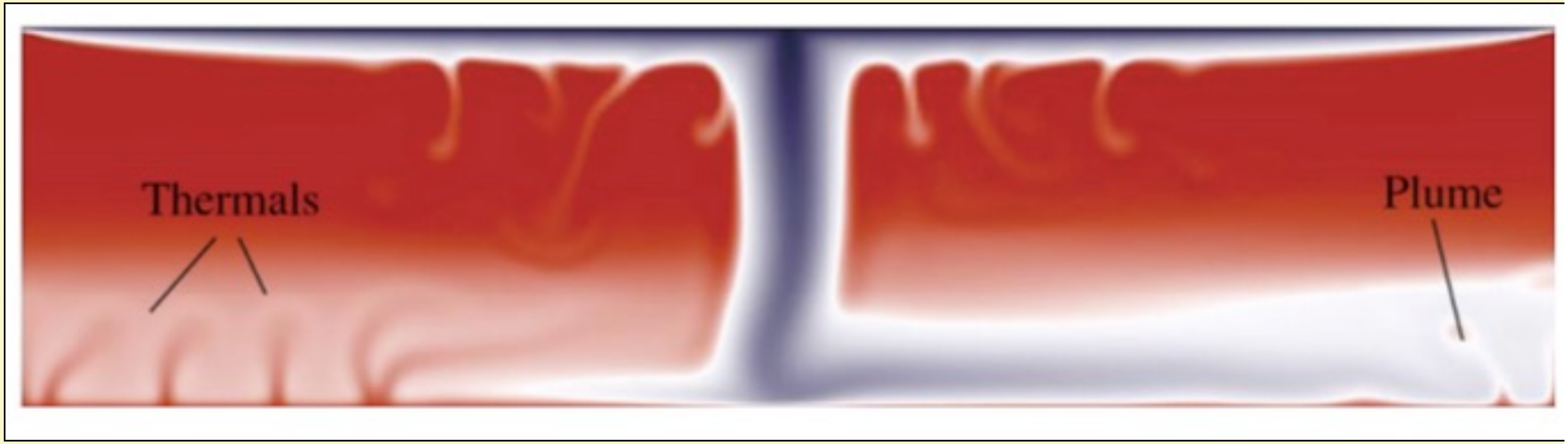
Redmond & King 2007

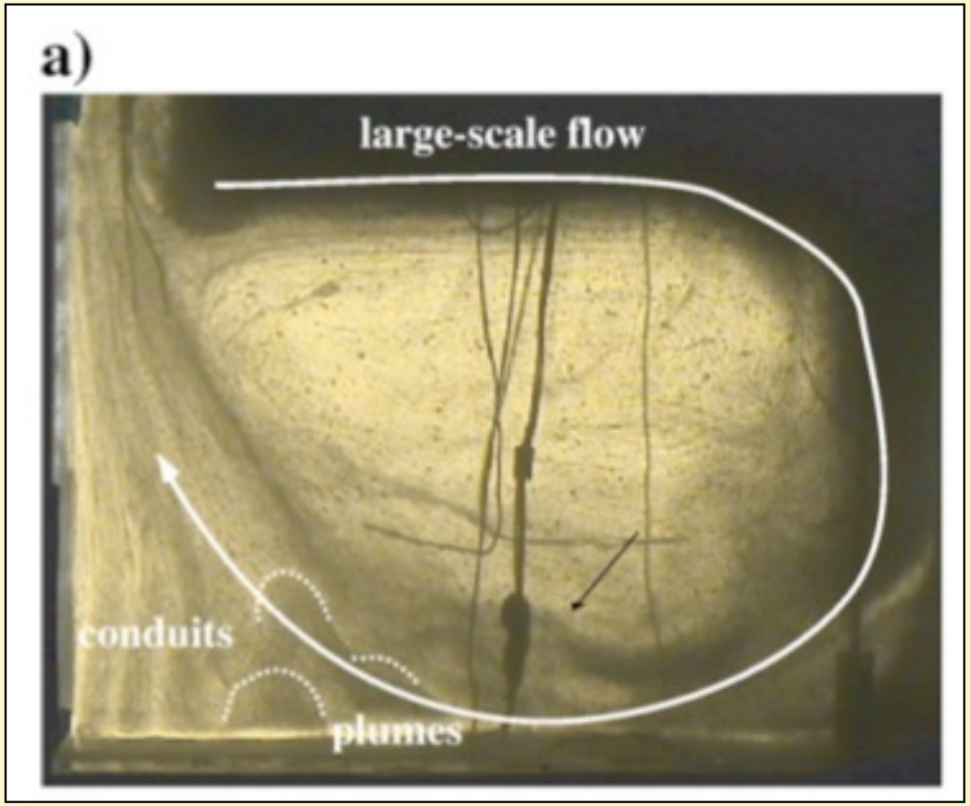


Io: High Ra



Volcanism through a thin lithosphere



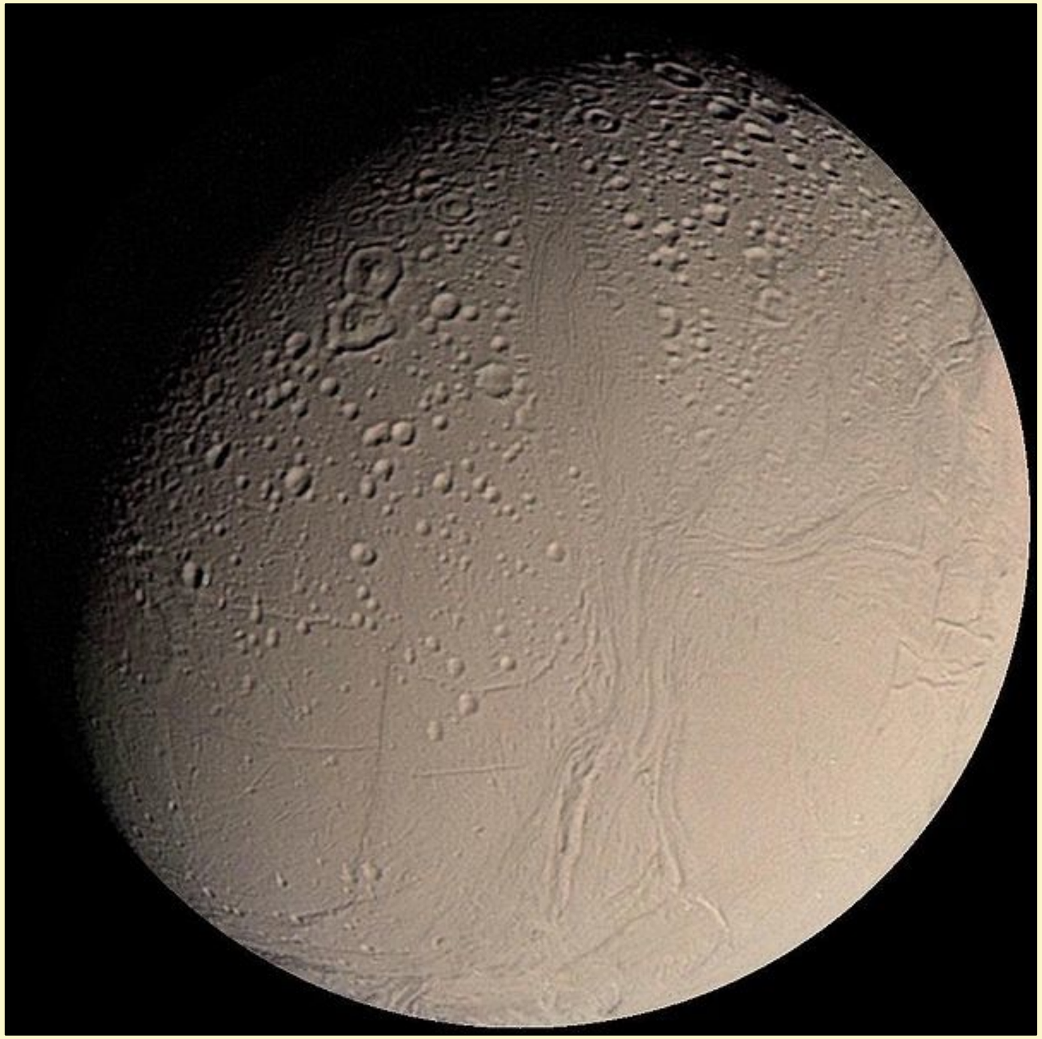


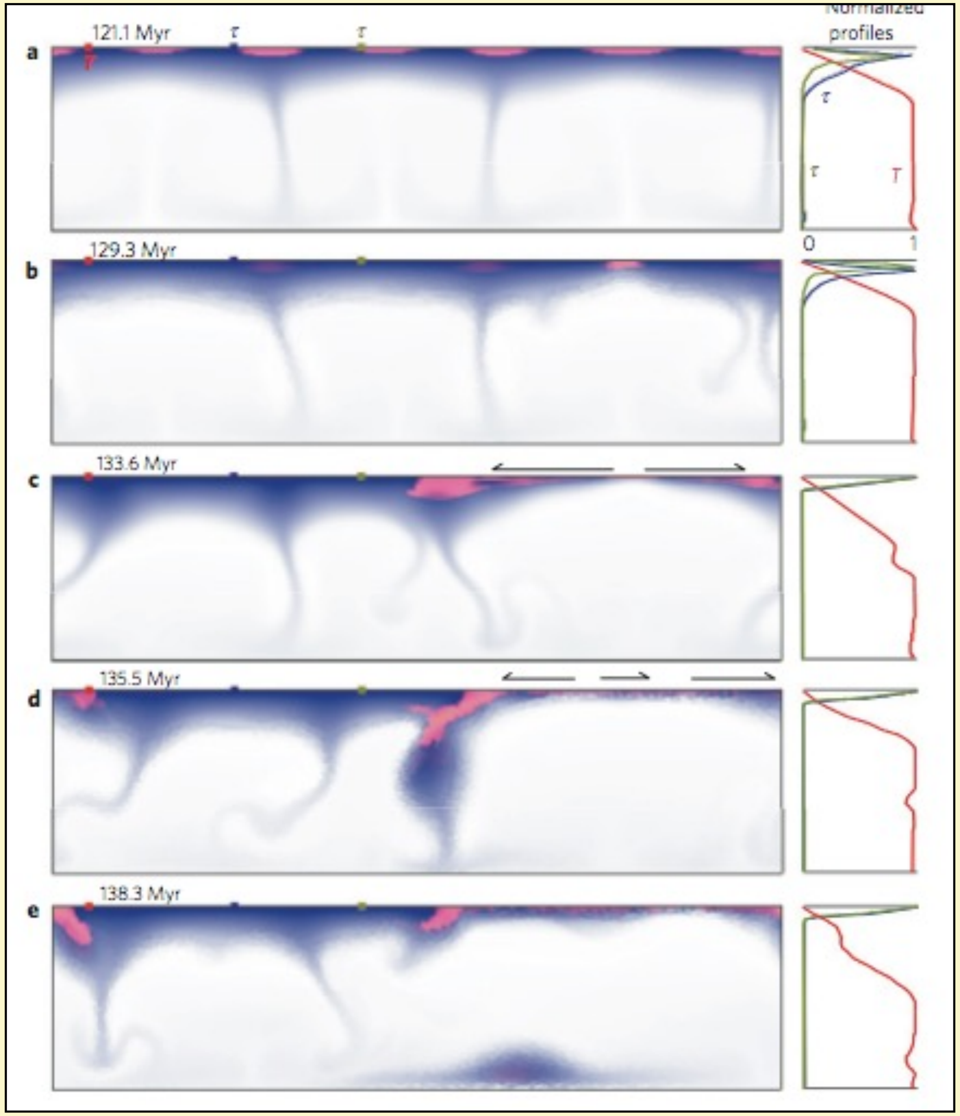
Venus:

No plate tectonics,
but the entire lithopshere
sometimes sinks into
the mantle, resurfacing
the entire planet.

***Robin et al.*, 2007**

Enceladus: Convection in solid ice

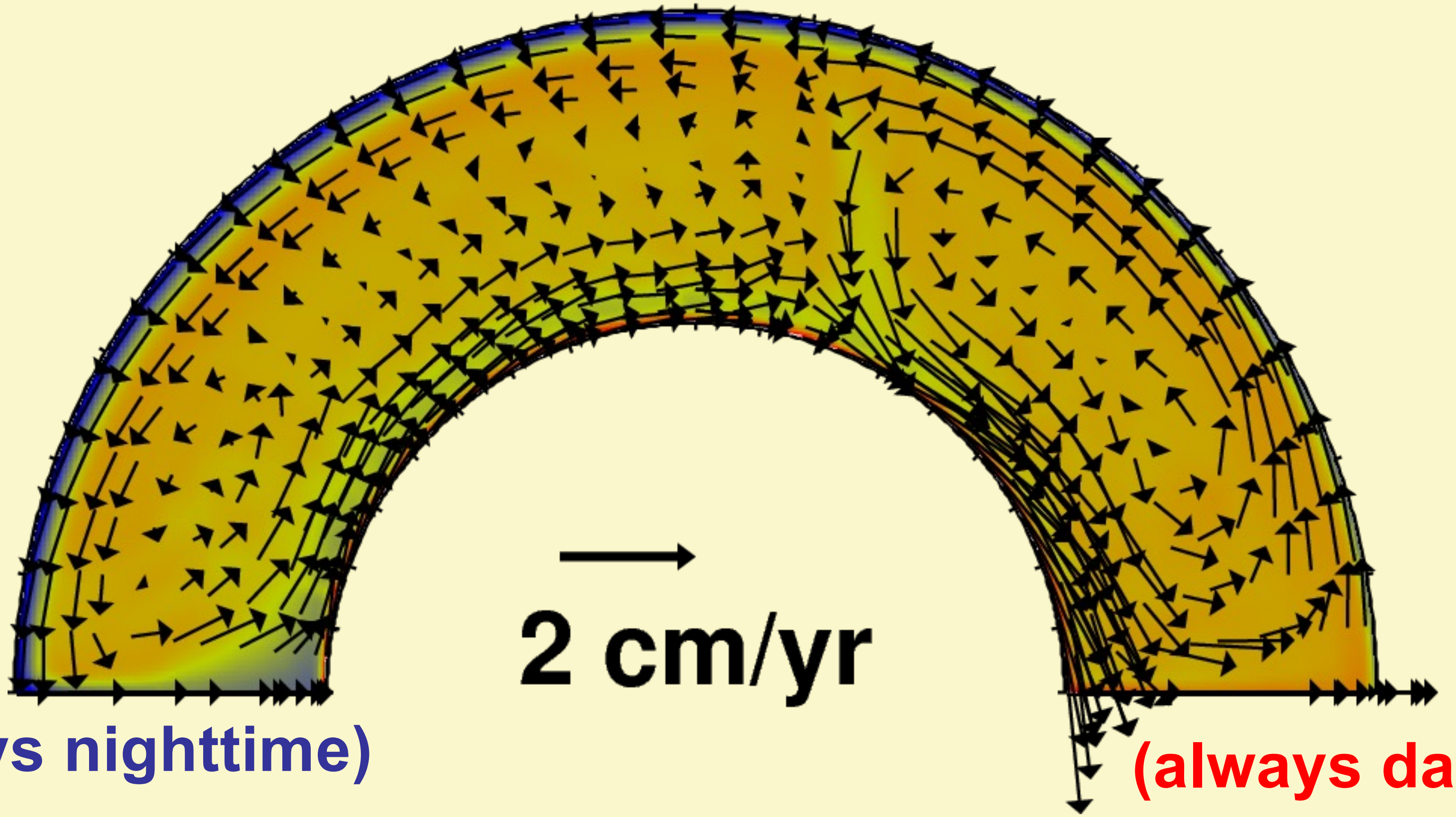




O'Neill and Nimmo, *2010*

Exoplanets: Many different styles!

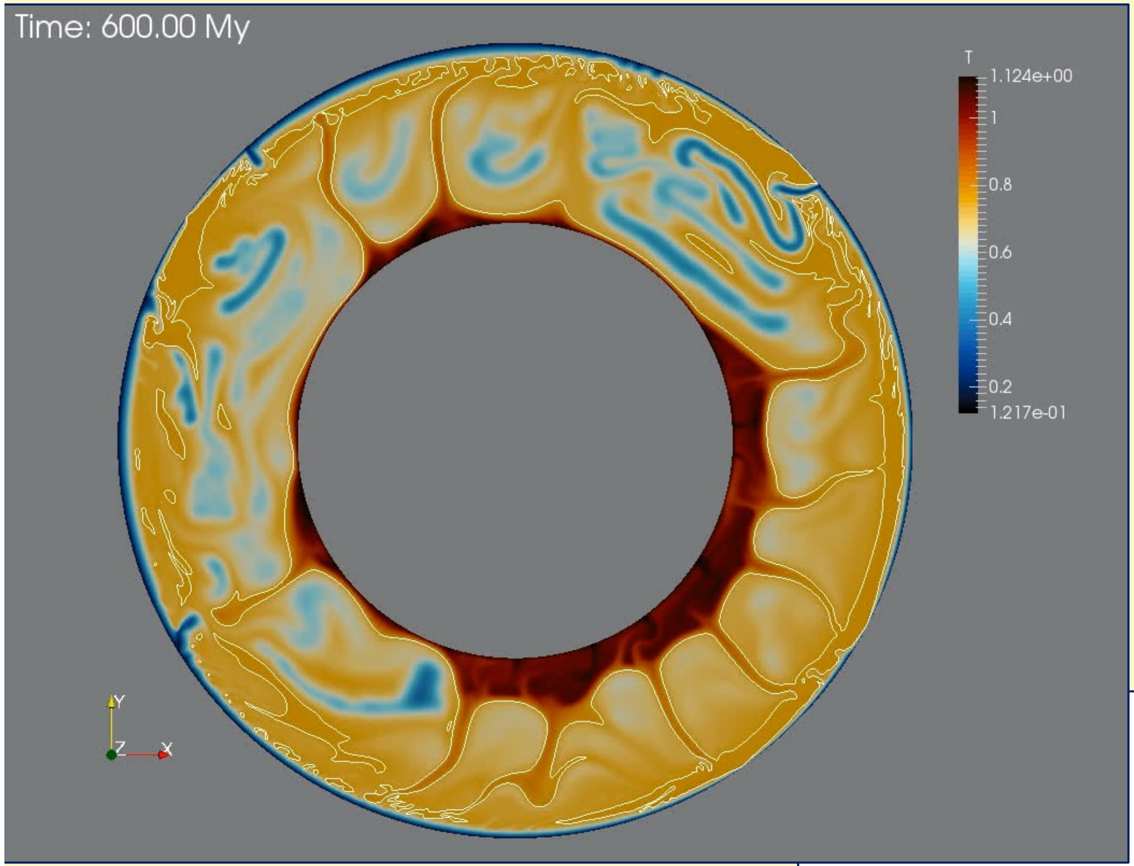
Tidally-locked example



COLD SIDE (always nighttime)

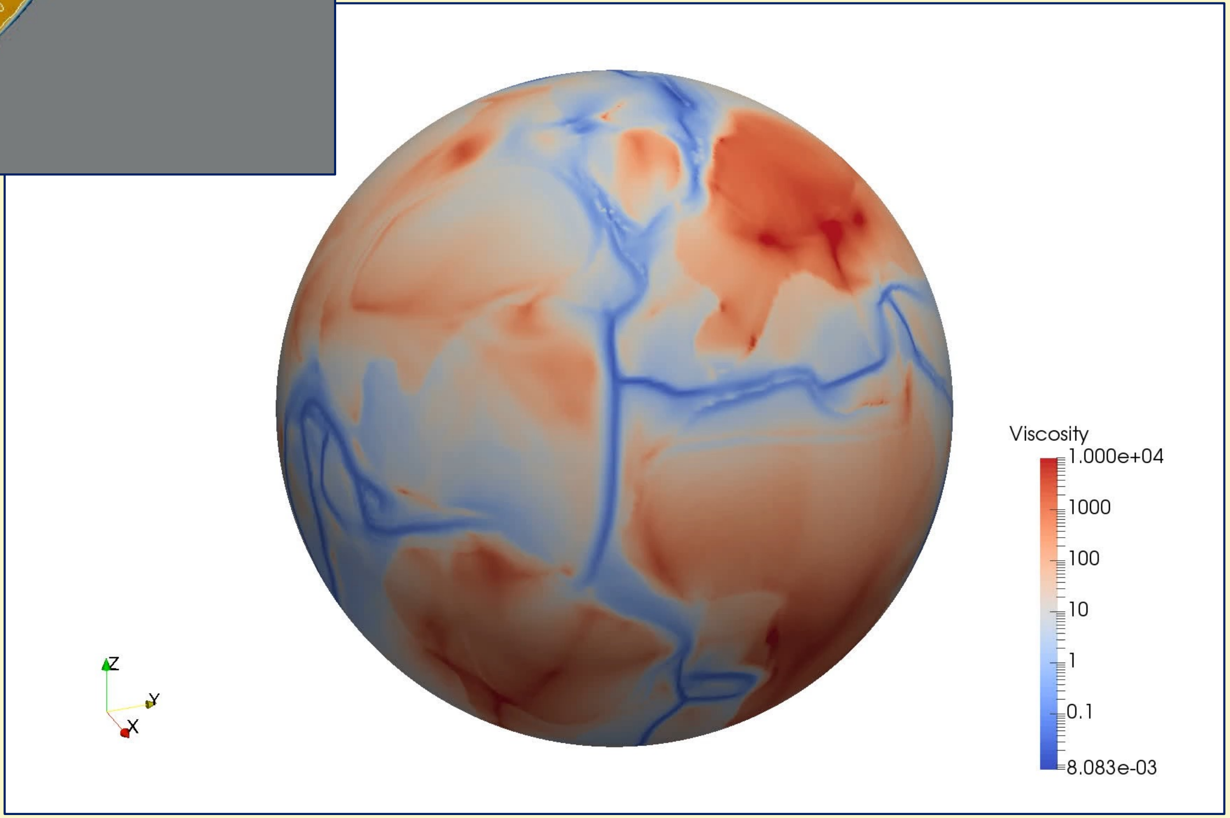
HOT SIDE (always daytime)

van Summeren, Conrad, & Gaidos, 2011



Lithosphere tectonics governs mantle convection

→ The lithosphere regulates cooling rates



Arnould et al. [2018]

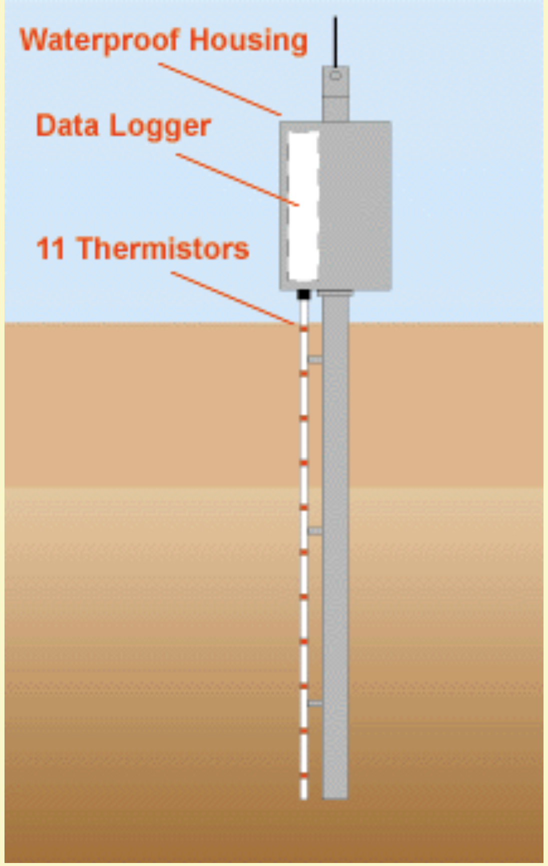
Cooling at the Earth's Surface

Heat flows down a temperature gradient:

$$q_z = -k \frac{dT}{dz}$$

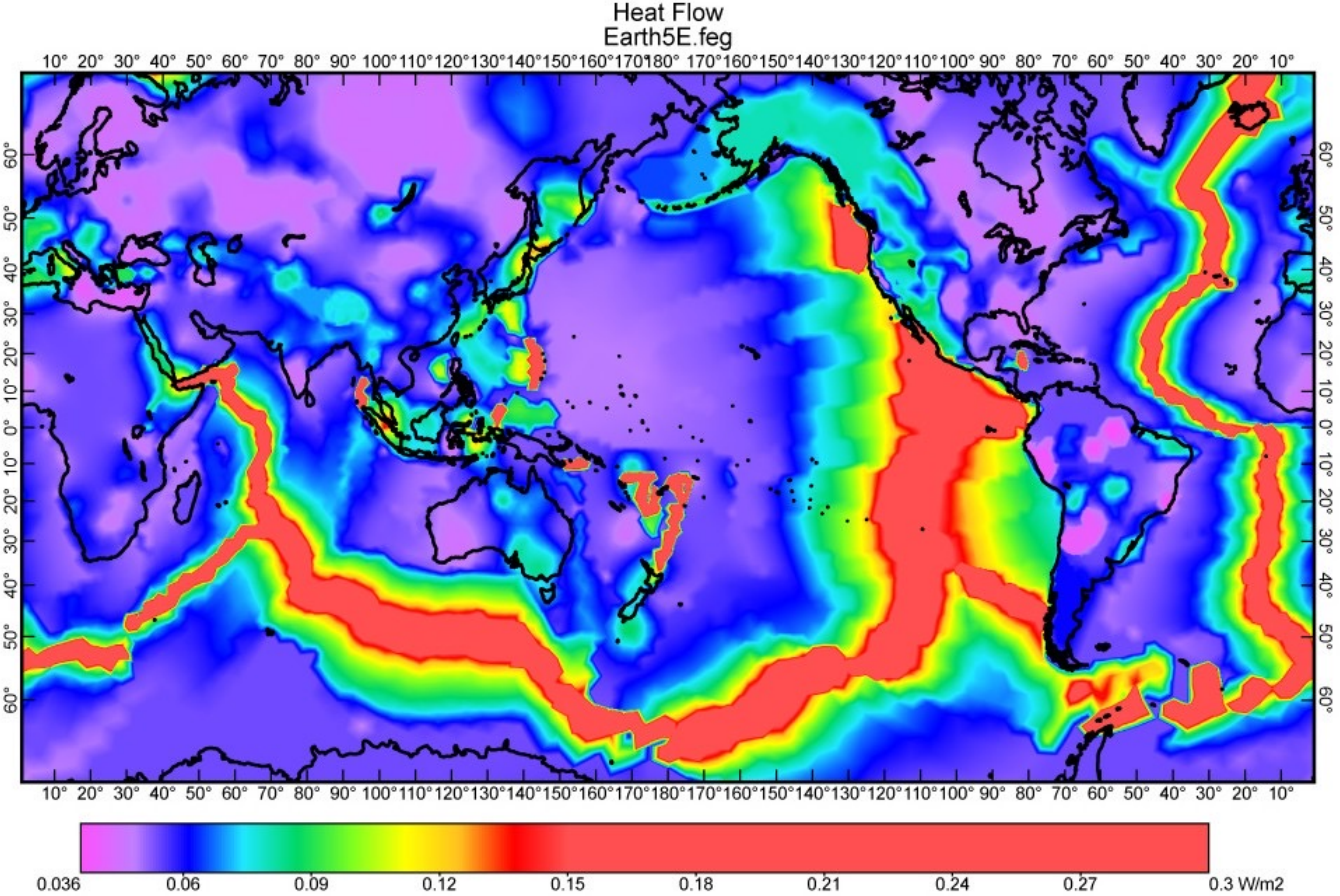
k = thermal conductivity
typically k ~ 2-3 W/m/K

Then we can measure heat flow by measuring dT/dz

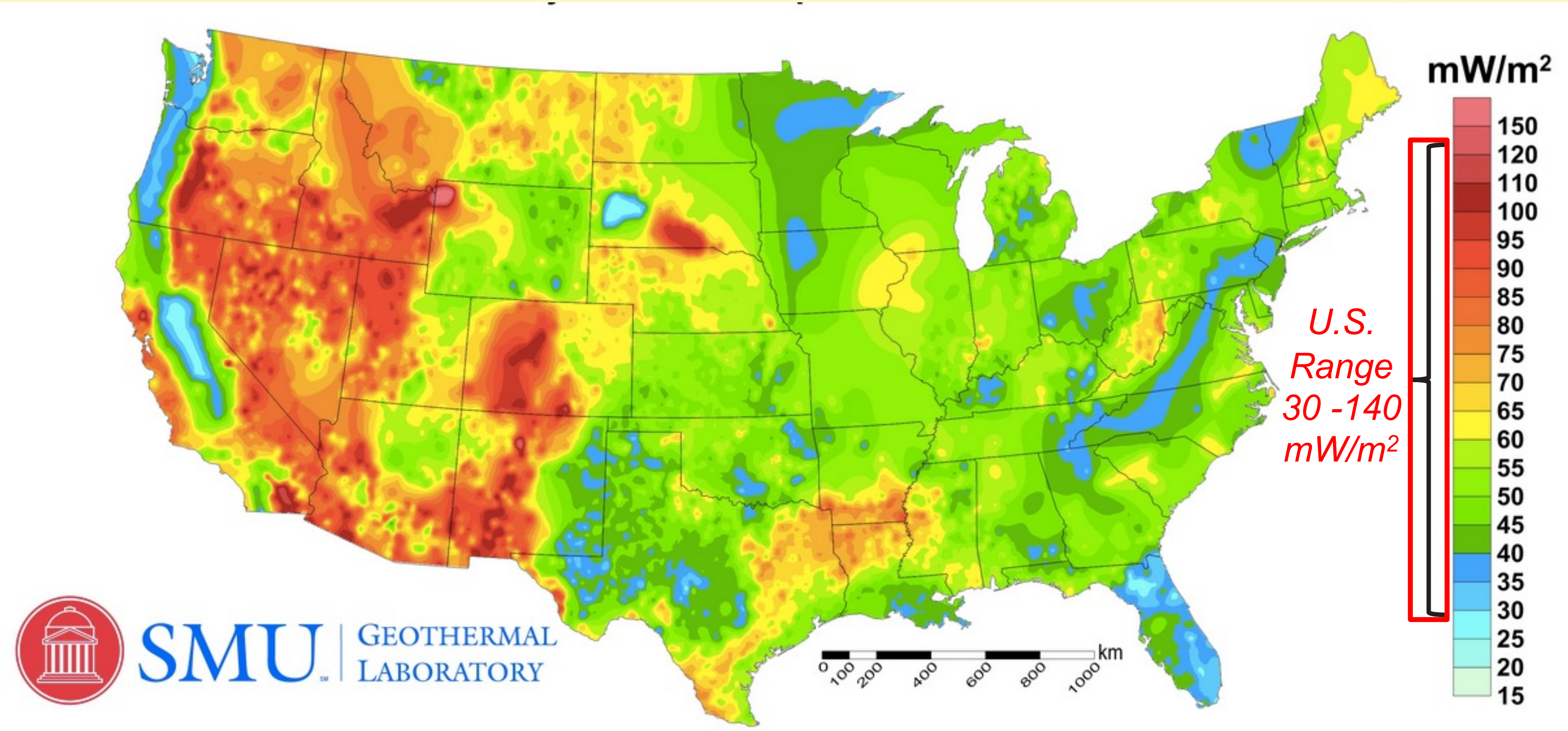


For submarine environments:
Use a Heat Flow Probe
Probe is 3-4 m long

For continental environments:
Measure heat flow in a cave, mine or borehole (deeper than ~300 m)



20° C/km 40° C/km 60° C/km 80° C/km

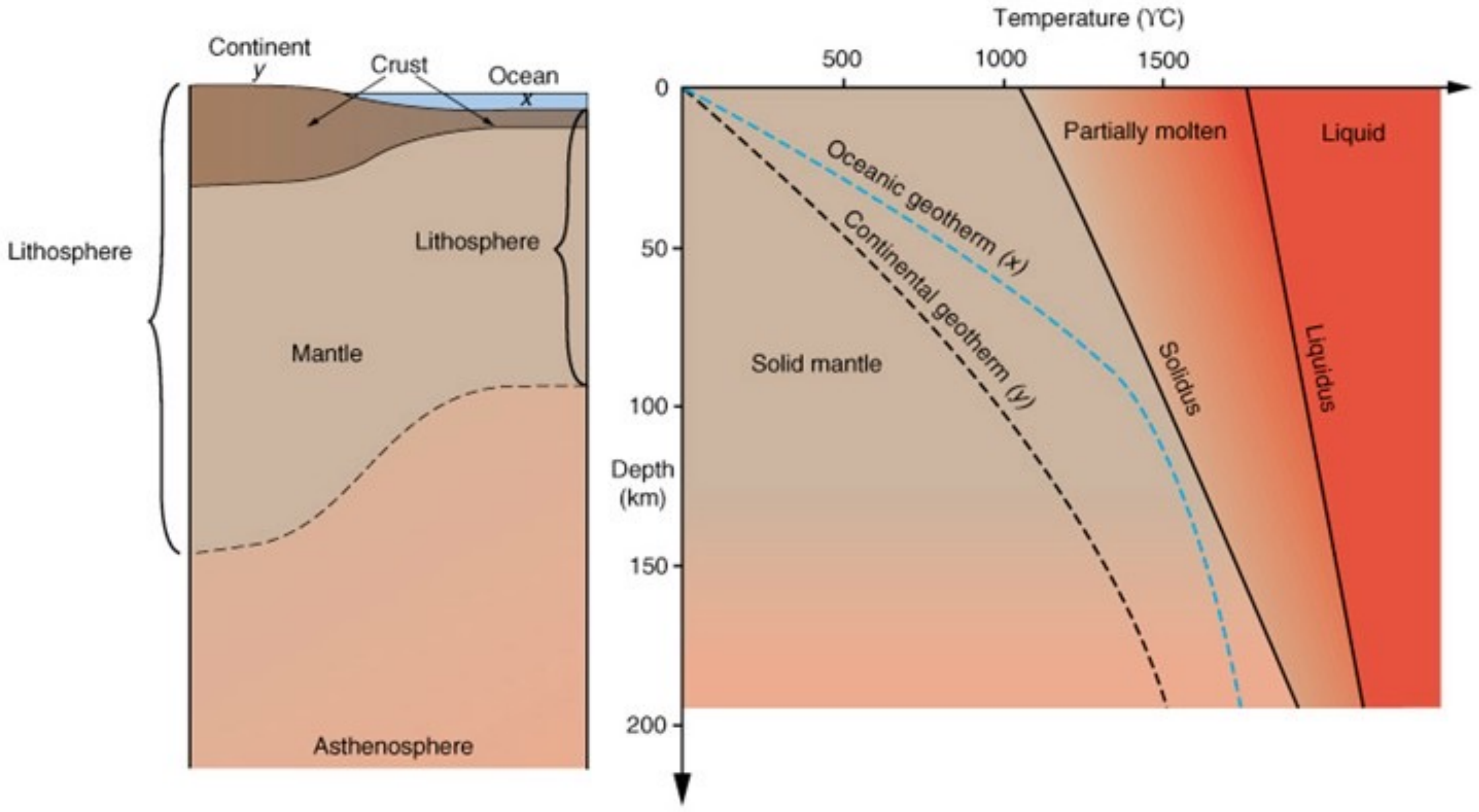


U.S. Range 30 -140 mW/m²

What causes such large variations in heat flow?

Temperature vs. depth in the lithopshere

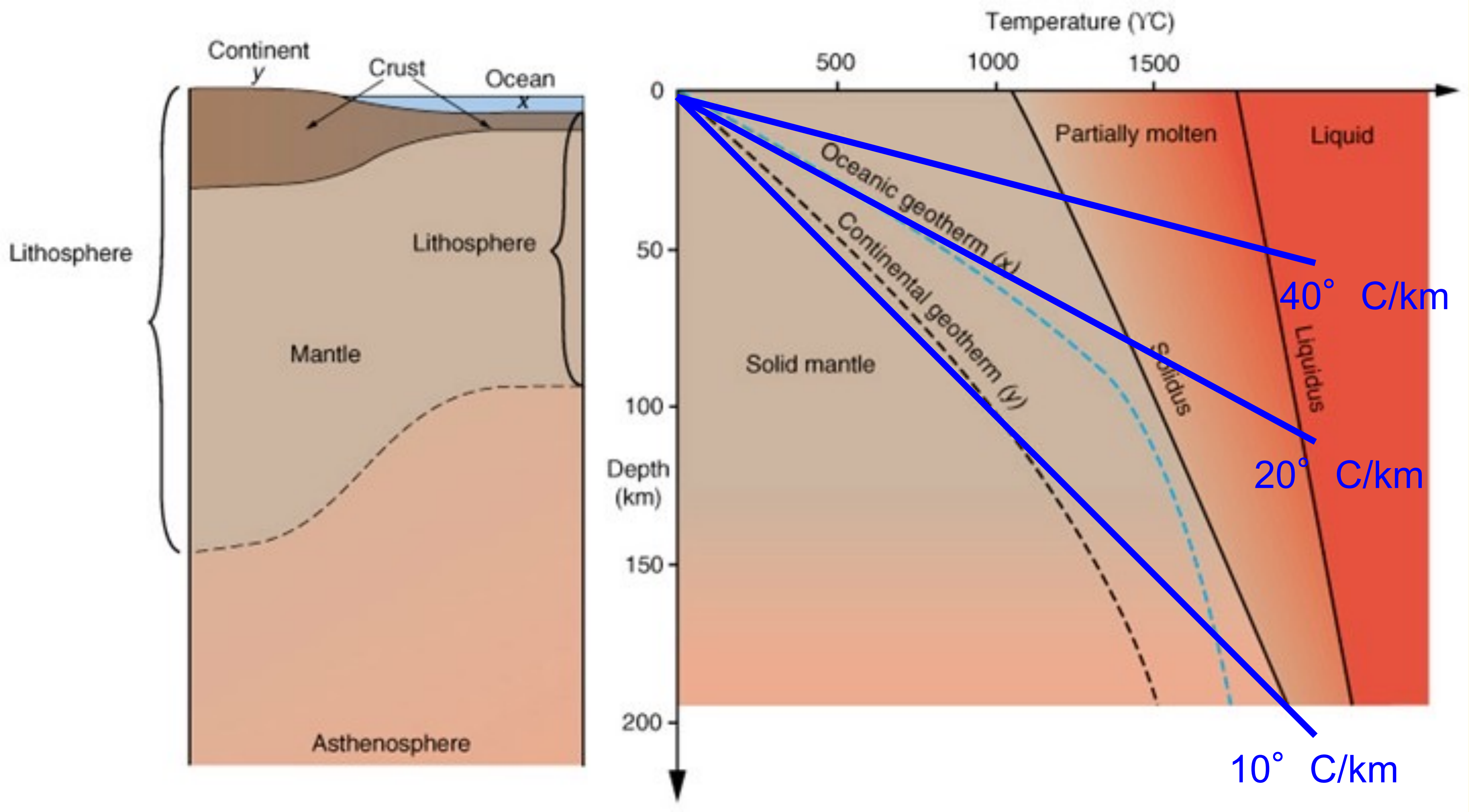
→ Surface geotherms cannot continue deeper than 50-100 km



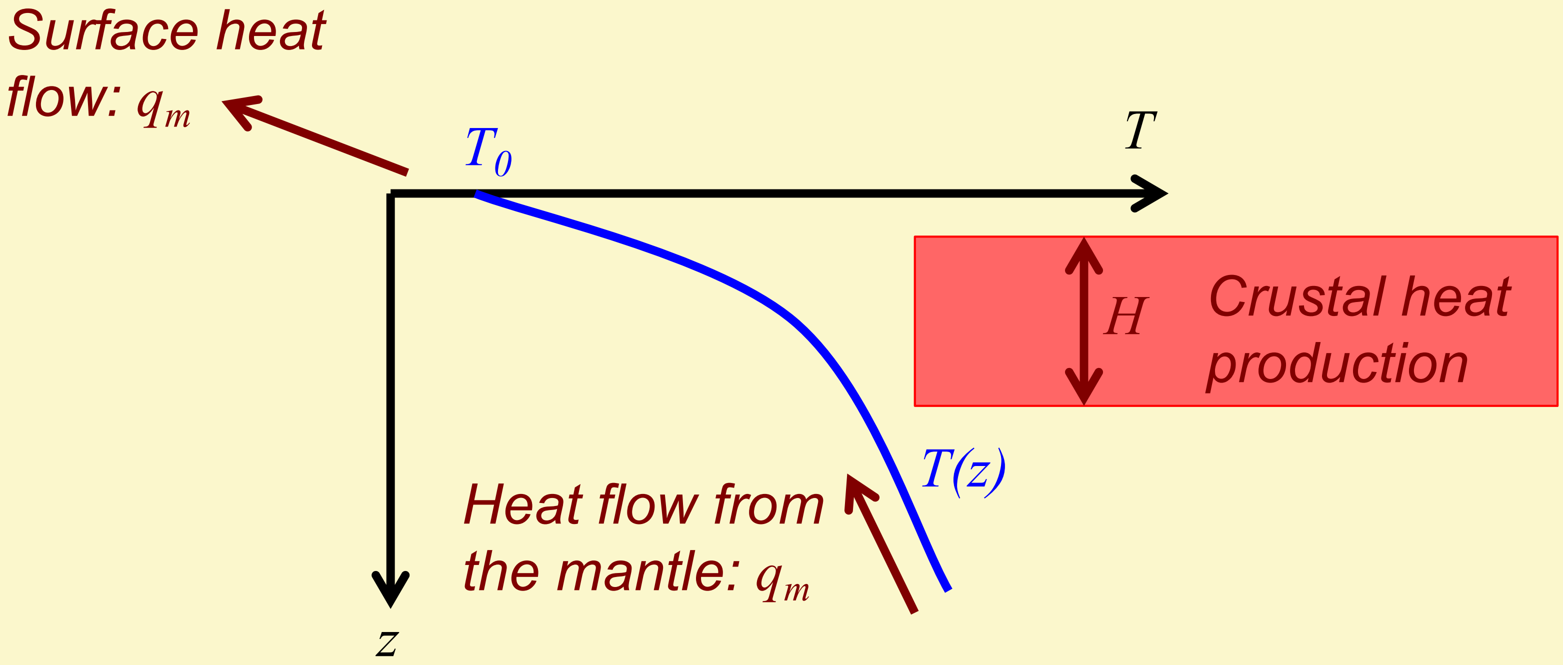
Temperature vs. depth in the lithopshere

→ Surface geotherms cannot continue deeper than 50-100 km

What causes these geotherms to turn?

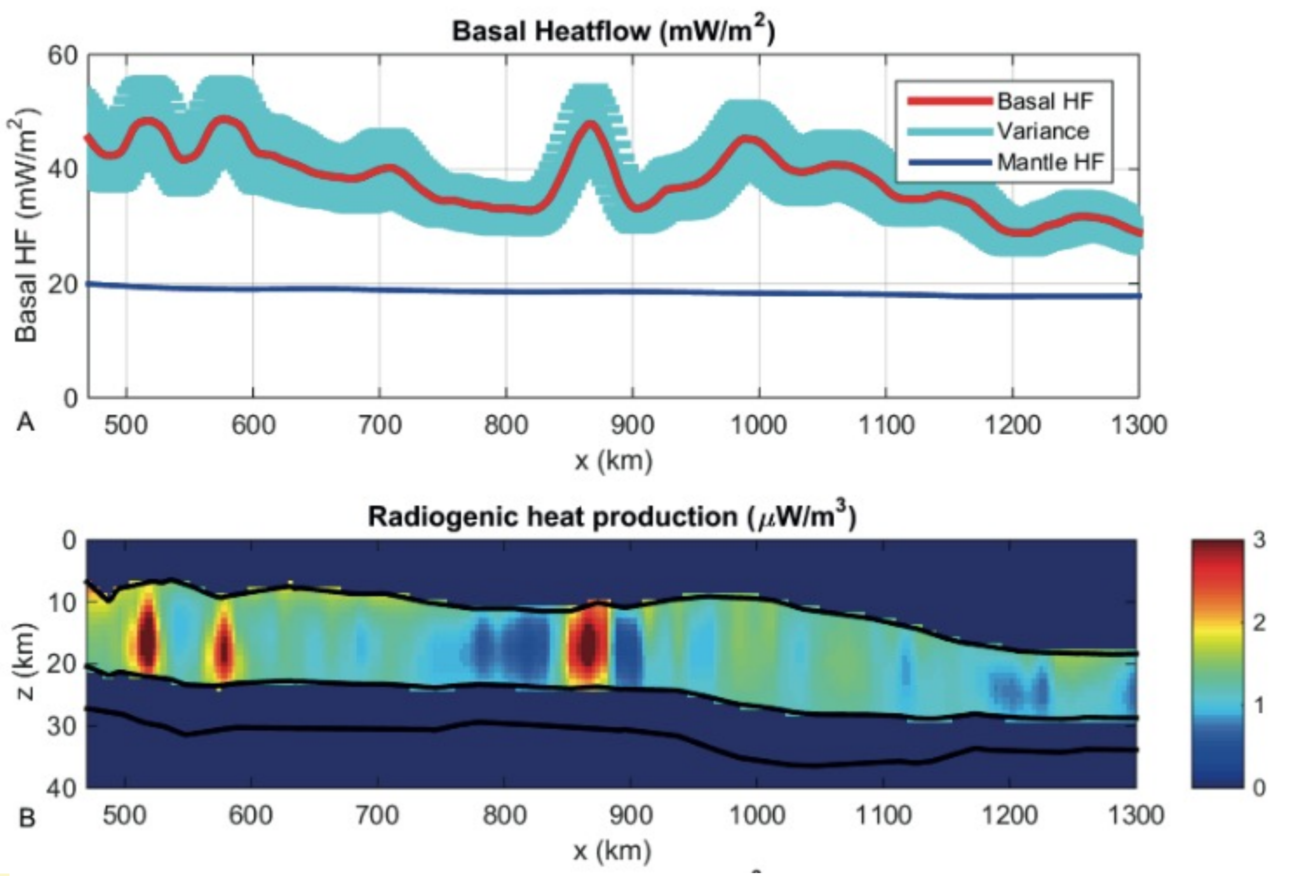


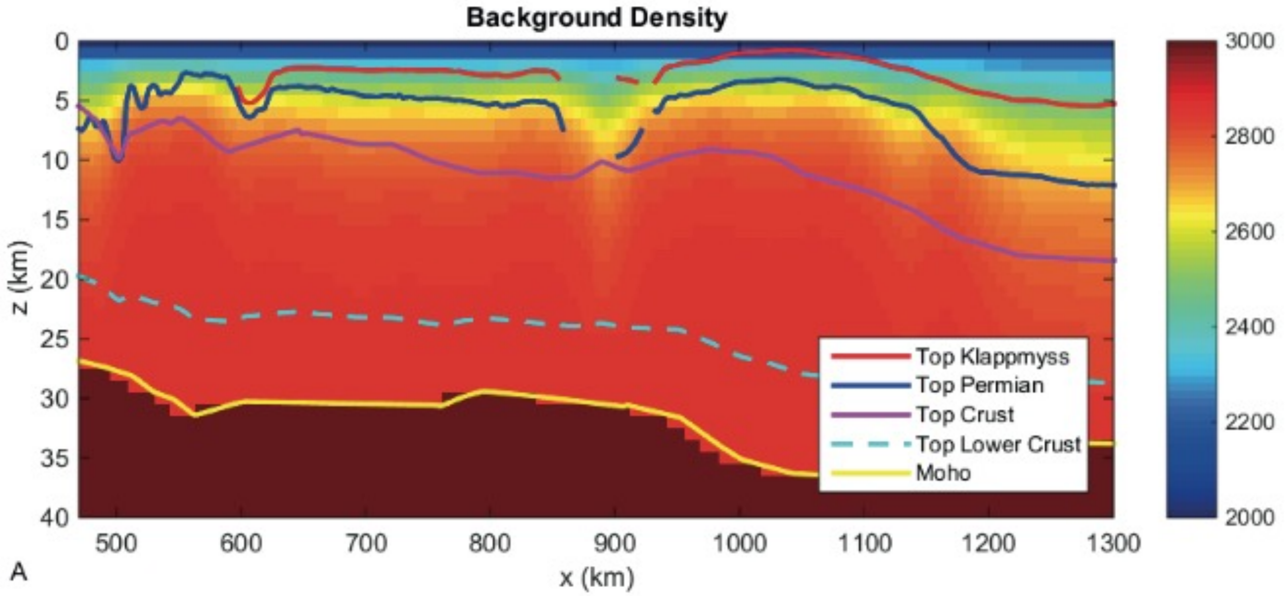
Option 1: There is a heat source in the lithosphere



This solution could be stable in steady-state (continental regions)

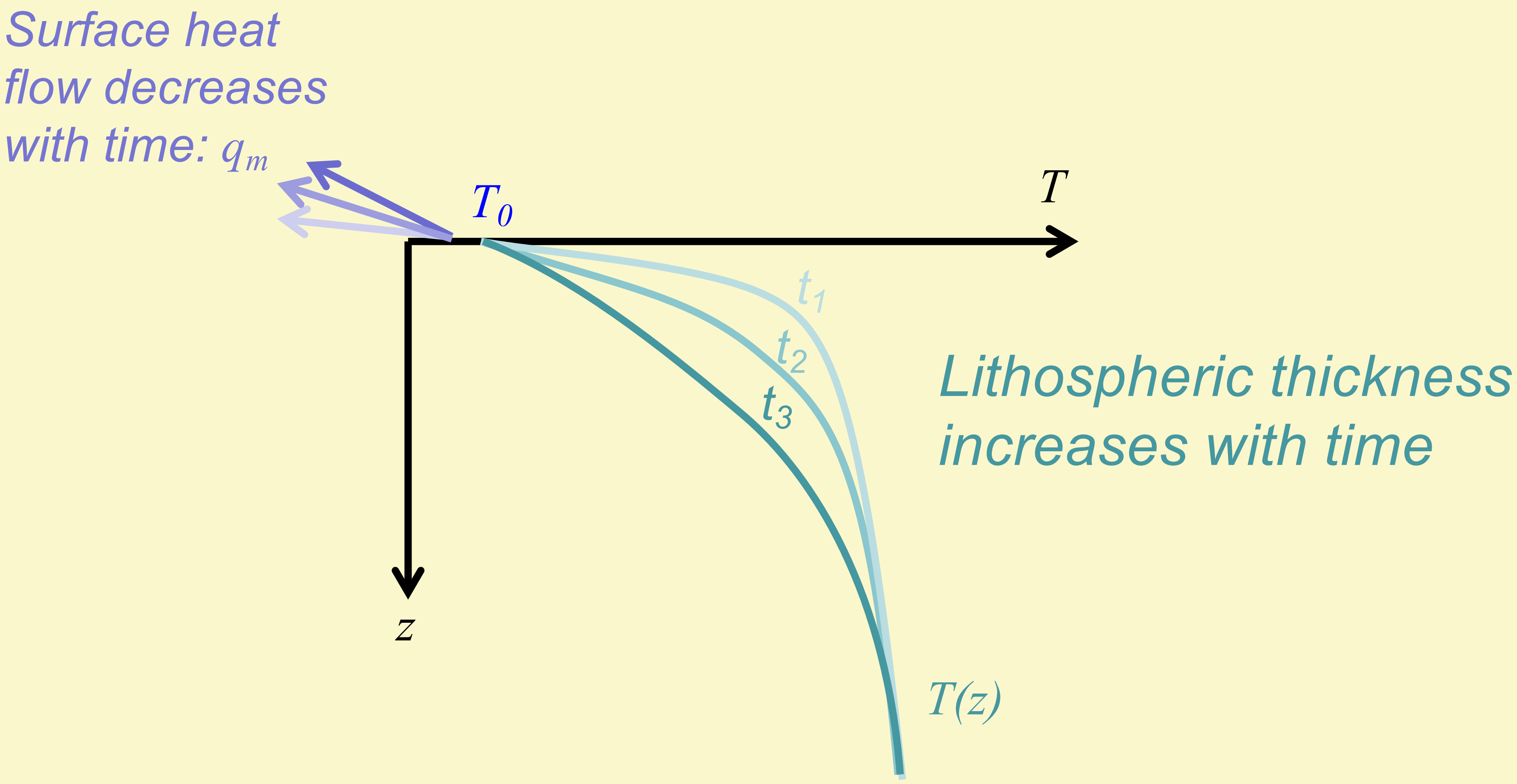
Thermal modeling of a cross section across the Barents Sea





Hokstad et al. [*Norwegian Journal of Geology,* 97, 241-254, 2017]

Option 2: The lithosphere is not in thermal steady-state


Surface heat flow decreases with time: q_m

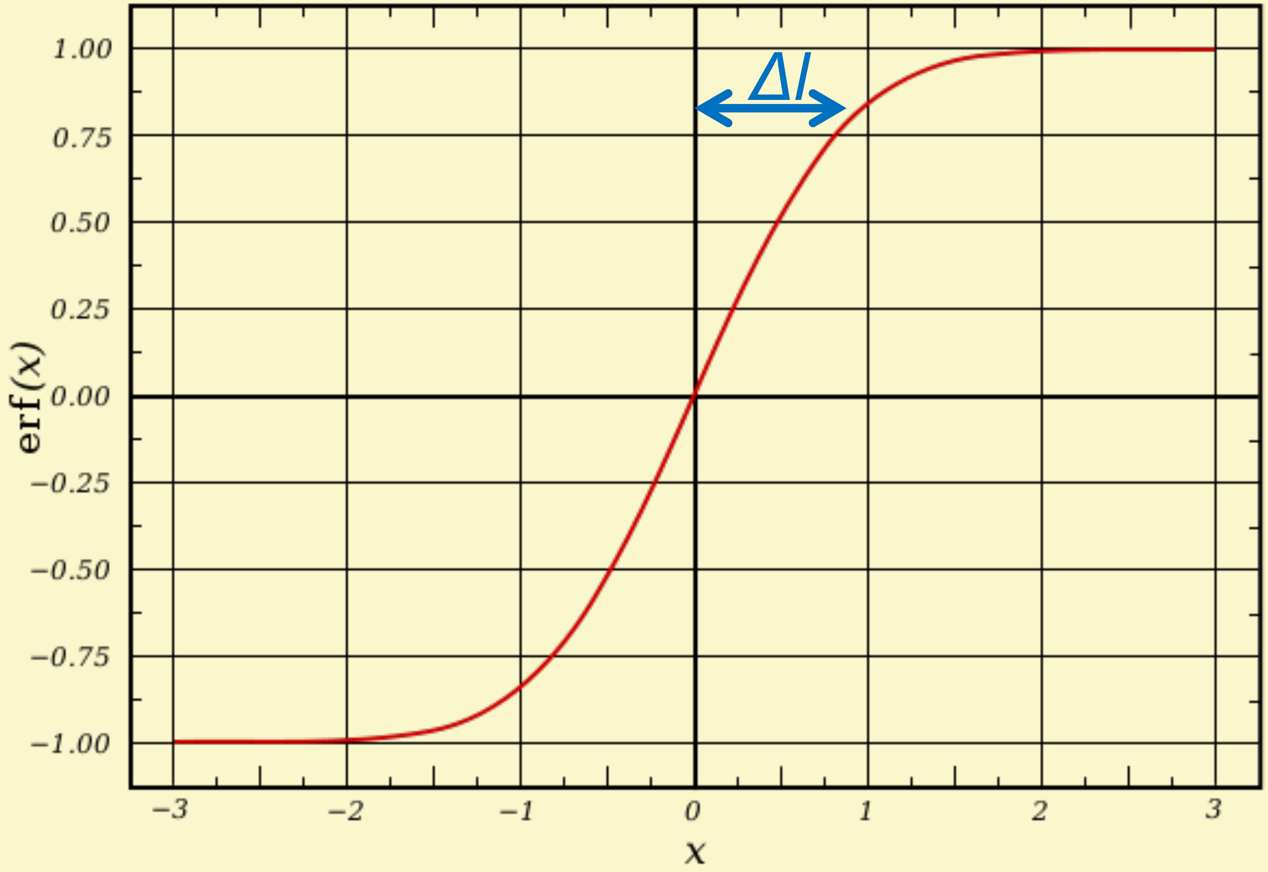
Lithospheric thickness increases with time

Time-Dependent Solution to the Heat Equation

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \frac{H}{c_p}$$

$\kappa = \frac{k}{\rho c_p}$ is the thermal diffusivity

for rocks, $\kappa \sim 10^{-6}$ m^2/s



The solution to halfspace cooling is the **Error Function**

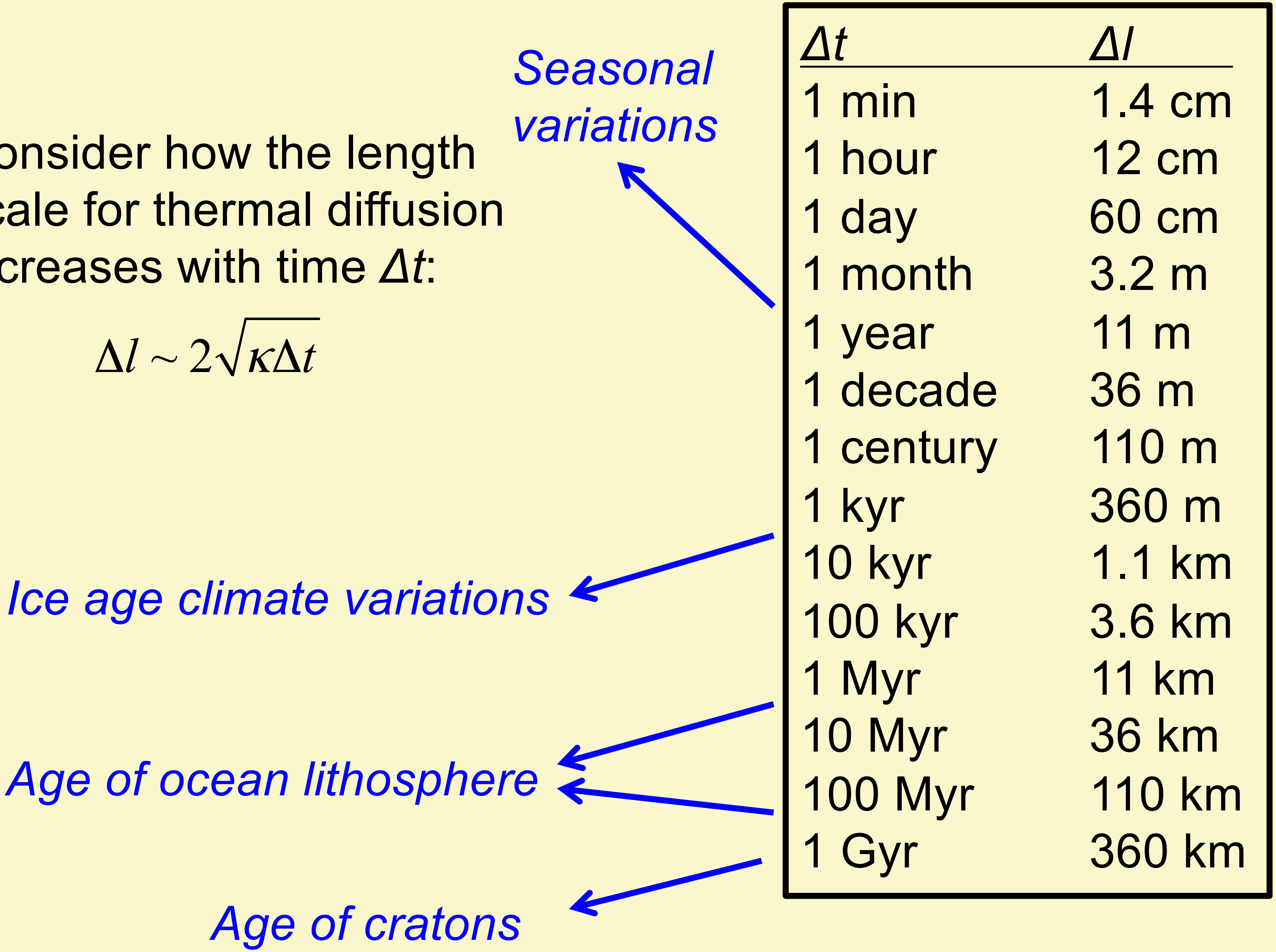
Temperature diffuses across a length scale Δl in a timescale Δt according to:

$$\Delta l \sim 2\sqrt{\kappa \Delta t}$$

Thermal diffusion is slow on geological timescales

Consider how the length scale for thermal diffusion increases with time *Δt*:

$$\Delta l \sim 2\sqrt{\kappa \Delta t}$$



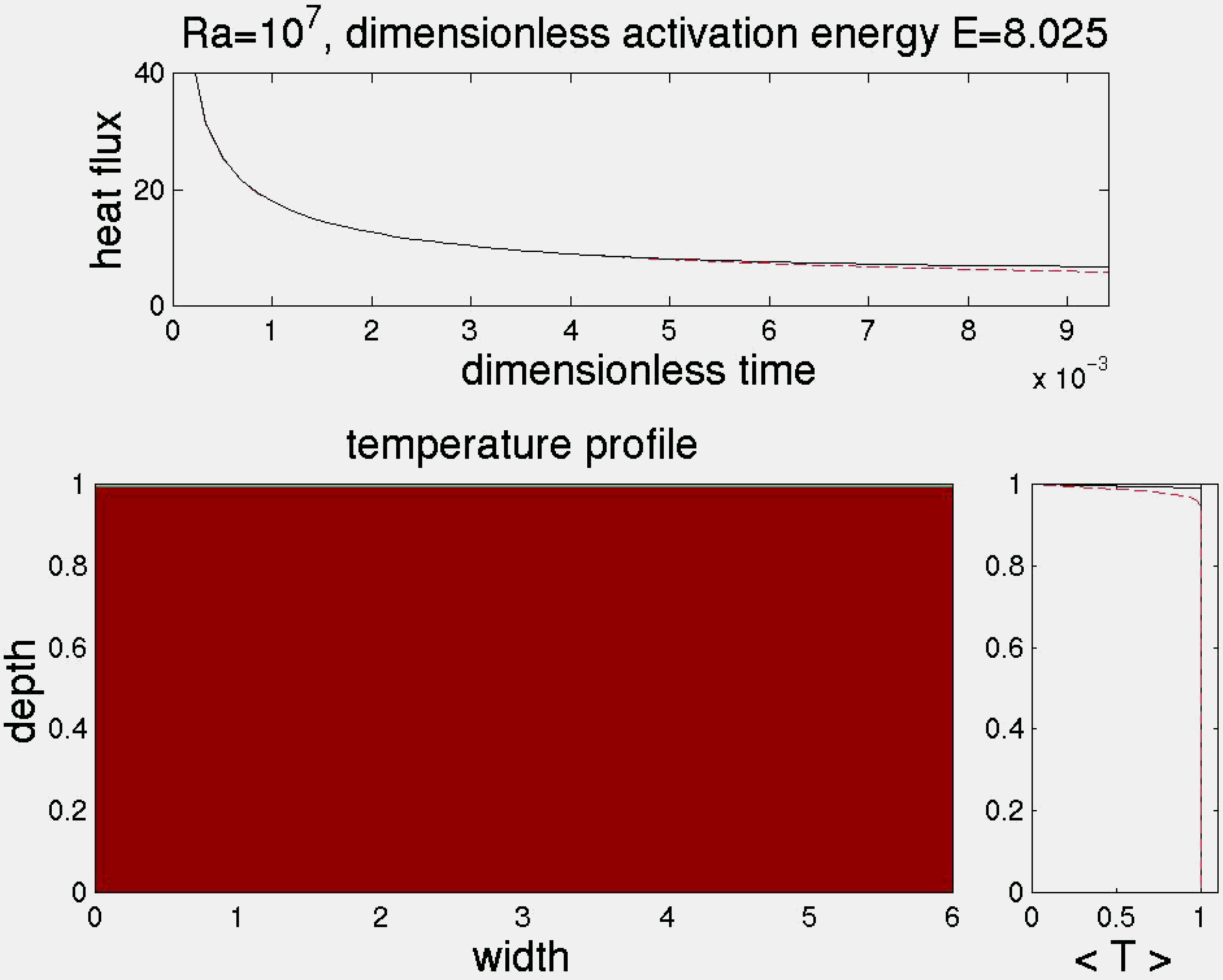
Δt	*Δl*
1 min	1.4 cm
1 hour	12 cm
1 day	60 cm
1 month	3.2 m
1 year	11 m
1 decade	36 m
1 century	110 m
1 kyr	360 m
10 kyr	1.1 km
100 kyr	3.6 km
1 Myr	11 km
10 Myr	36 km
100 Myr	110 km
1 Gyr	360 km

Seasonal variations

Ice age climate variations

Age of ocean lithosphere

Age of cratons


Ra=10^7, dimensionless activation energy E=8.025

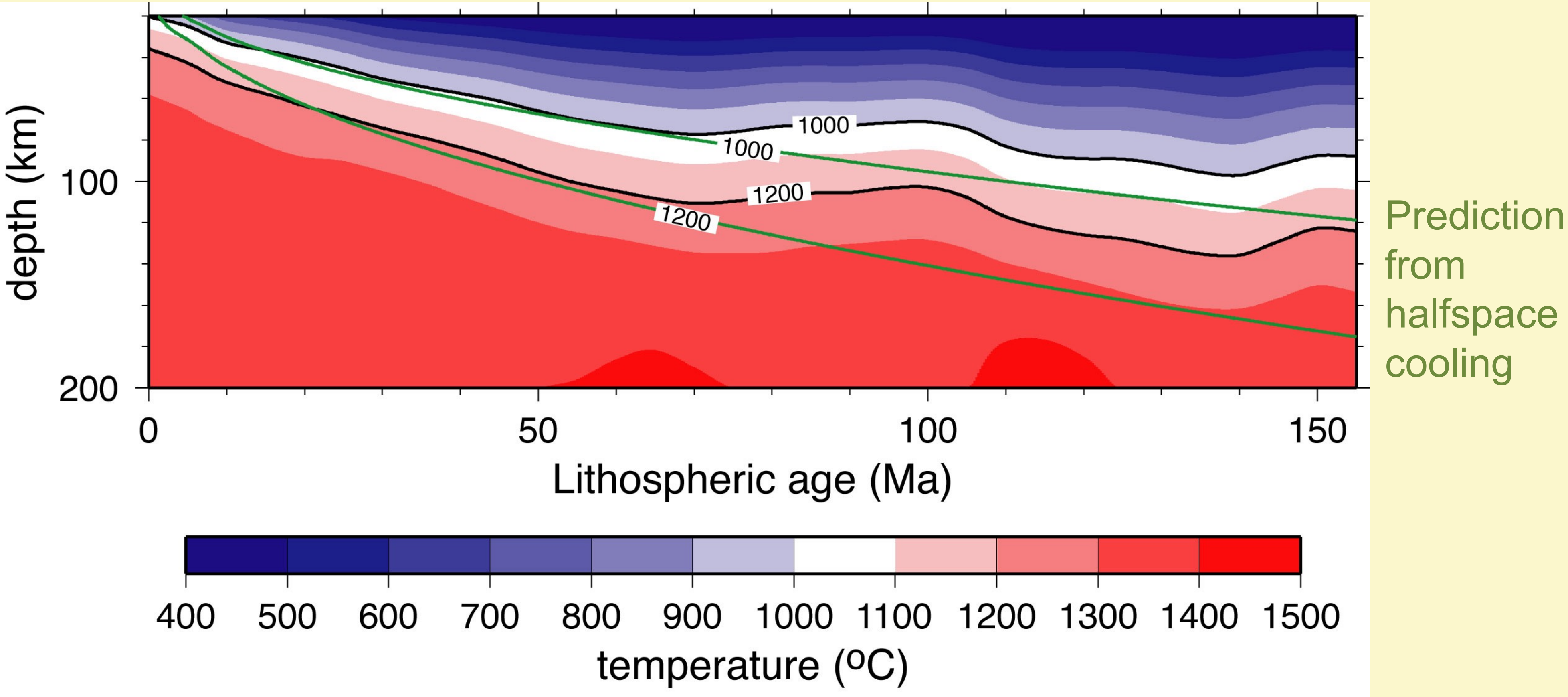
temperature profile

The oceanic lithosphere follows halfspace cooling

→ Out to about 80 Million years

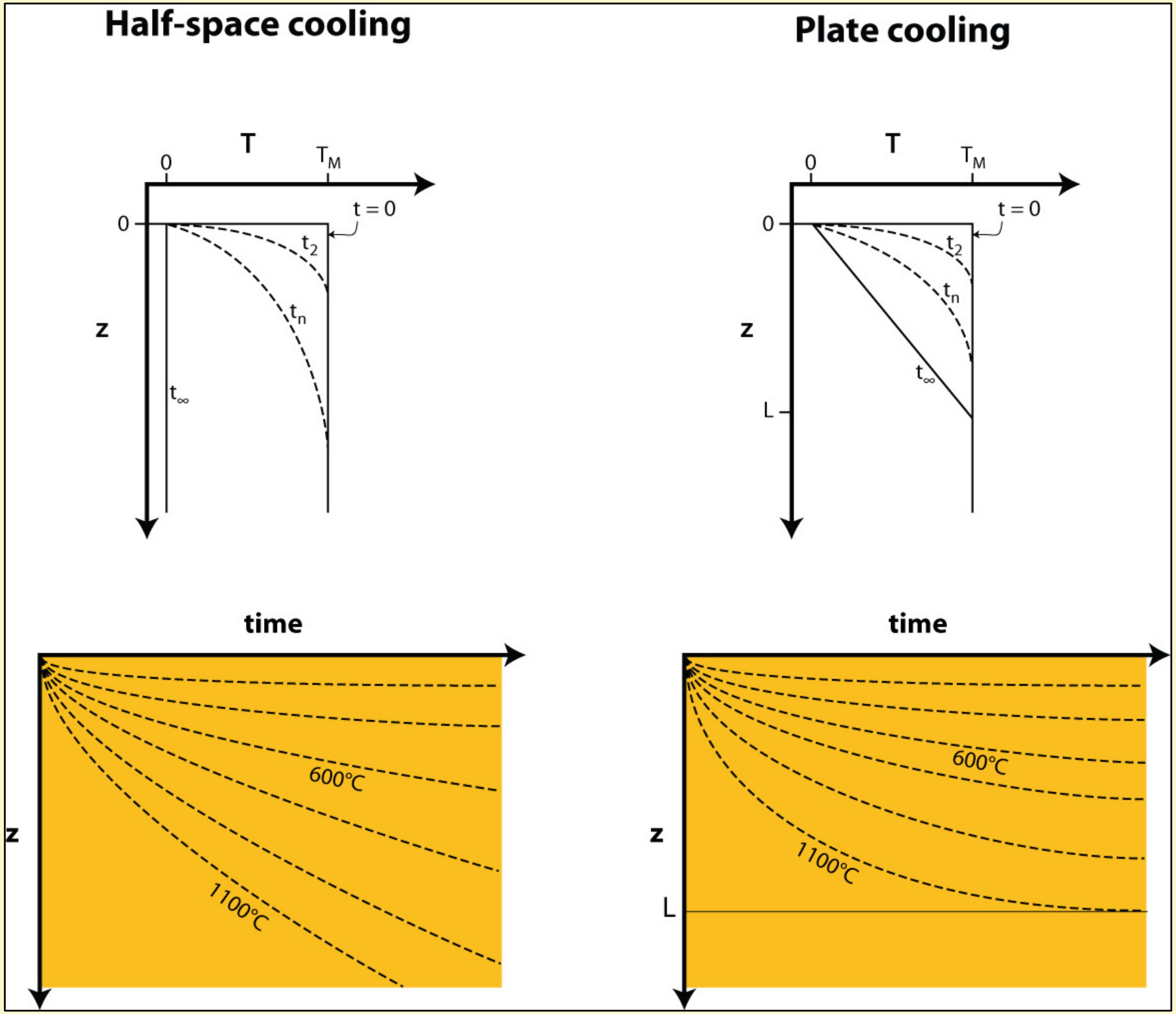
→ Lithosphere thickness reaches ~100 km

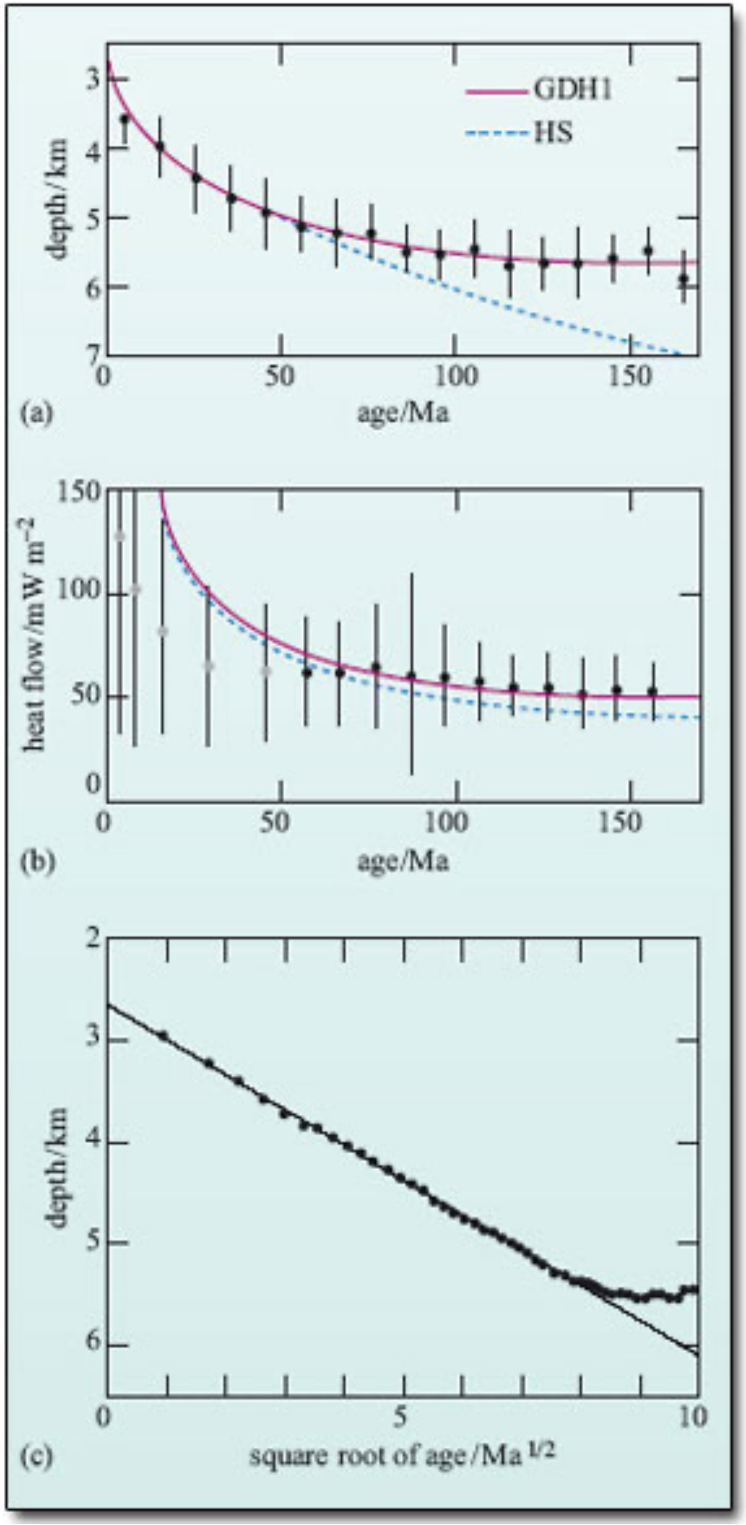
Thermal Structure of the Pacific – based on seismic observations



Ritzwoller et al. [*EPSL,* 2004]

We expect extra heat flow and thinner lithosphere if there is a "maximum plate thickness"





GDH1 Model **[*Stein & Stein*, 1992]**
An empirical relationship

Depth (m) as a function of age t (Myr)

$D(t) = 2600 + 365\,\mathrm{sqrt}(t)$ for $t<20$ Myr

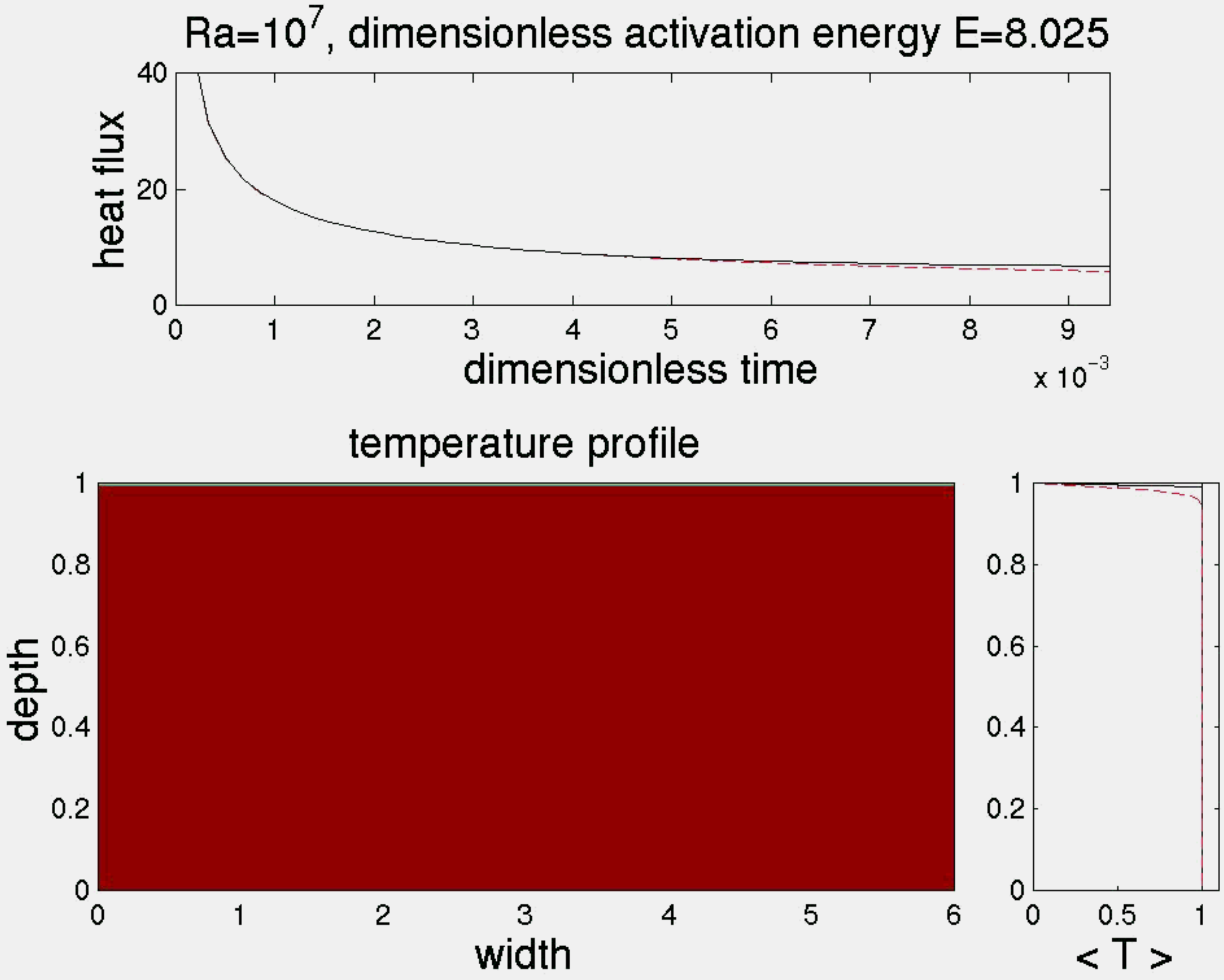
$= 5651 - 2473\exp(-0.0278\,t)$ for $t>20$ Myr

Heat Flow (mW/m^2)

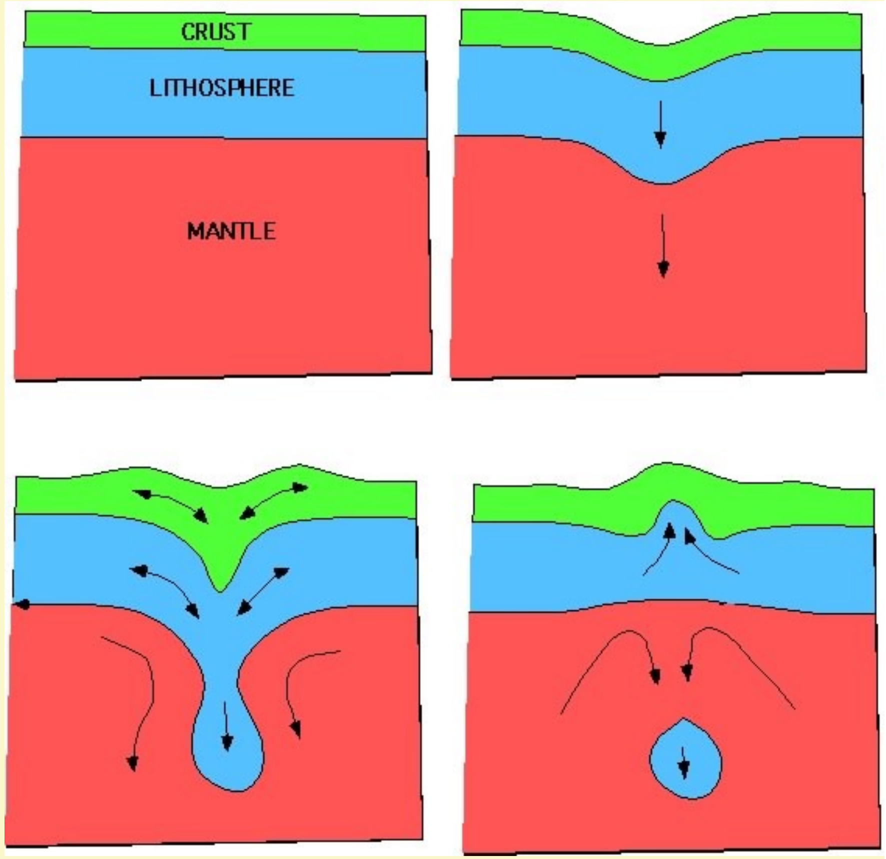
$q(t) = 510\,t^{-1/2}$ for $t<55$ Myr

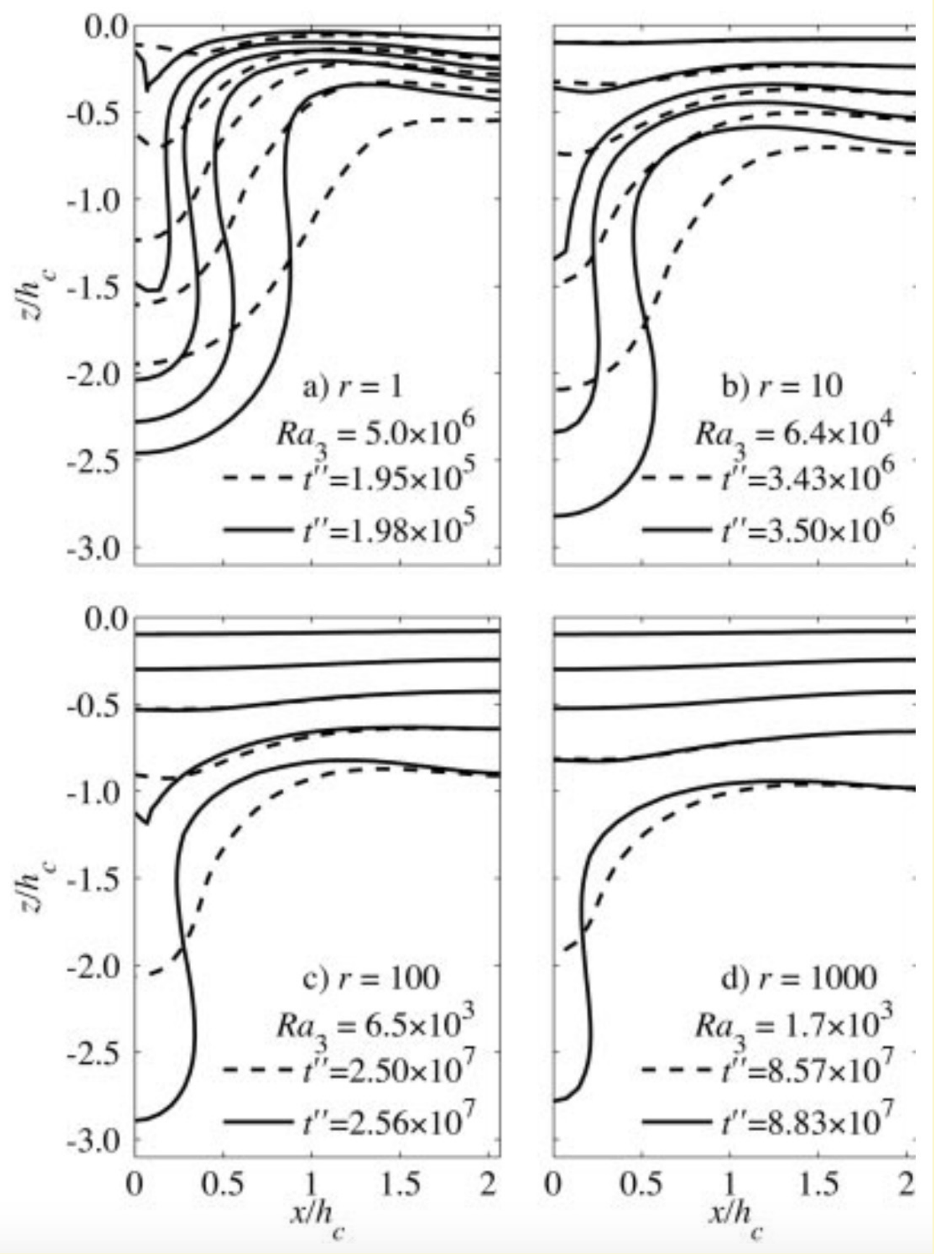
$= 48 + 96\exp(-0.0278\,t)$ for $t>55$ Myr

Why is plate thickness limited?


Ra=10^7, dimensionless activation energy E=8.025
heat flux
40
20
0
0
1
2
3
4
5
6
7
8
9
x 10^-3
dimensionless time
temperature profile
depth
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
width
1
0.8
0.6
0.4
0.2
0
0
0.5
1
< T >

Small-Scale Convection – Lithospheric Drips



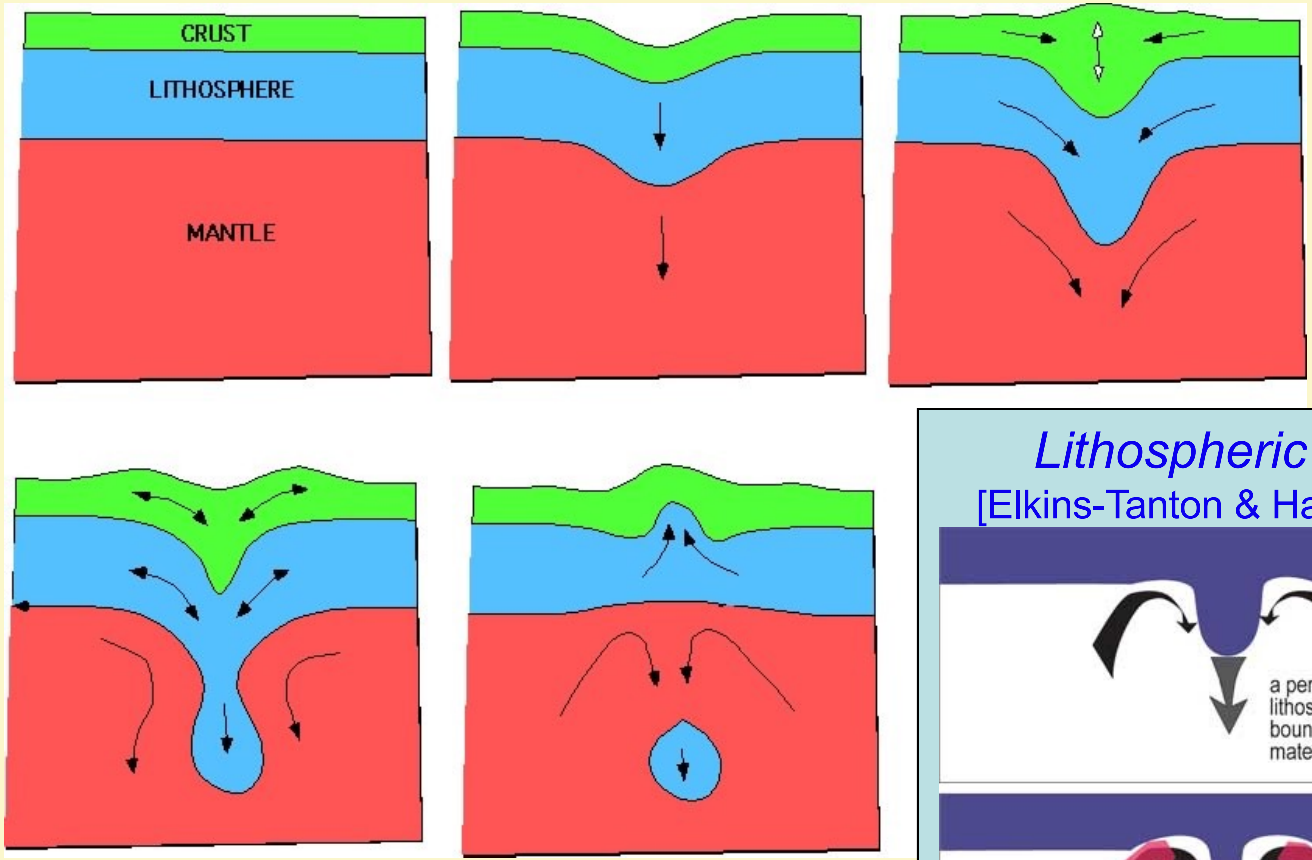


Cold “drips” from the lithospheric base

Return flow produces minor volcanism and uplift

Conrad & Molnar [1999]

Small-Scale Convection – Lithospheric Drips

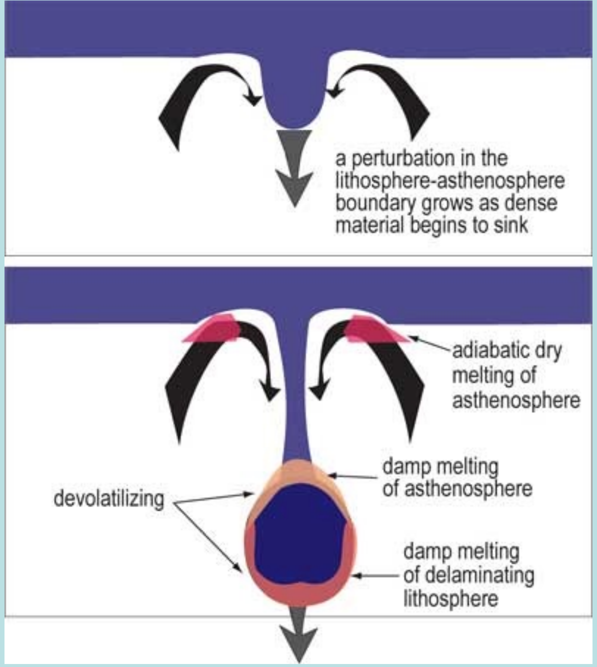


Cold "drips" from the lithospheric base

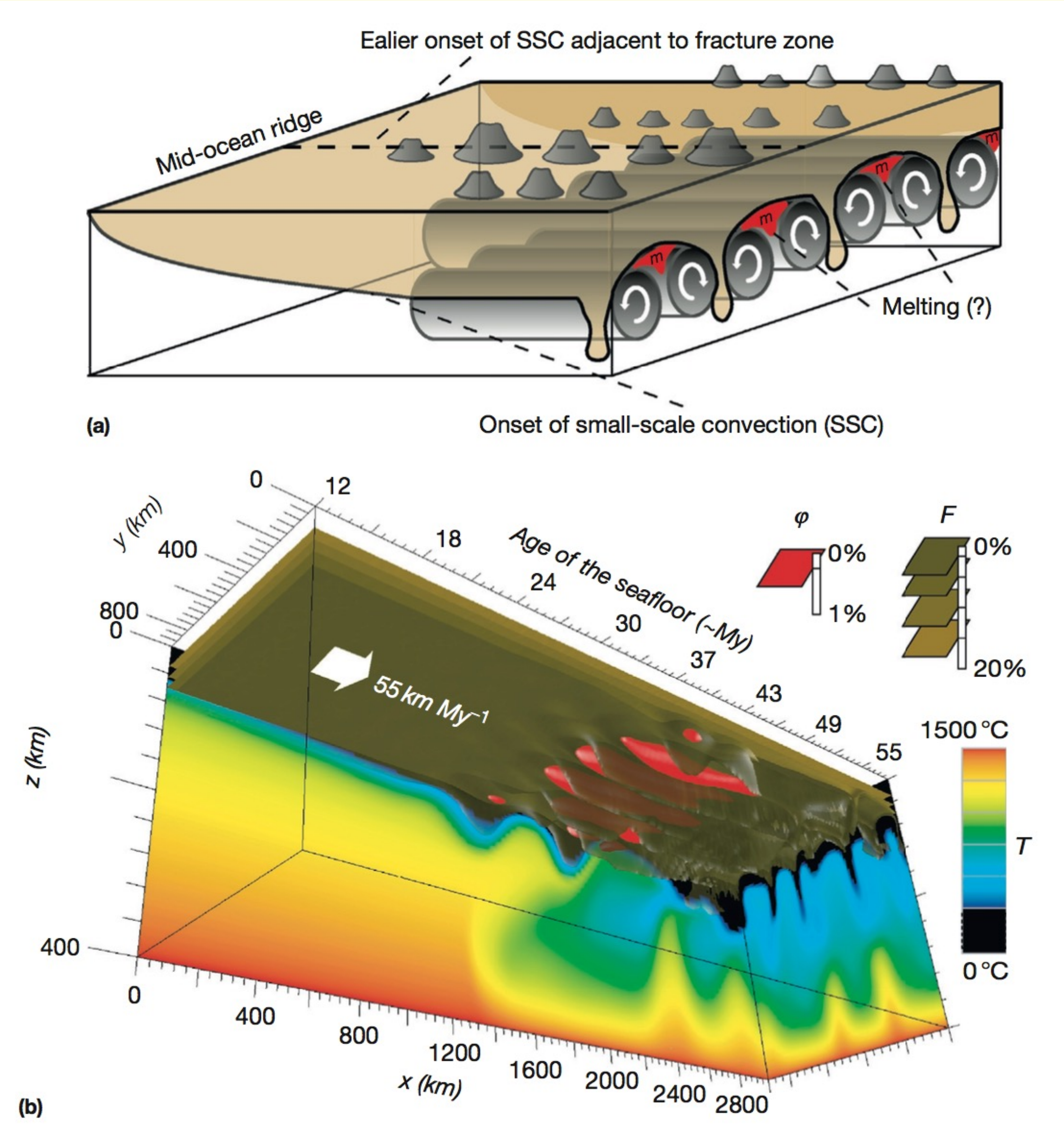
Return flow produces minor volcanism and uplift

Lithospheric Drips

[Elkins-Tanton & Hager, 2000]



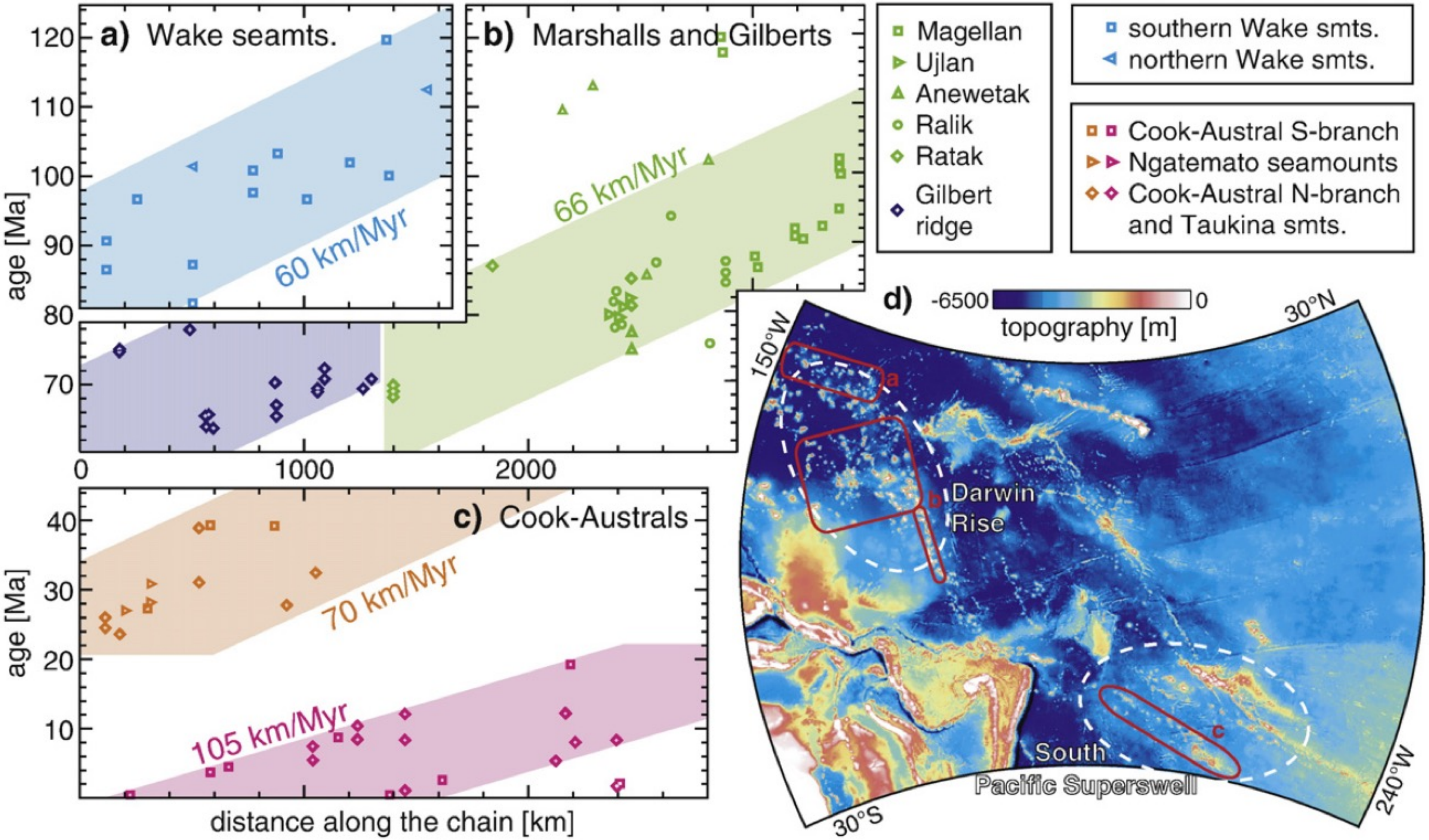
Small-Scale Convection beneath oceanic lithosphere



Small-Scale Convection (SSC) beneath the oceanic plates [*Ballmer et al.*, 2015]

Richter Rolls

SSC may explain some mountains and minor volcanism.



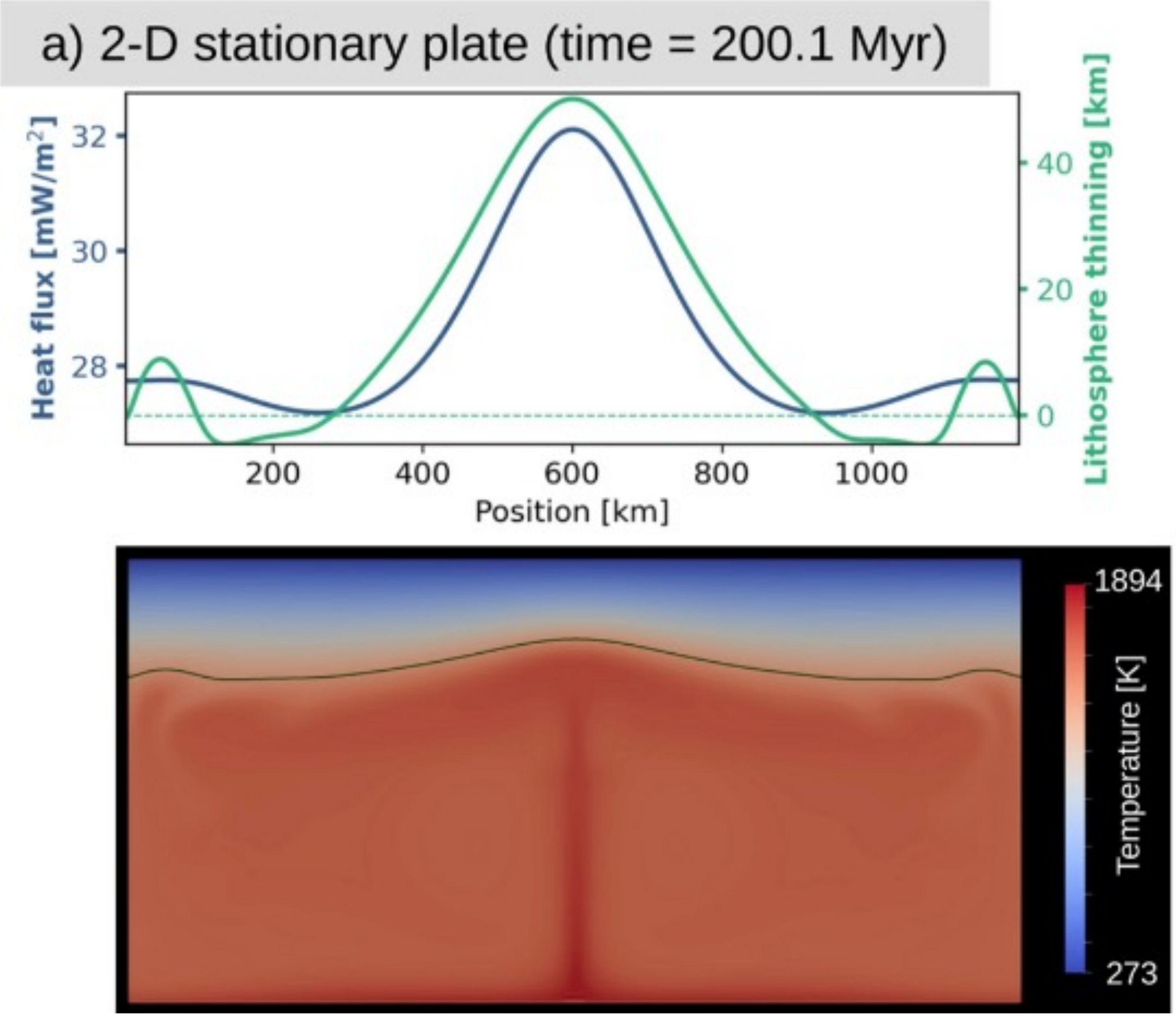
Ballmer et al. [2010]

Transient Heat Flow in Continental Lithosphere

A mantle plume impinges on continental lithosphere:

→ Lithospheric thinning

→ Extra heat flux at the surface



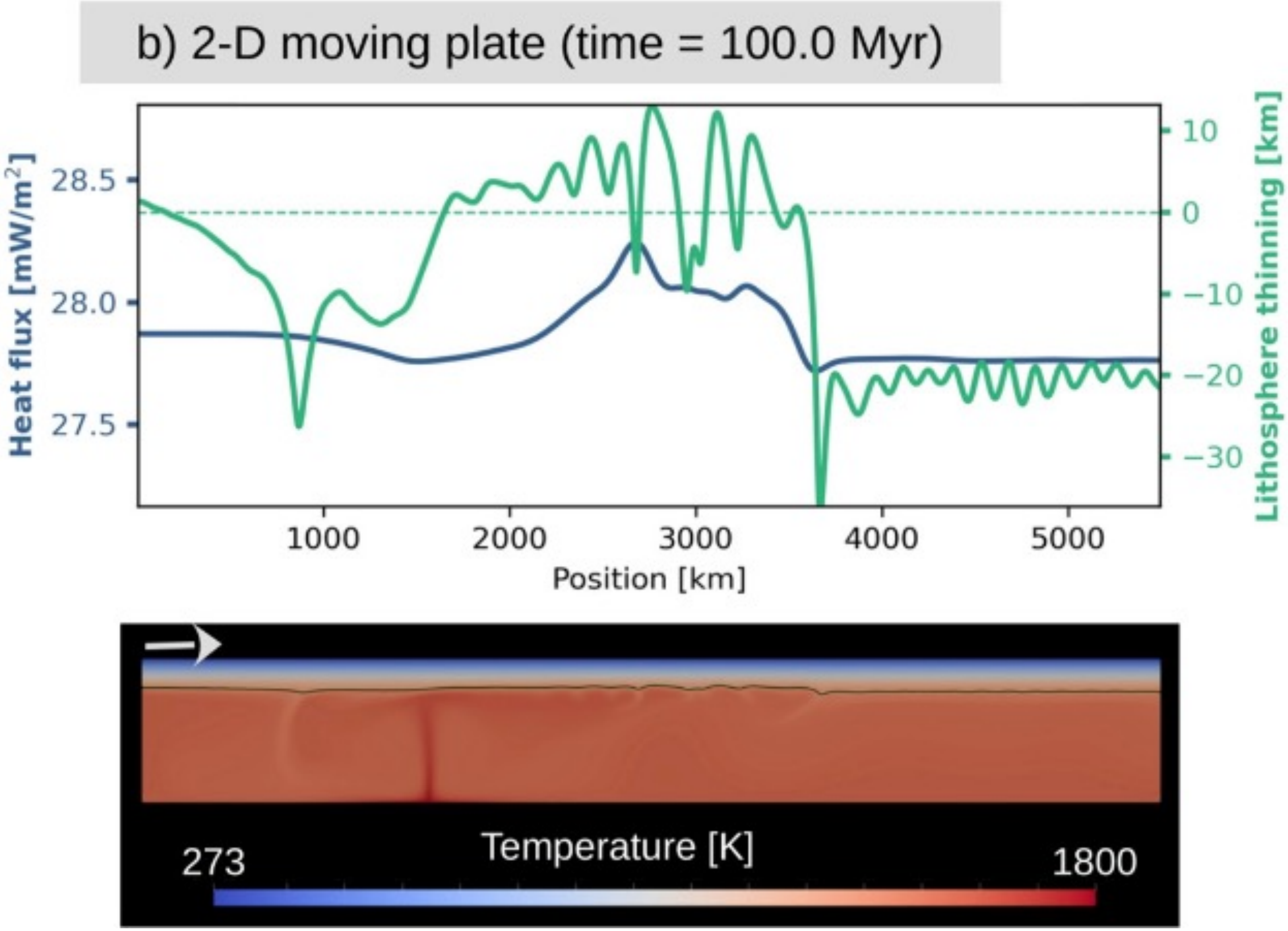
Heyn and Conrad [*GRL*, 2022]

Transient Heat Flow in Continental Lithosphere

A mantle plume impinges on continental lithosphere:

→ Lithospheric thinning

→ Extra heat flux at the surface



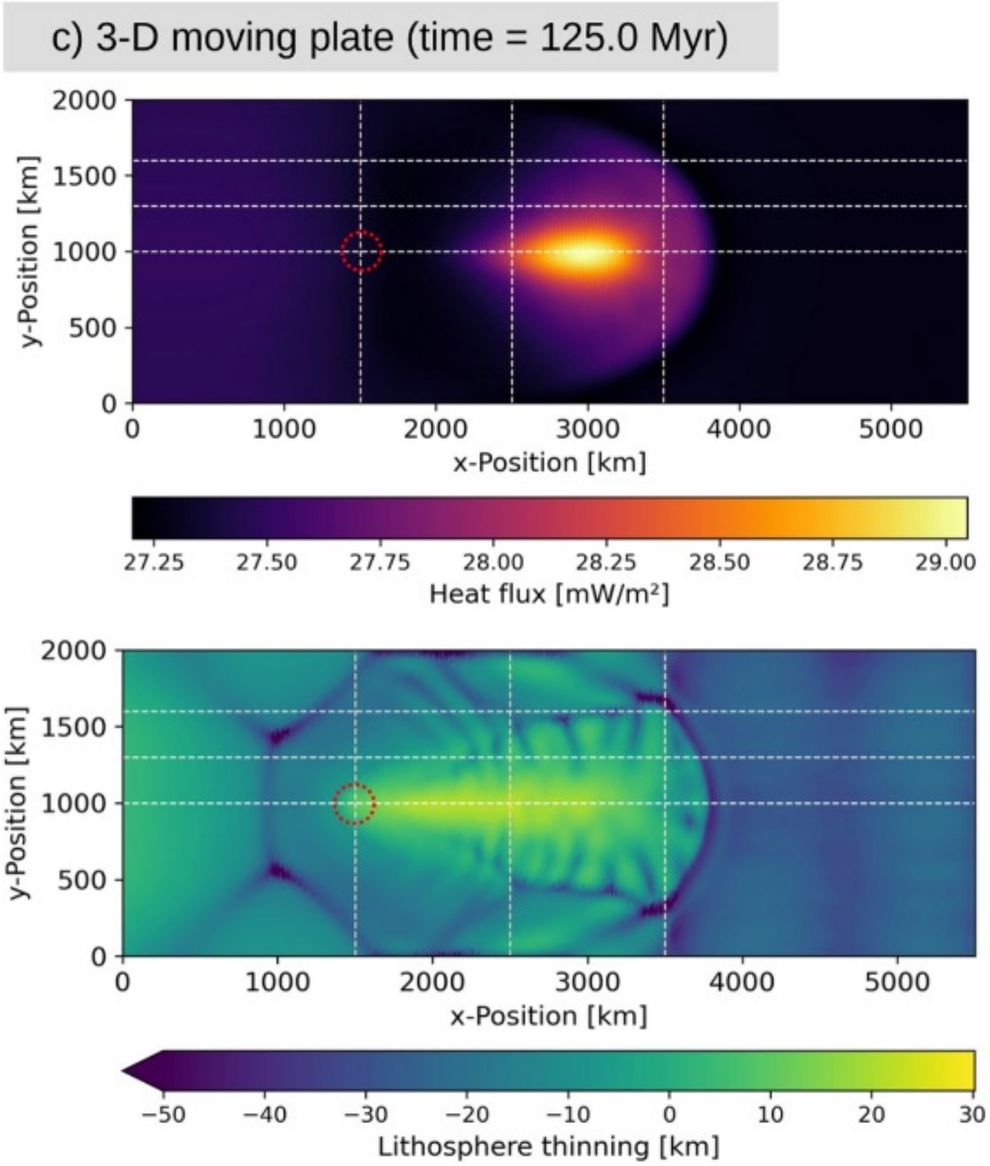
Heyn and Conrad [*GRL*, 2022]

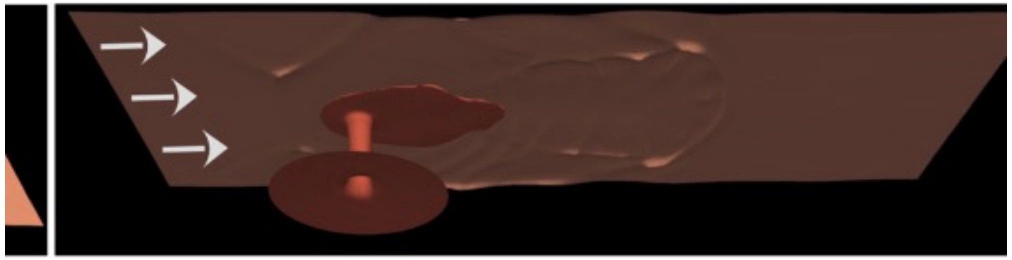
Transient Heat Flow in Continental Lithosphere

A mantle plume impinges on continental lithosphere:

→ Lithospheric thinning

→ Extra heat flux at the surface





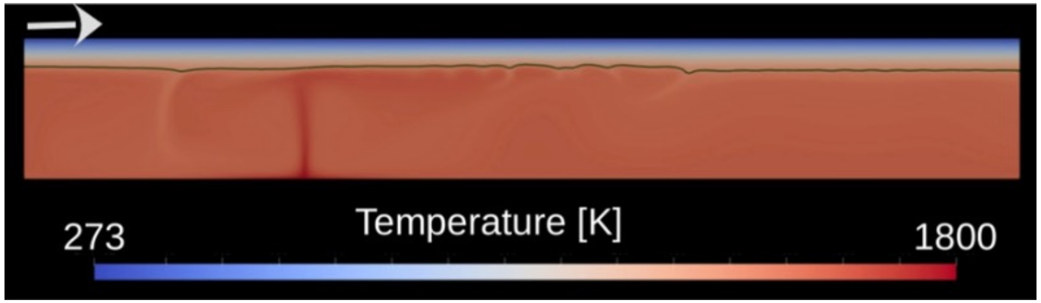
How does heat flow scale with lithospheric thinning?

Heyn and Conrad [*GRL*, 2022]

Transient Heat Flow in Continental Lithosphere

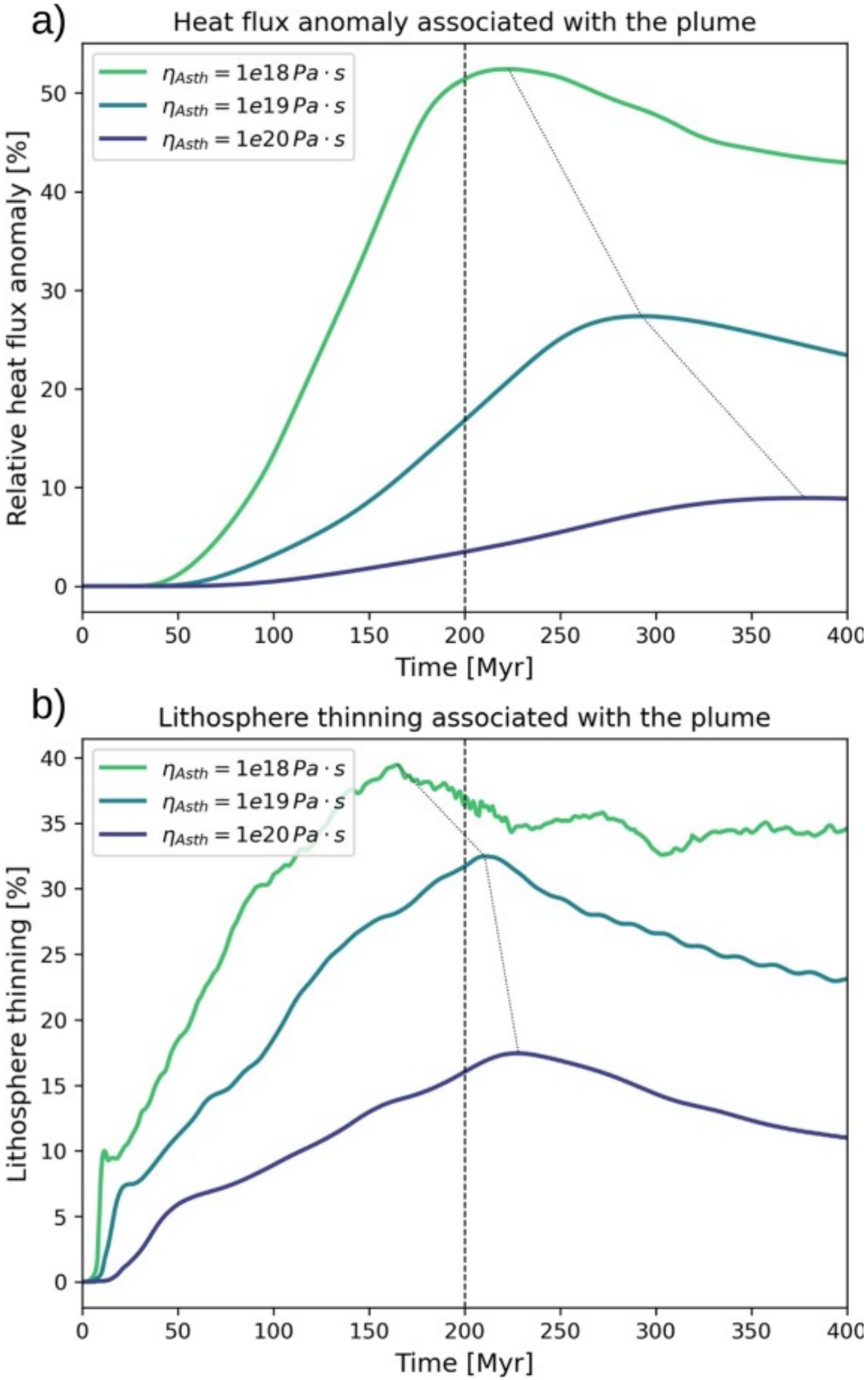
→ More lithospheric thinning leads to more heat flow

→ Peak heat flow is delayed by 40 to 100 Myr after lithospheric thinning



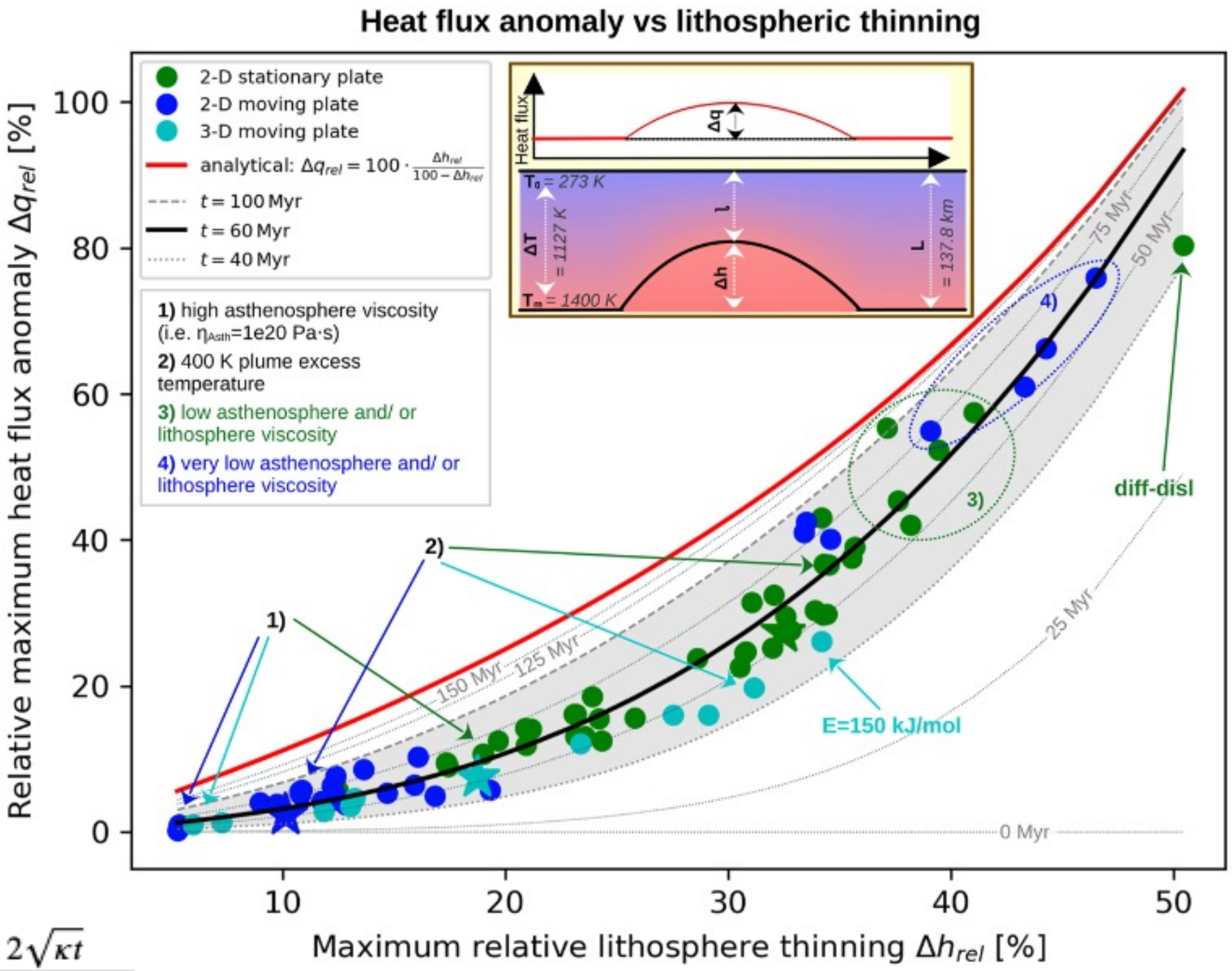
→ Heat travels slowly through the lithosphere

Heyn and Conrad [*GRL*, 2022]



Transient Heat Flow in Continental Lithosphere

Scaling relationship between amount of lithospheric thinning and heat flow anomaly



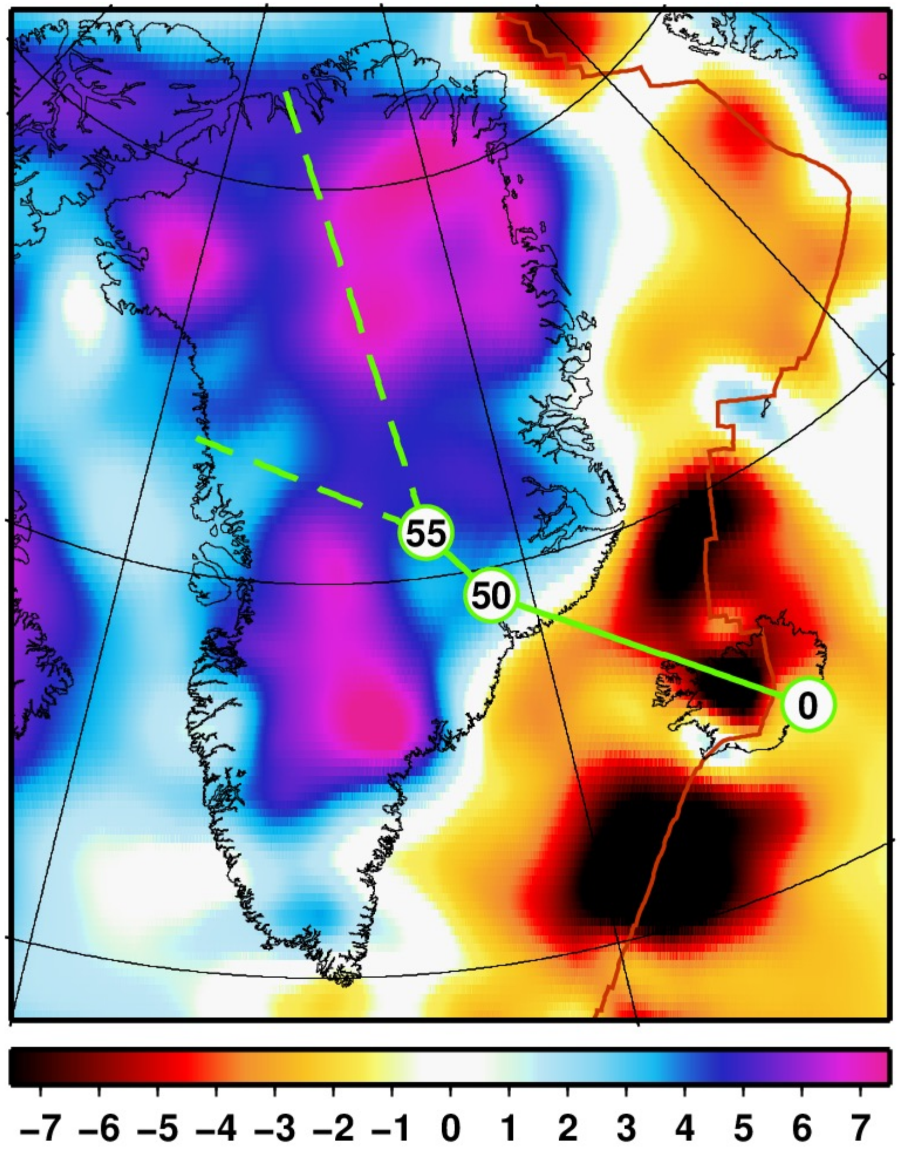
The equations:

$$d = \frac{2\sqrt{\kappa t}}{l} = \frac{2\sqrt{\kappa t}}{L(1-\Delta h_{rel})}$$

$$\Delta q_{rel}(t) = \frac{\Delta q}{q_0} = \frac{\Delta h_{rel}}{1-\Delta h_{rel}}\left(1-2\sum_{n=1}^{\infty}(-1)^{n-1}\exp\left[-\frac{n^2\pi^2 d^2}{4}\right]\right)$$

Heyn and Conrad [*GRL*, 2022]

North Atlantic seismic velocity structure from *Celli et al.* [2021]

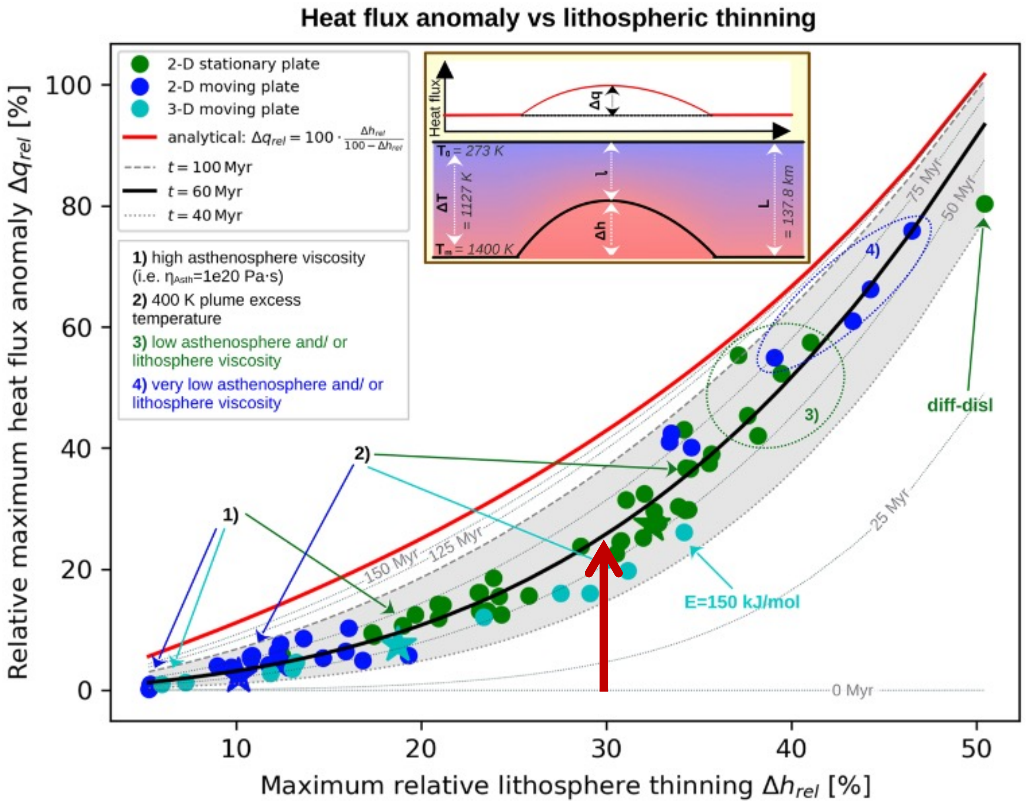


seismic velocity anomaly (%) at 150 km depth

If the Iceland Plume:

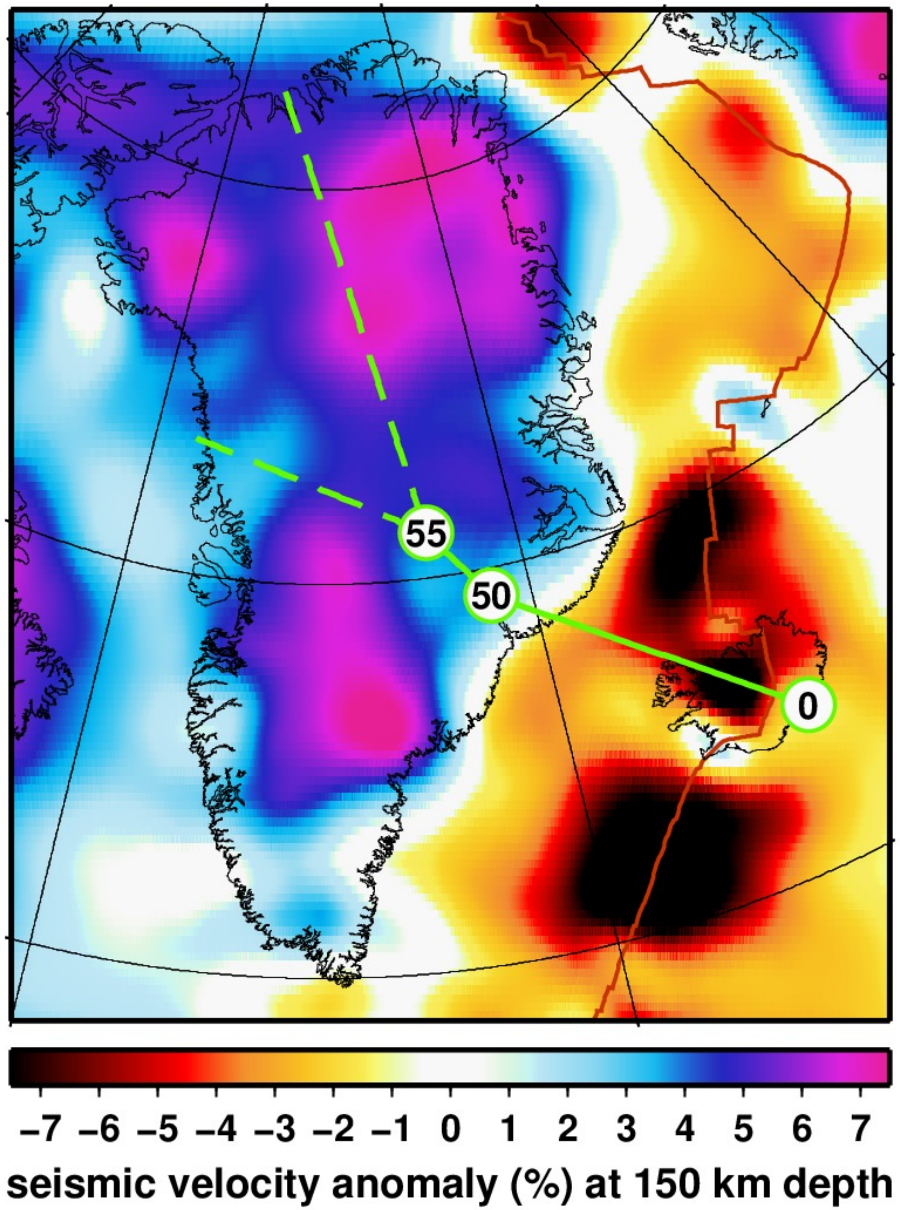
→ thins the lithosphere by 30%

→ we expect a heat flux anomaly of about 20%

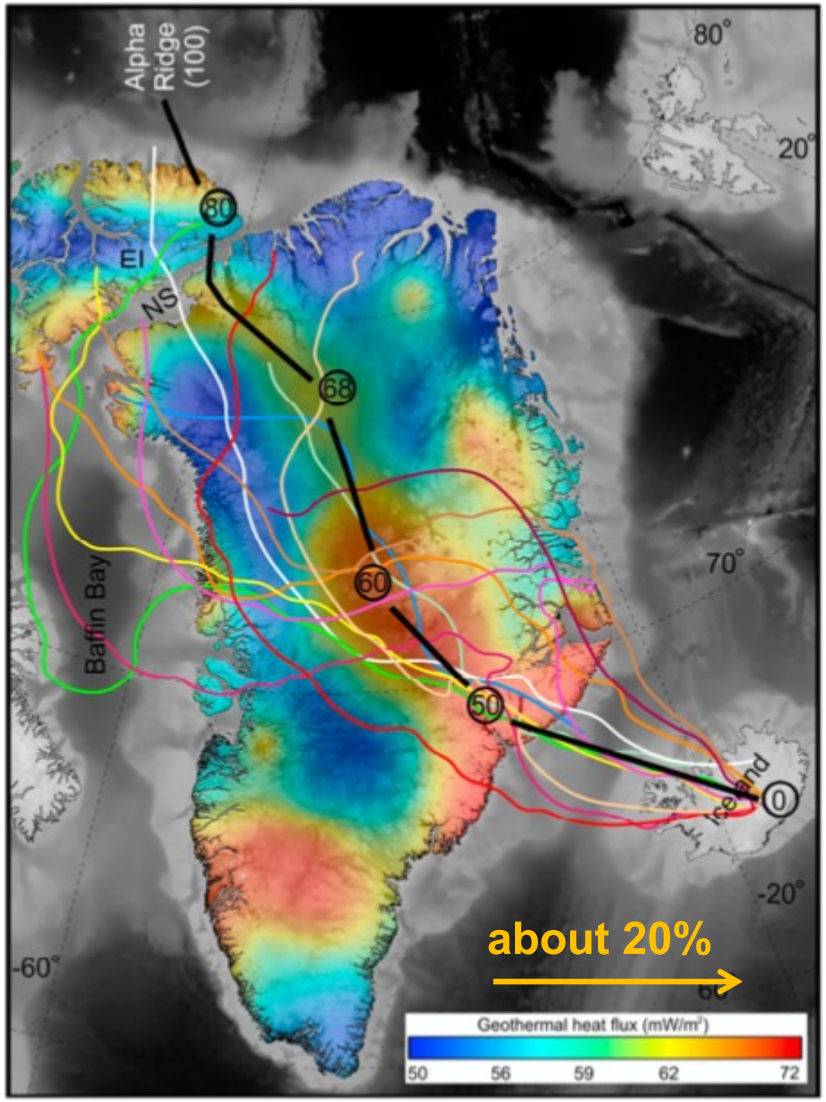


Heyn and Conrad [*GRL*, 2022]

North Atlantic seismic velocity structure from *Celli et al.* [2021]

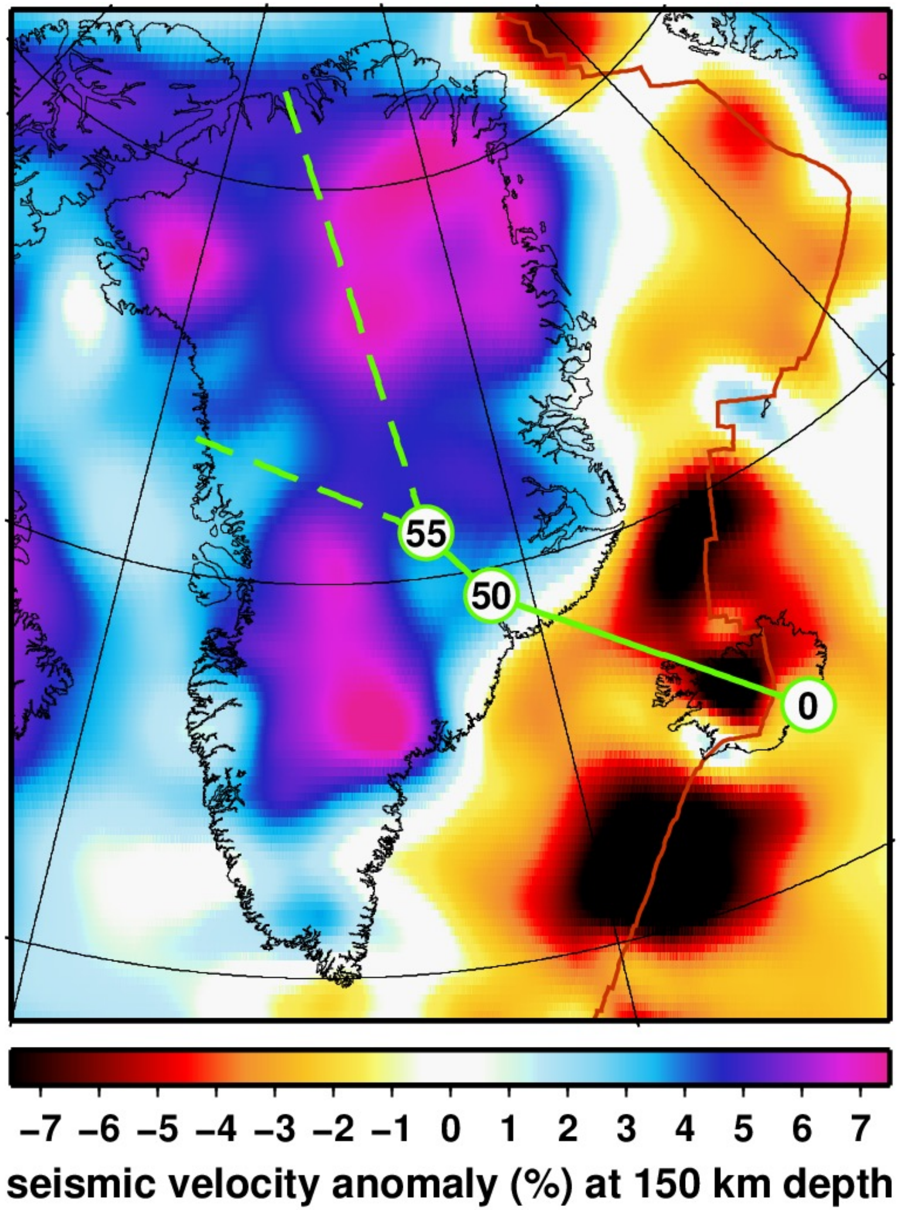


Geothermal Heat Flux from *Martos et al.* [2018]



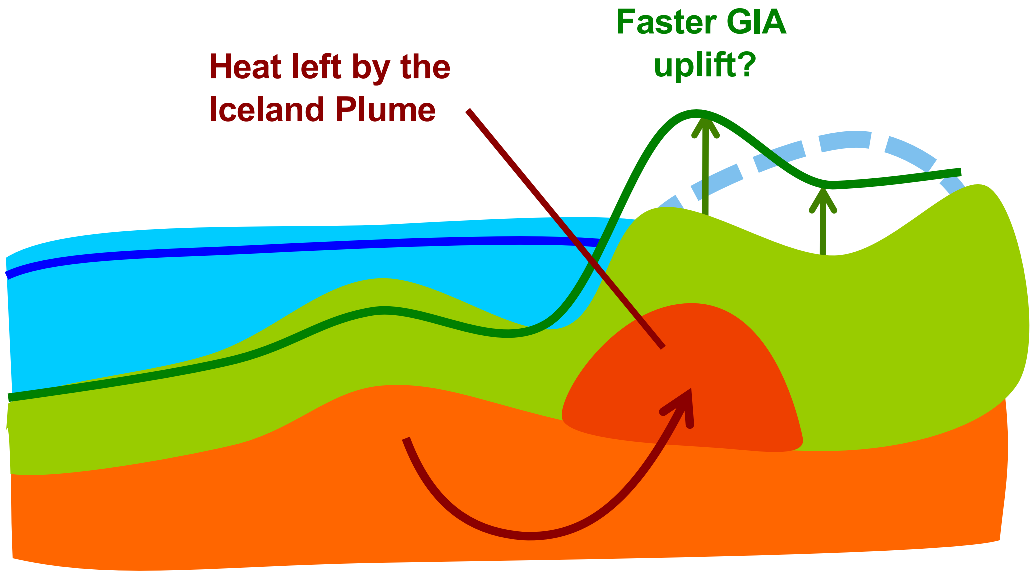
Heyn and Conrad [*GRL*, 2022]

North Atlantic seismic velocity structure from *Celli et al.* [2021]

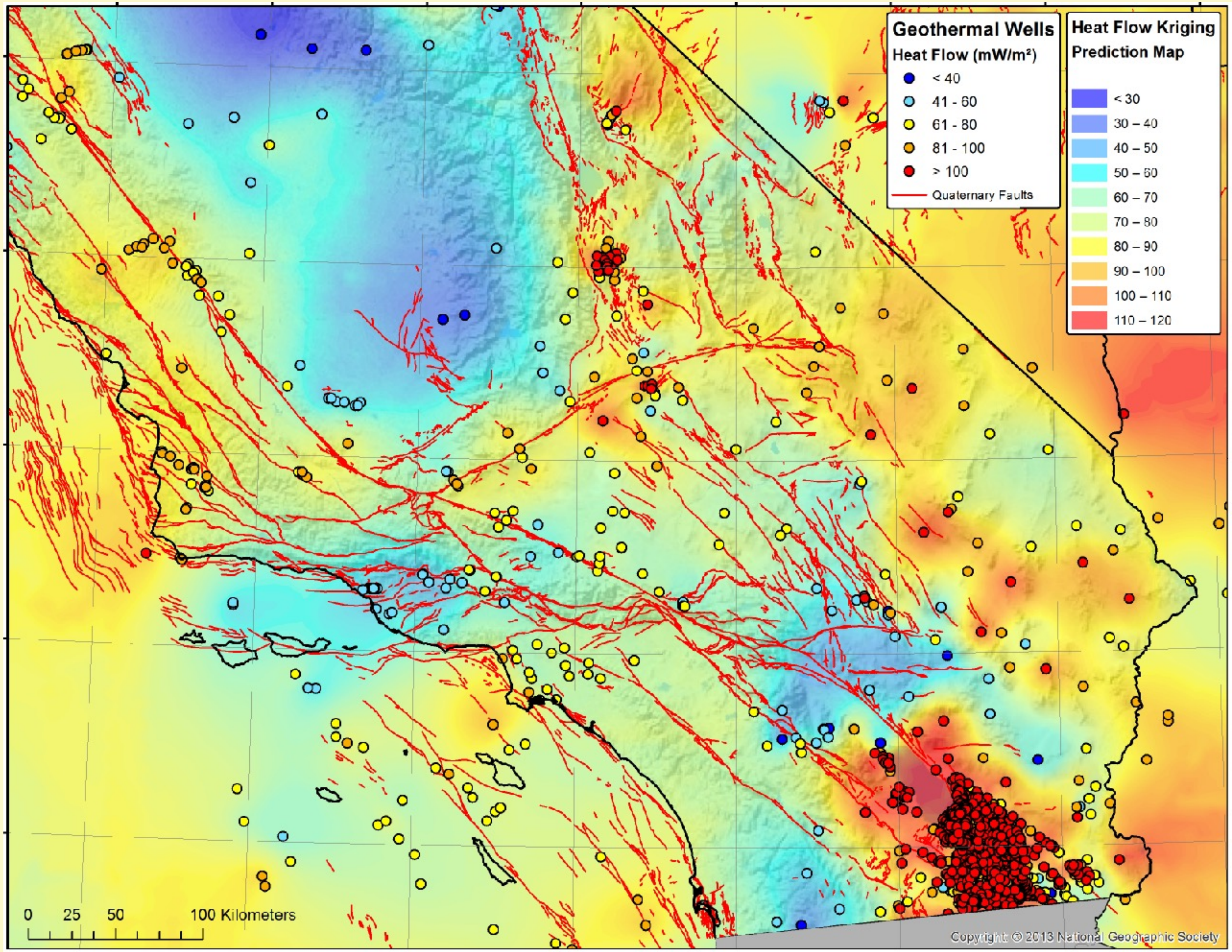


- Greenland passed over the Iceland plume before 50 Ma
- SE Greenland may sit above thin thermal lithosphere

→ What is the impact on the mechanical lithosphere?

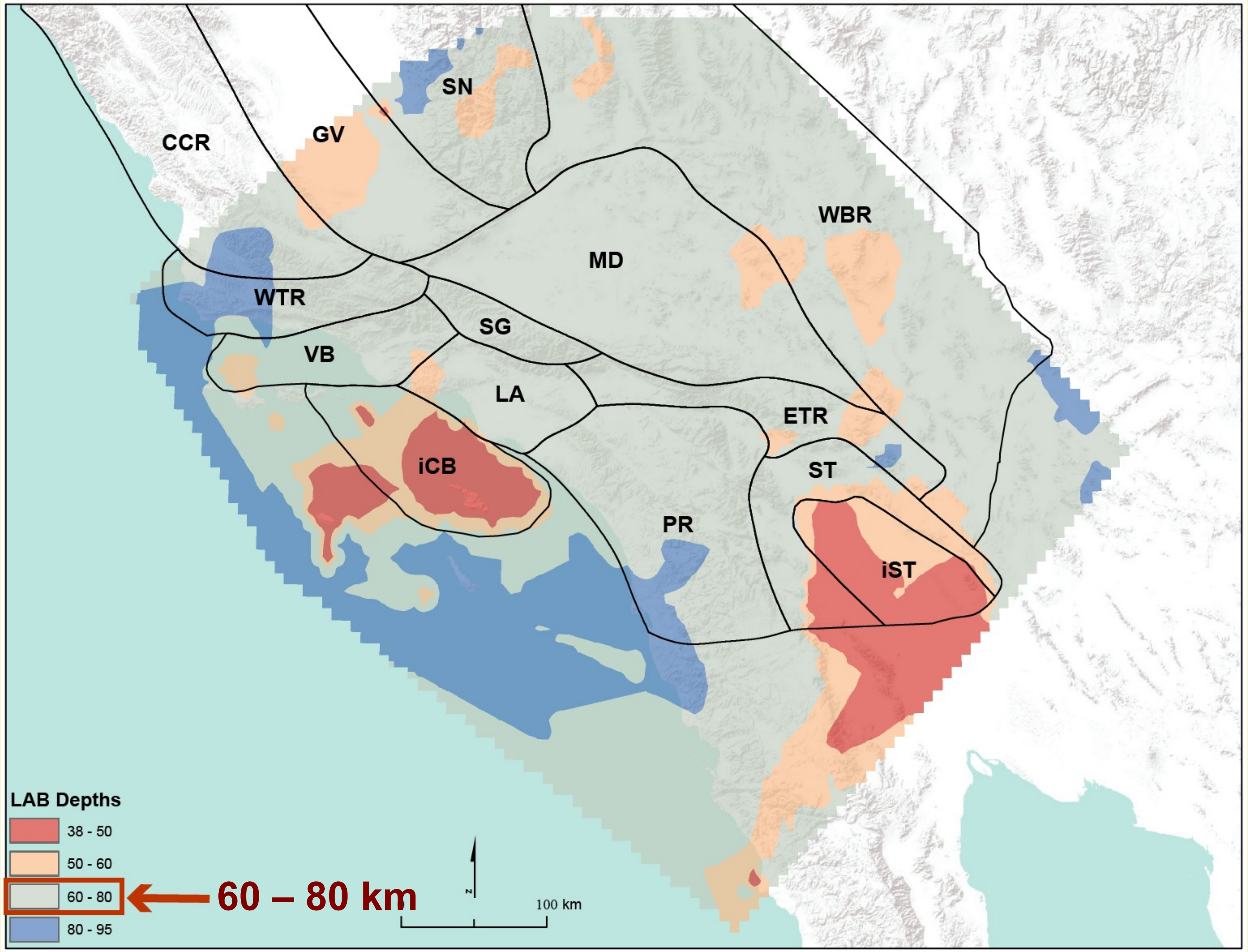


Heat flow map of Southern California → Large variations!



Thatcher et al. [2019]

LAB depths are ~70 km or less across SoCal



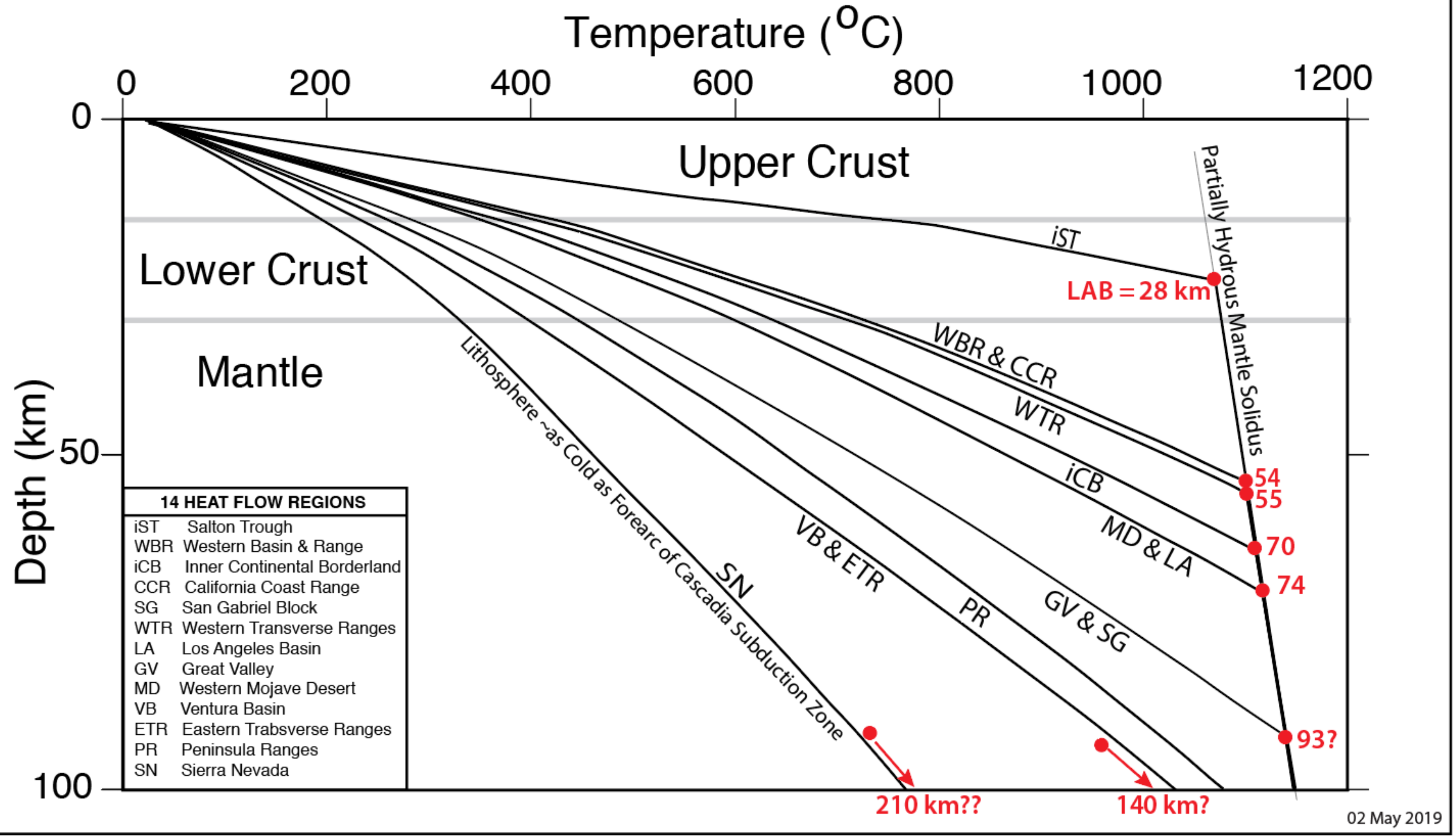
60 – 80 km

Thatcher et al. [2019]

Assume similar crustal thickness and heat production

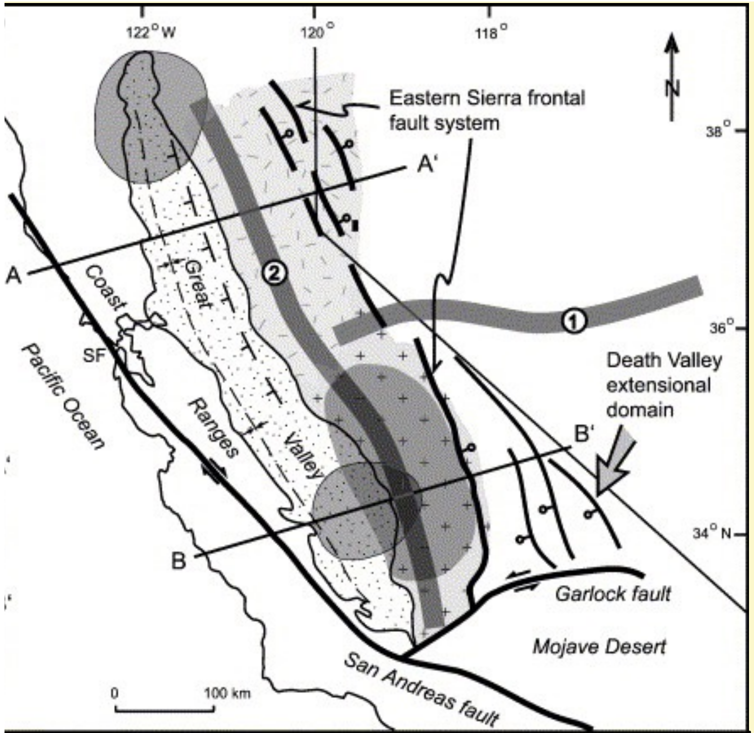
Steady State 1D SoCal Geotherms for Standard Continental Thermal Model

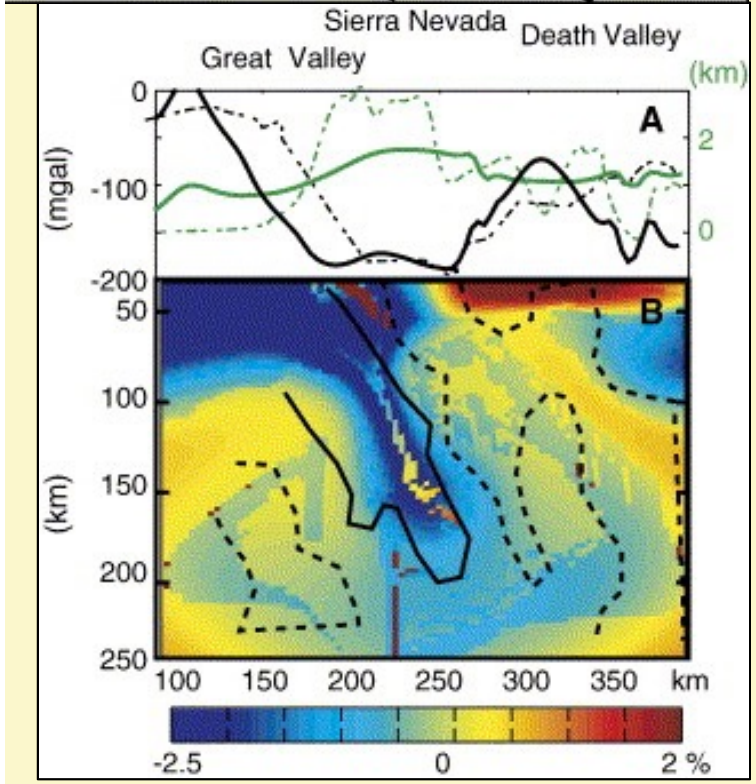
If Correct Imply Some Surprisingly Thick Lithospheric Keels Beneath SoCal



02 May 2019

Thatcher et al. [2019]



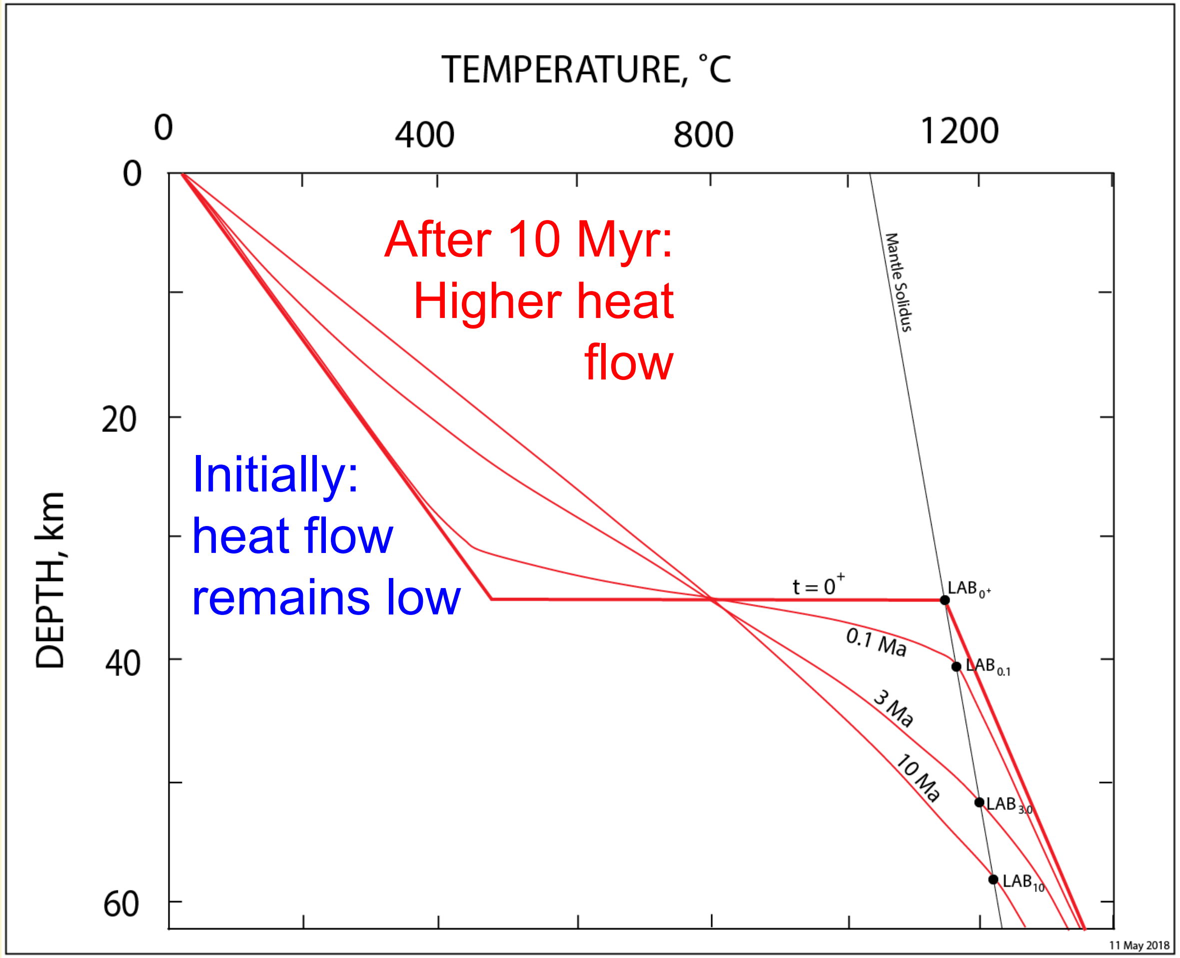


LePourhiet et al. [2006]

Lithospheric Drips / Delamination

→ Remove lithosphere but the change in heat flow is delayed

→ Importance of transient solutions!



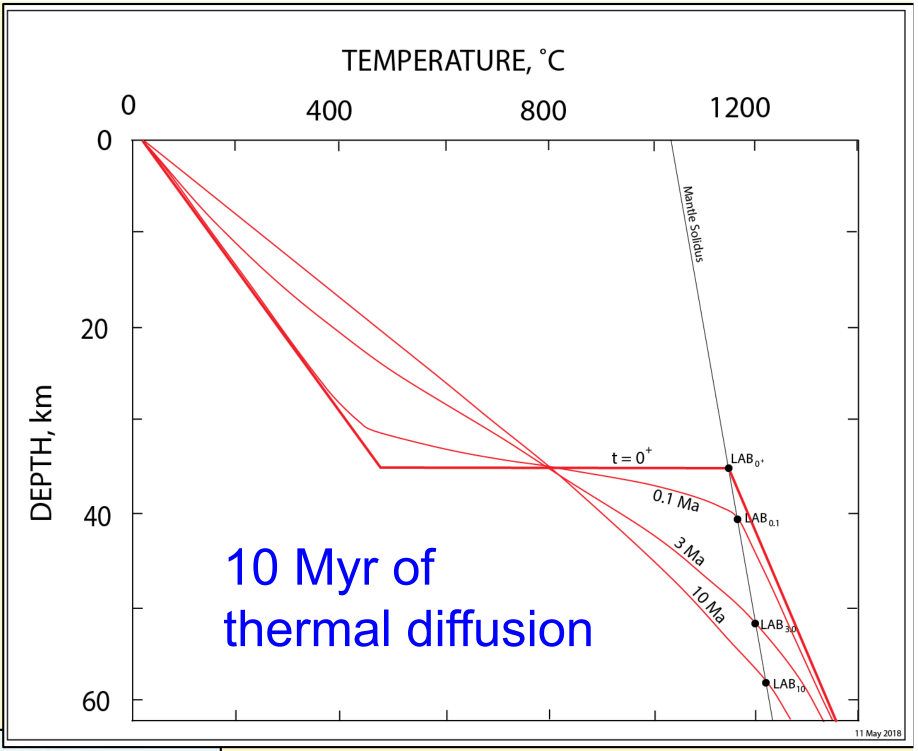
After 10 Myr: Higher heat flow

Initially: heat flow remains low

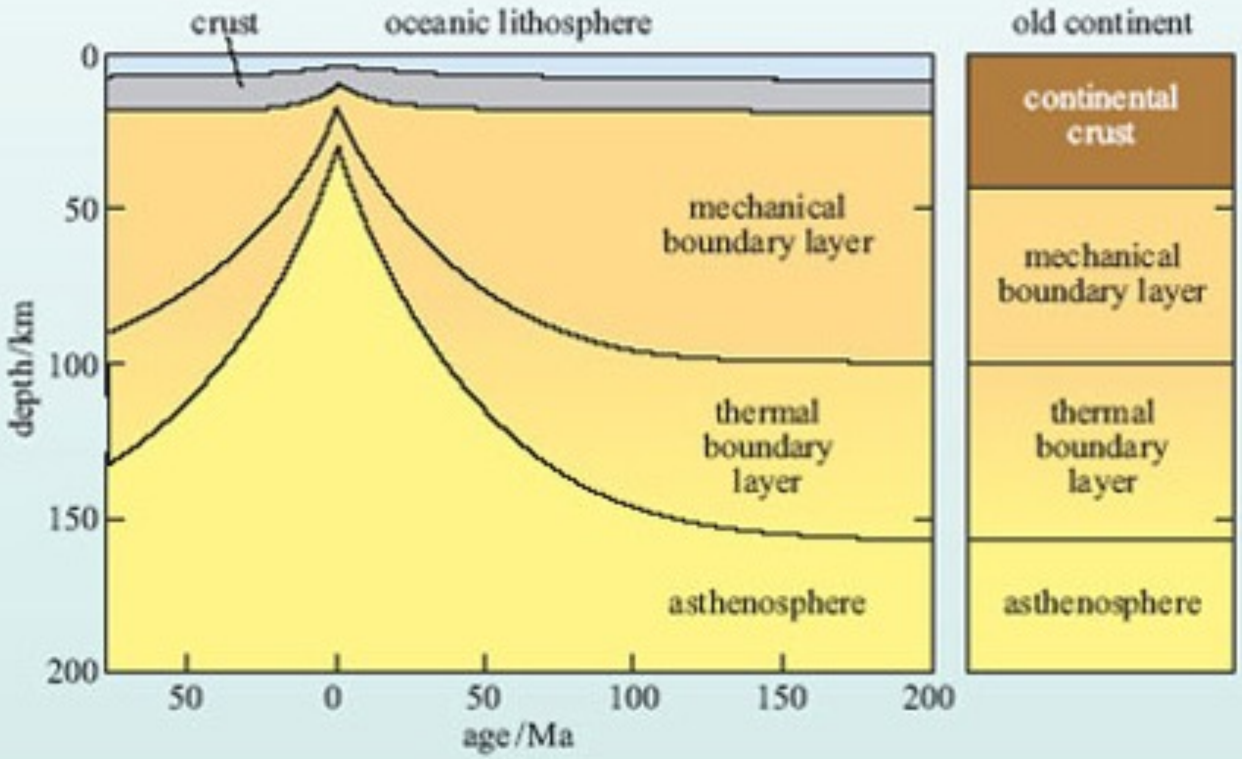
Lachenbruch & Sass 1980

The Thermal Lithosphere

- → Is integral to mantle convection
- → Transmits heat from the mantle
- → Can be removed by drips, delamination, or subduction
- → Is typically thicker than the mechanical boundary layer (e.g., see Elastic lithosphere lecture)



10 Myr of thermal diffusion



- → Thermal diffusion is slow for length scales of ~100 km
- → But thermal anomalies within the lithosphere can last for several 10s of Myr