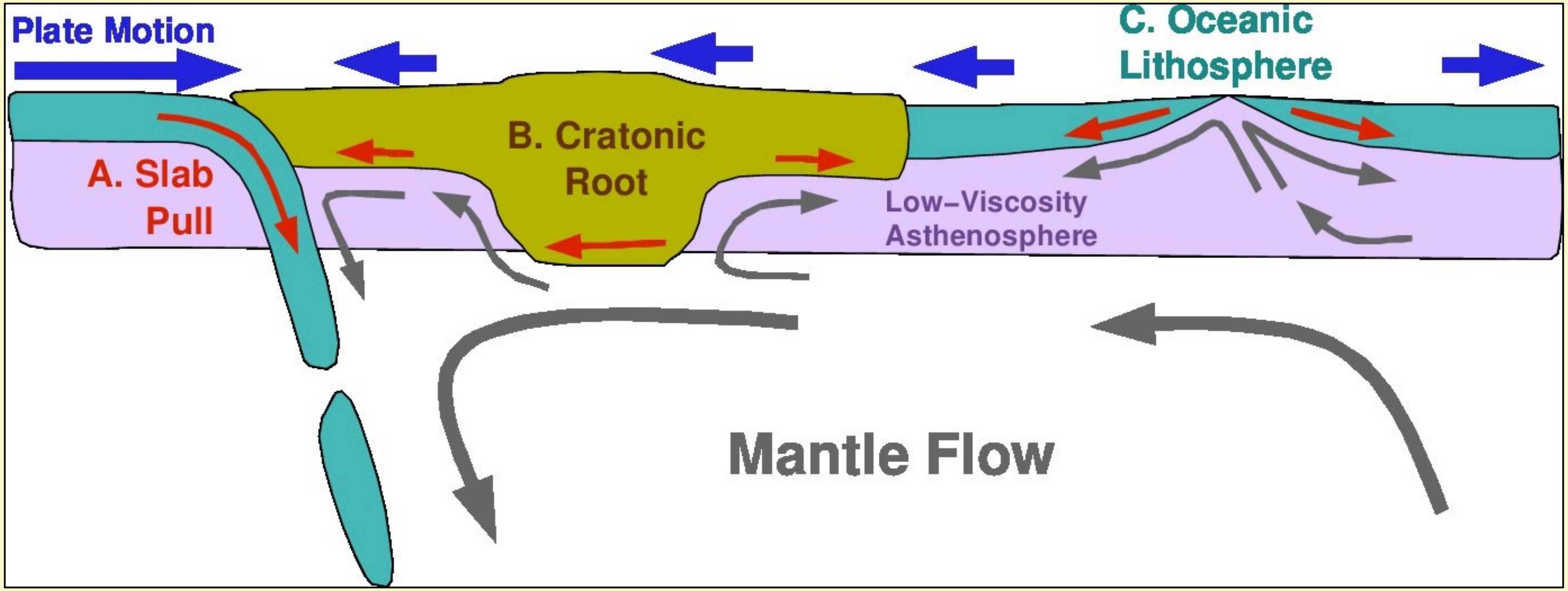
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

Valerie Maupin
Clint Conrad



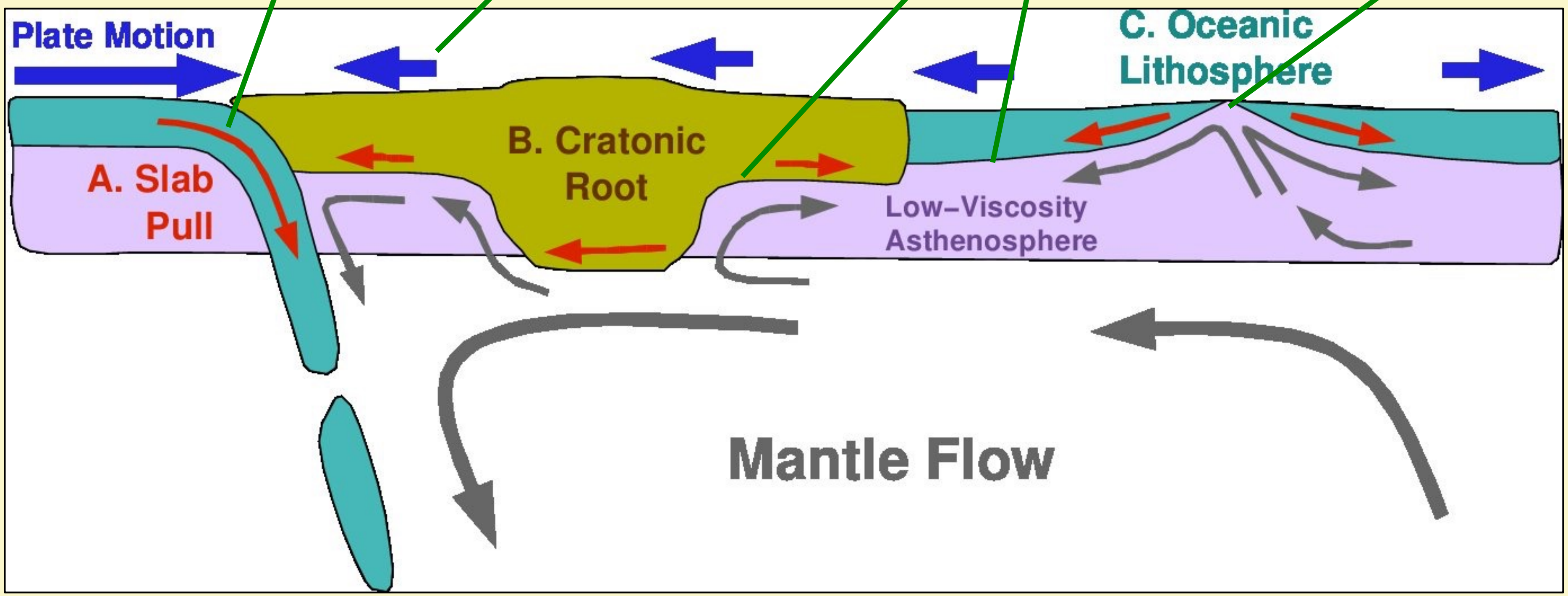
Geodynamic Processes of the Lithosphere & Asthenosphere

Tectonic Lithosphere:
Plate Motions

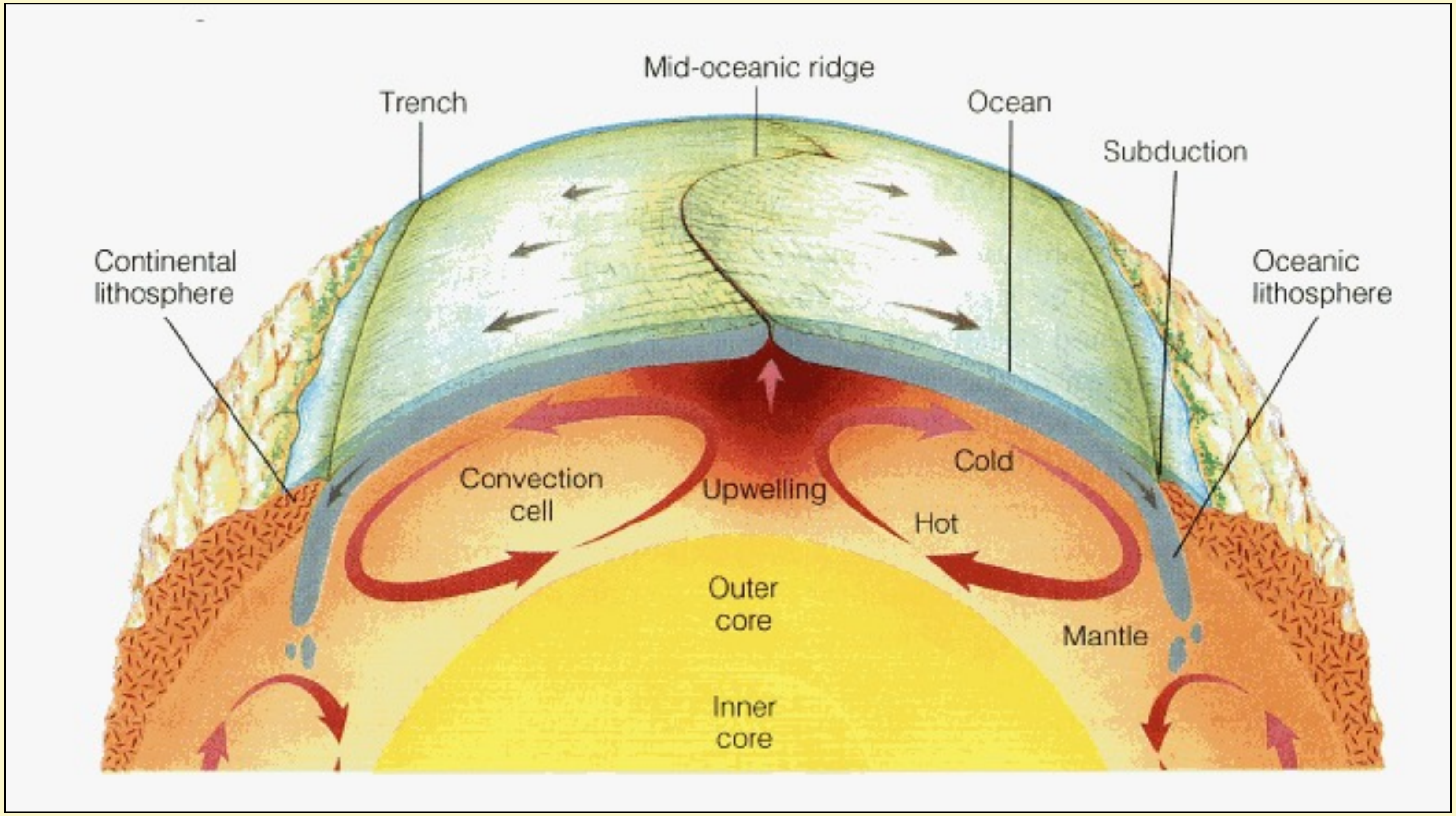
Thermal Lithosphere:
Convection

Elastic Lithosphere:
Plate Flexure

Volcanism

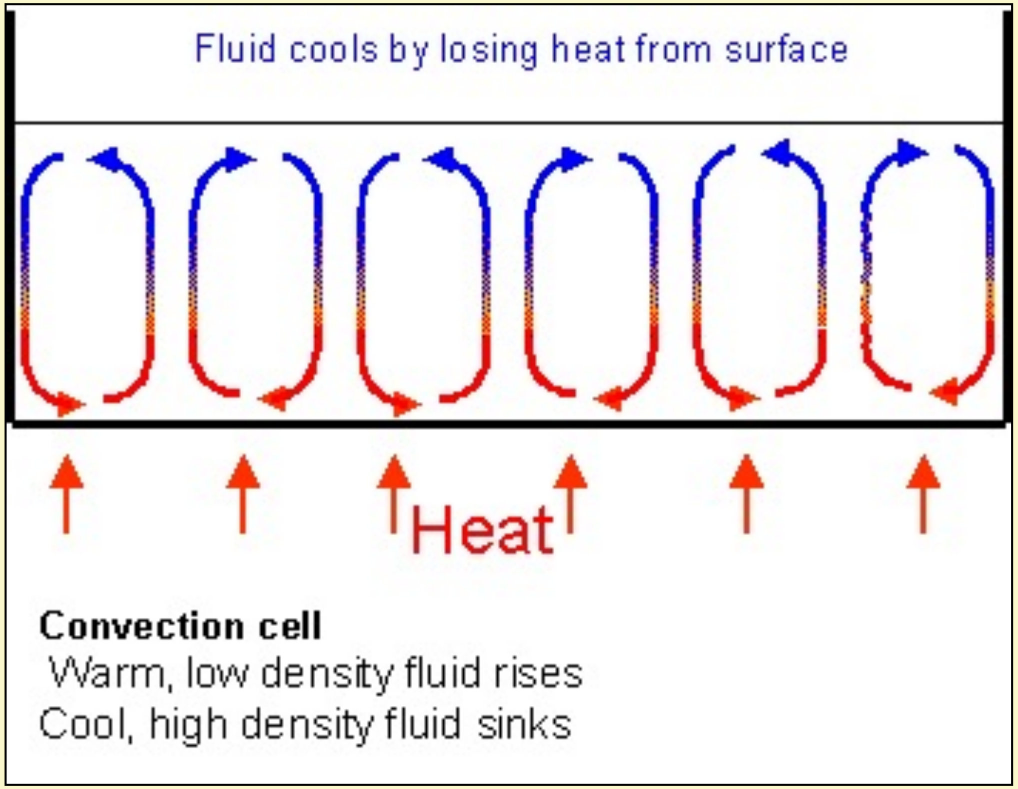


Mantle Convection in the Earth



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

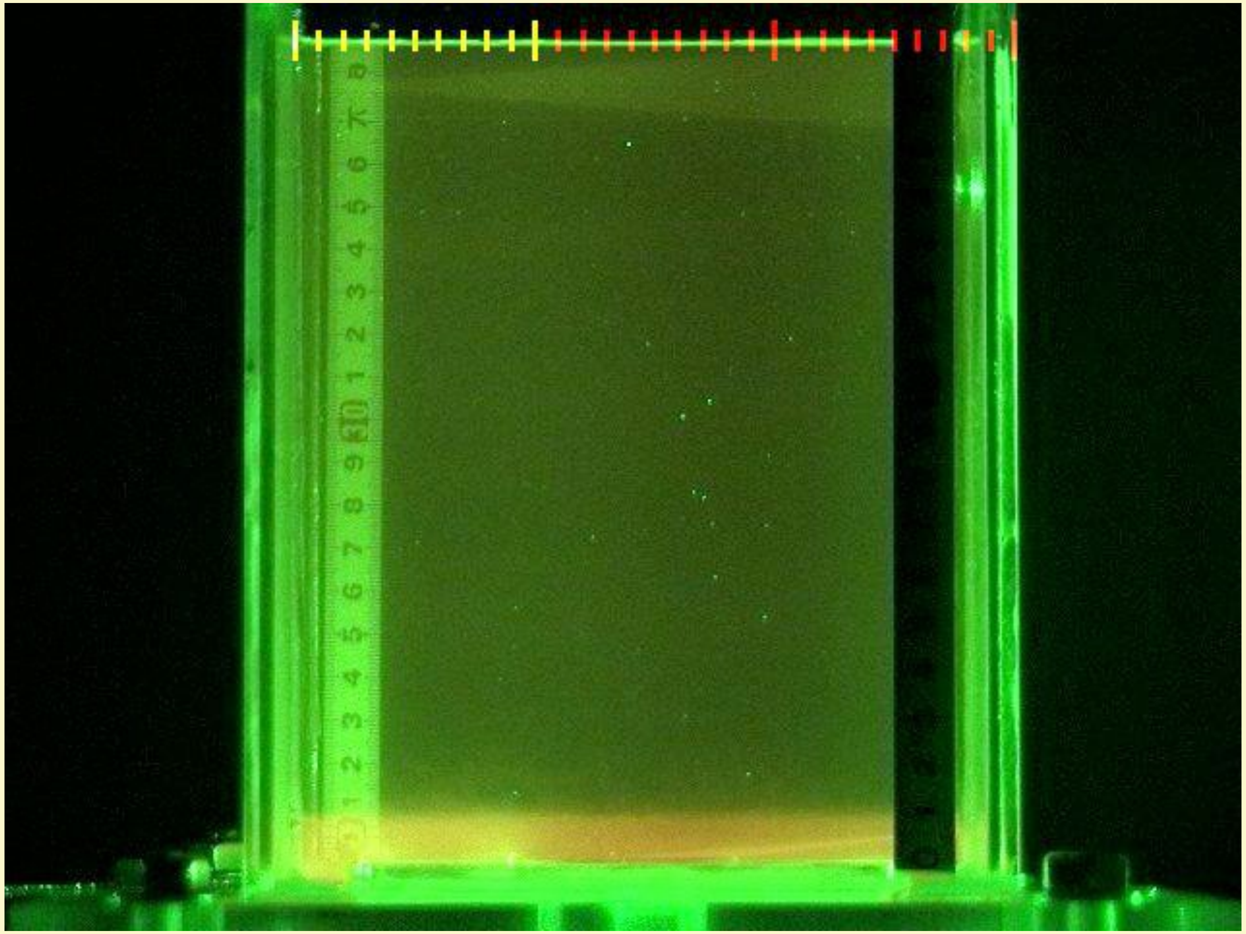
How Convection Works



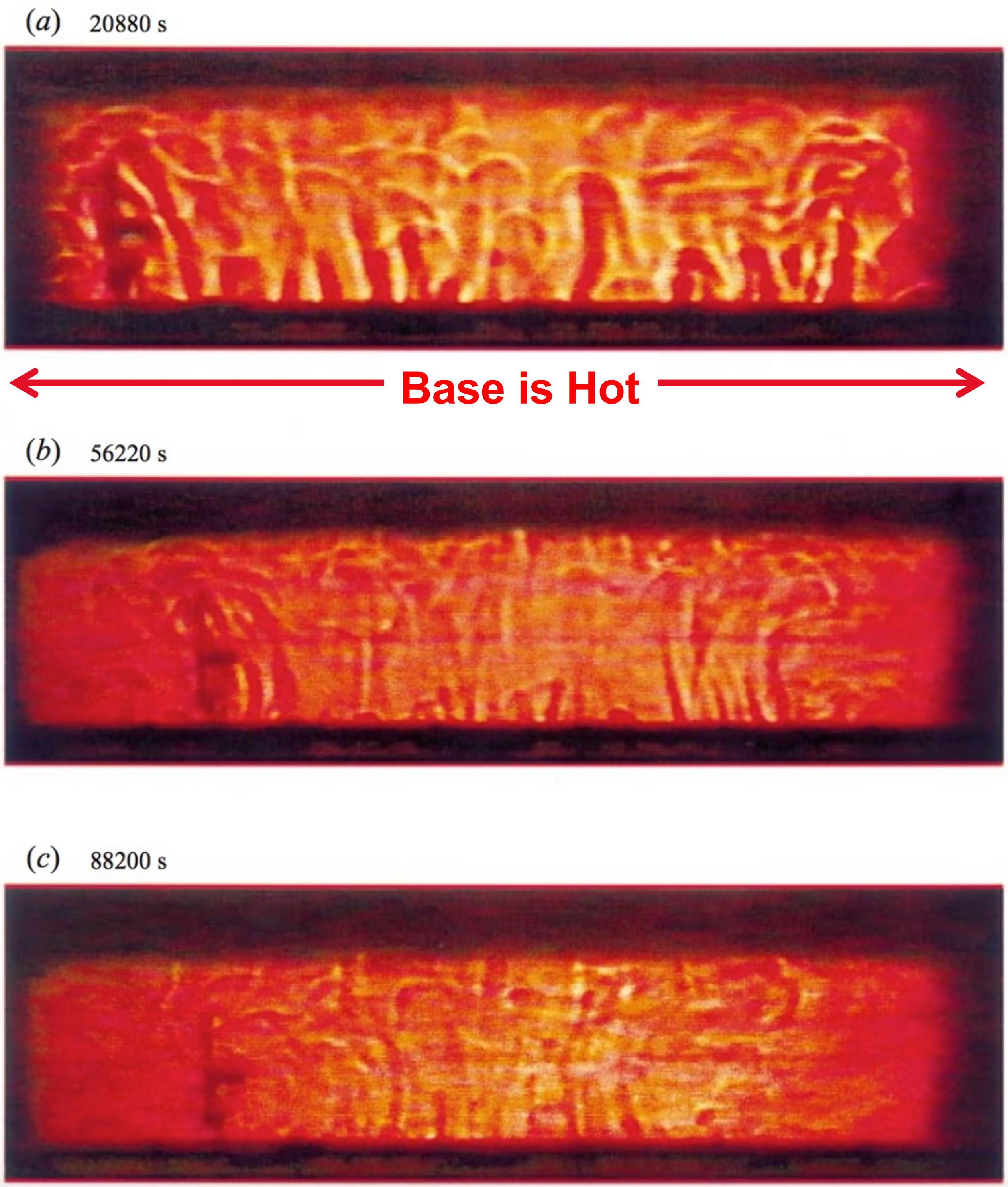
Cold Fluid Sinks

Hot Fluid Rises

Convection:
A Plume Experiment in Corn Syrup



Heat source at the base



Laboratory experiment of convection in a tank of corn syrup.

Lithgow-Bertelloni et al. [2001]

Tank is getting hotter with time

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)

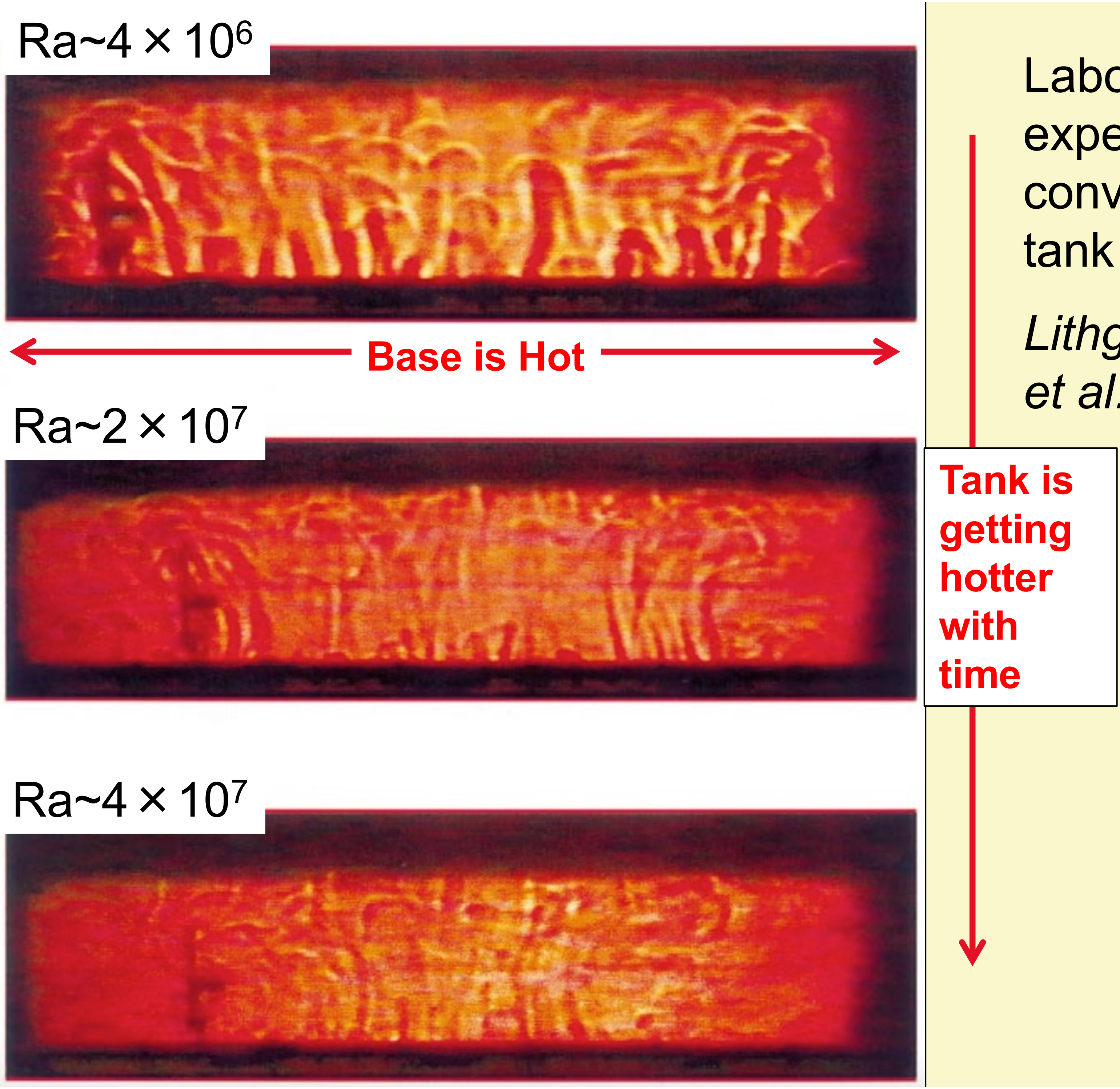
$\eta =$ Mantle viscosity (10^{21} Pa s)

Convection occurs if Ra > Ra_{cr}

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

Using these parameters for the mantle: $\mathbf{Ra_m \sim 7 \times 10^7}$

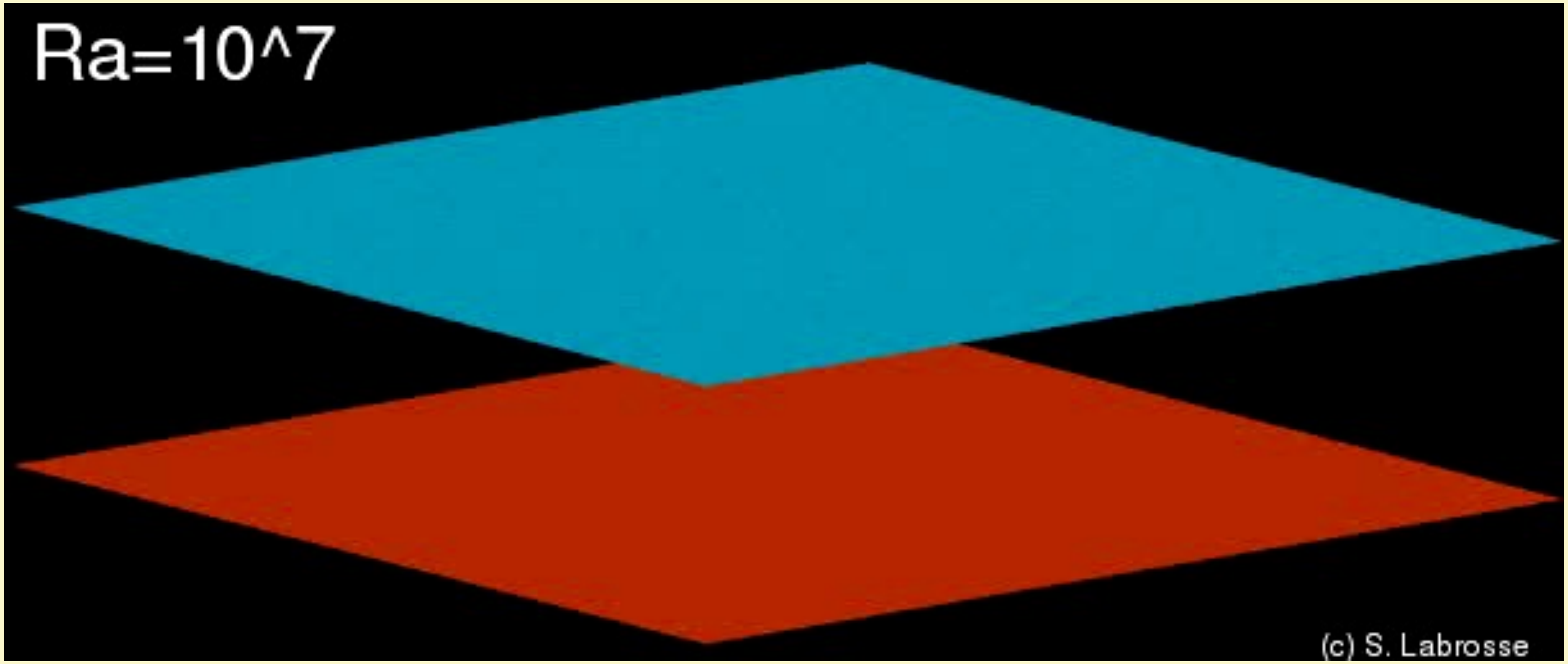
→ This "model" of the mantle implies vigorous convection



Laboratory experiment of convection in a tank of corn syrup.

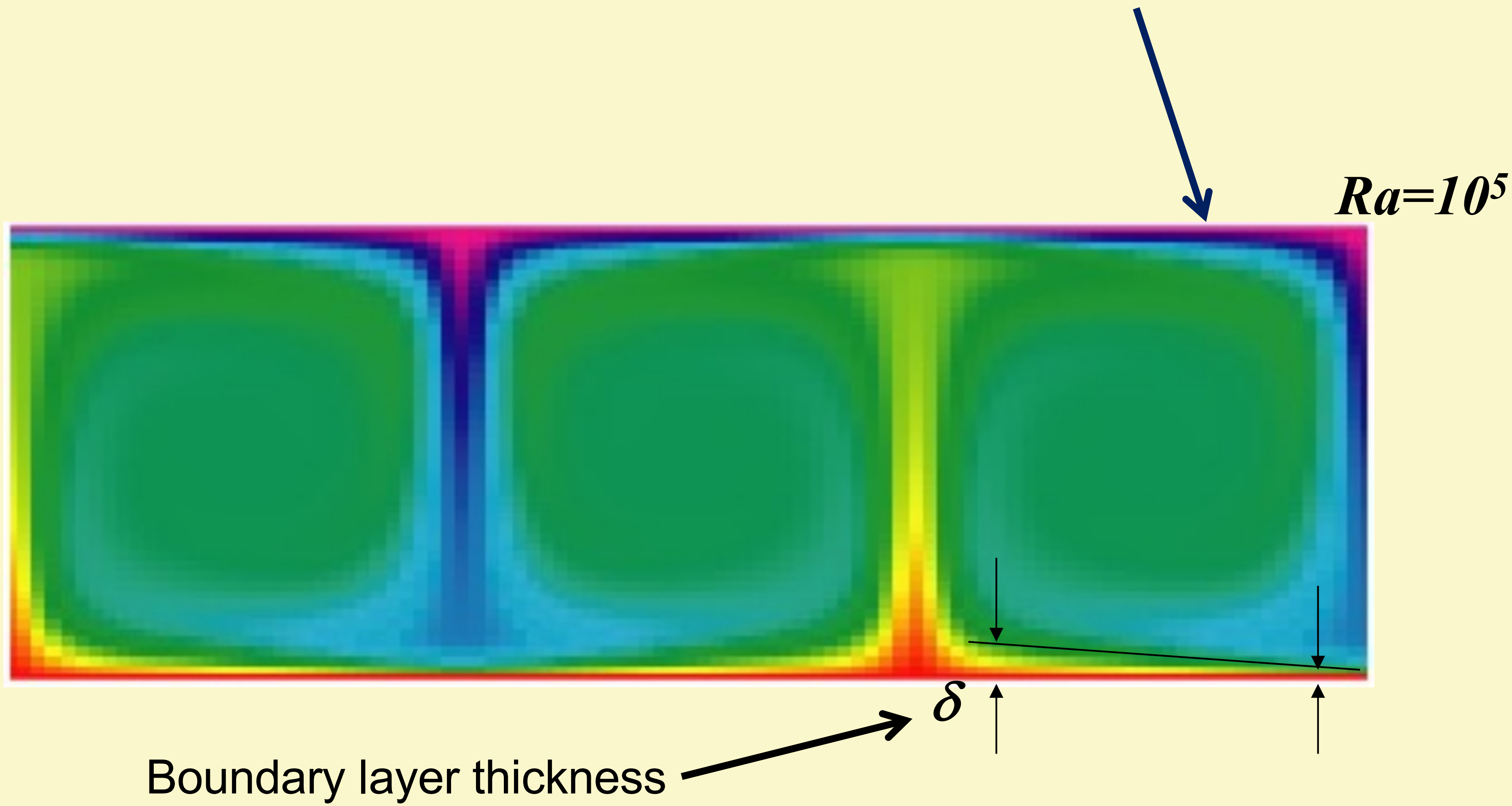
Lithgow-Bertelloni et al. [2001]

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**



Mantle Convection: Effect of Rayleigh Number

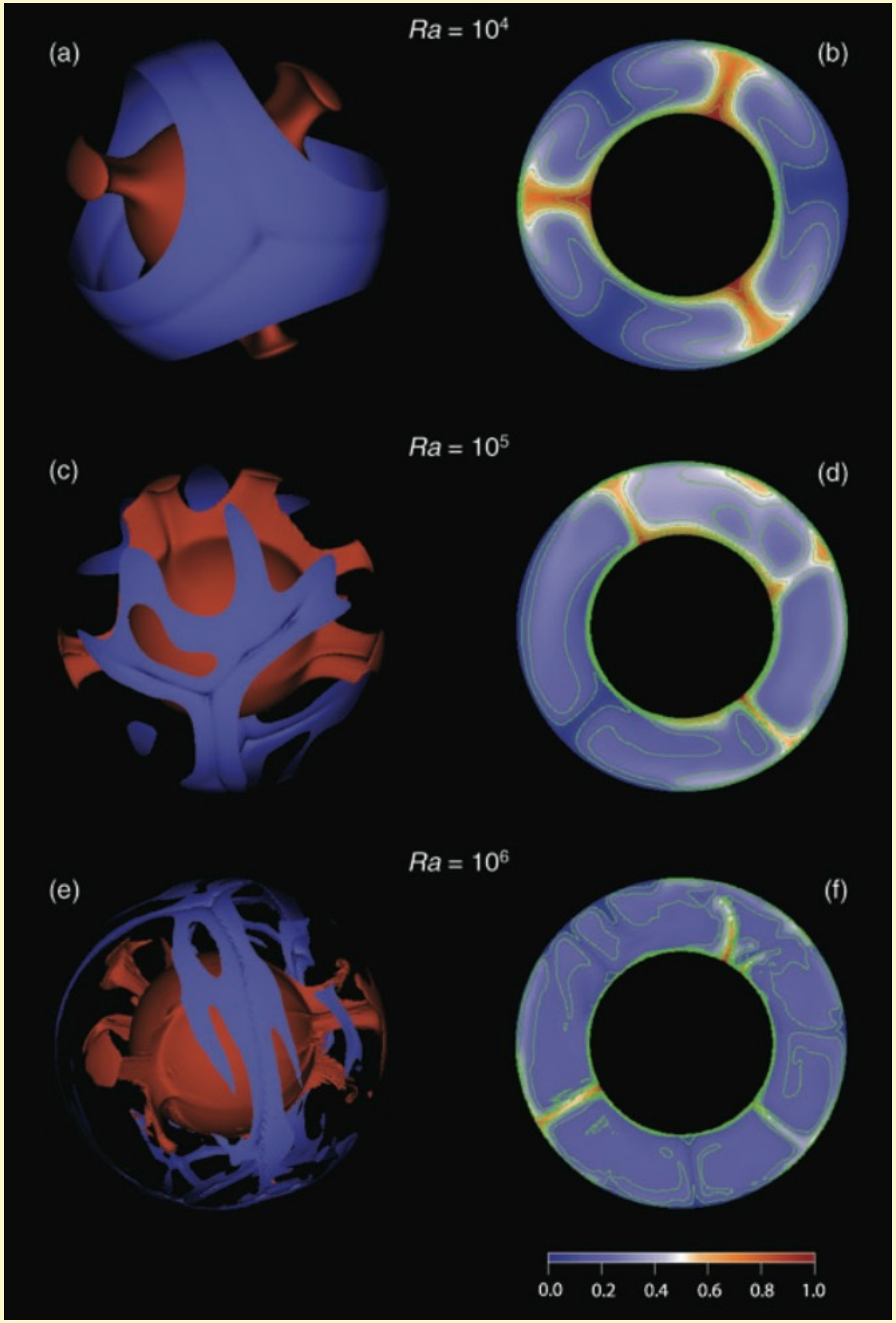
Deschamps et al., 2010

Style and vigor of convection changes with Ra

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

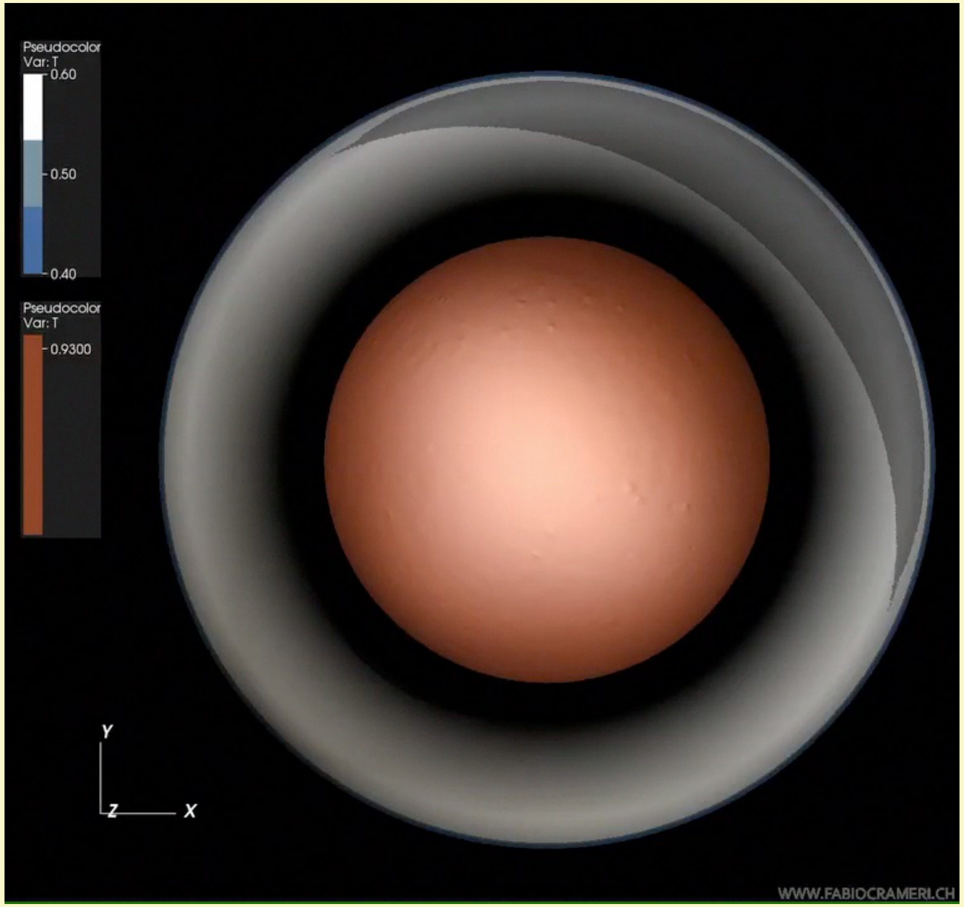
Plate velocity $v_p \sim Ra^{\frac{2}{3}}$

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

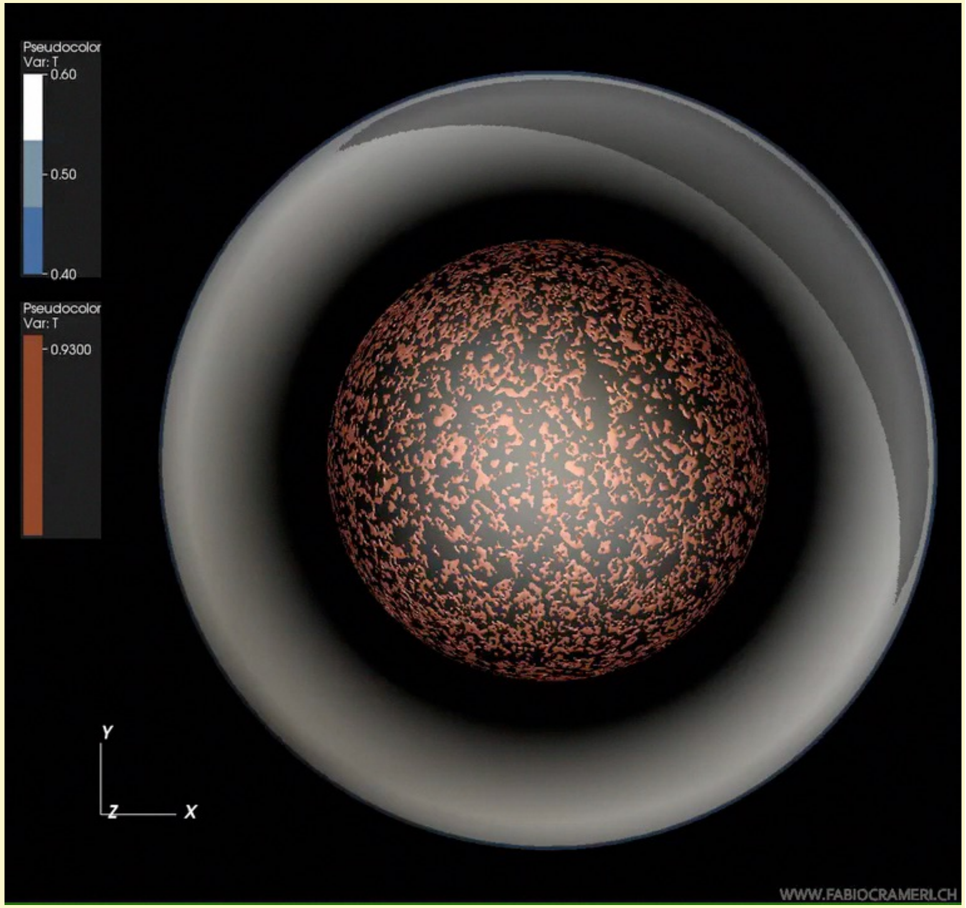


Mantle Convection: Impact of the Lithosphere

Crameri & Tackley [2016]



Lithosphere cannot break
→ "stagnant lid" convection
→ Mantle remains hot



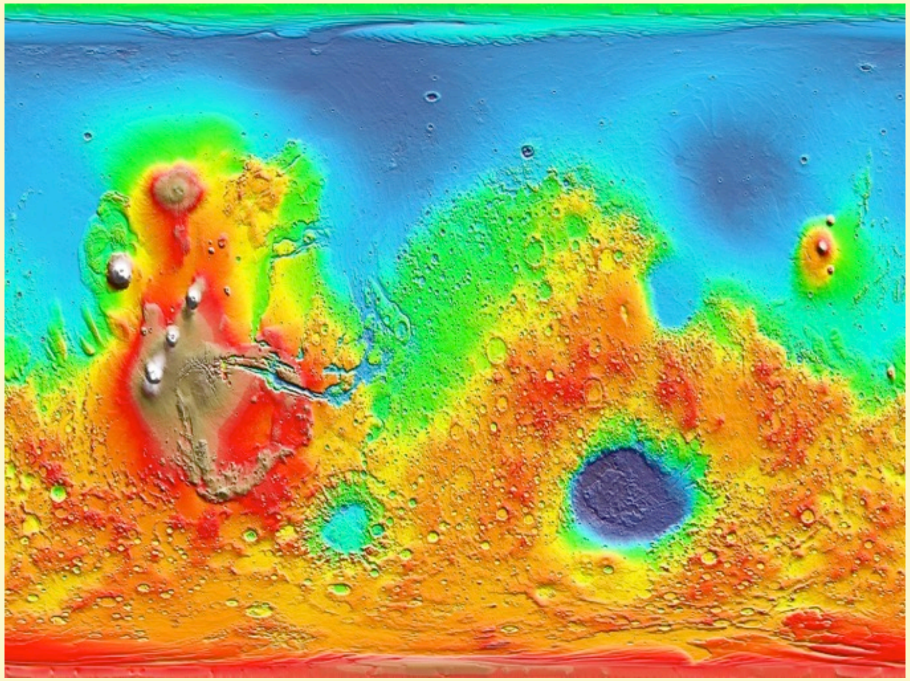
Lithosphere can break
→ Subduction forms
→ Plate tectonics

The Lithosphere and Convection on other Planets:

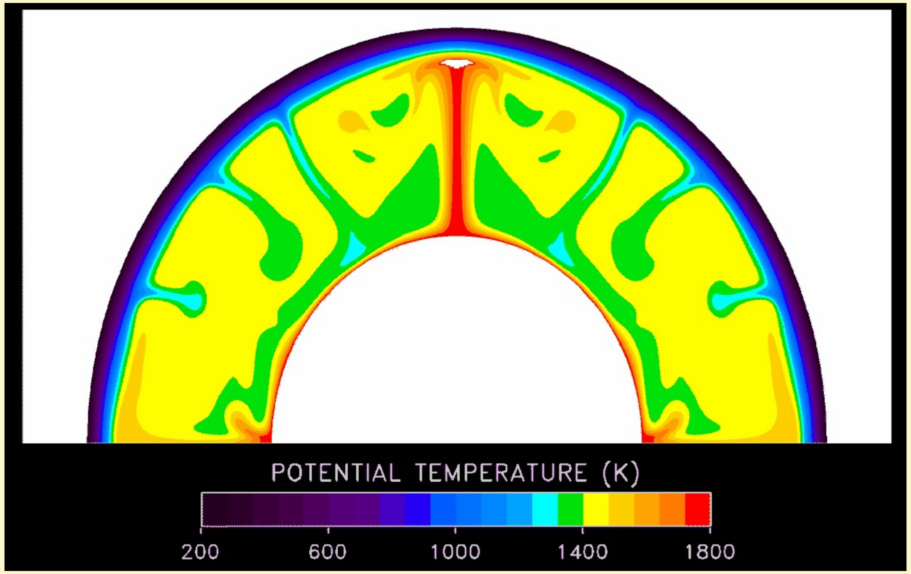
Moon, Mars, Venus, Mercury: Surfaces are much older than Earth's: Probably no plate tectonics

Instead, mantle convection beneath a “stagnant lid”

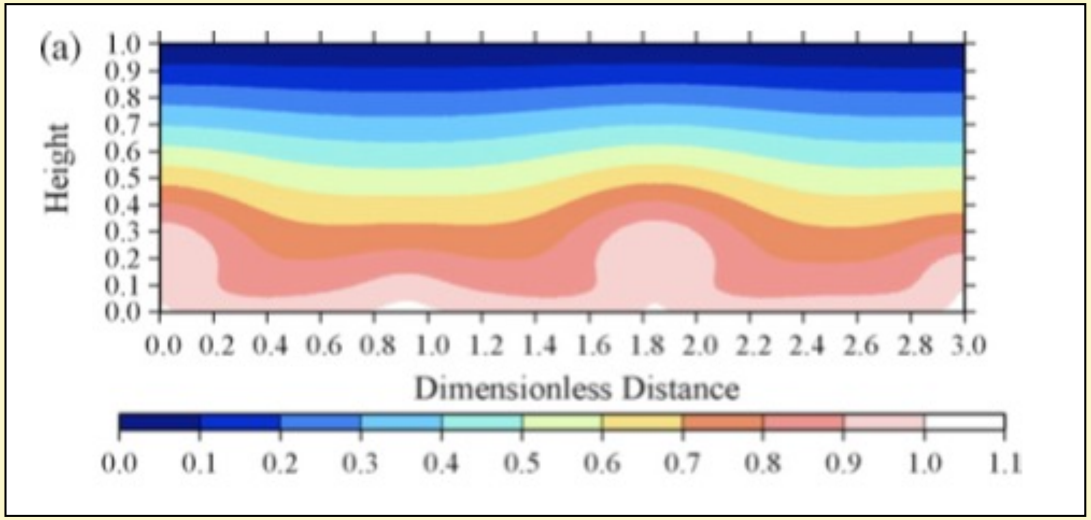
Mars Topography



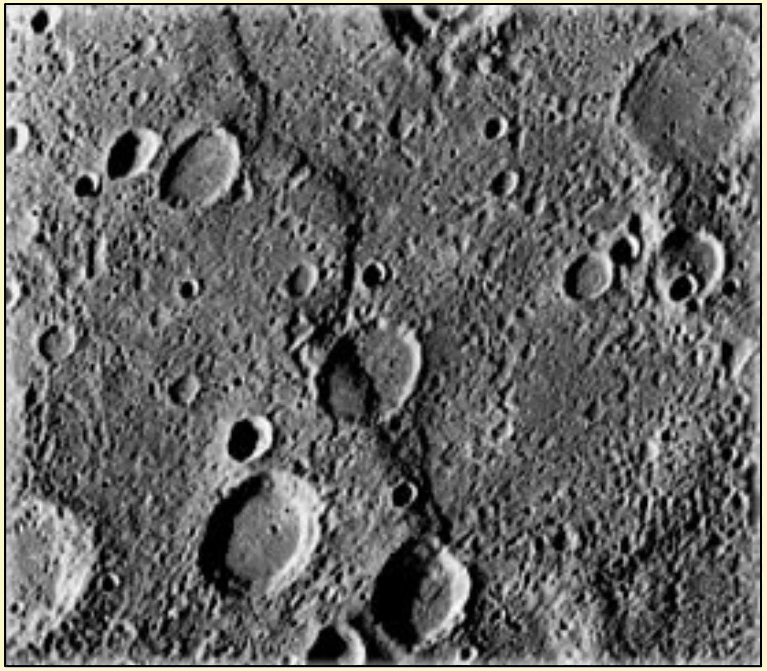
Model of Mars Convection



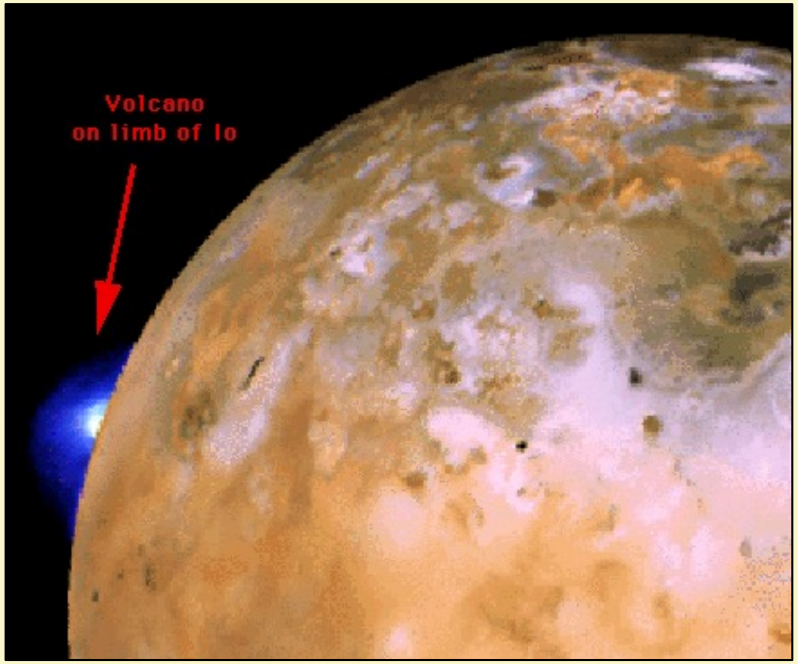
Mercury: Low Ra



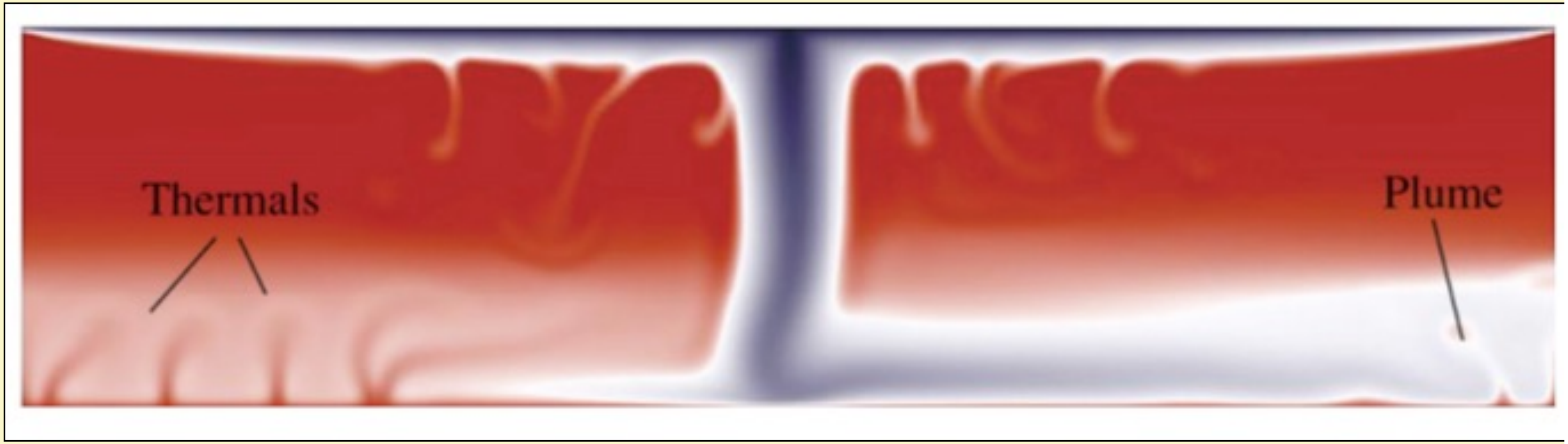
Redmond & King 2007



Io: High Ra



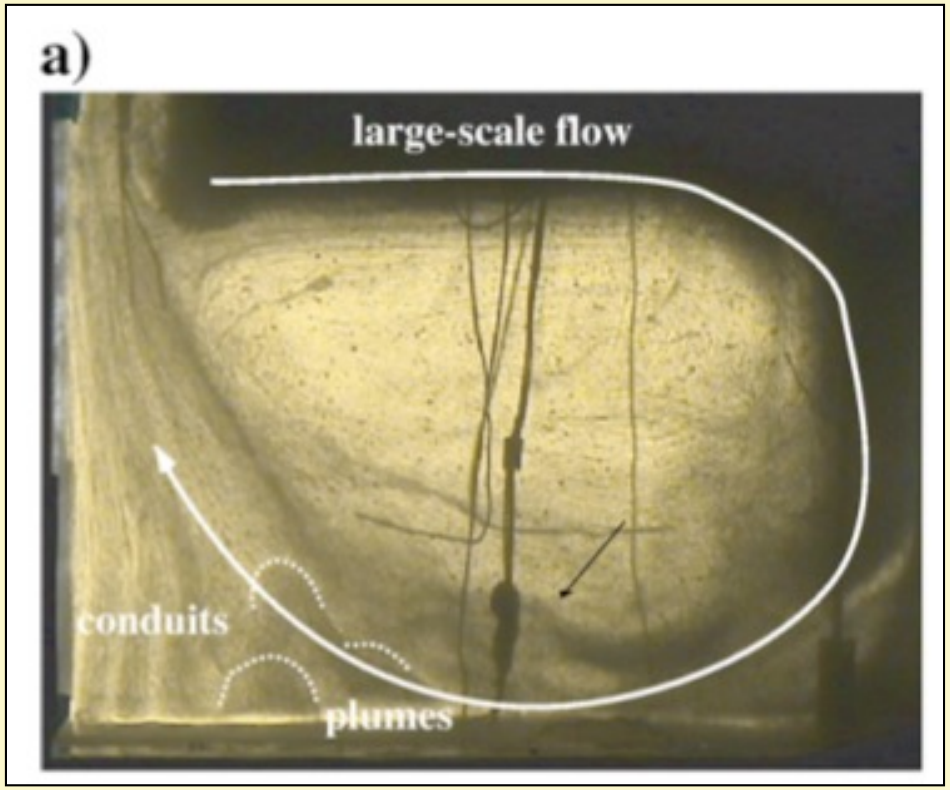
Volcanism through a thin lithosphere



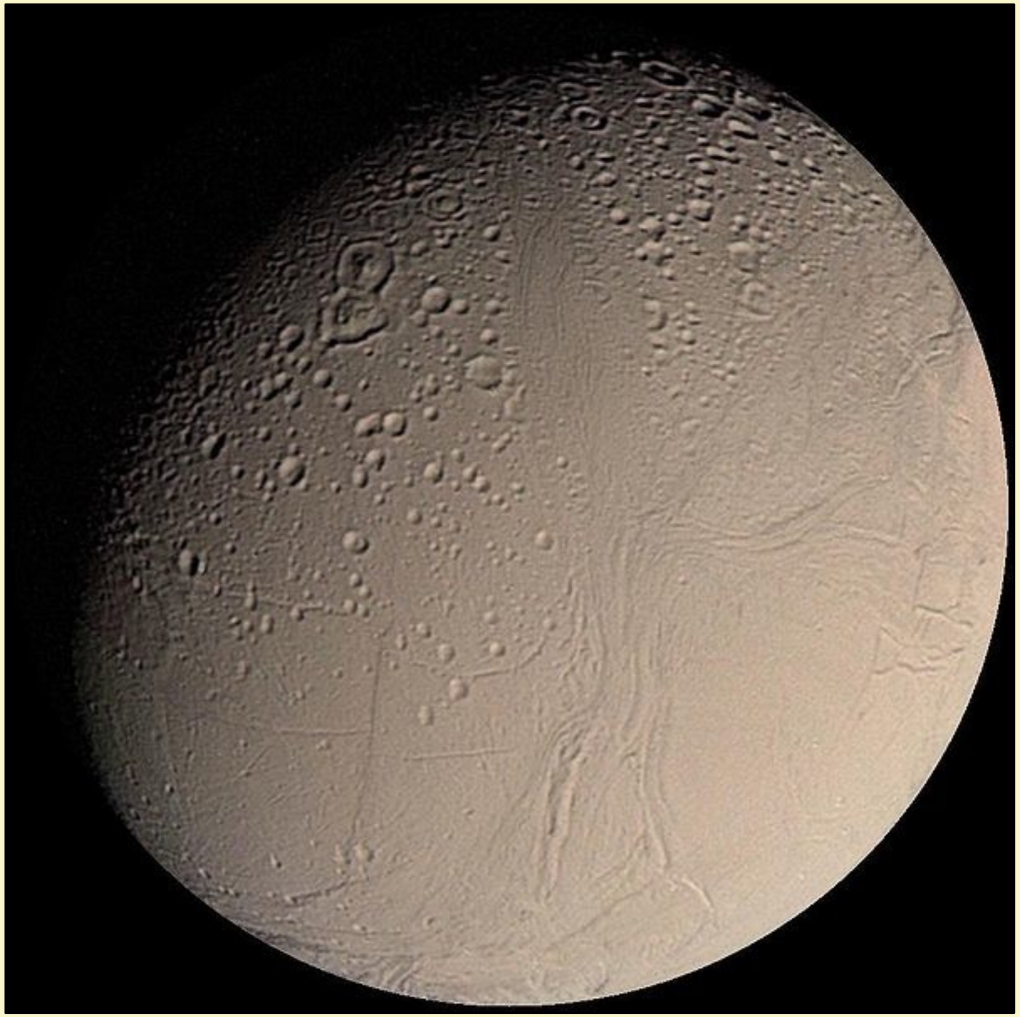
Venus:

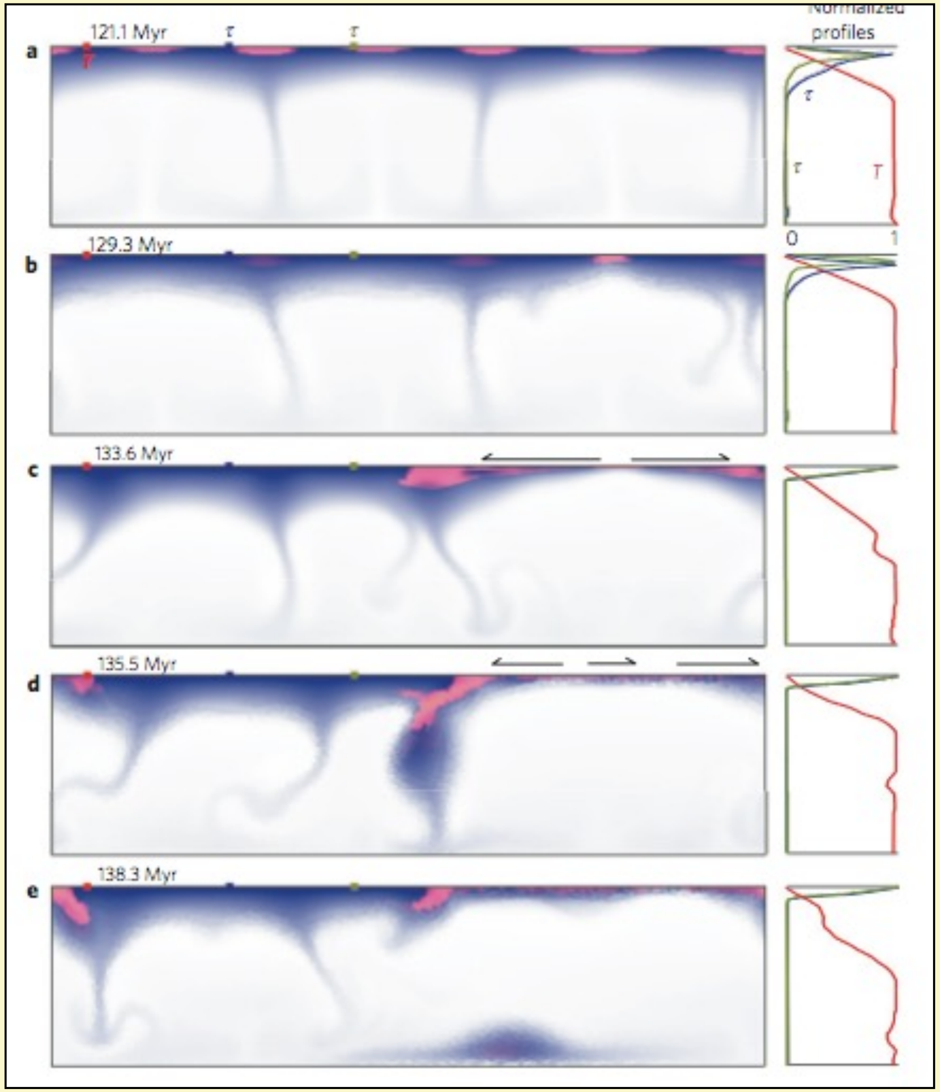
No plate tectonics,
but the entire lithopshere
sometimes sinks into
the mantle, resurfacing
the entire planet.

Robin et al., 2007



Enceladus: Convection in solid ice



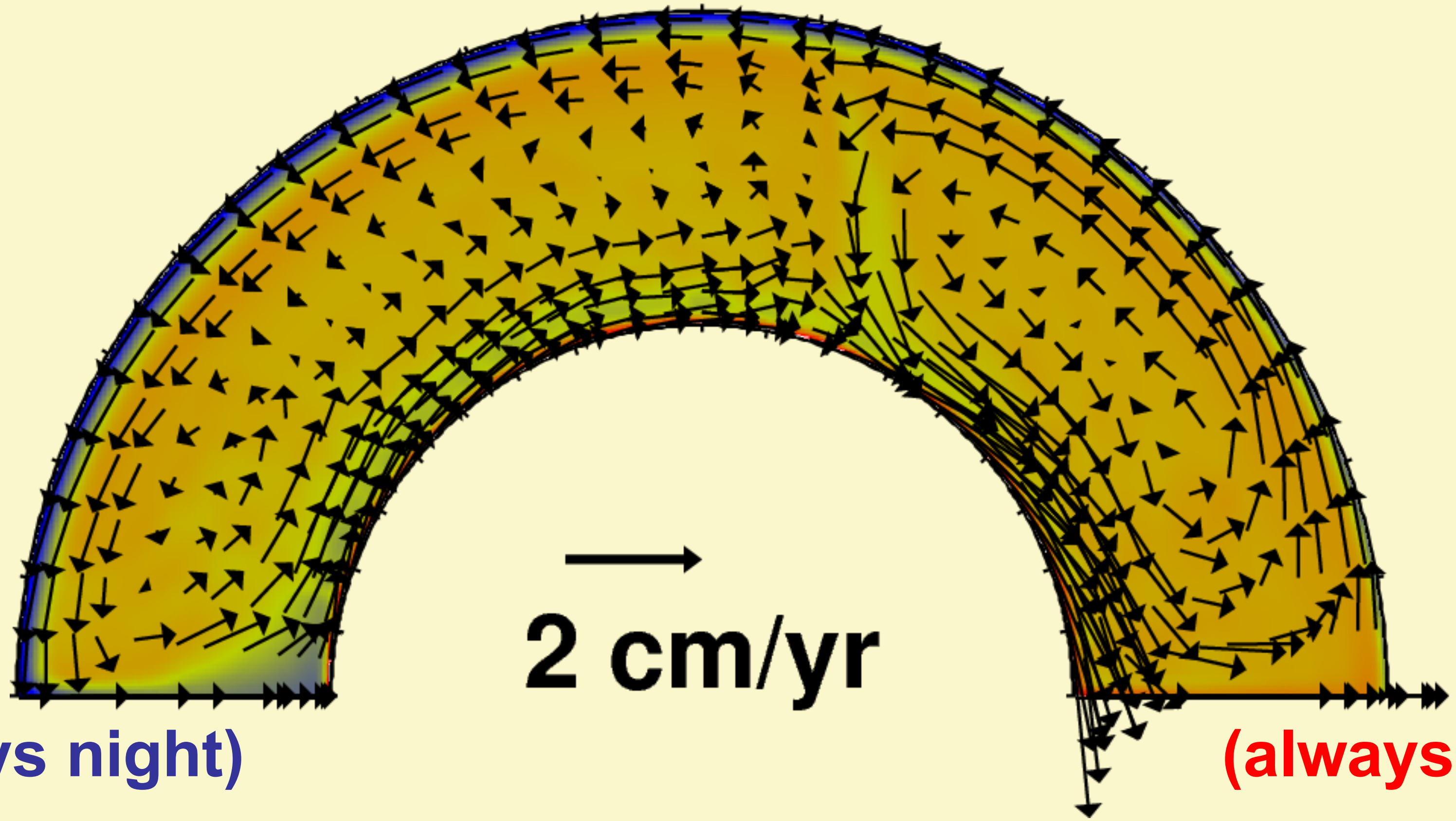


O'Neill and Nimmo, *2010*

Exoplanets: Many different styles!

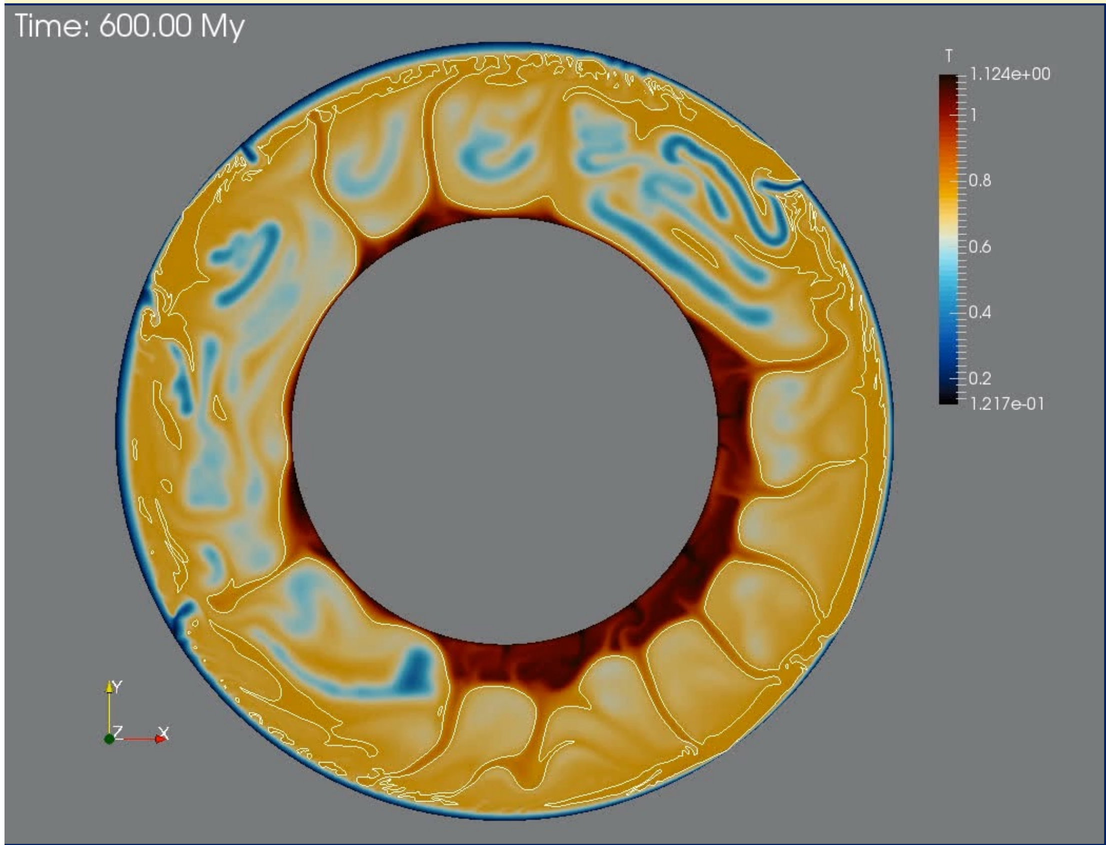
Tidally-locked example

COLD SIDE (always night)

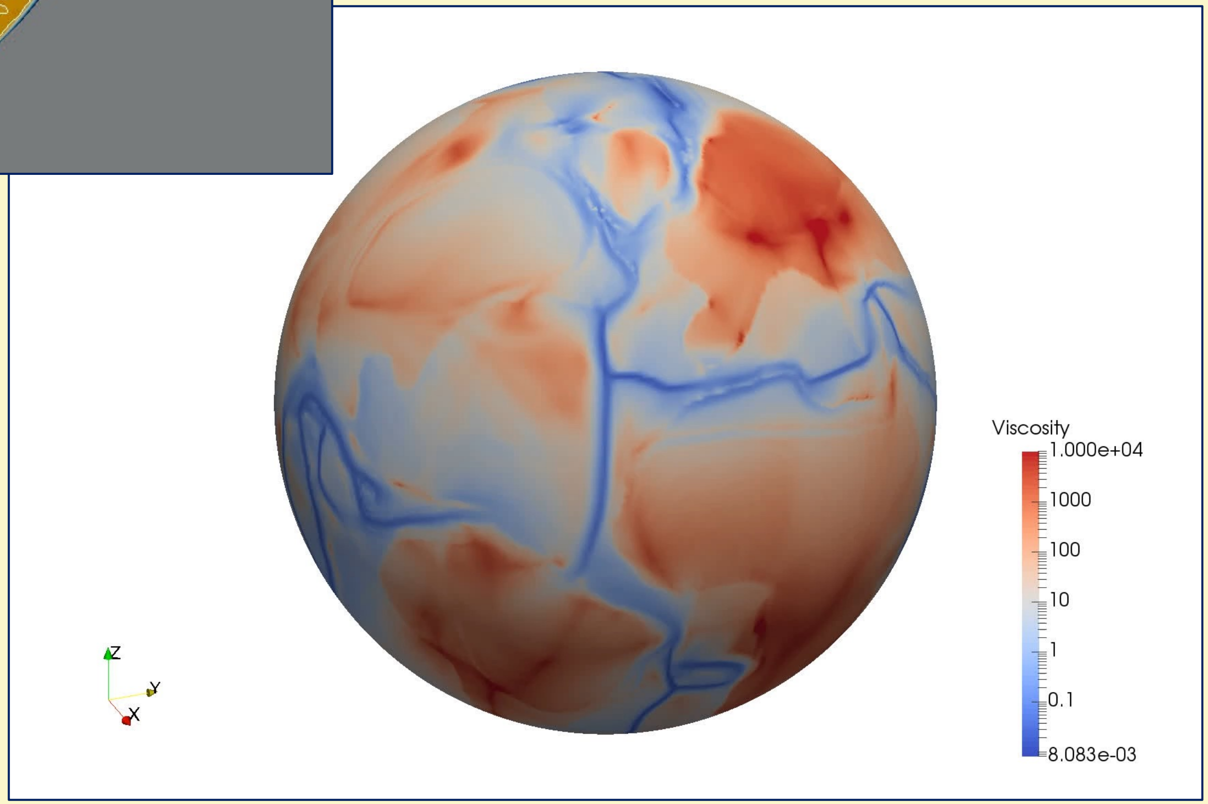


HOT SIDE (always day)

van Summeren, Conrad, & Gaidos, 2011



Tectonics of the lithosphere govern mantle convection
→ Controls mantle cooling



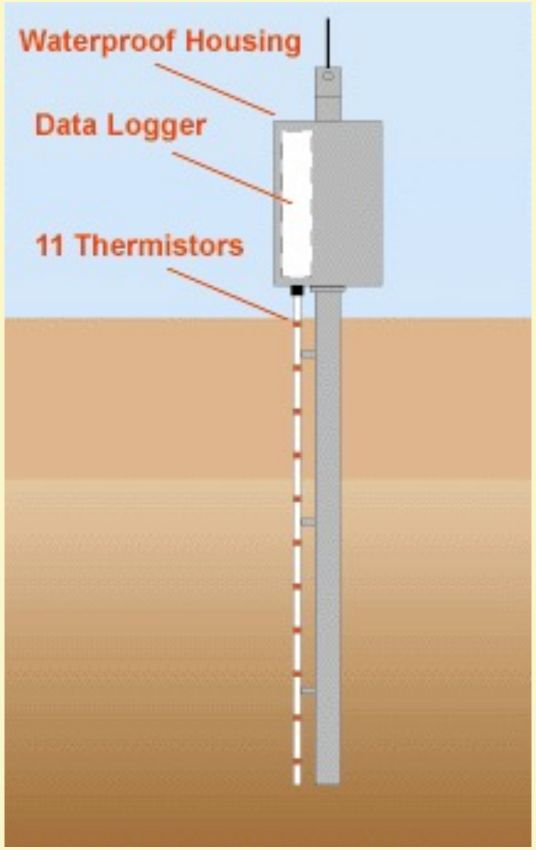
Arnould et al. [2018]

Heat flows down a temperature gradient:

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

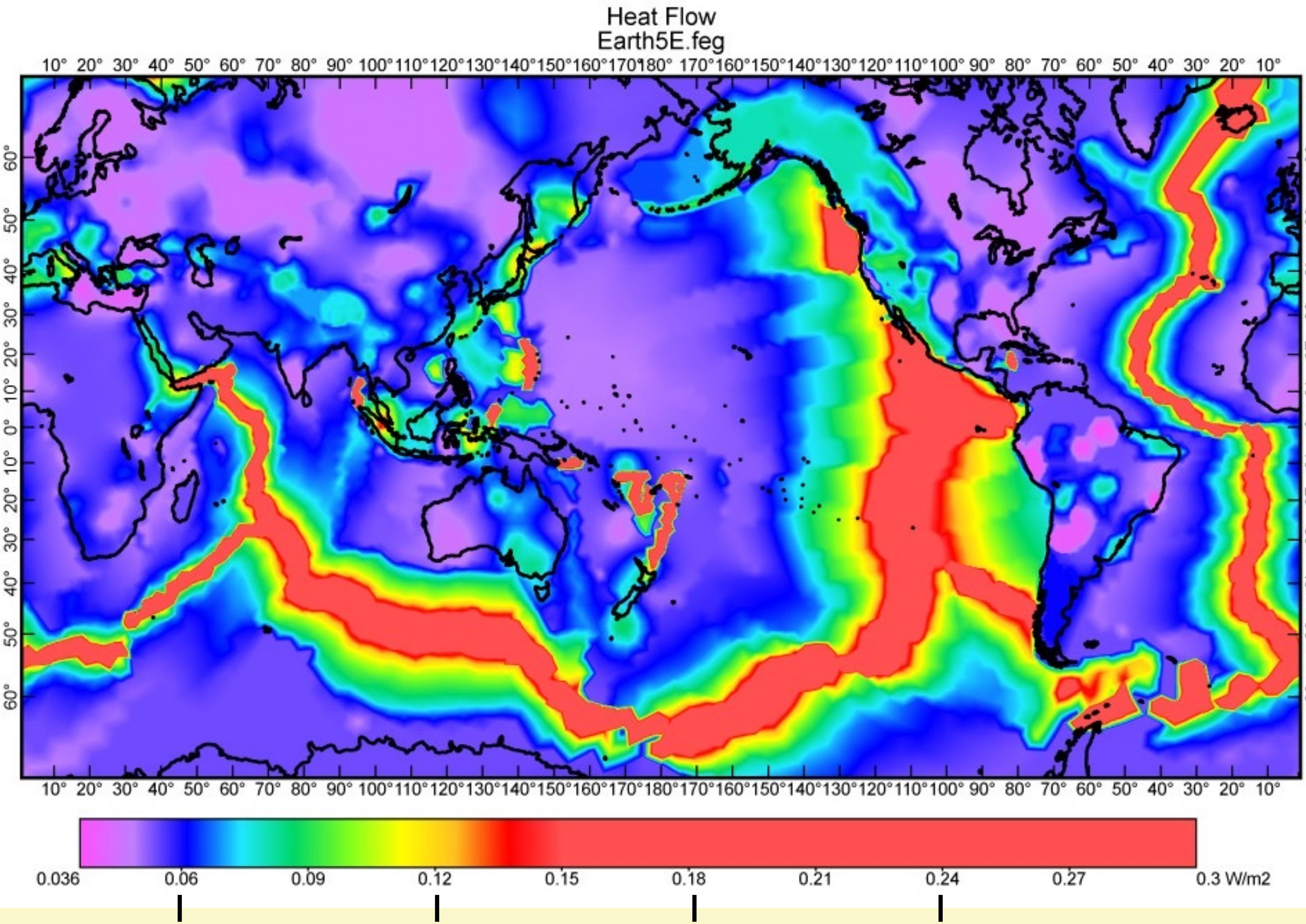
k = thermal conductivity
typically k ~ 2-3 W/m/K

Then we can measure heat flow by measuring dT/dz



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

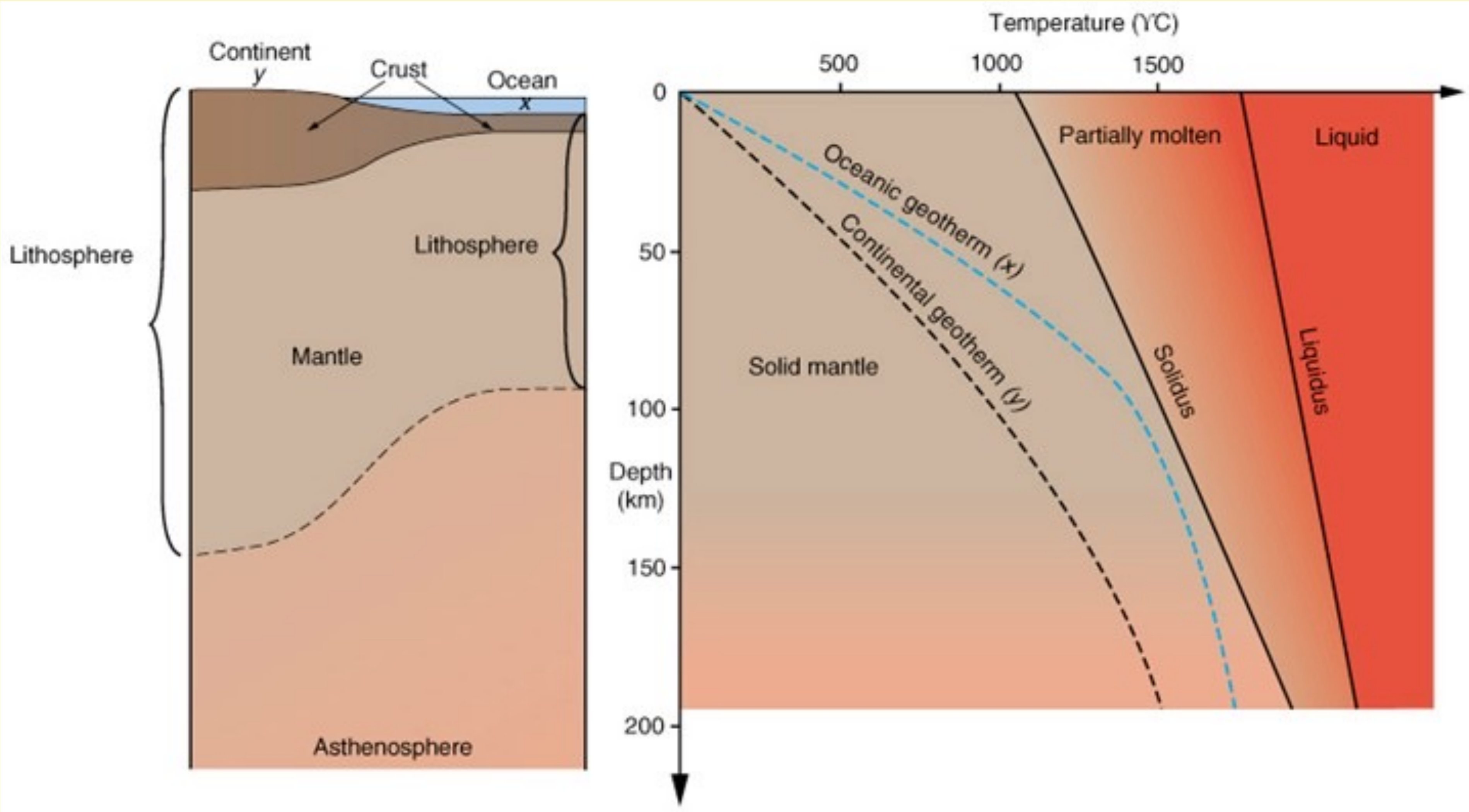
For continental environments:
Measure heat flow in a cave, mine or borehole (deeper than ~300 m)



20° C/km 40° C/km 60° C/km 80° C/km

Temperature vs. depth in the lithopshere

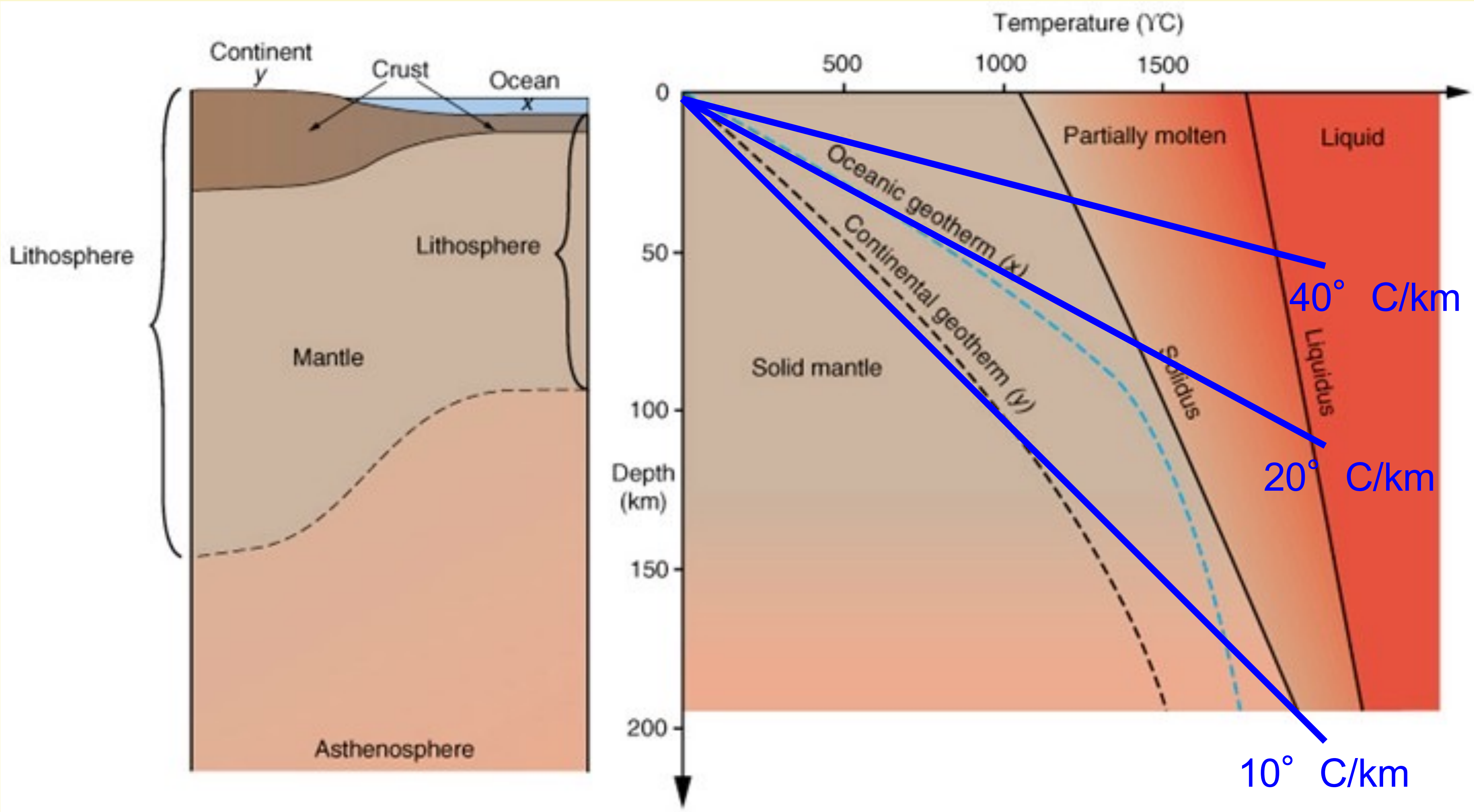
→ Surface geotherms cannot continue deeper than 50-100 km



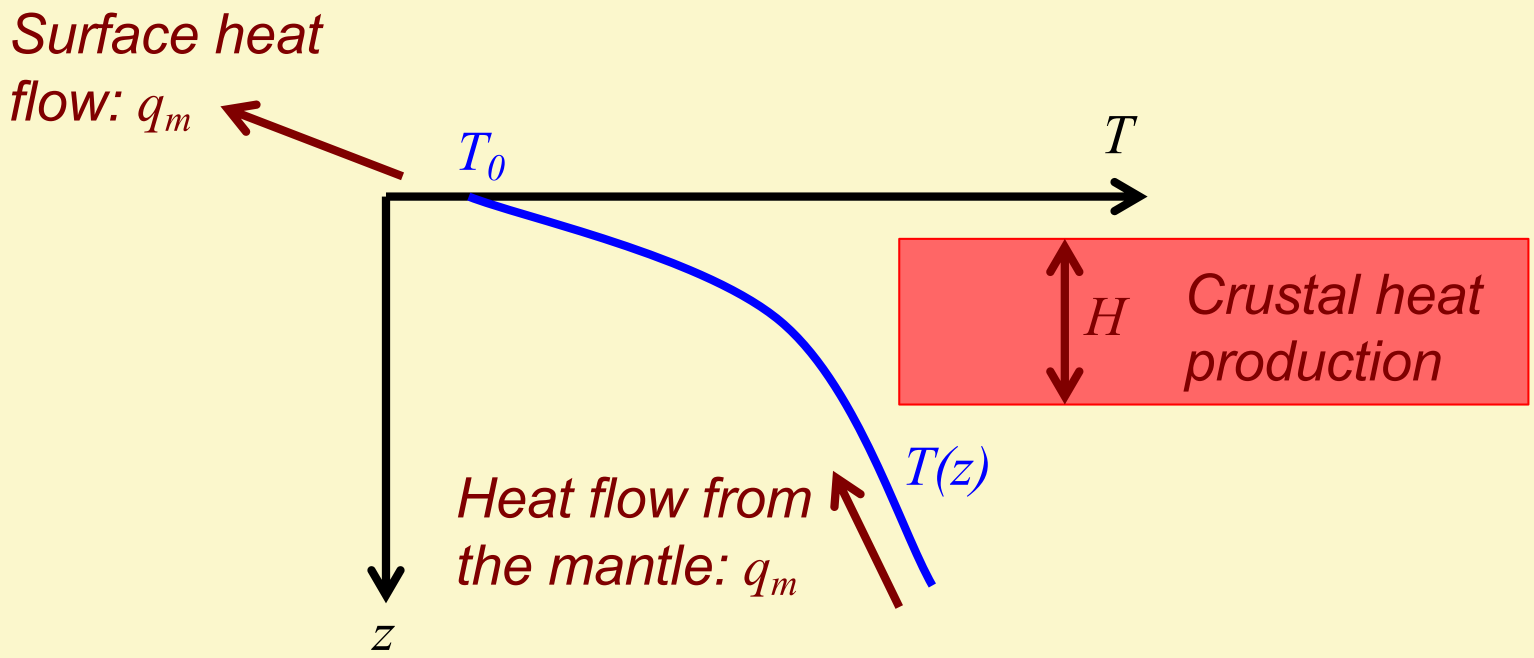
Temperature vs. depth in the lithopshere

→ Surface geotherms cannot continue deeper than 50-100 km

What causes these geotherms to turn?

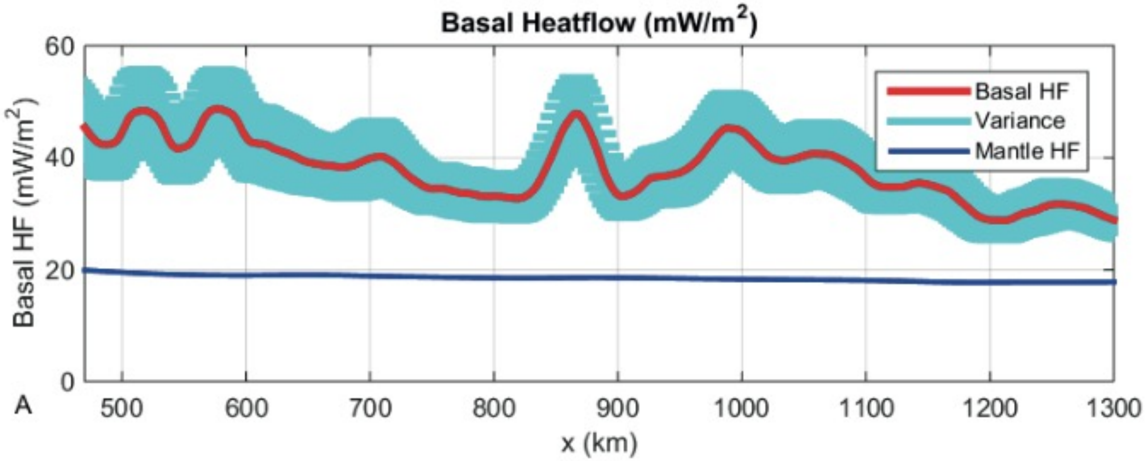


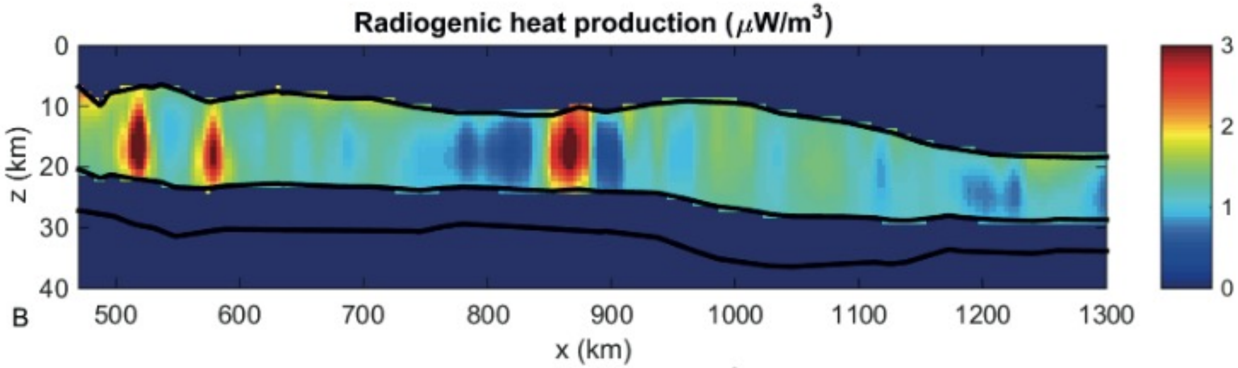
Option 1: There is a heat source in the lithosphere

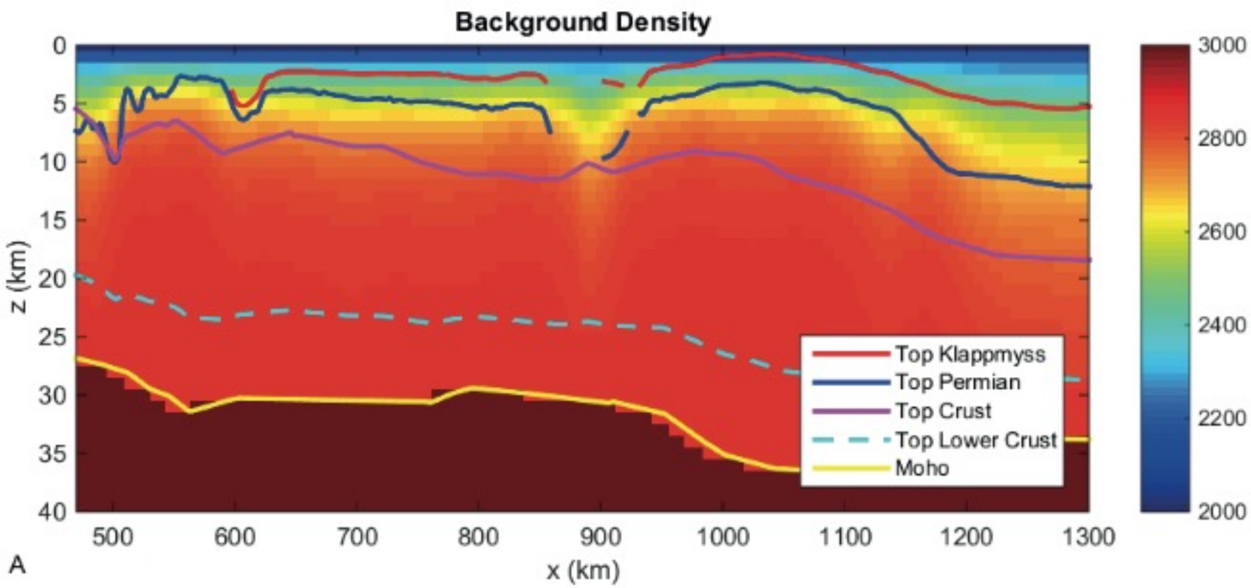


This solution could be stable in steady-state (continental regions)

Thermal modeling of a cross section across the Barents Sea

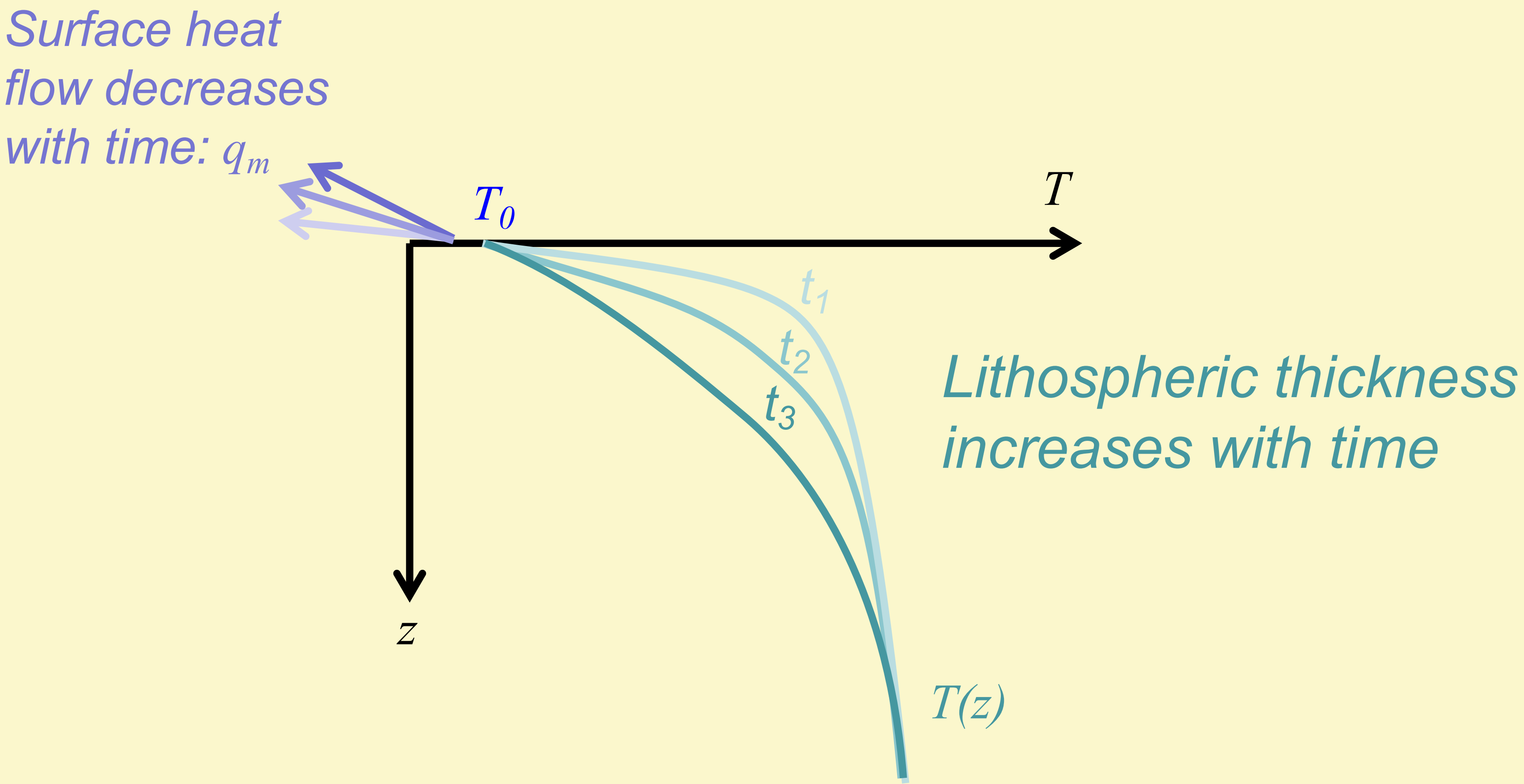






Hokstad et al. [Norwegian Journal of Geology, 97, 241-254, 2017]

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

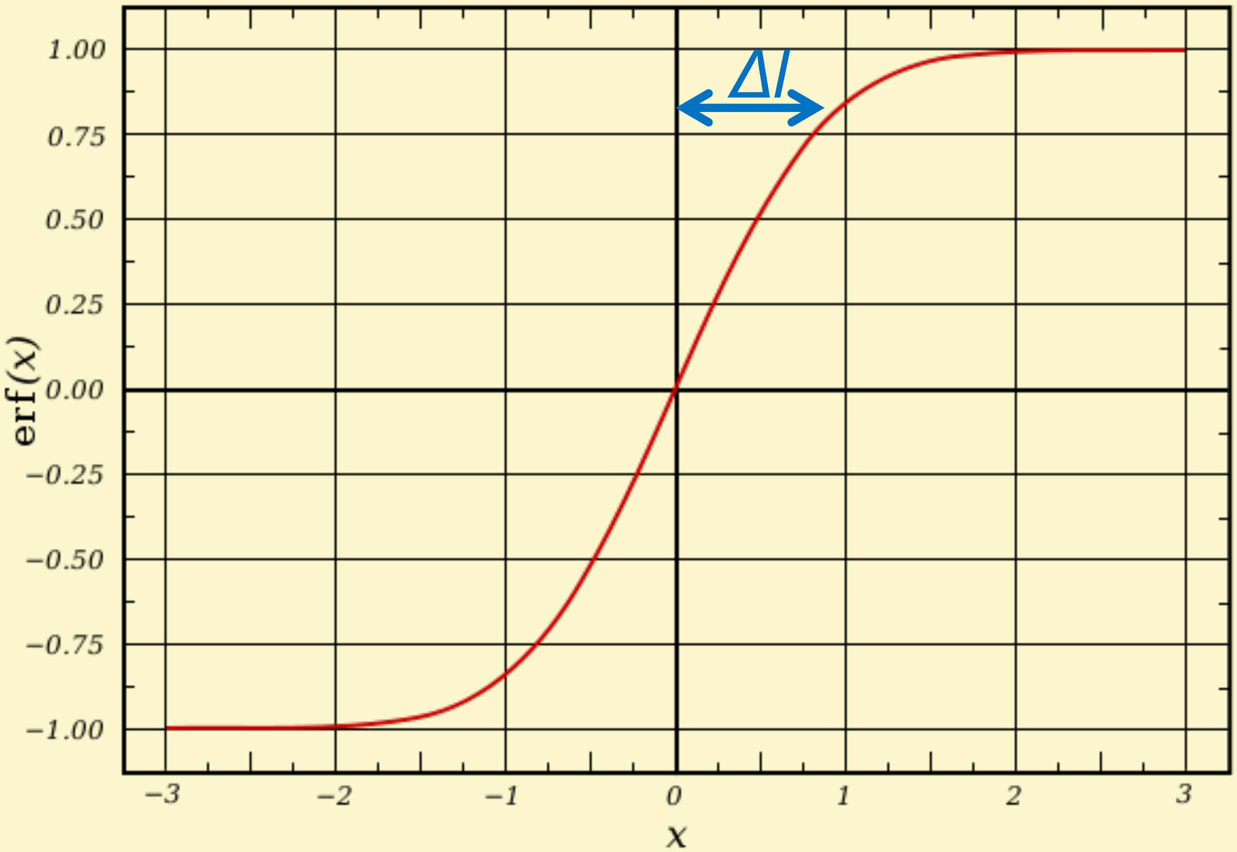


Time-Dependent Solution to the Heat Equation

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

$$\kappa = \frac{k}{\rho c_p}$$ 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:

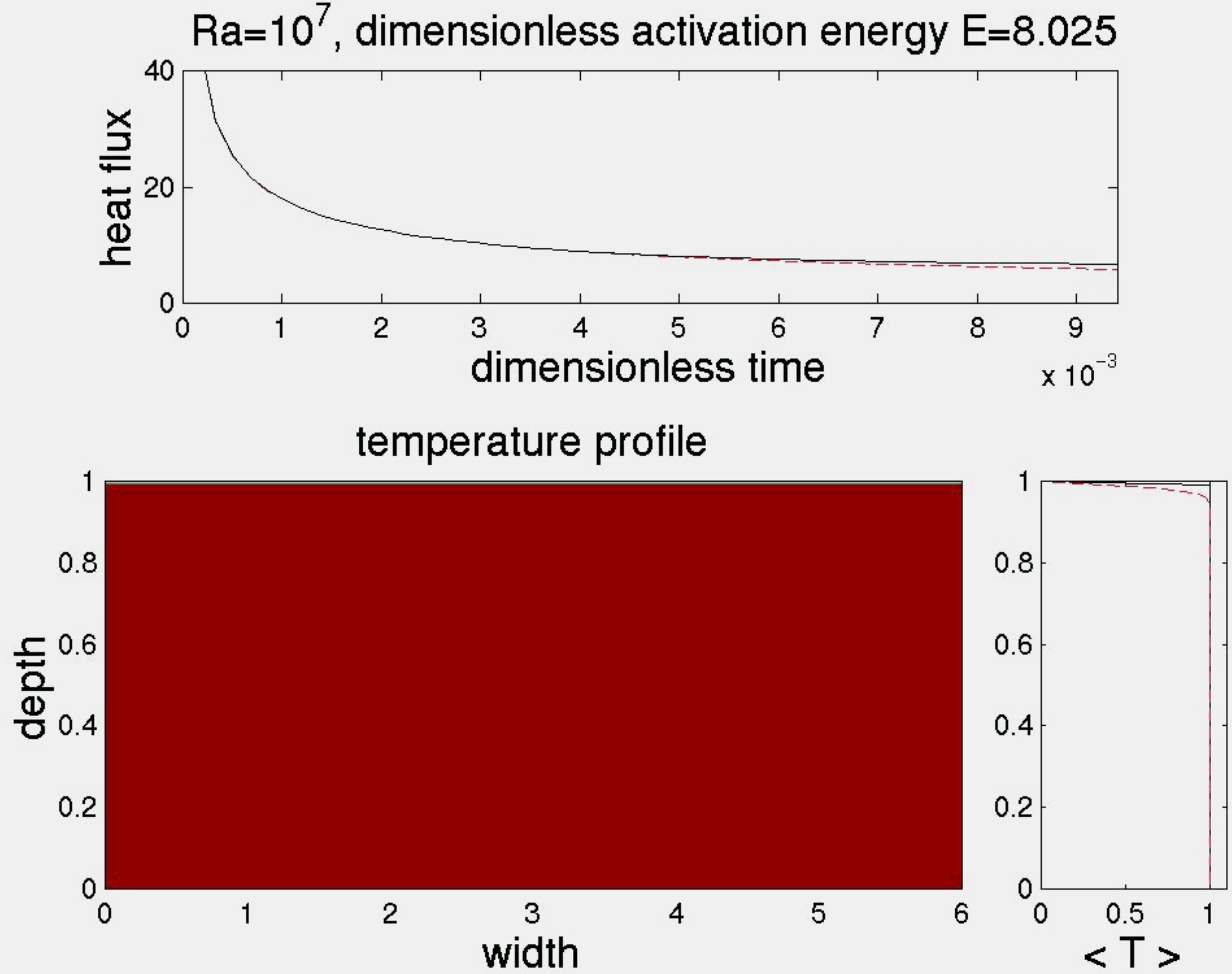
$$\Delta l \sim 2\sqrt{\kappa \Delta t}$$

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	*Seasonal variations*
1 year	11 m	
1 decade	36 m	
1 century	110 m	
1 kyr	360 m	*Ice age climate variations*
10 kyr	1.1 km	
100 kyr	3.6 km	
1 Myr	11 km	*Age of ocean lithosphere*
10 Myr	36 km	
100 Myr	110 km	*Age of ocean lithosphere*
1 Gyr	360 km	*Age of cratons*



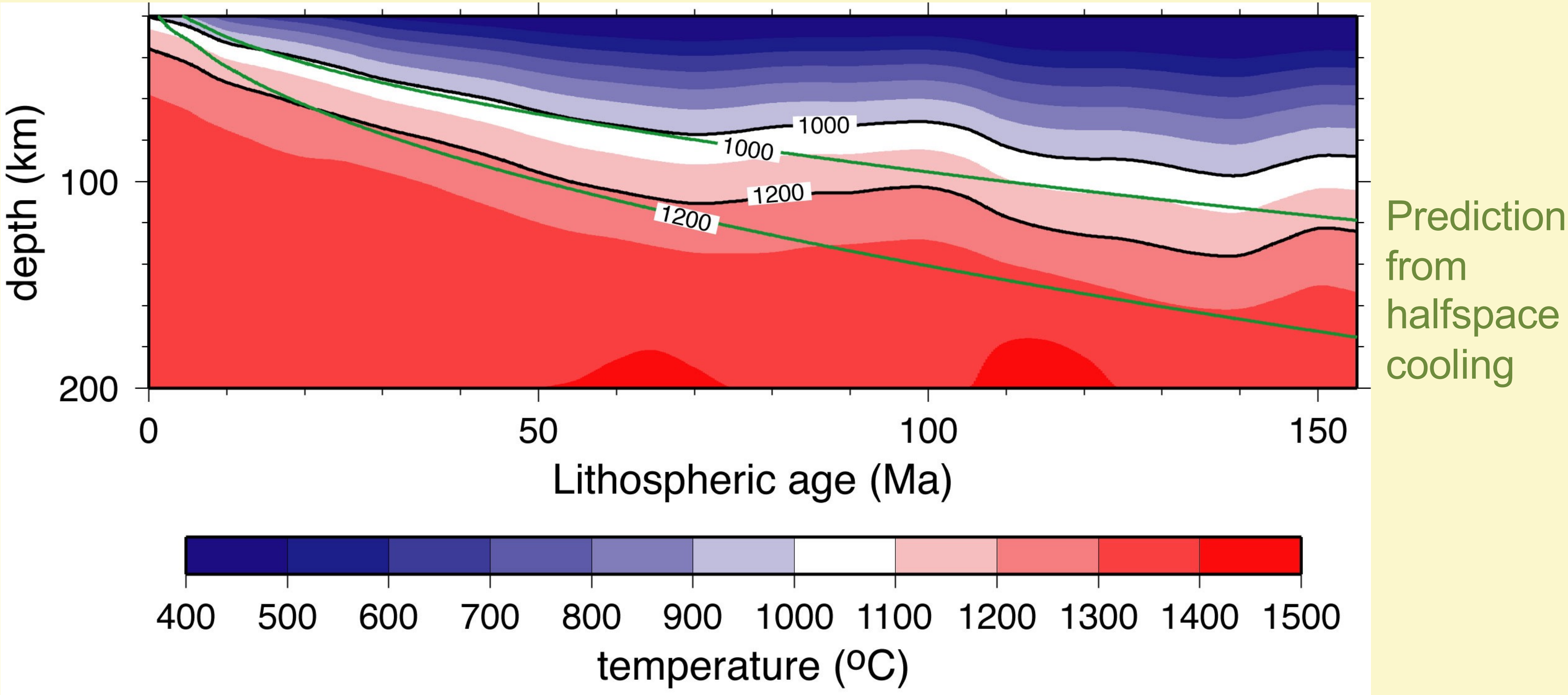
Ra=10^7, dimensionless activation energy E=8.025
heat flux
40
20
0
0
1
2
3
4
5
6
7
8
9
dimensionless time
x 10^-3
temperature profile
depth
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
width
1
0.8
0.6
0.4
0.2
0
0
0.5
1
< T >

The oceanic lithosphere follows halfspace cooling

→ Out to about 80 Million years

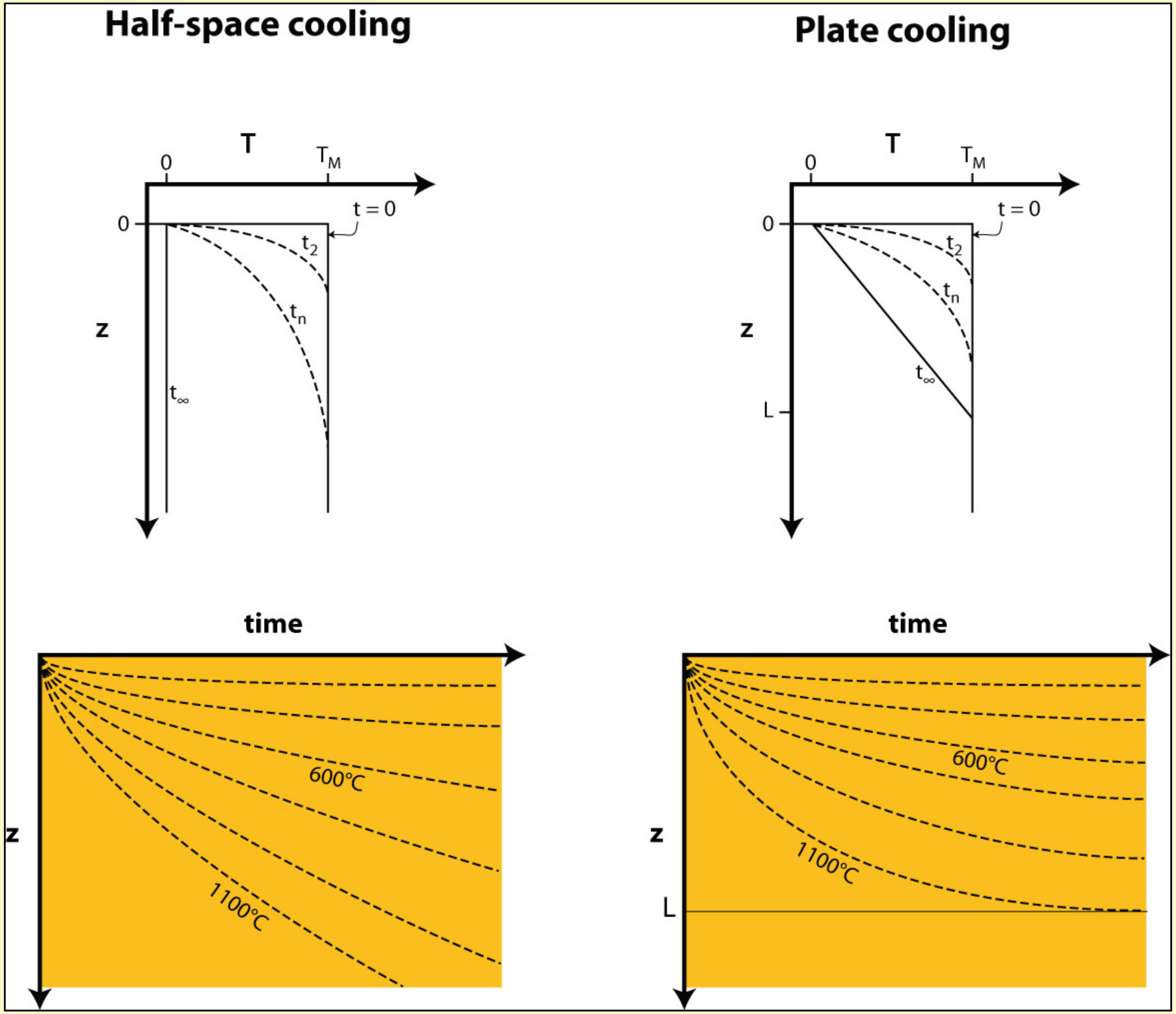
→ Lithosphere thickness reaches ~100 km

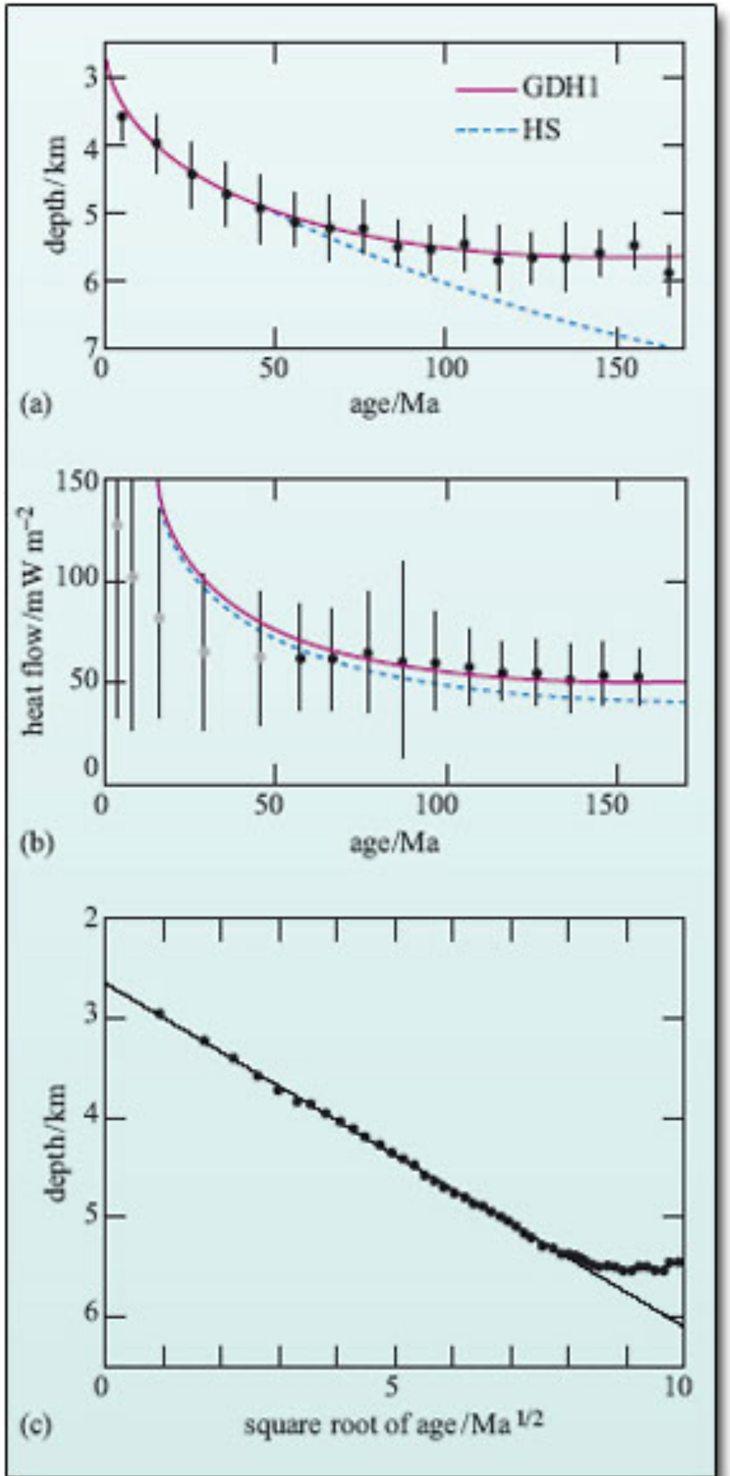
Thermal Structure of the Pacific – based on seismic observations



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

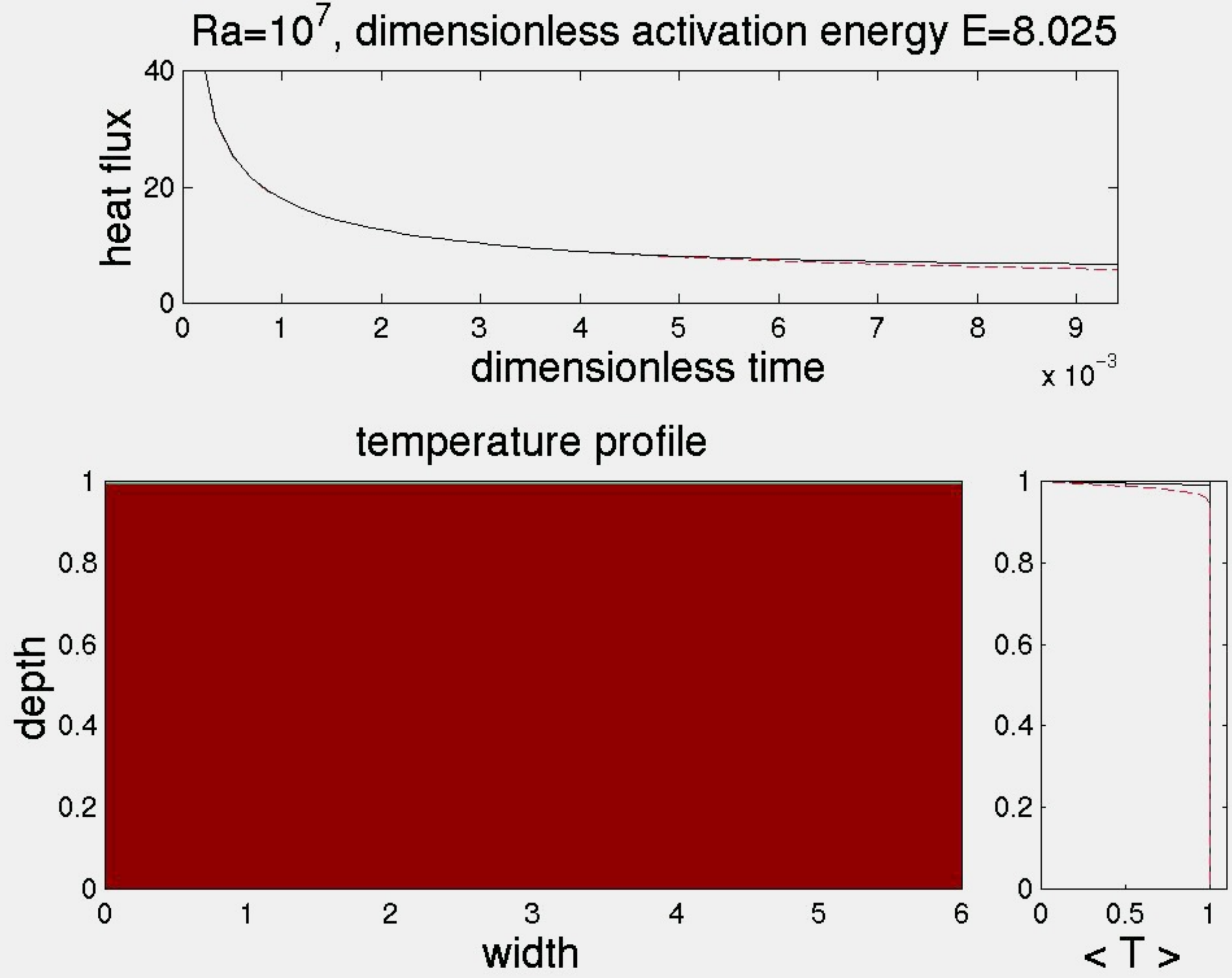
Depth (m) as a function of age t (Myr)

D(t) = 2600 + 365 sqrt(t) for t<20 Myr
= 5651 – 2473 exp(-0.0278 t)
for t>20 Myr

Heat Flow (mW/m²)

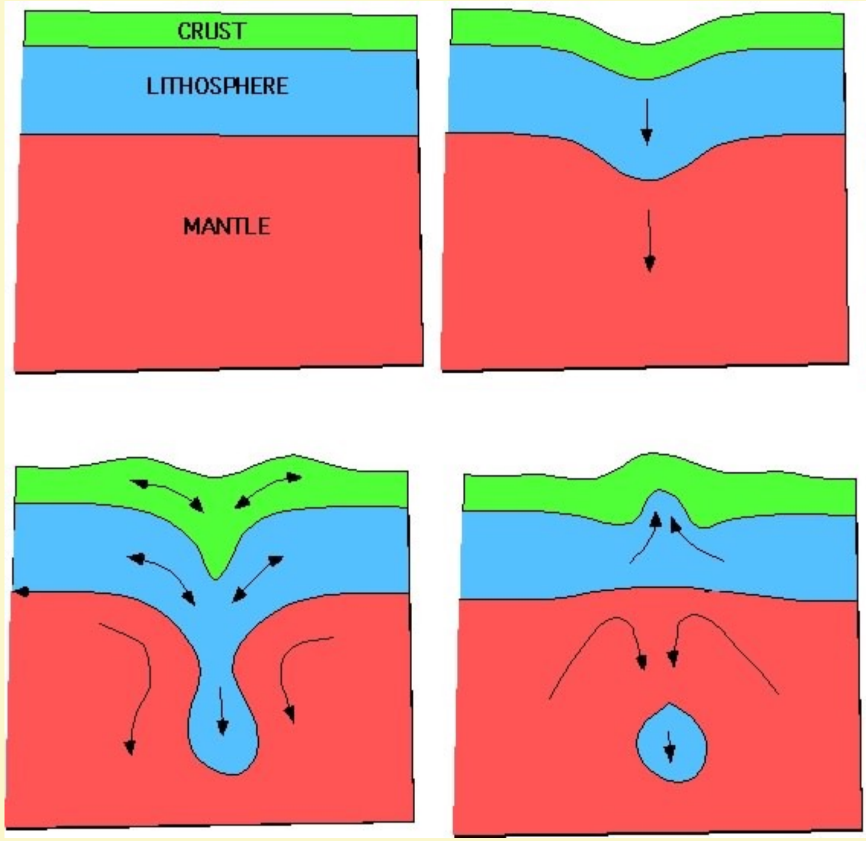
q(t) = 510 $t^{-1/2}$ for t<55 Myr
= 48 + 96 exp(-0.0278 t)
for t>55 Myr

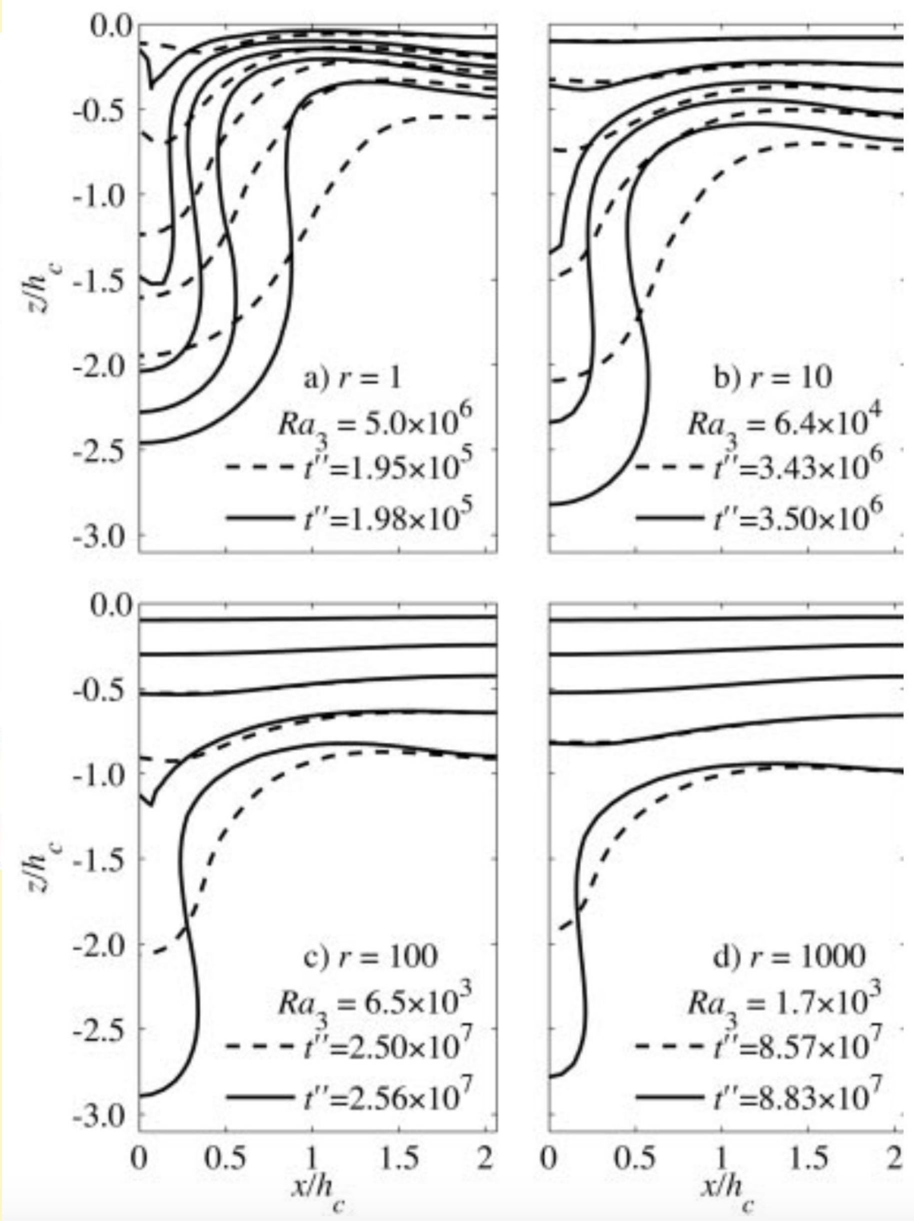
Why is plate thickness limited?



Ra=10^7, dimensionless activation energy E=8.025
heat flux
dimensionless time
x 10^-3
temperature profile
depth
width
< T >

Small-Scale Convection – Lithospheric Drips



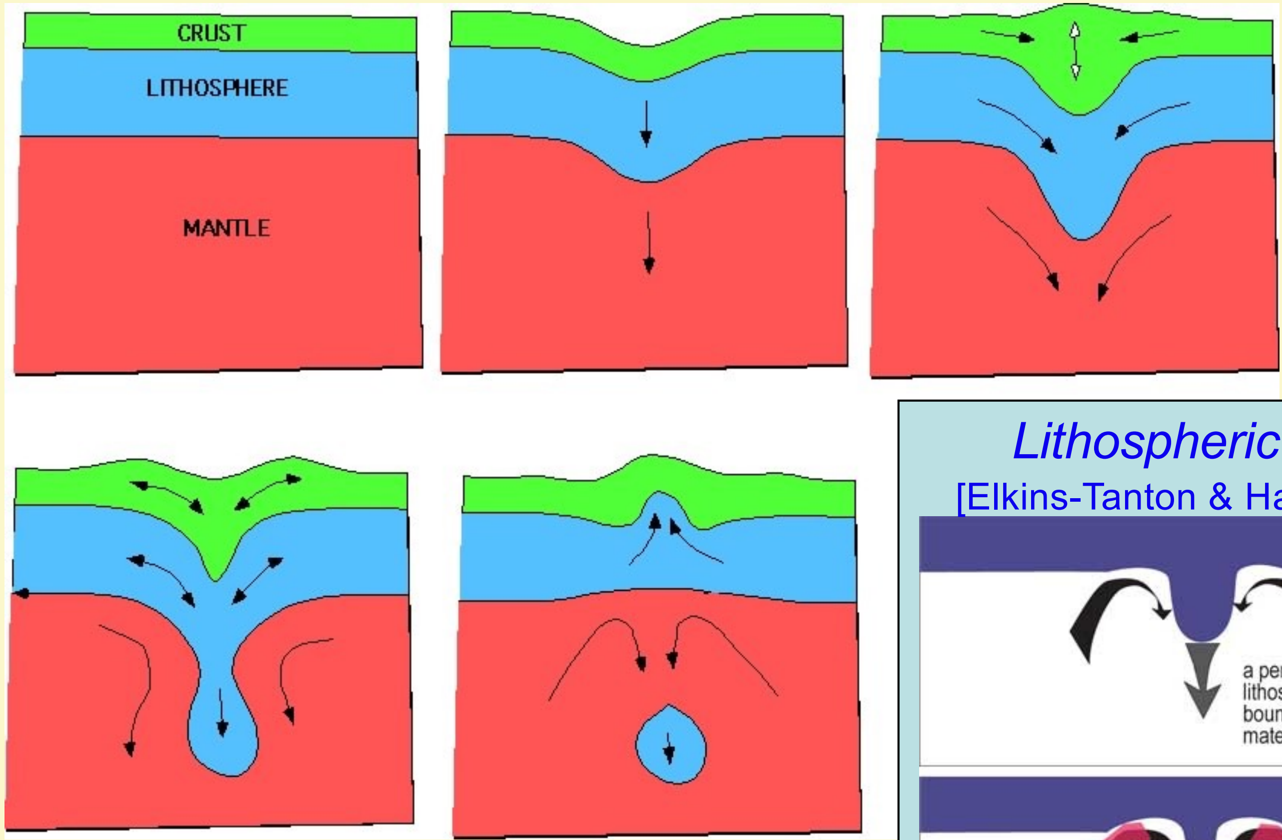


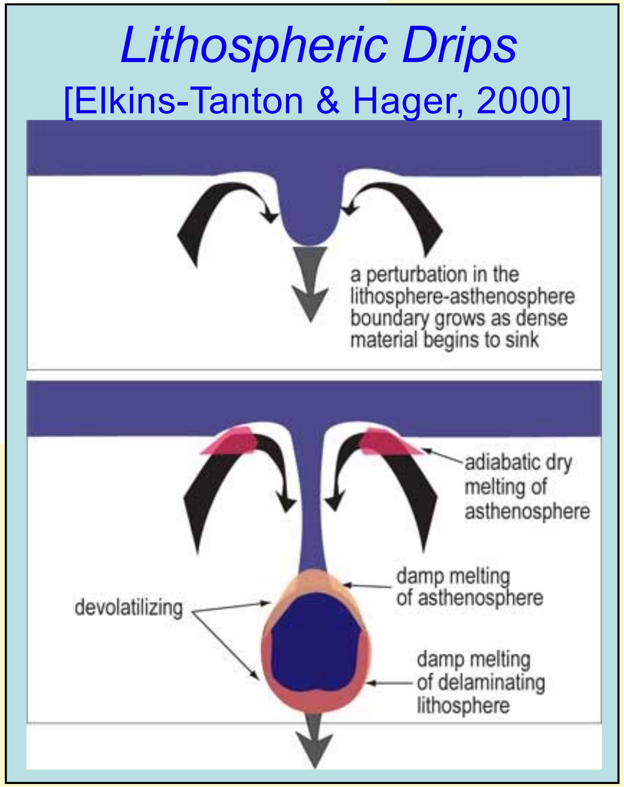
Cold “drips” from the lithospheric base

Return flow produces minor volcanism and uplift

Conrad & Molnar [1999]

Small-Scale Convection – Lithospheric Drips

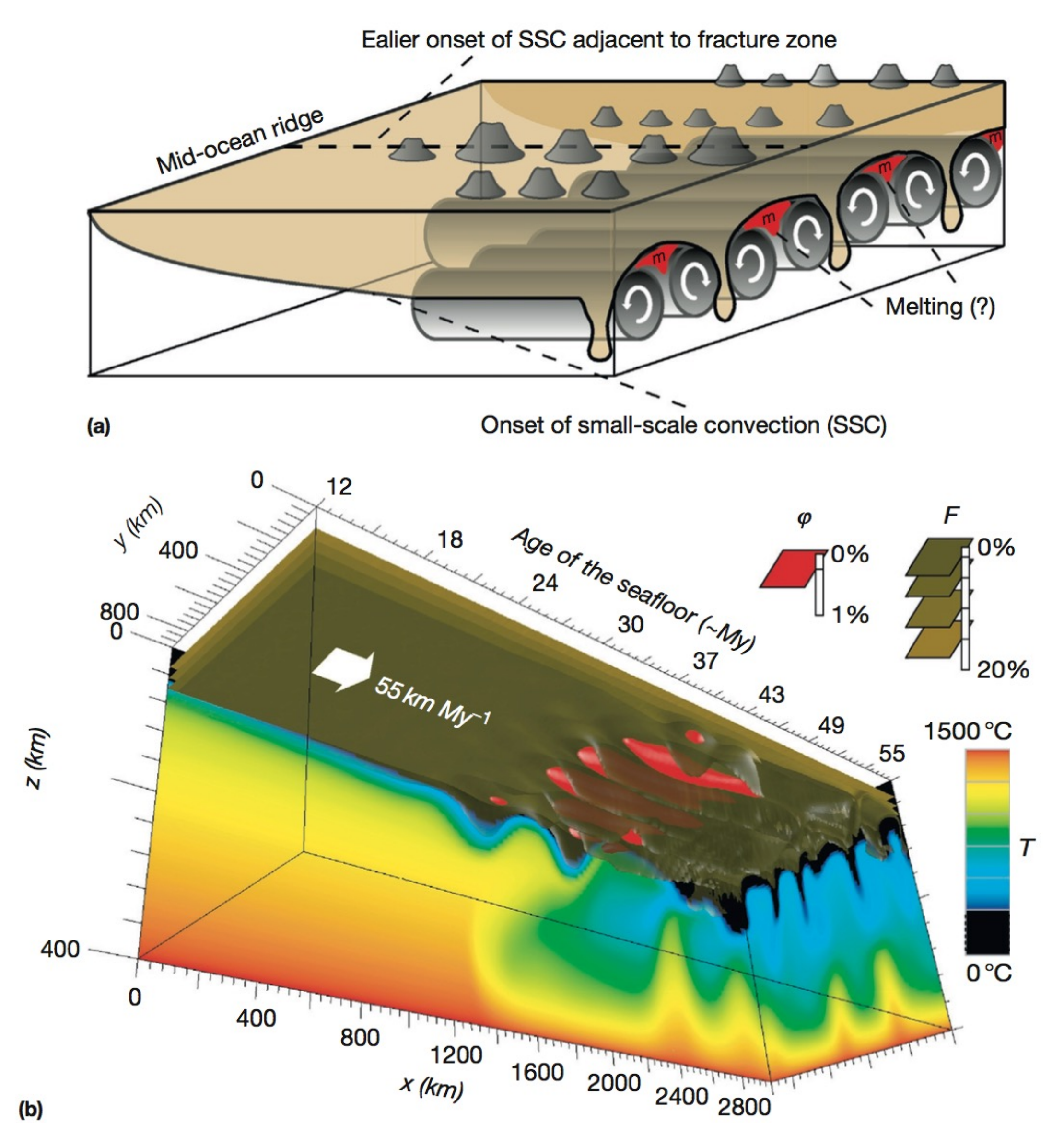




Cold "drips" from the lithospheric base

Return flow produces minor volcanism and uplift

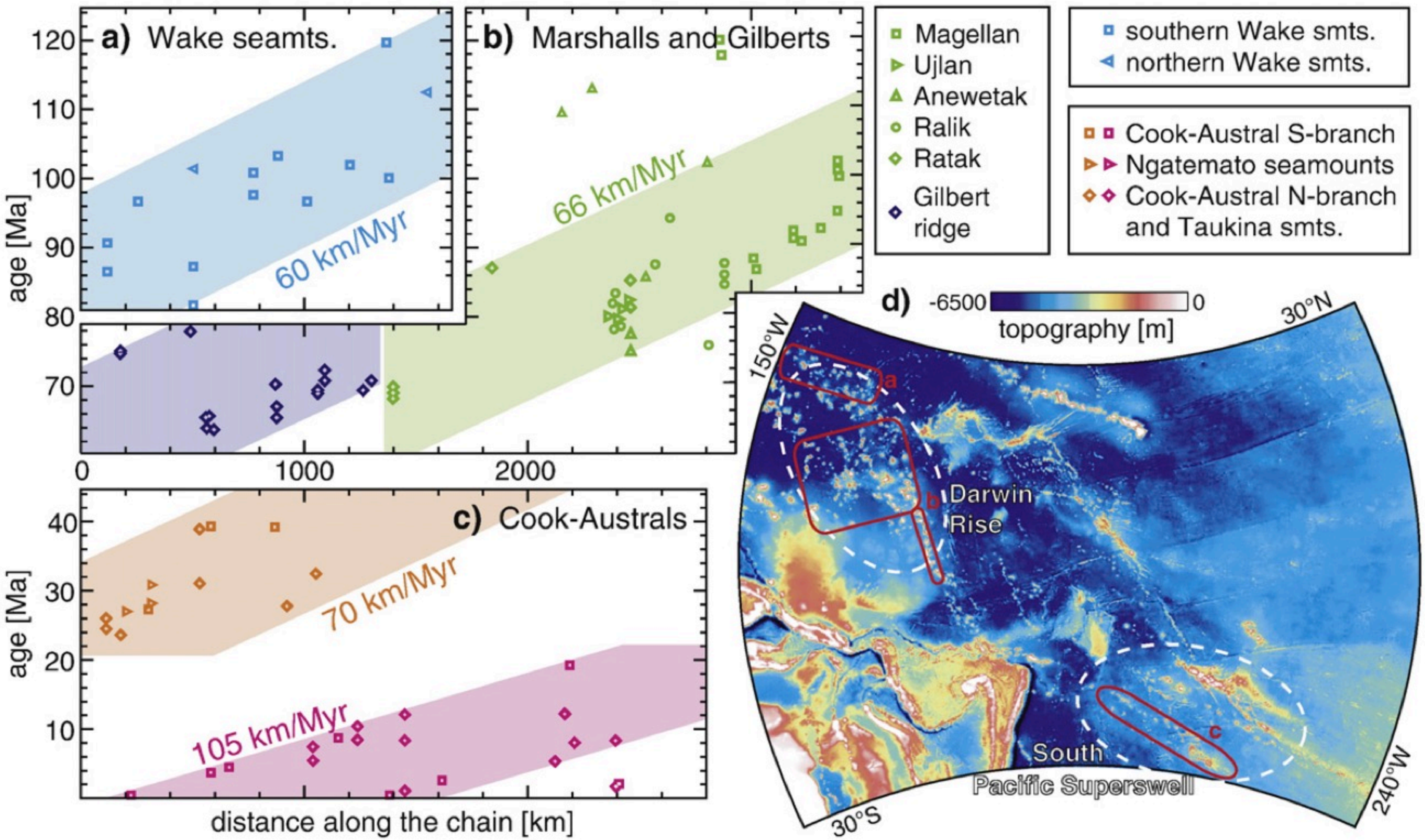
Small-Scale Convection beneath oceanic lithosphere



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

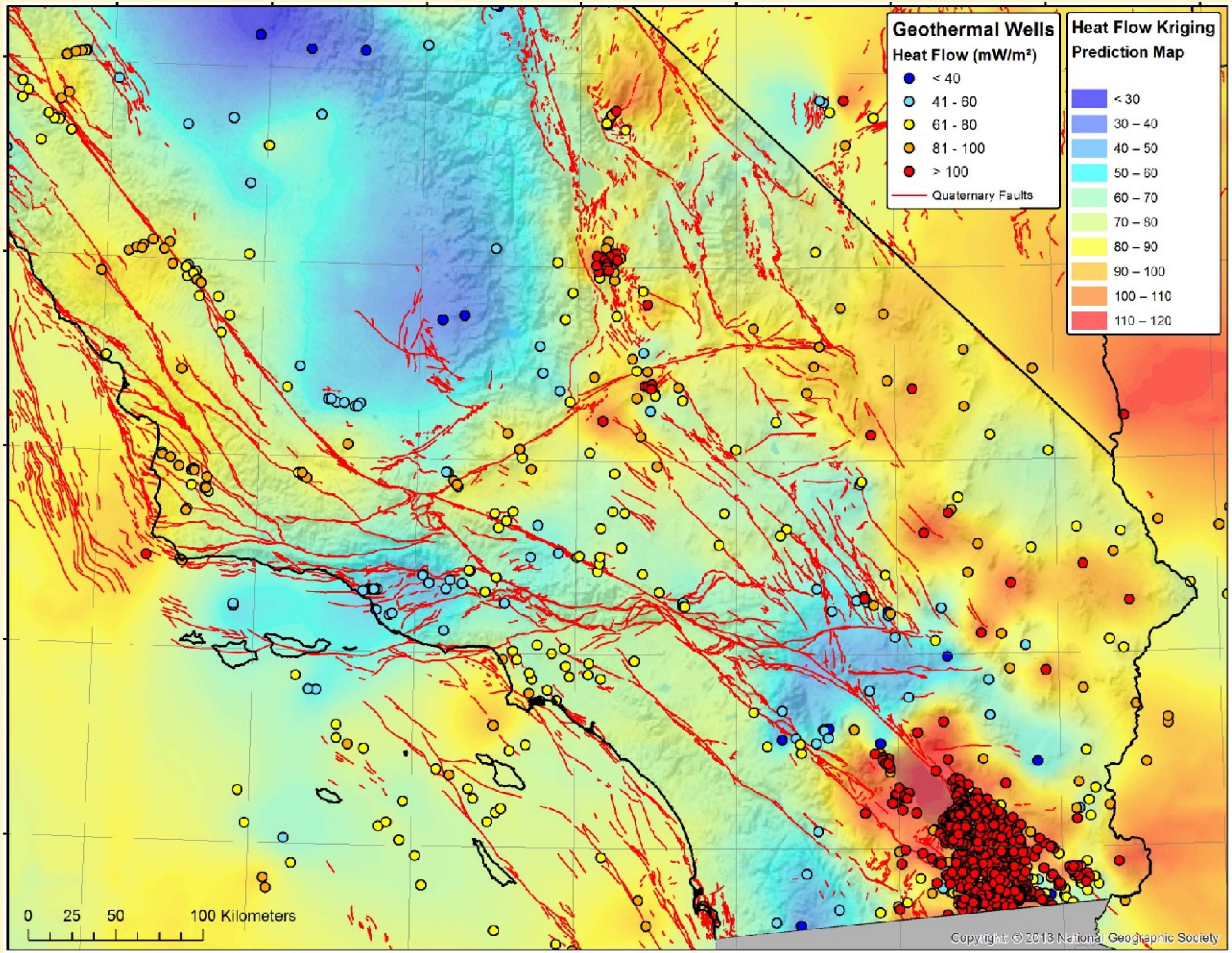
Richter Rolls

SSC may explain some mountains and minor volcanism.



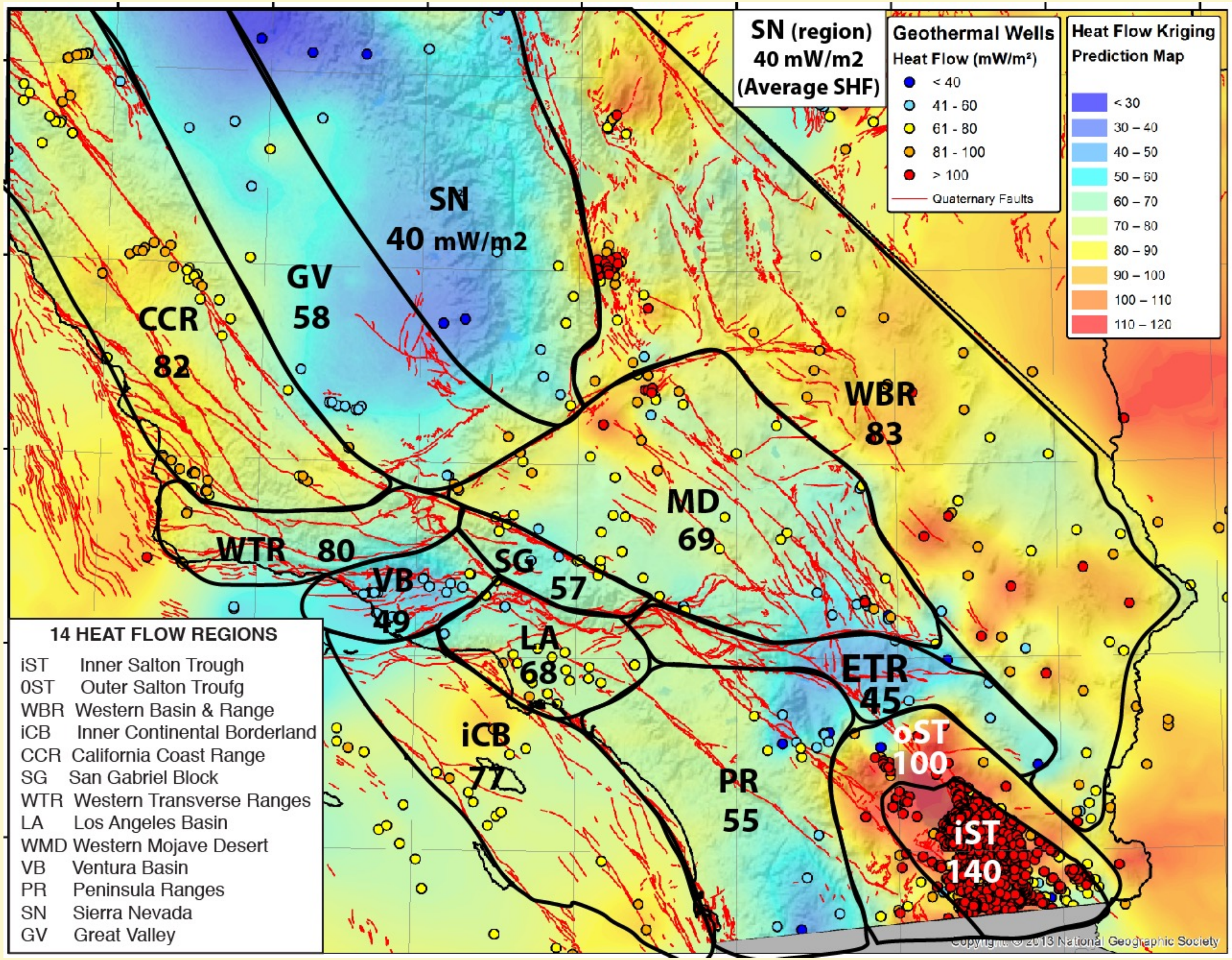
Ballmer et al., 2010

Large variations even within a small area: So. Cal.



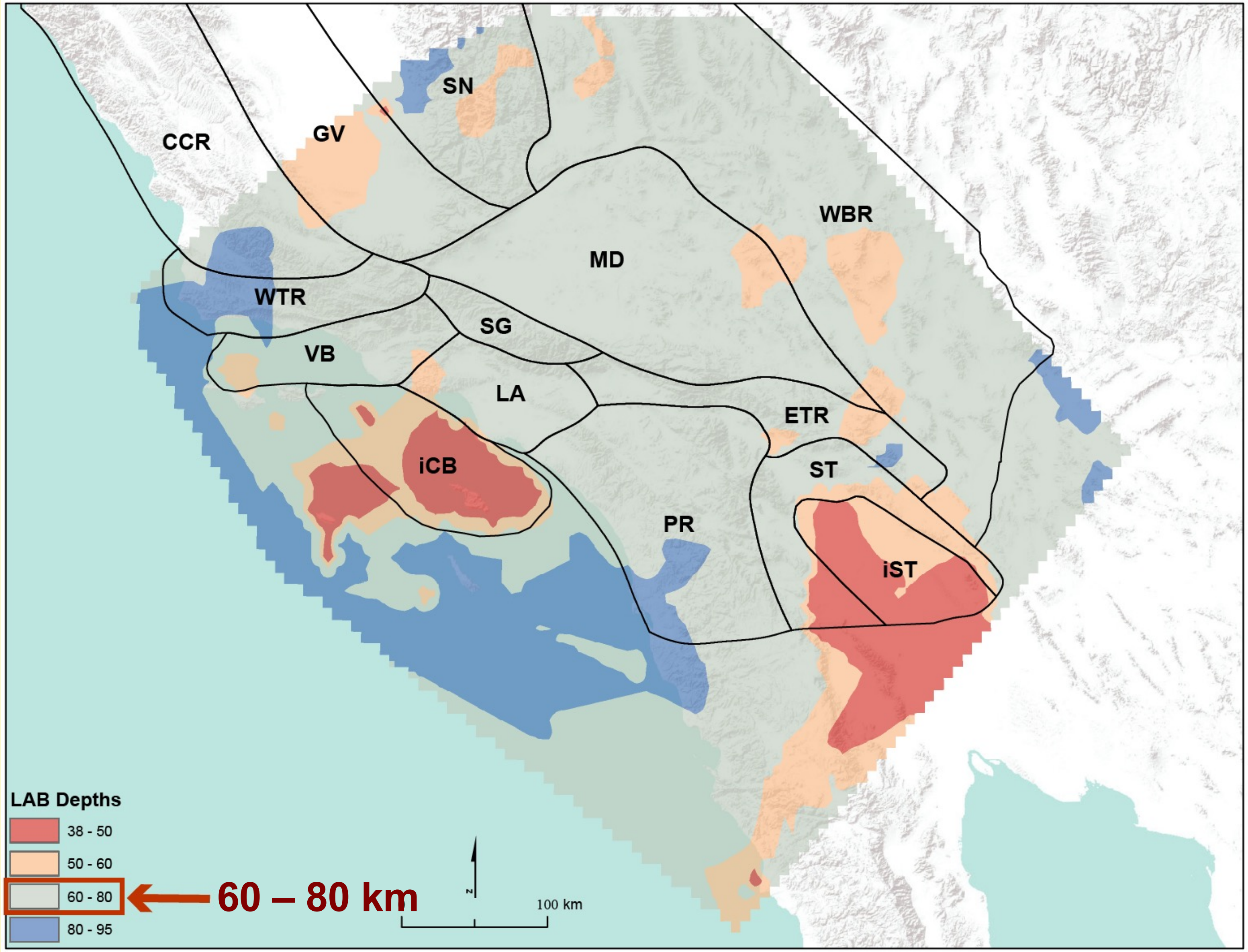
Thatcher et al. [2019]

Large variations even within a small area: So. Cal.



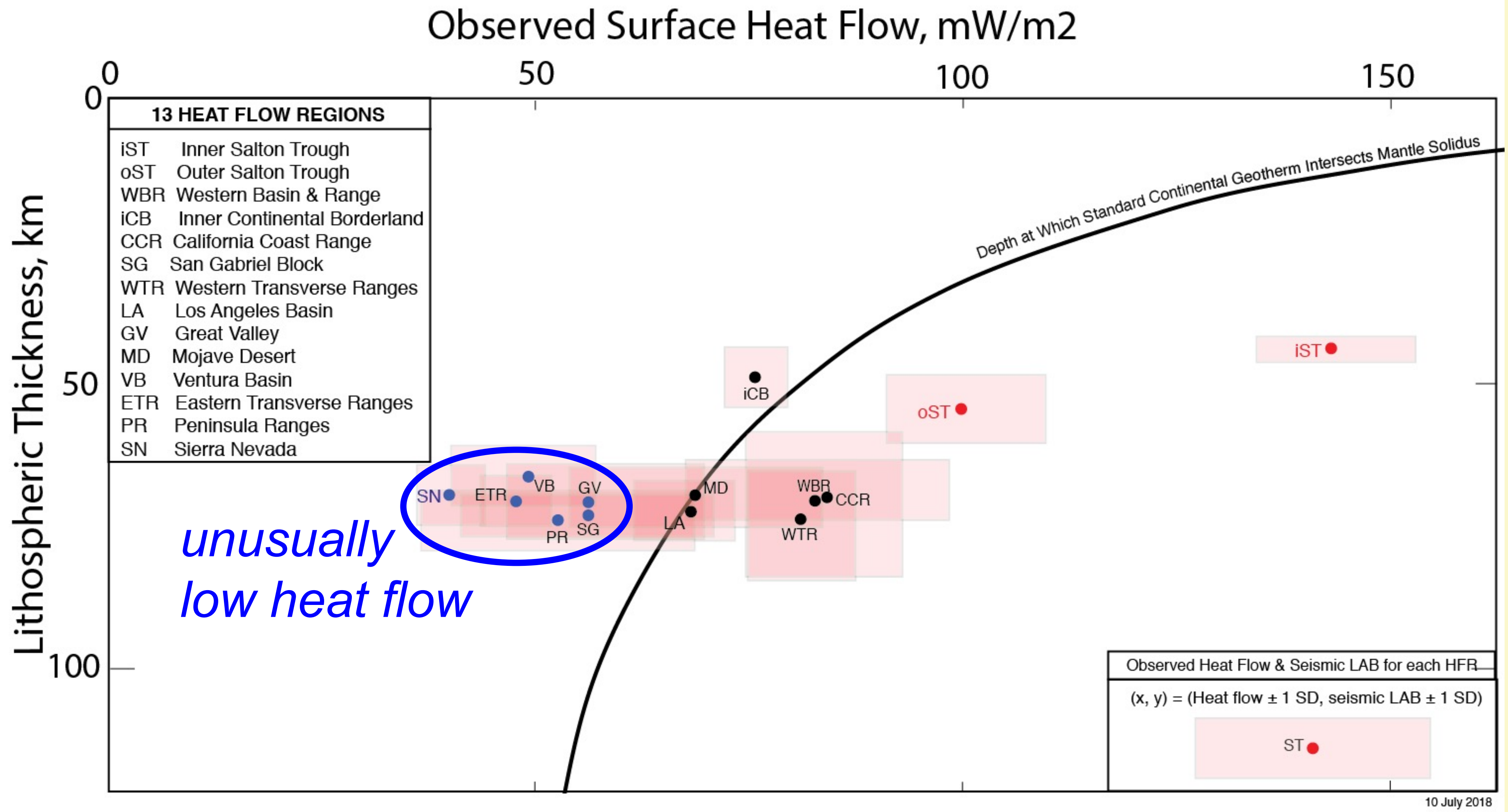
Thatcher et al. [2019]

LAB depths are ~70 km or less across SoCal



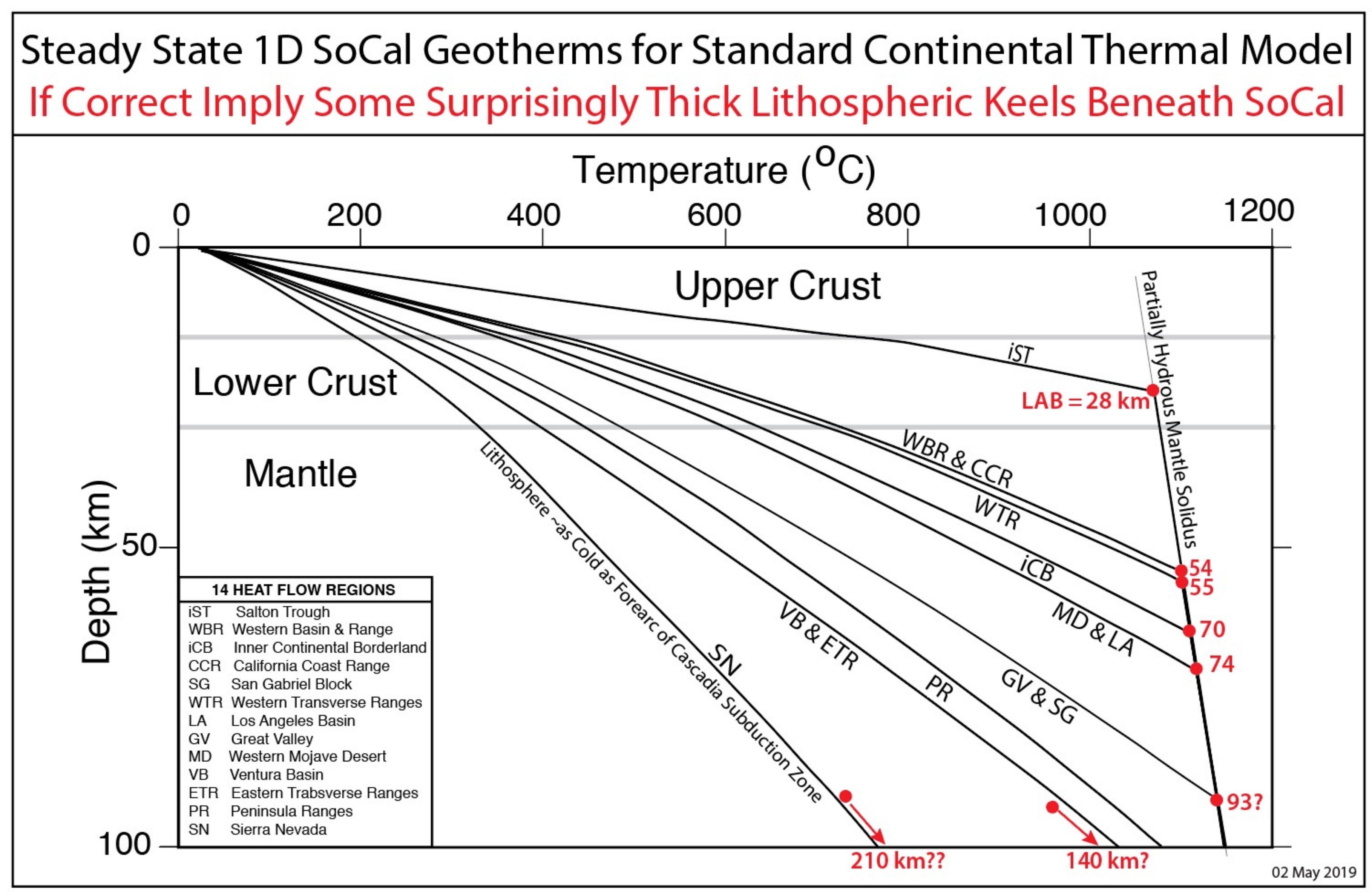
Thatcher et al. [2019]

Large variations in heat flow despite constant LAB depth



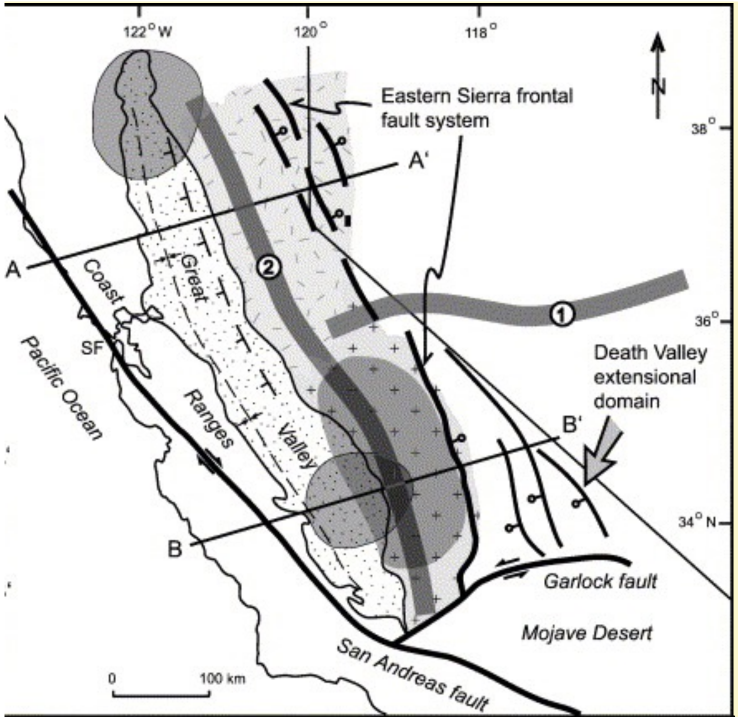
Thatcher et al. [2019]

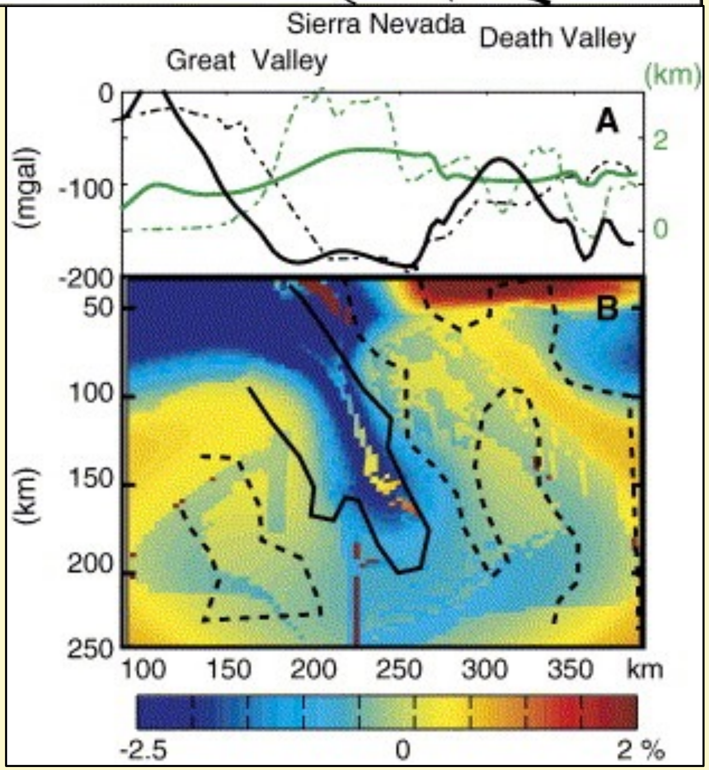
Assume similar crustal thickness and heat production



Thatcher et al. [2019]

LePourhiet et al. [2006]

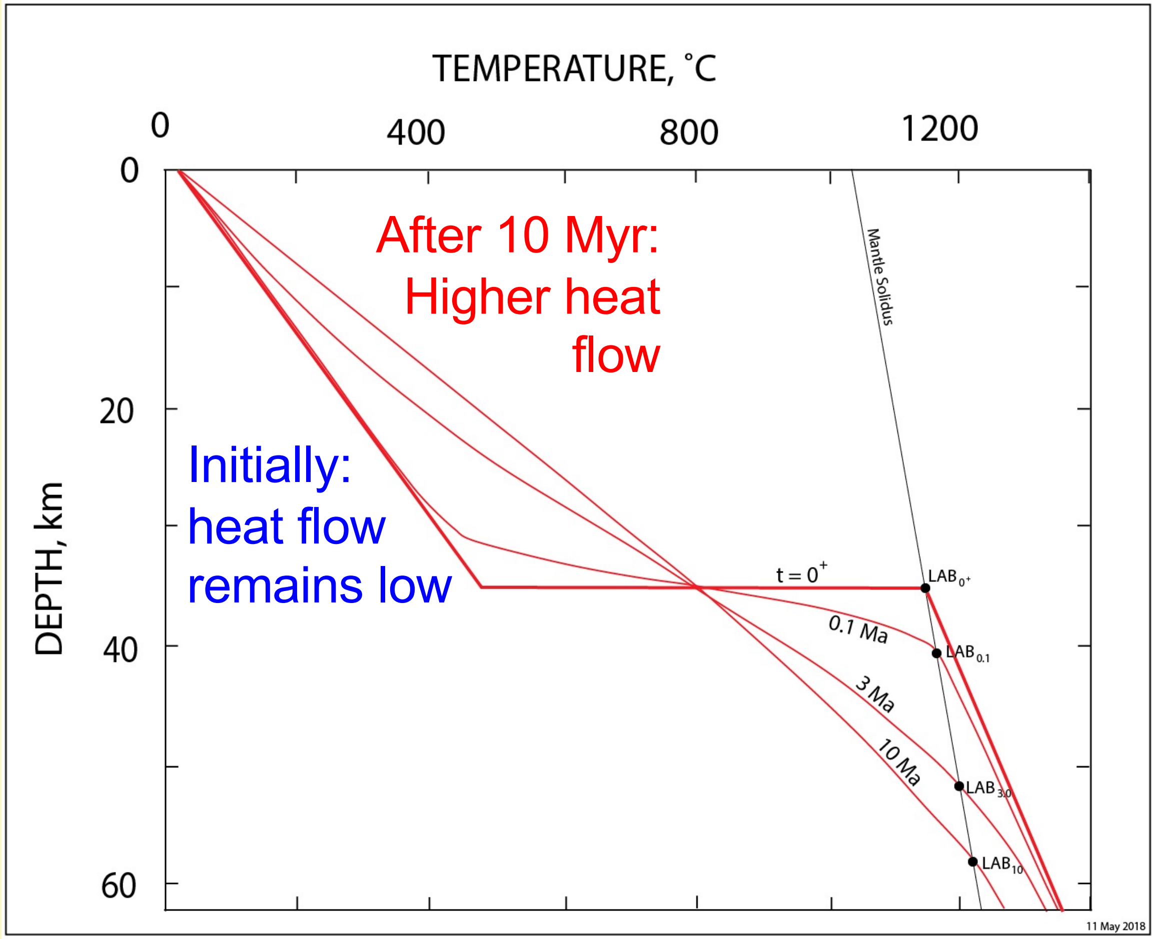




Lithospheric Drips / Delamination

→ Remove lithosphere but the change in heat flow is delayed

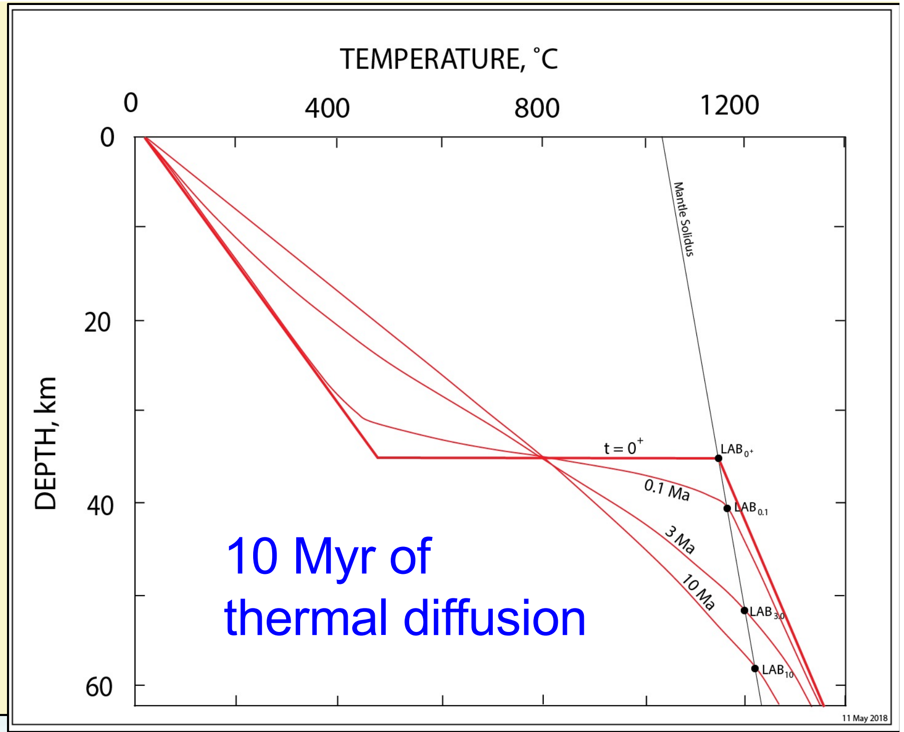
→ Importance of transient solutions!

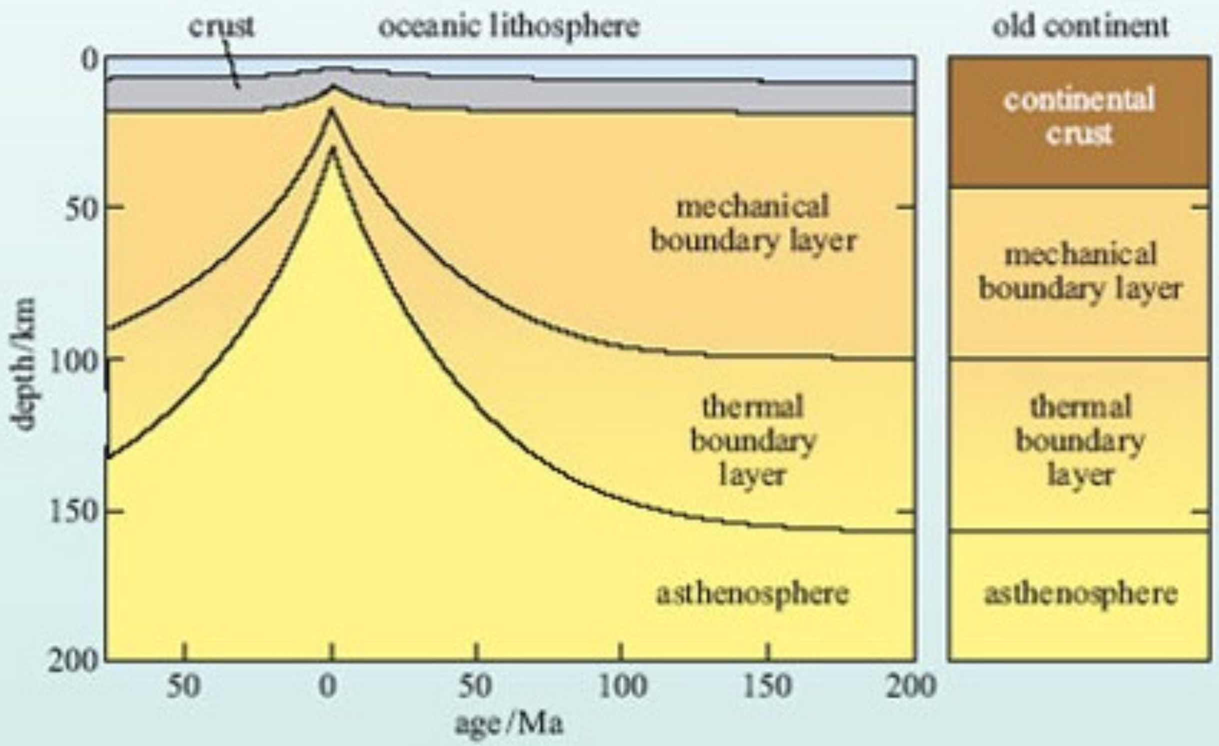


Lachenbruch & Sass 1980

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





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