Thermal structure of the lithosphere

Fabio Cammarano
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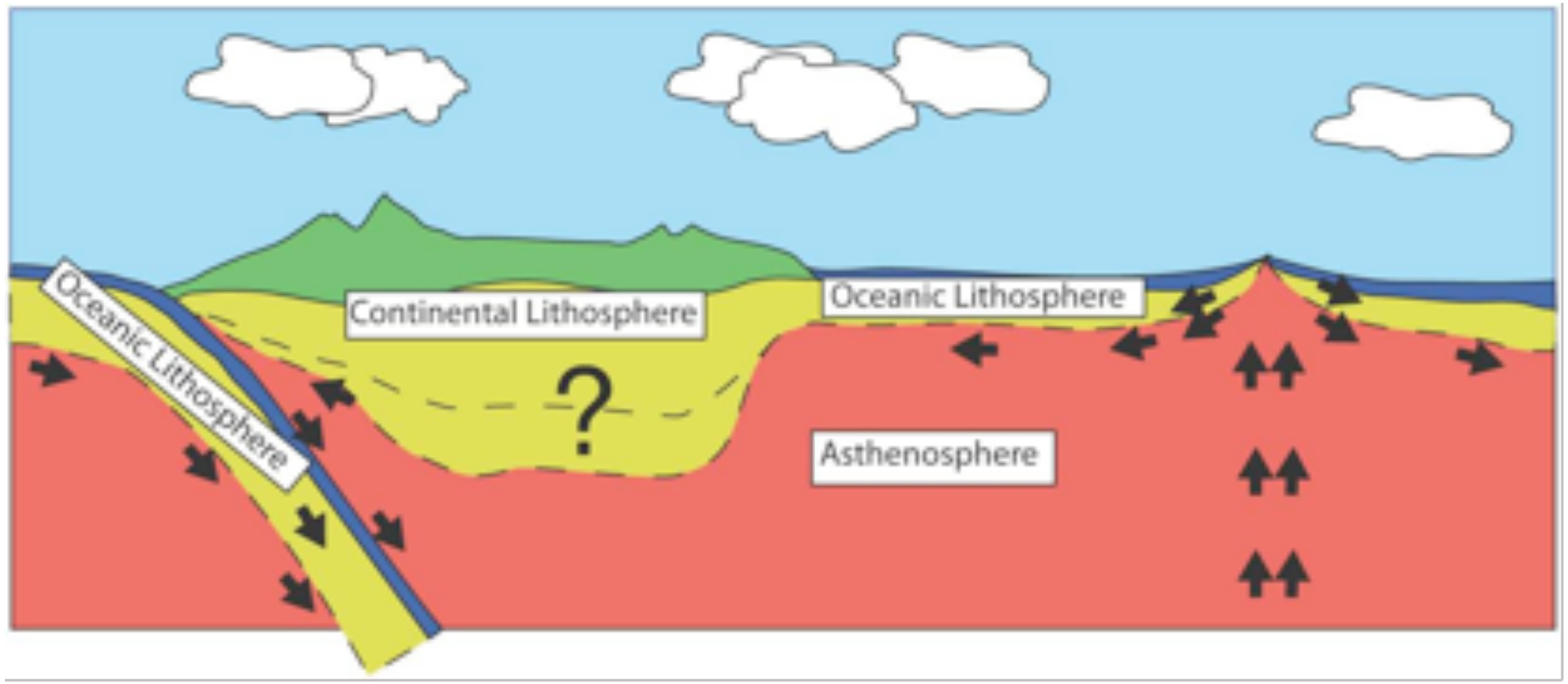
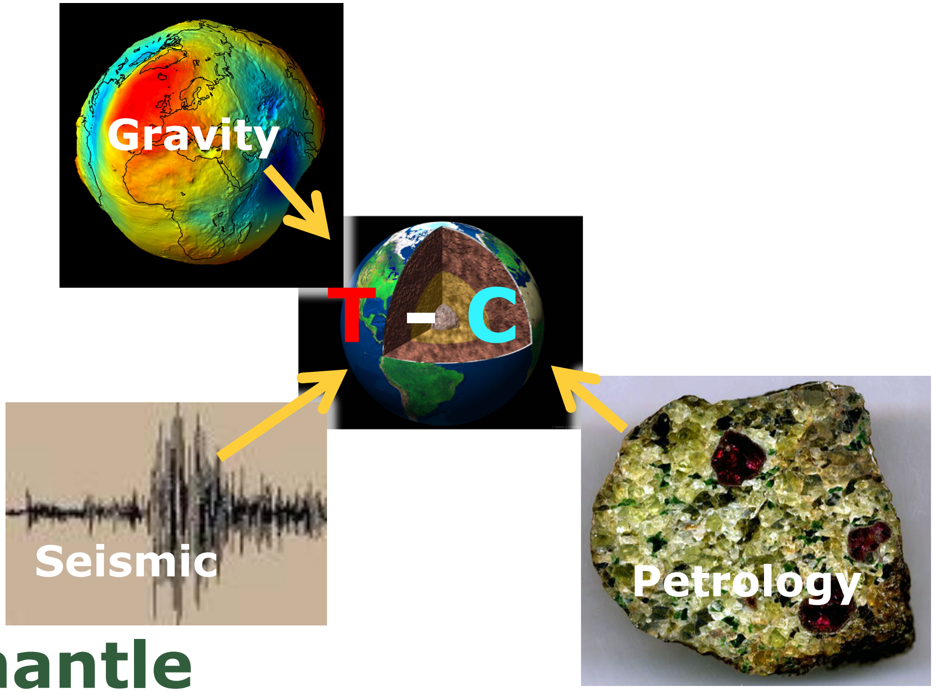


My research

I use an interdisciplinary approach - seismology, mineral physics, geodynamics - to study the interior of the Earth and planetary bodies



- **Physical properties of the Earth's mantle**
- **Inversion of Seismic waveforms and gravity data for temperature and composition**
- **Compositional and thermal structure of the lithosphere**
- **Planetary studies**

Why is important to infer the thermal structure of the lithosphere?

Temperature controls the strength and deformation of the lithosphere

Mapping the thermal structure is essential for understanding tectonic processes and lithospheric evolution

This knowledge is crucial for mineral and hydrocarbon exploration, as well as geothermal energy resources

How to infer the thermal structure?

Seismology provides the best resolved images of Earth's interior structure!

- ✓ Since the 80's, **seismic tomography** is helping to resolve mantle 3-D structure. Yet, even large-scale structures lack a clear physical meaning.

WHY?

- ✓ Trade-off between temperature (T) and composition (C)
- ✓ Uncertainties in mineral physics, i.e. in the relationships between seismic velocities and T-C
- ✓ Interpretation requires absolute seismic velocities
- ✓ Seismic models are different => *it is known that differences arises from **data types** used and **coverage**, their relative **weighting**, **damping** factors, model **parametrization**, **crustal and anisotropic corrections, starting reference model**..., but tracing back the exact sources of differences between models is very hard.*

Lecture outline

1. Basic physical concepts and key thermal parameters

- Heat transfer mechanisms: **convection, conduction**

- Governing law: the **heat equation**!
  - Oceanic lithosphere: **Cooling models**
  - Continental geotherm: **steady-state solution**

- Knowledge of key rock parameters (**thermal conductivity, heat capacity, density, radiogenic heat production**) and expected range

- Direct observational constraints: **Petrological** (P-T geothermobarometry) and **heat-flow** data for the thermal structure of the lithosphere

Lecture outline

2. Seismological constraints and global lithospheric thermal models

- How to interpret seismic velocities? ➔ **elastic** and **anelastic properties** of rocks

- **Seismological constraints** => analysis of existing models to extract robust features

- **Global thermal models of lithosphere**

- How to improve them? ➔ **better seismic structure**: ambient noise dispersion curves of surface waves, receiver functions, body-waves from regional and teleseismic events, improving models of seismic attenuation. **Integrating with non-seismic data**: gravity and magneto-telluric studies, **improve knowledge of elastic and anelastic rock properties:** better shear properties of minerals, role of fluids

"Heat is the junk of energy."
— My high school physics teacher

Three laws of thermodynamics:

1. Energy can change from one form to another but cannot be created or destroyed (law of conservation of energy).
For instance, energy is absorbed during heating and melting, while it is released during cooling and solidification.

2. Work can be fully converted into heat
(but not the other way around– making a perpetual engine impossible).

3. Absolute zero (T= -273 ^{o}C) is unattaible*.*
As a system mears absolute zero, all processes progressively slow down (and eventually cease).

Heat is abundant on Earth!

"Heat is the junk of energy."
— My high school physics teacher

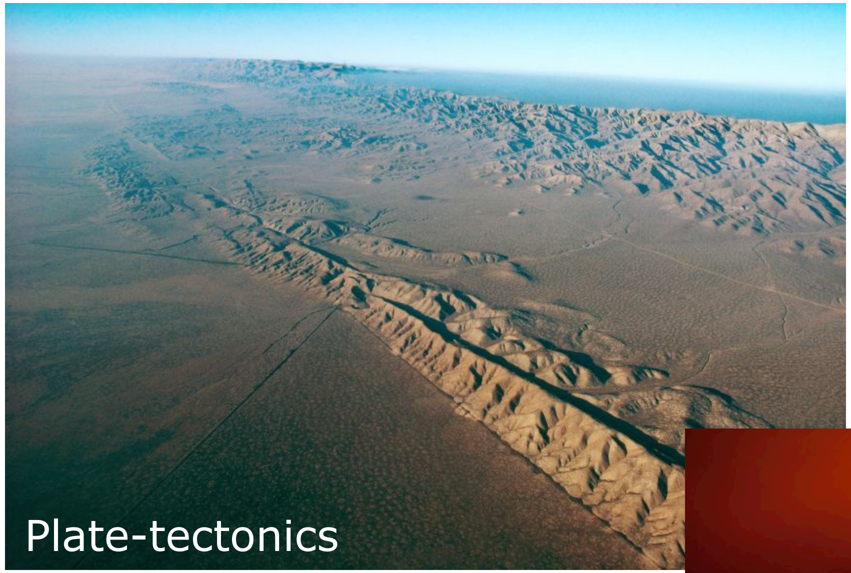
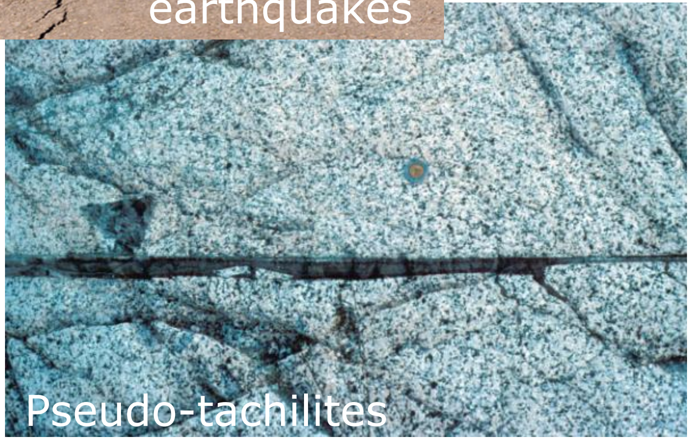


Plate-tectonics


earthquakes


volcanoes


Pseudo-tachilites

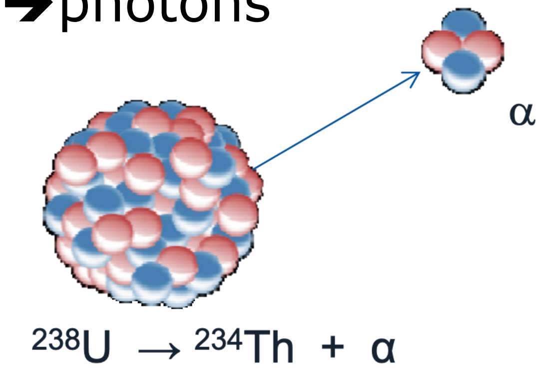
Where the heat comes from?

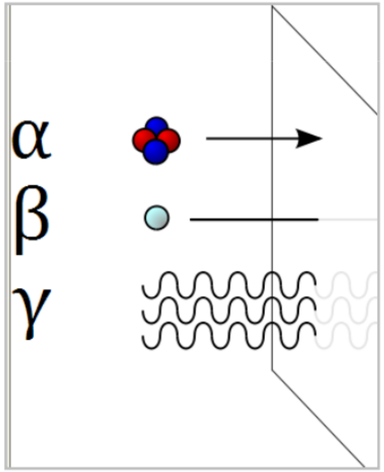
Primordial heat

- ***Earth's accretion*** *(impact and gravitational energy) ➔ liquid (mostly iron) core gives a constraint on CMB temperature*

Radiogenic heat

α decay ➔ ^{4}He nucleus
β decay ➔ electrons or positrons
γ decay ➔ photons





- *Provide additional internal heating in the mantle* (primarily **Uranium (U-238), Thorium (Th-232),** and **Potassium (K-40)).**
- *It is* ***relevant for the Earth's continental crust****, where radioactive elements concentrate*

Radiogenic heat

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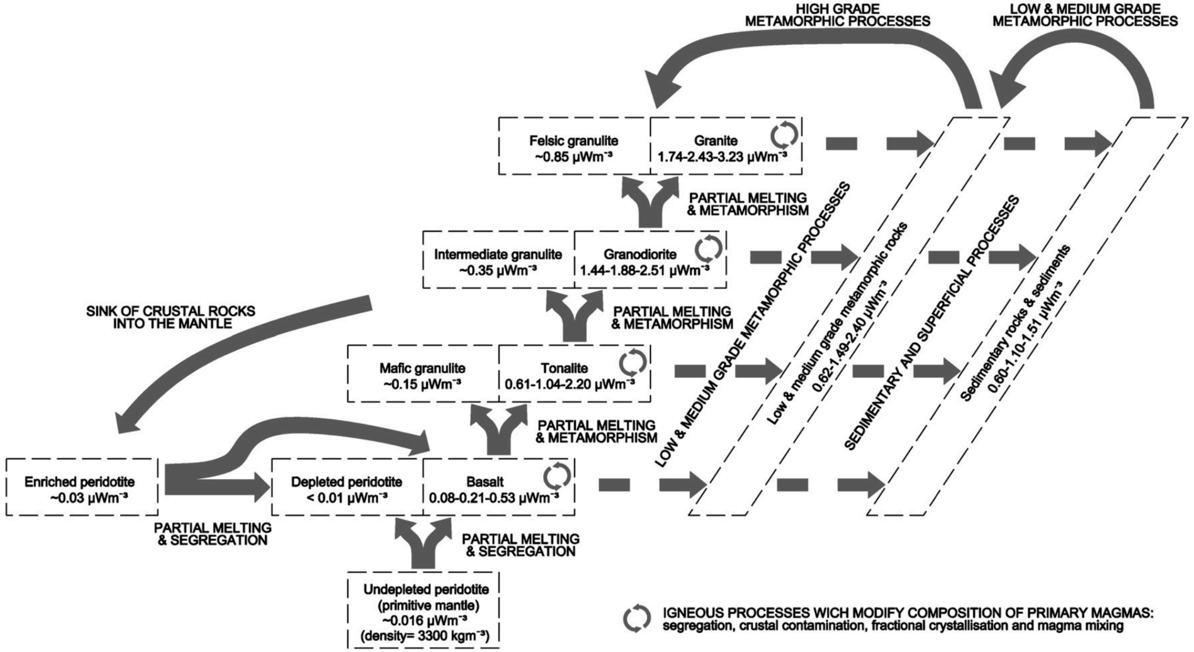
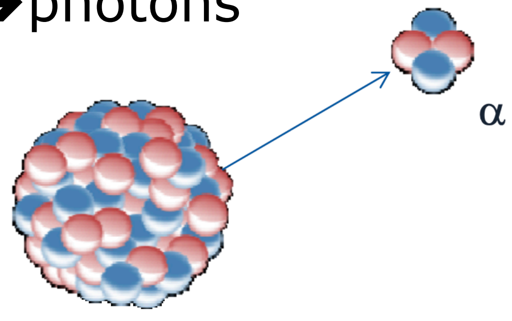
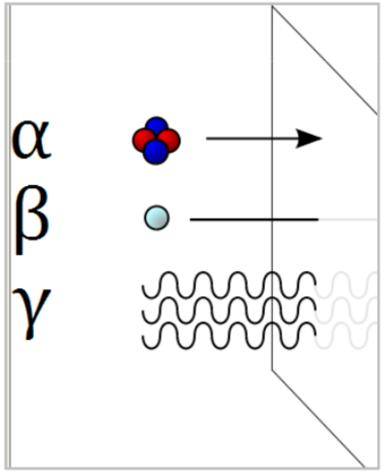


Vila et al. 2010



^{238}U $\rightarrow$ ^{234}Th + α



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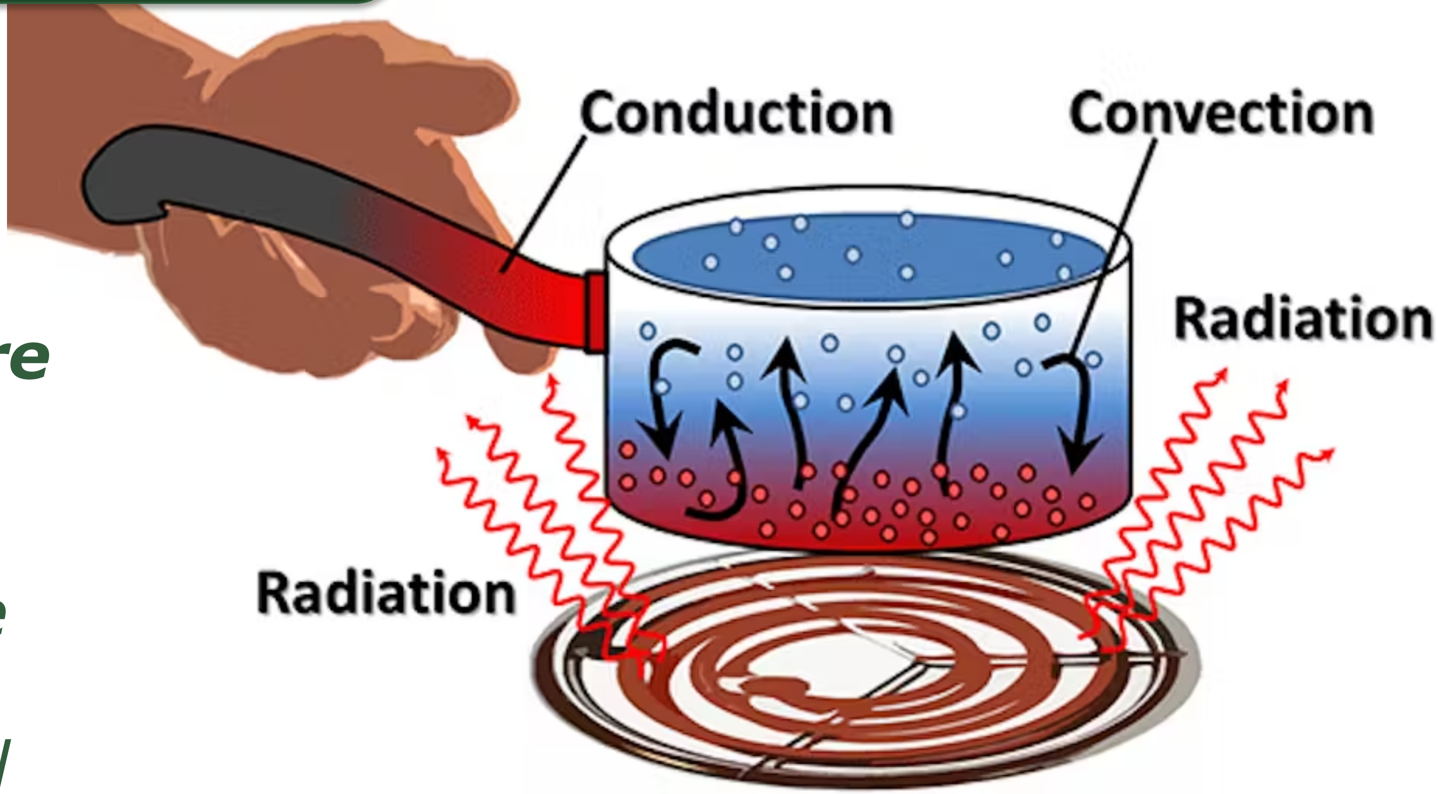
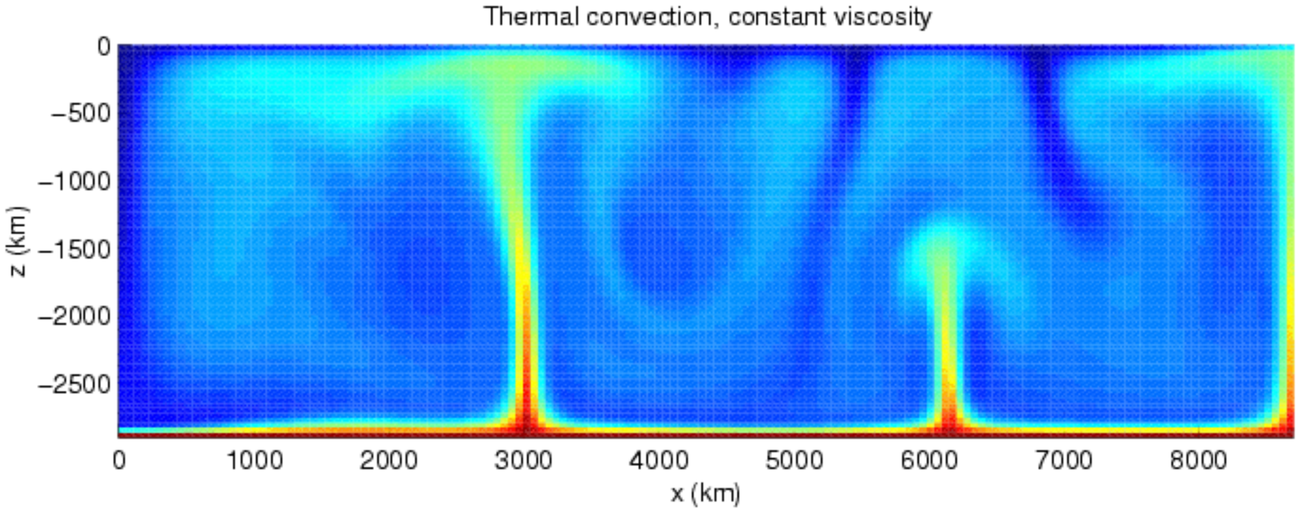
Inside the Earth, heat can be transferred through conduction and convection. Radiation is less efficient

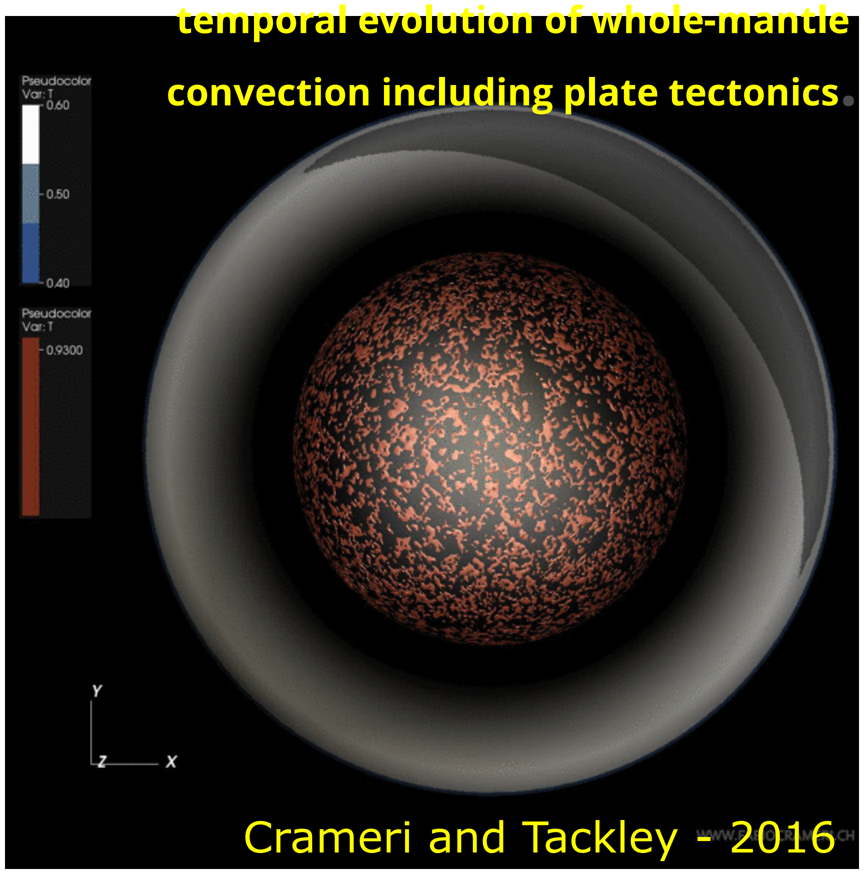
- ***Conduction:*** *heat diffuse through material: slow, no motion of material ➔* ***dominates in the lithosphere***

- ***Convection:*** *heat is transferred through convective currents of hot material (less dense) rising and cold material (denser) sinking => fast, adiabatic process*



In spite of not well-known viscosity, ***convection*** *should the most efficient way of transfer heat in the mantle*



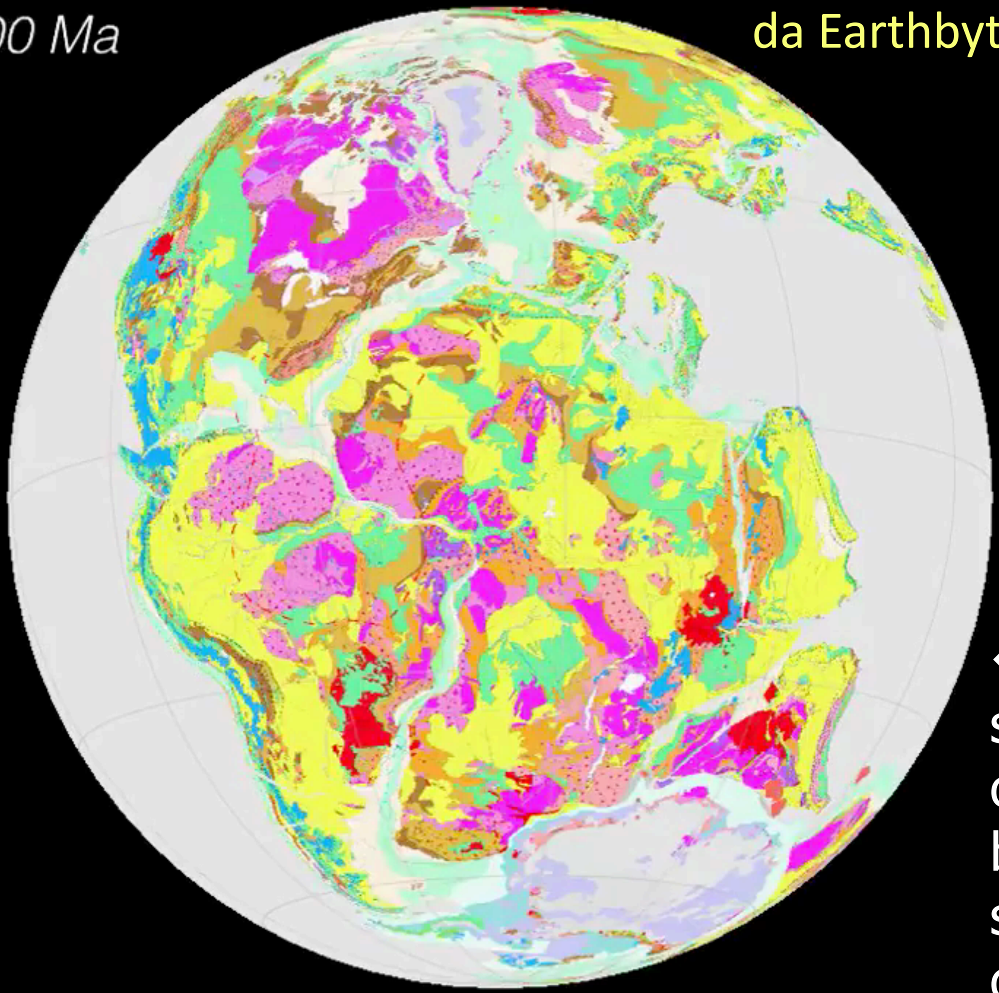


$$Ra = \frac{\rho \alpha g \Delta T D^3}{\kappa \eta};$$

Rayleigh number: Dimensionless number characterizing the balance between buoyancy-driven flow and resistive (frictional) forces.

Plate-tectonics *– a revolution in Earth Sciences*

- The motion of the plate creates new oceans and closes old ocens – Wilson cycle– giving rise to supercontinents



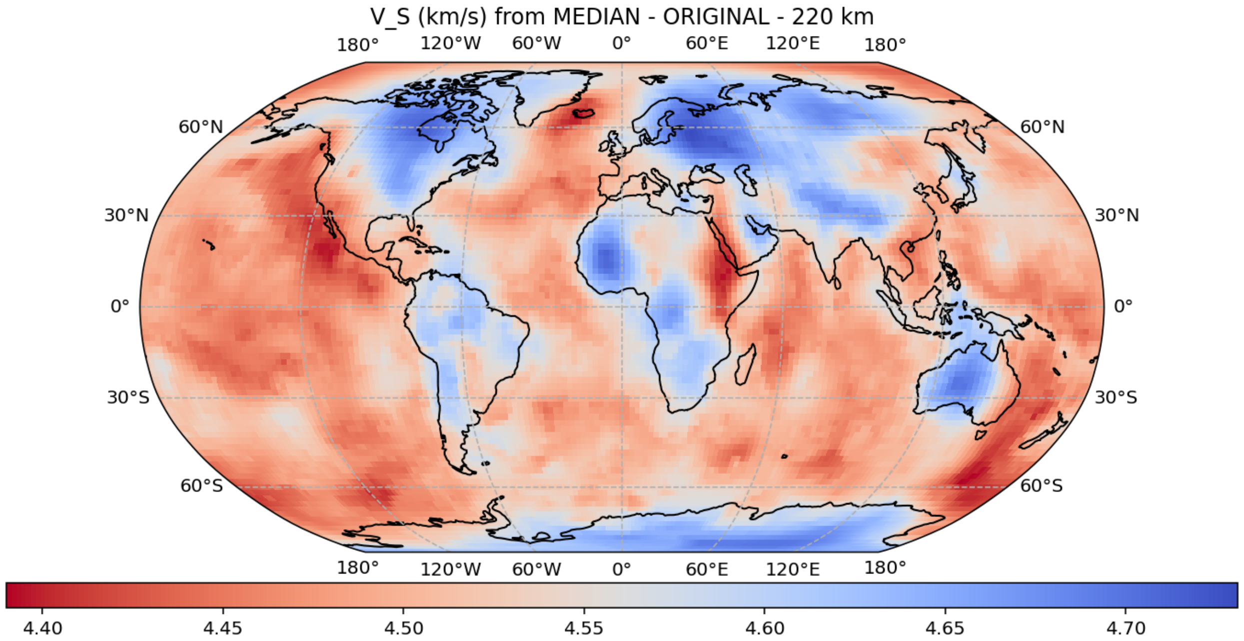
continents
(> 3 billion years)

oceans
(<200 million y.)

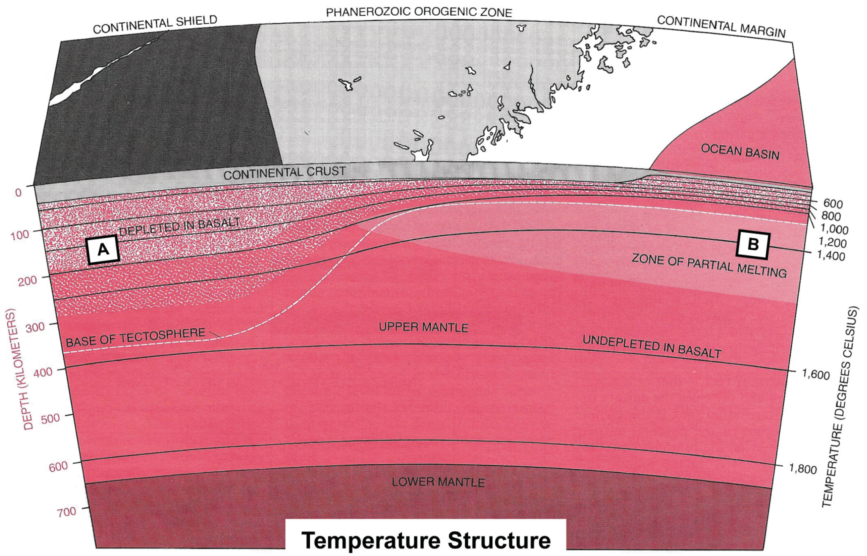
- ❖ Earth is a very dynamic system, yet the stable part of continents formed > 3 billion of years ago and, since then, survive destruction!

Jordan's tectosphere (from 1978)

High seismic velocity of lithospheric mantle beneath continents, absence of global gravity anomalies associated with these structure and petrological arguments indicate that continental lithosphere is thick, cold and chemically depleted➔ ***Tectosphere*** *compared to the surrounding mantle*



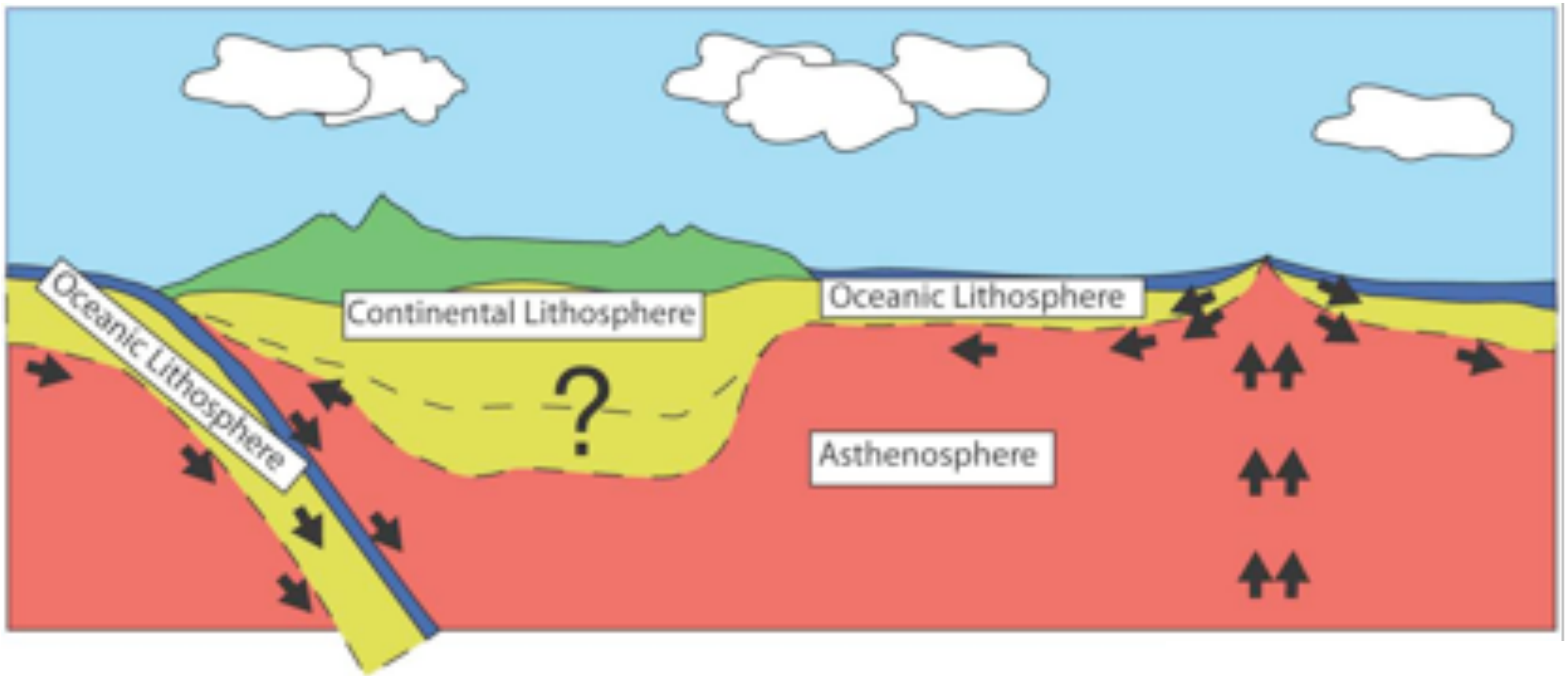
plotted with a python script we will see this afternoon



Higher densities due to lower temperatures are almost exactly balanced by lower densities due to lower ratios of Fe/Mg and Al/Mg (basalt depletion hypothesis) => isopycnic hypothesis

***Oceanic lithosphere**: young, thin, negligible radiogenic heat production*

***Continental lithosphere**: old, thick, relevant radiogenic heat production in the sialic (upper) crust*



Two worlds, one equation: **the heat equation**

$$\frac{\partial T}{\partial t} = k_d \nabla^2 T$$

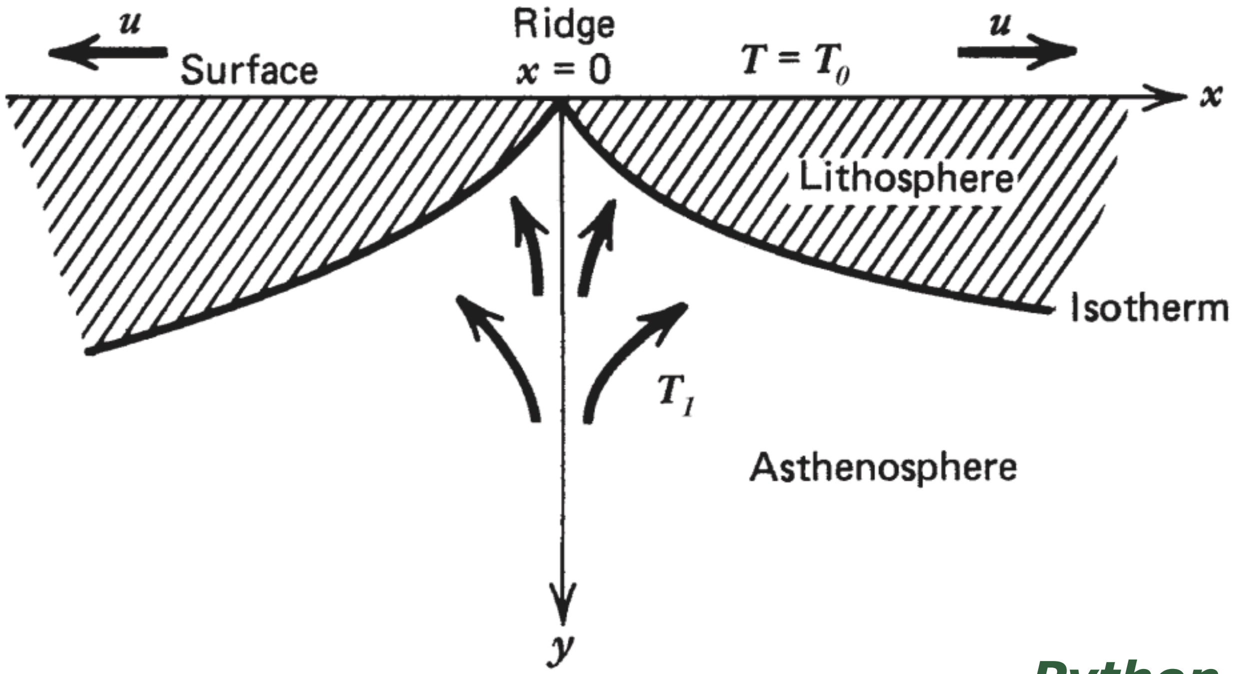
I distributed some note written together with ChatGPT

When oceanic lithosphere forms at mid-ocean ridges, it is initially hot and starts **cooling** as it moves away from the ridge axis.

=> become denser and subside,
heat flow at surface diminishes

Half space cooling model

Plate cooling model



Python scripts of cooling models this afternoon

- *The governing equation for the conductive lithosphere is the* ***heat equation***

$$\frac{\partial T}{\partial t} = k_d \nabla^2 T$$

describes how heat diffuse through a medium over time

$$k_d = \frac{k_t}{c_P\ \rho}$$

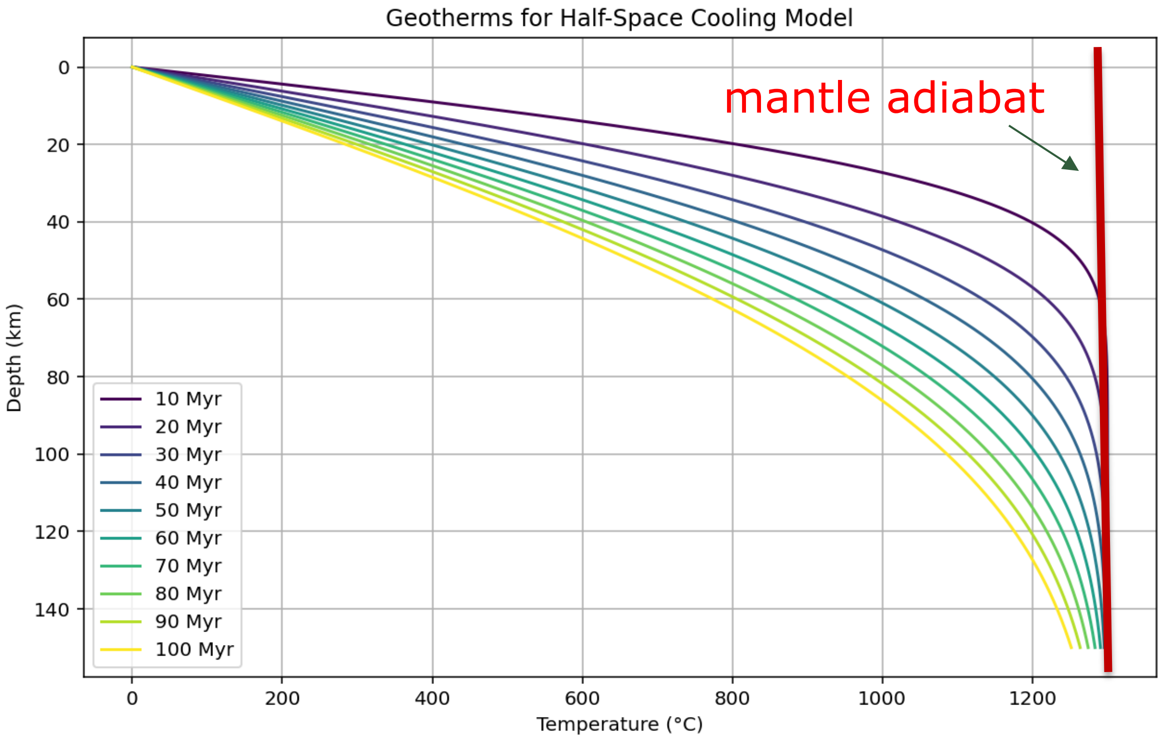
materials with high thermal diffusivity transfer heat quickly because they conduct heat well (high thermal conductivity) and store less heat per unit volume (low volumetric heat capacity).

- *Practically is sufficient to solve the* ***1_D equation*** *(no horizontal exchange of heat) and not consider radiogenic heat for* ***oceanic lithosphere***

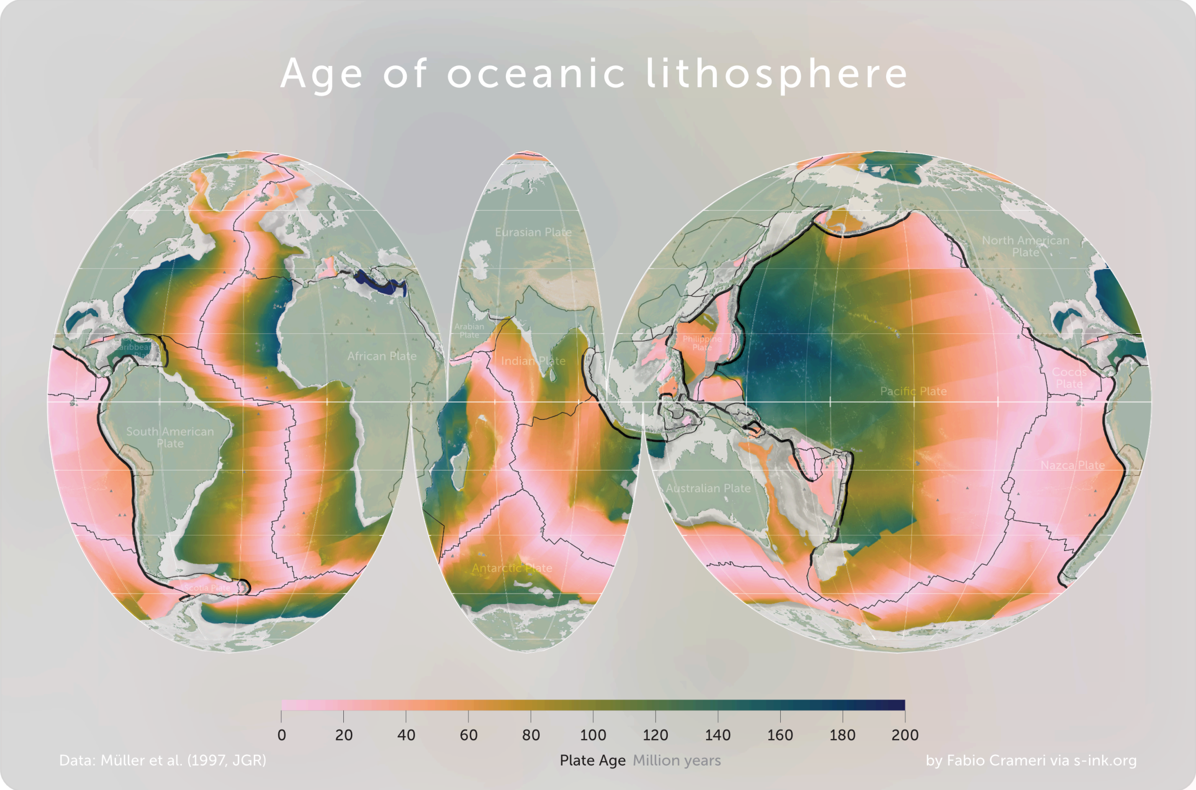
$$\rho(z,T) C_P(z,T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k(T) \frac{\partial T}{\partial z}$$

Fabio Crameri - 2023

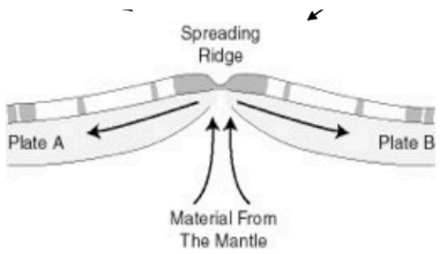
Cooling models gives relatively ***simple thermal structure*** *=> predict* ***bathymetry*** *and* ***heat flow***



Computed with a python script we will see this afternoon



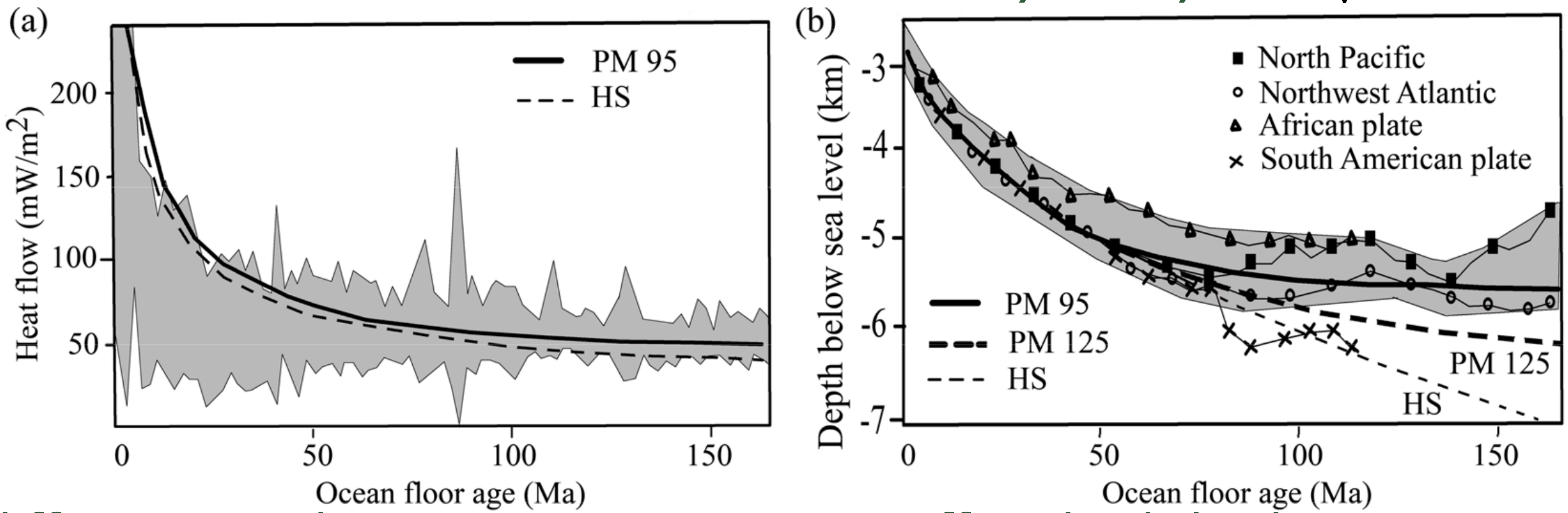
Based on magnetic isochrons (magnetic field reversals)



Which model use? Bathymetry and heat flow seem to flatten > 80 m.y. ➔ Plate model wins

Heat flow $\sim\sqrt{age}$

bathymetry $\sim 1/\sqrt{age}$



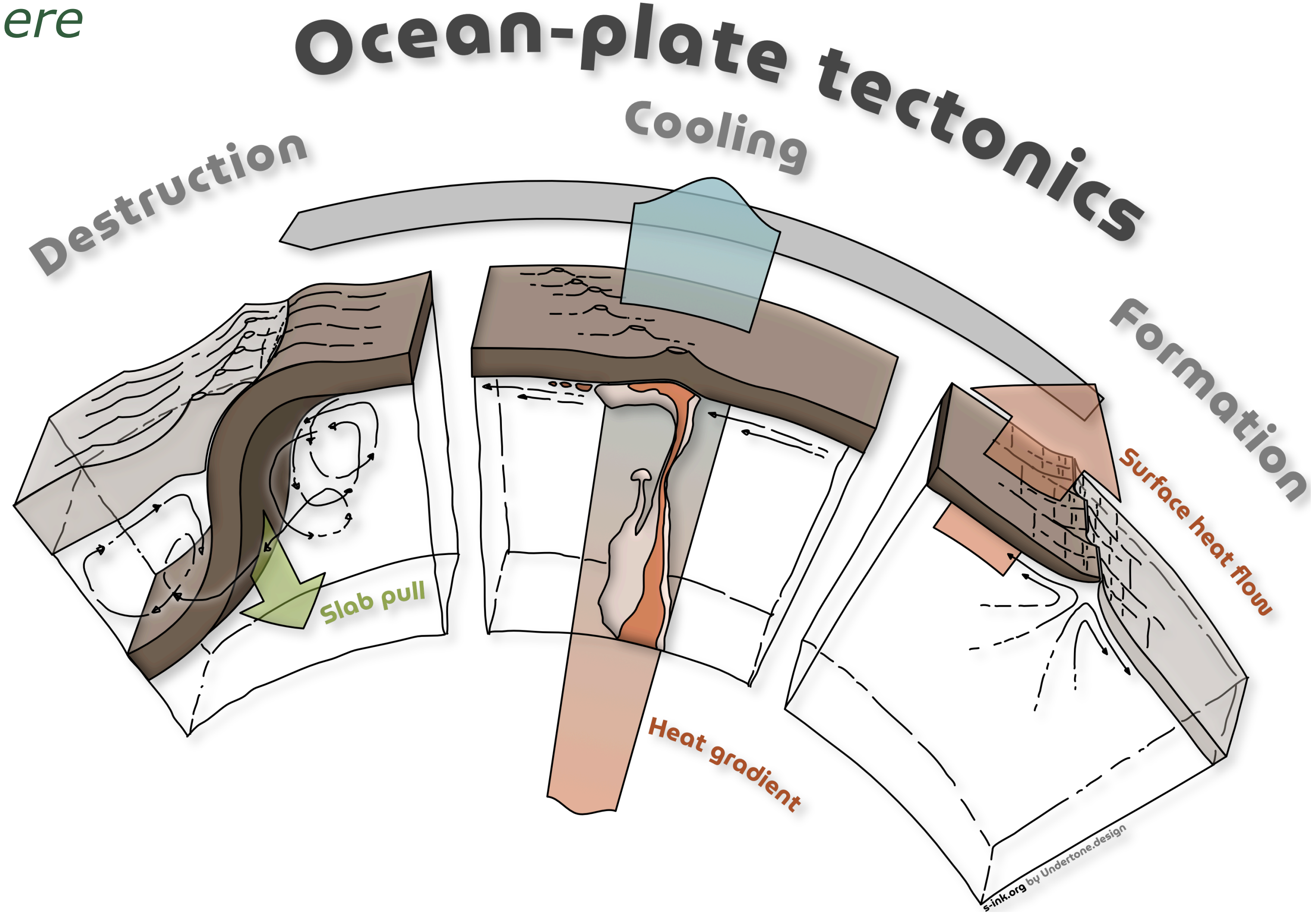
- *But different geodynamic processes may affect both bathymetry and heat-flow ➔ larg**e errors on average properties***
- *Also, heat-flow close to mid-oceanic ridge is affected by hdrothermal circulation (**advection**)*

➢ *Summary of oceanic lithosphere*

1. Thermal structure relatively simple ➔ **we can predict thermal thickness of lithosphere**

2. Other geodynamics processes and data uncertainties may bias our view

3. We shall see **seismic constraints** soon



Fabio Crameri - 2019

For old continents, a **steady-state solution of the heat equation**, adding a model of the radiogenic heat distribution within the crust can be used ➔ **continental geotherms**

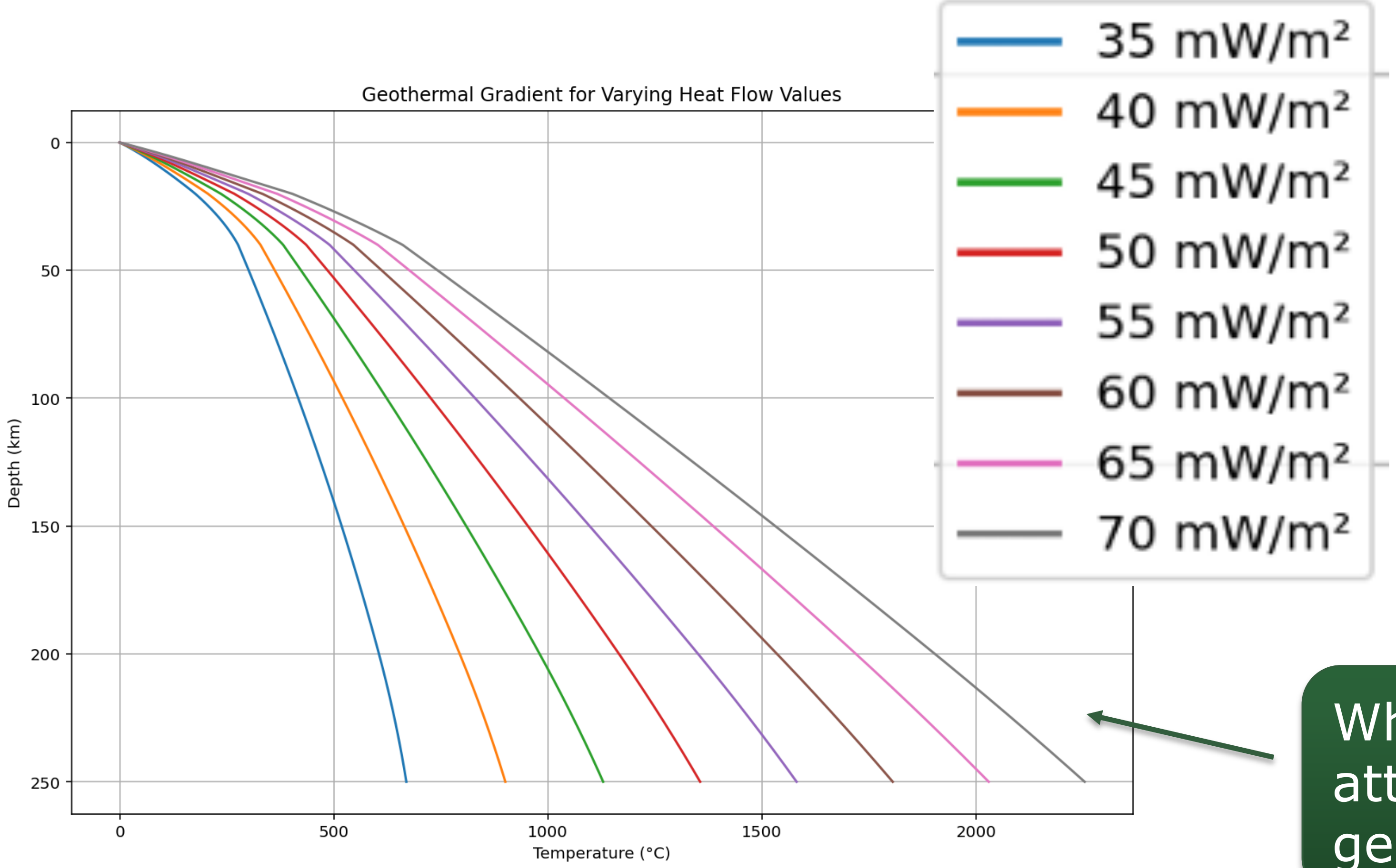
$$T_B = T_T + \frac{q_t}{k_t}\Delta z - \frac{A\Delta z^2}{2\,k_t}$$

Solve iteratively, starting from the top

Limitations:

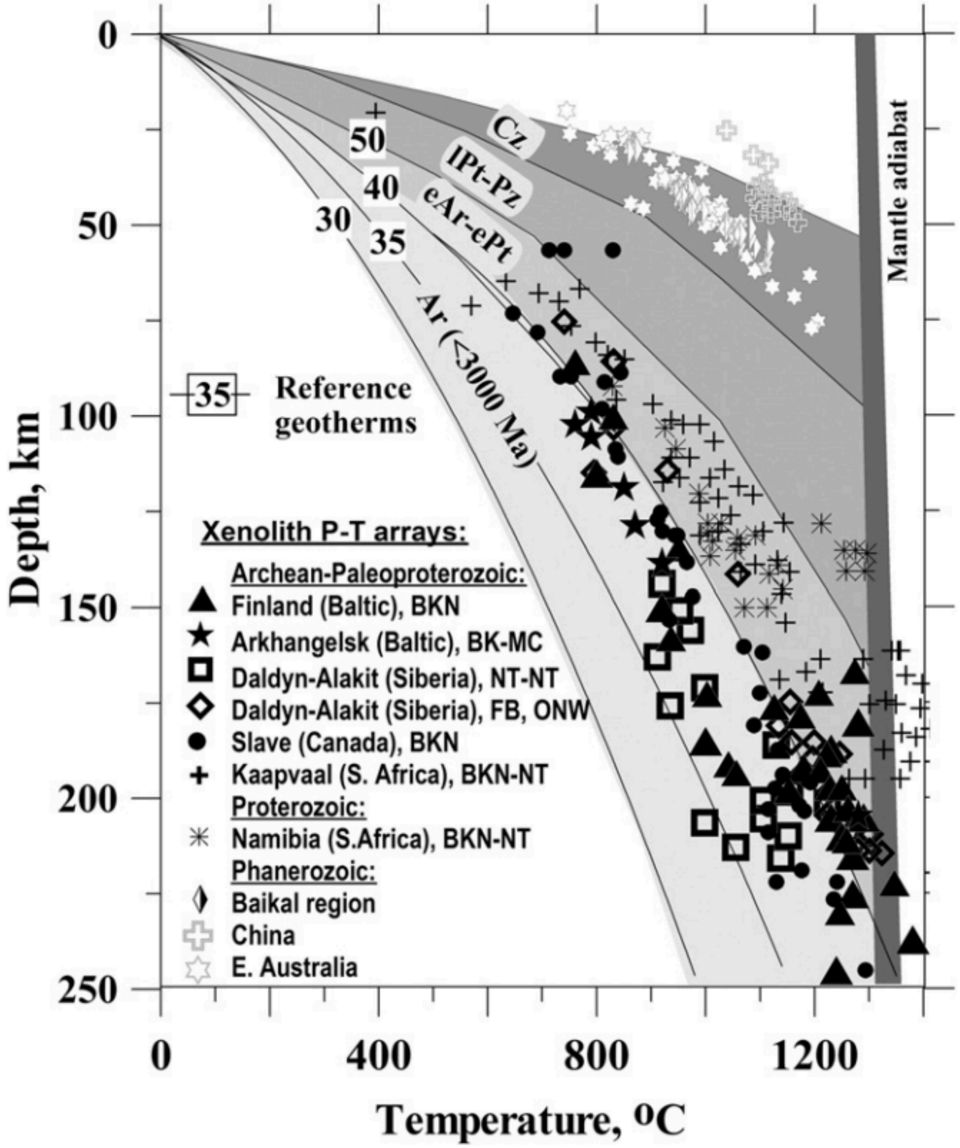
- poorly known distribution of radiogenic elements
- uncertainties in thermal properties
- no lateral exchange of heat considered

continental geotherms: temperature distribution is non-linear (if radiogenic heat is set to zero, what happen?)



Computed with a python script we will see this afternoon

What do you note that cannot be attained in the purely conductive geotherm at high heat-flux?



Artemieva- 2019

Petrological constraints

Xenolith thermo-barometry gives independent constraints on continental geotherm

Limitations:

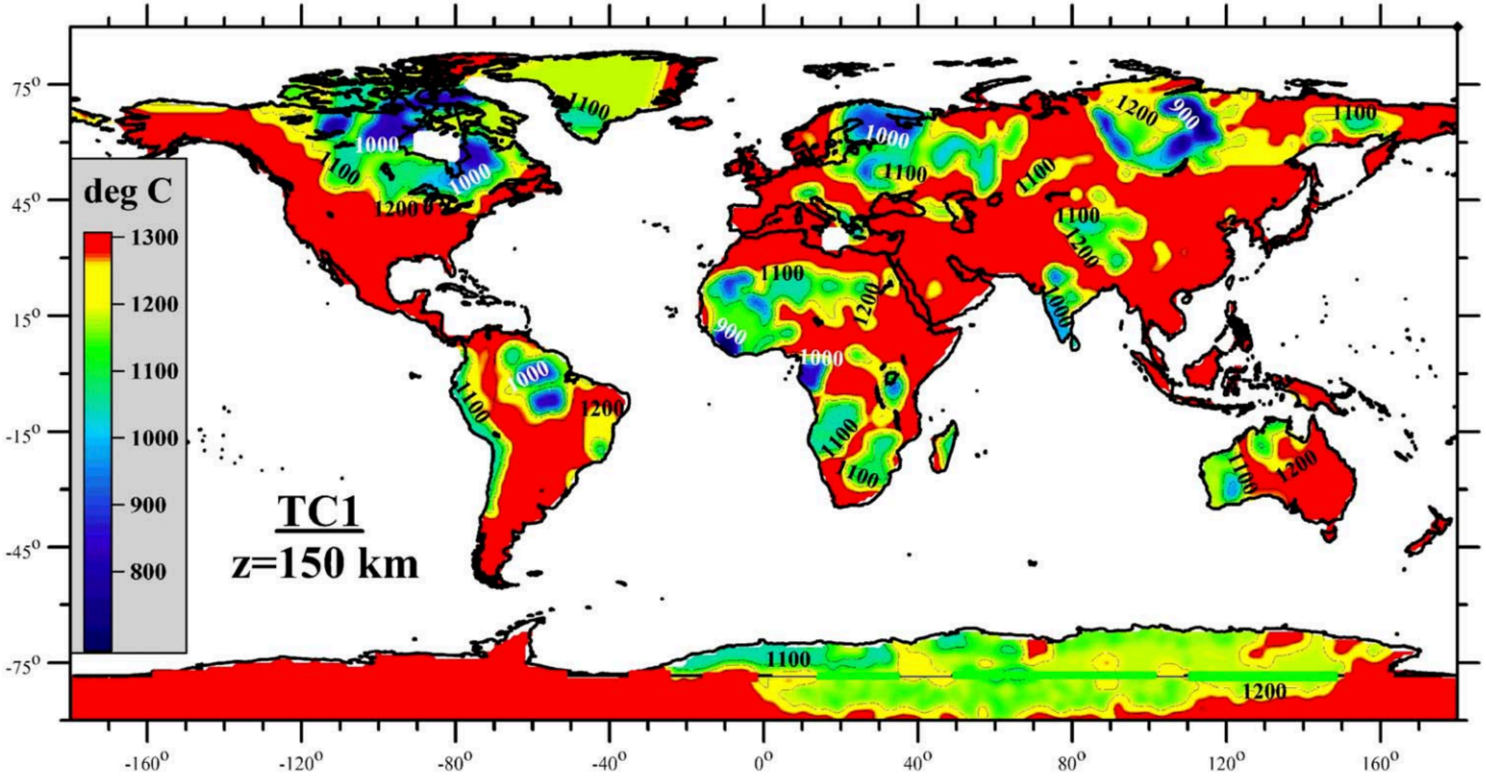
- Data uncertainties: Different methods give rather different P-T paths

- *Heat flow and petrological constraints together give an age-dependent relationship*

- *Possible to build a **global lithospheric thermal model** based on these data and on petrological provinces of different age (TC1)*

Limitations

1. Uncertainties in the P-T path of mantle xenoliths
2. Unknown distribution of radiogenic heat production
3. Poor resolution at a global scale (data-points)
4. Extrapolation to larger depths may lead to unreliable results. For instance, lateral heat exchange is not accounted.

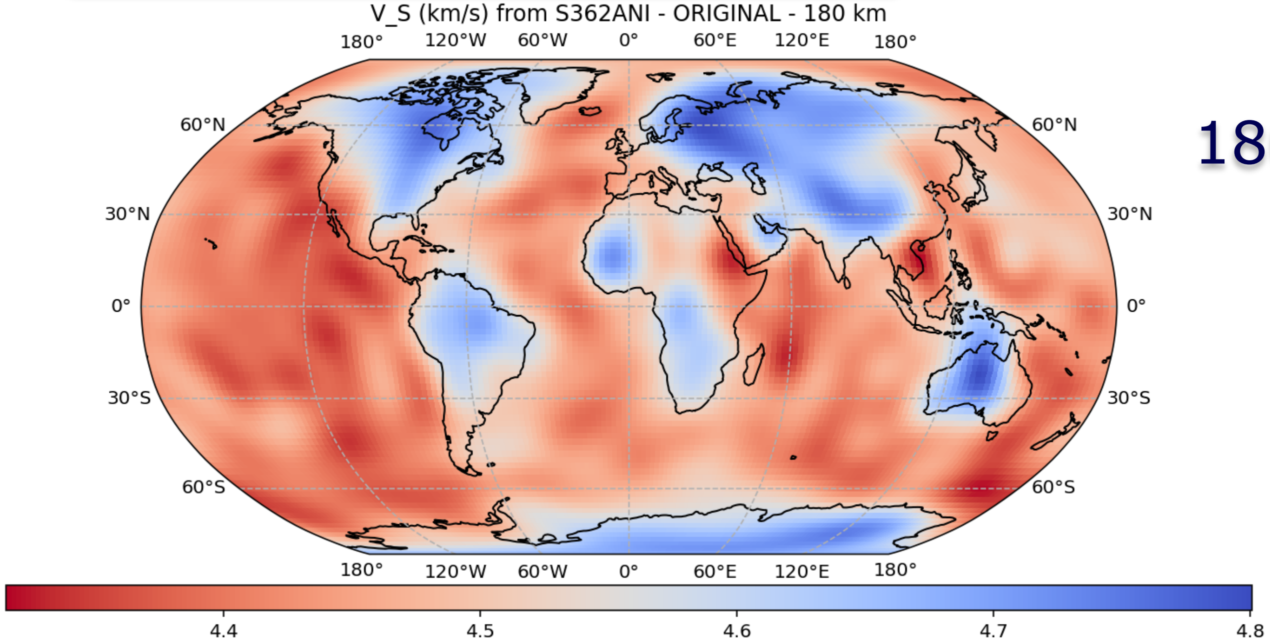


TC1 – Artemieva 2006

SEISMIC CONSTRAINTS ARE FUNDAMENTAL

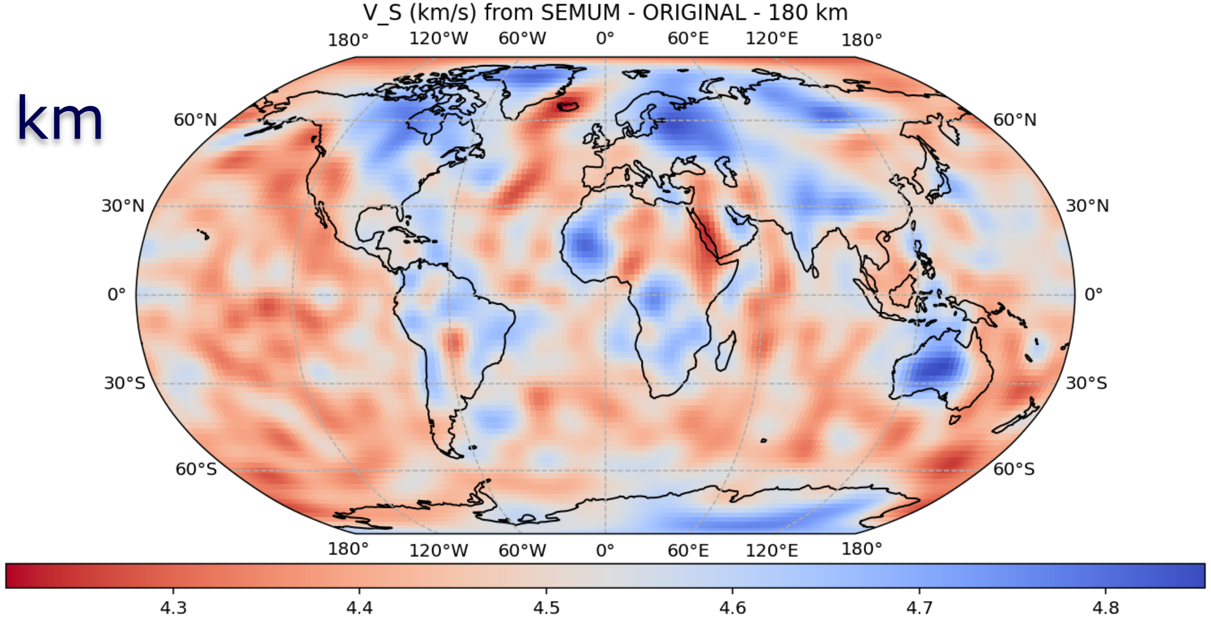
- *Global VS seismic models give the best constraint on lithosphere structure at a global scale => **they all have surface-wave constraints***

S362ANI, Harvard model



180 km

SEMUM, Berkeley model



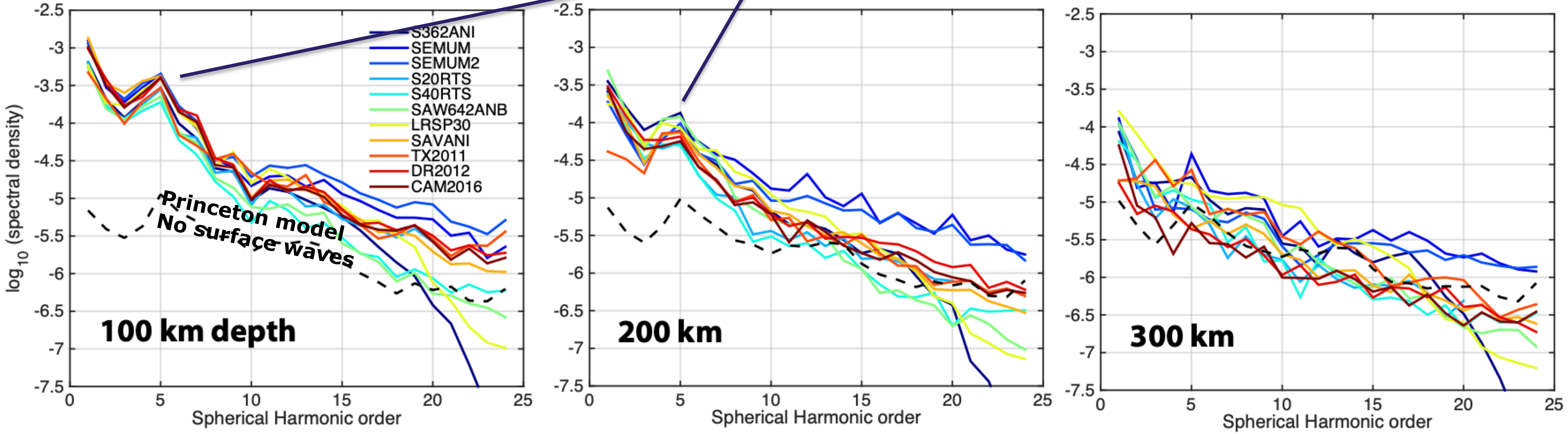
Plotted with a python script we will use this afternoon, most of results from Cammarano and Guerri 2017

*Different model resolution is not only due to different data and methods, but also from **regularization** (imply subjective choices)*

- A multiscale, statistical analysis of the available models helps to identify the robust and less robust features

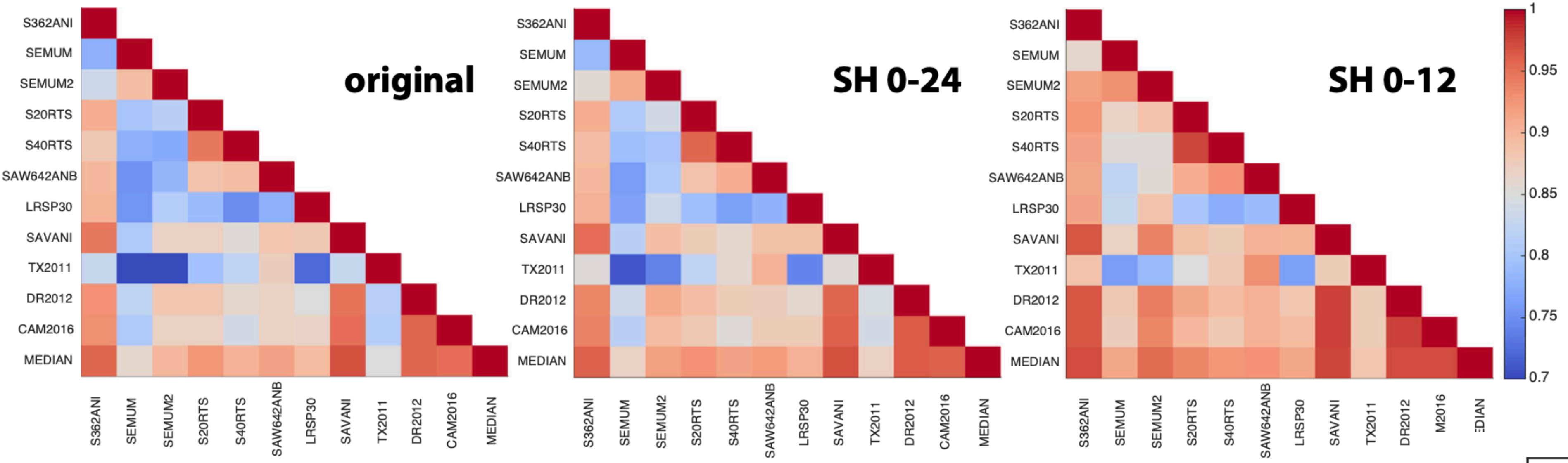
Spectral analysis of 11 models

Continental lithosphere signal



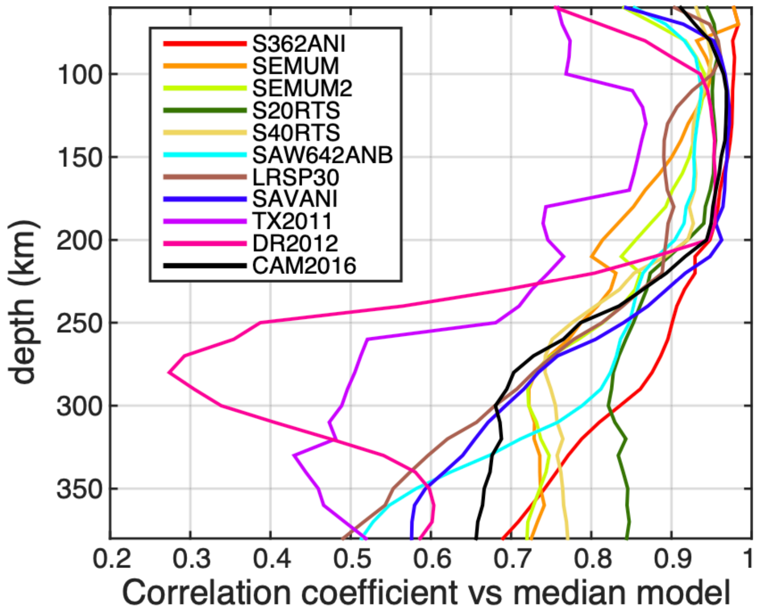
Correlation between models

180 km



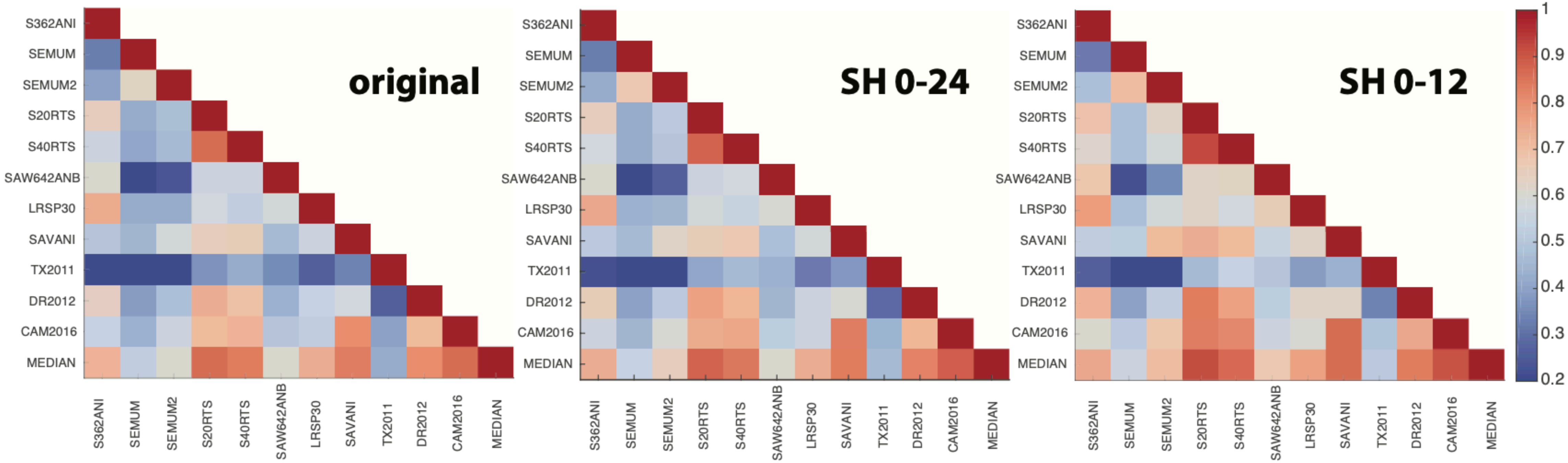
- ***Structural features** correlate very well up to 200 km, especially at longer wavelength*

- *Below this depth, correlation decreases rapidly => due to poor data resolution. Note that some specific variations also depend on a-priori constraints of the model (see TX2011, Texas mode, and DR2012, Debayle&Ricard model)*



180 km - 100 km

Correlation of ΔVS /ΔZ



- *Change of V_S with depth are different between models, even at very long wavelength => this would translate into* ***very different thermal gradient***

- *This is due to the* ***poor constraint on absolute velocities***

V_P, V_S, ρ (P, T, C) from MINERAL PHYSICS

Elasticity (P,T) — Laboratory + numerical data => equation of state

+

Phase equilibria (P,T) => C (P,T) — Experimental or thermodynamical modeling (Gibbs free energy minimization)

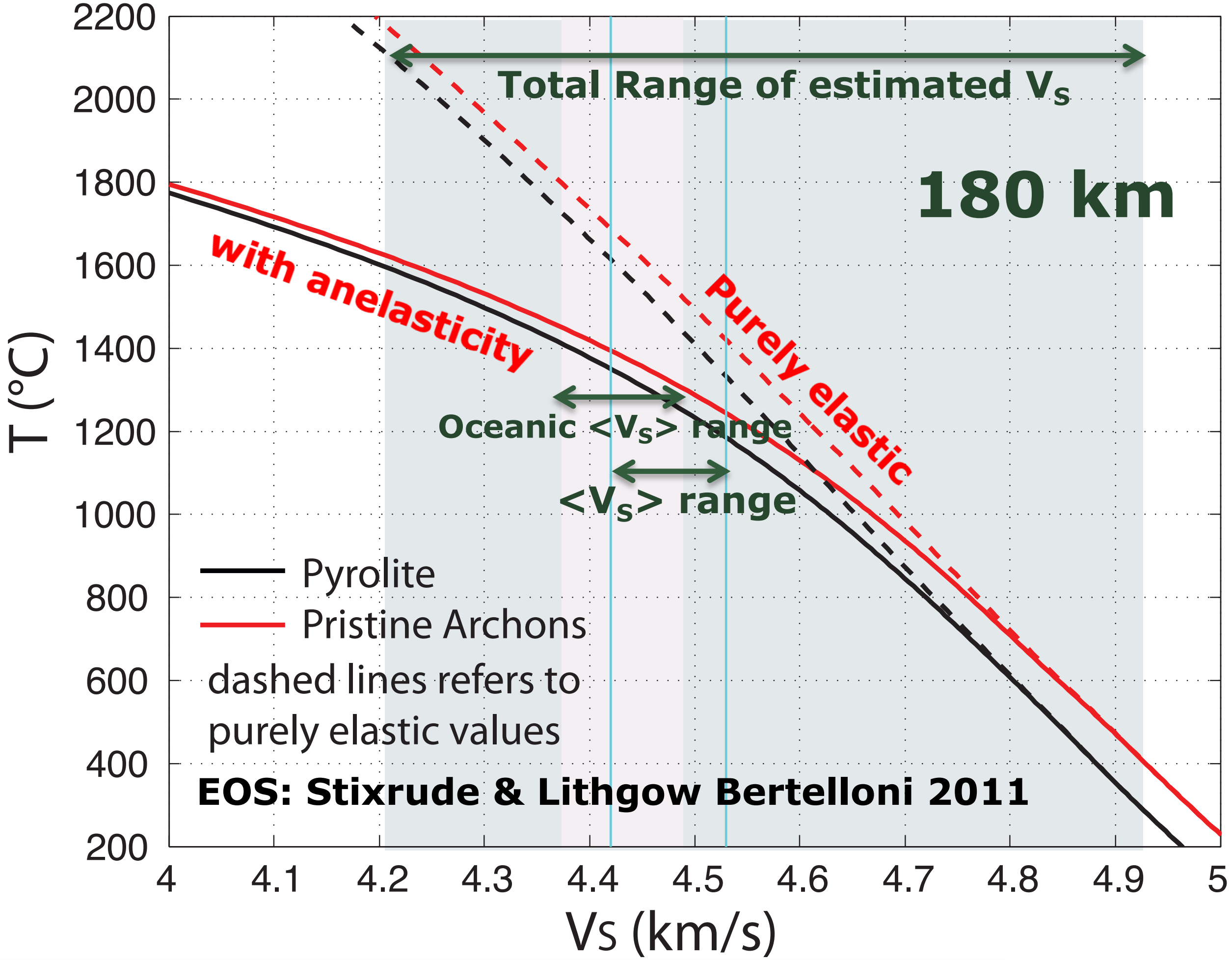
↓

V_P, V_S, ρ (P, T, C) — Average rock properties (e.g., Voigt-Reuss-Hill averaging scheme)

+

Anelasticity — Laboratory + analogy with rheology => $\partial V_{P,S}/\partial T$ function of T

✓ Mineral physics (elastic and anelastic parameters) => **V_S(P,T) for given compositions**



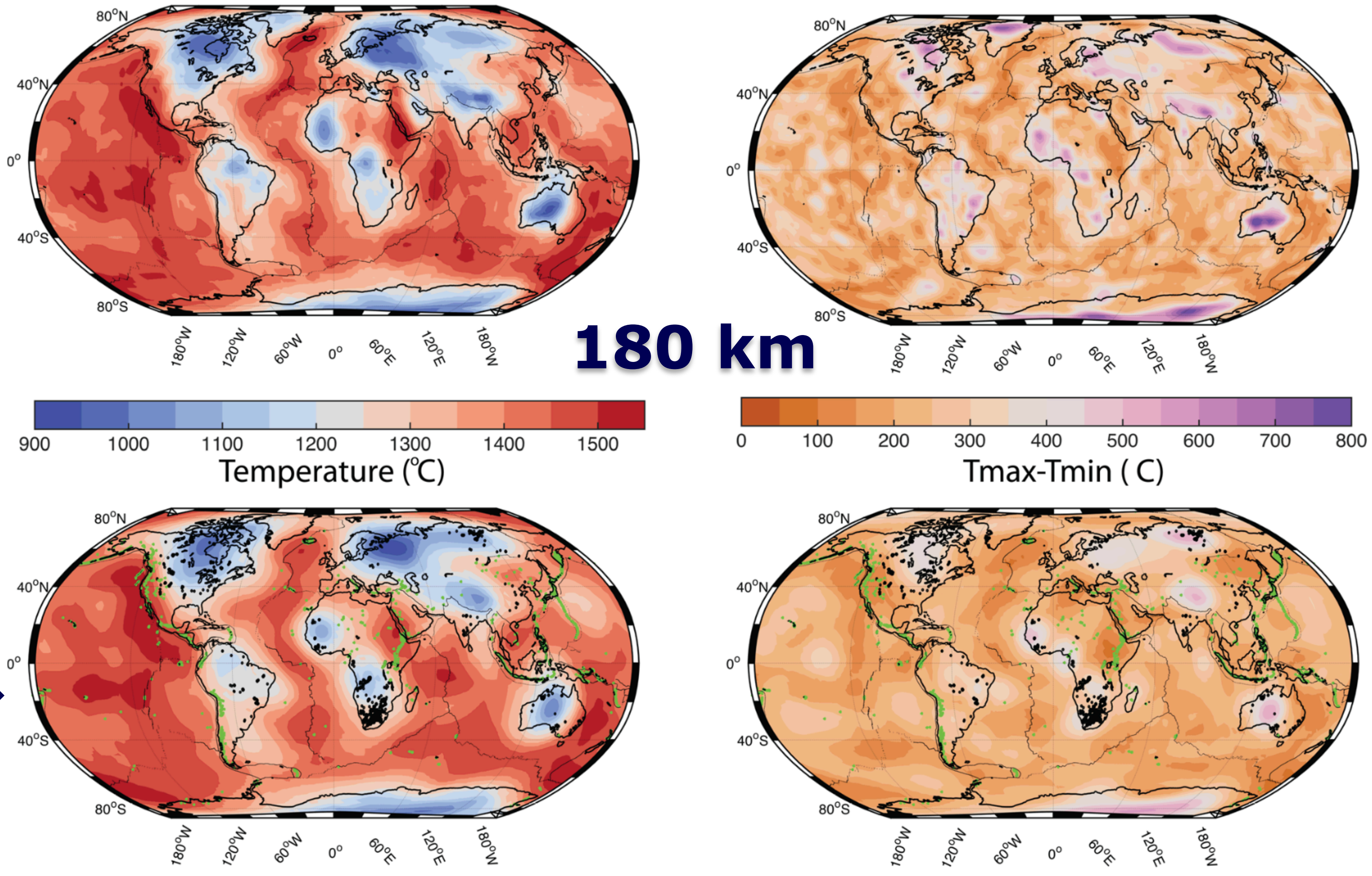
➢ V_S variations **mostly sensitive to T**
➢ **Anelasticity effects** should be considered

- T structure is well determined, but **absolute temperature** is affected by variation in amplitudes of V_S anomalies between models

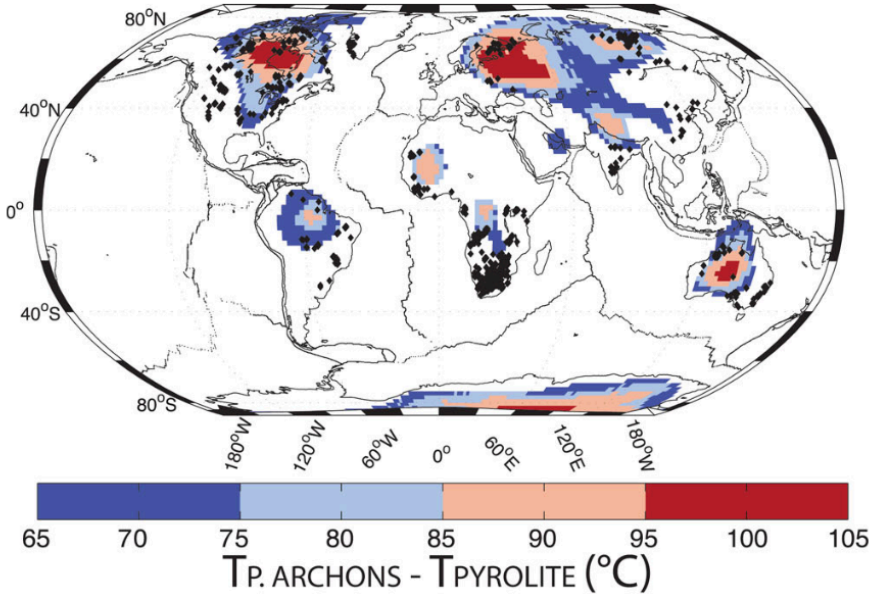
Original models ➔

Median temperatures and max-min variations

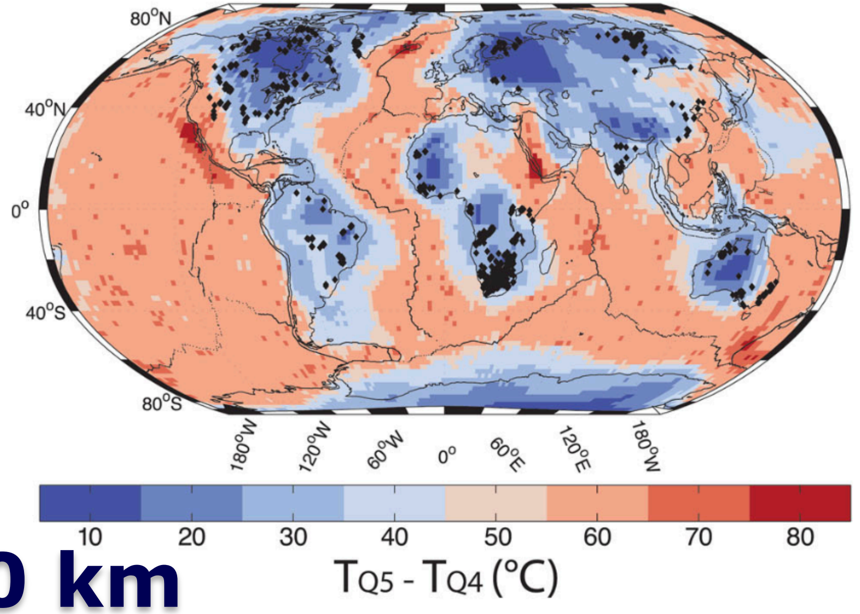
Expanded up to SH24➔



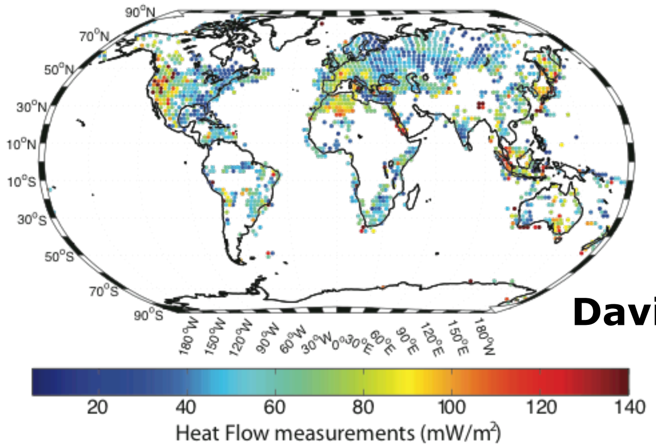
- The difference in absolute V_S between the models is the main factor of uncertainty for lithospheric temperatures



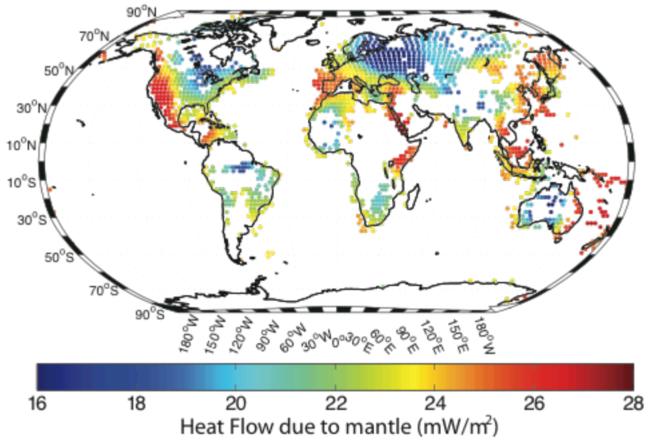
- Accounting for first-order **compositional** variations between continents/ocean
- And for the large uncertainties in anelasticity do not vary much inferred **temperatures**



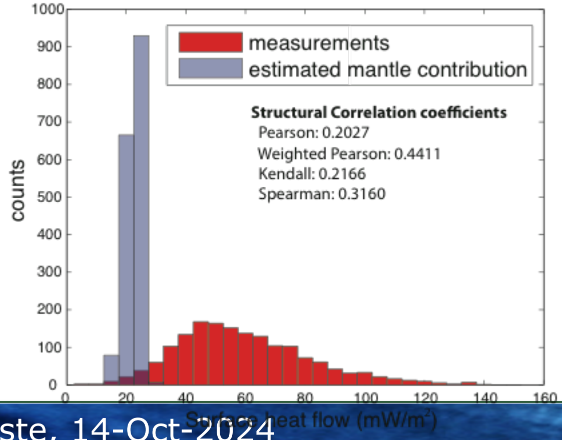
180 km



Davies 2010 2X2 HF



Based on seismically inferred T and no radiogenic heat

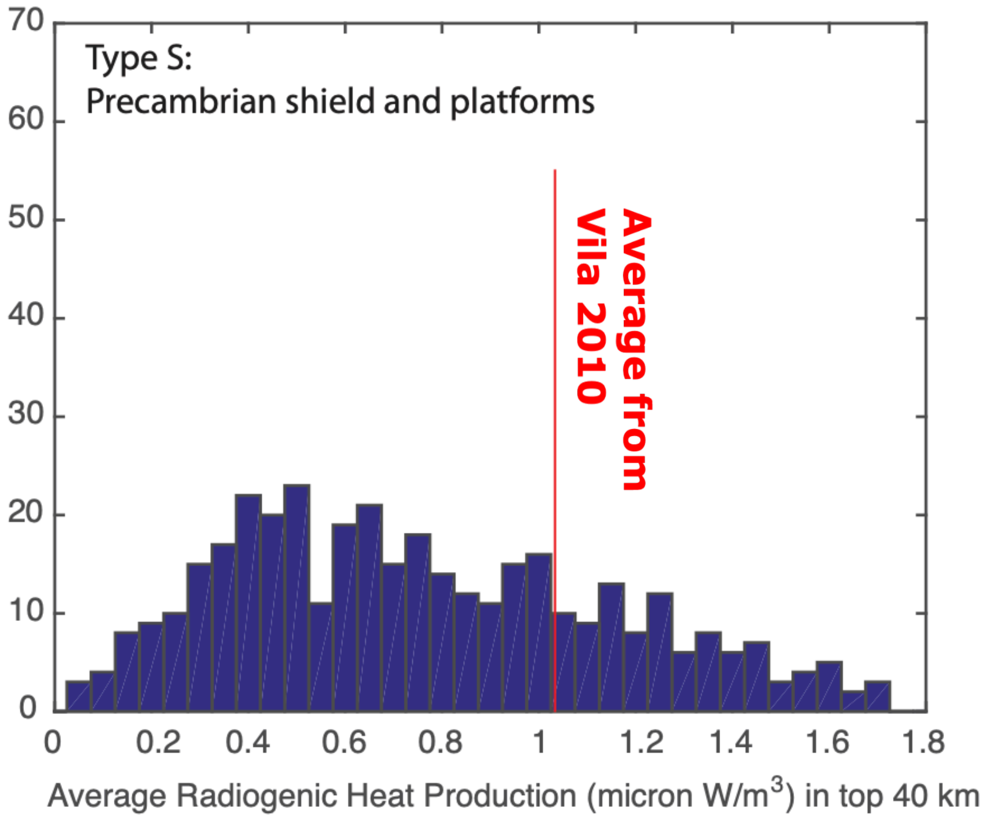


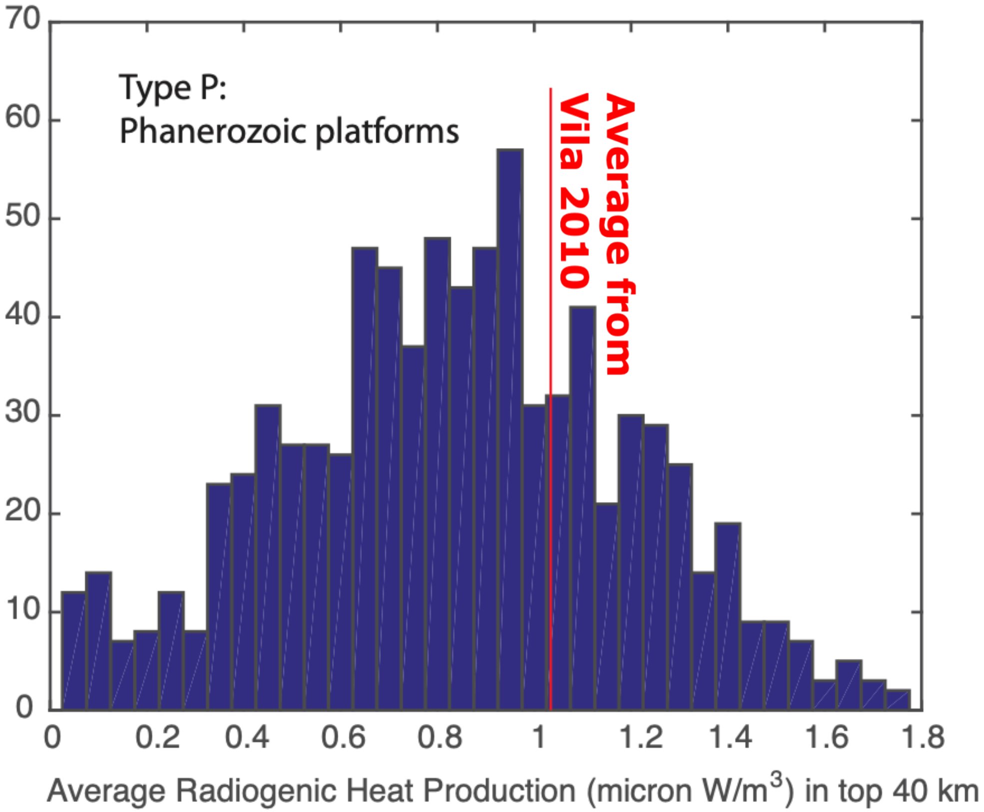
Constraints on absolute T:

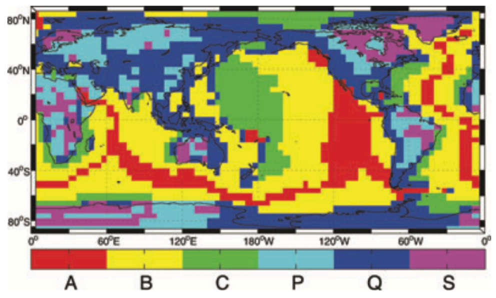
- Heat-flow surface data provide additional constraints on continental lithospheric T structure
- Geochemical inferred oceanic T (1280-1400 ° C, e.g. Gale 2014) and cooling models on oceanic regions.

Long-wavelength T structure known in the UM => **seismically inferred T models**

- We estimated **radiogenic heat contribution** in old crust by inverting continental geotherms to satisfy both our seismically inferred temperatures at lithospheric depth than heat-low





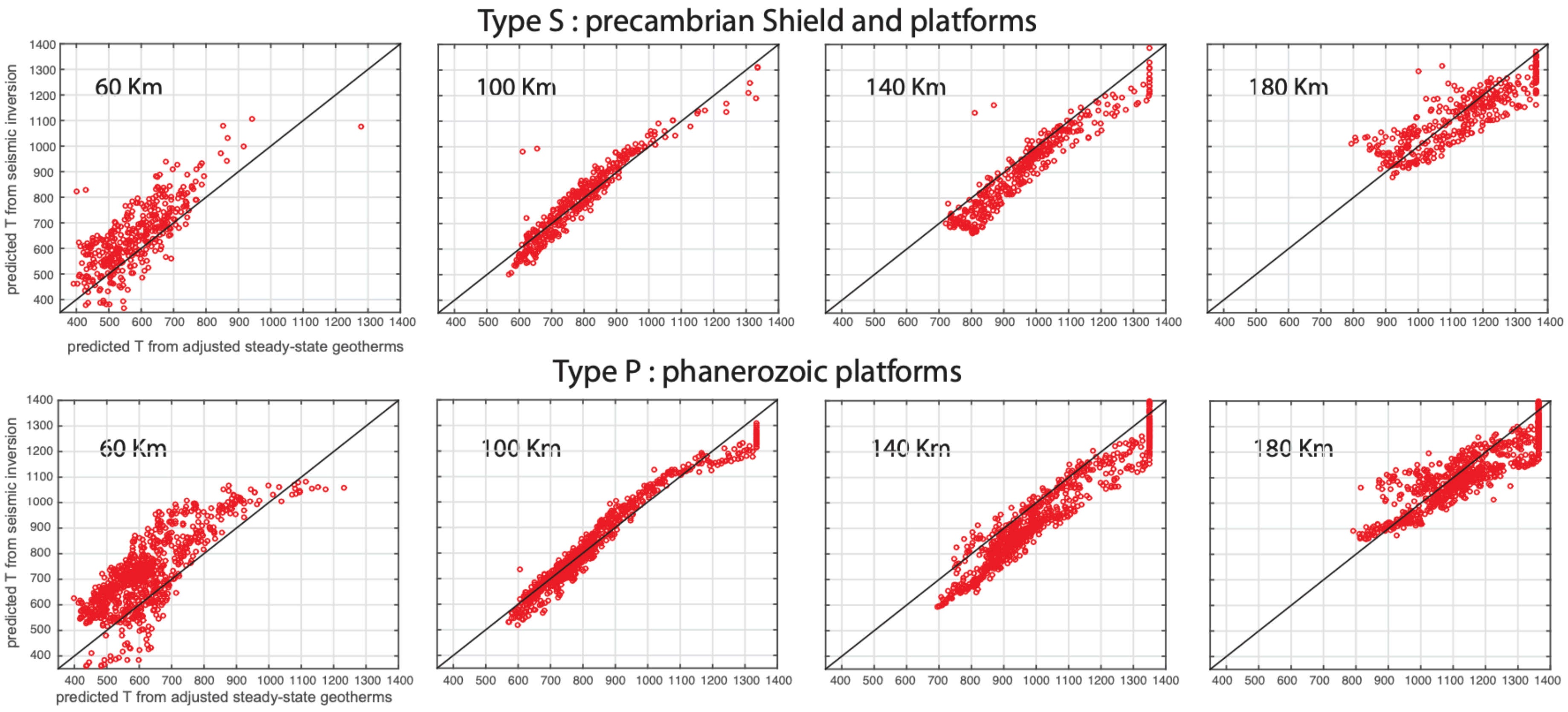


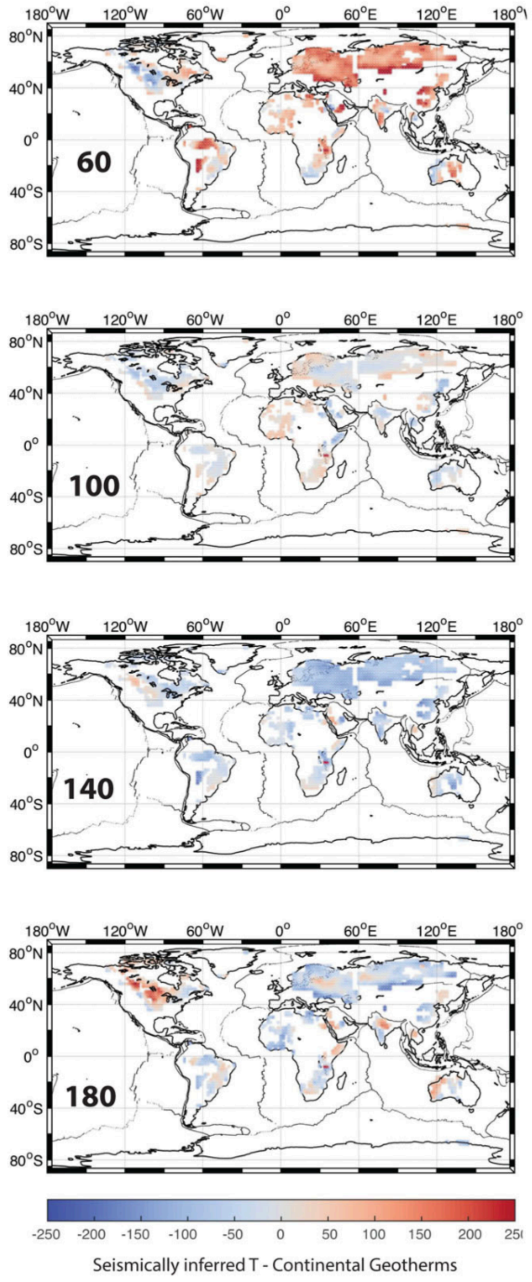
GTR1 - Jordan 81

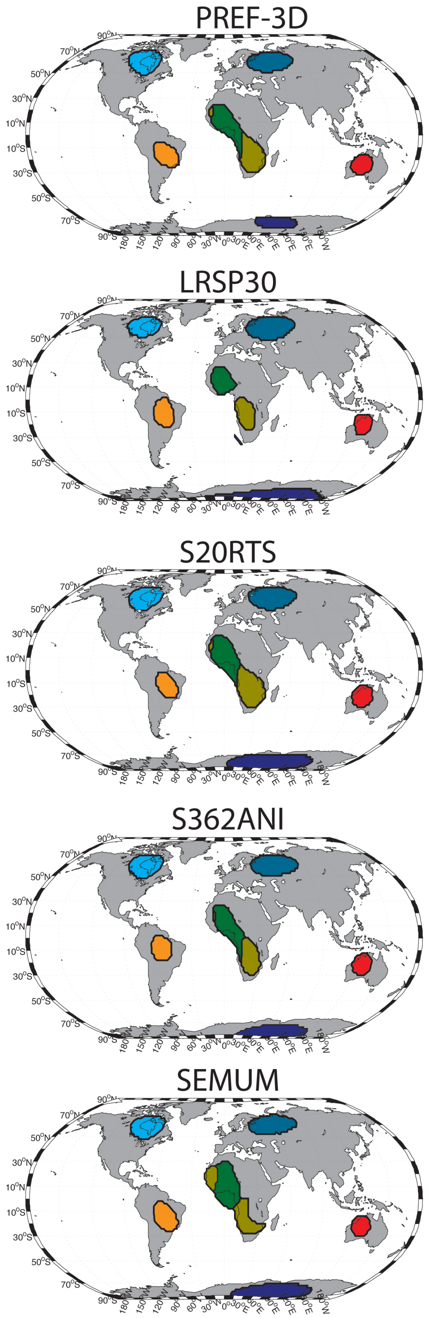
Limitations:

- Heat-flow data are sparse, not provide a global coverage

➢ Deviation of our **seismically inferred temperatures** from **inverted geotherms** can be due to (already suggested) compositional stratification of **continental lithosphere** or to uncertainties



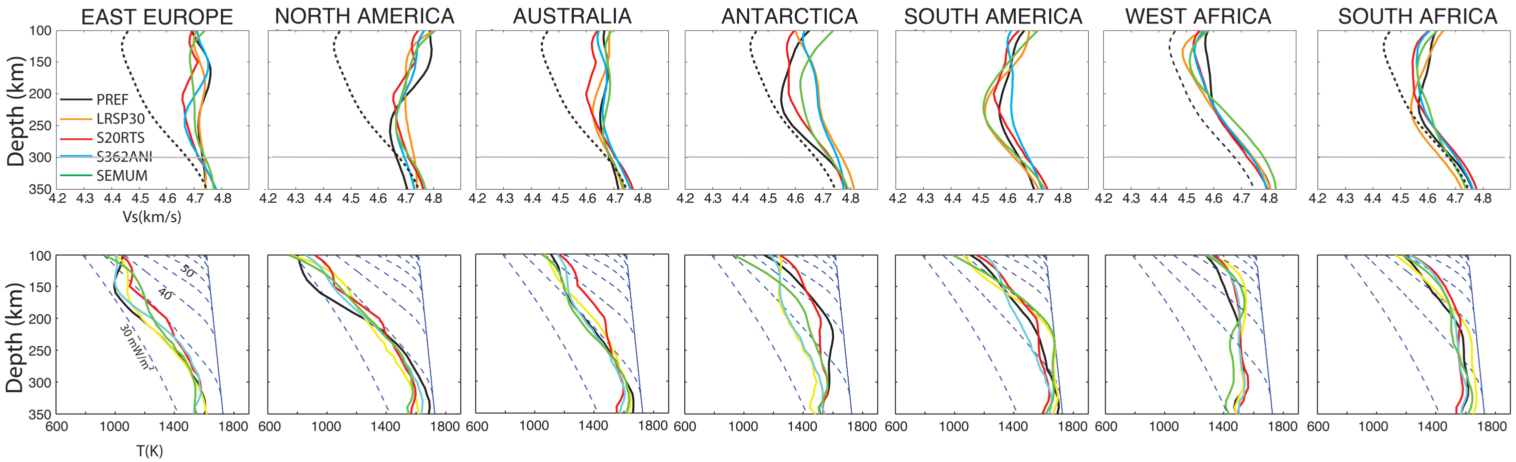




How thick is the continental lithosphere?

cluster analysis

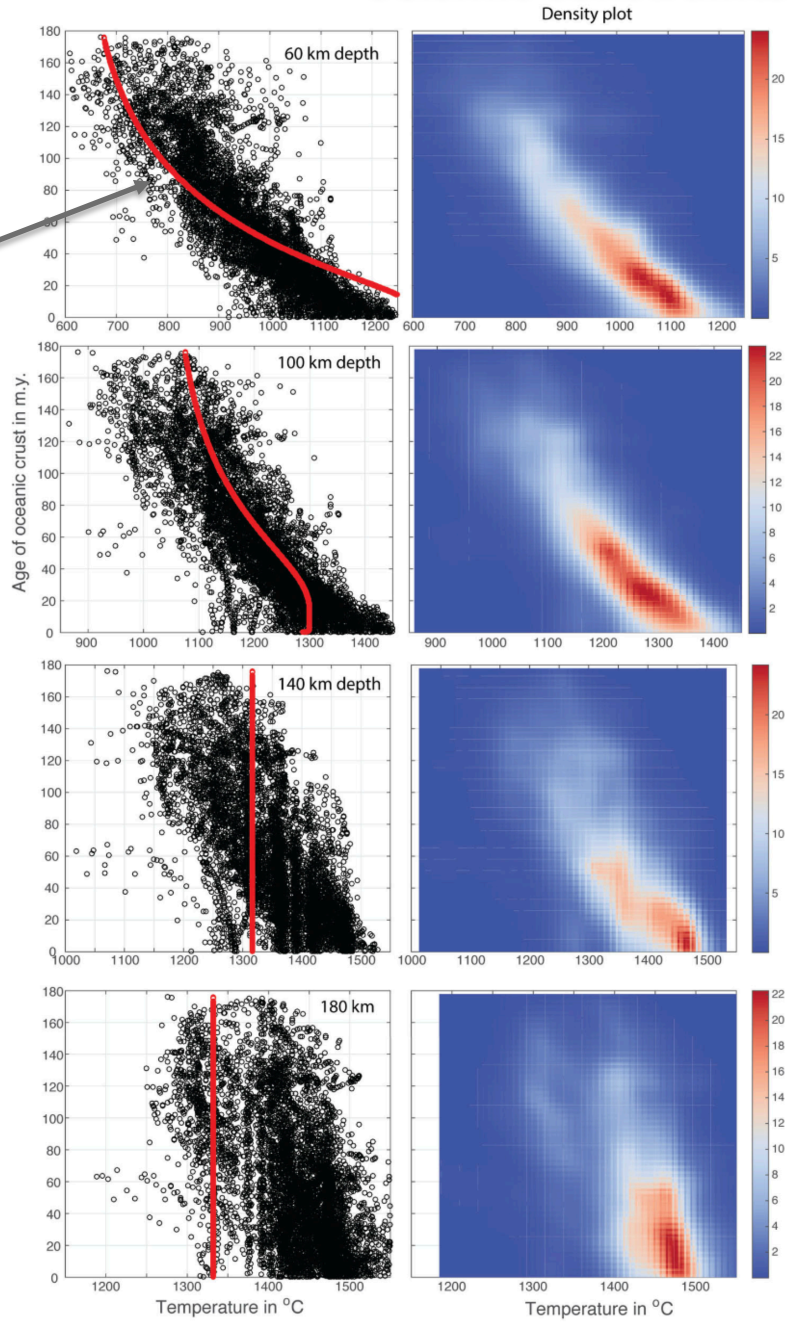
- Cratonic clusters are a robust feature of seismic models
- All models have **similar V_S trend with depth** in each region.
- The largest clusters are faster than the average **well below 250 km**.
- The increase in velocity around 250 km depth is observed in the large continental blocks, but a similar gradient also occurs in oceanic regions.
- V_S depth profiles vary between cratons (see North America vs Europe, for example)



SH 0-8

- At a first-order, seismological models obtain temperatures consistent with cooling models

Plate cooling model prediction

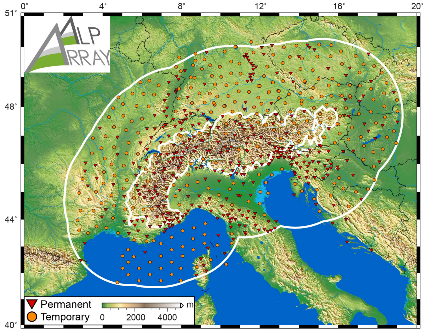


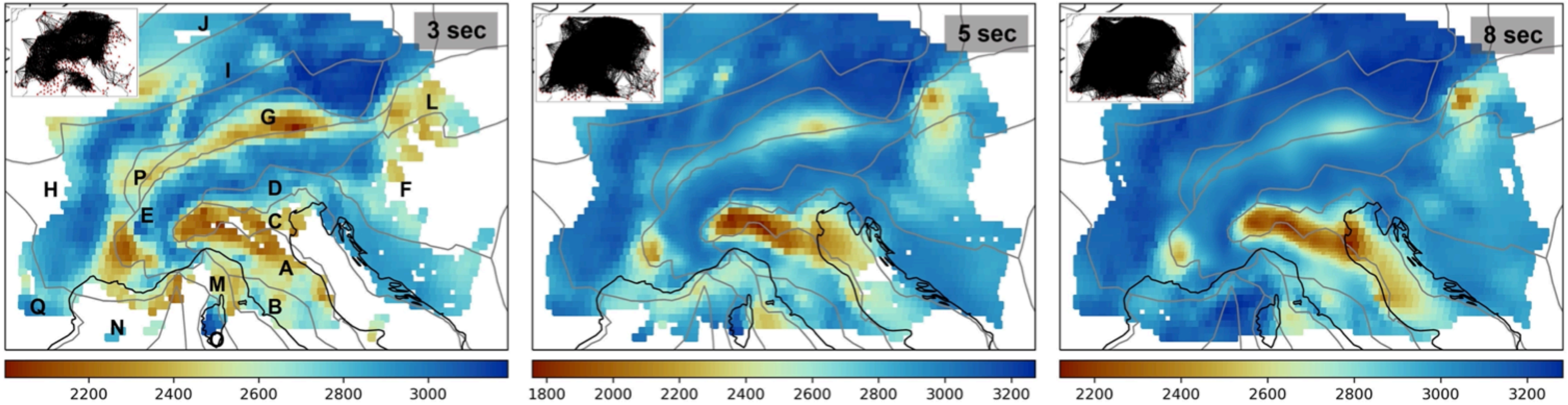
- Inferred temperatures at shallow depth nearby min-oceanic **ridges are lower than expected**.
- Temperature variations with age occurs **well below** (~150 km) the typical depth of oceanic plates.

Trade-off with composition? Is seismic resolution good enough? how to improve it? How to obtain more reliable absolute velocities?

Improving crustal structure

- Better data coverage of continental areas (Usarray, AusArray, Alparray)
  - Ambient noise cross-correlation allows to determine group and phase velocities of surface-wave at **short-period**
- Combine with receiver functions helps to better constrain the Moho

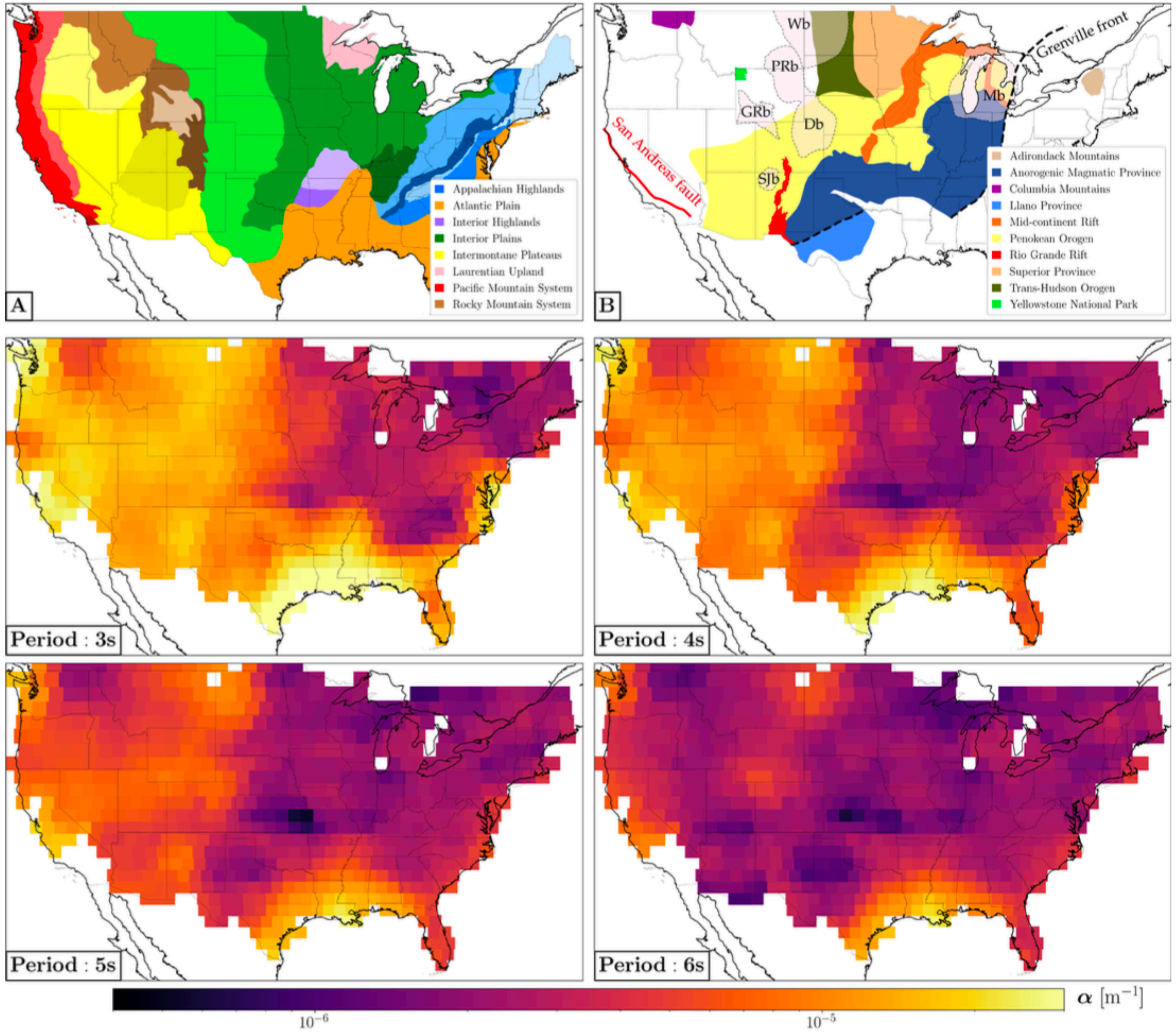




Example of phase velocity maps of Rayleigh waves extracted by cross-correlation of ambient noise between Alparray stations (Roisenberg et al. 2024)

Seismic attenuation

- **Seismic Attenuation** is more sensitive to temperature (and fluids) than velocities
- Rayleigh-wave **attenuation maps** can be retrieved from ambient noise



Attenuation maps of Rayleigh waves at short period *(Magrini et al. 2021)*