Plate Tectonics: Linking Surface Geology to Earth's Deep Interior

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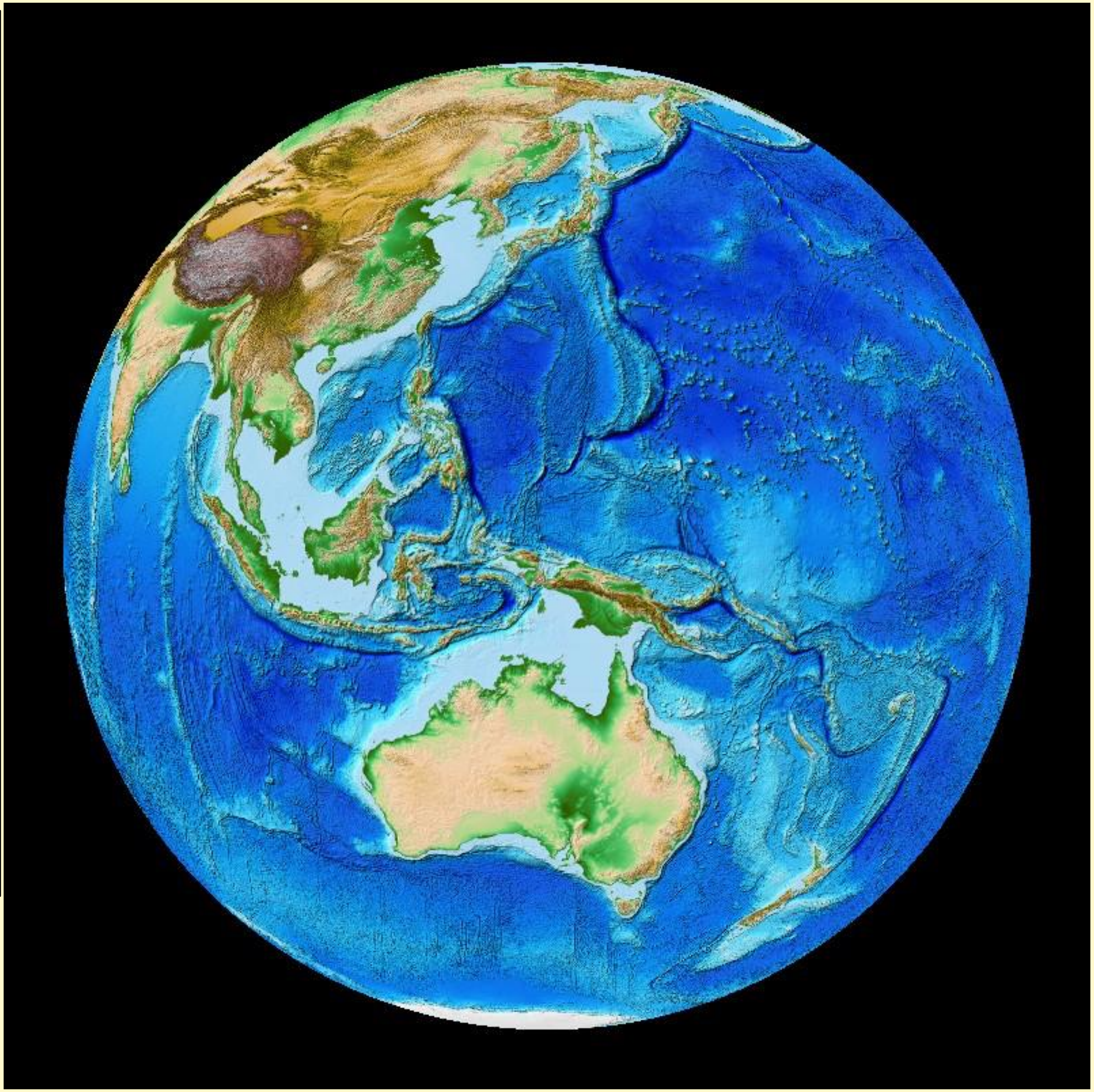
The Centre for Earth Evolution and Dynamics

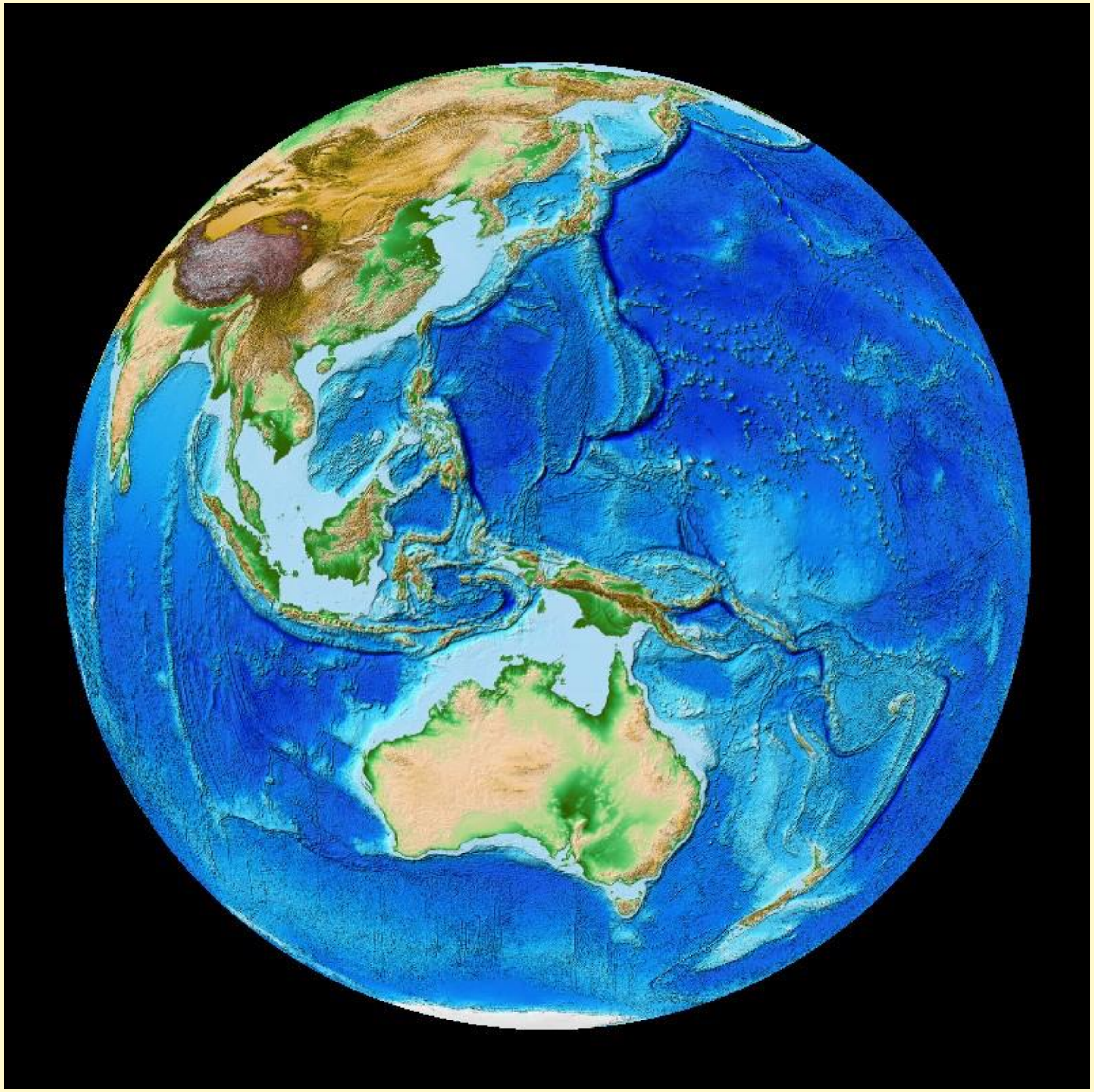


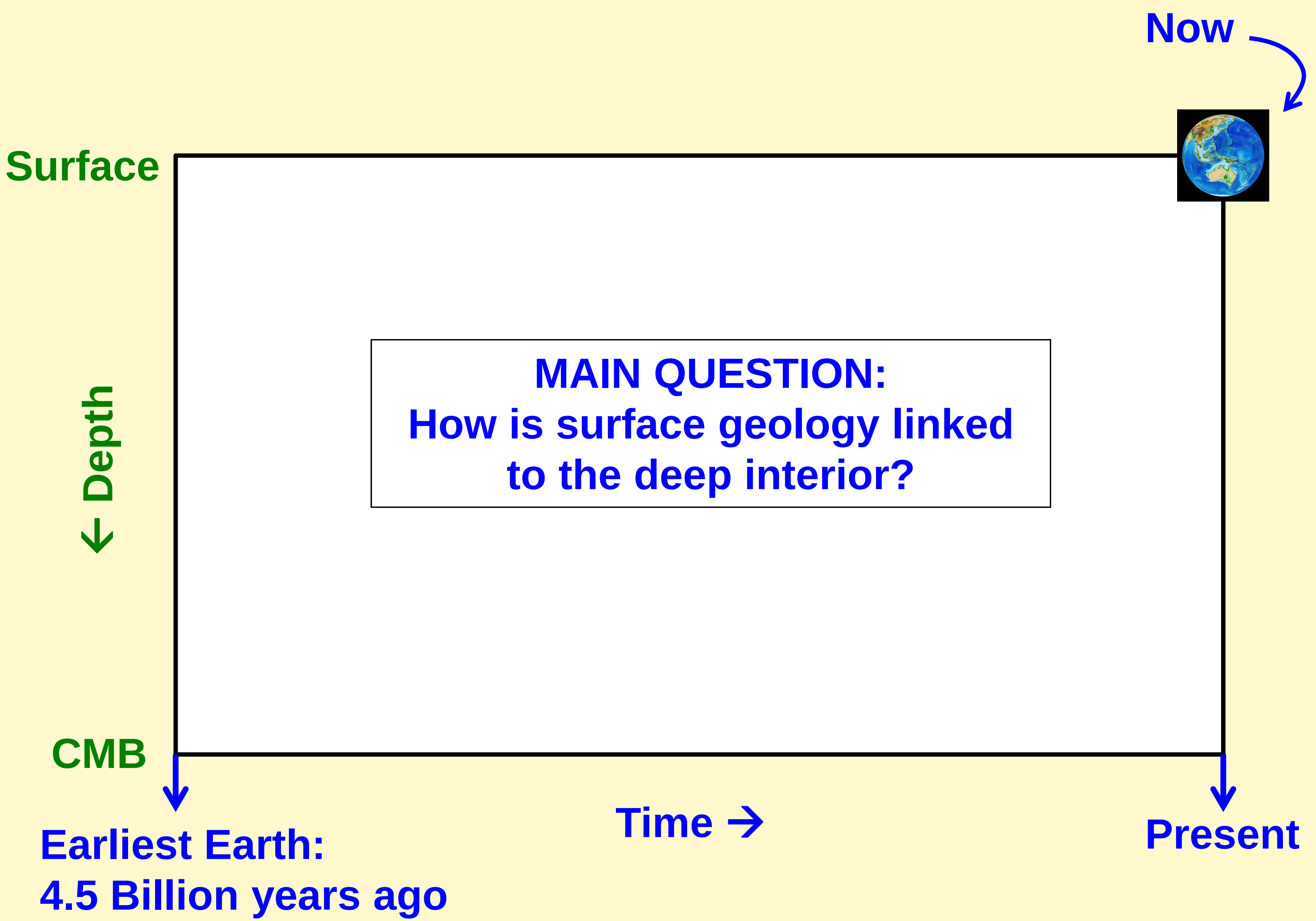
From observations at the surface:

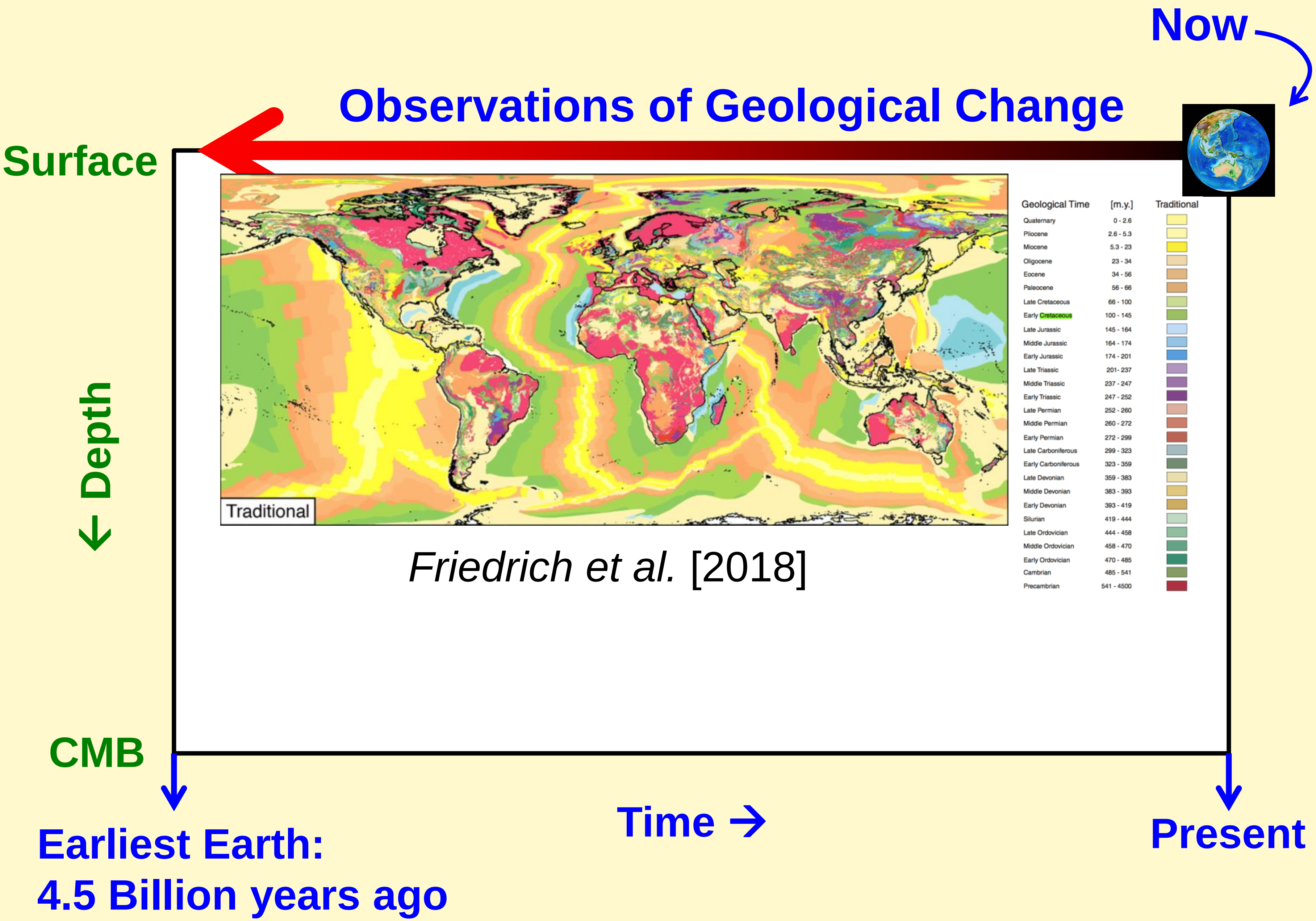
→ **Geologic change:** expresses a long time history

→ **Tectonic change:** great forces arise from the deep interior

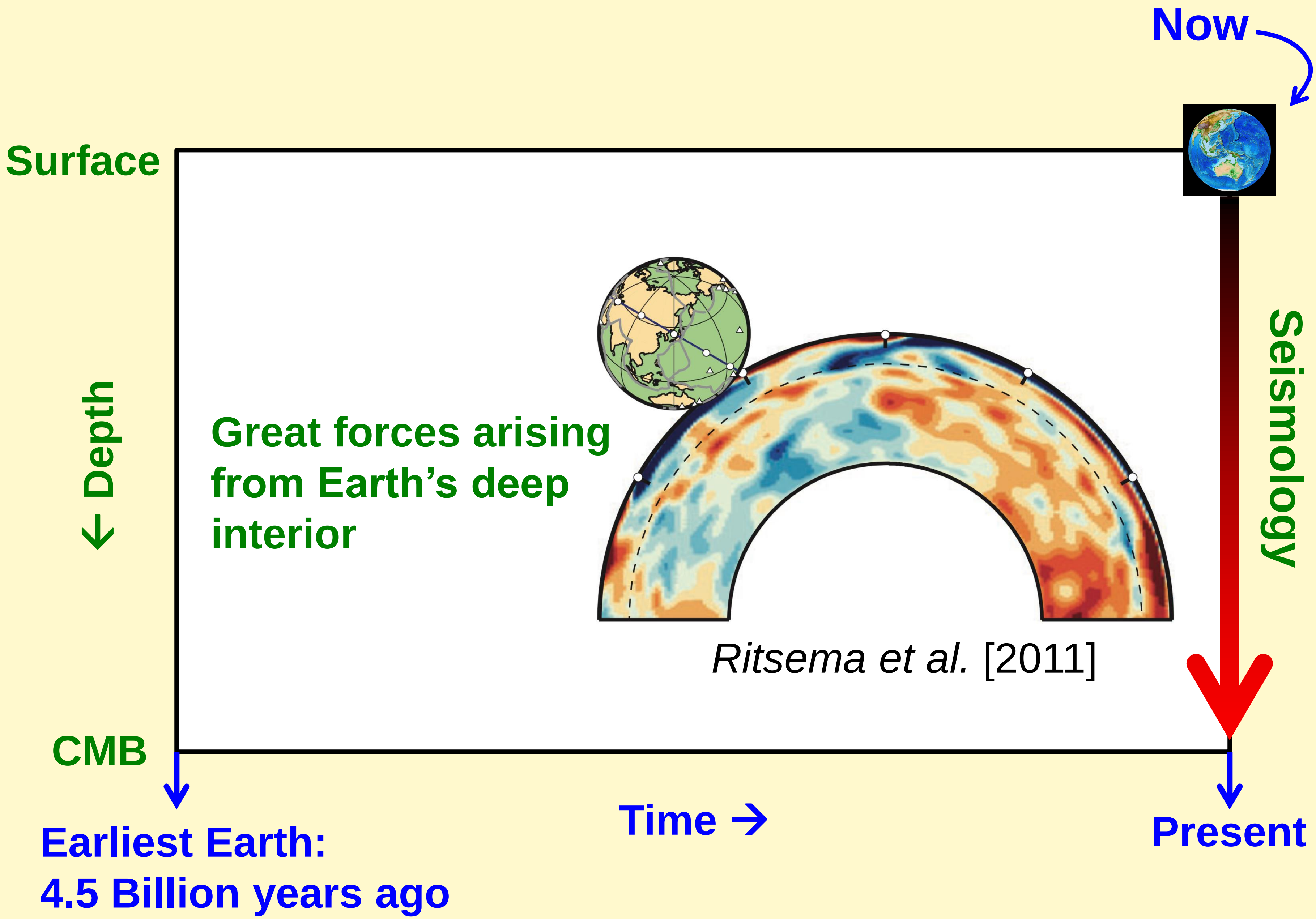
MAIN QUESTION: How is surface geology linked to the deep interior?

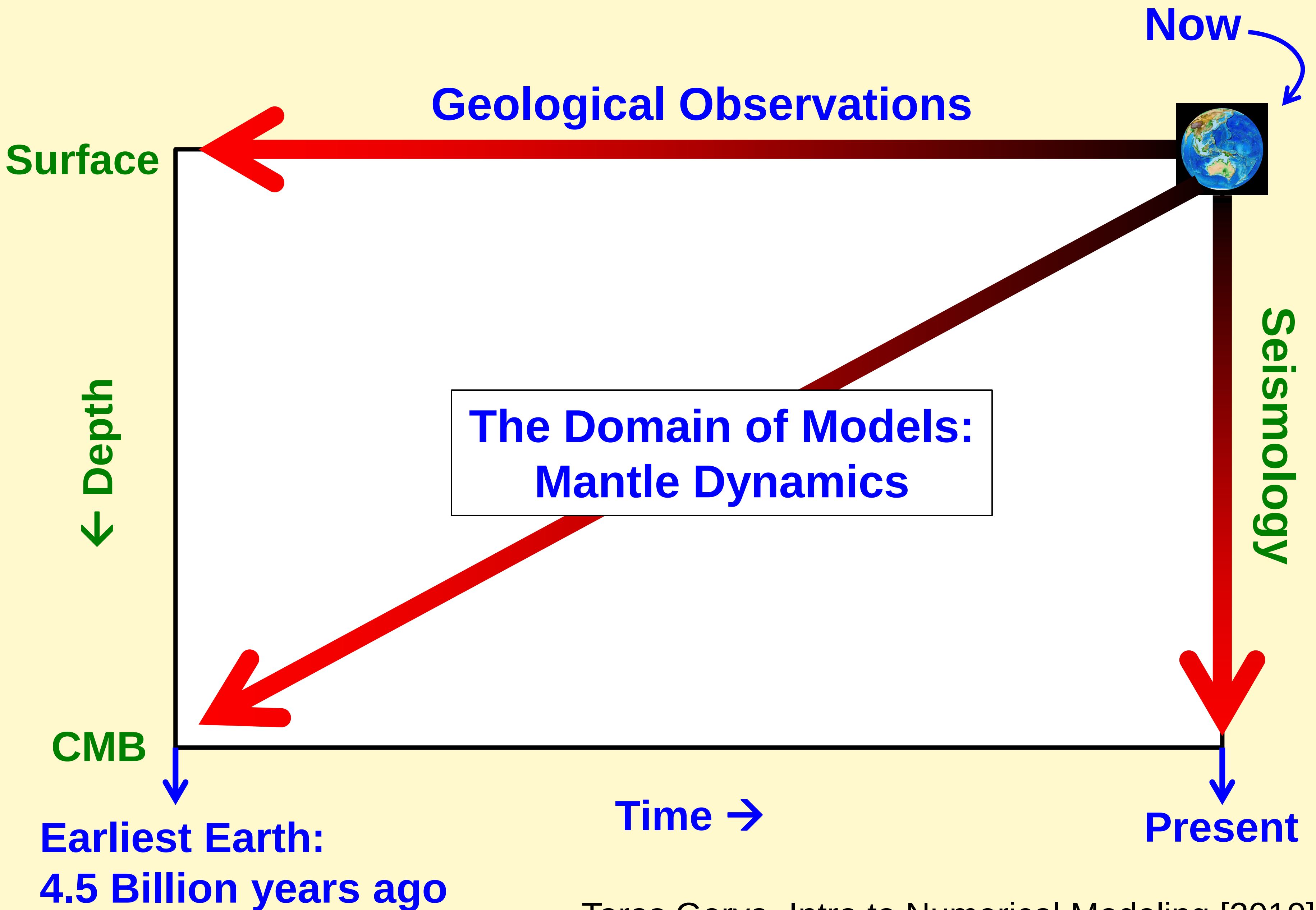



Now
Surface
MAIN QUESTION:
How is surface geology linked
to the deep interior?
← Depth
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present



Now
Observations of Geological Change
Surface
↓ Depth
CMB
Traditional
Geological Time
[m.y.]
Traditional
Quaternary 0 - 2.6
Pliocene 2.6 - 5.3
Miocene 5.3 - 23
Oligocene 23 - 34
Eocene 34 - 56
Paleocene 56 - 66
Late Cretaceous 66 - 100
Early Cretaceous 100 - 145
Late Jurassic 145 - 164
Middle Jurassic 164 - 174
Early Jurassic 174 - 201
Late Triassic 201- 237
Middle Triassic 237 - 247
Early Triassic 247 - 252
Late Permian 252 - 260
Middle Permian 260 - 272
Early Permian 272 - 299
Late Carboniferous 299 - 323
Early Carboniferous 323 - 359
Late Devonian 359 - 383
Middle Devonian 383 - 393
Early Devonian 393 - 419
Silurian 419 - 444
Late Ordovician 444 - 458
Middle Ordovician 458 - 470
Early Ordovician 470 - 485
Cambrian 485 - 541
Precambrian 541 - 4500
Friedrich et al. [2018]
Earliest Earth:
4.5 Billion years ago
Time →
Present


Now
Surface
↓ Depth
Great forces arising from Earth's deep interior
Ritsema et al. [2011]
Seismology
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present

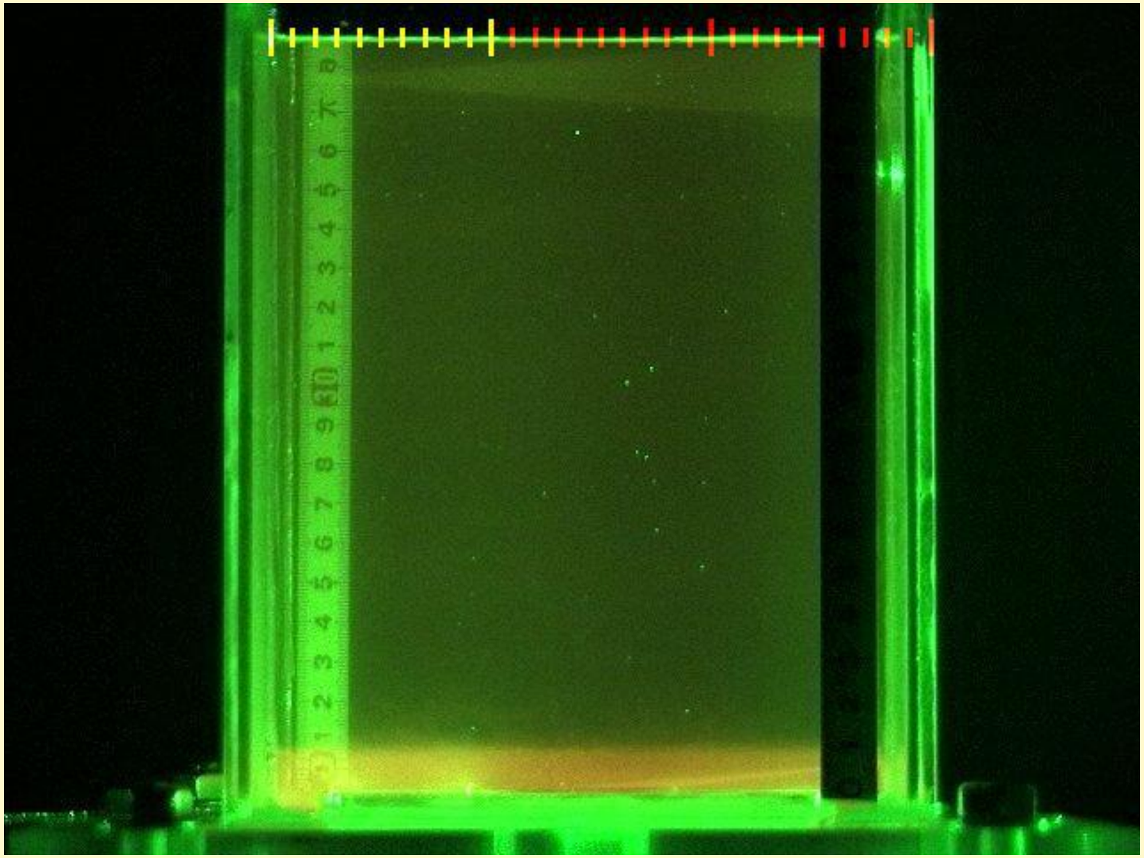


Taras Gerya, Intro to Numerical Modeling [2010]

Models of Mantle Dynamics

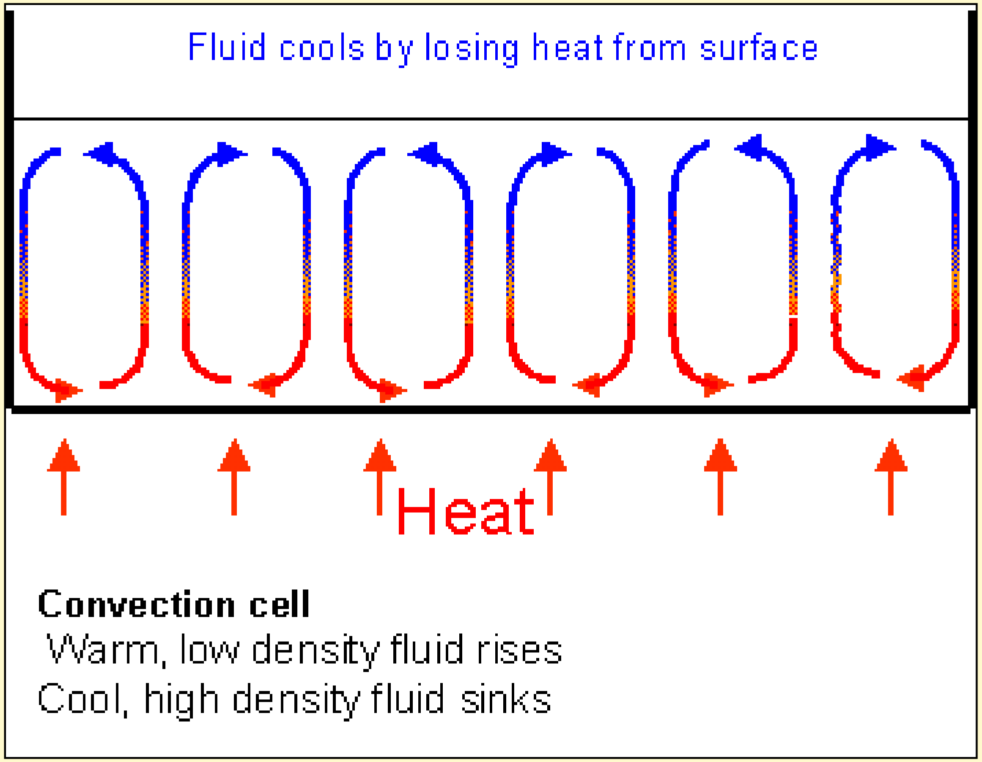
→ A model is a ***representation*** of some a physical process
→ A model should be ***useful*** for understanding the process
→ A model should be ***testable*** in some way

"All models are wrong but some are useful." [George Box,1987]



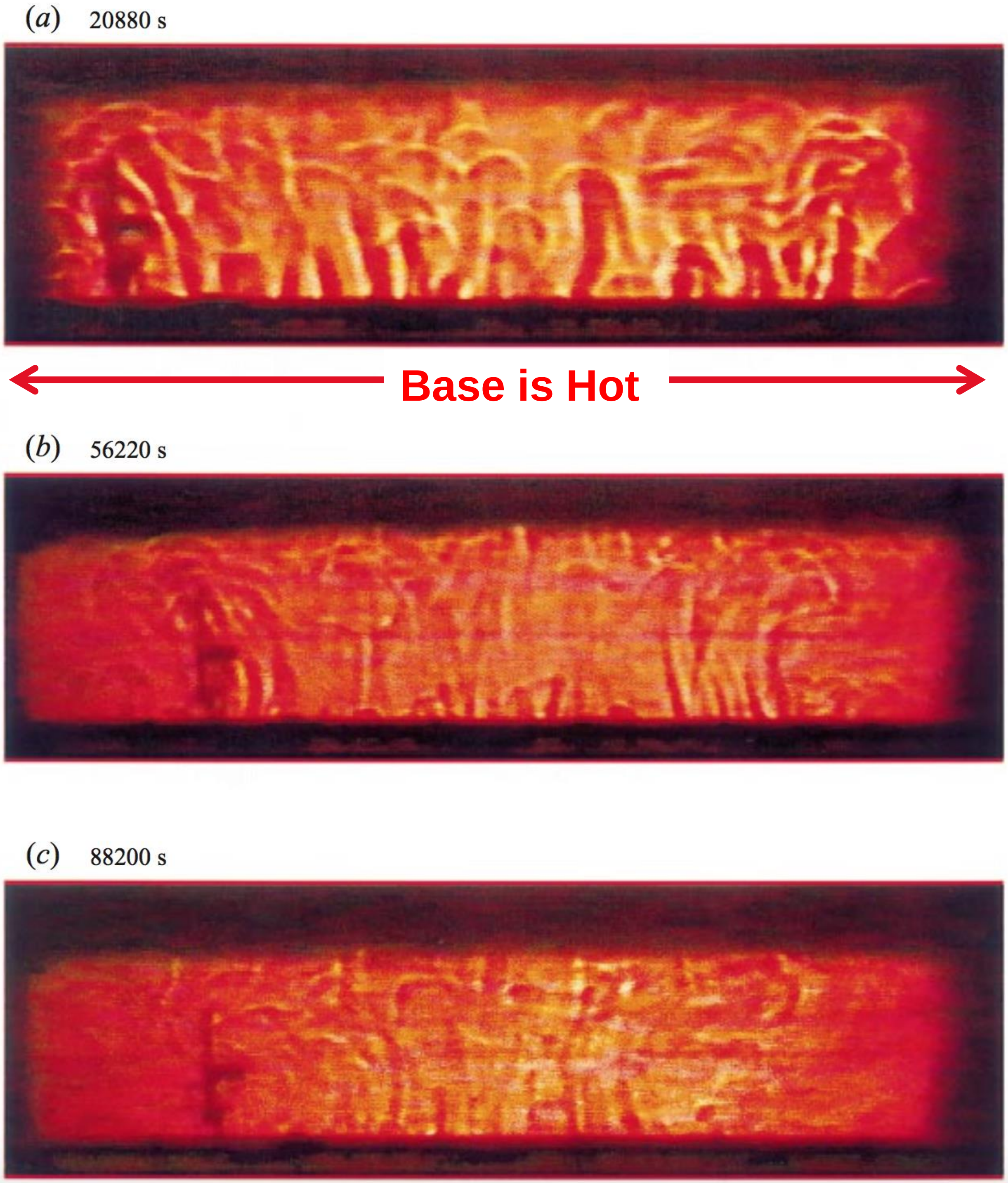
A Plume Experiment in Corn Syrup

How Convection Works



Cold Fluid Sinks

Hot Fluid Rises



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**:

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

ρ = density (3300 kg/m^3)

g = gravity (10 m/s^2)

α = thermal expansivity (3×10^{-5} K^{-1})

ΔT = Temperature contrast across mantle (3000 K)

D = Depth of Mantle (2860 km)

κ = Thermal diffusivity (10^{-6} m^2/s)

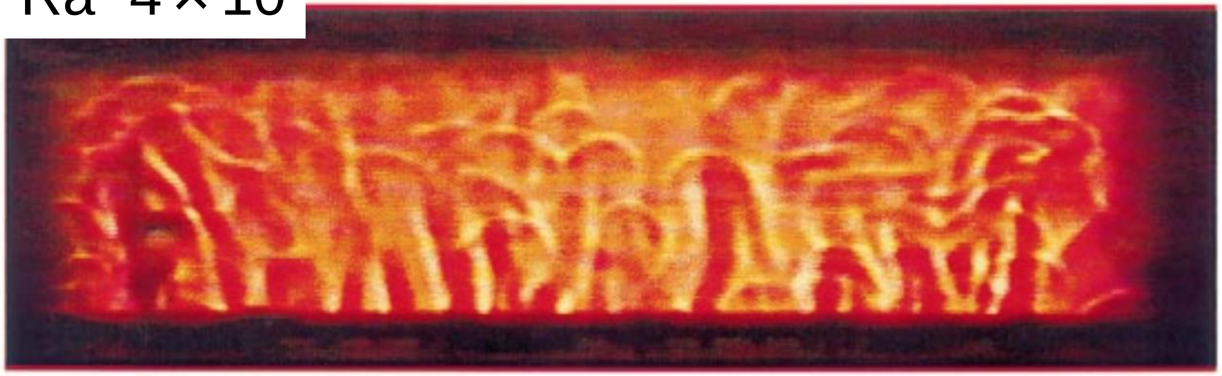
η = Mantle viscosity (10^{21} Pa s)

Convection occurs if Ra > 657

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

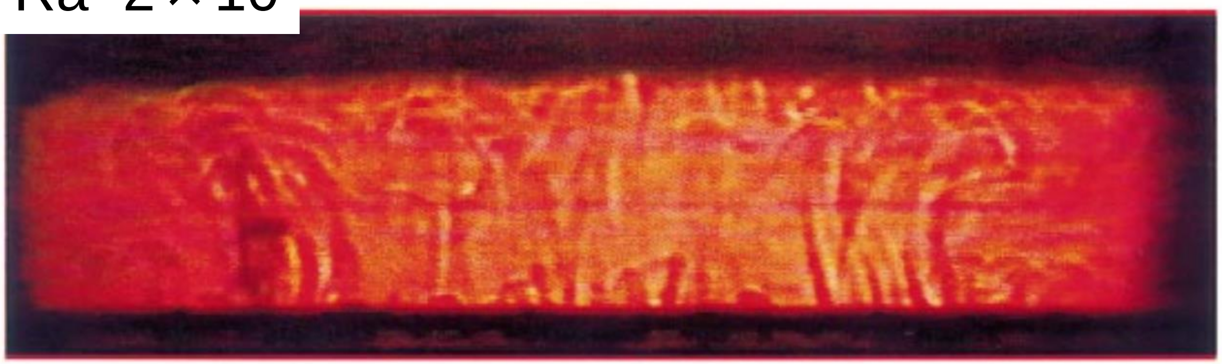
→ **This "model" implies vigorous convection in the mantle**

$Ra \sim 4 \times 10^6$

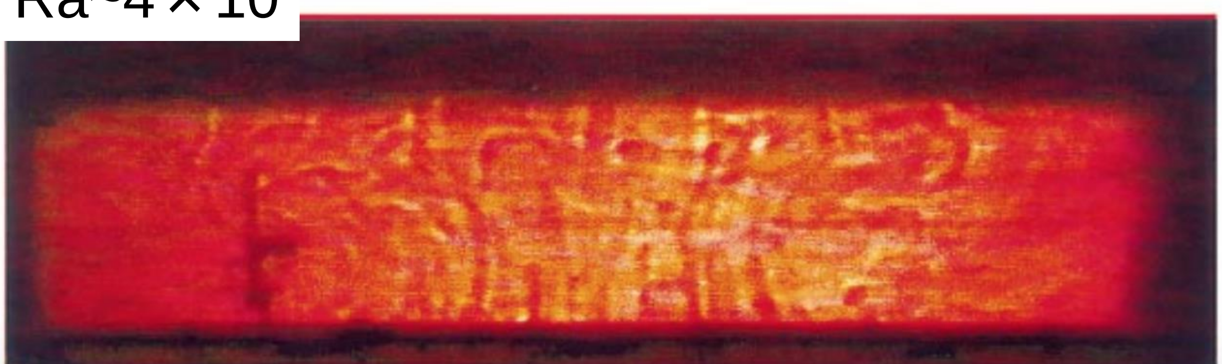


← **Base is Hot** →

$Ra \sim 2 \times 10^7$



$Ra \sim 4 \times 10^7$



Laboratory experiment of convection in a tank of corn syrup.

Lithgow-Bertelloni et al. [2001]

Rayleigh number is getting larger with time

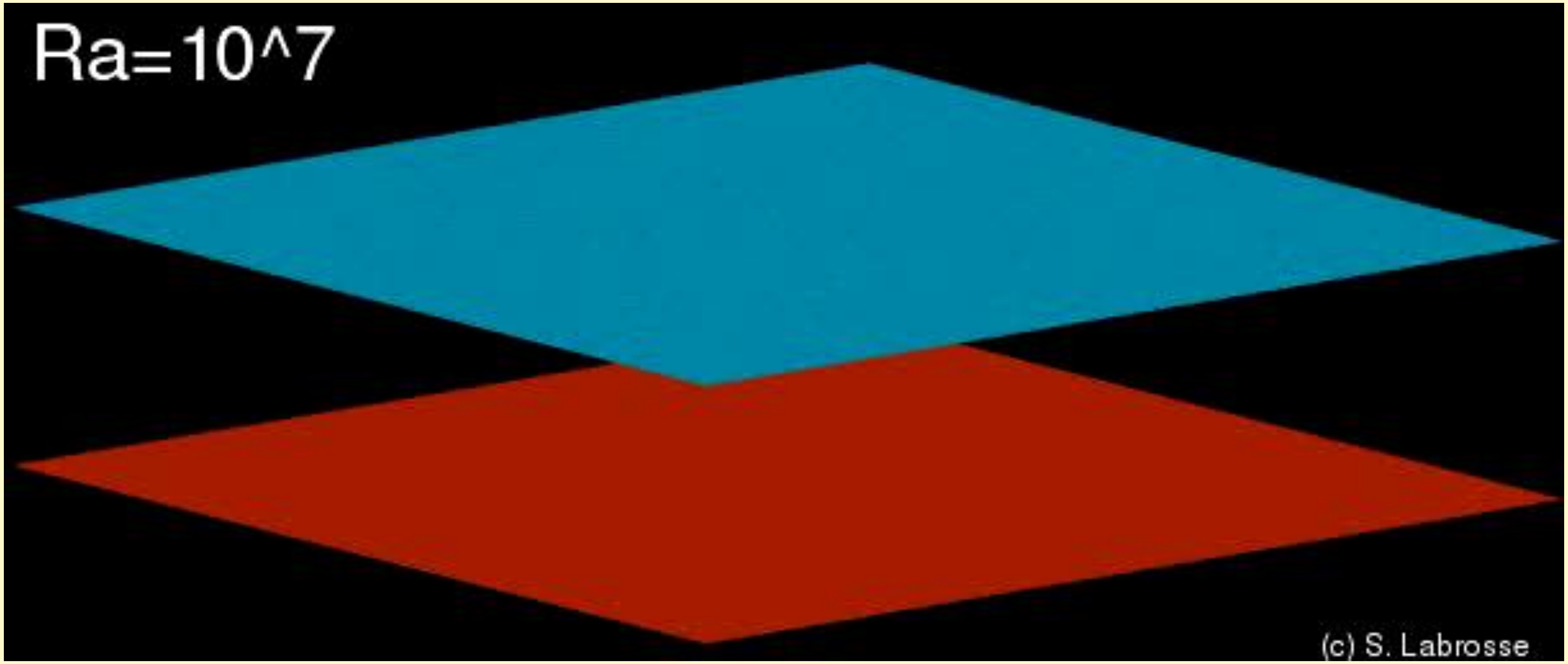
→ Vigorous Convection!

How to solve for mantle dynamics using a computer:

1. Express the physics of convection using equations

Conserve Mass:	$\nabla \cdot \boldsymbol{v} = 0$
Conserve Momentum:	$-\nabla p + \eta \nabla^2 \boldsymbol{v} + \boldsymbol{f} = 0$
Conserve Energy:	$\delta T/\delta t + \boldsymbol{v} \cdot \nabla T = \kappa \nabla^2 T + H/C$

2. Solve these equations for the mantle geometry



Stéphane Labrosse website

How to solve for mantle dynamics using a computer:

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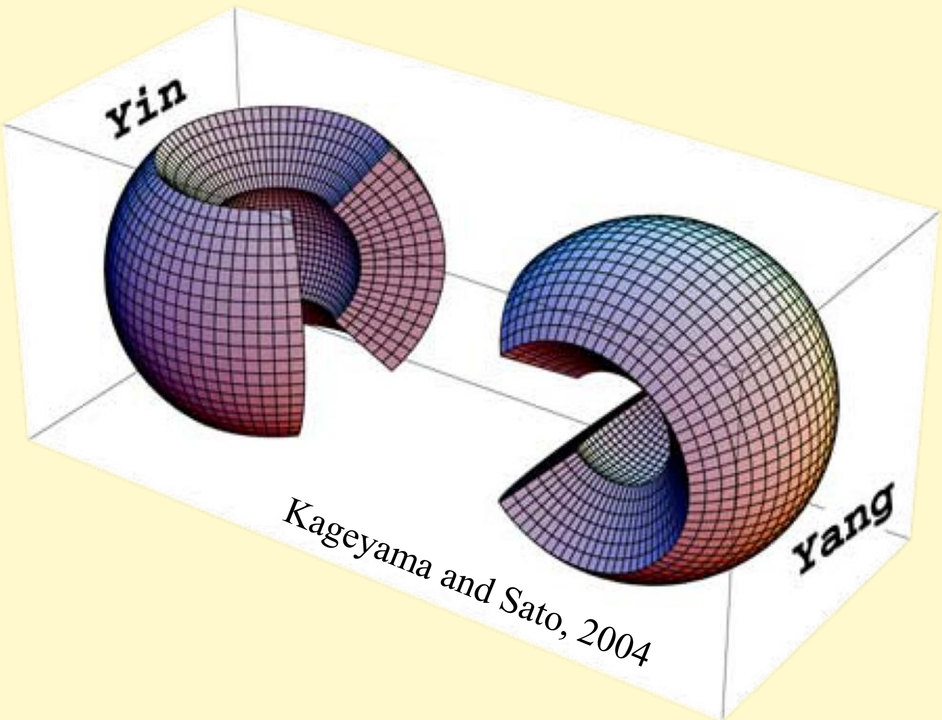
Conserve Energy:	$\delta T / \delta t + \boldsymbol{v} \cdot \nabla T = \kappa \nabla^2 T + H/C$

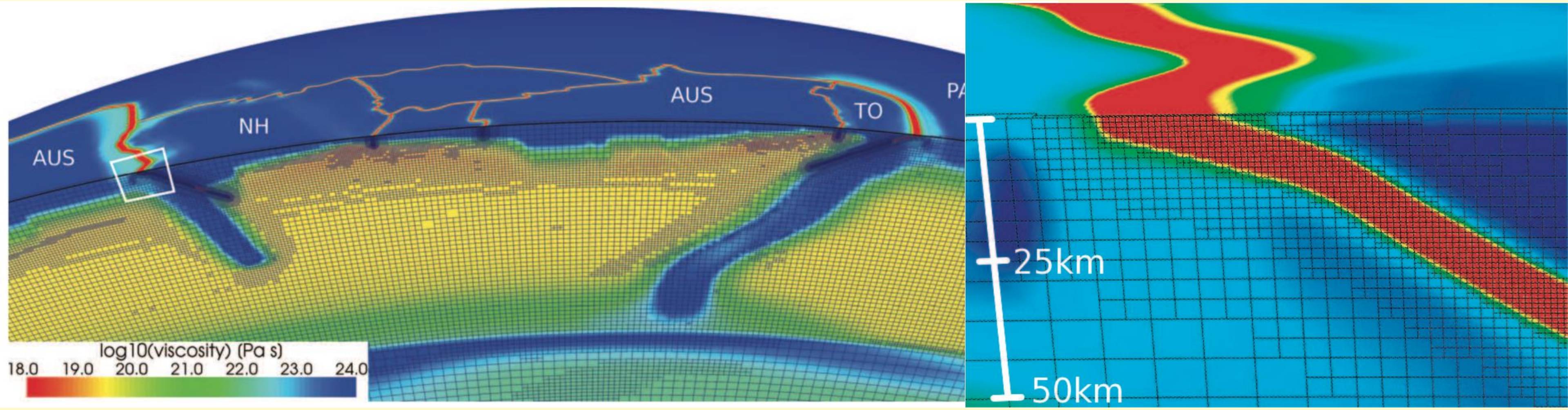
2. Solve these equations for the mantle geometry

An grid useful
for the mantle



How to solve for mantle dynamics using a computer:

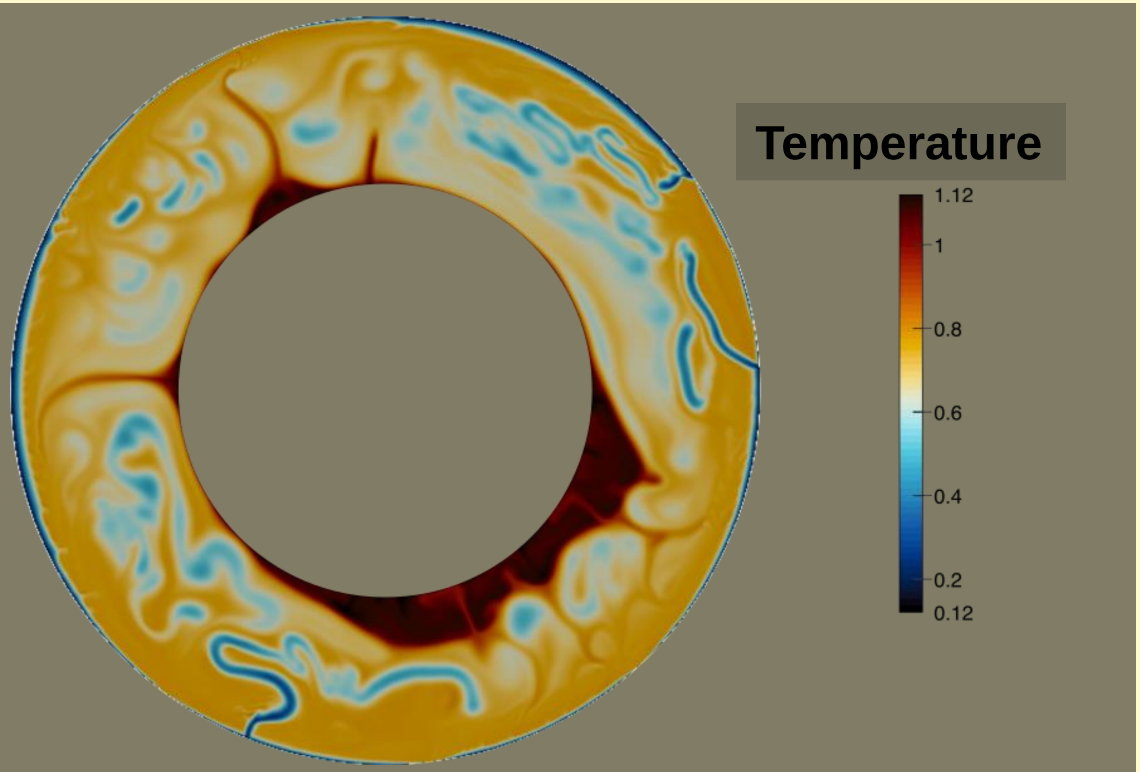
1. **Express the physics of convection using equations**
2. **Solve these equations for the mantle geometry**
3. **We must make some <u>major</u> simplifications:**
   → Our model will have less complexity than Earth



Stadler et al. [2010]

How to solve for mantle dynamics using a computer:

1. **Express the physics of convection using equations**
2. **Solve these equations for the mantle geometry**
2. **We must make some <u>major</u> simplifications**
3. **We must make some <u>major</u> assumptions:**
   → We can't be sure of the interior structures



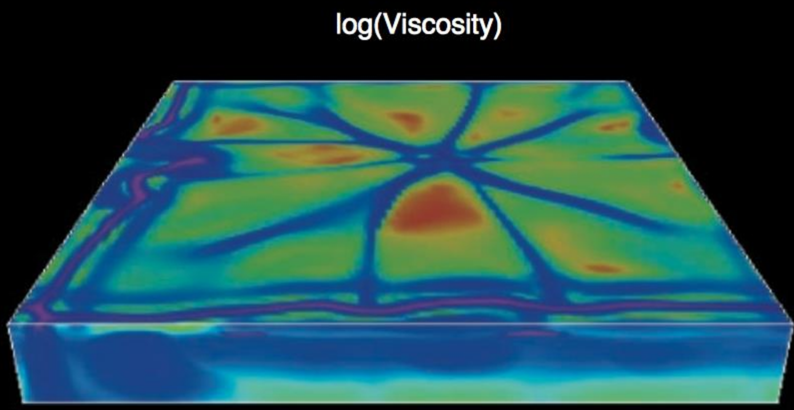
How stiff is the mantle?

→ Cold temperatures make rocks stiffer

→ The tectonic plates should be very stiff!

Arnauld & Coltice [2018]

How stiff are the plates?

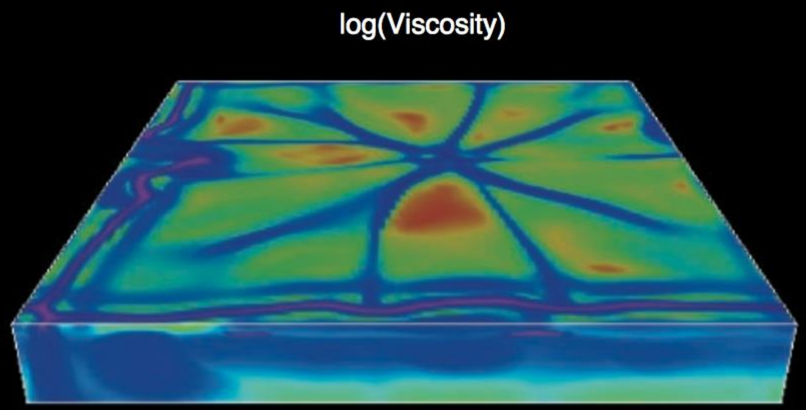


Red → no deformation
Green → slow deformation
Blue → fast deformation

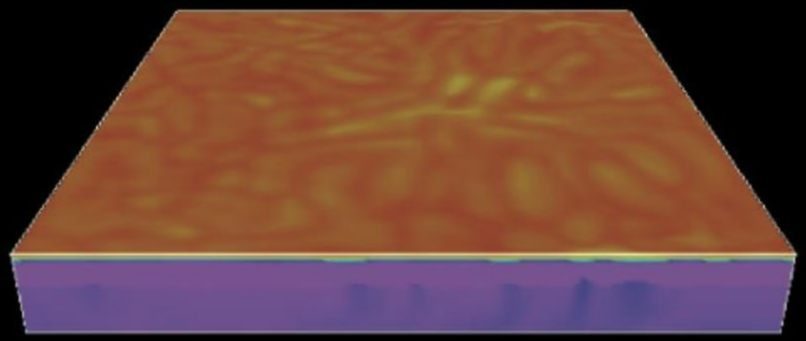
Tackley [2000]

Weak plates
→ Deformation is distributed across the plate

How stiff are the plates?



Red → no deformation
Green → slow deformation
Blue → fast deformation

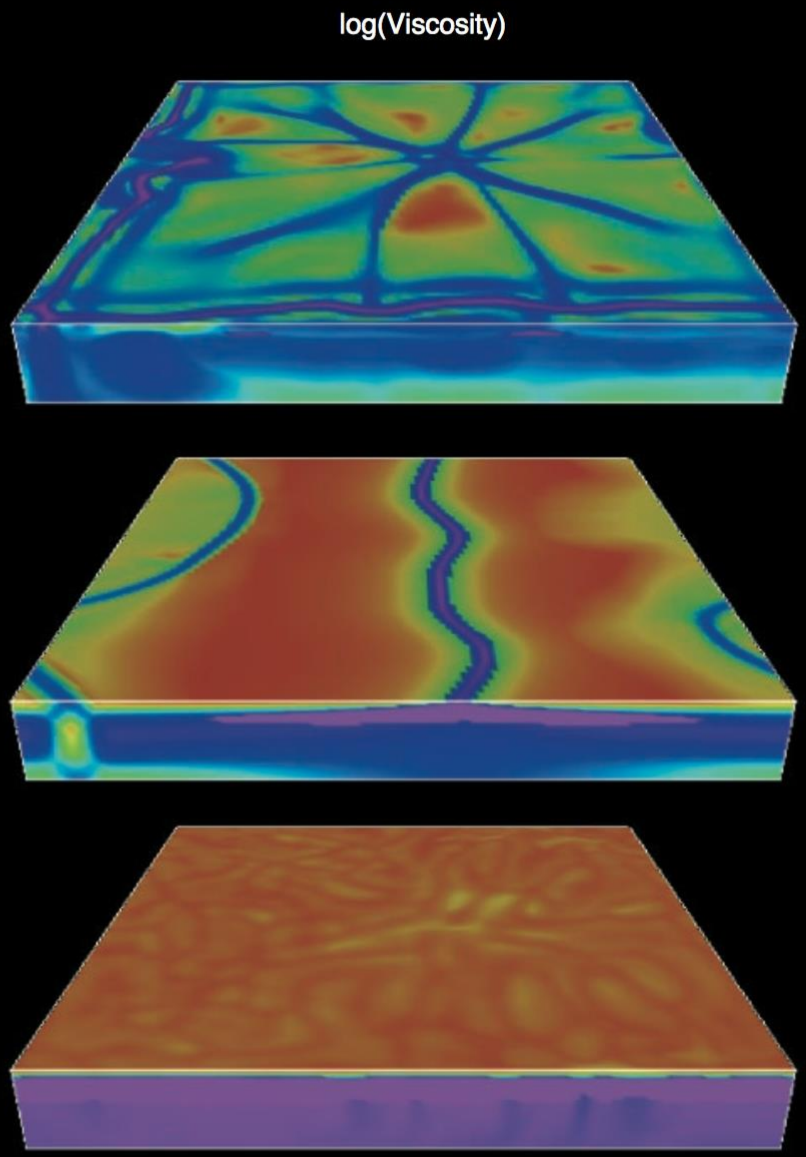


Tackley [2000]

Weak plates
→ Deformation is distributed across the plate

Strong plates
→ The plates cannot deform

How stiff are the plates?



Tackley [2000]

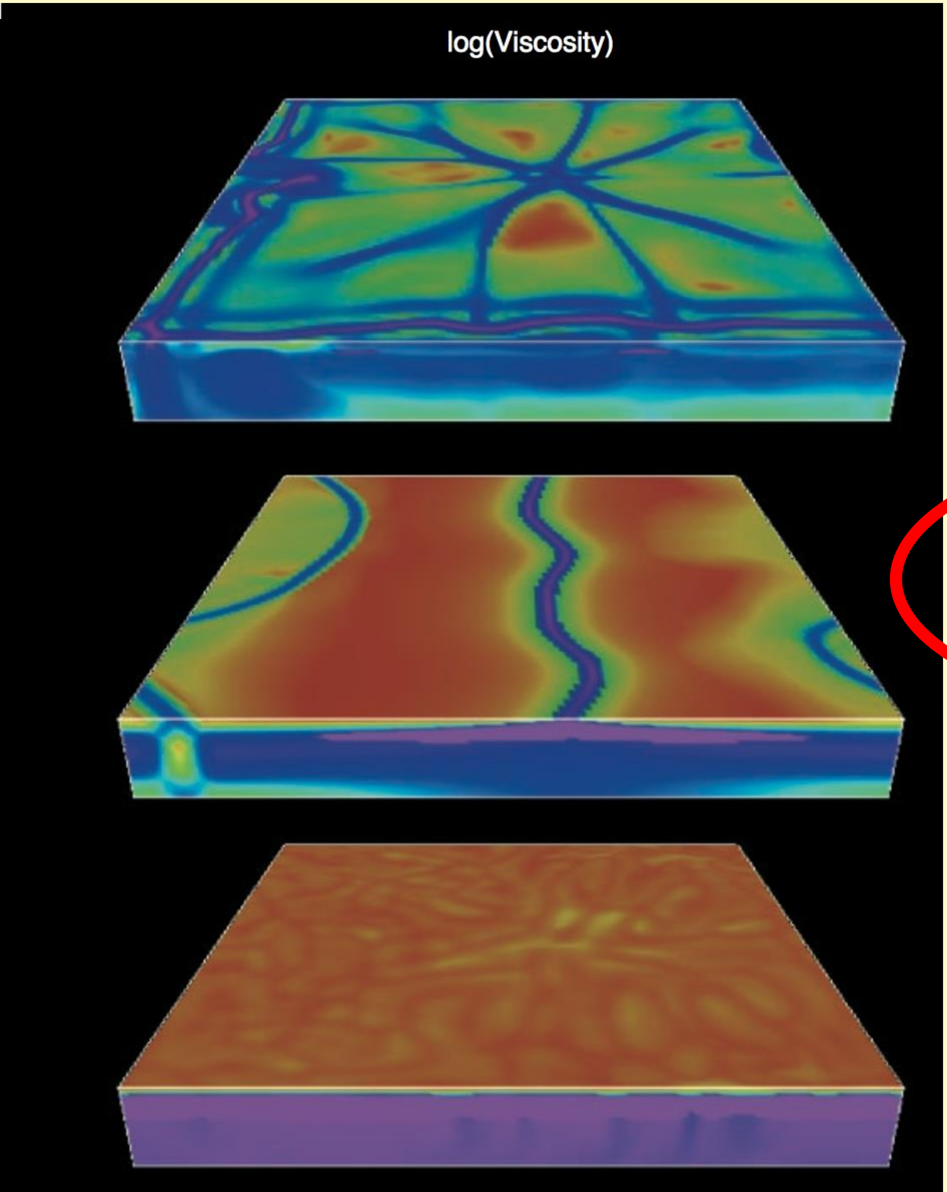
Weak plates
→ **Deformation is distributed across the plate**

Intermediate stiffness
→ **Deformation is localized at plate boundaries**

Strong plates
→ **The plates cannot deform**

Red → no deformation
Green → slow deformation
Blue → fast deformation

How stiff are the plates?



Tackley [2000]

Weak plates
→ Deformation is distributed across the plate

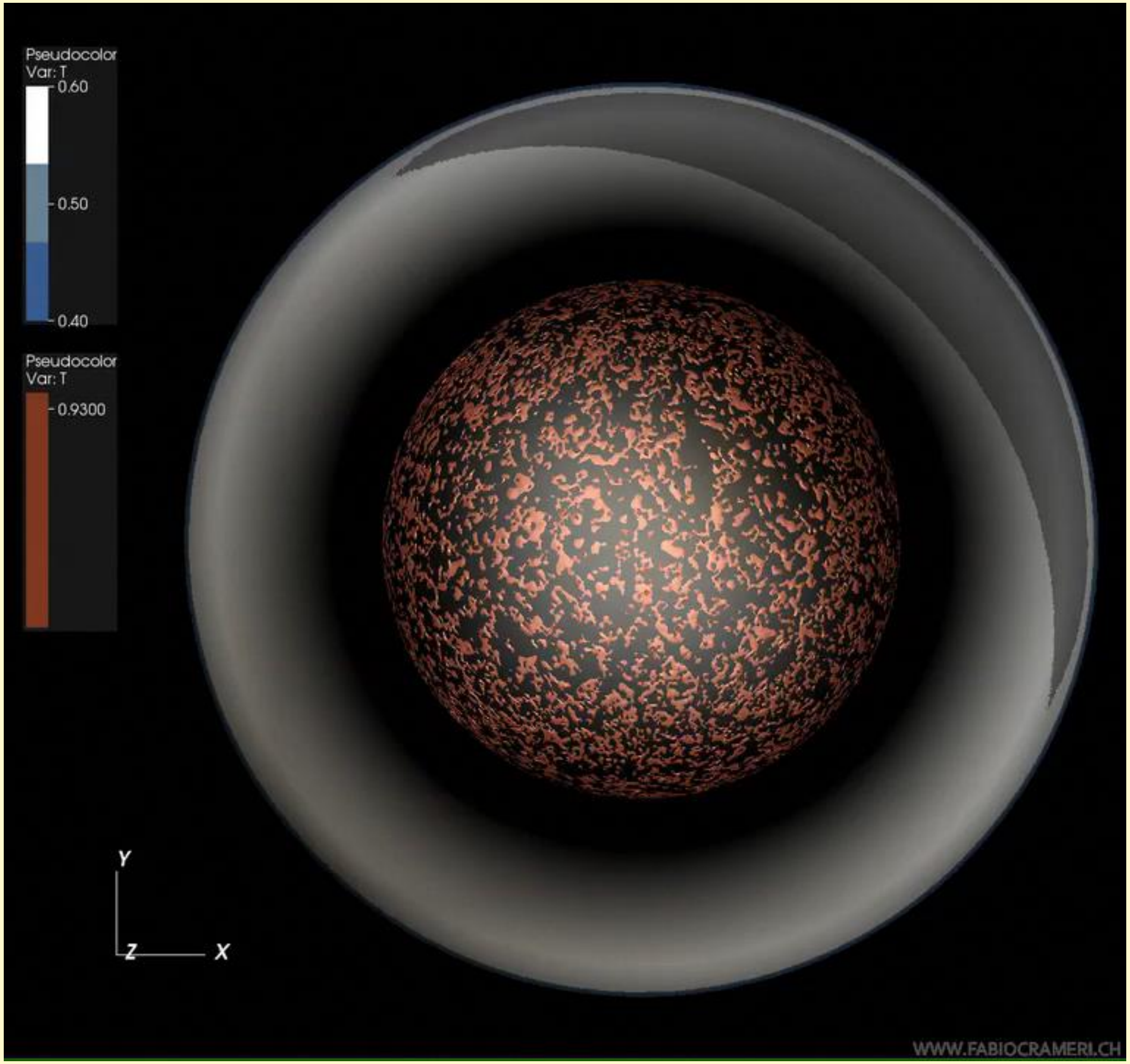
The most Earth-like model!

Intermediate stiffness
→ Deformation is localized at plate boundaries

Strong plates
→ The plates cannot deform

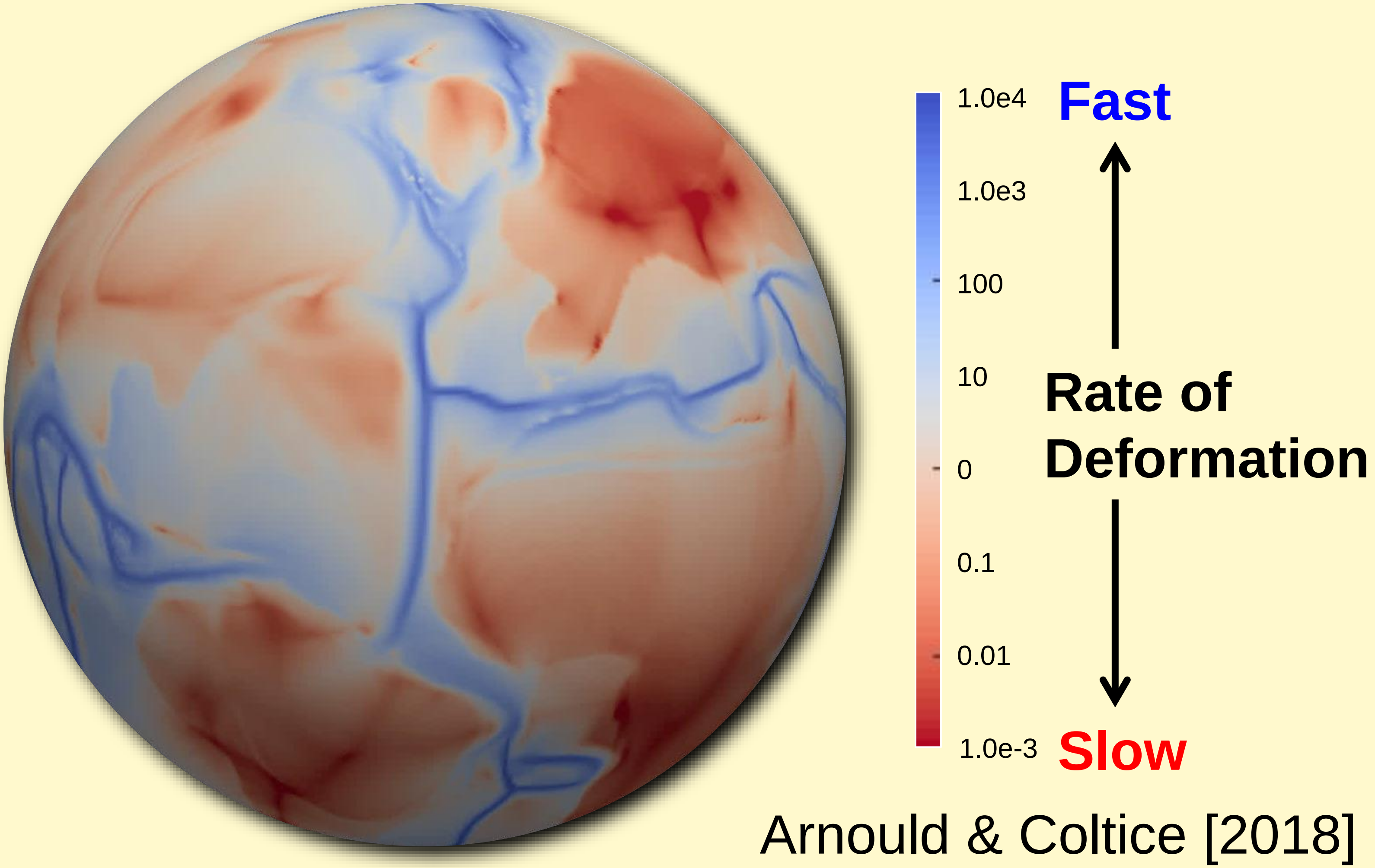
Red → no deformation
Green → slow deformation
Blue → fast deformation

Mantle Convection: The role of plate motions



Crameri & Tackley [2016]

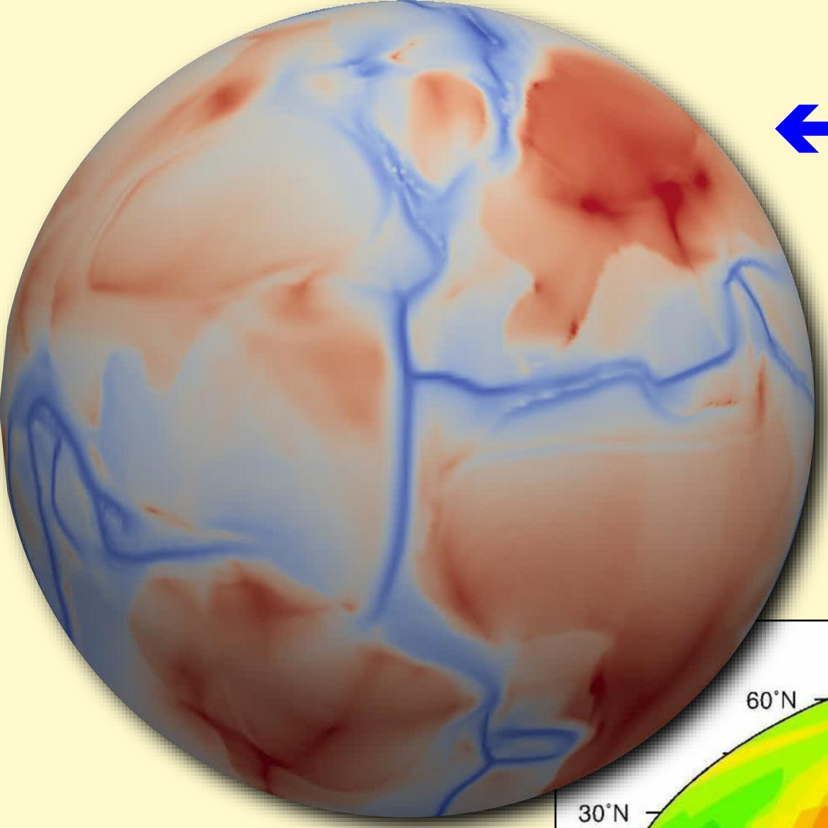
Testing Mantle Convection Models



Arnould & Coltice [2018]

Is this a useful representation of plate tectonics?

→ How to test this model?

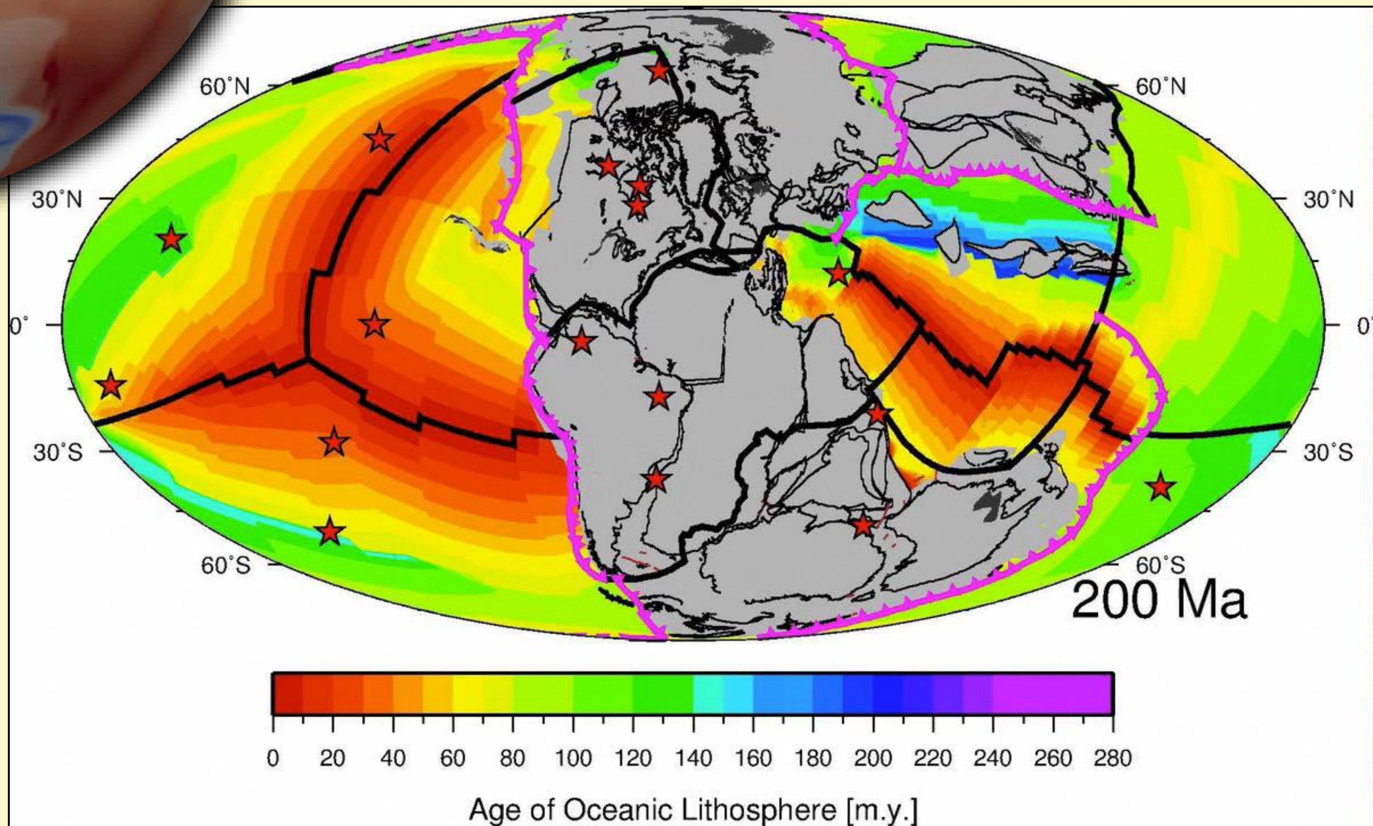


← **Mantle Flow Model**

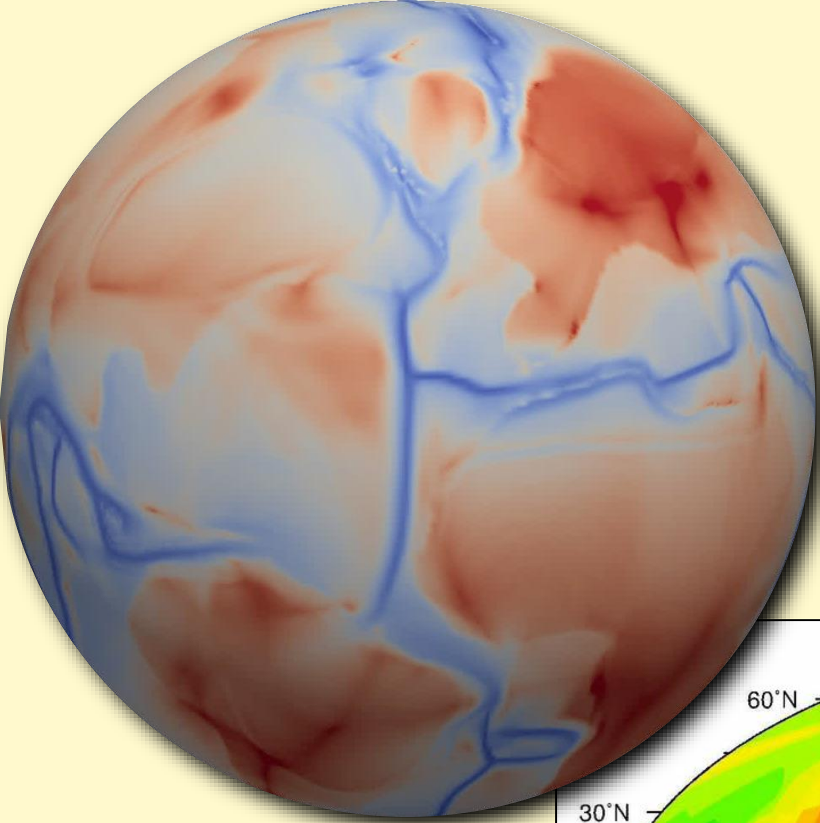
[*Arnould & Coltice*, 2018]

How do they compare?

Observation:
Plate Reconstruction ↓



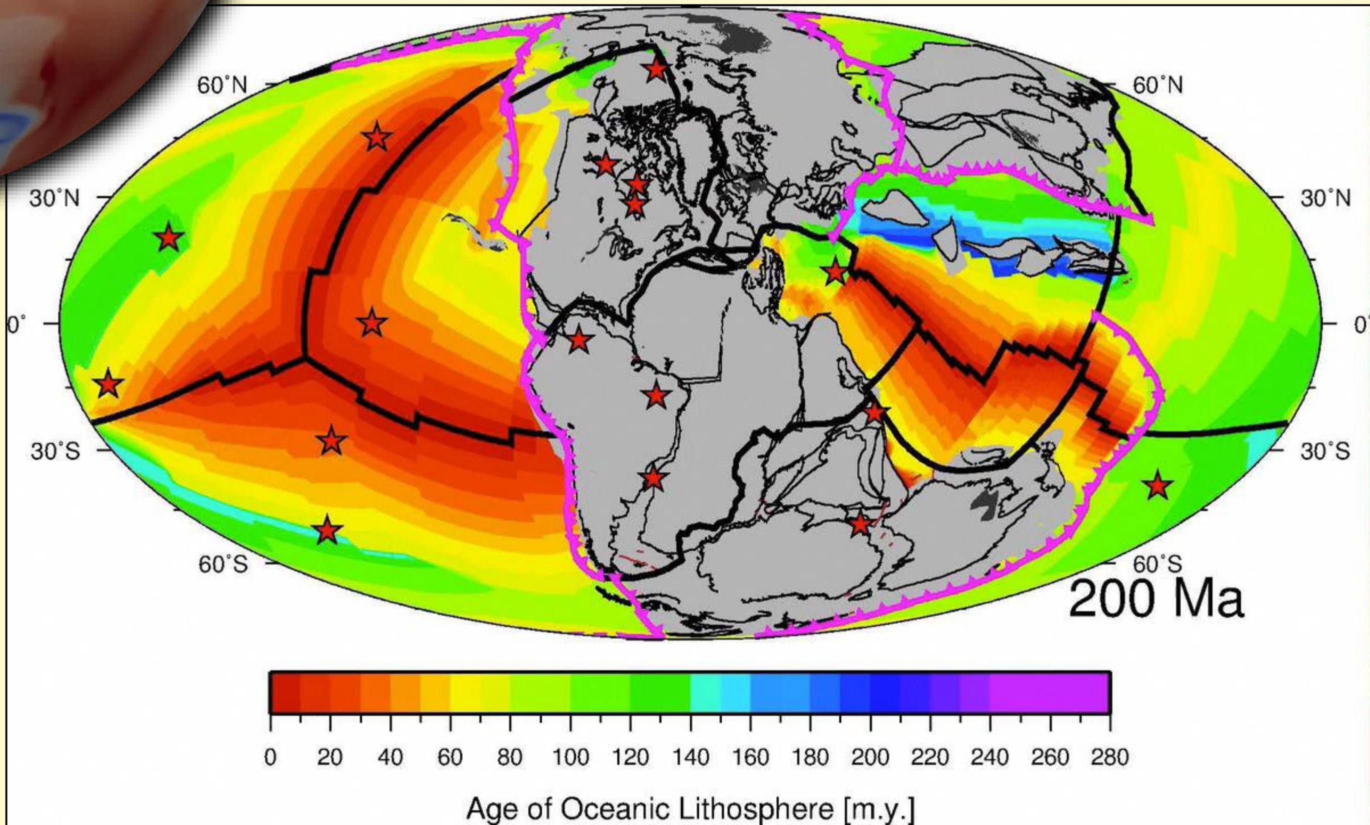
Seton et al. [2012]



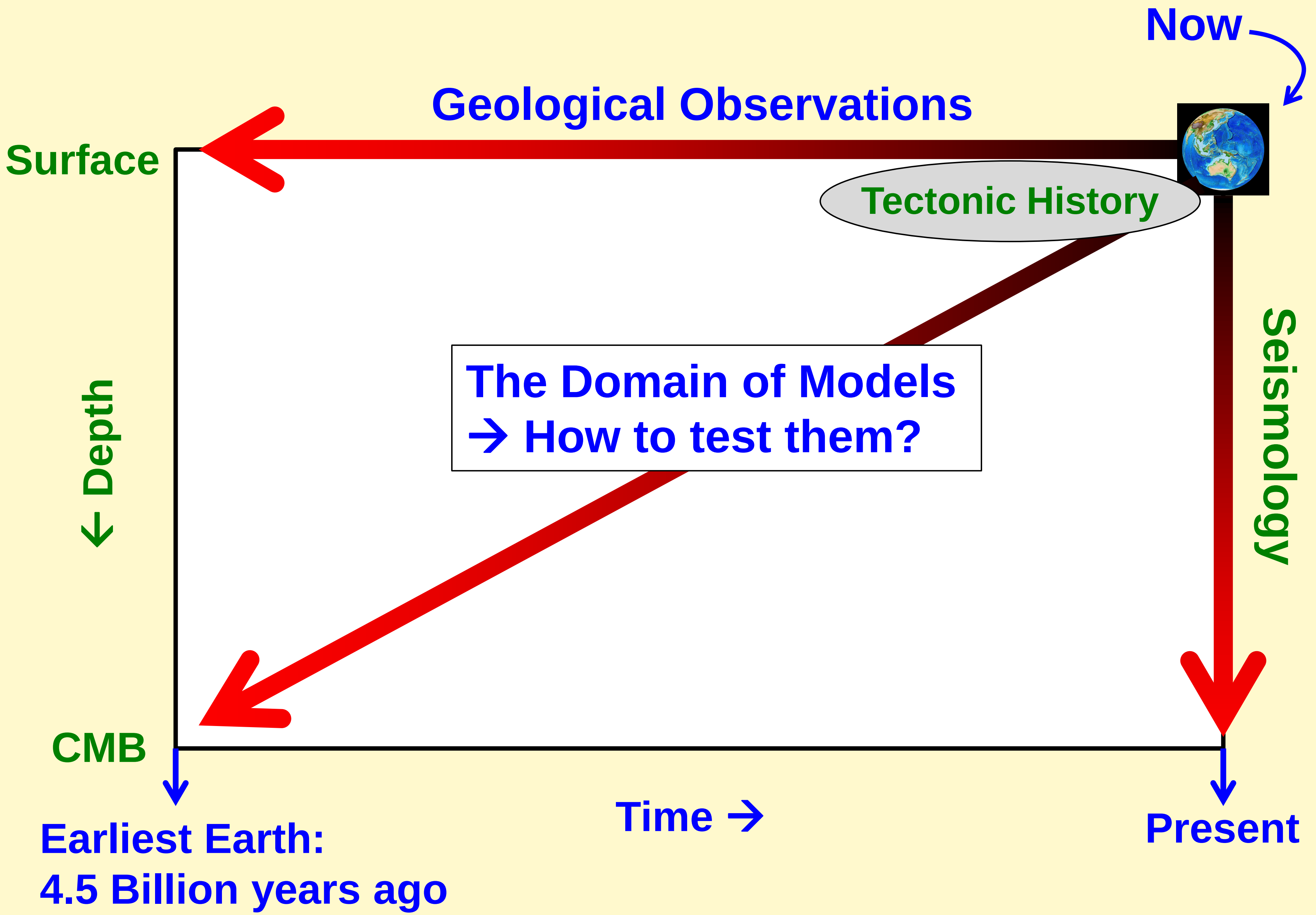
7 comparisons:

→ Spacing of boundaries
→ Length & Width of boundaries
→ Duration of boundaries
→ Deformation rate
→ Migration rate of boundaries
→ Boundary type

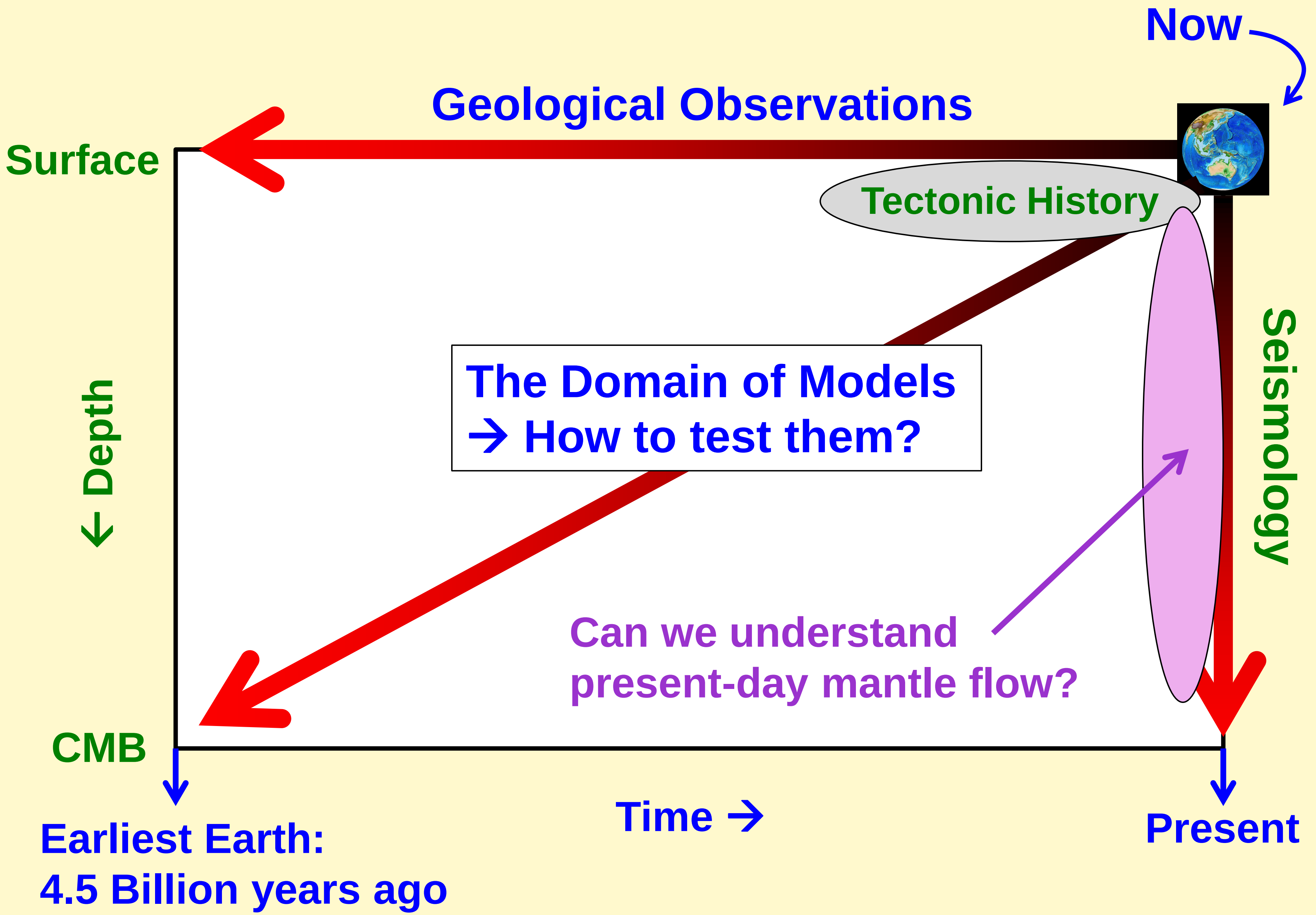
[*Arnould & Coltice*, 2018]



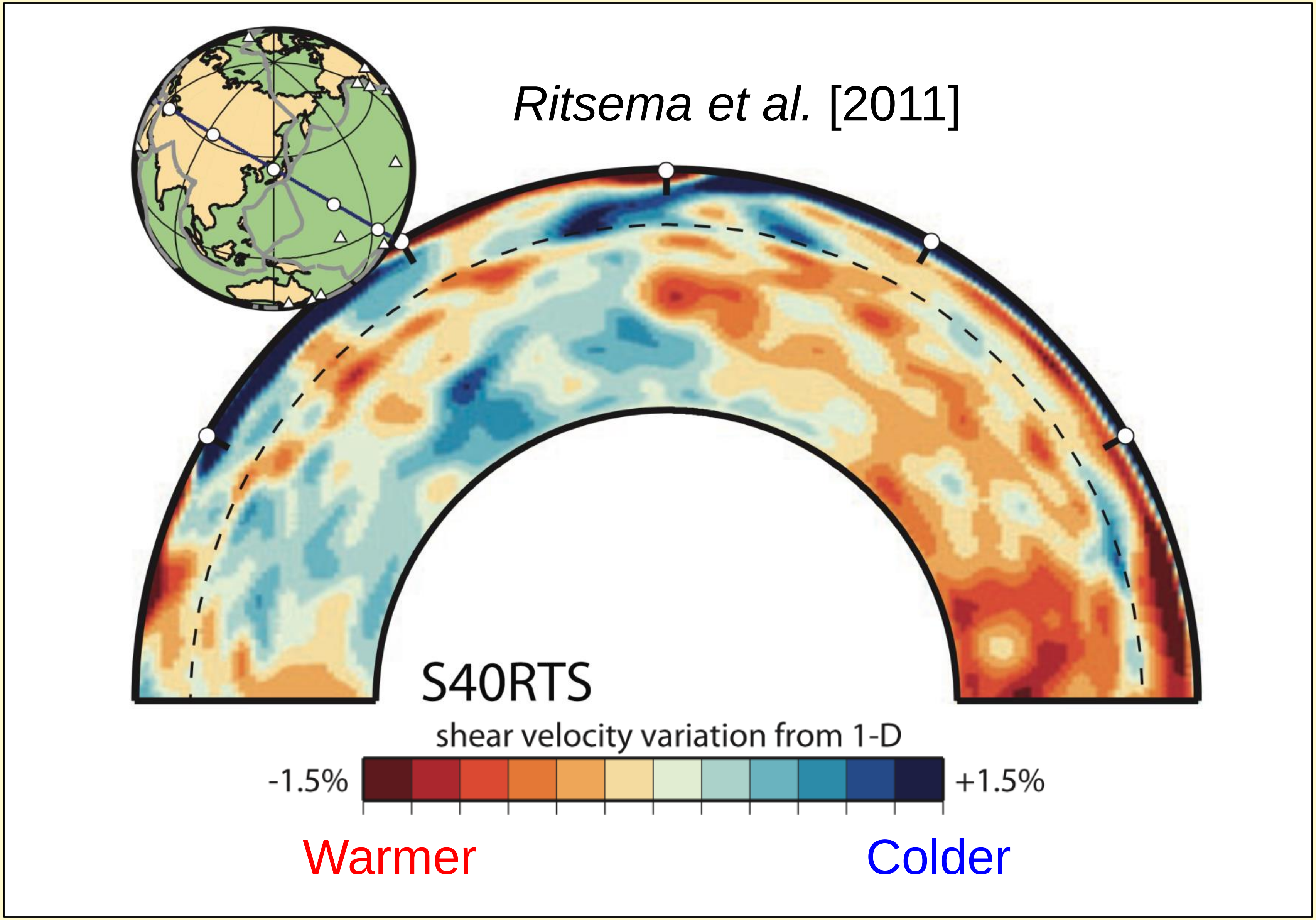
Seton et al. [2012]



Now
Geological Observations
Surface
Tectonic History
↓ Depth
Seismology
The Domain of Models
→ How to test them?
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present


Now
Geological Observations
Surface
Tectonic History
Seismology
↓ Depth
The Domain of Models
→ How to test them?
Can we understand
present-day mantle flow?
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present

Seismology shows us a snapshot of mantle structures
→ What is the flow pattern?



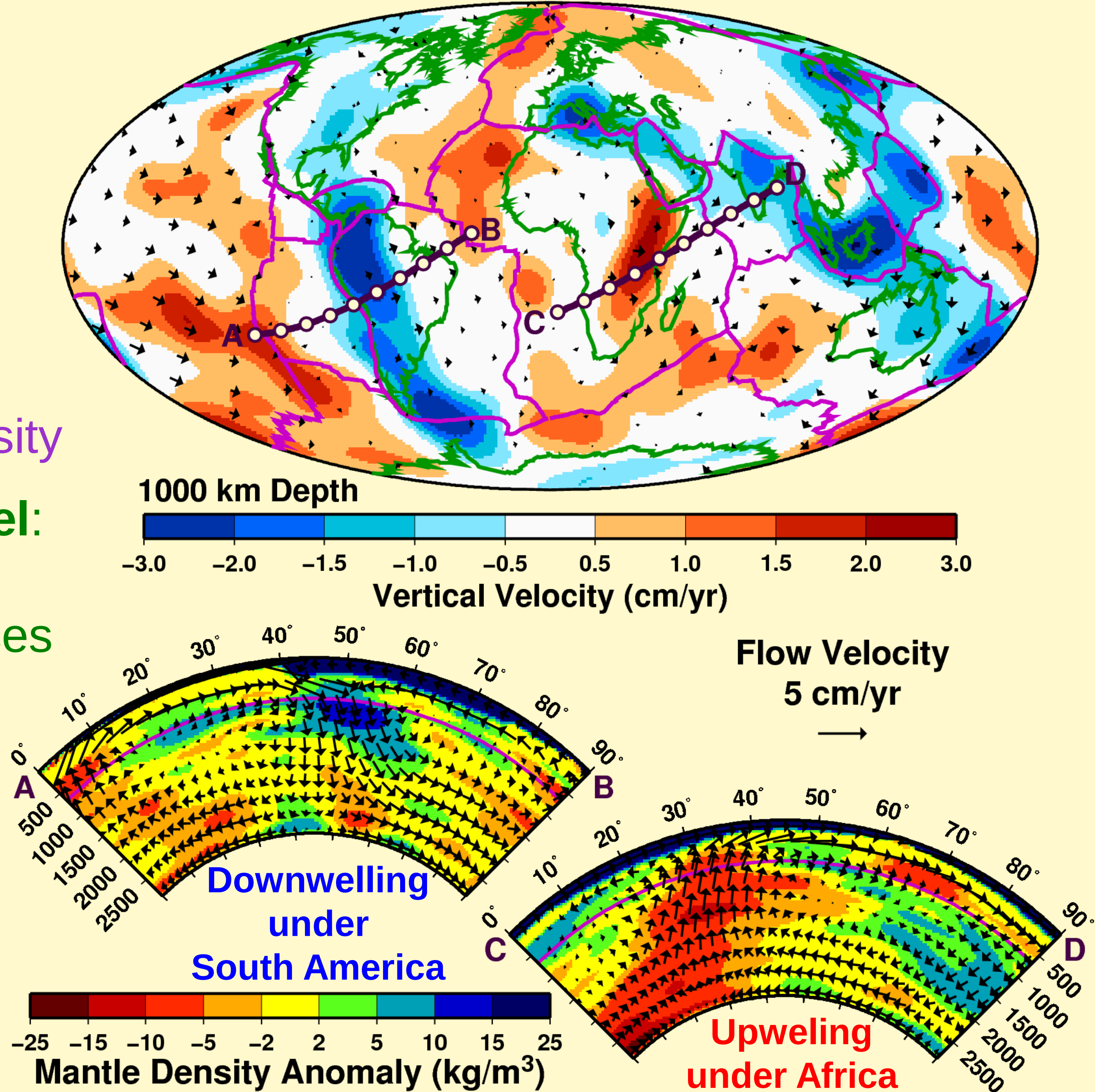
Global Mantle Circulation Models

Input:

- Mantle Densities
- Mantle Viscosity

Output of Model:

- Mantle Flow
- Tectonic Forces
- Surface Deformation



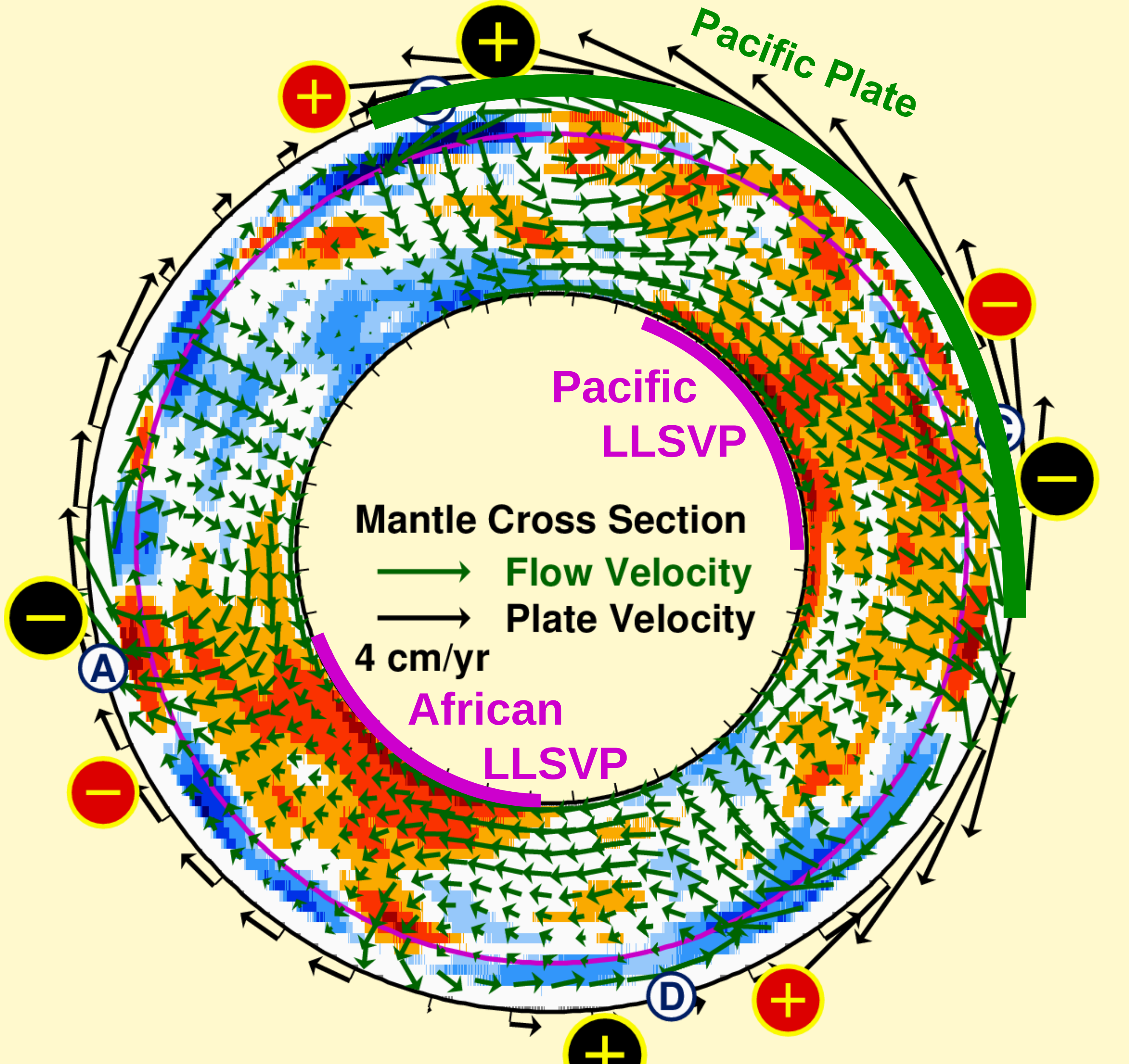
Global Mantle Circulation Models

Input:
- Mantle Densities
- Mantle Viscosity

Output of Model:
- Mantle Flow
- Tectonic Forces
- Surface Deformation

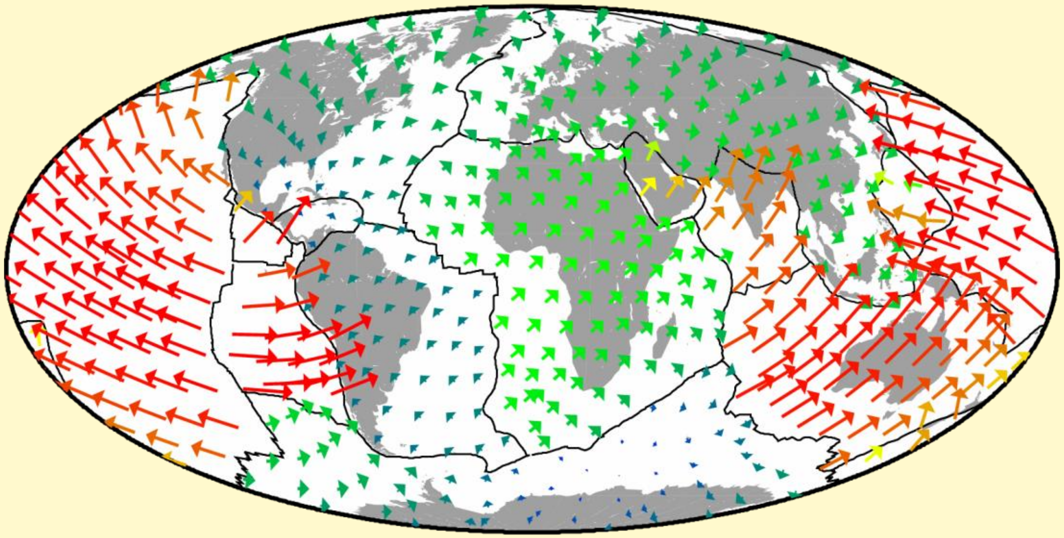
↓

Compare to Present-day Observations

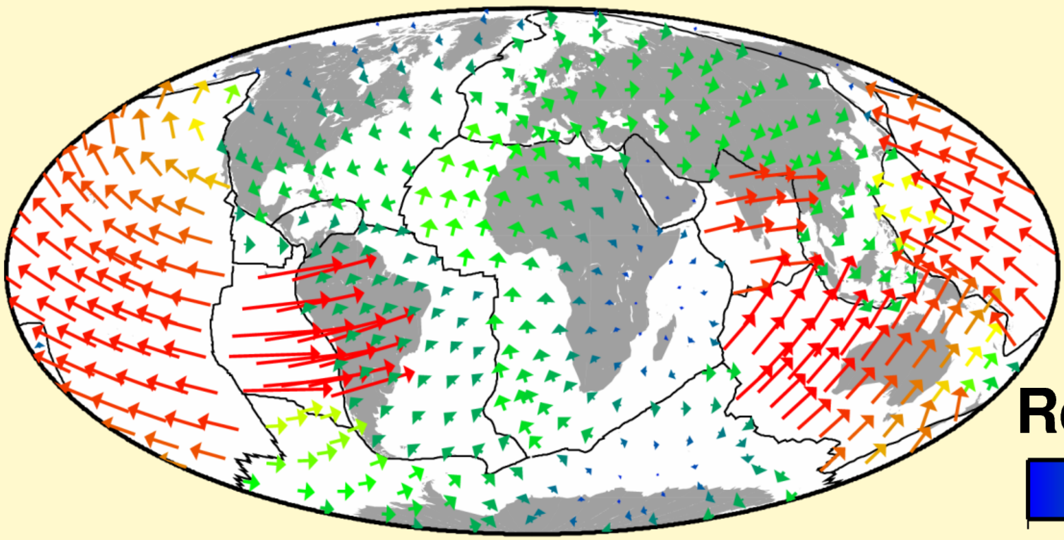


LLSVP = Large Low Slow-Velocity Province
→ **Continent-sized structures on the CMB**

Observed Plate Motions

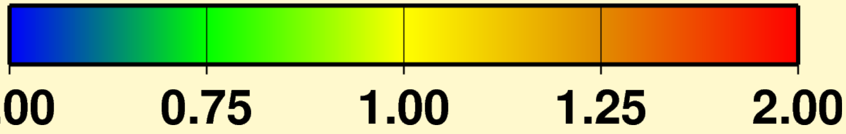


Predicted Plate Motions

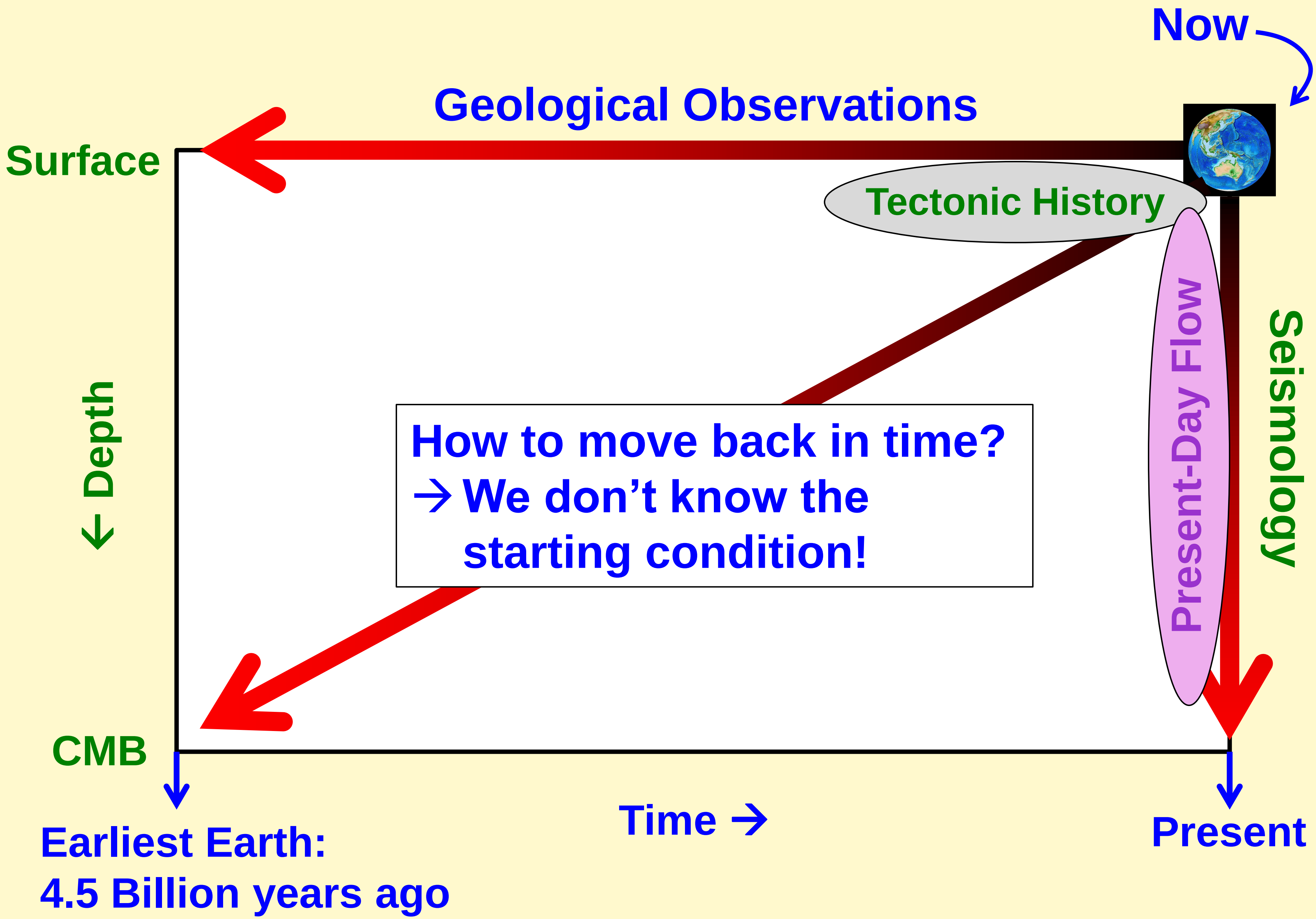


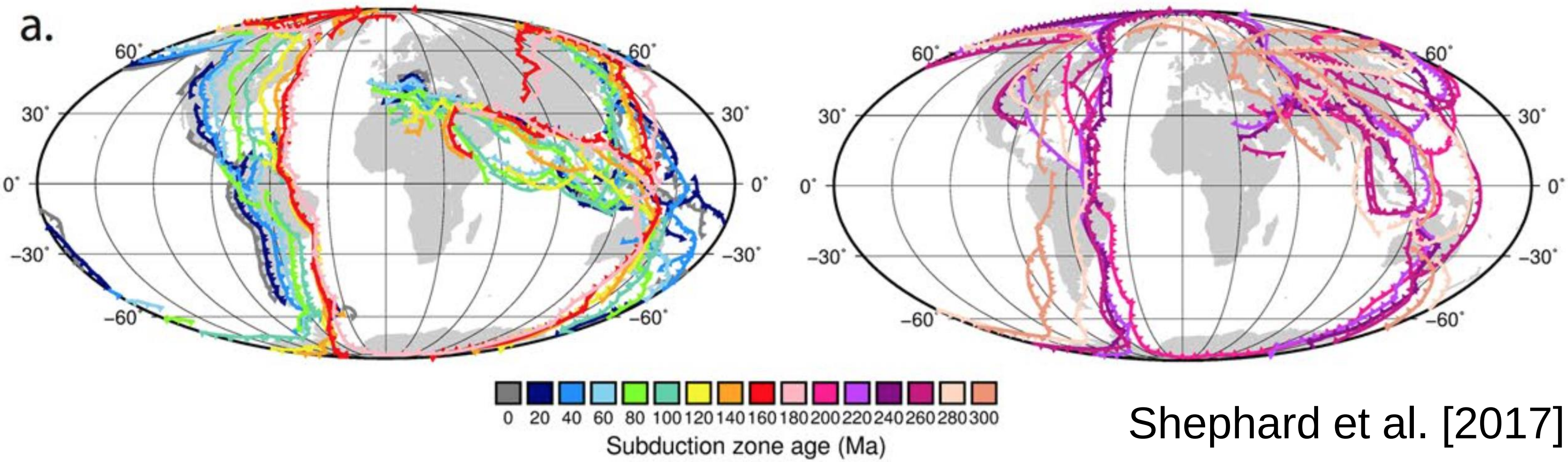
The flow model predicts plate motions!

Relative Velocity Magnitude

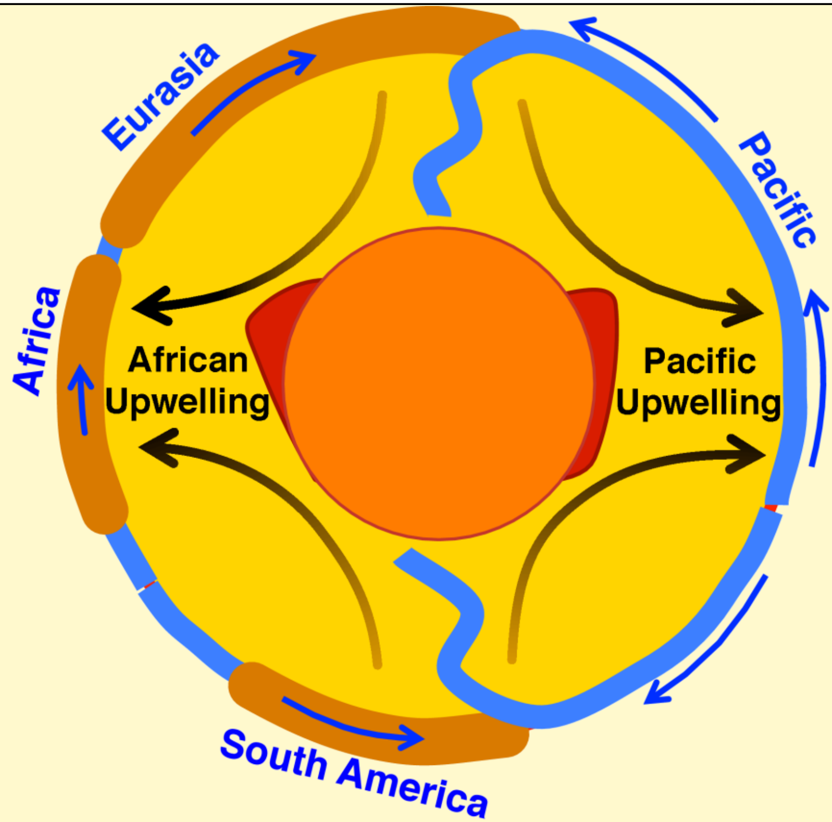


van Summeren et al. [2012]


Now
Geological Observations
Surface
Tectonic History
Present-Day Flow
Seismology
← Depth
How to move back in time?
→ We don't know the
starting condition!
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present



Shephard et al. [2017]

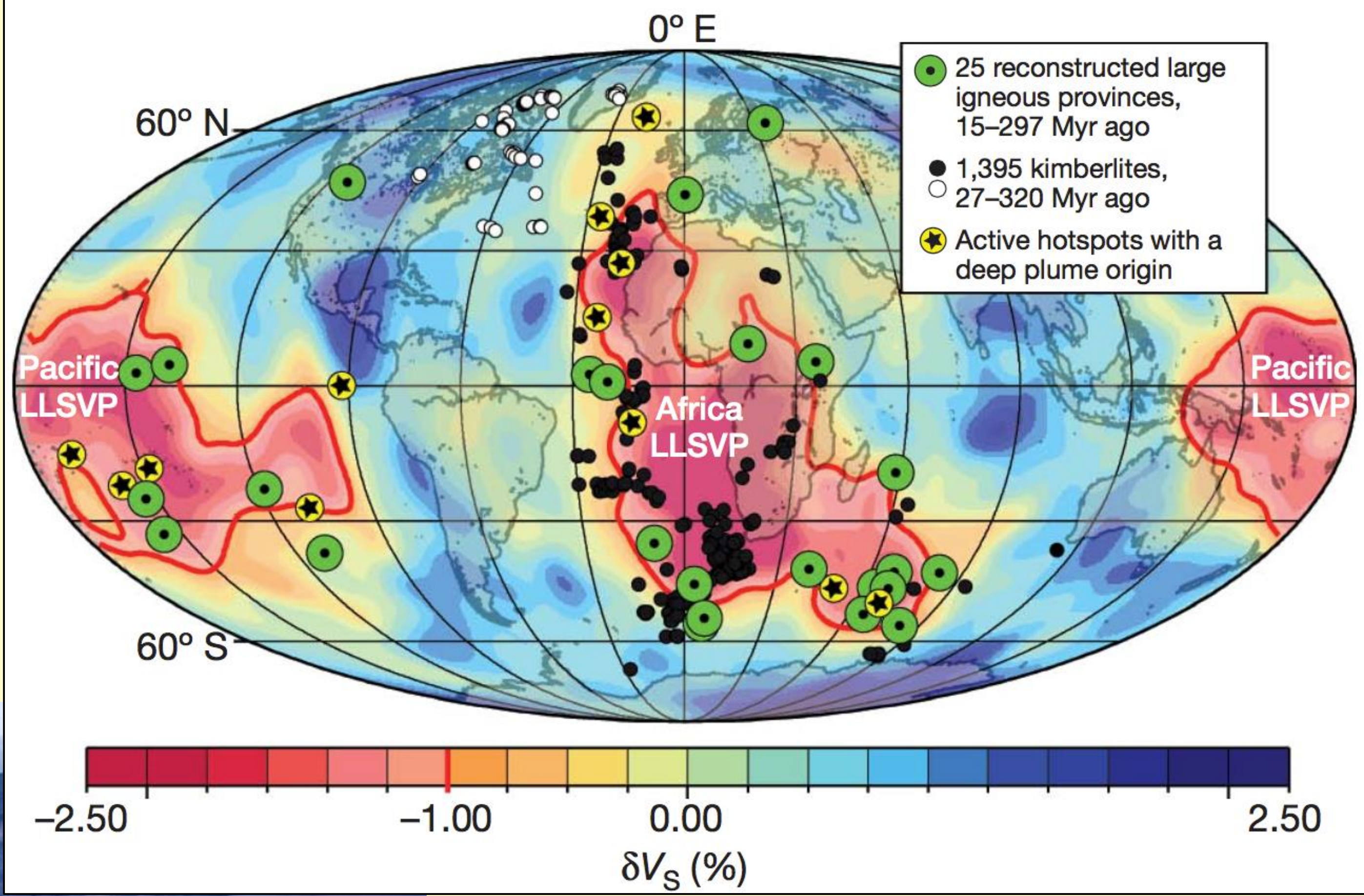


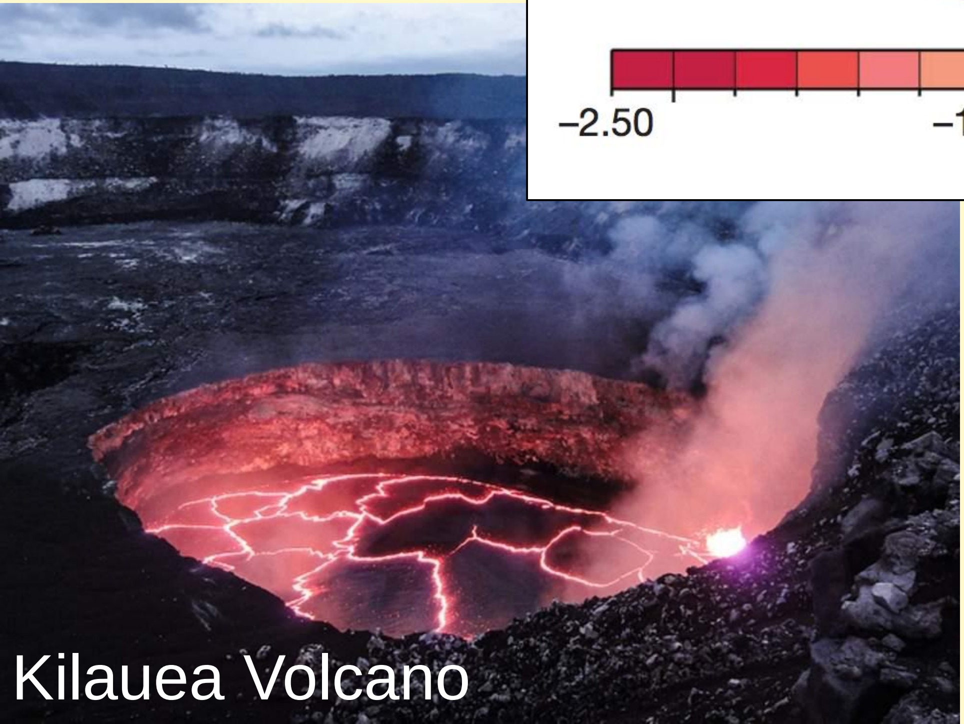
Looking backward in time

→ Subduction locations have mostly remained the same for 300 Myr!

Long-term stability for intraplate volcanism

→ Hotspots
→ Flood Basalts
→ Diamonds



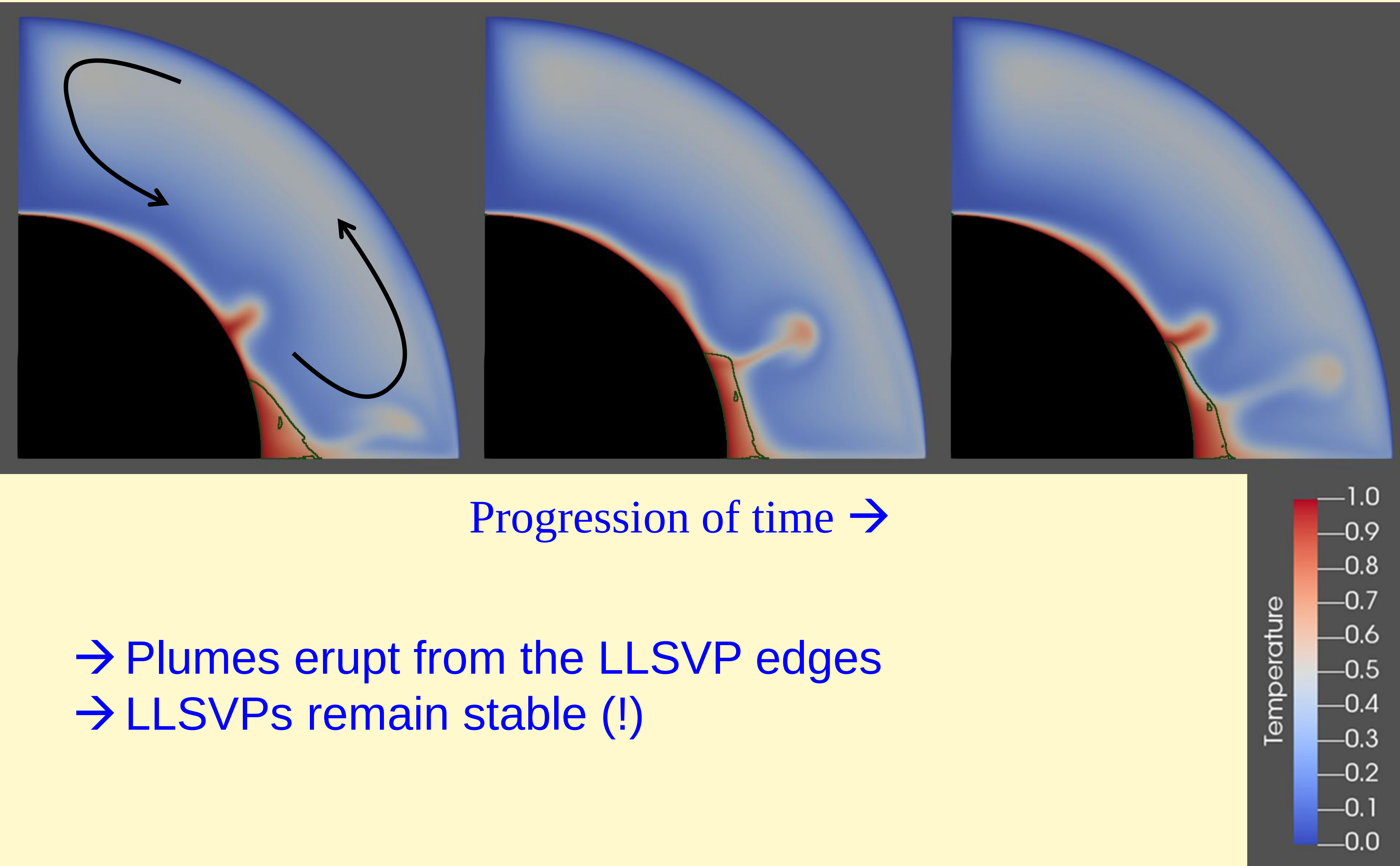


Plumes rise from the edges of the LLSVPs
(dense regions on the core-mantle boundary)

Torsvik et al., [*Nature*, 2010]

Why do plumes rise from the LLSVP edges?

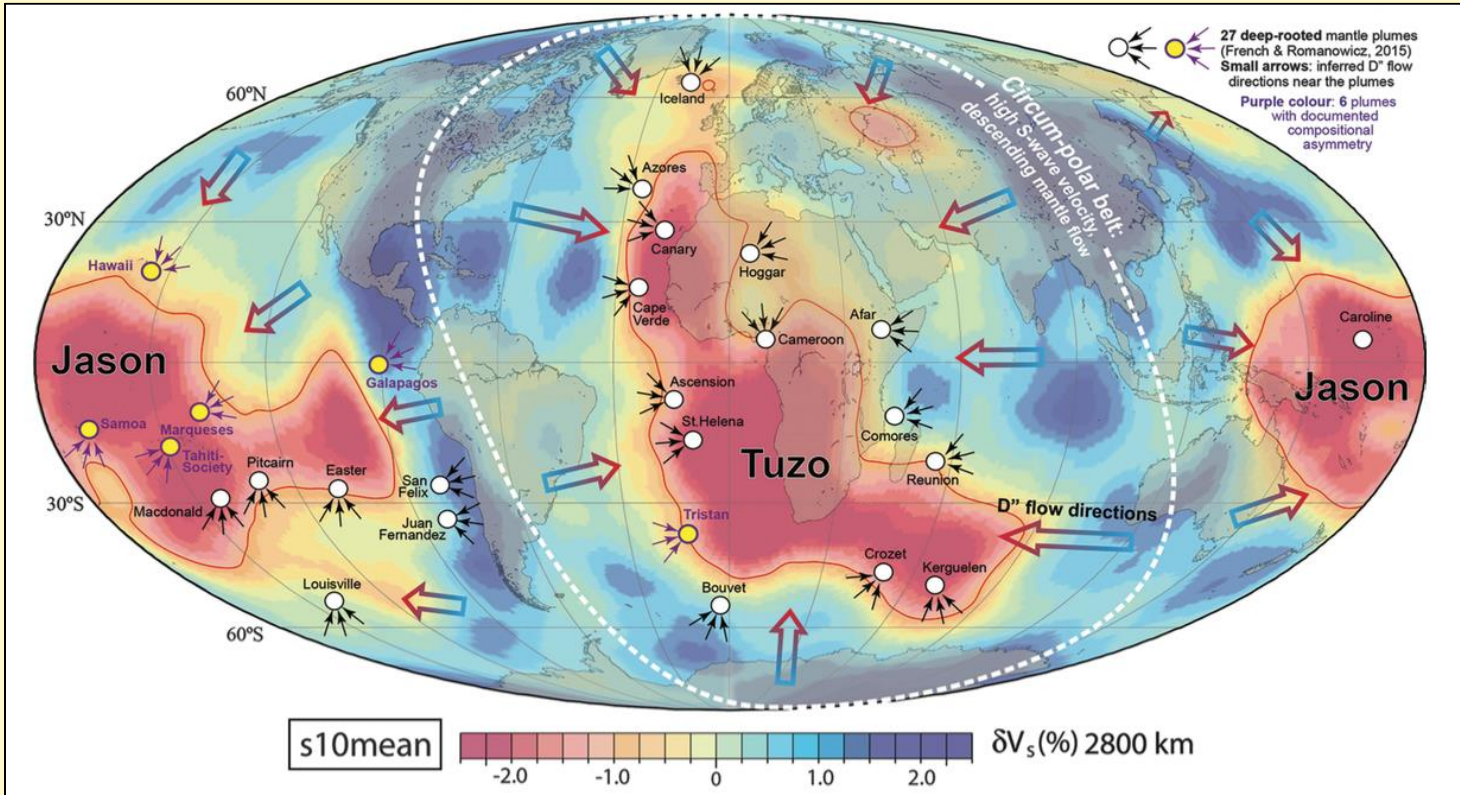
Heyn et al. [2018]

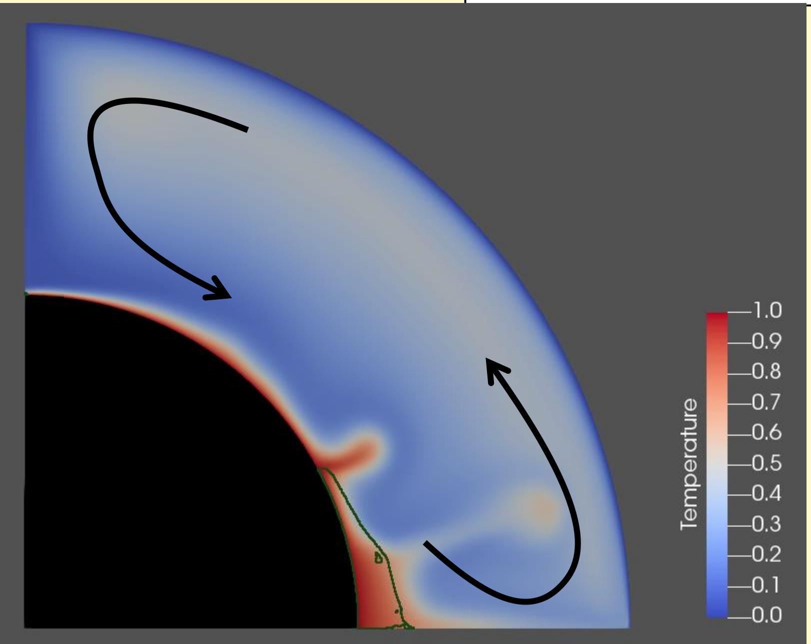


Progression of time →

→ Plumes erupt from the LLSVP edges
→ LLSVPs remain stable (!)

Torsvik et al. [2016]

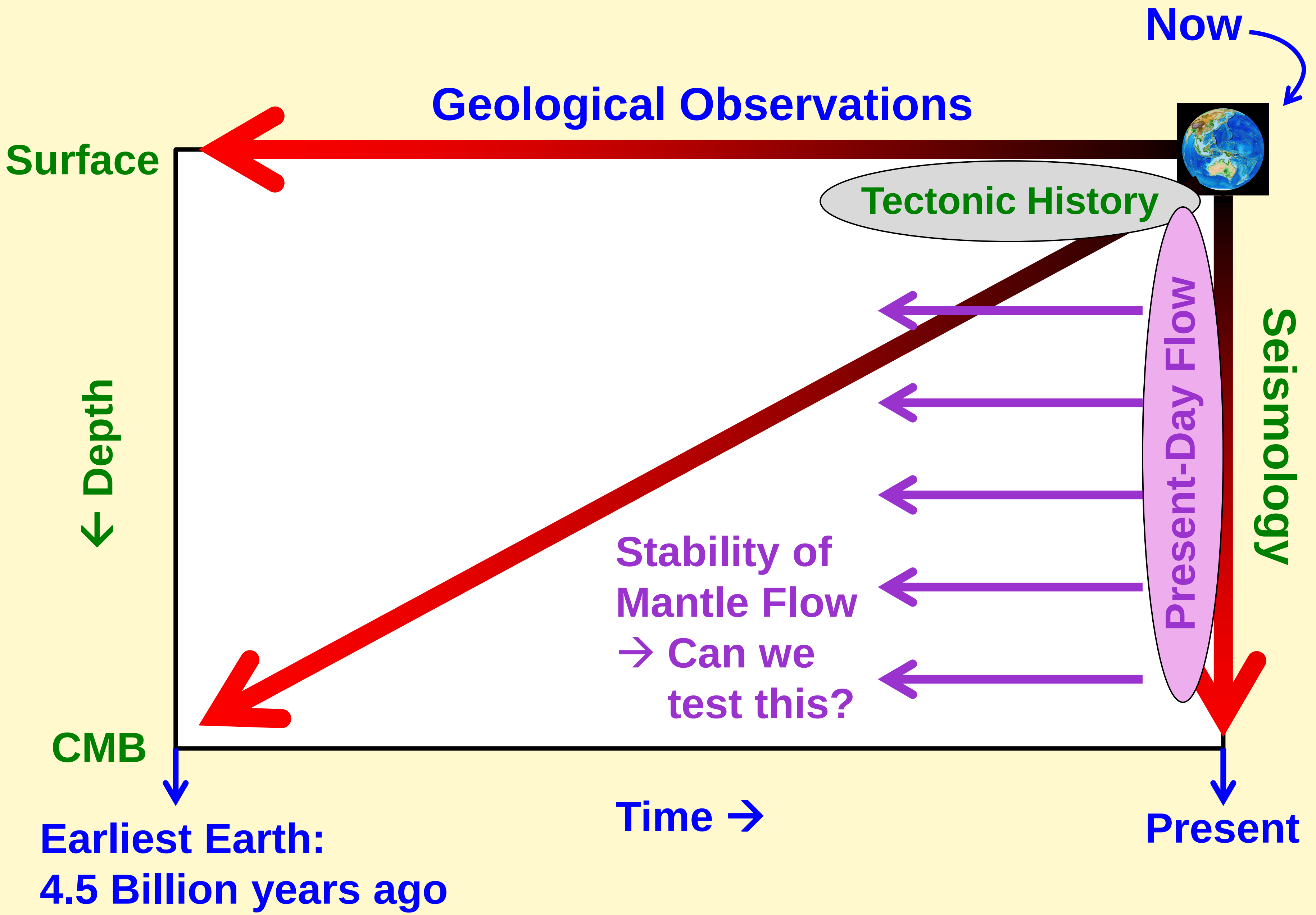




Long-Term Stability for Mantle Dynamics (!!!)

- Stable LLSVPS
- Stable circumpolar belt of subduction

→ Stable flow pattern: For how long?



Now
Geological Observations
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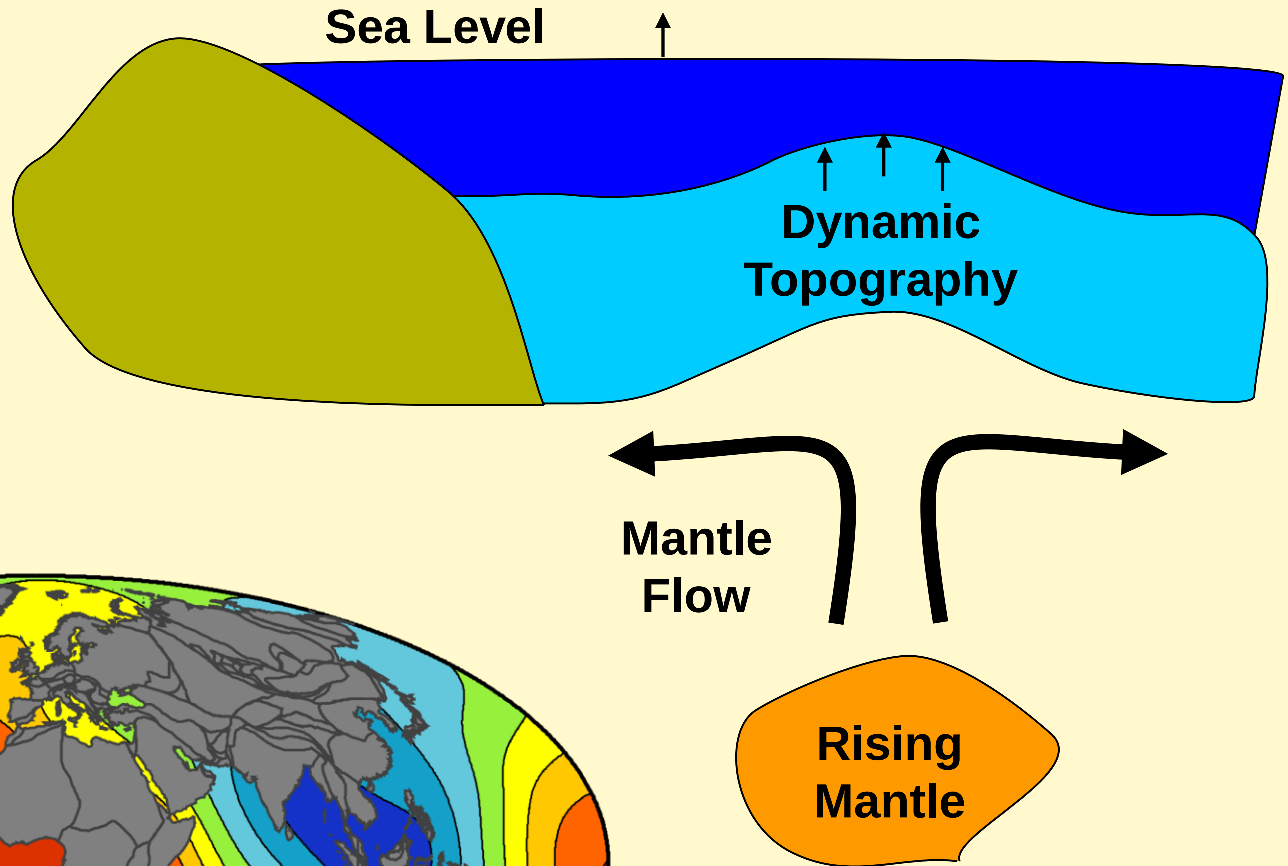
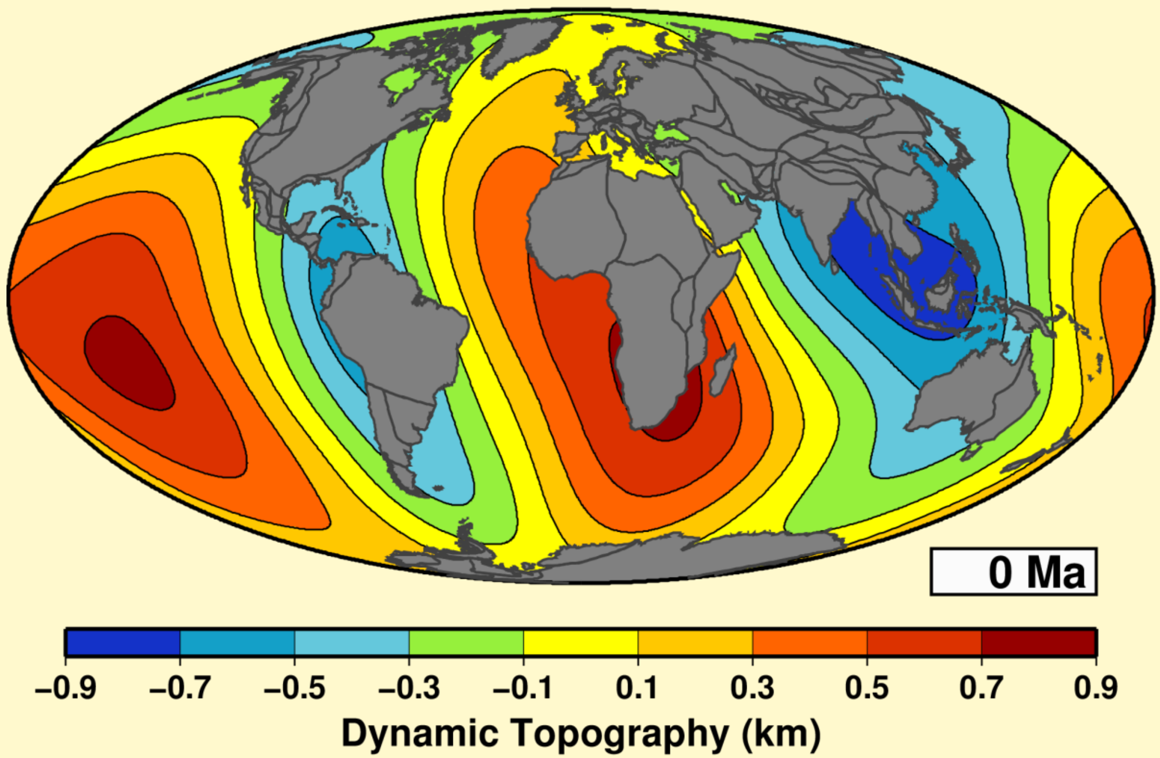
Present-Day Flow
Seismology
↓ Depth
Stability of
Mantle Flow
→ Can we
test this?
CMB
Time →
Earliest Earth:
4.5 Billion years ago
Present



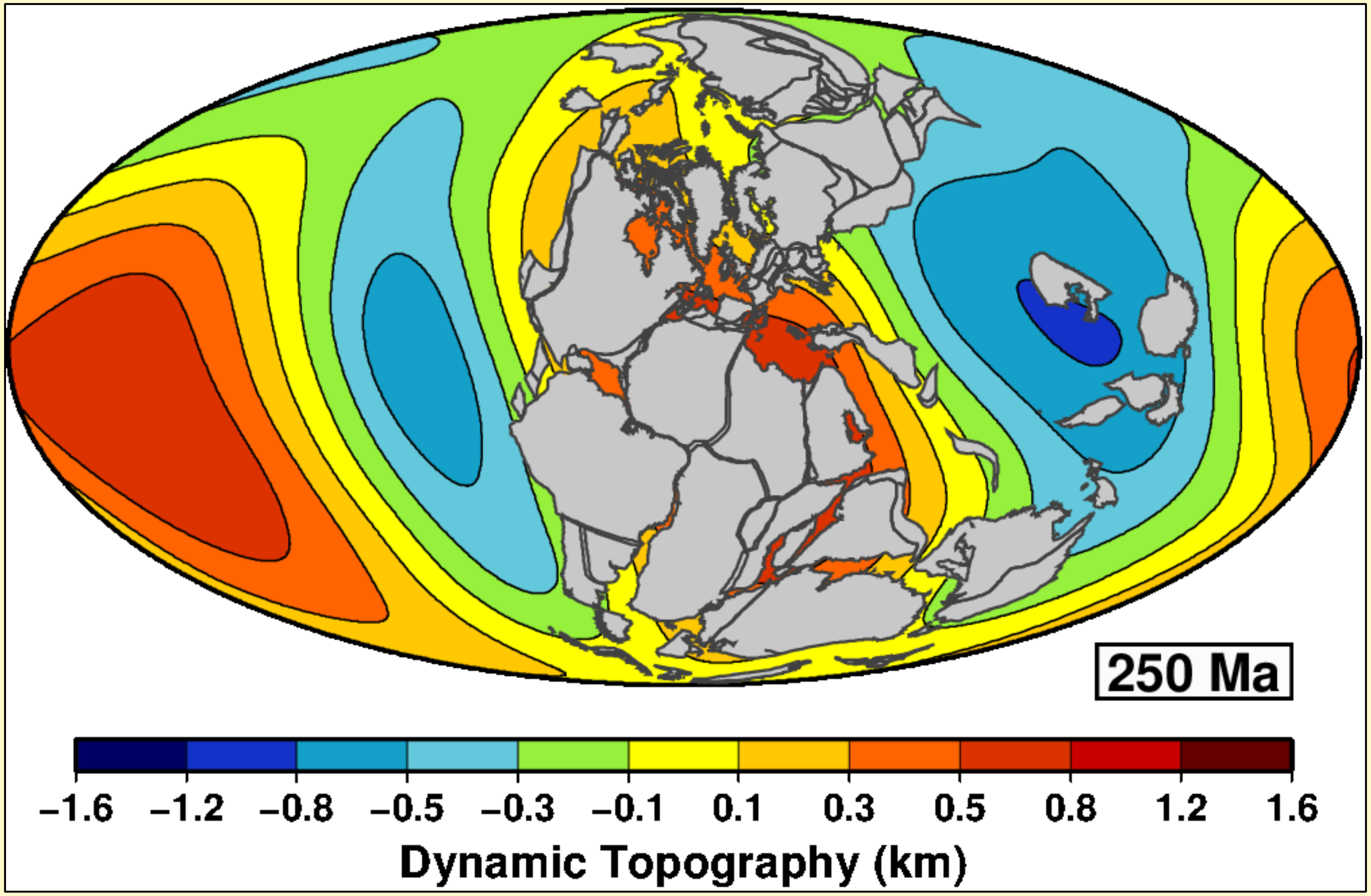


Dynamic Topography:
Deflection of the surface by mantle flow

The continents move relative to the stable mantle flow.

→ They should uplift or subside as they drift over the flow pattern.

→ Compare to flooding observations on continents.



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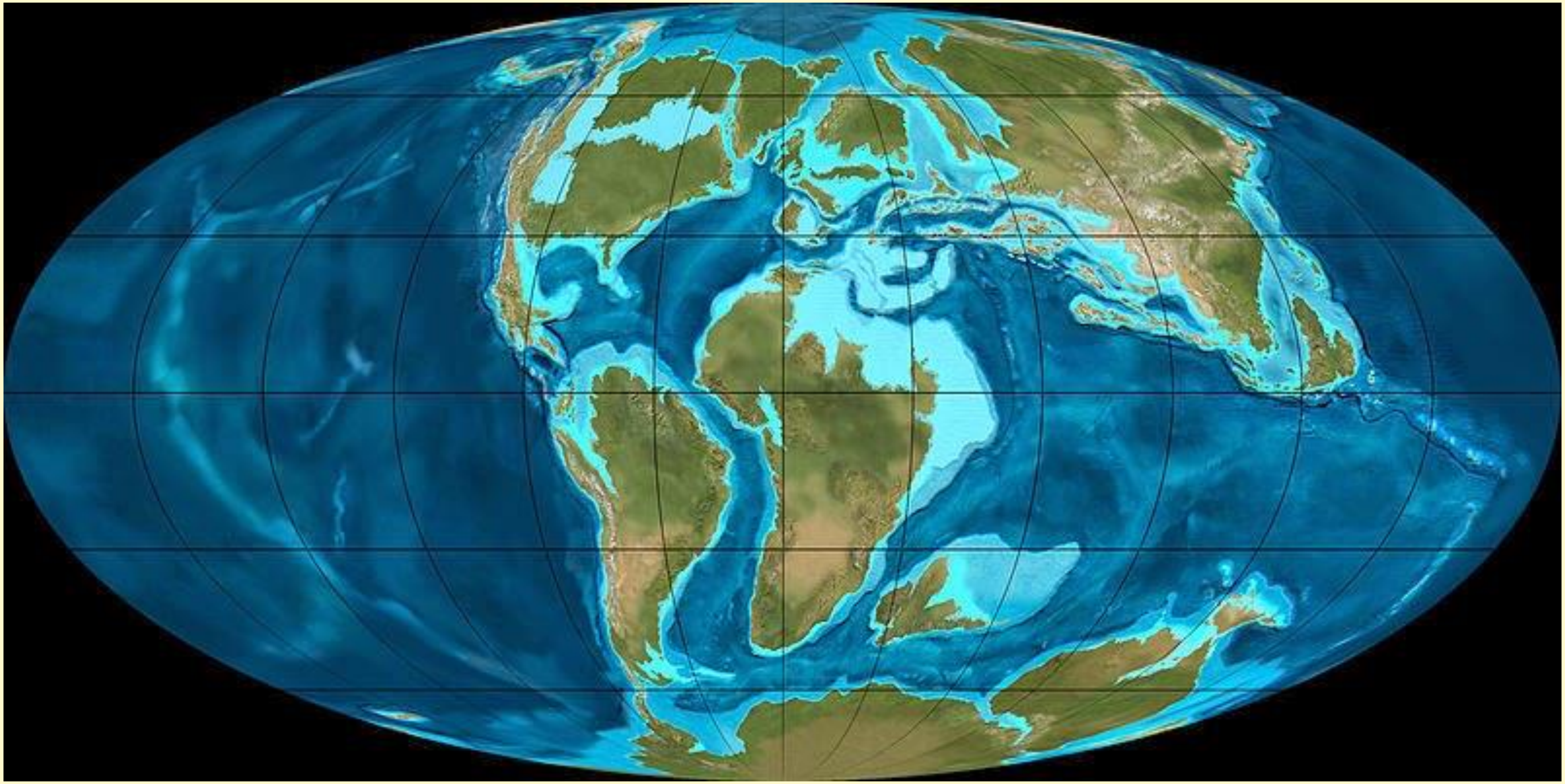
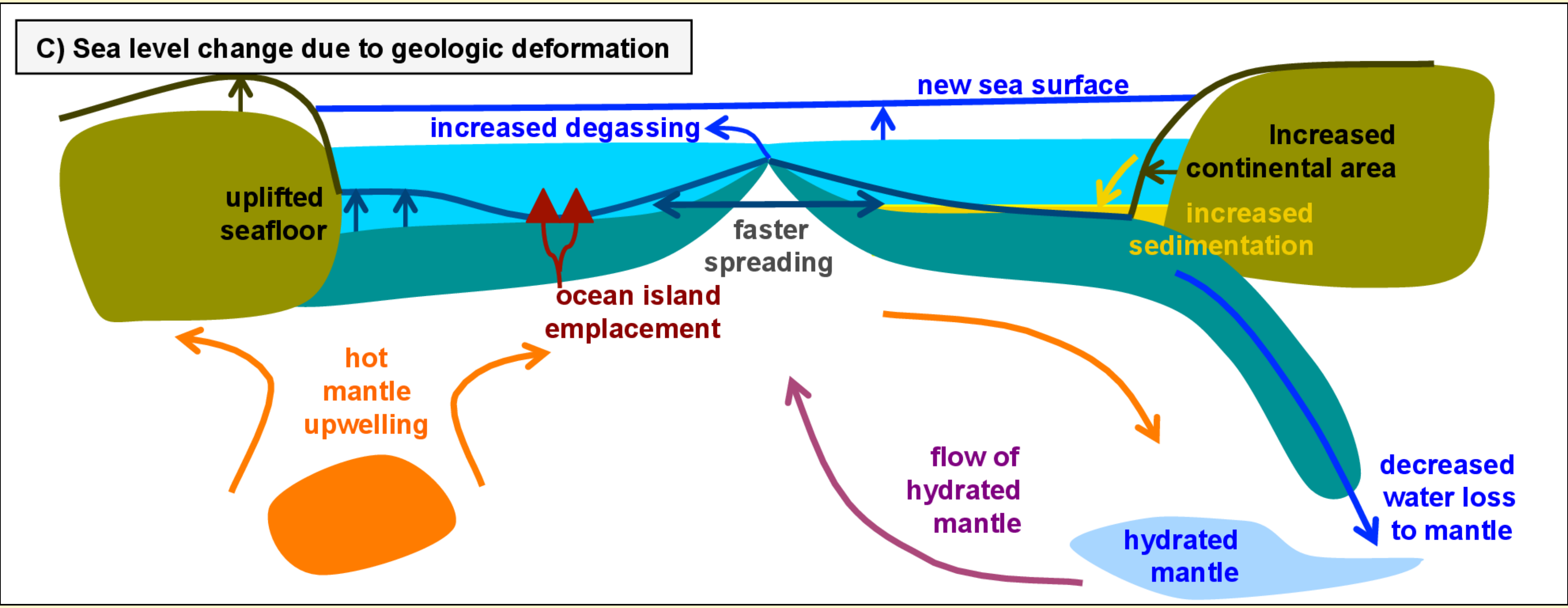


Global topography at 105 Ma [Blakey]

Caution: Geologic constraints can be complex!

Example: Many factors affect sea level change



Conrad [2013]

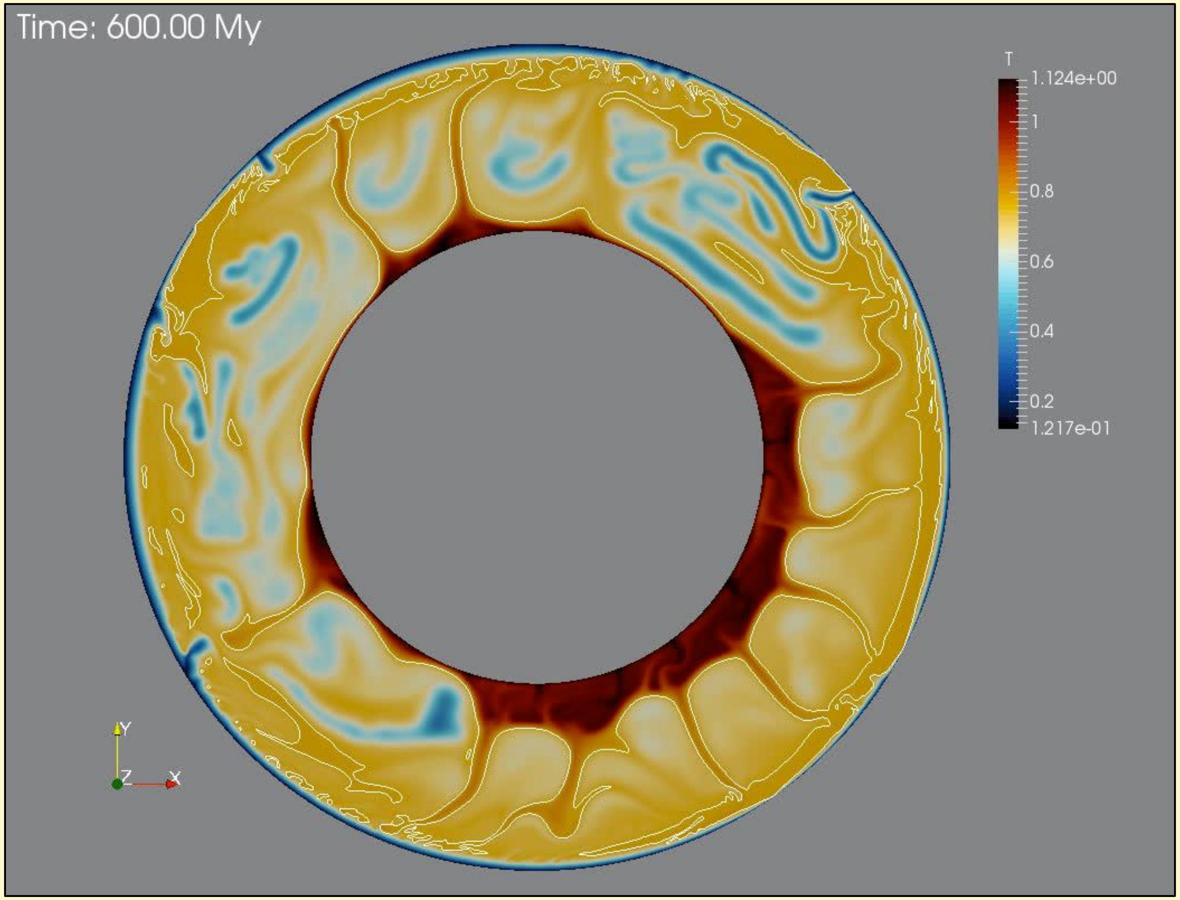
Conclusions

Models can help us understand mantle flow.

These models can explain:

→ Plate tectonic behavior arising from mantle flow

→ Patterns of present-day mantle flow



The next challenge: Mantle flow for past times

→ How stable is the mantle flow pattern?

→ Can we relate past flow to geologic observations?