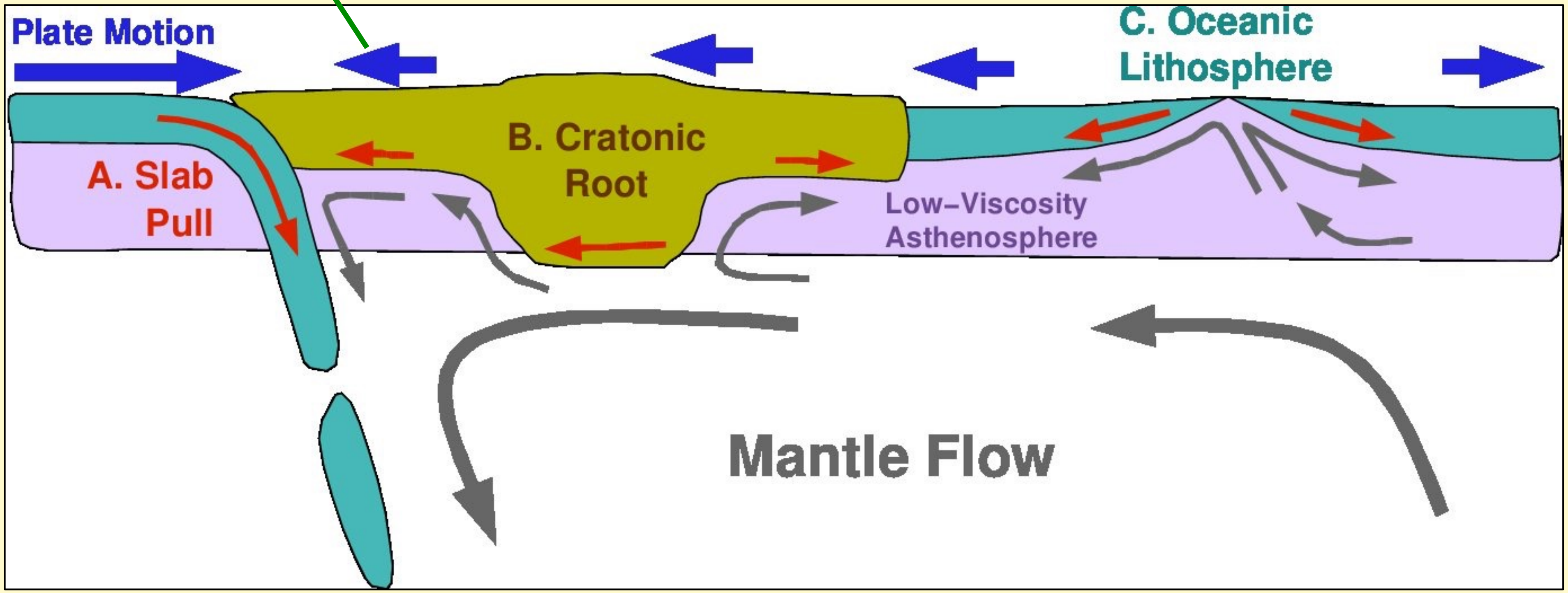
Lithosphere and Asthenosphere: Composition and Evolution

GEO-DEEP9300

Tectonic Lithosphere:
Plate Motions

Valerie Maupin
Clint Conrad



Journal of Geophysical Research

1968

Vol. 73, No. 6, March 15, 1968

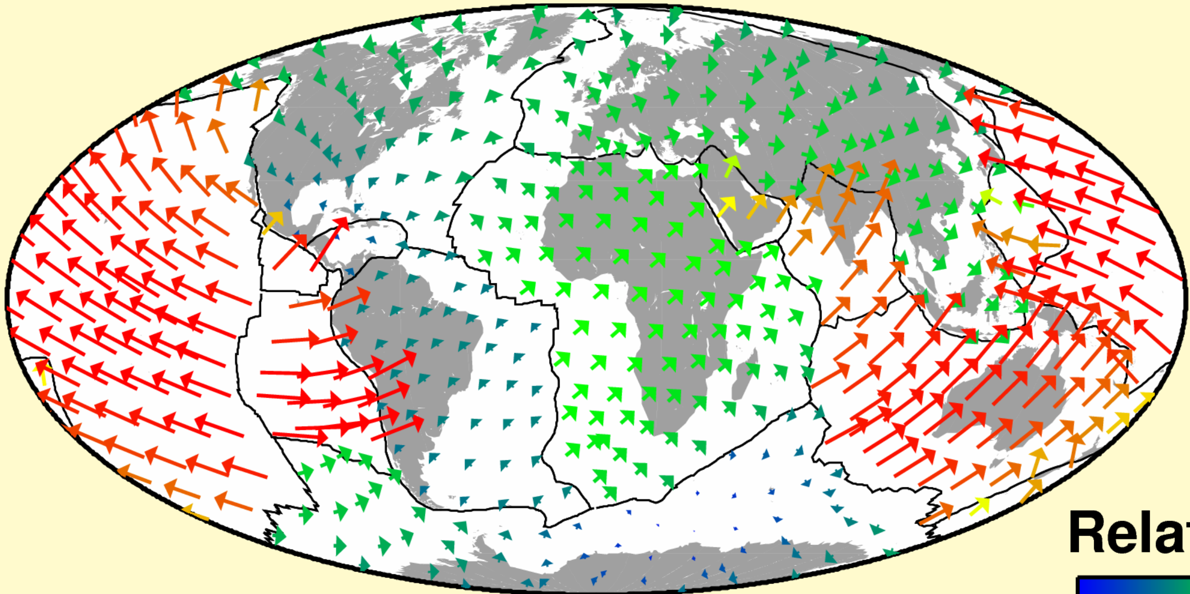
Rises, Trenches, Great Faults, and Crustal Blocks[1]

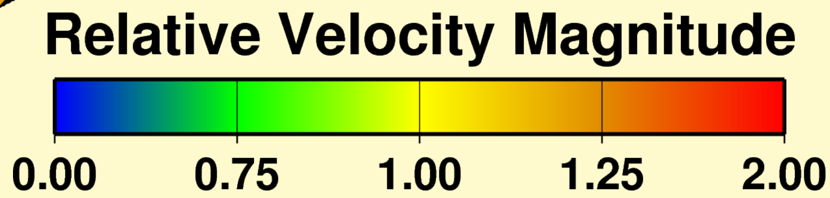
W. Jason Morgan

Department of Geology, Princeton University, Princeton, New Jersey 08540
and Department of Geology and Geophysics, Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

> 50 Years of Plate Tectonics!

Observed Plate Motions





Ultimately, the plate motions are the surface expression of mantle convection.

But how, specifically, are they linked to convection?

What is the driving force?

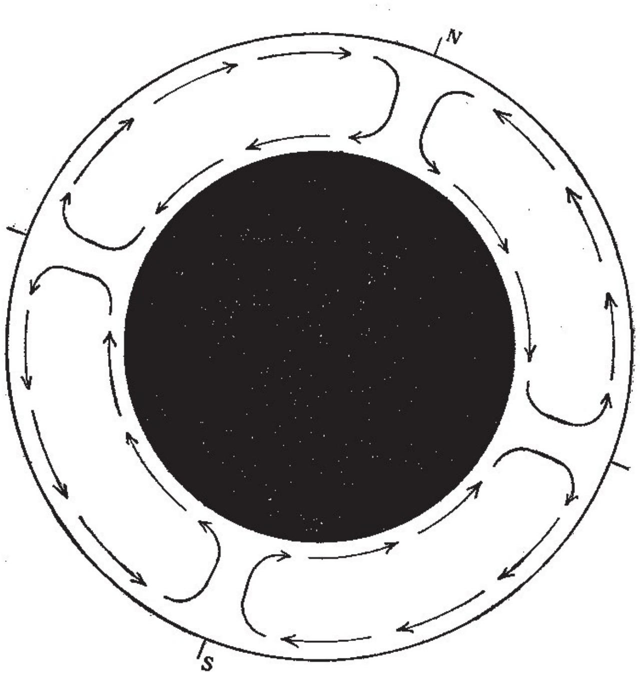
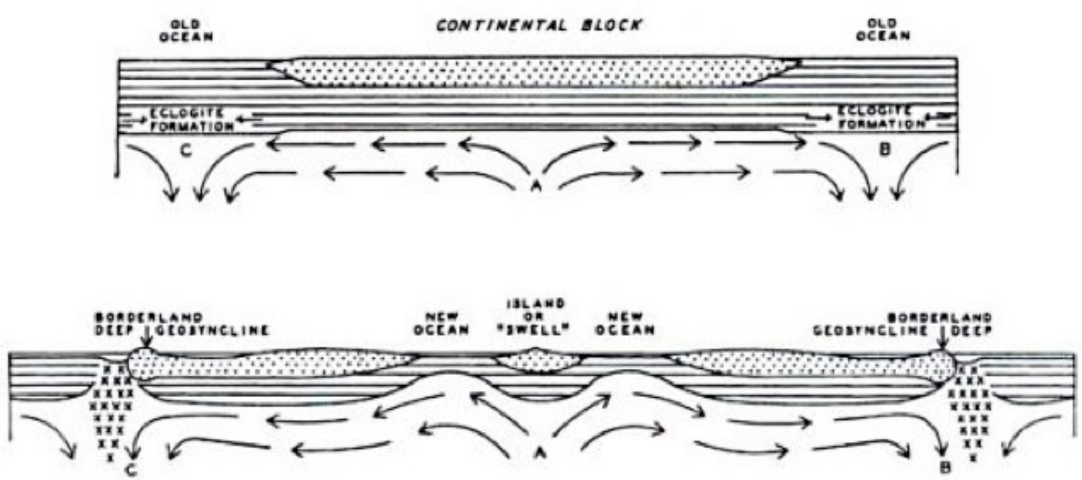
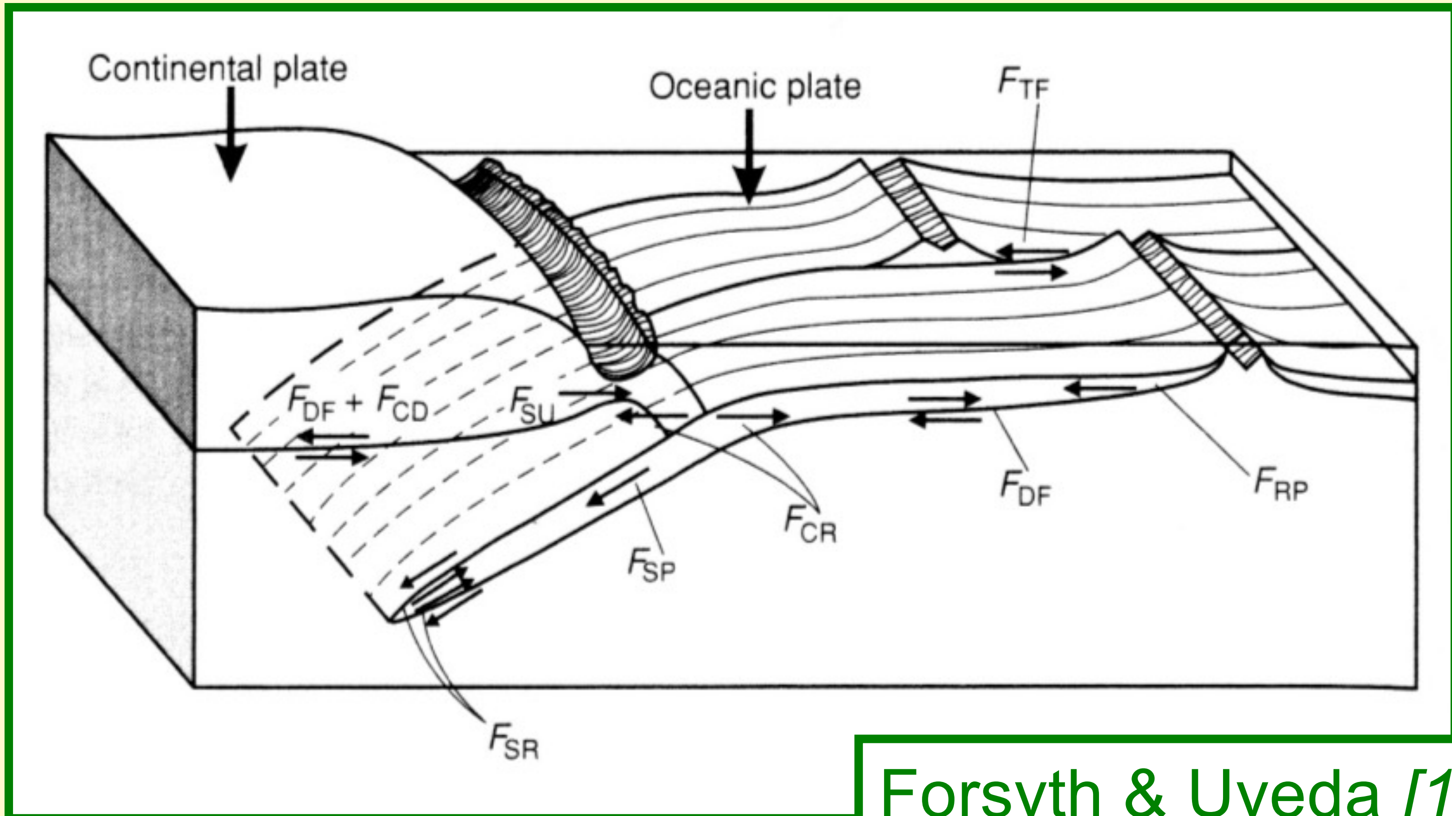


Fig. 1.[1]



Holmes [1931]

Plate Tectonics: What is the Diving Force?



Forsyth & Uyeda *[1975]*

Driving Forces

F_{DF} = Drag Force

F_{SP} = Slab Pull

F_{CD} = Continental Drag

F_{RP} = Ridge Push

Resisting Forces

F_{DF} = Drag Force

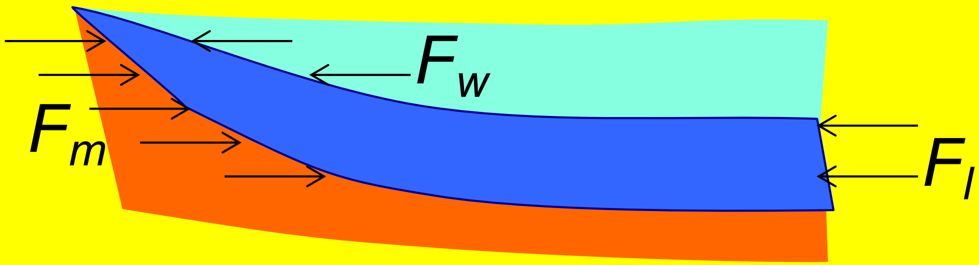
F_{TF} = Transform Resistance

F_{CR} = Colliding Resistance

F_{SR} = Slab Resistance

Estimates of the Major Plate-Driving Forces

Ridge Push



F_{RP} = **Integrated Pressure Difference**

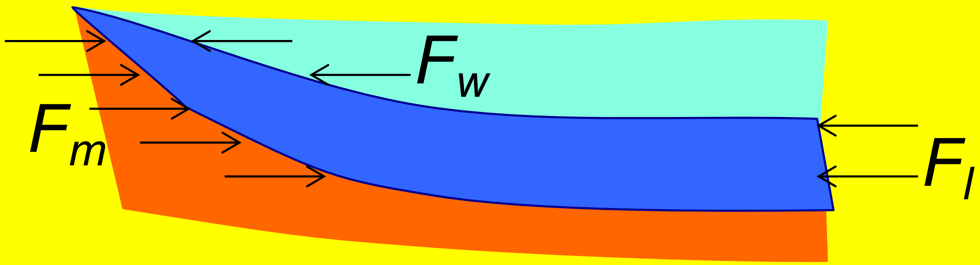
$$F_{RP} = F_m - F_w - F_l$$

$$F_{RP} = \int_0^d \rho_m g z \, dz - \int_0^w \rho_w g z \, dz - \int_w^d \rho_l g z \, dz$$

$F_{RP} \sim 2 \times 10^{12}$ **N/m for 50 Myr old seafloor**

Estimates of the Major Plate-Driving Forces

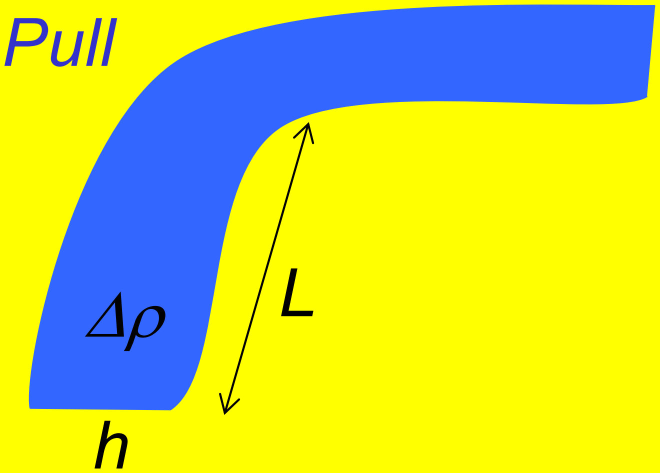
Ridge Push



2×10^{12} N/m

Turcotte & Schubert [2002]

Slab Pull



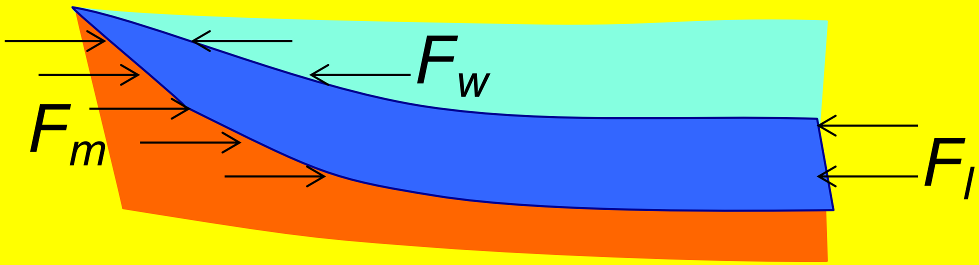
F_{SP} = **Excess weight of slab** = $\Delta\rho g h L$

$$F_{SP} = \left(50\frac{kg}{m^3}\right)\left(10\frac{m}{s^2}\right)(75km)(600km)$$

$F_{SP} \sim 3 \times 10^{13}$ **N/m for 50 Myr old slab**

Estimates of the Major Plate-Driving Forces

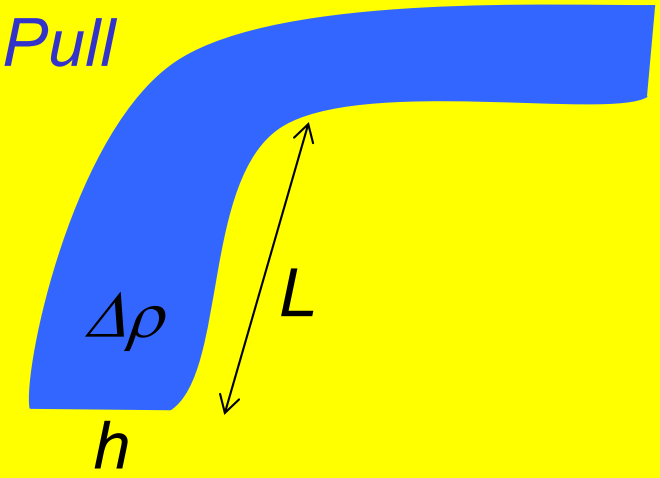
Ridge Push



2×10^{12} N/m

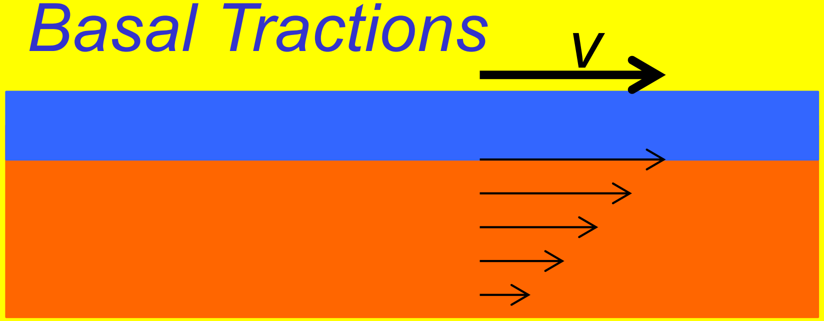
Turcotte & Schubert [2002]

Slab Pull



2×10^{13} N/m

Basal Tractions



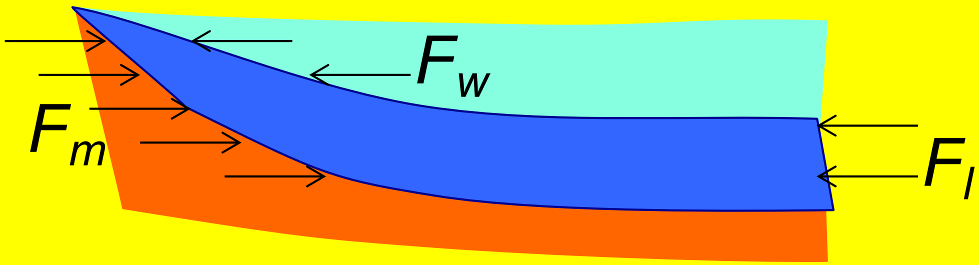
F_{BT} = **Integrated Shear Stress Beneath Plate**

$$F_{BT} = \eta_{asth}\frac{V}{h}L = (10^{20}\,Pas)\left(\frac{10cm/yr}{150km}\right)5000km$$

$$F_{SP} \sim (2MPa)(5000km) = 1\times10^{13}\ \textbf{N/m}$$

Estimates of the Major Plate-Driving Forces

Ridge Push

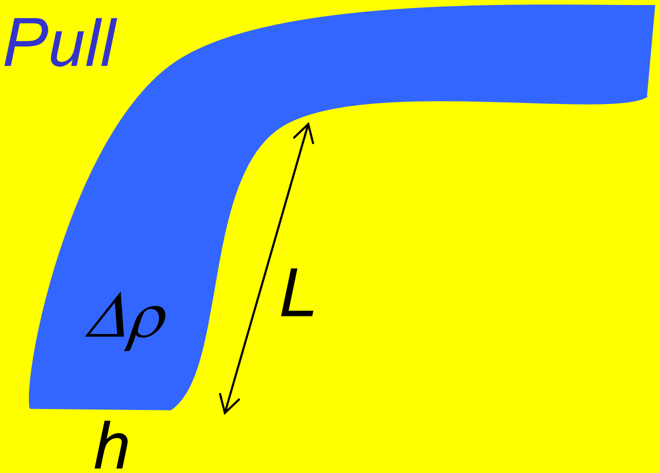


2×10^{12} N/m

(much smaller)

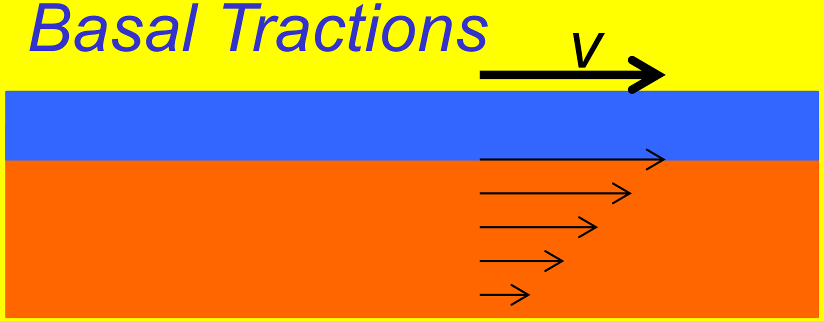
Turcotte & Schubert [2002]

Slab Pull



2×10^{13} N/m

Basal Tractions



1×10^{13} N/m

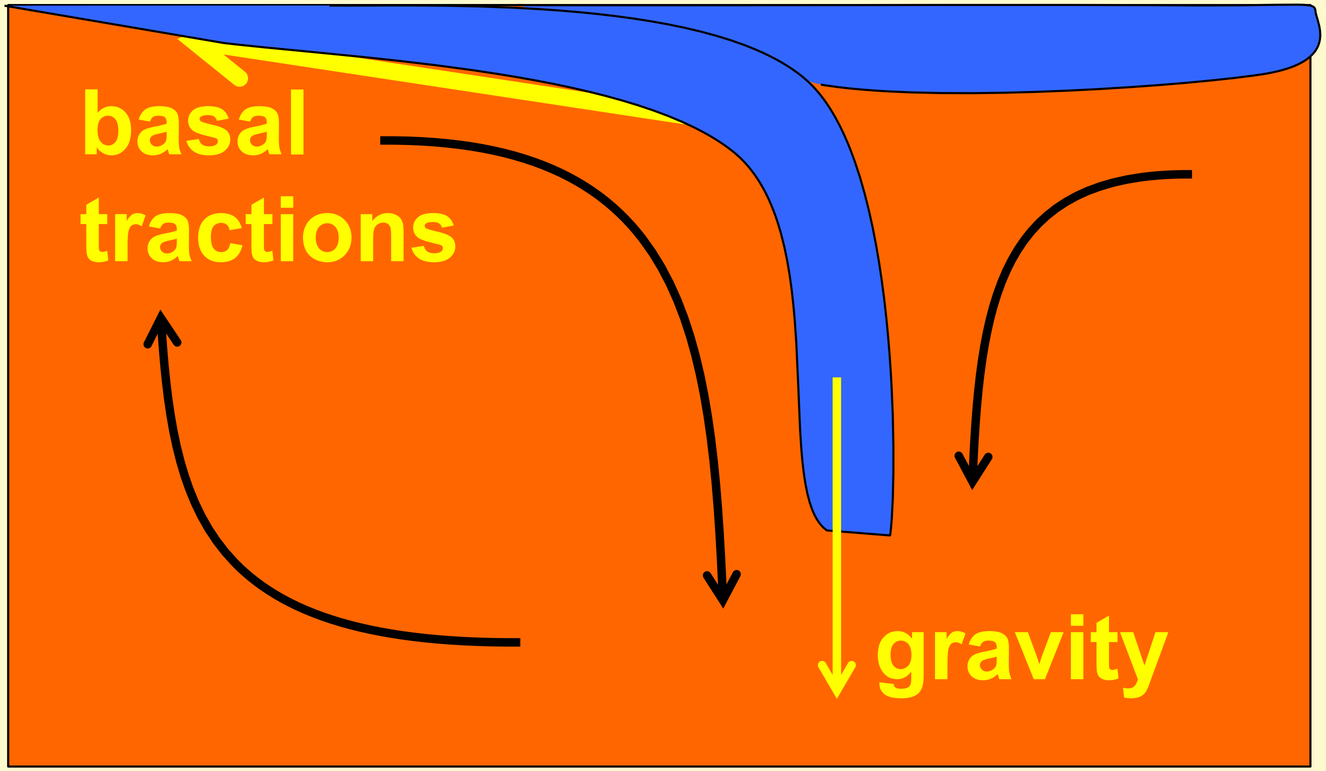
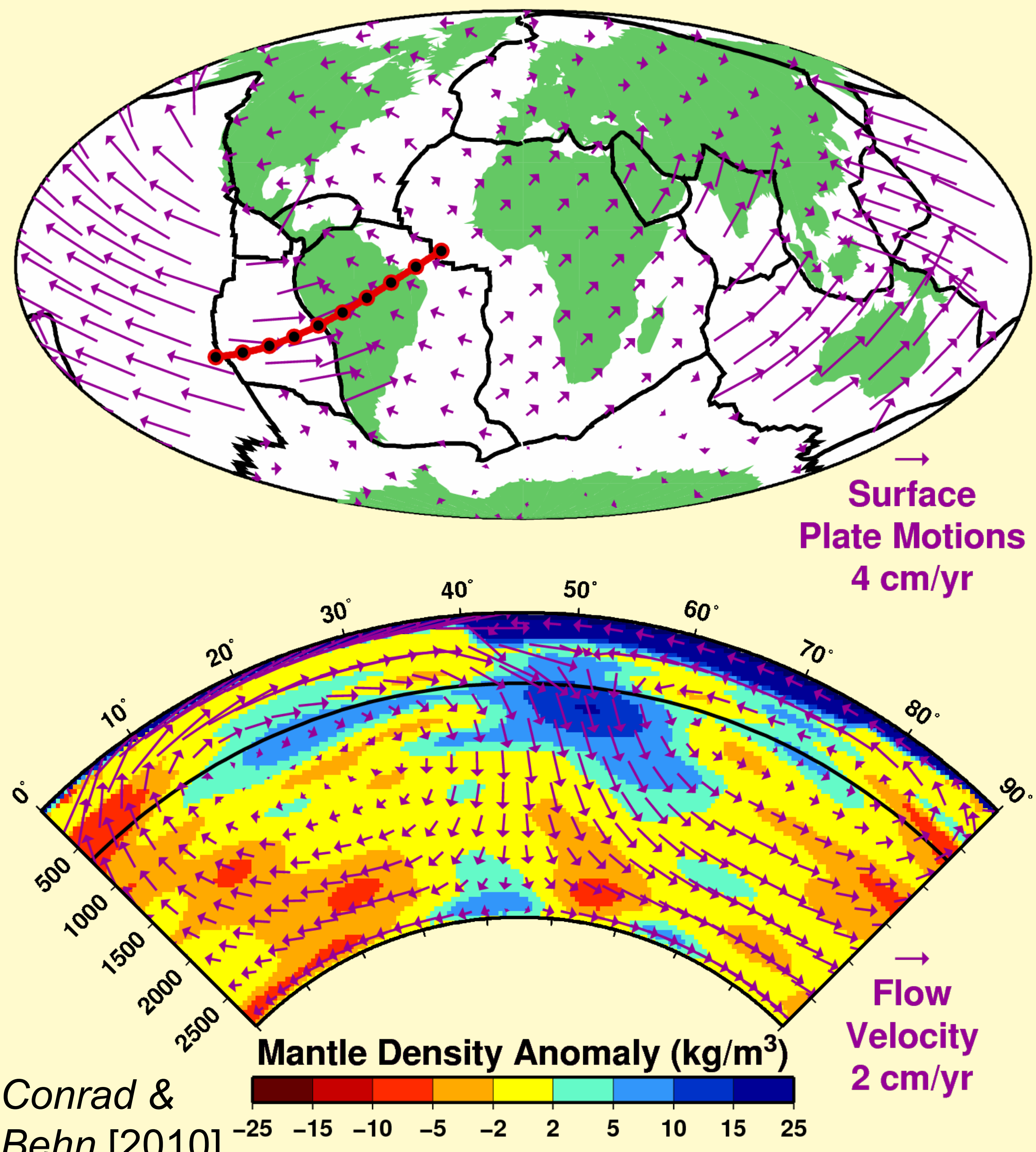


Plate Motions:
A force balance between:

(1) Gravity acting on mantle density heterogeneity

and

(2) Mantle deformation by viscous flow



Conrad & Behn [2010]

Plate Motions:
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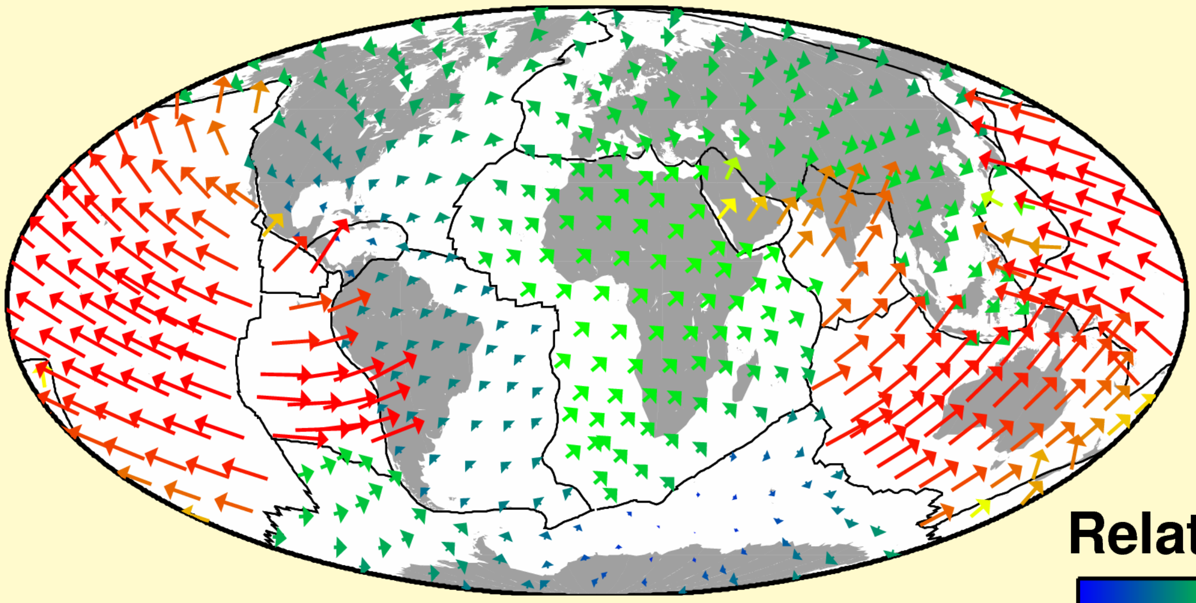
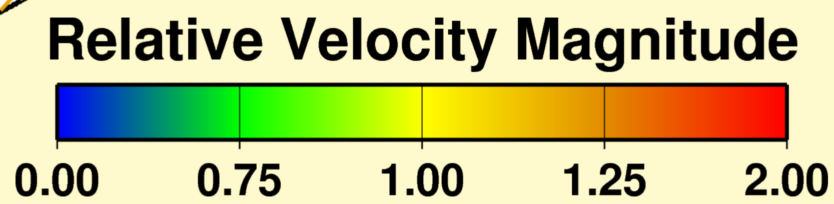


Observed Plate Motions



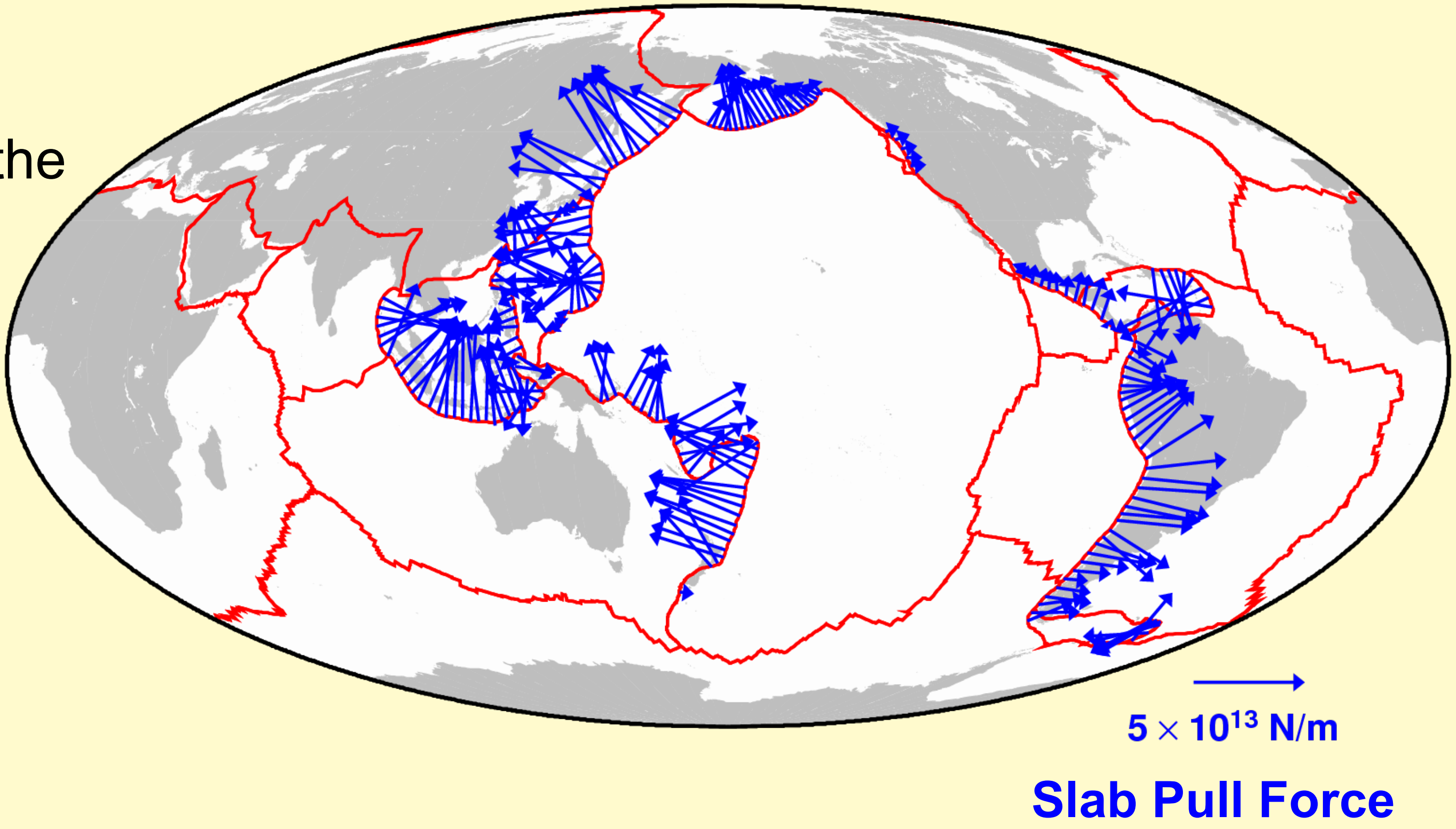
Observation: $\dfrac{\textbf{Subducting Plate Speeds}}{\textbf{Overriding Plate Speeds}} \approx 3.5$

Hypothesis 1: Slab pull speeds up the subducting plates

Hypothesis 2: Larger basal traction slows down the overriding plates

Slab Pull

estimated from the *Lallemand et al.* [2005] dataset.



Hypothesis 1: Slab pull speeds up the subducting plates

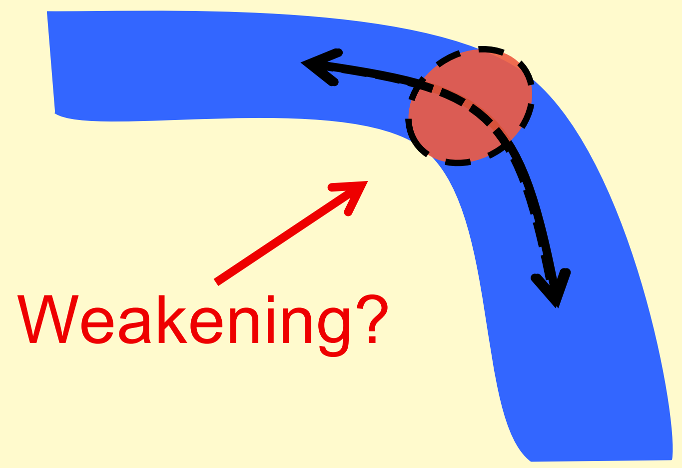
How large is the slab pull force?

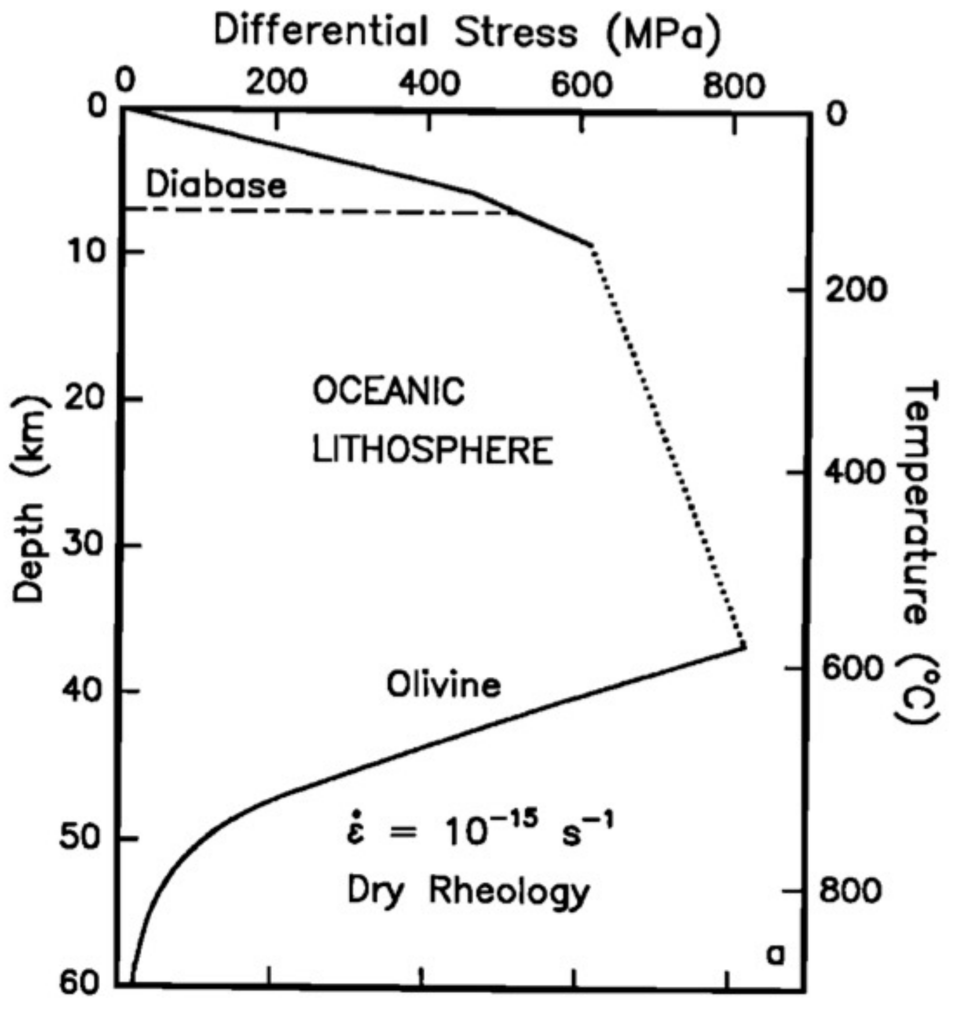
Maximum pull from slabs:
$F_{pull} = 5\times10^{13}$ N/m

Assume a plate thickness:
h = 100 km

Then the pull stress is:
$\sigma_{pull} = 500$ MPa

Slabs may not be strong enough to support all of their own weight!





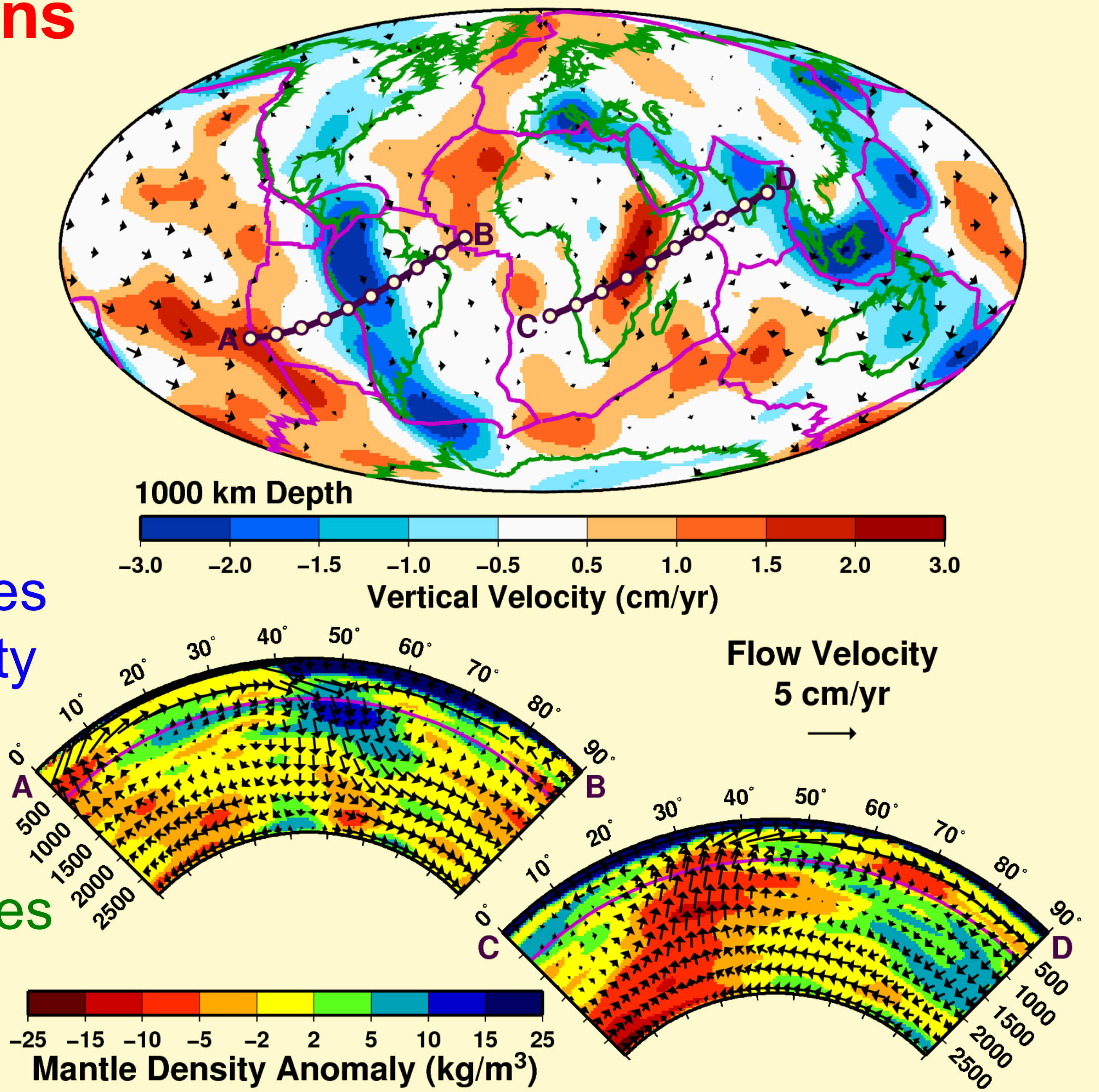
Kohlstedt et al. [1995]

Basal Tractions

Compute from Global Mantle Circulation Models

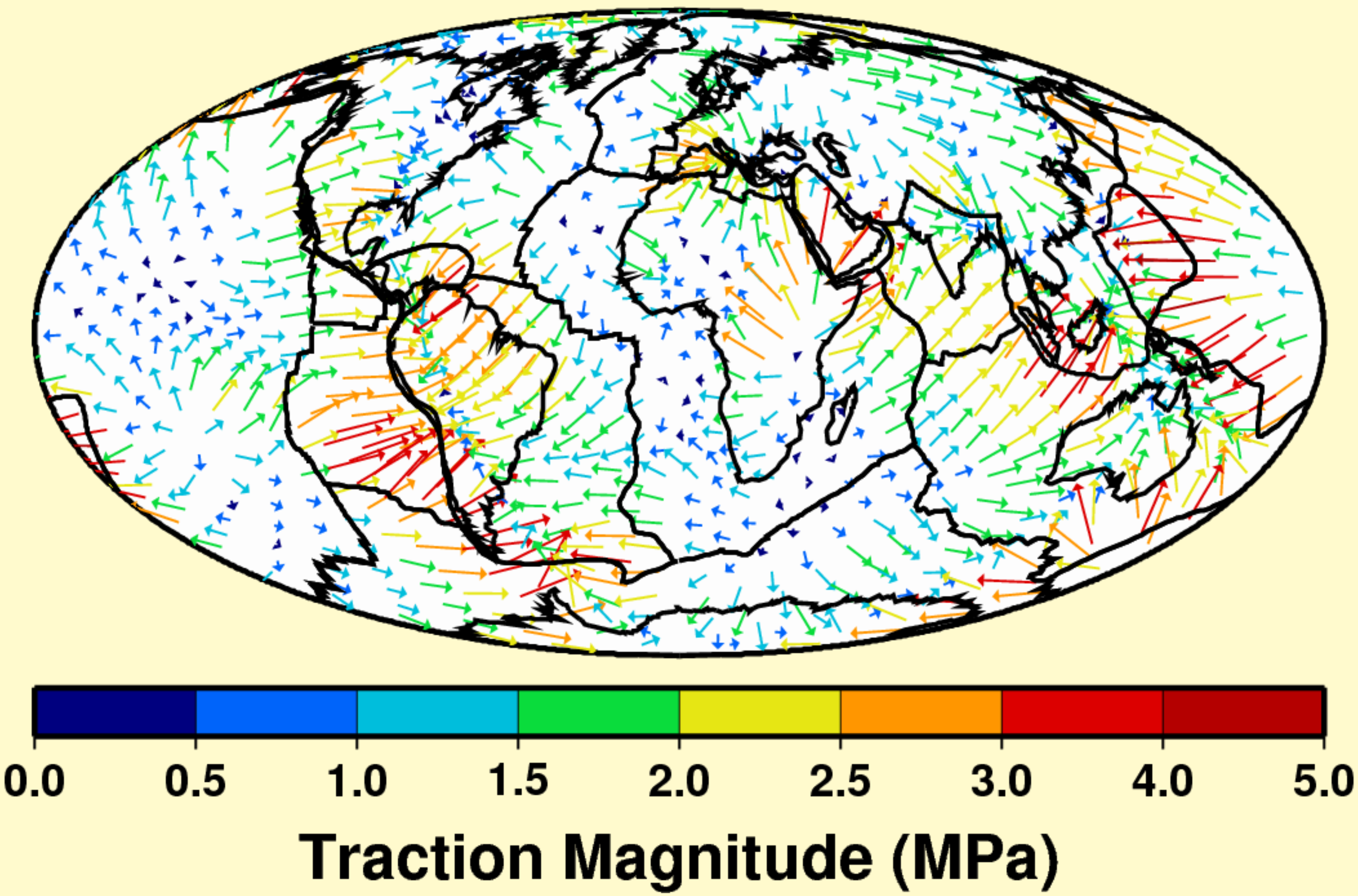
Input:
- Mantle Densities
- Mantle Viscosity

Output:
- Mantle Flow
- Forces on Plates



Conrad & Behn [2010]

Basal Tractions

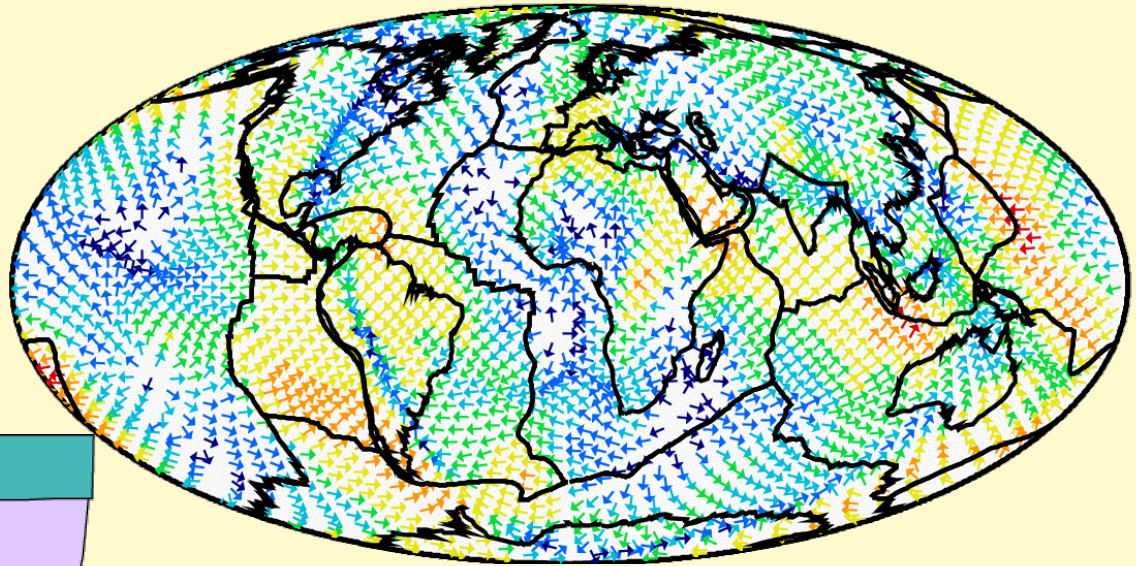


Hypothesis 2: Larger basal traction slows down the overriding plates

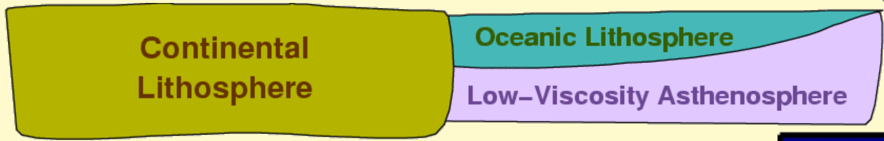
Basal Tractions

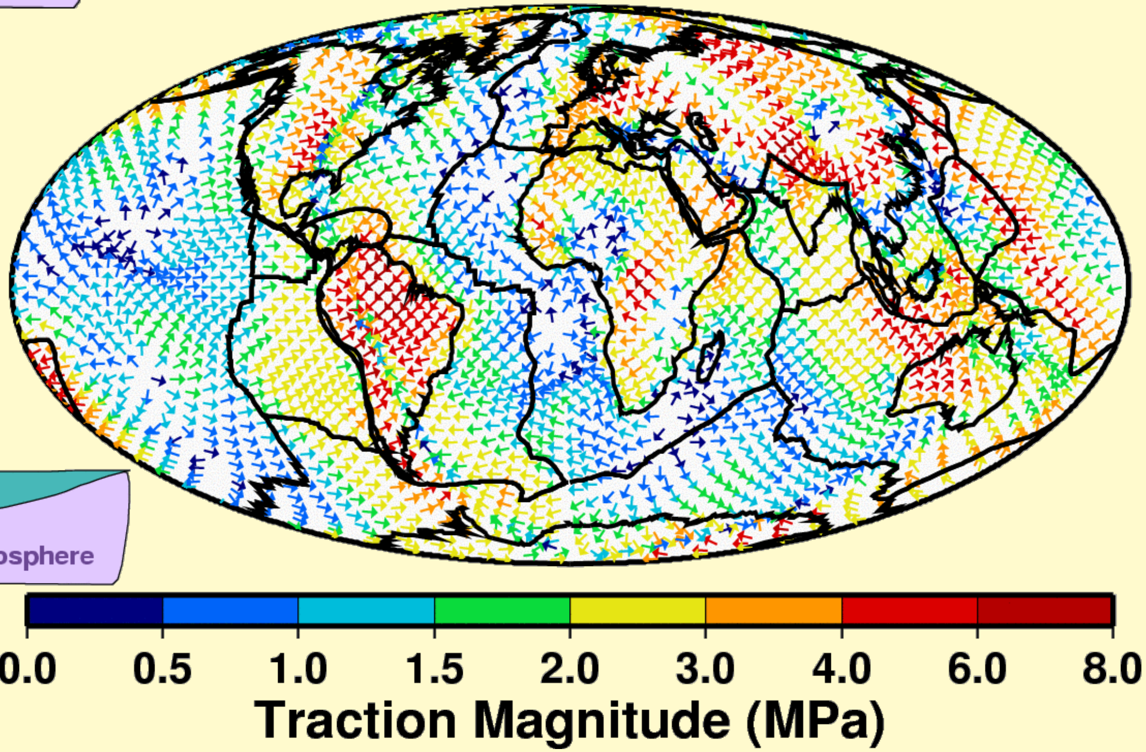
depend on lithosphere thickness

Layered Viscosity



Cratons

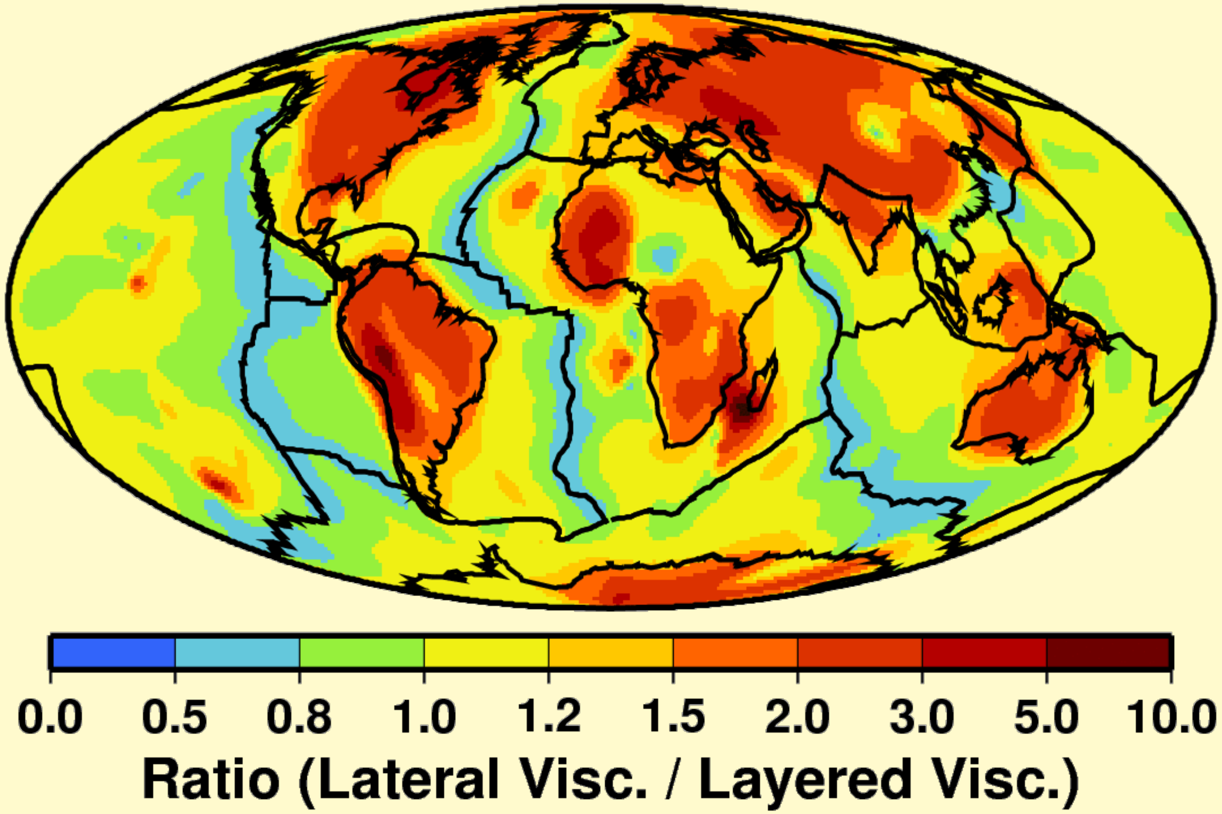




Basal Tractions

depend on lithosphere thickness

Ratio of Traction Magnitudes

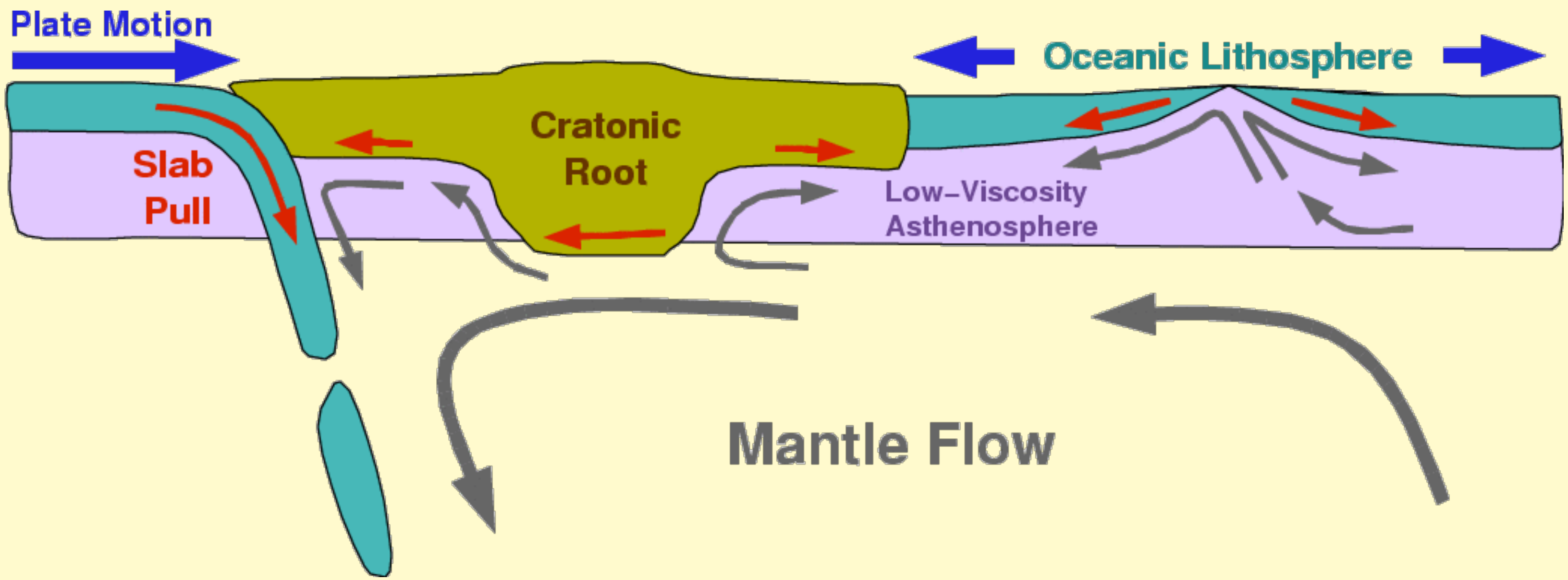


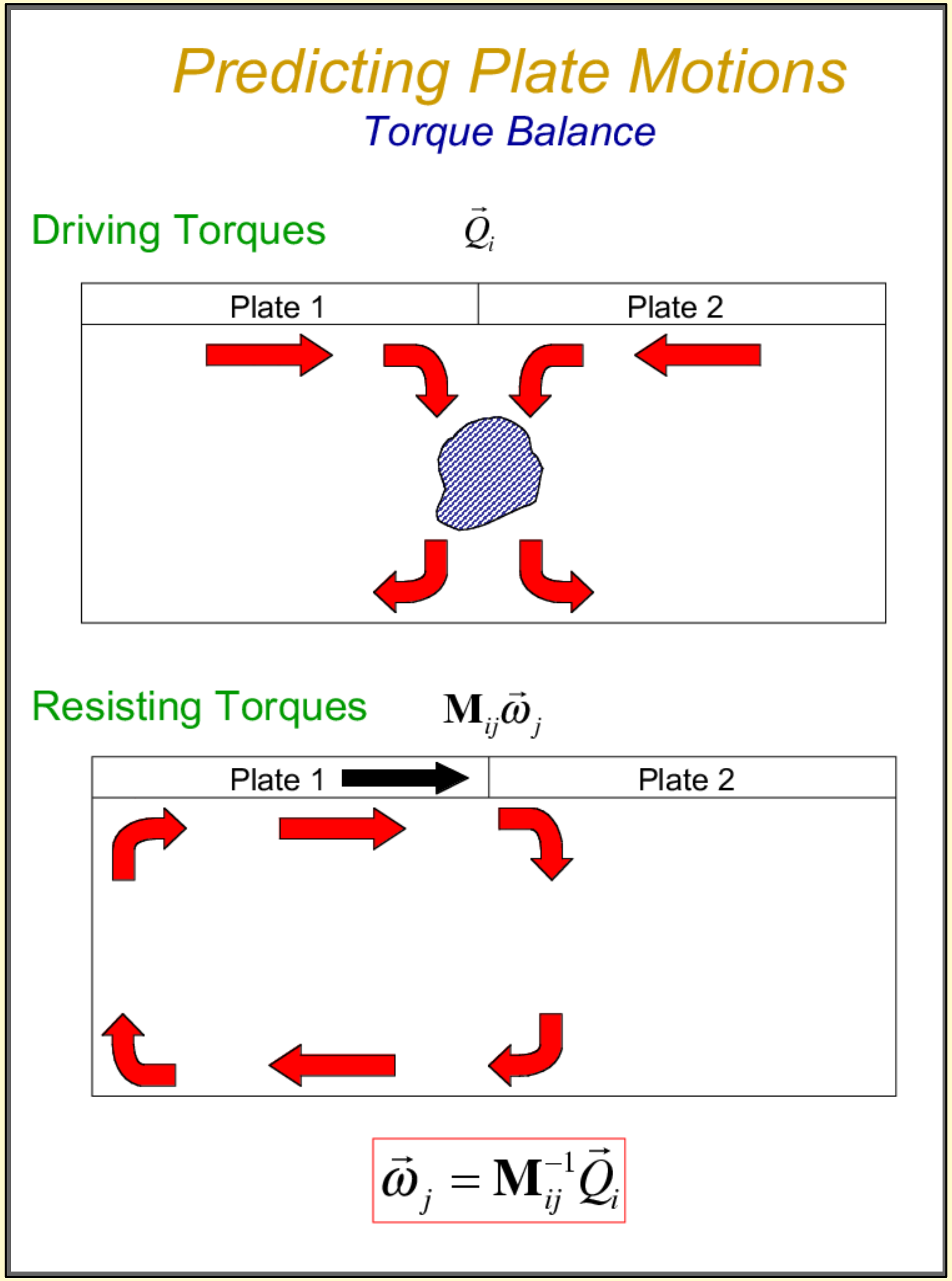
Conrad & Lithgow-Bertelloni [2006]

The link between plate motions and mantle flow depends on rheology

1. **Coupling of the slabs to the subducting plates**
   → Depends on slab strength
2. **Coupling of mantle flow to the surface plates**
   → Depends on viscosity beneath the plates

Problem: Neither is well constrained!





Predict Plate Motions

Torque Balance Approach

[*Lithgow-Bertelloni & Richards,* 1998]

Compute the driving forces for each plate:

F_{pull} Slab Pull Force
F_{flow} Basal Tractions (from flow)

Apply to each plate to obtain the torques Q_i

Plate motions are determined by a torque balance:

$$\vec{\omega}_j = \mathbf{M}_{ij}^{-1}\left(Q_{flow} + Q_{pull}\right)_i$$

Observed Plate Velocity

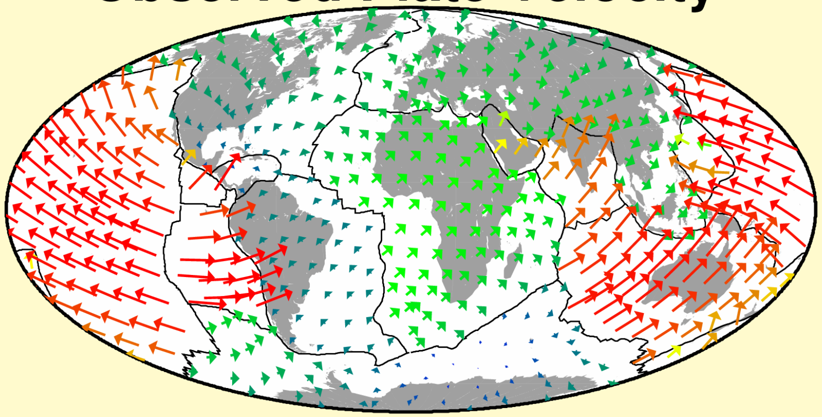
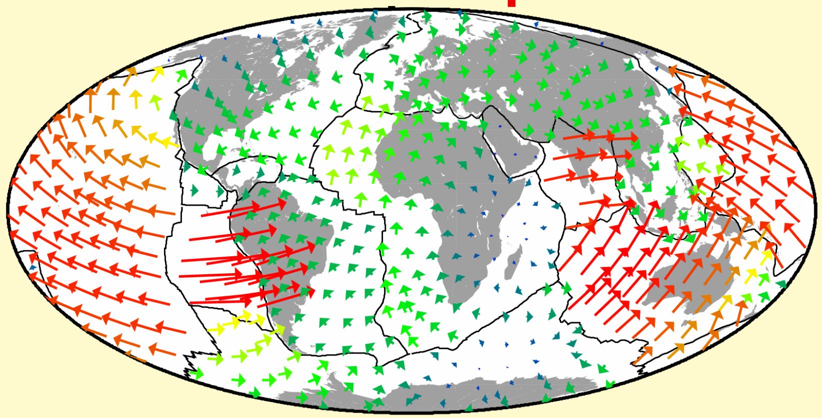


Plate velocity ratio = 3.5

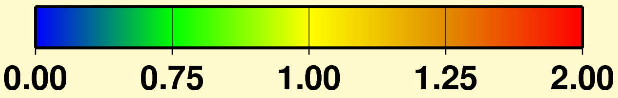
No Asthenosphere



Slab pull fraction = 100%

Plate vel. ratio: 3.2 Misfit: 0.23

Relative Velocity Magnitude



Observed Plate Velocity

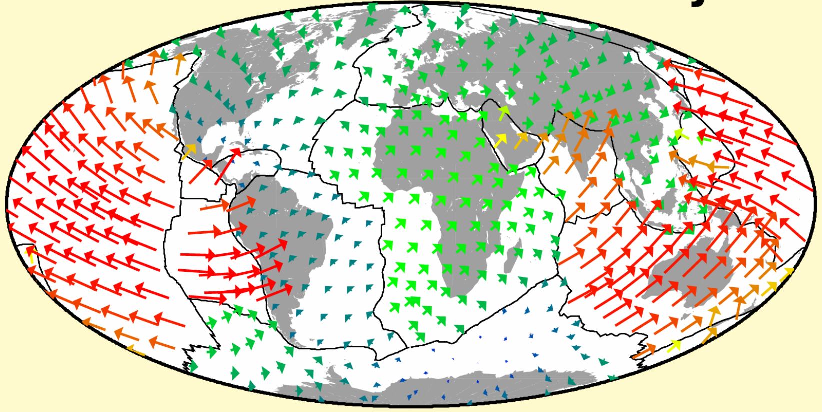
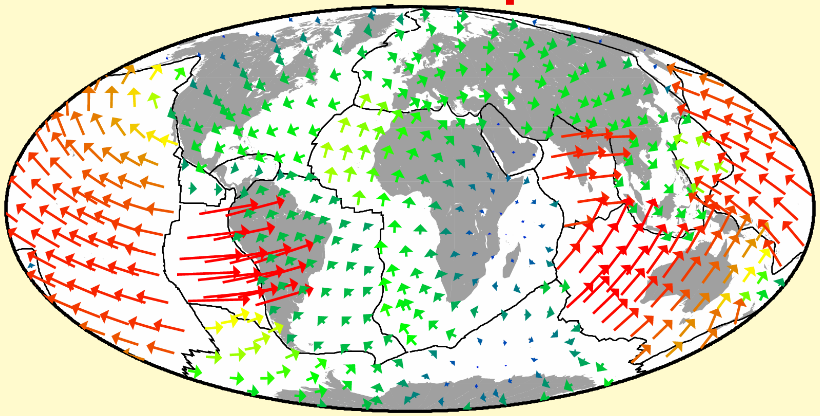


Plate velocity ratio = 3.5

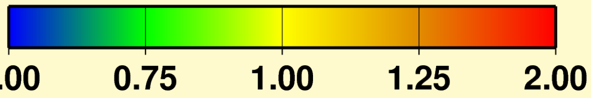
No Asthenosphere



Slab pull fraction = 100%

Plate vel. ratio: 3.2 Misfit: 0.23

Relative Velocity Magnitude



Misfit Function

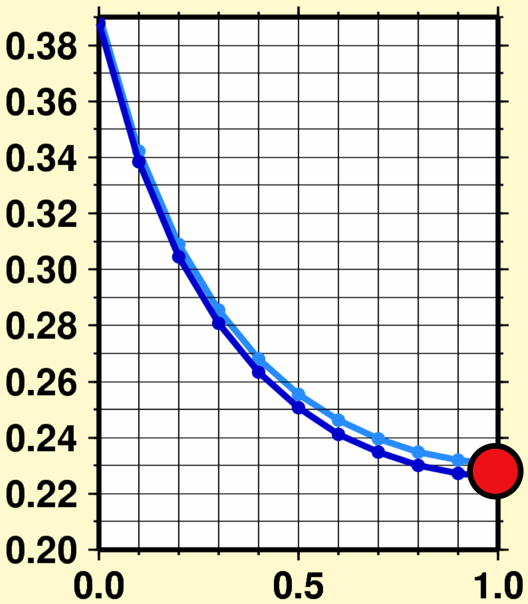
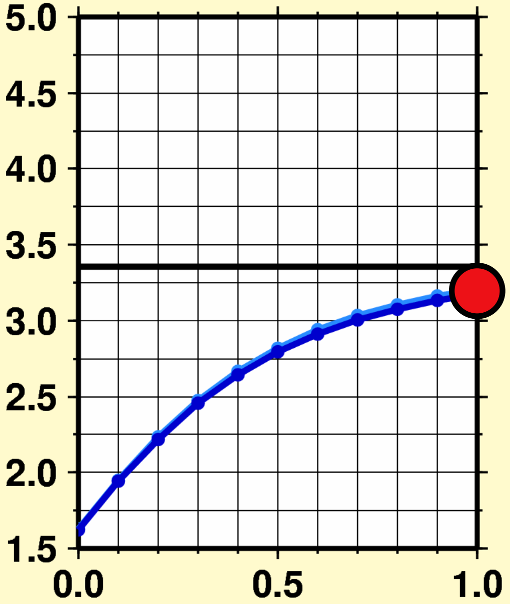


Plate Speed Ratio



Observed (NUVEL–1A)

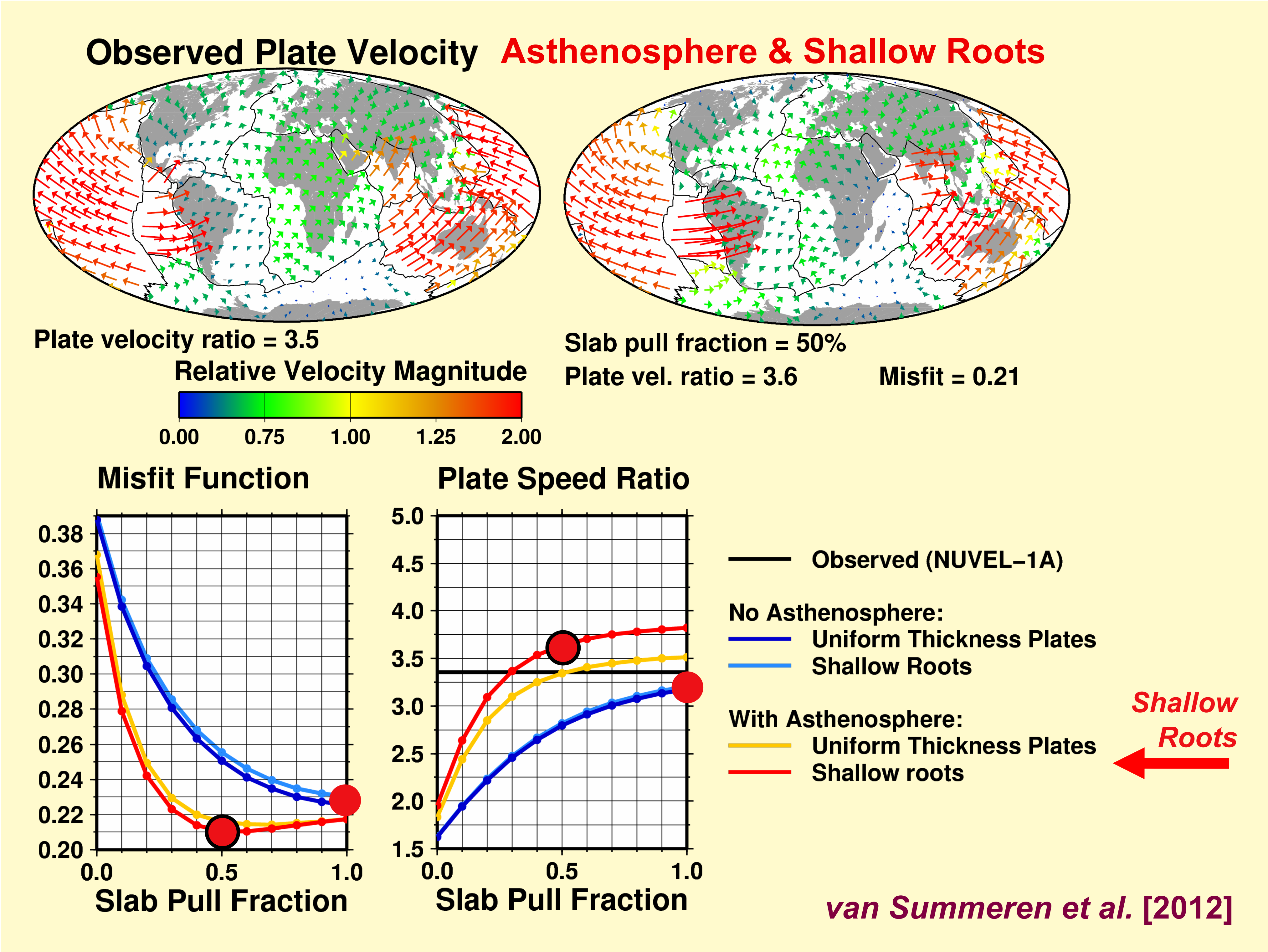
No Asthenosphere:

Uniform Thickness Plates

Shallow Roots

No Asthenosphere

van Summeren et al. [2012]


Observed Plate Velocity
Asthenosphere & Shallow Roots
Plate velocity ratio = 3.5
Relative Velocity Magnitude
0.00 0.75 1.00 1.25 2.00
Slab pull fraction = 50%
Plate vel. ratio = 3.6
Misfit = 0.21
Misfit Function
0.38 0.36 0.34 0.32 0.30 0.28 0.26 0.24 0.22 0.20
0.0 0.5 1.0
Slab Pull Fraction
Plate Speed Ratio
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5
0.0 0.5 1.0
Slab Pull Fraction
Observed (NUVEL−1A)
No Asthenosphere:
Uniform Thickness Plates
Shallow Roots
With Asthenosphere:
Uniform Thickness Plates
Shallow roots
Shallow Roots
van Summeren et al. [2012]

Observed Plate Velocity

Deep Roots

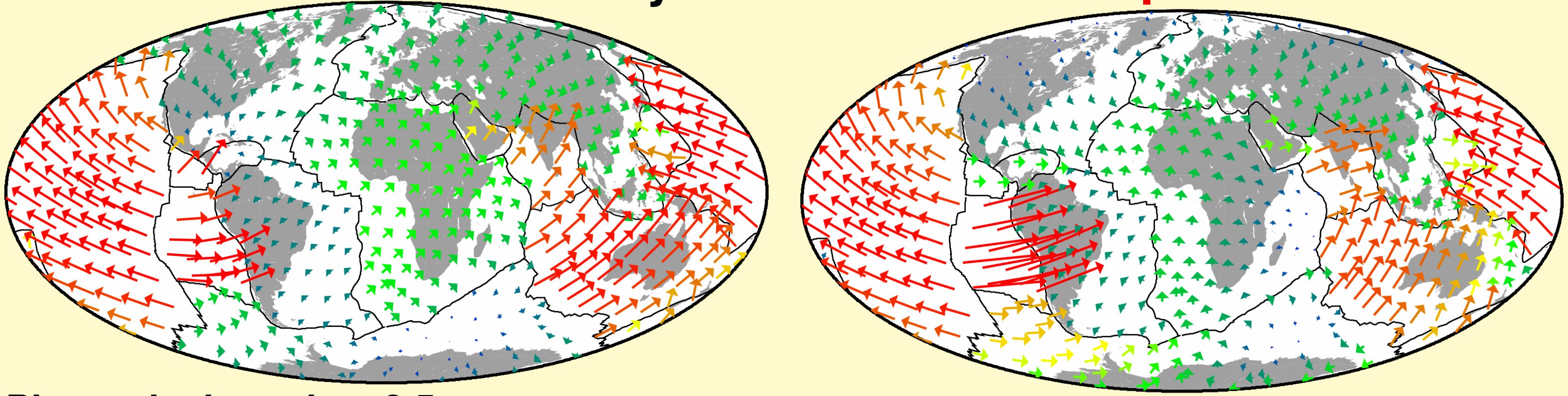
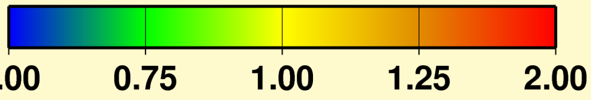


Plate velocity ratio = 3.5

Slab pull fraction = 20%.
Plate velocity ratio = 3.7   Misfit = 0.24



Misfit Function

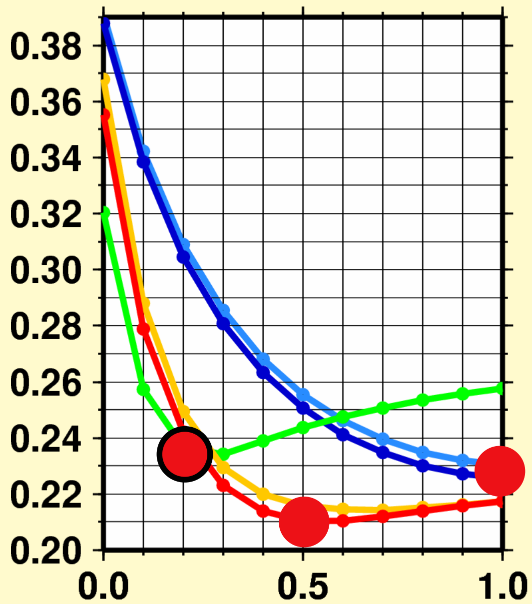
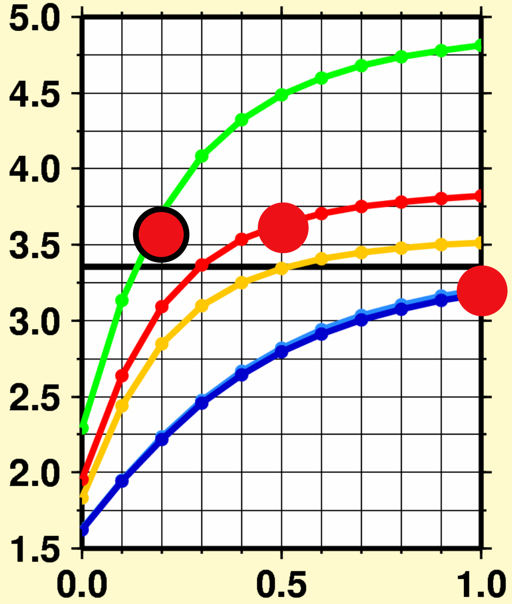


Plate Speed Ratio



Observed (NUVEL−1A)

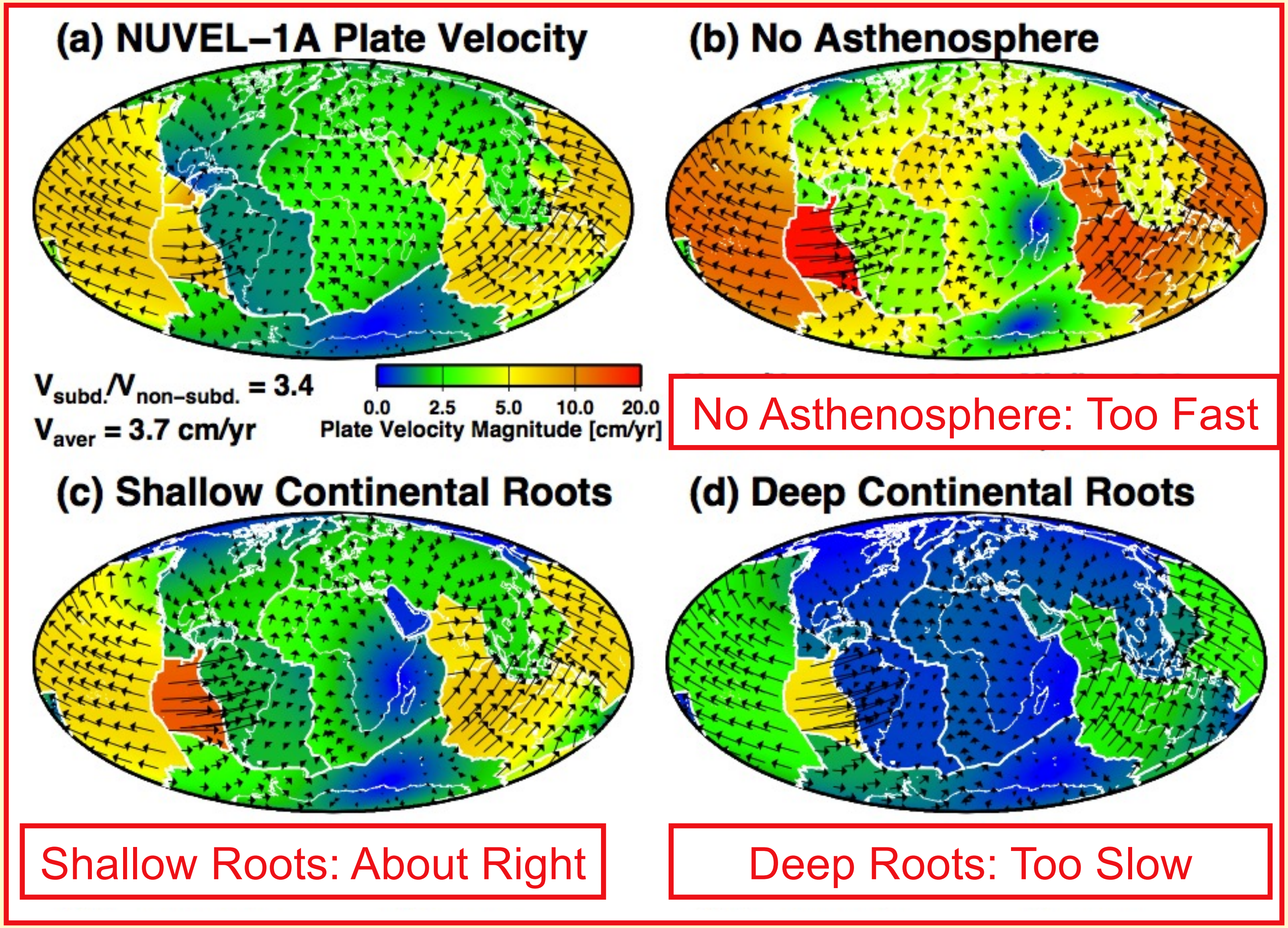
No Asthenosphere:
Uniform Thickness Plates
Shallow Roots

With Asthenosphere:
Uniform Thickness Plates
Shallow roots
Deep Roots

Deep Roots

van Summeren et al. [2012]

Which model works best?
Assume upper mantle viscosity: 3-6 $\times 10^{20}$ Ps s



van Summeren et al. [2012]

The Major Plate-Driving Forces:

1. **Slab Pull**: Slabs are partially coupled to plates
   (about 50% of upper mantle slab weight)
   ➔ speeds the subducting plates

2. **Basal Tractions**: Plates motions are coupled to mantle flow,
   but through a low-viscosity asthenosphere
   ➔ partly decouples cratons from flow

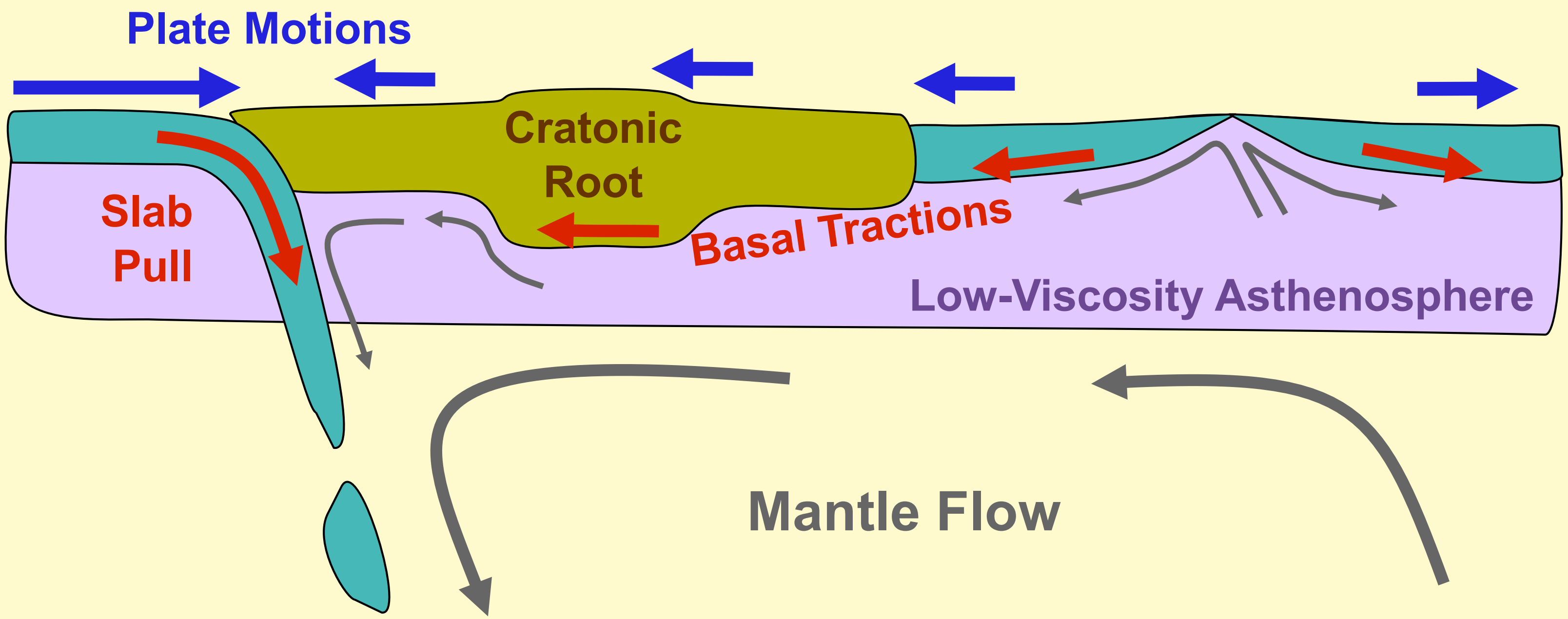
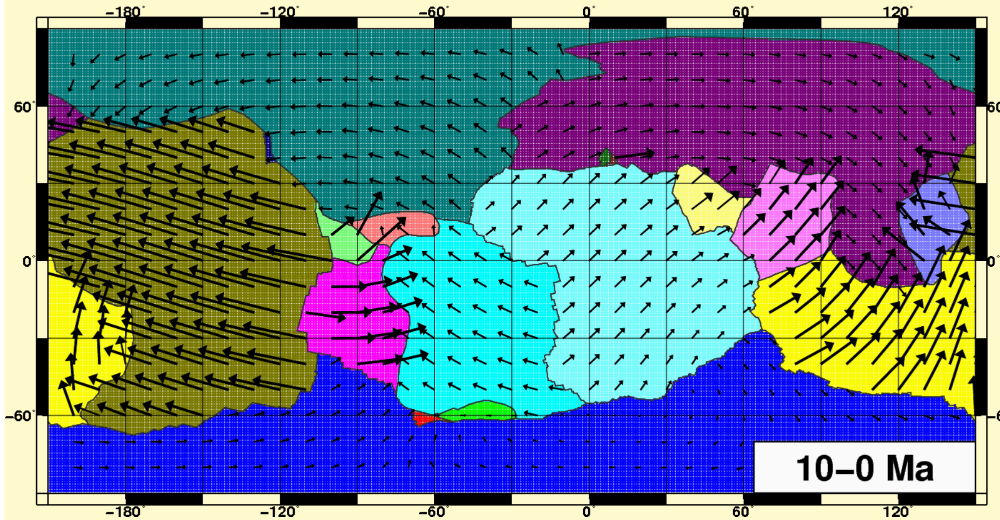


Plate Tectonic Reconstruction [*Torsvik et al.*, 2010]



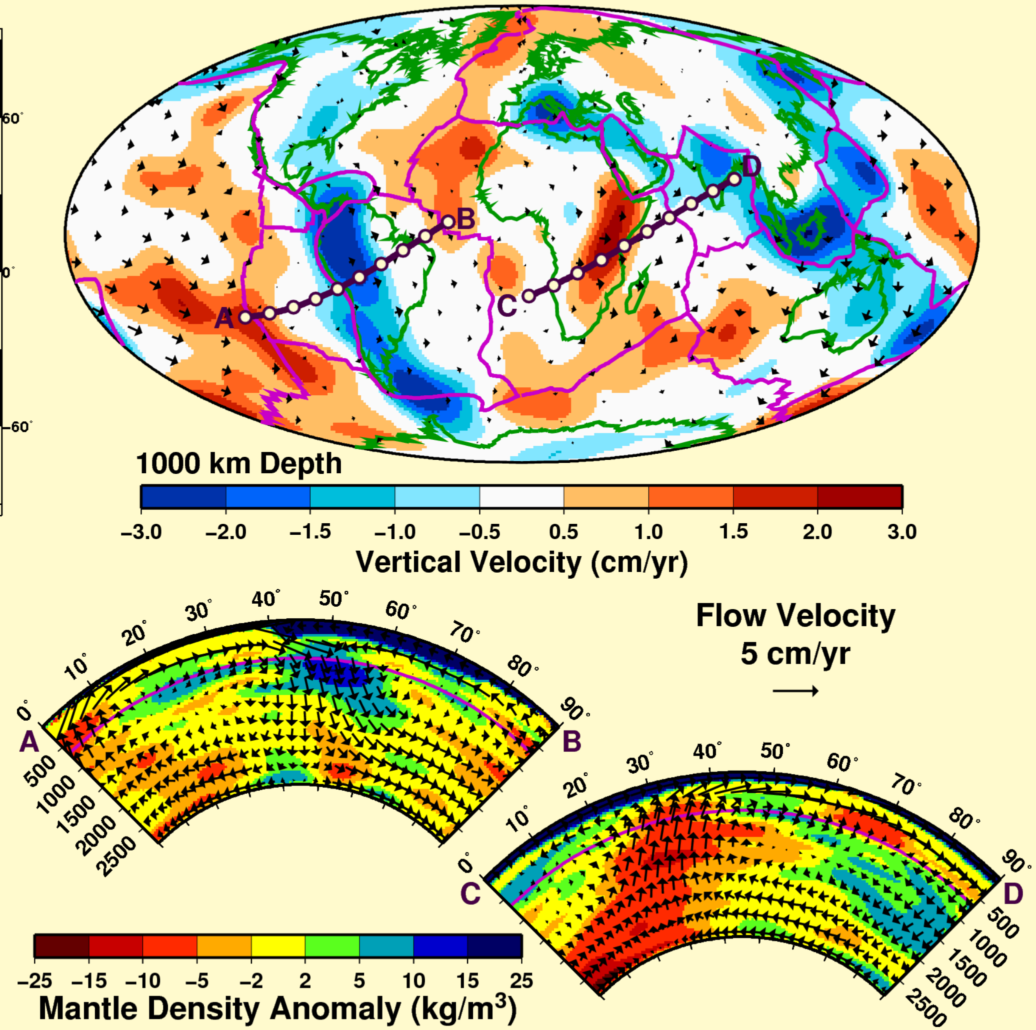
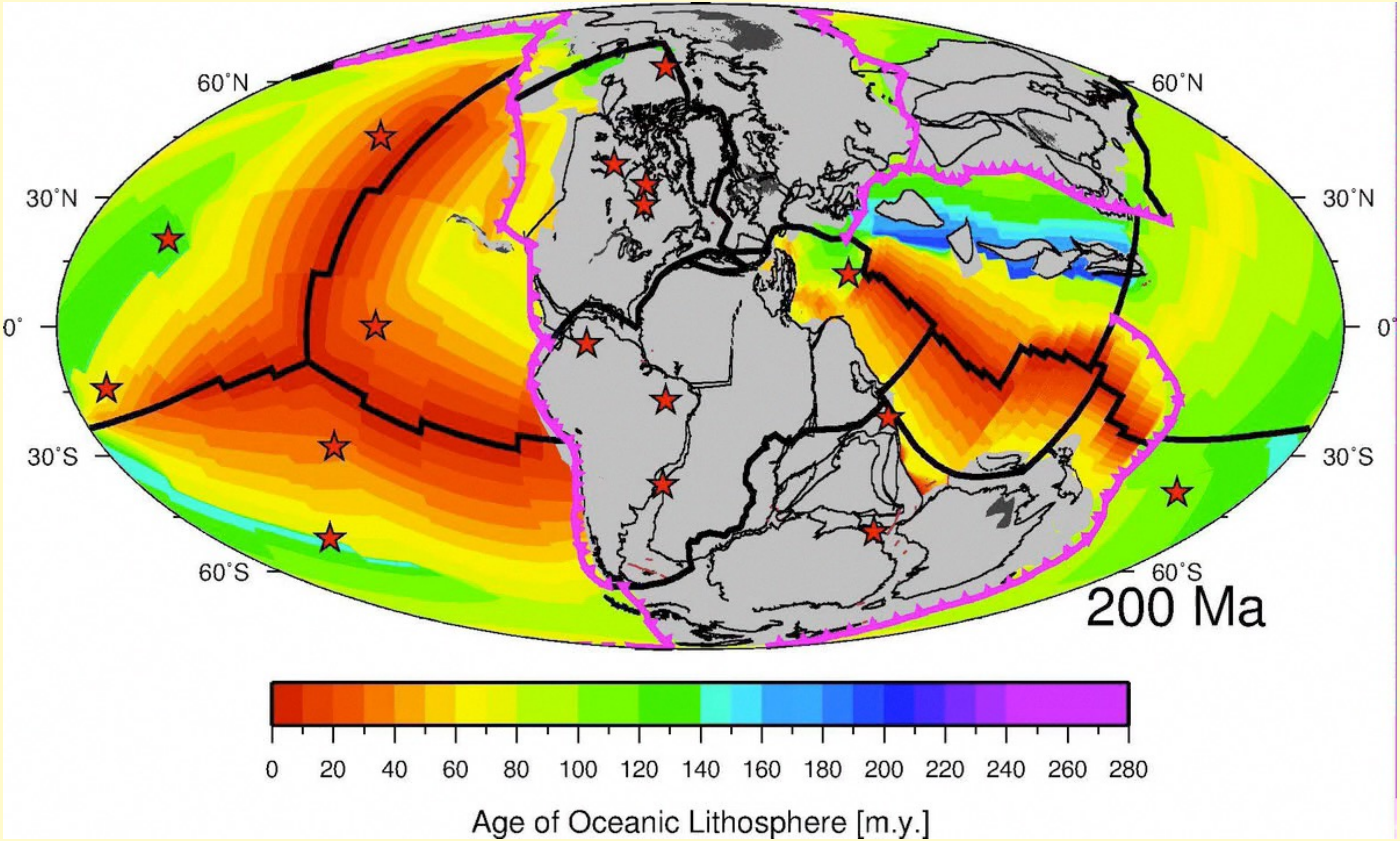


Plate motions are intimately linked with mantle flow.

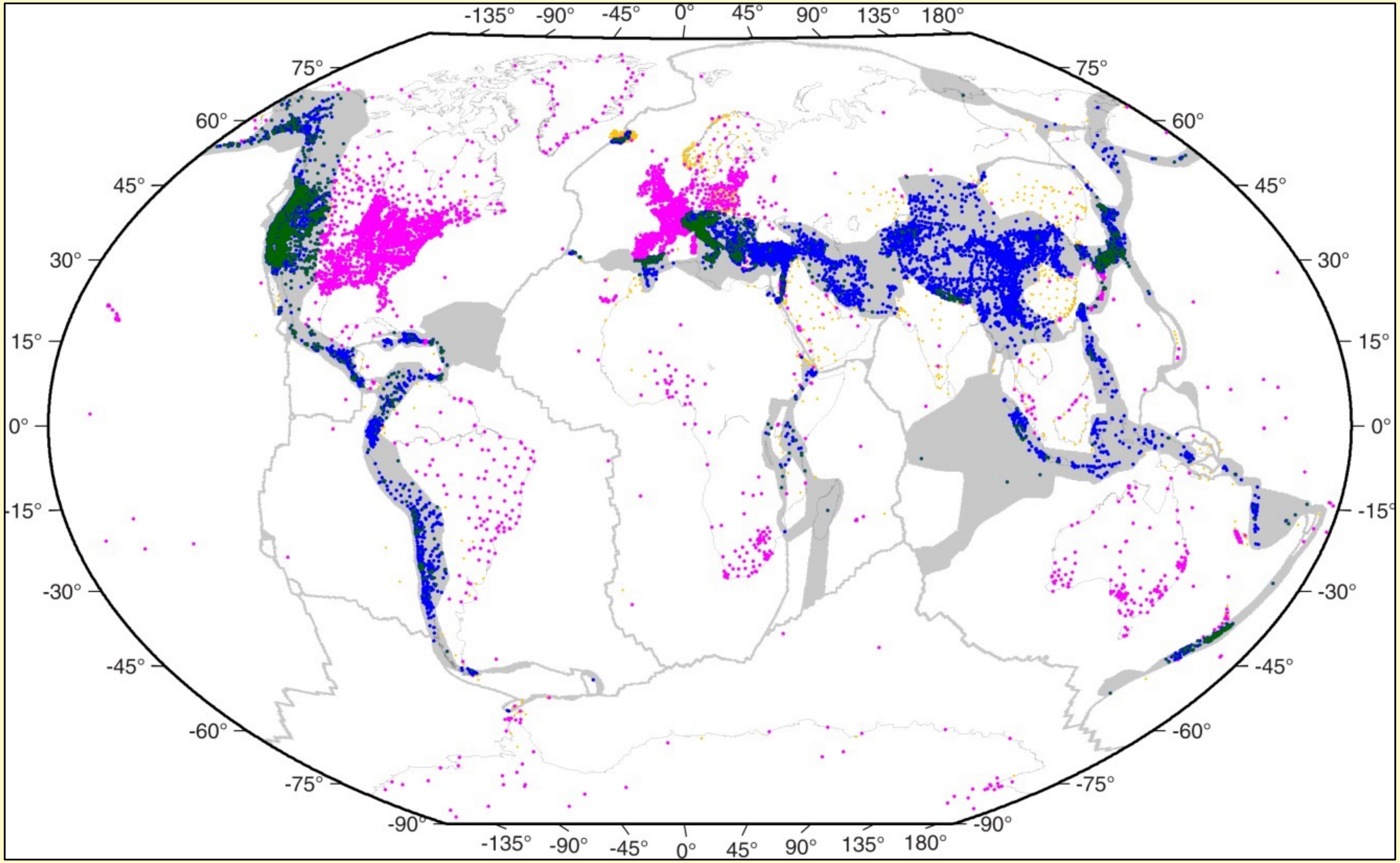
Conrad & Behn [2010]

Can we understand the time-dependence of tectonics?



Seton et al. [2012]

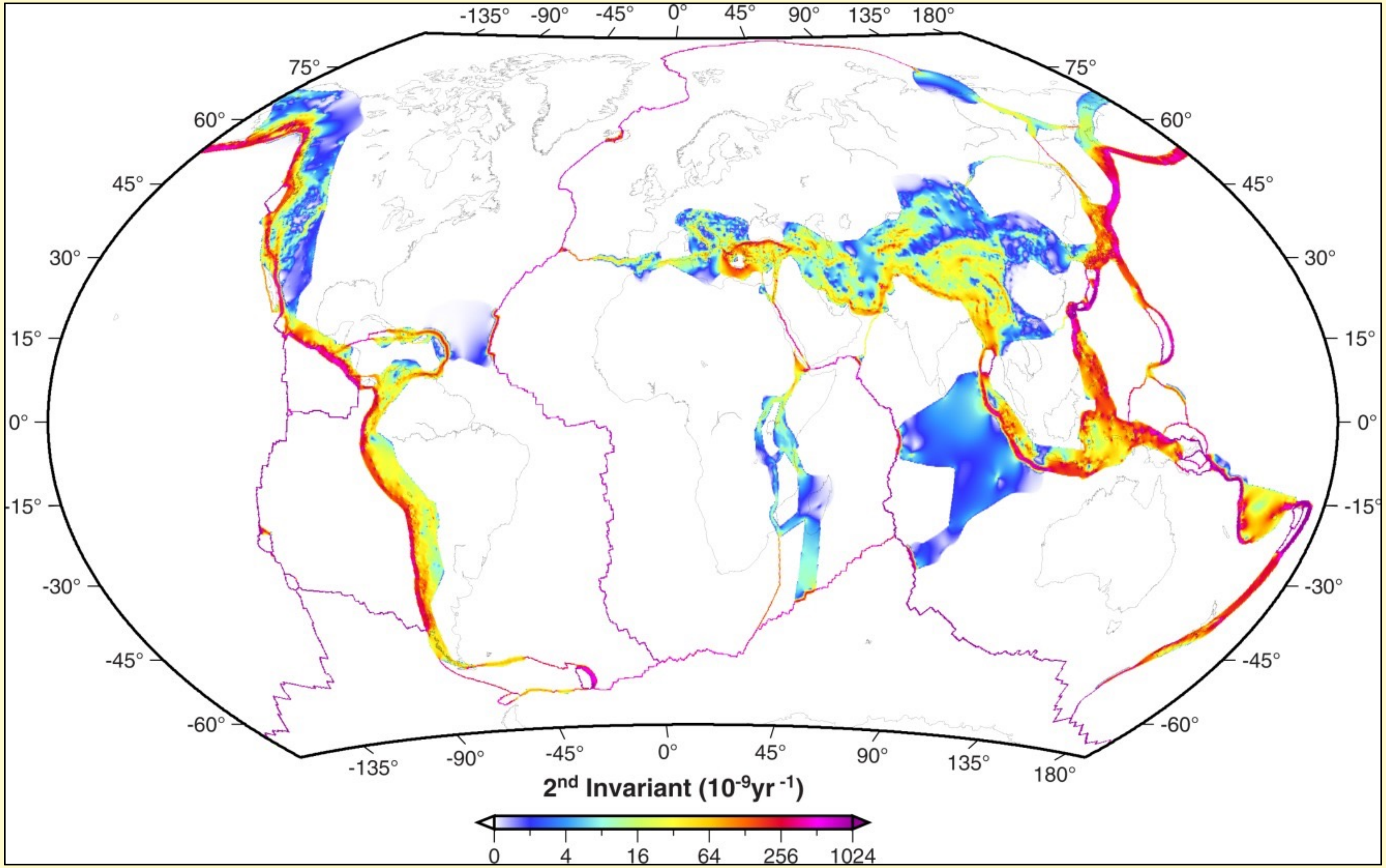
Characterizing Lithosphere Deformation



Dots: GPS stations Strain Rate Model*: Kreemer et al,* [2014]

White: 50 assumed rigid plates Grey: diffuse deformation

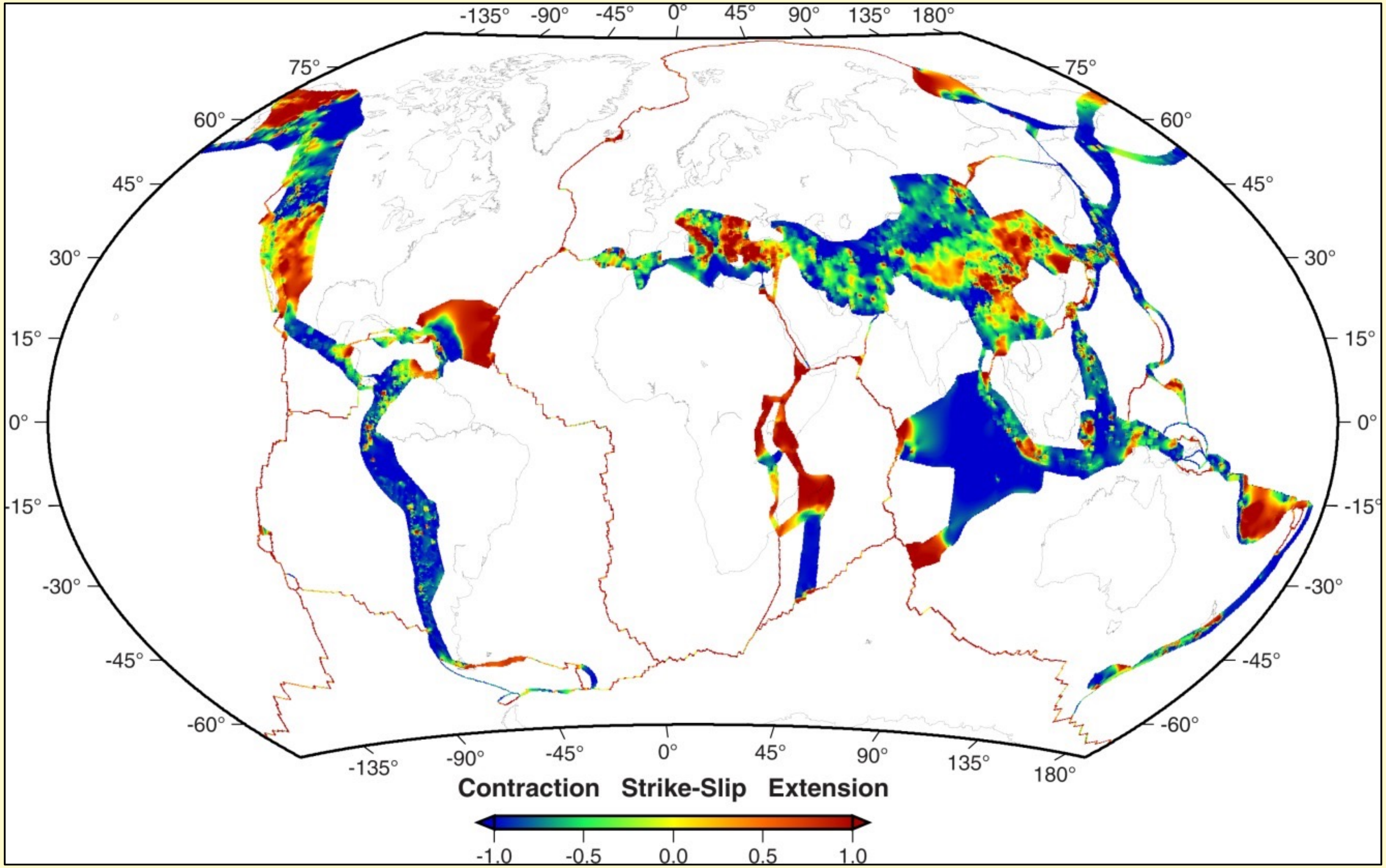
Characterizing Lithosphere Deformation



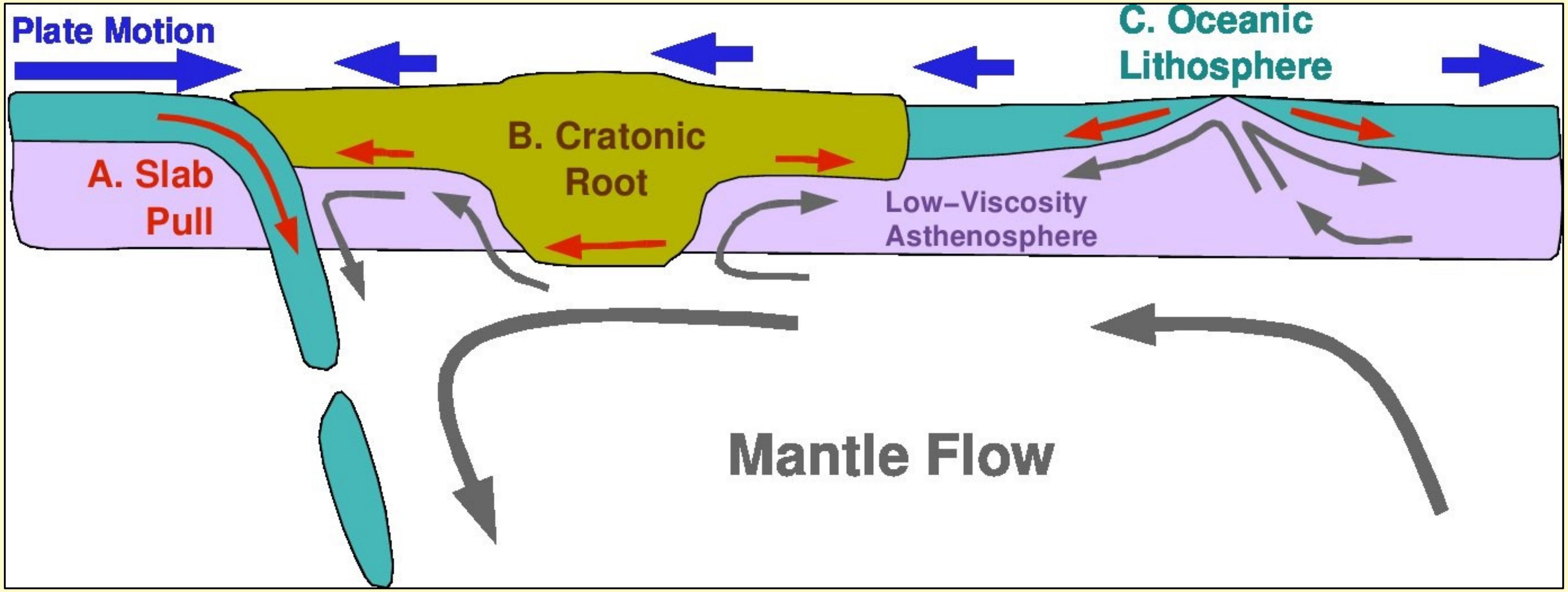
Strain Rate Model*: Kreemer et al,* [2014]

Wide areas of slow deformation → atypical plate tectonics

Characterizing Lithosphere Deformation



Style of Deformation
→ Relates to underlying stresses



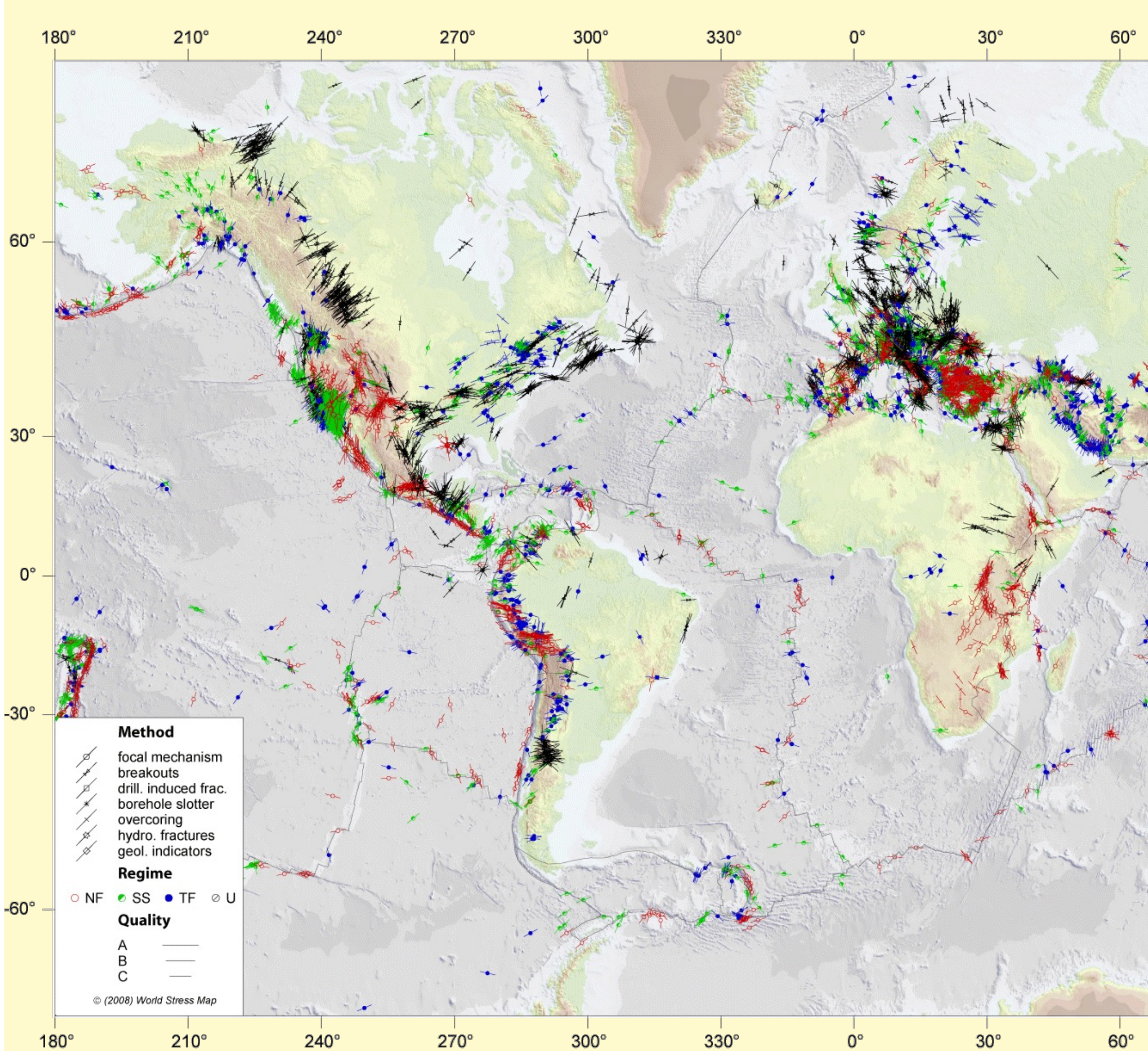
Can observe lithospheric stresses directly?

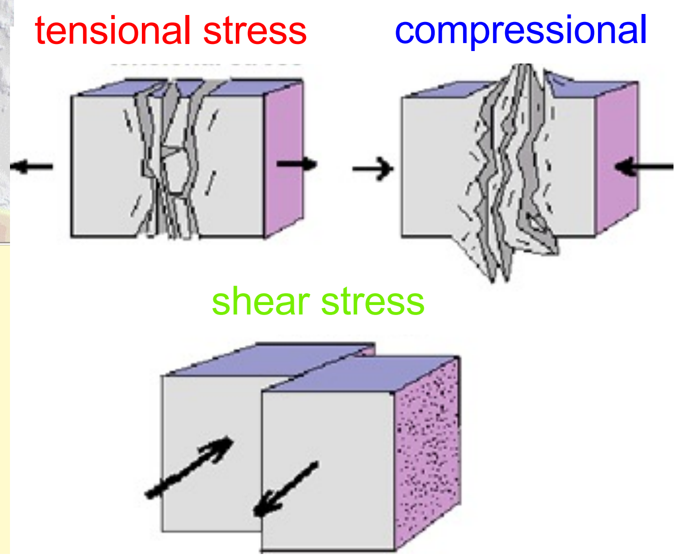
Stresses are generated by:

→ Tractions from mantle flow
→ Stresses transmitted elastically within the plates
→ Topography

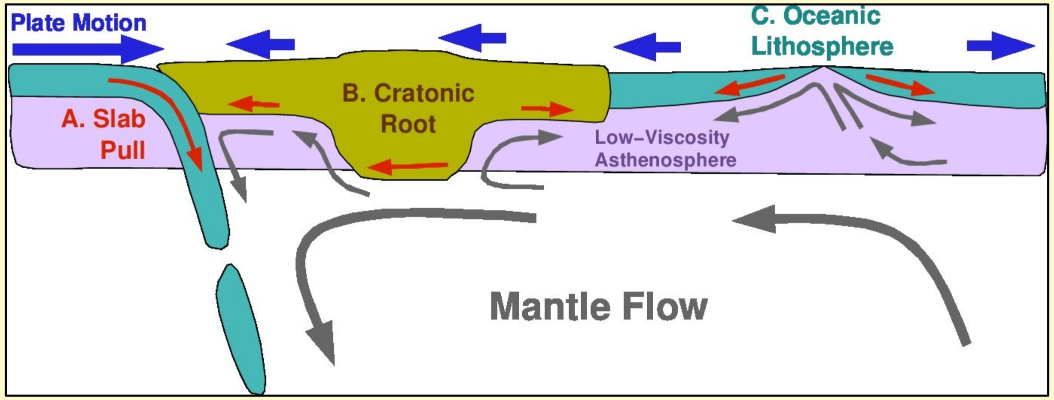
Observations are from:

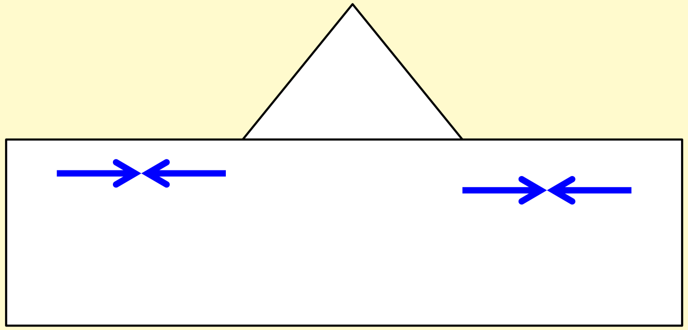
→ Borehole breakouts
→ Seismic focal mechanisms
→ Hydro-fractures
→ Geologic indicators





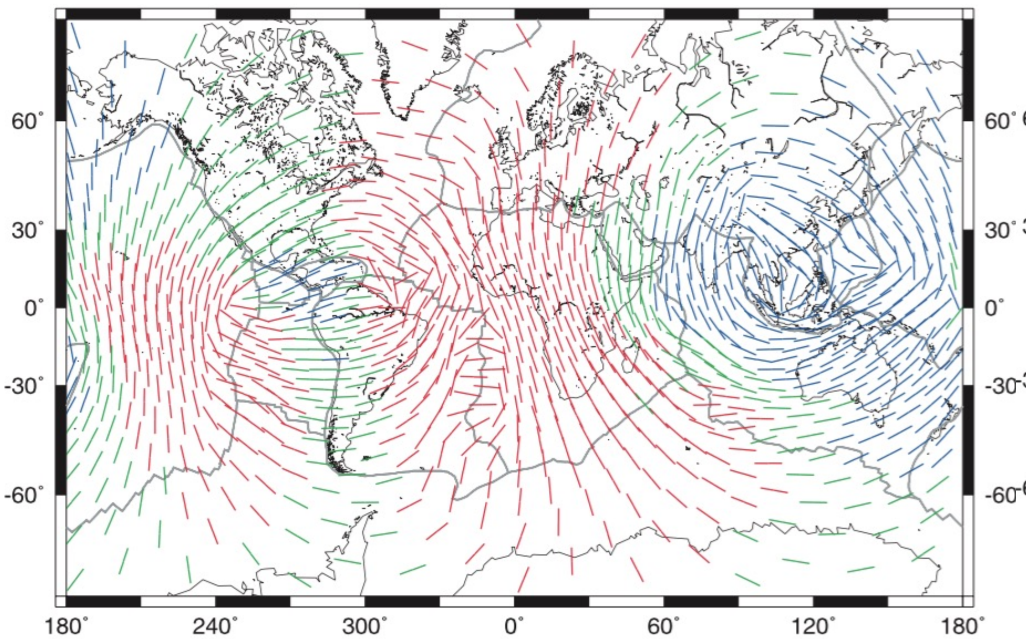
World Stress Map [*Heidbach et al.*, 2018]:
Observations of lithospheric stresses
What causes these variations?

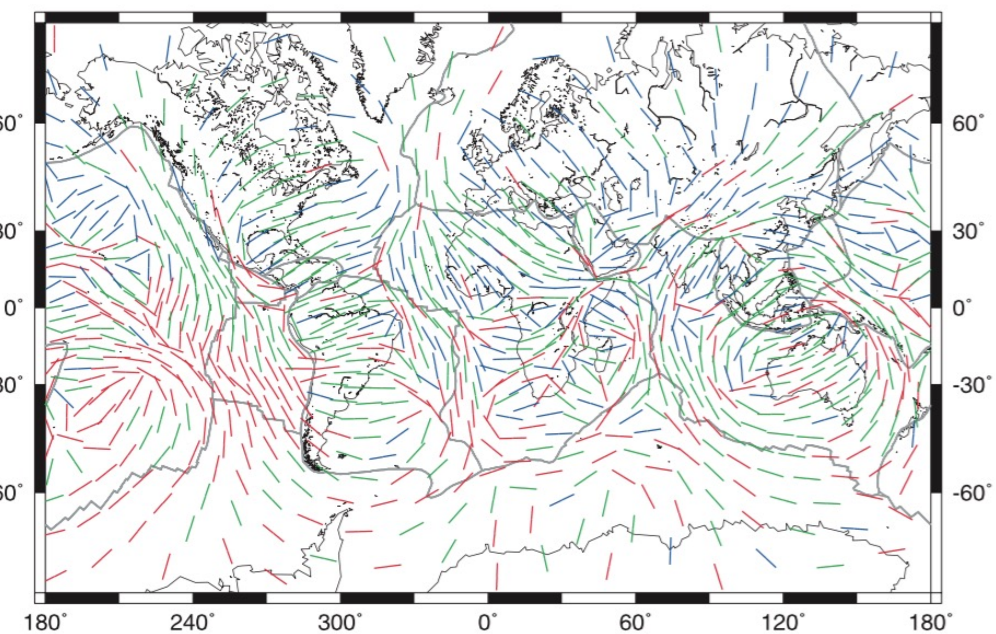




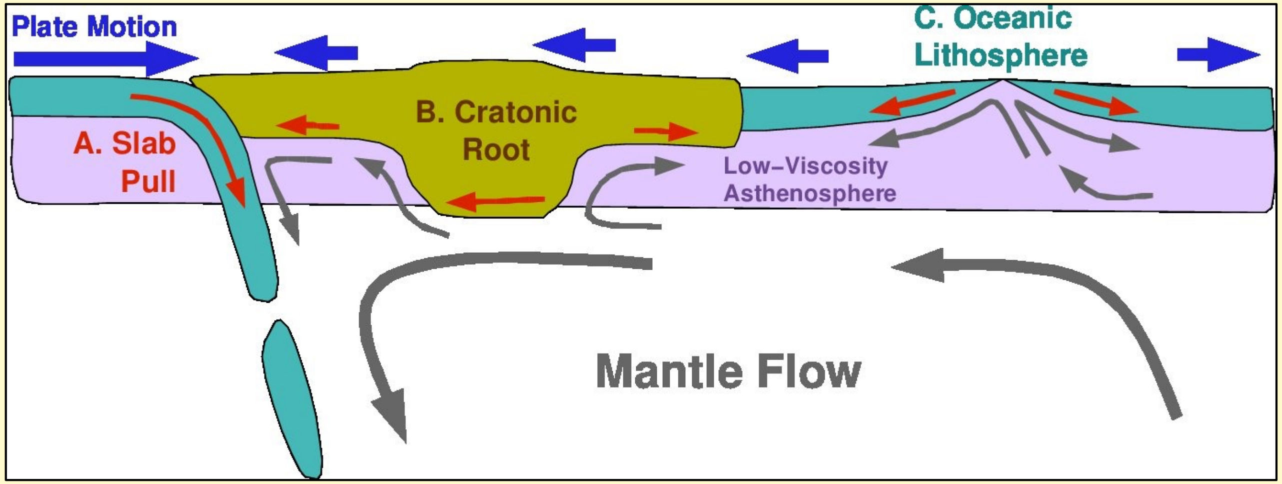
Stresses from mantle flow

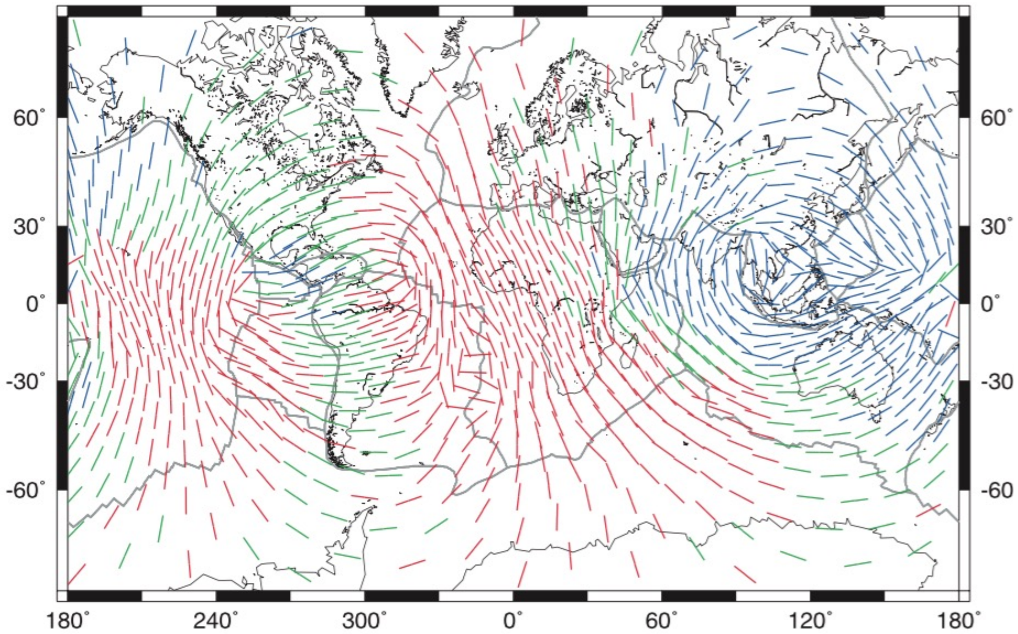
Stresses from topography

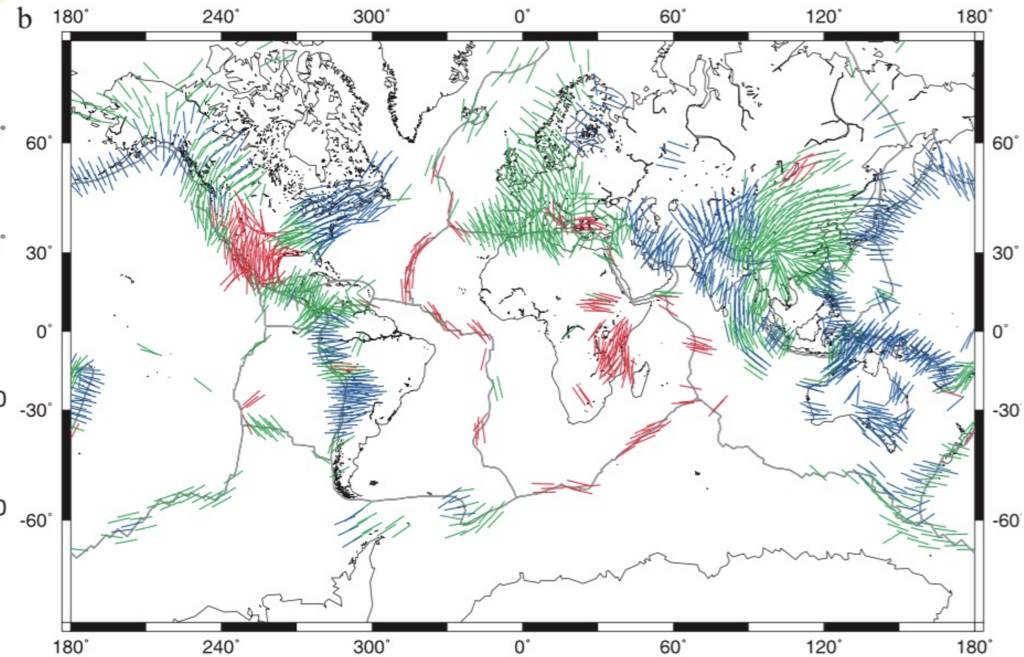




Lithgow-Bertelloni & Guynn [2004]



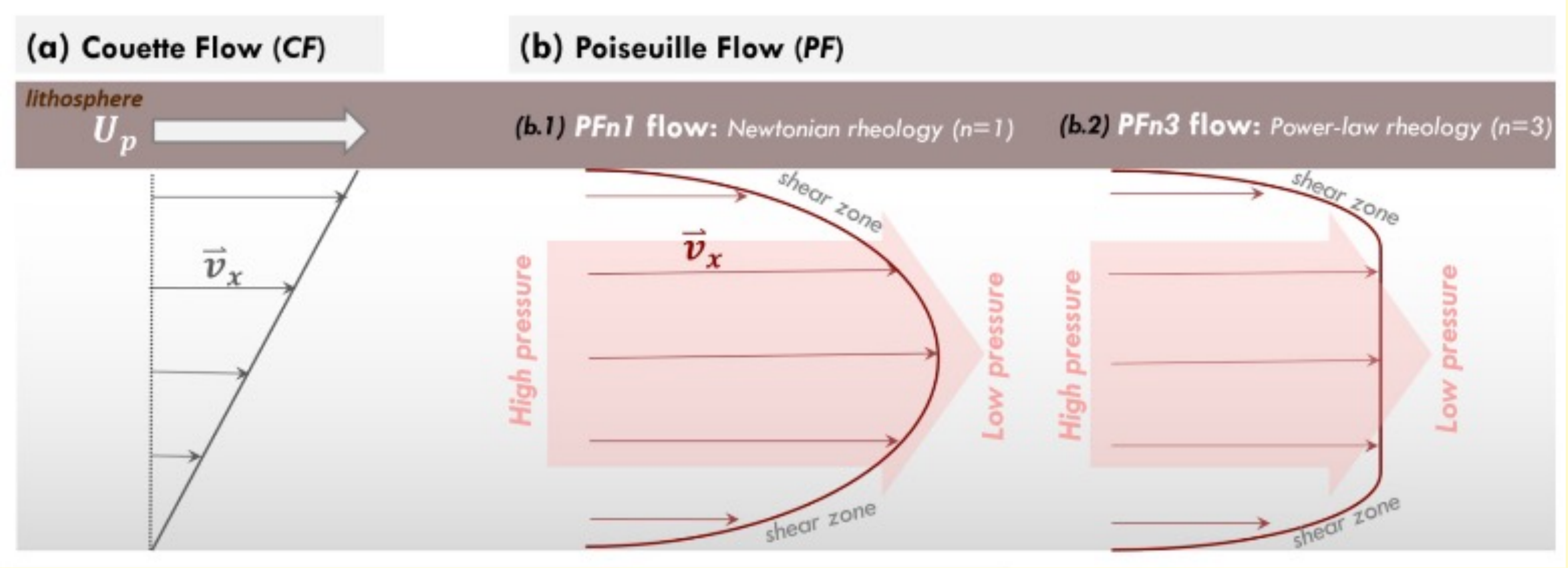




Combined Stresses *Observed Stresses*

Lithgow-Bertelloni & Guynn [2004]

Characterizing Asthenospheric Flow

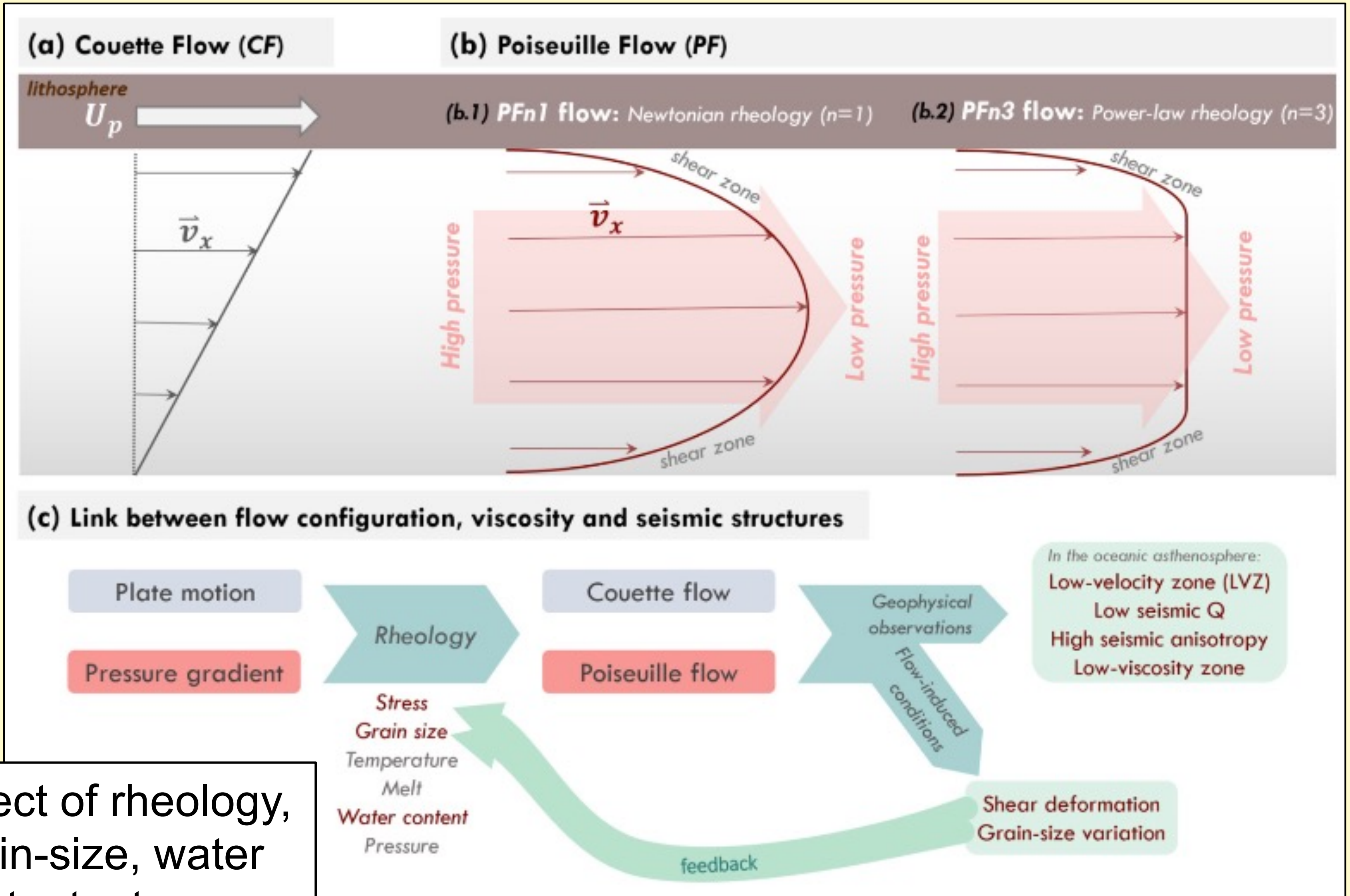


Couette Flow:
Shear deformation between the plate and the mantle below

Poiseuille Flow:
Driven by pressure gradients between different locations in the mantle.

Ramirez et al. [EPSL, 2023]

Characterizing Asthenospheric Flow



Effect of rheology, grain-size, water content, etc

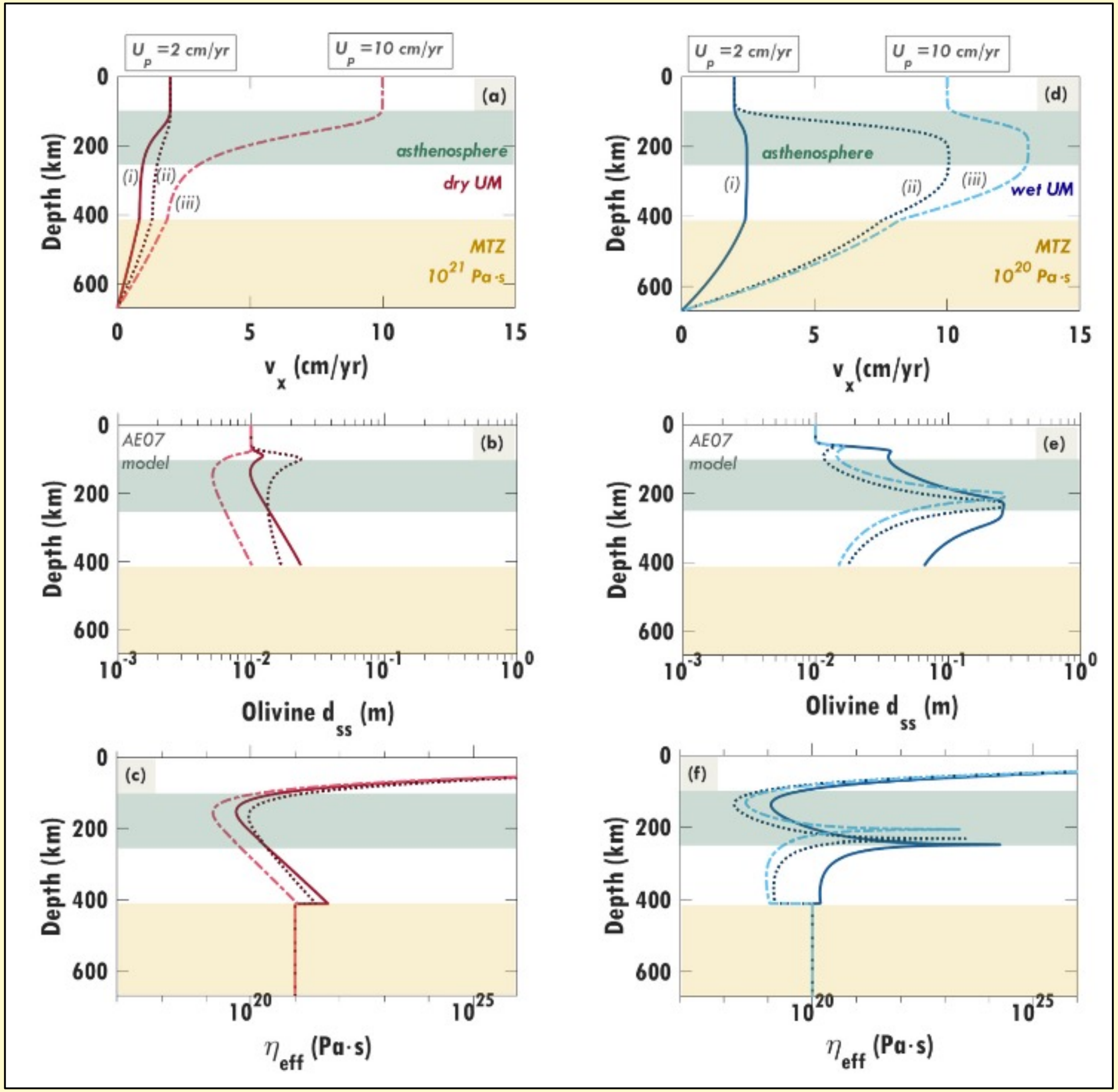
Ramirez et al. [EPSL, 2023]

Characterizing Asthenospheric Flow

Flow Velocity
→ driven by plate motions and pressure gradients

Olivine Grain Size
→ deformation reduces grain size

Effective Viscosity
→ smaller grains lead to smaller viscosity



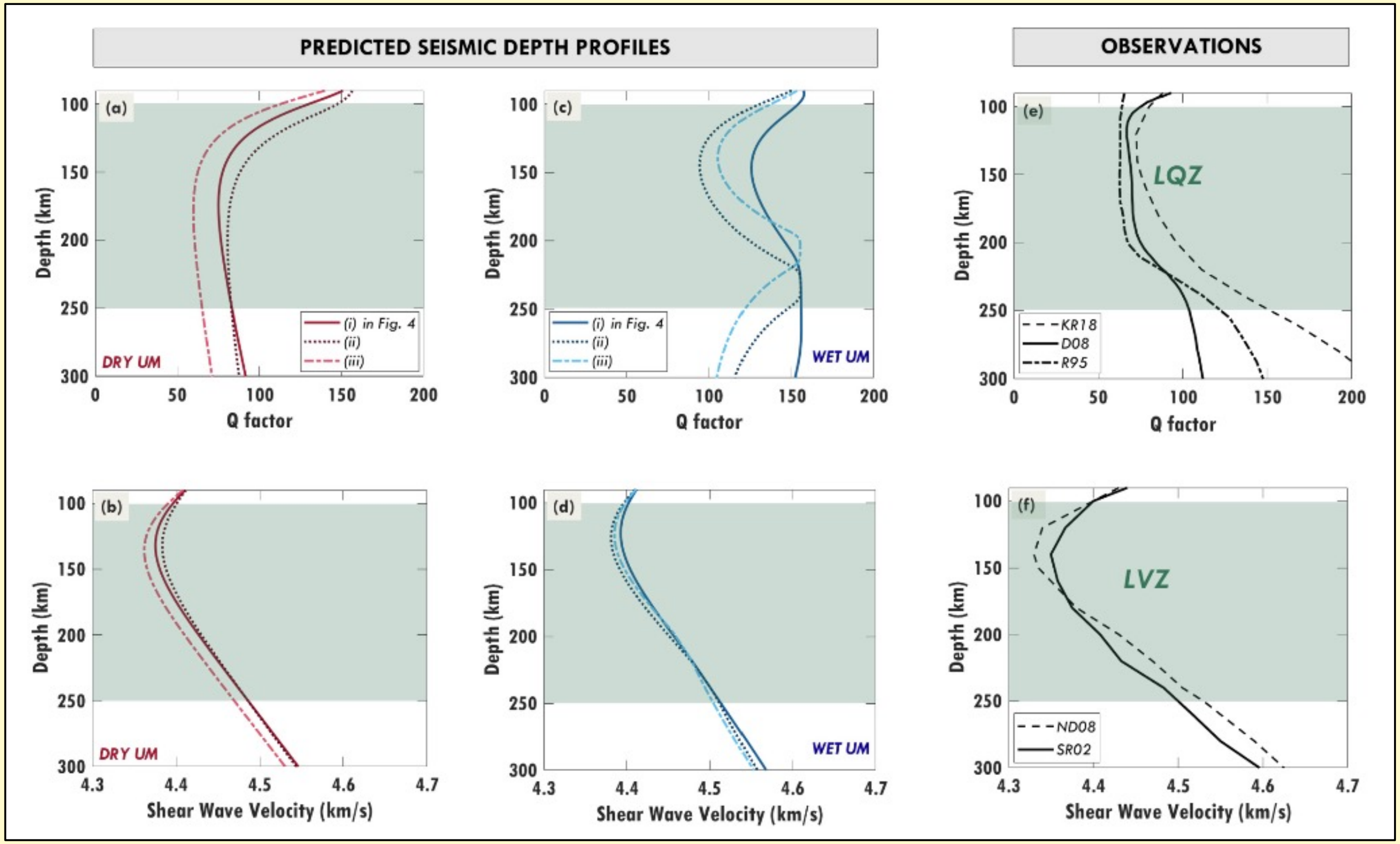
Ramirez et al. [EPSL, 2023]

Characterizing Asthenospheric Flow

→ Is Poiseuille Flow Necessary to Explain Seismic Observations?

Seismic Attenuation
→ Sensitive to grain-size and other factors

Seismic Velocity
→ Sensitive to temperature and other factors

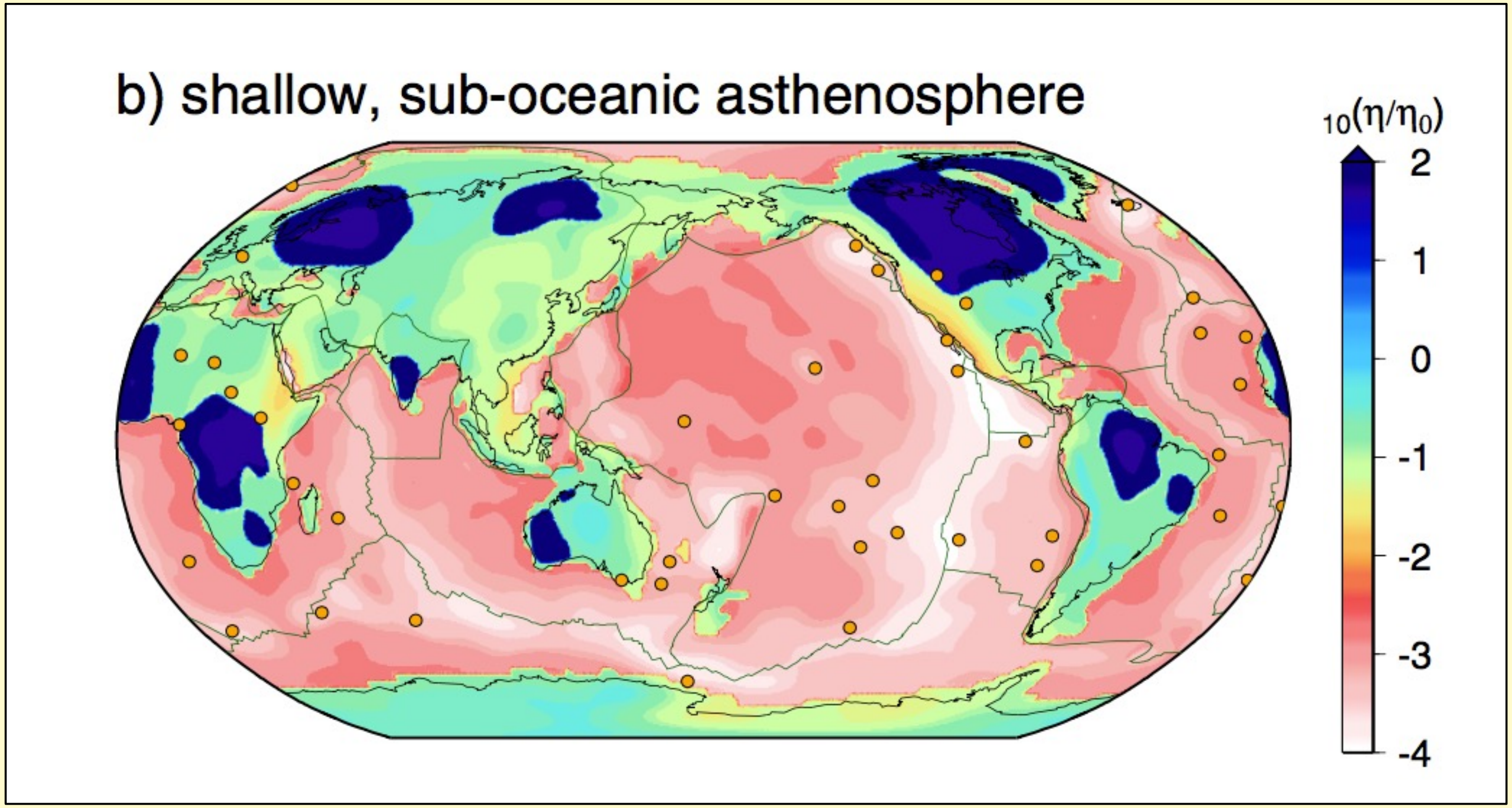


Ramirez et al. [EPSL, 2023]

Characterizing Asthenospheric Flow

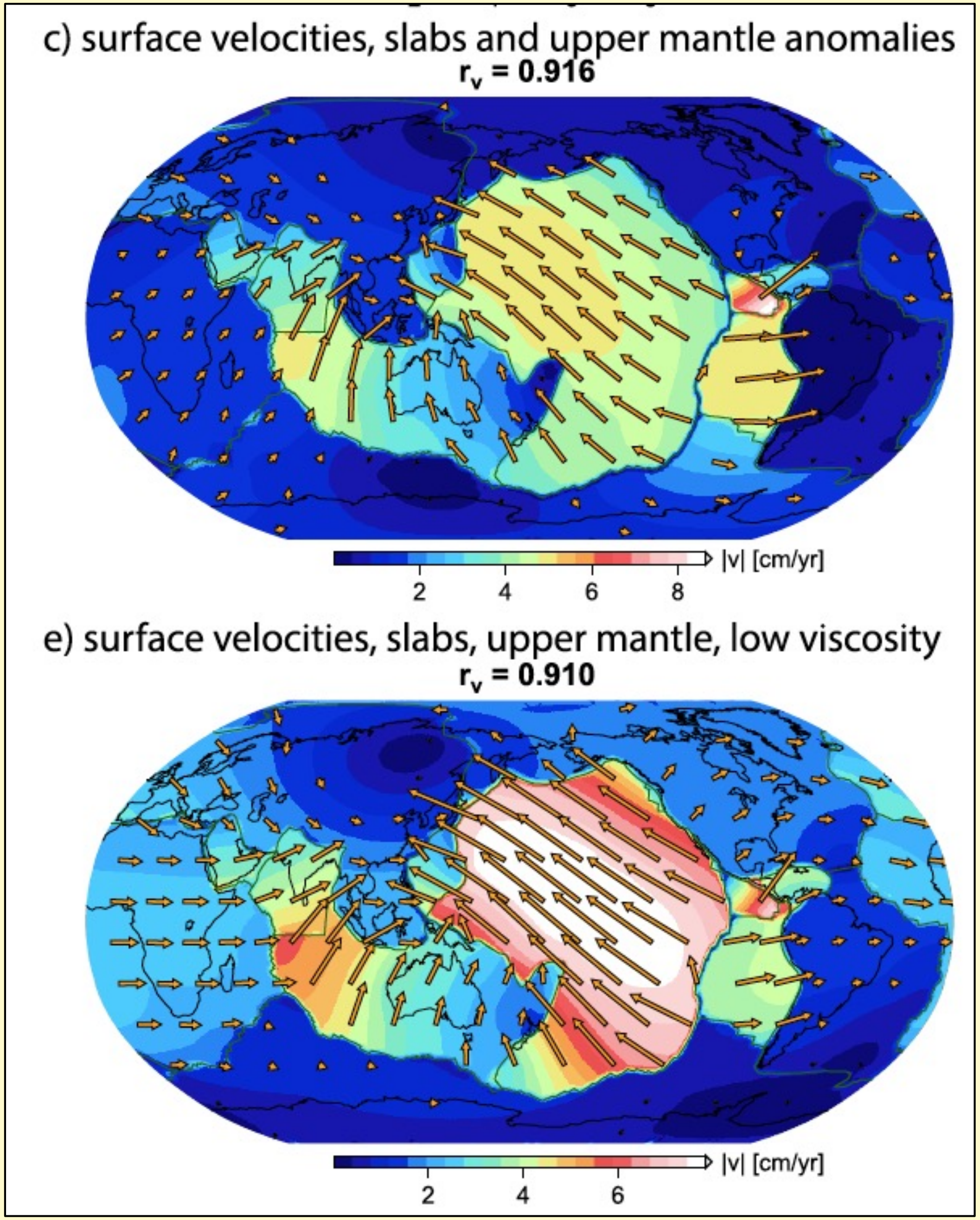
The "super-weak" asthenosphere

Becker [*Gcubed,* 2017]



For global tectonics, asthenosphere viscosity makes a difference…

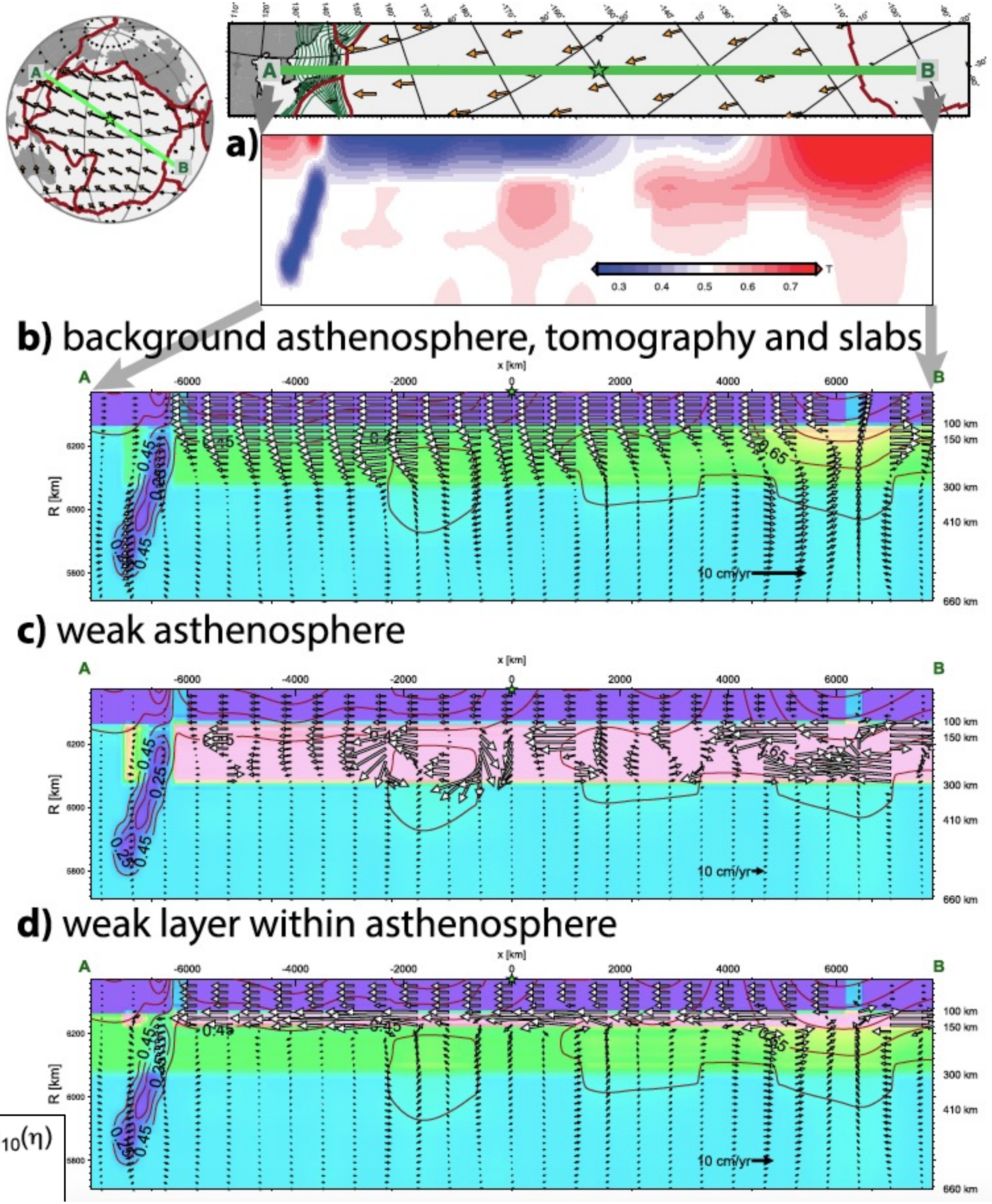
“Super-weak” viscosity in the asthenosphere: Viscosity reduced by a factor of 100 →

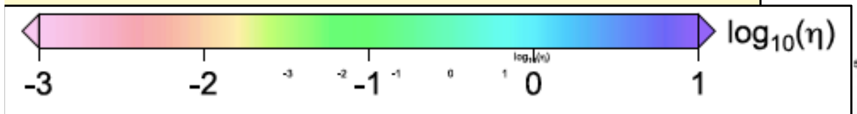


Becker [*Gcubed*, 2017]

Becker [*Gcubed*, 2017]

Locally, the asthenosphere viscosity makes a big difference for flow patterns…





Conclusions

→ **Plates motions are driven mostly by:**

- **Slab Pull**
- **Mantle Flow (via basal tractions on plates)**

→ **Plates and mantle are linked through the asthenosphere.**

Questions:

- **What is the viscosity of the asthenosphere?**
- **How rigid are the plates?**
- **What are the flow patterns in the asthenosphere?**