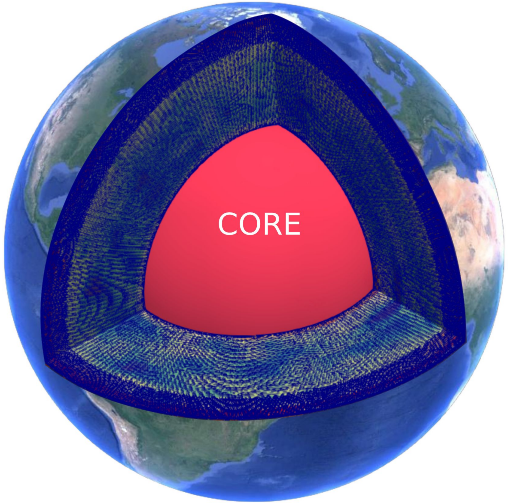
Integration of Geophysical Constraints in Global Mantle Flow Models for Insights Into Plate Tectonics



With:
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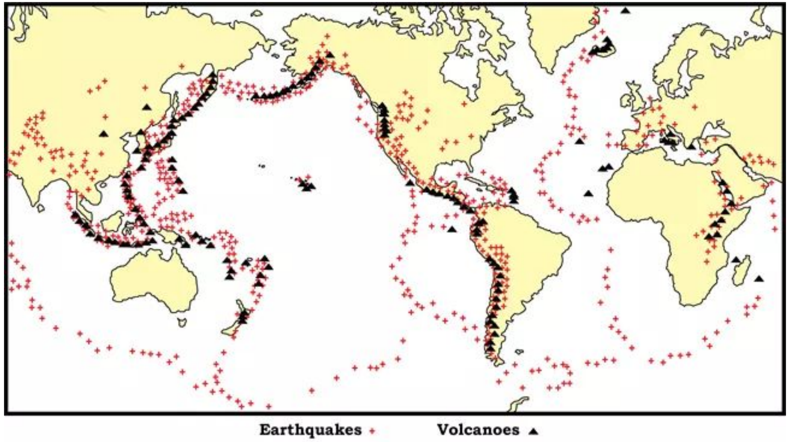
FRONTERA

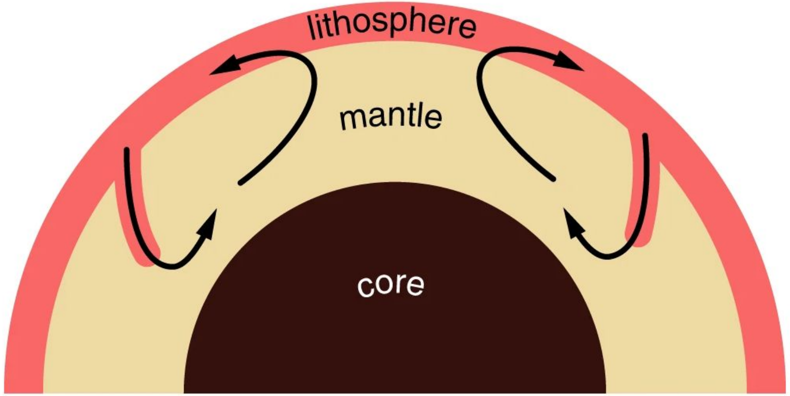
CIG COMPUTATIONAL INFRASTRUCTURE for GEODYNAMICS

Why plate tectonics?

- The locations of most earthquakes and volcanoes correspond to plate boundaries
- Plate driving forces can better help us understand the locations and hazard related to earthquakes and volcanoes
- Plate tectonics is closely linked to the underlying mantle flow



Robert J. Lillie, (2005)



Karato and Barbot (2018)

Why Numerical Modeling?

Many surface processes can be linked to the deep interior, which remains largely inaccessible

We can use numerical models to understand the physical processes constrained with the observed geophysical data

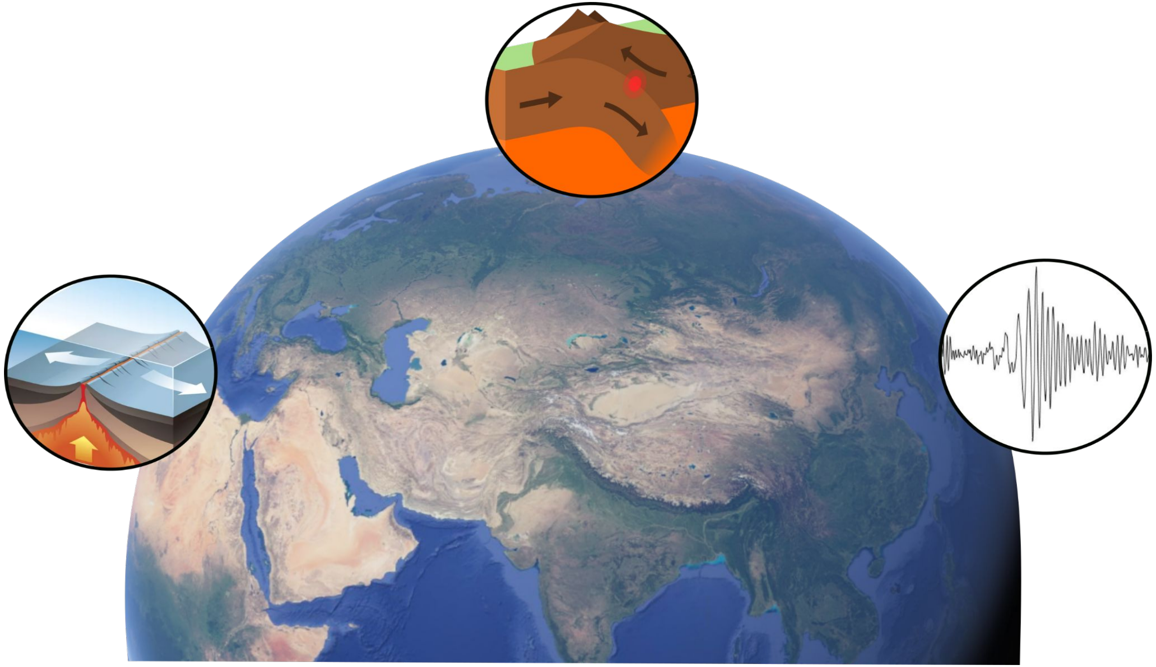
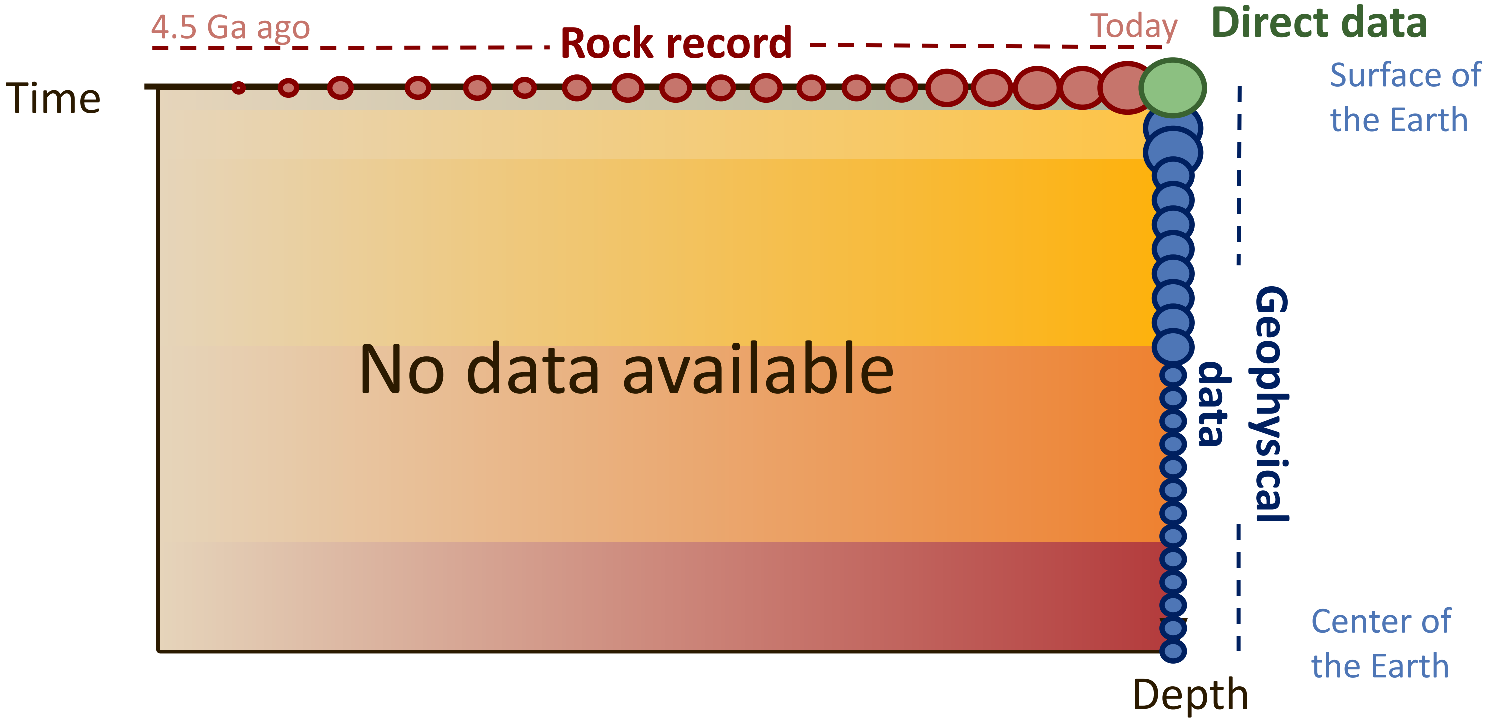


Image modified from Prof. Juliane Dannberg, Introduction to Geophysics and Tectonics course

Available Observational Constraints



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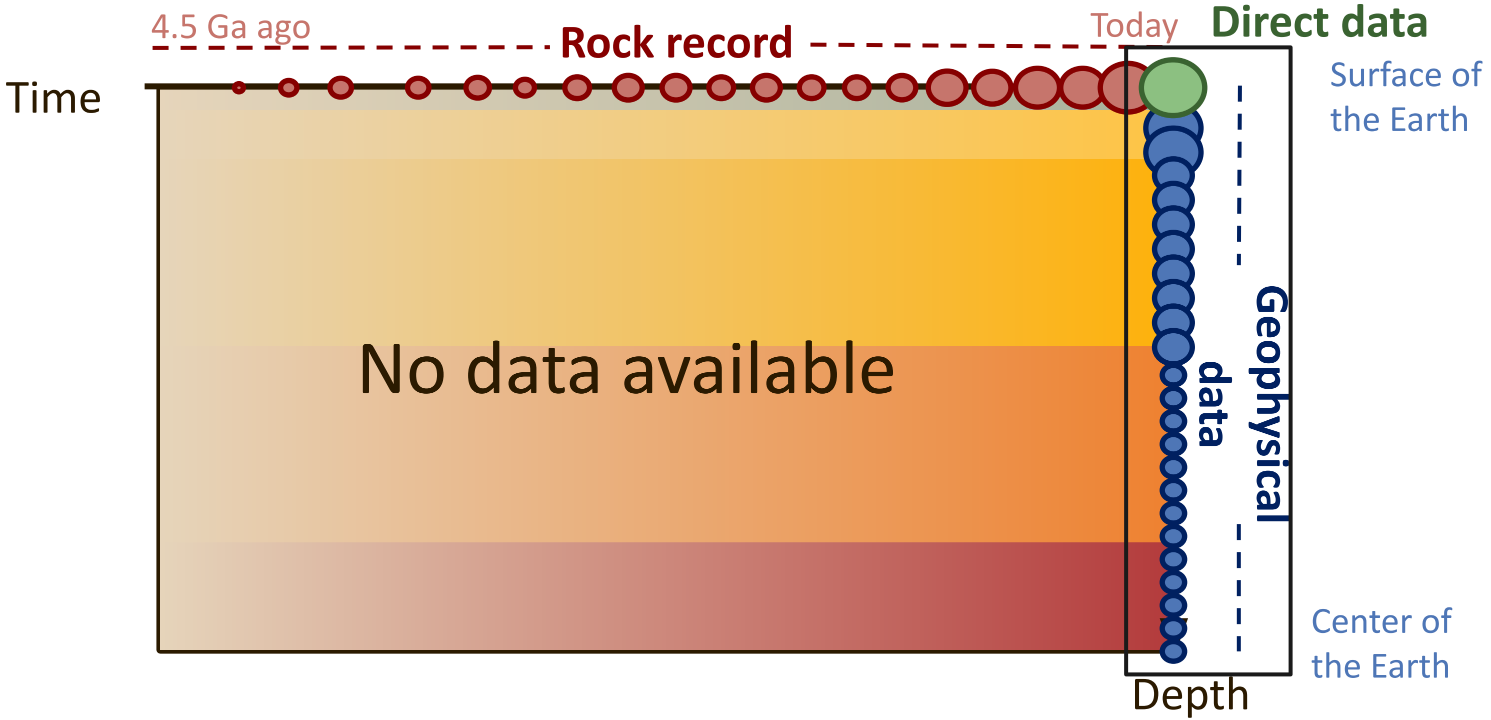
Available Observational Constraints



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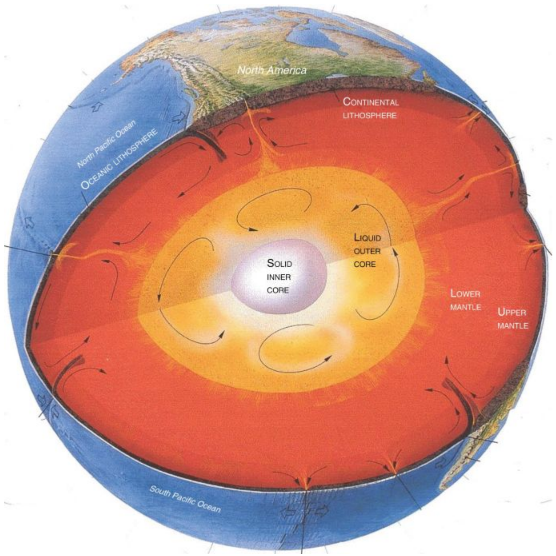
Geodynamic World Builder

Developing global mantle flow models

ASPECT

Mantle is **~2800 km** thick and moves at speeds of **~cm/year**
Numerical models allow us to understand the physics over this spatial and temporal timescales!

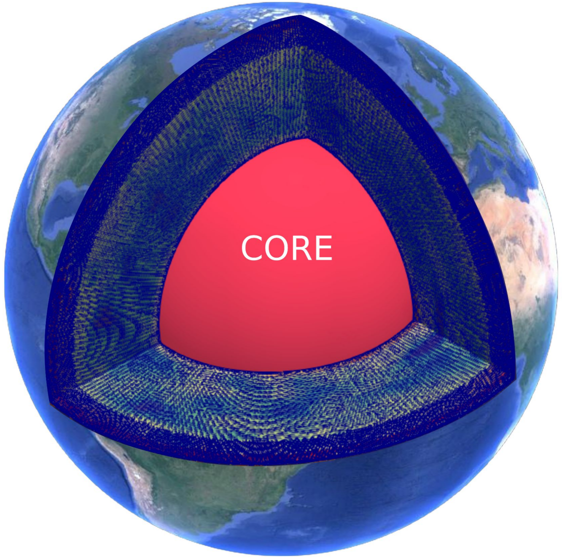


Lamb and Sington (1998)

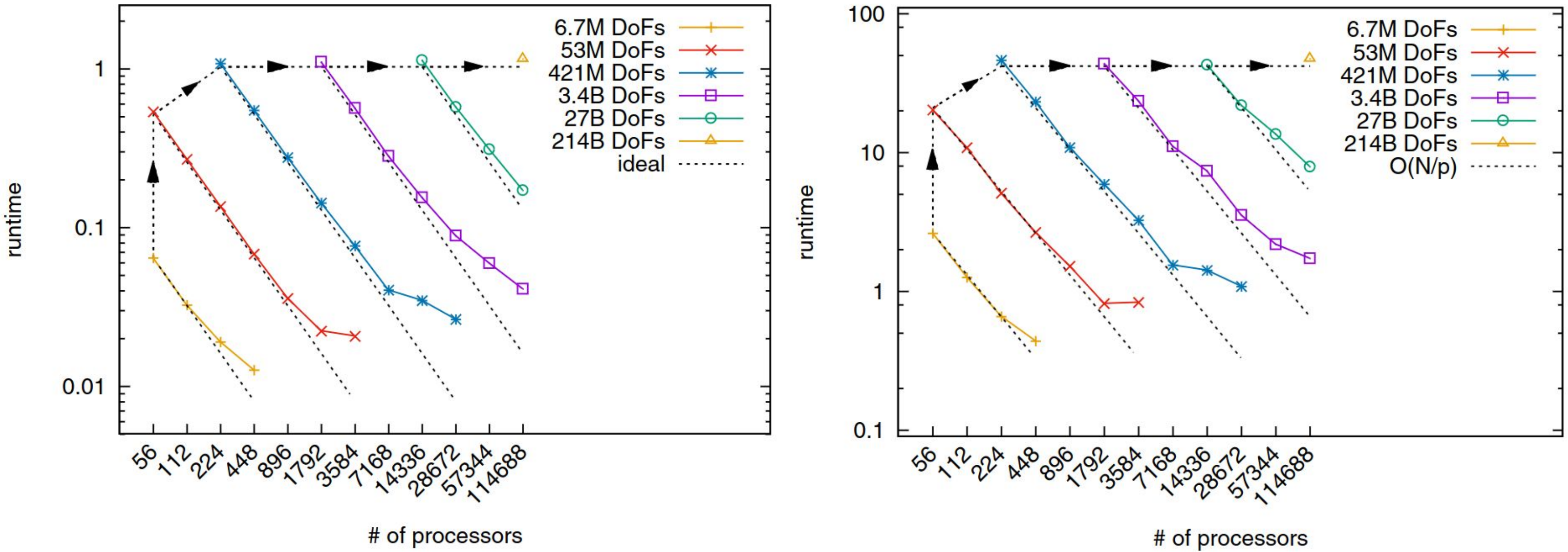
+

$$\begin{aligned} -\nabla\cdot(2\eta\dot{\varepsilon}) + \nabla p &= \rho\mathbf{g}, \\ \nabla\cdot(\rho\mathbf{u}) &= 0, \end{aligned}$$

Equations for mantle convection: Conservation of mass and momentum



Why ASPECT?

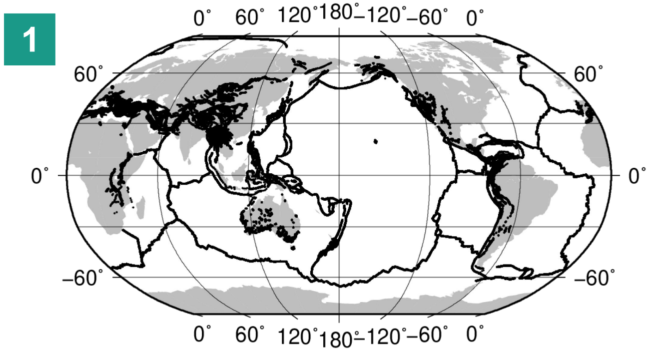


Clevenger and Heister (2020)

Scaling tests for a globally refined Stokes problem in ASPECT on Frontera using multiple nodes

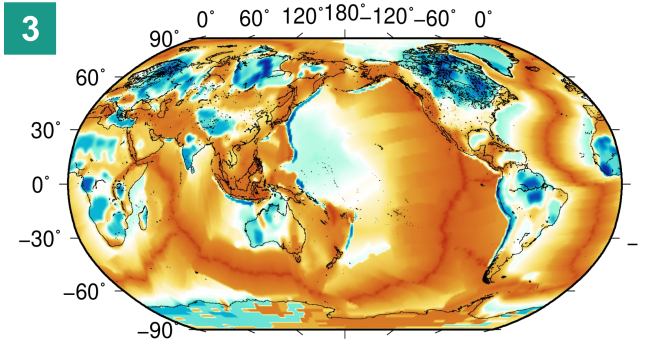
Integrating Recent Geophysical Constraints

1



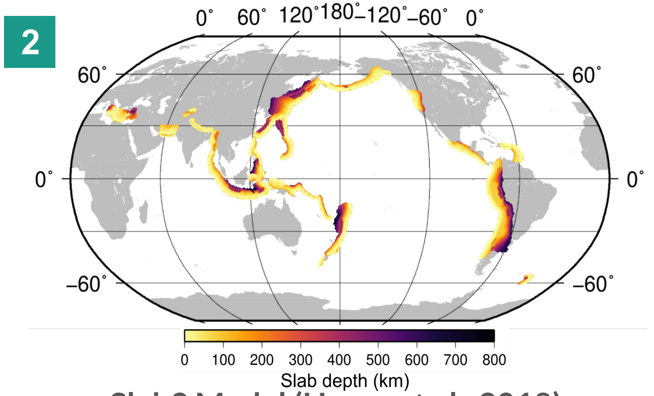
Global Earthquake Model (Pagani et al., 2018b)

3



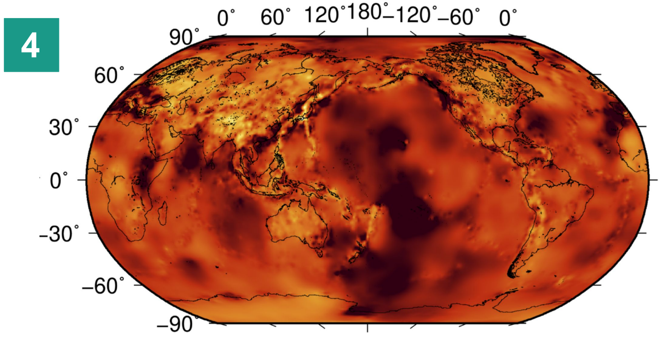
TM1 Model (Osei Tutu et al., 2018b), LAB depths (Priestley et al., 2018)

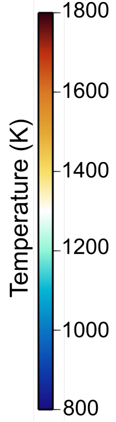
2



Slab2 Model (Hayes et al., 2018)

4





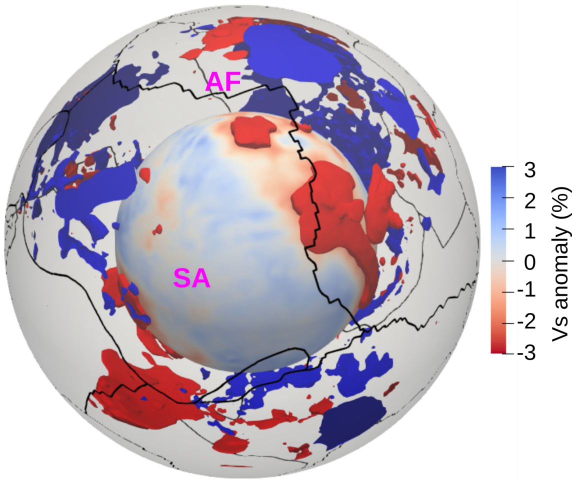
LLNL-G3D-JPS (Simmons et al., 2016)

Based on the results from our previous study, we use well-defined slabs from the Slab2 model.

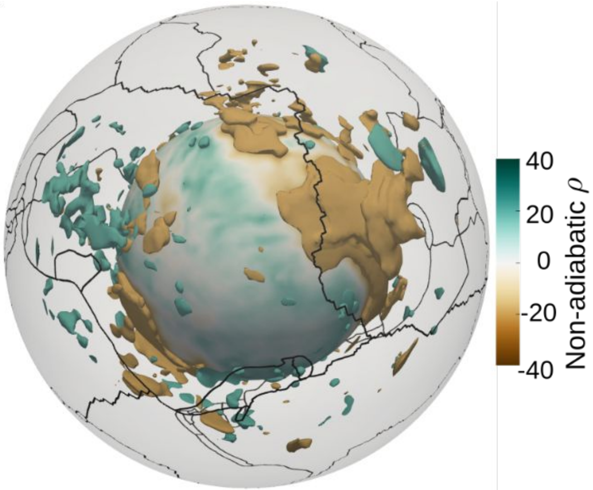
Converting observations to physical properties

ASPECT

Density distribution



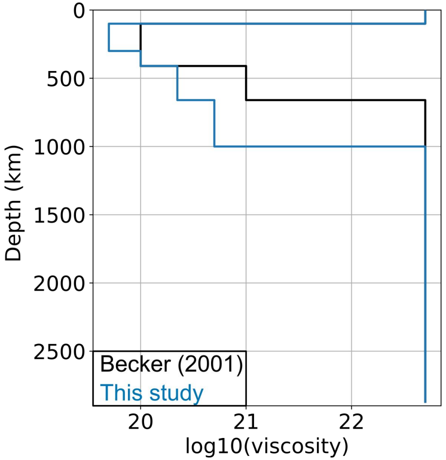
Geophysical observations



Physical properties

★ The modeled velocities are generated self-consistently from the interplay between the computed frictional and buoyancy forces

Viscosity Distribution



Laterally averaged reference viscosity profile

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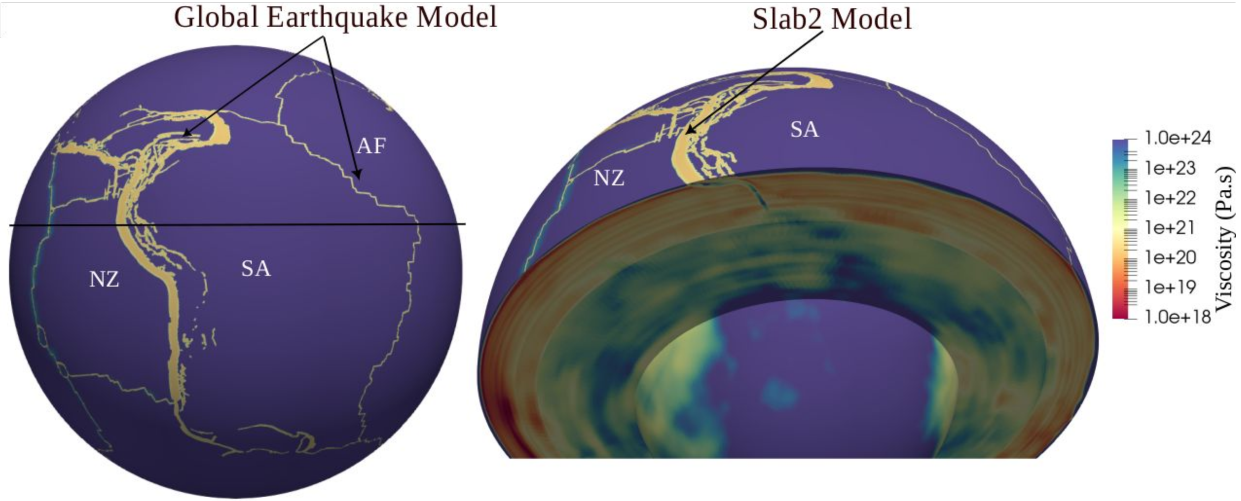
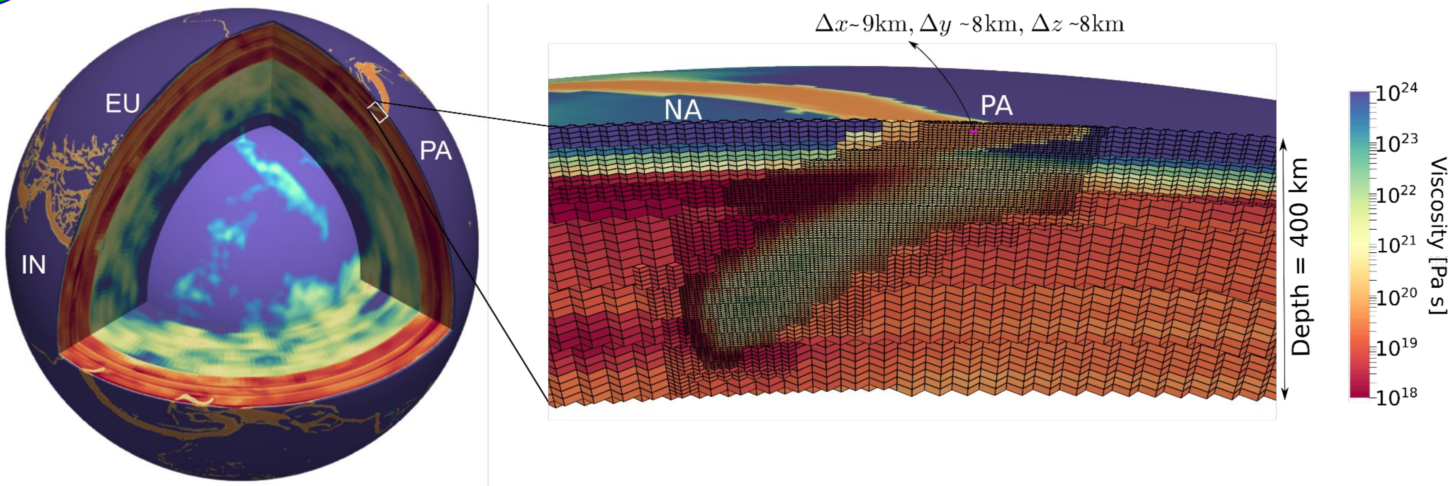


Weak zones representing plate boundaries

We use composite creep rheology with imposed plate boundaries, averaged to a 1D profile

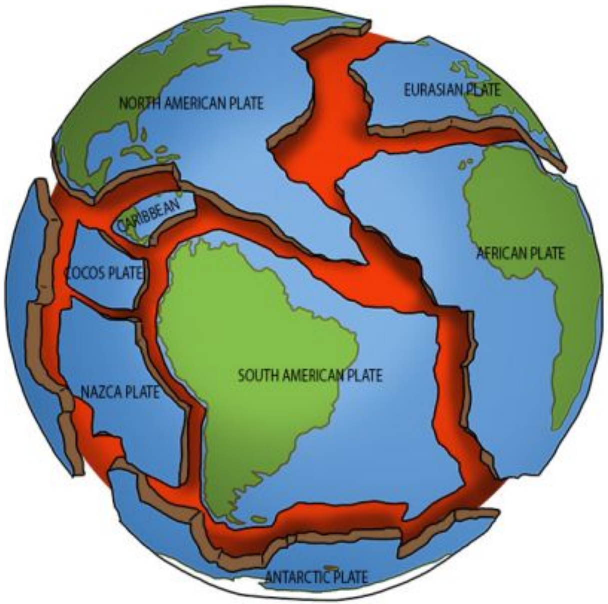
Model Setup



Our models are **instantaneous**, solving for the momentum and mass balance equations with prescribed temperatures.

Minimum **cell size ~ 9 km**.

Exploring the parameter space



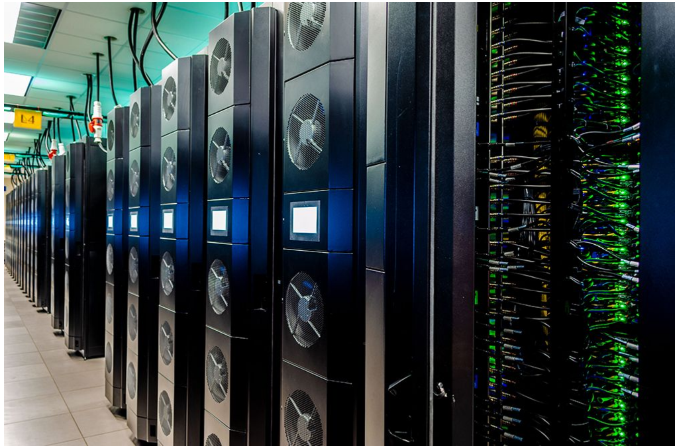
We vary:

1. **Plate boundary viscosity:** frictional forces along the plate boundaries
2. **Asthenospheric viscosity:** frictional forces at the base of the plates
3. **Mid-mantle viscosity:** the ease with which the slabs can pull the plates into the lower mantle

We compute pointwise RMS residual against the observed GPS velocities to quantify the models

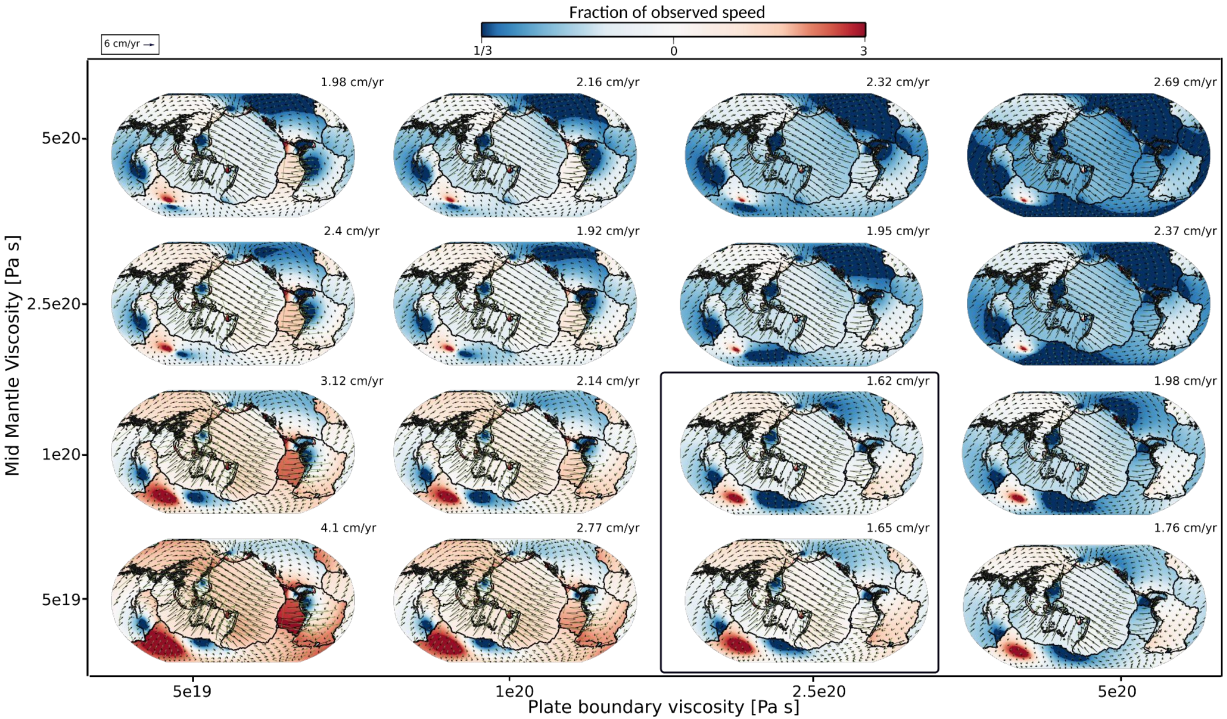
Model runs

- We run around 40 models
- Each model has around 2B DoF
- Each models take around 3 hours using 5376 cores
- Model output size about 18 GB
- Used paraview in parallel using 32 processors for model output visualization



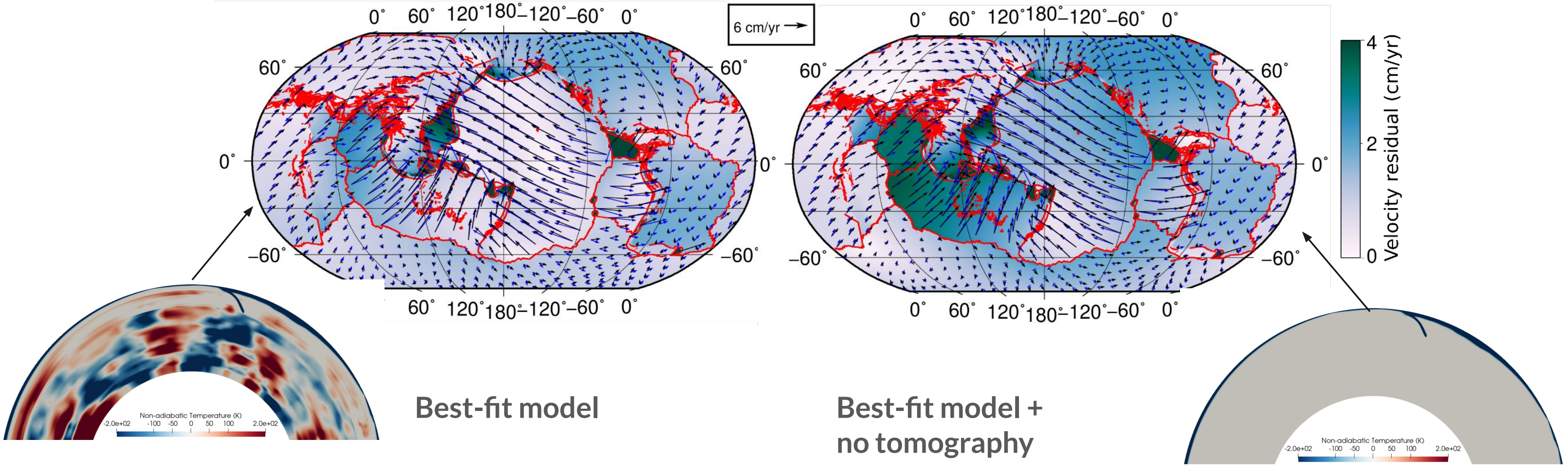
Impact of Mid-mantle and Plate Boundary Viscosity

- Residual increases as we reduce both fault and mid-mantle viscosity
- Best-fit models have **low mid-mantle viscosity** and **intermediate fault viscosity**
- Slower plates are influenced more with the viscosity variation



Asthenosphere viscosity = 1e20 Pas

Contribution of Slab Pull



Best-fit model

Angular fit = 93.7%
Speed res = 0.7 cm/yr
Velocity res = 1.6 cm/yr

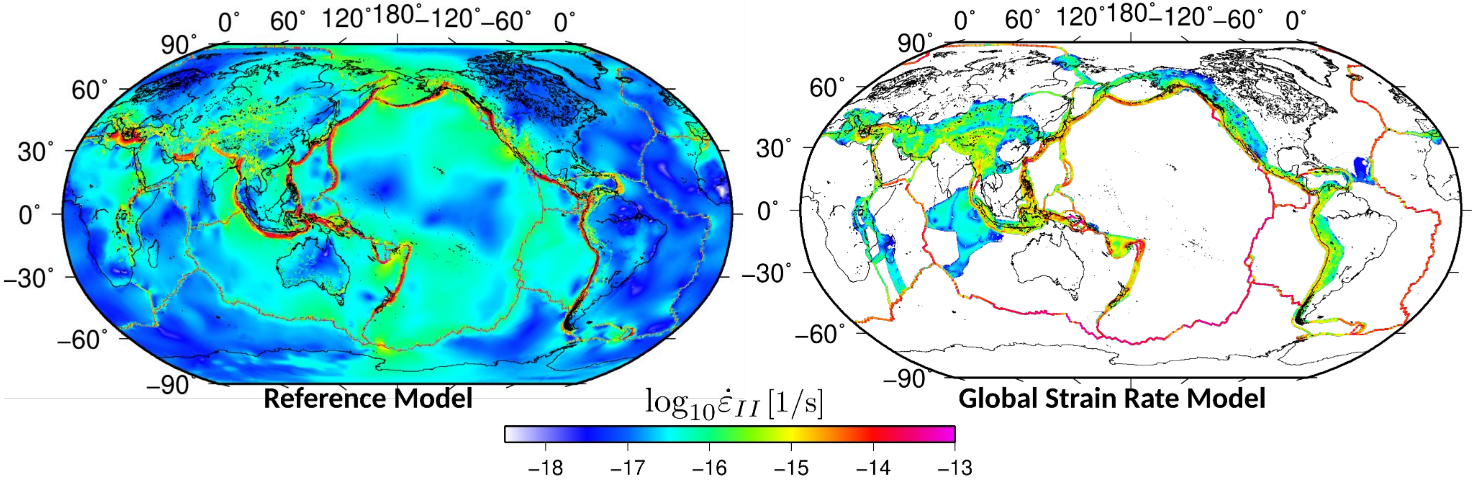
Best-fit model + no tomography

Angular fit = 91.4%
Speed res = 1.1 cm/yr
Velocity res = 2. cm/yr

★ In presence of slabs and lithospheric structure only, 75% of the best-fit model speeds are observed

Comparison with Strain Rates

- **ZONE I:** Very high strain rates at discrete boundaries
- **ZONE II:** Intermediate strain rates in the continental rifts and around slabs within the oceanic plates
- **ZONE III:** Very low deformation at intraplate zones



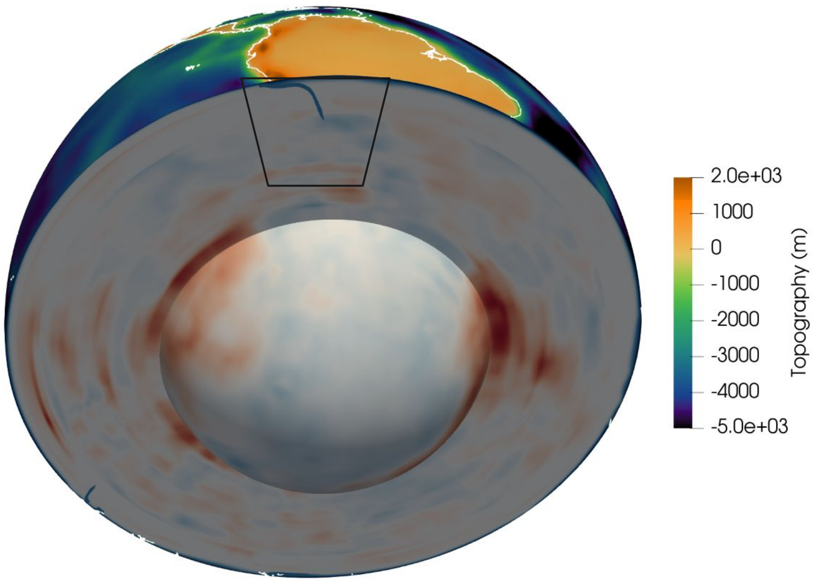
Reference Model

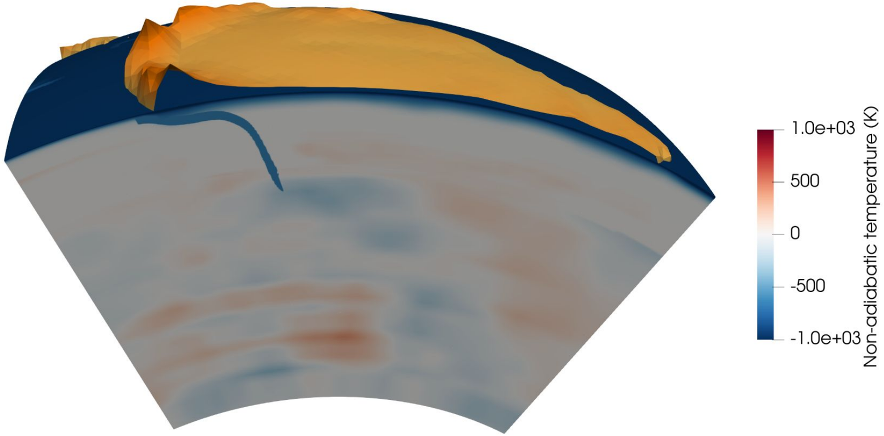
Global Strain Rate Model

Summary

- Our best fit has plate boundary viscosity **2.5e20 Pas**, asthenosphere viscosity **5e19 Pas**, and mid-mantle viscosity of **1e20 Pas**
- Our models suggest that slab pull explains 75% of the total driving force in the plates
- In our current models, we have included topography and are computing horizontal maximum stress directions from our best-fit model

Current Models with Topography





Stresses arise due to combination of gravitational potential energy including sub-lithospheric flow and lithospheric density and thickness variations