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Observational constraints on global quantitative models of the coupled plates/mantle system

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Basic knowledge on mantle convection/plate tectonics

Tectonic plates

Upper thermal boundary layer of the convecting system

Mantle

Heated from within.

Solid, but it convects as a fluid over Myr

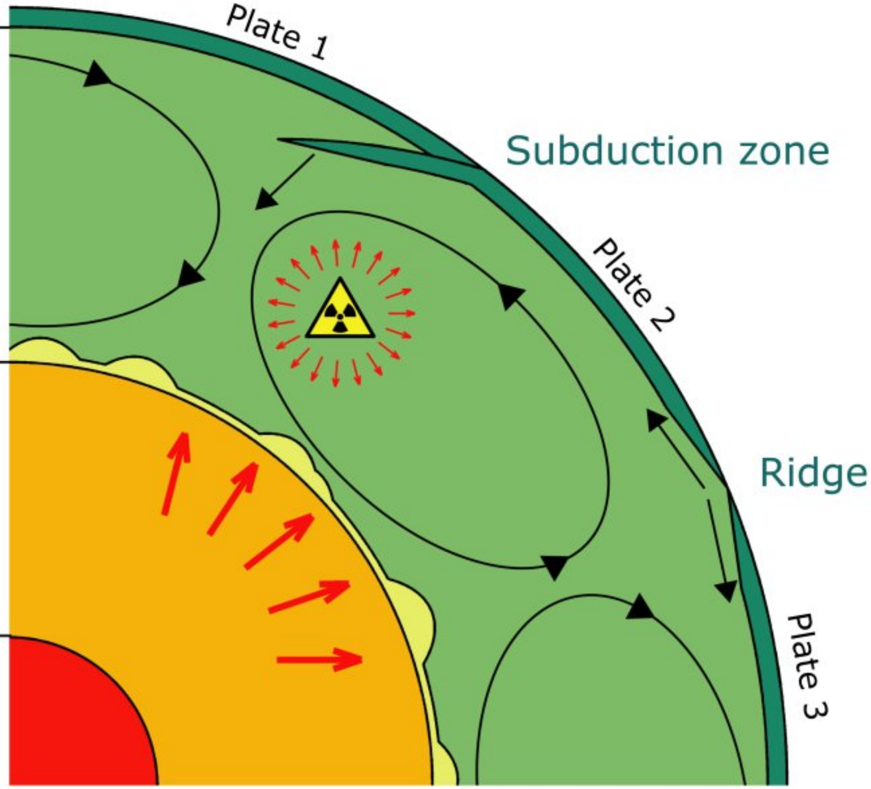
Outer core

Liquid.

It releases heat into the mantle.

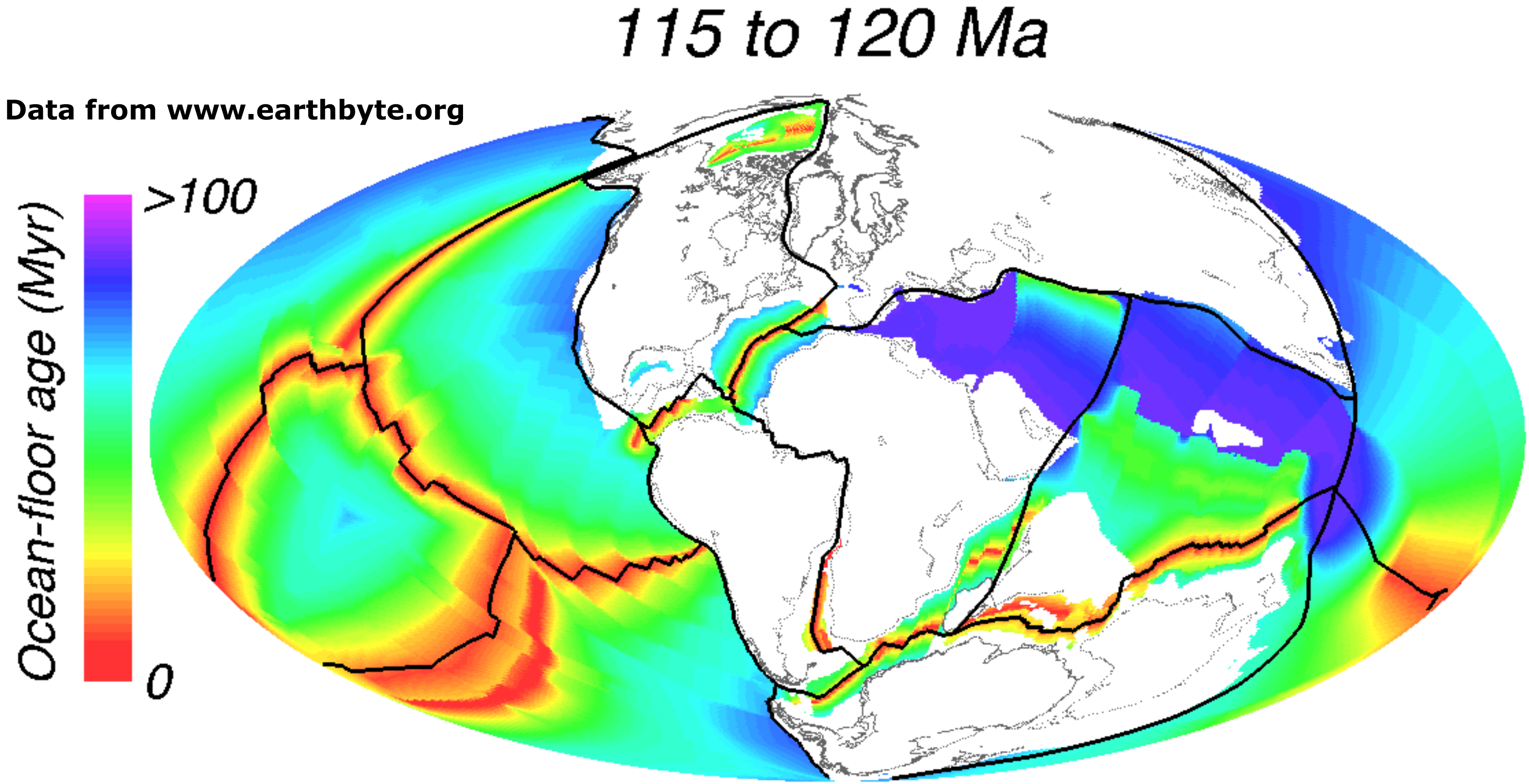
Inner core

Solid.



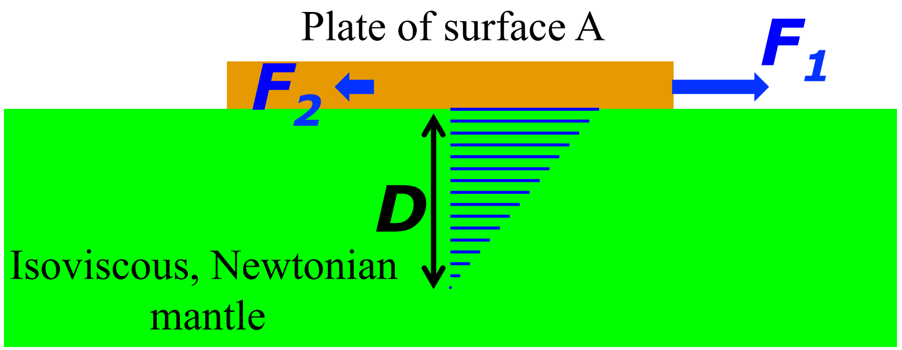
- ✓ *Plates are part of, and move in response to, convection within Earth's mantle.*
- ✓ *These motions are the surface expression of shallow- as well as deep-rooted geological processes.*

Reconstructed plate motions for the past 120 Myr



- ✓ *The geological record indicates significant variation of plate motions through time.*
- ✓ *From this, what inferences can we derive about the large-scale dynamics of the global plates/mantle system?*

Force balance of plates in 1D planar geometry



F_1 *is a force driving the plate towards the right-hand side. It could represent, for instance, the net pull exerted by a sinking slab on the trailing plate.*

F_2 *resists* ***F_1****.* ***F_2*** *may represent the total friction along brittle interfaces with neighbor plates. Alternatively, it could represent the contribution of deviatoric stresses.*

As soon as the plate moves, it shears the underlying mantle to a depth D. By virtue of 3rd Newton's law, viscous shear stresses resist the plate motion. ***The quicker the plate moves, the larger are shear stresses exerted by the viscous mantle****.*

After a while, motion remains steady because shear stresses balance the net of ***F_1*** *and* ***F_2****.*

Force balance of plates in 1D planar geometry

Forces acting upon the plate will cause it to move with velocity $v(t)$. The dynamics of this simple system is governed by 2^{nd} Newton's law

$$F_{net} = \text{mass} \cdot \text{acceleration} = m \cdot \frac{dv}{dt}$$

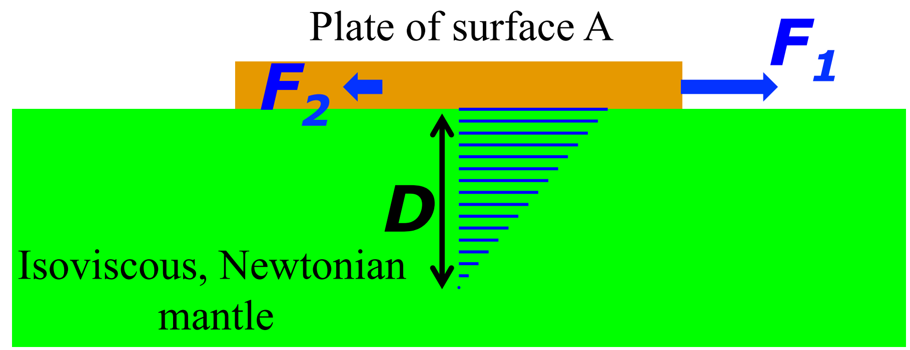
$$F_1 - F_2 - \mu \frac{v}{D} A = m \cdot \frac{dv}{dt}$$

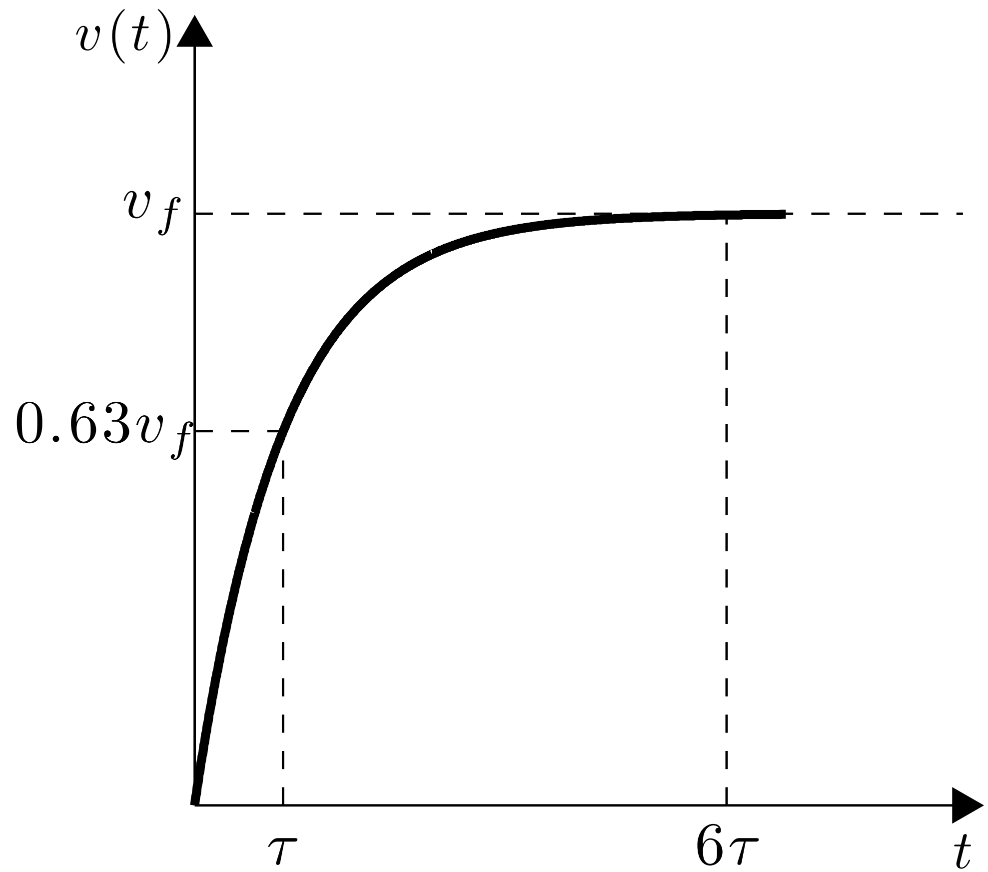
This differential equation has solution

$$v(t) = \frac{D(F_1 - F_2)}{\mu A} \cdot \left[1 - e^{-\frac{\mu A}{mD} t}\right]$$

or simply

$$v(t) = v_f \cdot \left[1 - e^{-\frac{t}{\tau}}\right]$$



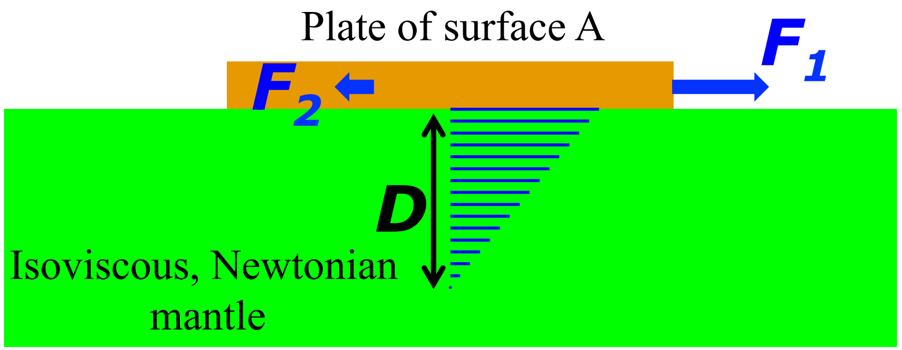


Force balance of plates in 1D planar geometry

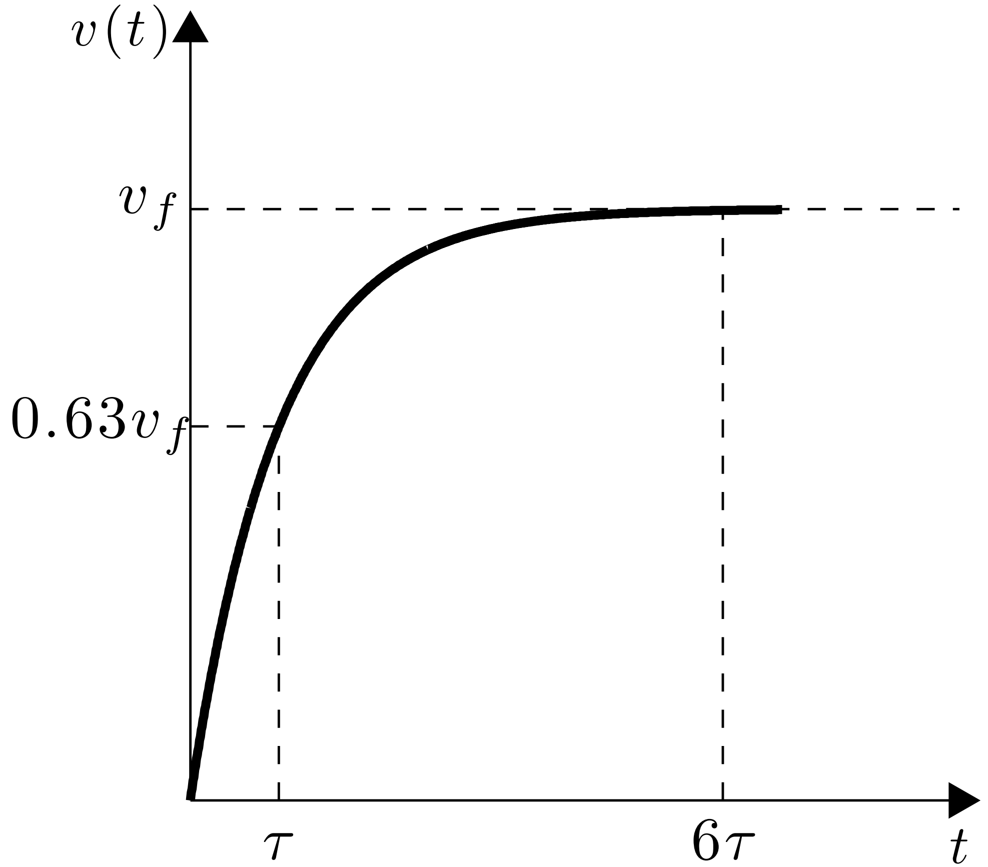
$$v(t) = v_f \cdot \left[1 - e^{-\frac{t}{\tau}}\right]$$

$$v_f = \frac{D(F_1 - F_2)}{\mu A}$$

$$\tau = \frac{mD}{A} \cdot \frac{1}{\mu}$$



- ✓ The final velocity is proportional to the net of all force, other than basal shear-stresses. Its variations reflect changes in the forces at play.
- ✓ Viscosity of the upper-mantle modulates such a balance.
- ✓ The time it takes to reach dynamic equilibrium depends on the upper-mantle viscosity, but is independent of forcing upon the plate.



Force balance of plates in 1D planar geometry

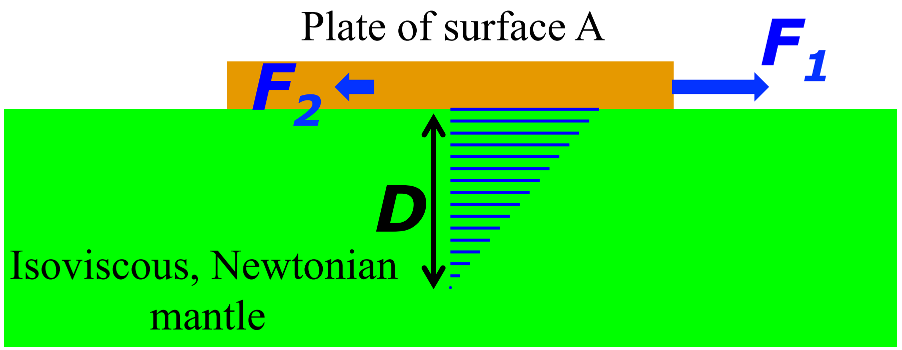
$$v(t) = v_f \cdot \left[1 - e^{-\frac{t}{\tau}}\right]$$

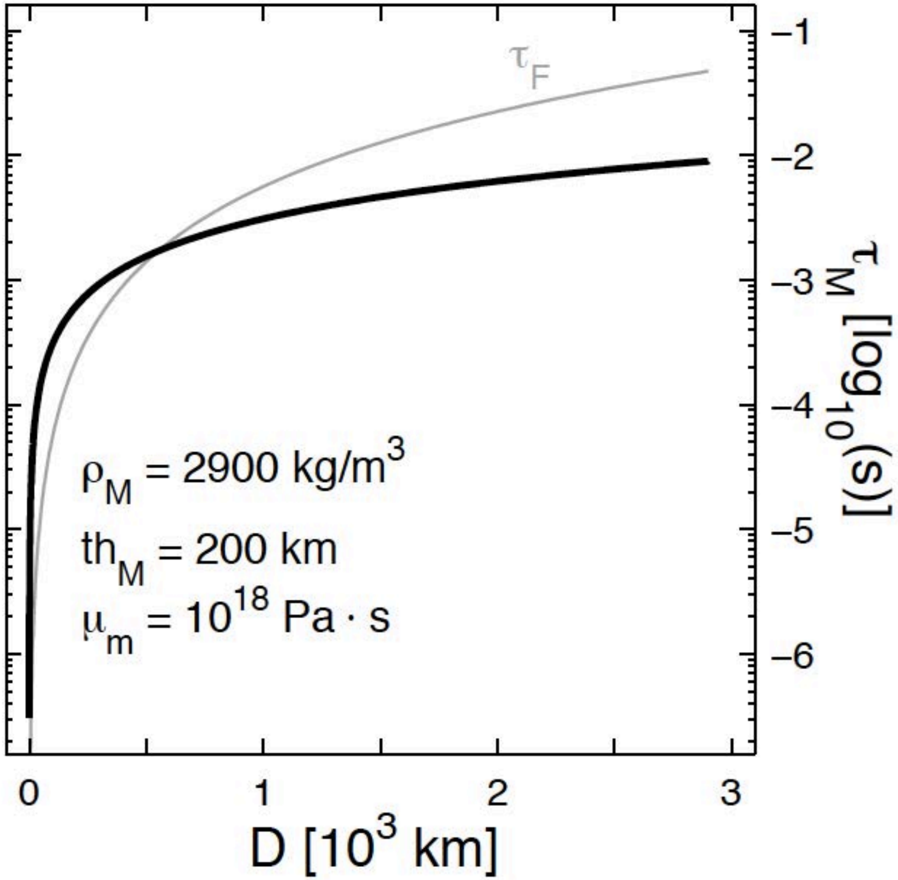
$$v_f = \frac{D(F_1 - F_2)}{\mu A}$$

$$\tau = \frac{mD}{A} \cdot \frac{1}{\mu}$$

An upper limit of τ exists. One can demonstrate that it is independent of the particular plate considered. Rather, it only depends on maximum thickness (th_M) and density (ρ_M) of the lithosphere, as well as on minimum mantle viscosity (μ_m).

$$\tau < (5D \cdot th_M \cdot \rho_M) \cdot \frac{1}{\mu_m} = \tau_M$$





Inferences from a simplified force balance of plates

- ✓ *The transient time of plates – that is, the time plates take to readjust their motions to changed forcing conditions – is of the order of the 10^{-2} seconds at most.*
- ✓ *This is far beyond the temporal resolution at which we are able to reconstruct plate motions. It implies that reconstructed plate motions are equilibrium motions.*
- ✓ *As such, they are always proportional to the net force (other than basal shear tractions) modulated by mantle viscosity.*
- ✓ *Stresses within Earth's mantle are transmitted instantaneously – in a geological sense – over distances comparable to Earth' size.*
- ✓ *This means that at any point beneath plates, mantle flow is the superimposition of contributions from everywhere else (e.g. subducting slabs or large-scale upwellings). Such an inference warrants a global approach in modelling the dynamics of tectonic plates.*

Inferences from a simplified force balance of plates

Let us imagine that v_1 represents the velocity of a plate from t_1 to t_m, and that v_2 represents the motion from t_m to t_2.

We can then say that the net of all forces other than shear tractions at the plate–base is

$$F_{net1} = v_1 \cdot \frac{\mu A_1}{D} \quad \text{from} \quad t_1 \text{ to } t_m$$

and

$$F_{net2} = v_2 \cdot \frac{\mu A_2}{D} \quad \text{from} \quad t_m \text{ to } t_2$$

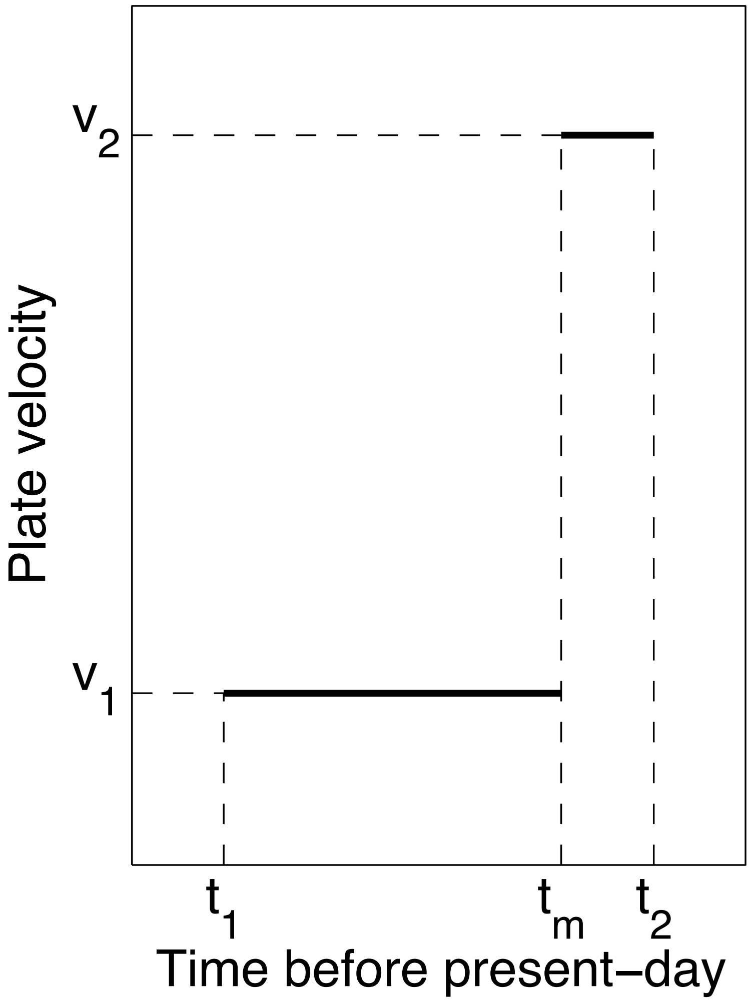
Therefore

$$\Delta F = F_{net1} - F_{net2} = v_1 \cdot \frac{\mu A_1}{D} - v_2 \cdot \frac{\mu A_2}{D}$$

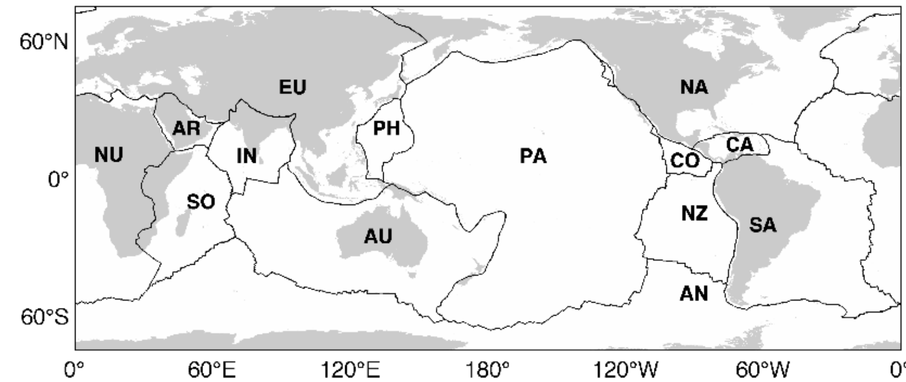
ΔF is the force variation needed to explain the plate–motion change.

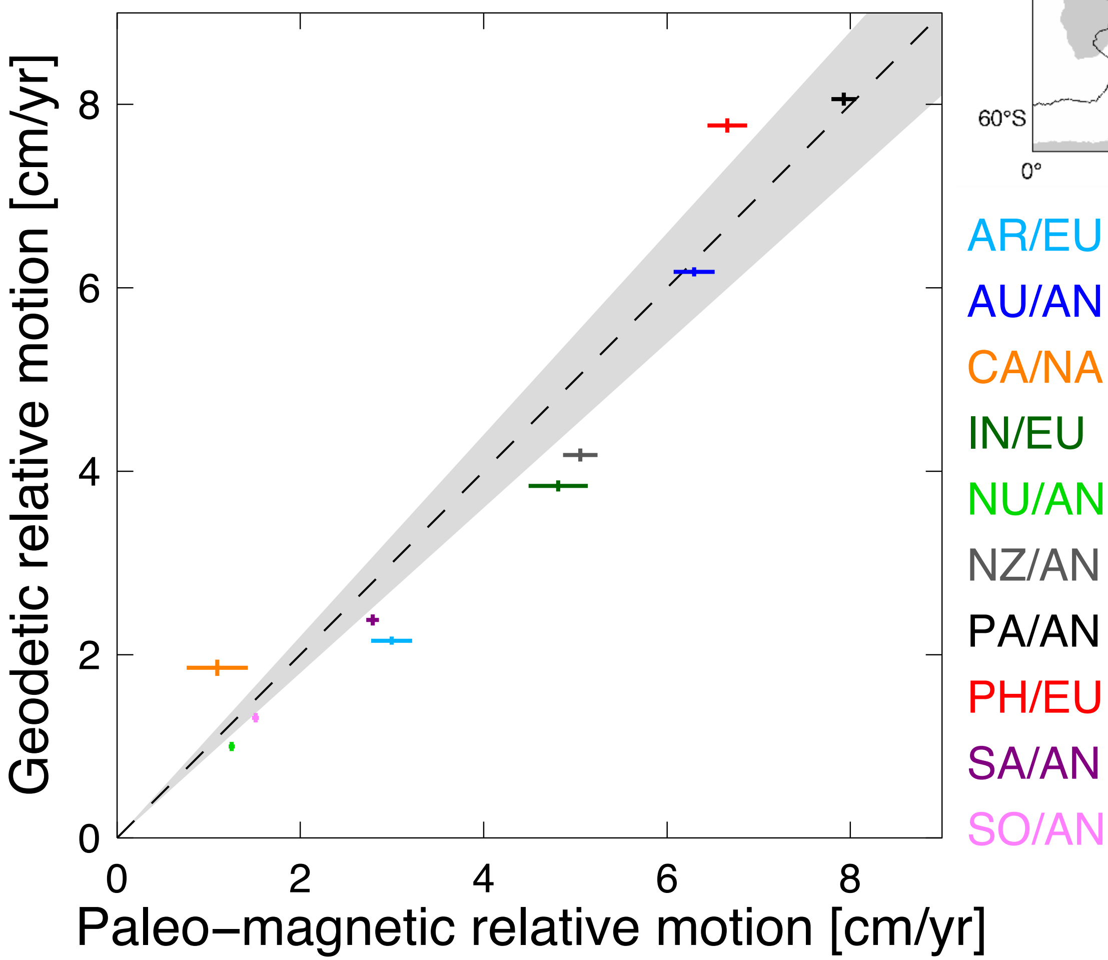
It may be estimated numerically, if v_1 and v_2 are known from kinematic reconstructions.

Because the plate–motion change occurred at most in $t_1 - t_2$, the minimum force variation–rate needed upon the plate is $\frac{\Delta F}{t_1 - t_2}$



Comparison of past-3.2-Myr and present-day plate motions





For datasets and a review, see

Gordon and Stein, 1999

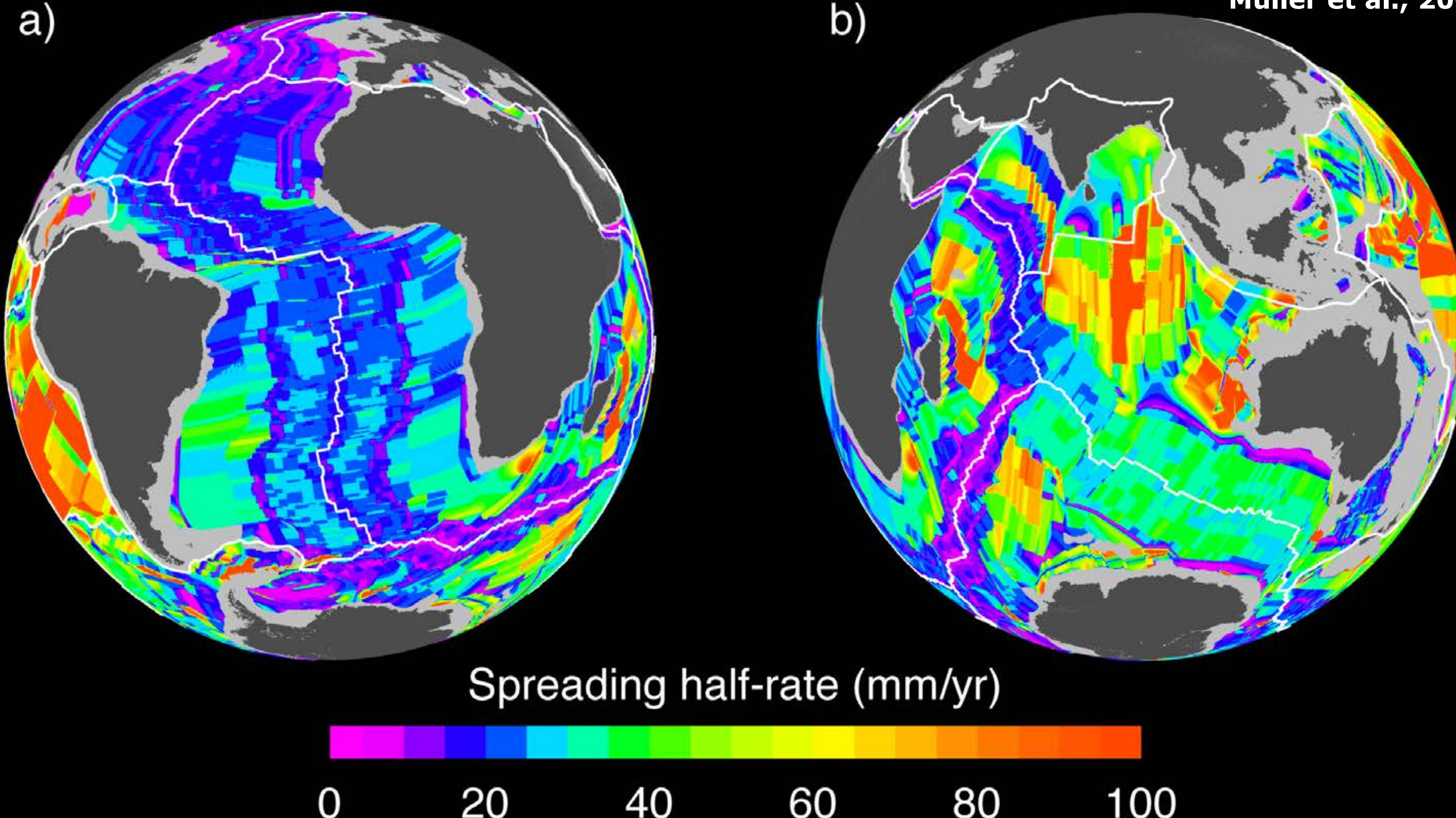
Sella et al., 2002

DeMets et al., 2010

Argus et al., 2010

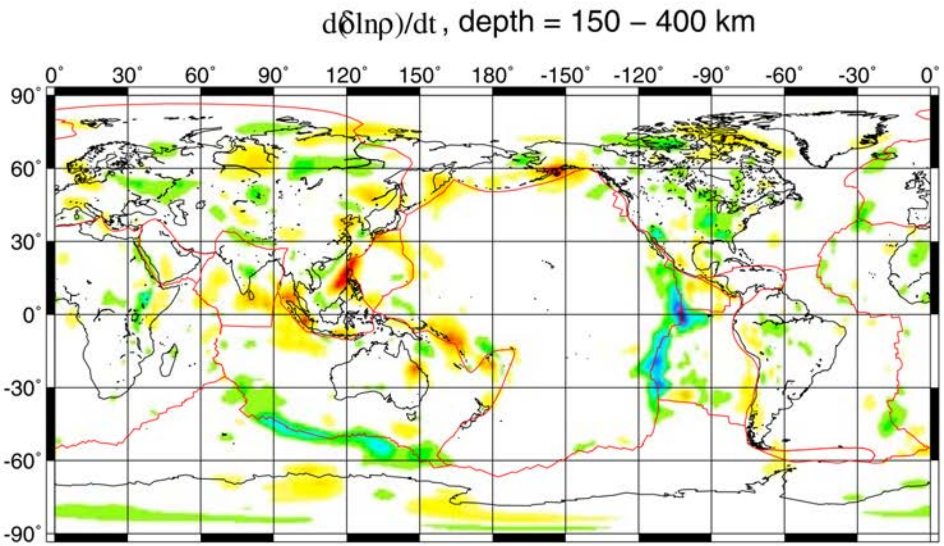
History of ocean-floor spreading since ~180 Ma

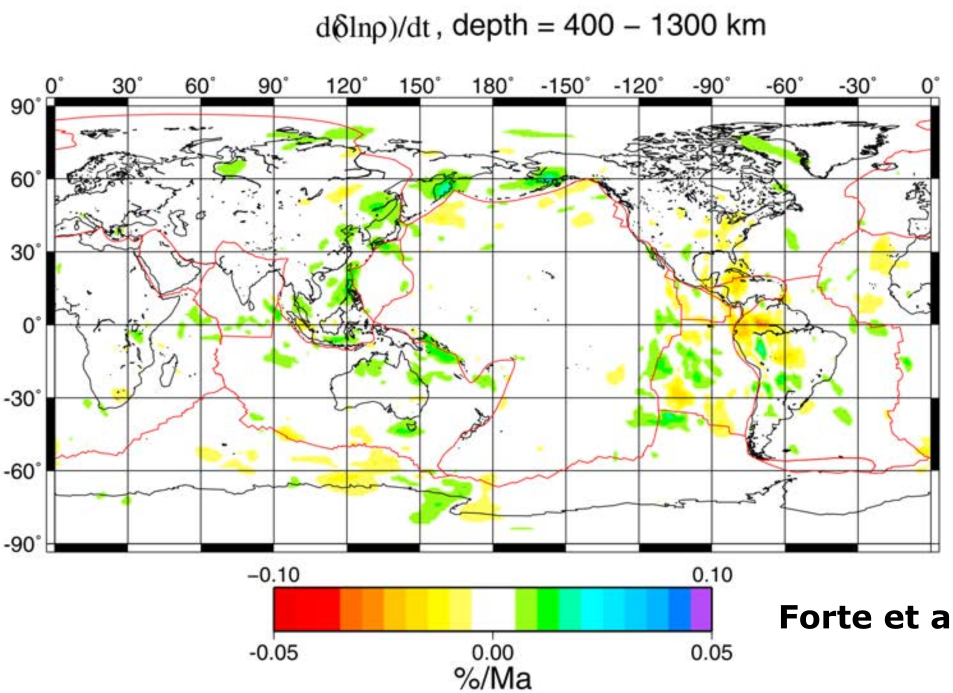
Müller et al., 2008



Rapid changes in spreading-rate reveal short time-scale variations (few Myr) of plate motions.

Time evolution of mantle-flow from 3D circulation models





✓Plotted are temporal variations of lateral density-differences, computed with respect to the layer-average.

✓From these model derivatives, one infers that mantle buoyancies may vary only by less than 2% over a 10-Myr time period.

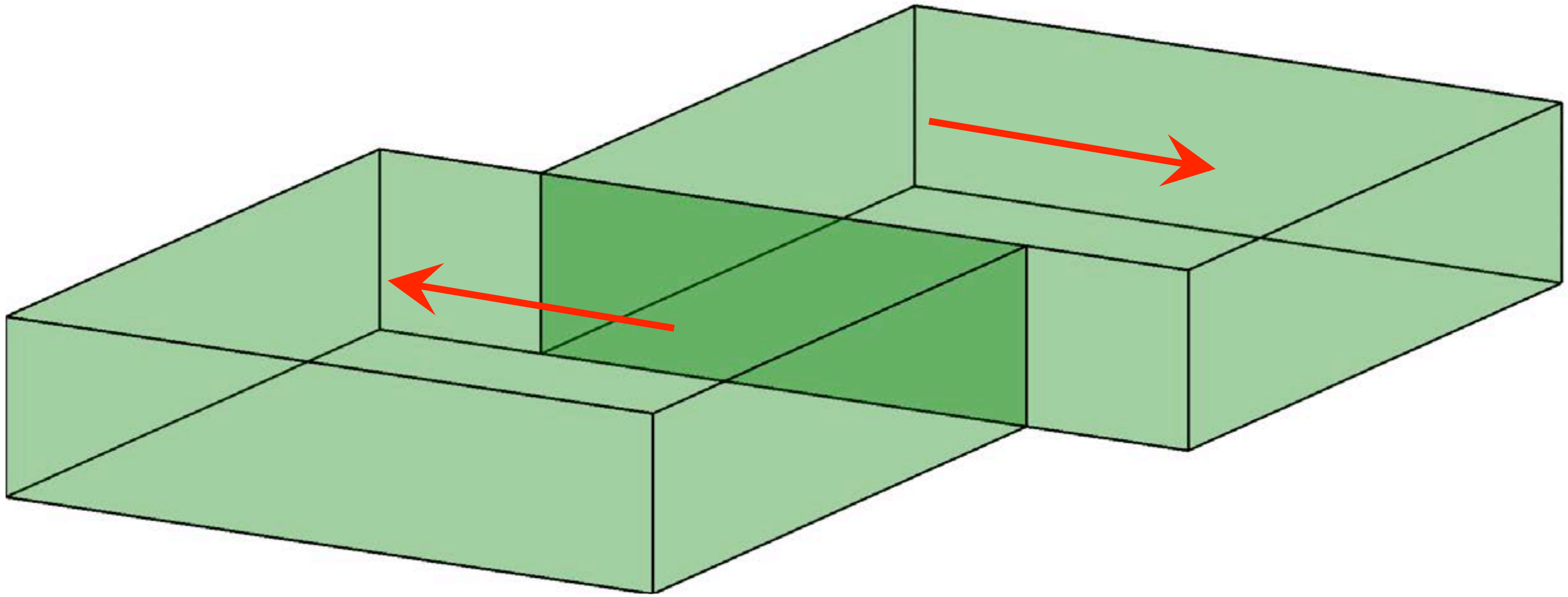
✓In fact, significant changes in the pattern of whole mantle flow occur typically over much longer time periods of 150 to 200 Myr (e.g. Bunge et al., 1998).

✓It is therefore unlikely that plate-motion changes over the short-term (few Myr) are the result of temporal variations in the mantle-convection pattern.

Forte et al., 2009

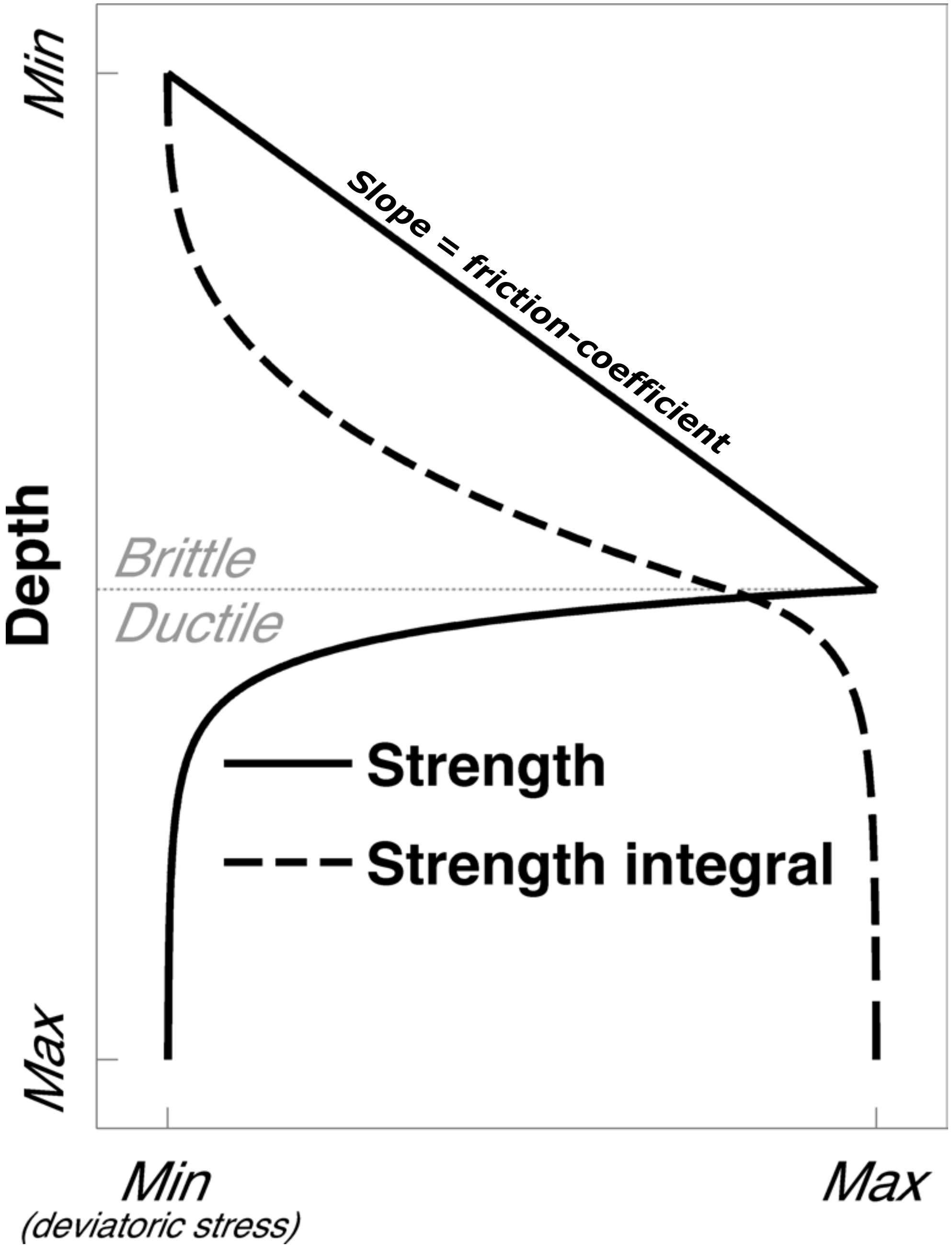
Strength of lithospheric plate boundaries

In faulted materials, such as along the interfaces between tectonic plates, strength is the stress level to achieve and maintain anywhere along the interface between parts (dark green) in order to initiate and sustain sliding.



To the purpose of dynamics, it is relevant knowing the total strength. That is, the integral of the local stress along the interface.

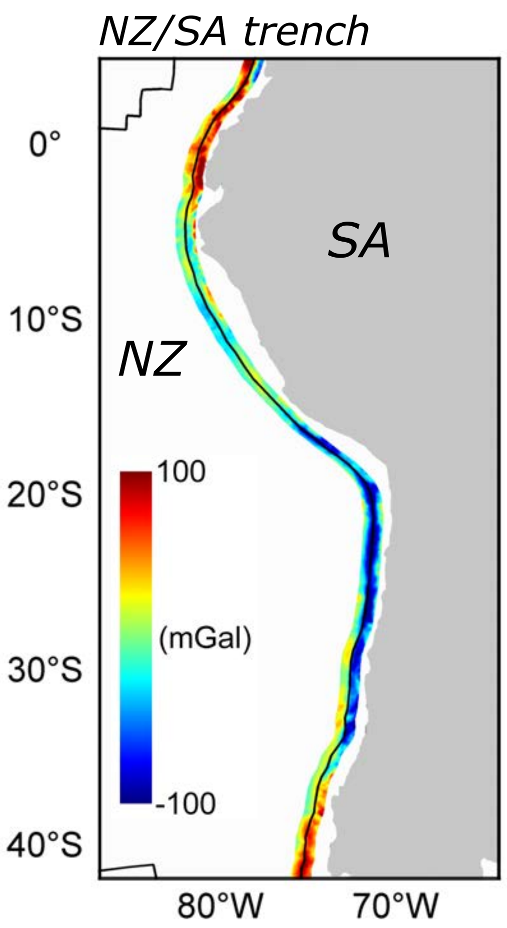
Strength of lithospheric plate boundaries

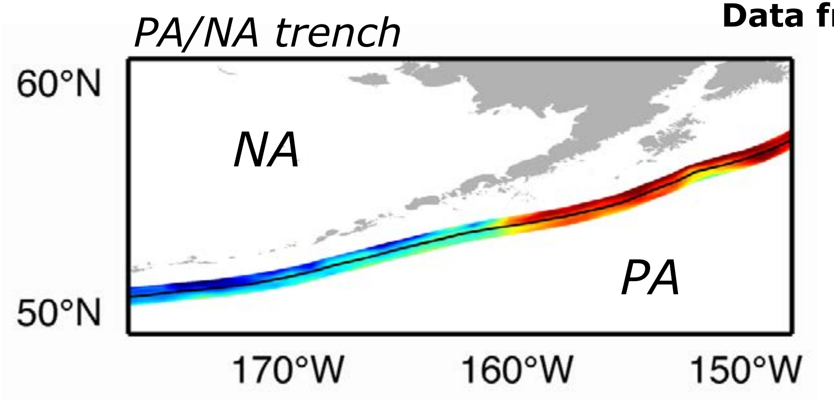


- ✓ The strength of lithospheric rocks has been constrained at the laboratory scale by numerous experiments, carried out at a range of temperature and pressure conditions (See Kohlstedt et al., 1995; Di Toro et al., 2011).
- ✓ Results are in line with studies at the regional scale (Suppe, 2007).
- ✓ Strength increases linearly with overburden pressure in the upper portion of the lithosphere (**brittle domain**). It then decreases exponentially with temperature in the deeper portion (**ductile domain**).
- ✓ The brittle domain contributes **~80%** of the total strength. **Such inference holds within the ranges of friction coefficients, temperature and strain rates typical of plate tectonics**.
- ✓ The coefficient of friction is the key parameter representing the total strength of lithospheric plate margins.

Other observations pointing to shallow-seated forces:
Free-air gravity anomalies above convergent margins

Data from Sandwell & Smith, 1997





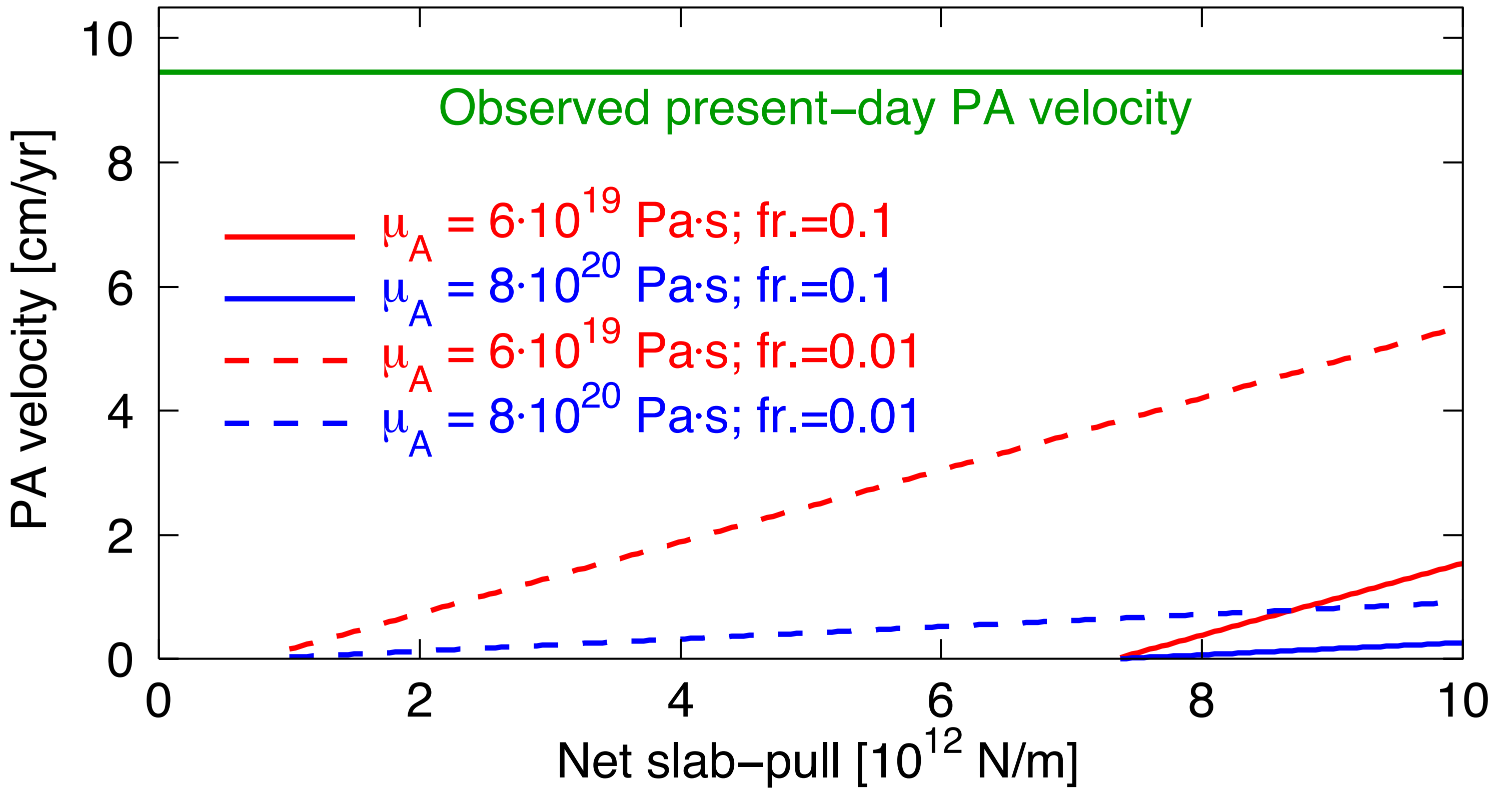
- ✓ Anomalies are computed with respect to the average cross profile of each margin.
- ✓ Large magnitudes, as high as 100 mGal.
- ✓ Short-wavelength variations along the margin.
- ✓ Ocean-floor aging and the presence of marine sediments explain only part of the gravity anomaly.
- ✓ These inferences hold true for several other plate margins.

This is suggestive of dominant shallow-seated forces at plate boundaries, responsible for ocean-floor deformation.

The need of plates/mantle coupling in quantitative models

At the present-day, the Pacific plate moves north-westward at ~9 cm/yr. Below are velocities predicted from a simple balance of

1. Net slab-pull along ~9000 km.
2. Frictional resistance along the brittle region of Pacific plate margins.
3. Resistive viscous drag from the passive mantle beneath the lithosphere.



This example illustrates the need of accounting for an actively convectiving mantle in global models of plate dynamics.

Ingredients for standard Mantle Circulation Models (MCMs)

✓ High numerical resolution (100 million grid points, 10 to 20 km grid spacing globally) permits modelling convection at ~10^9 internal Rayleigh number.

✓ **Plate motion history for past 150 Myr at least** (e.g. Earthbyte initiative).

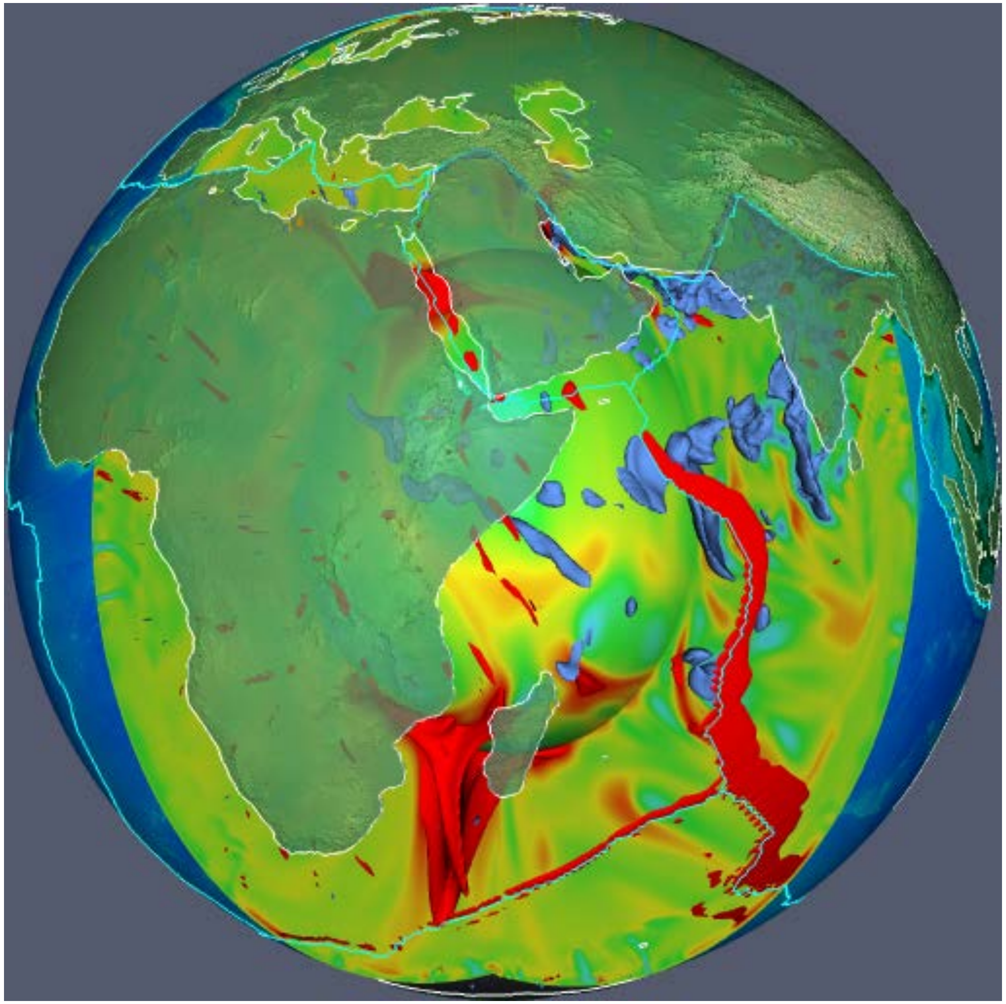
✓ **Depth-dependent viscosity** (Lambeck et al., 1996; Mitrovica & Forte, 2004).

✓ **Predominant internal heating** (Wasserburg et al., 1964)

✓ **Core heating in range 5% to 40%** (Lee et al., 2004; Bunge et al., 2005)

✓ **Petrology to link temperature to seismic observations** (e.g. Stixrude, 2005/2007; Piazzoni et al., 2007)

After Oeser et al., 2006

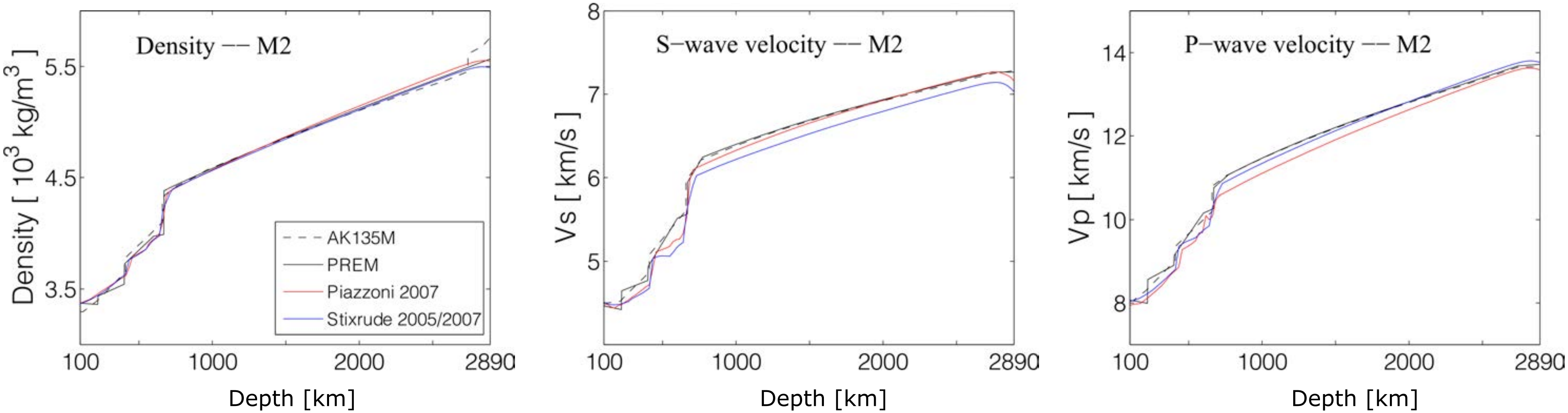


Red=hot, buoyant

Blue=cold, sinking

Radial profiles of Density, S- and P-Velocity from MCMs

Schuberth et al., 2009

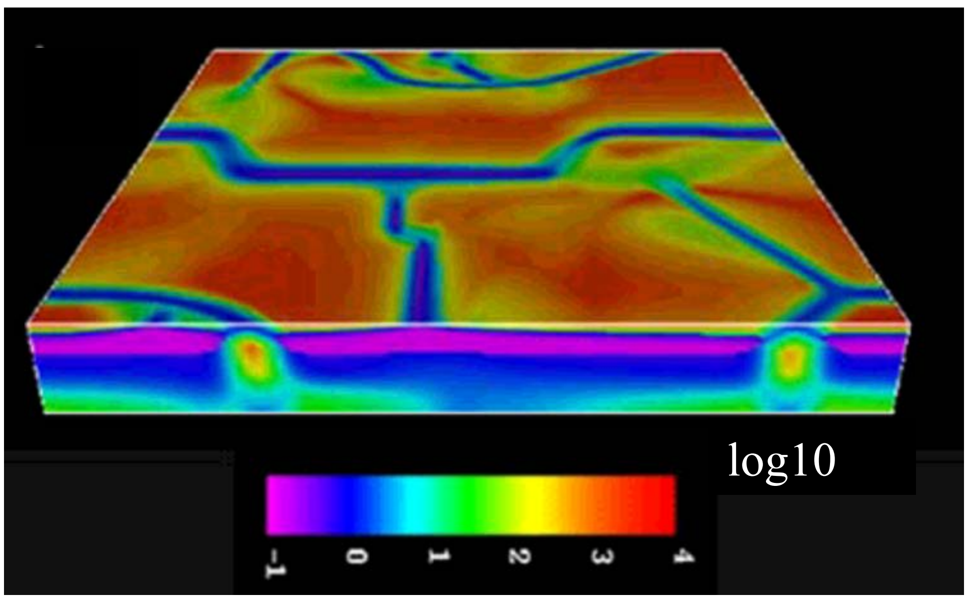


✓While there are small but relevant differences in seismic-velocity profiles, subject to a series of investigations (e.g. Farnetani & Samuel 2005, Ricard et al. 2005, Matas et al. 2007, Ritsema et al., 2009), **MCMs reproduce well density and therefore buoyancy within Earth's mantle.**

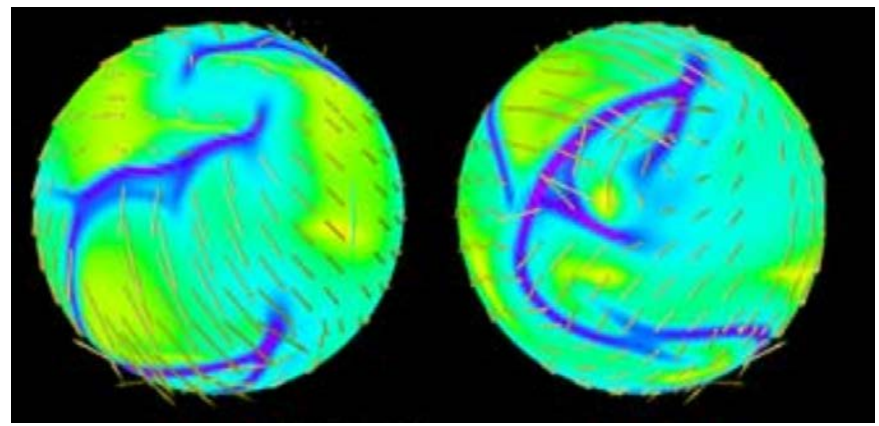
✓Furthermore, lateral temperature variations predicted by MCMs result in **lateral density variations up to ~70 kg/m**3** (Schuberth et al., 2009; Davies et al. 2012), in agreement with the range of values typical of plate tectonics/mantle convection.

Are MCMs able to reproduce plateness?

- ✓ The peculiarity of Earth's plate tectonics is that high strain-rates are associated with low stresses along narrow regions that separate wider areas of significant rigidity.
- ✓ This notion is often referred to as ***PLATENESS*** (See Bercovici, 1993 for a review).
- ✓ MCMs have been shown to be able to generate, under certain circumstances, a good degree of plateness.



Tackley, 2000



van Heck & Tackley, 2008

Note regions of high-viscosity and coherent velocity-patterns.

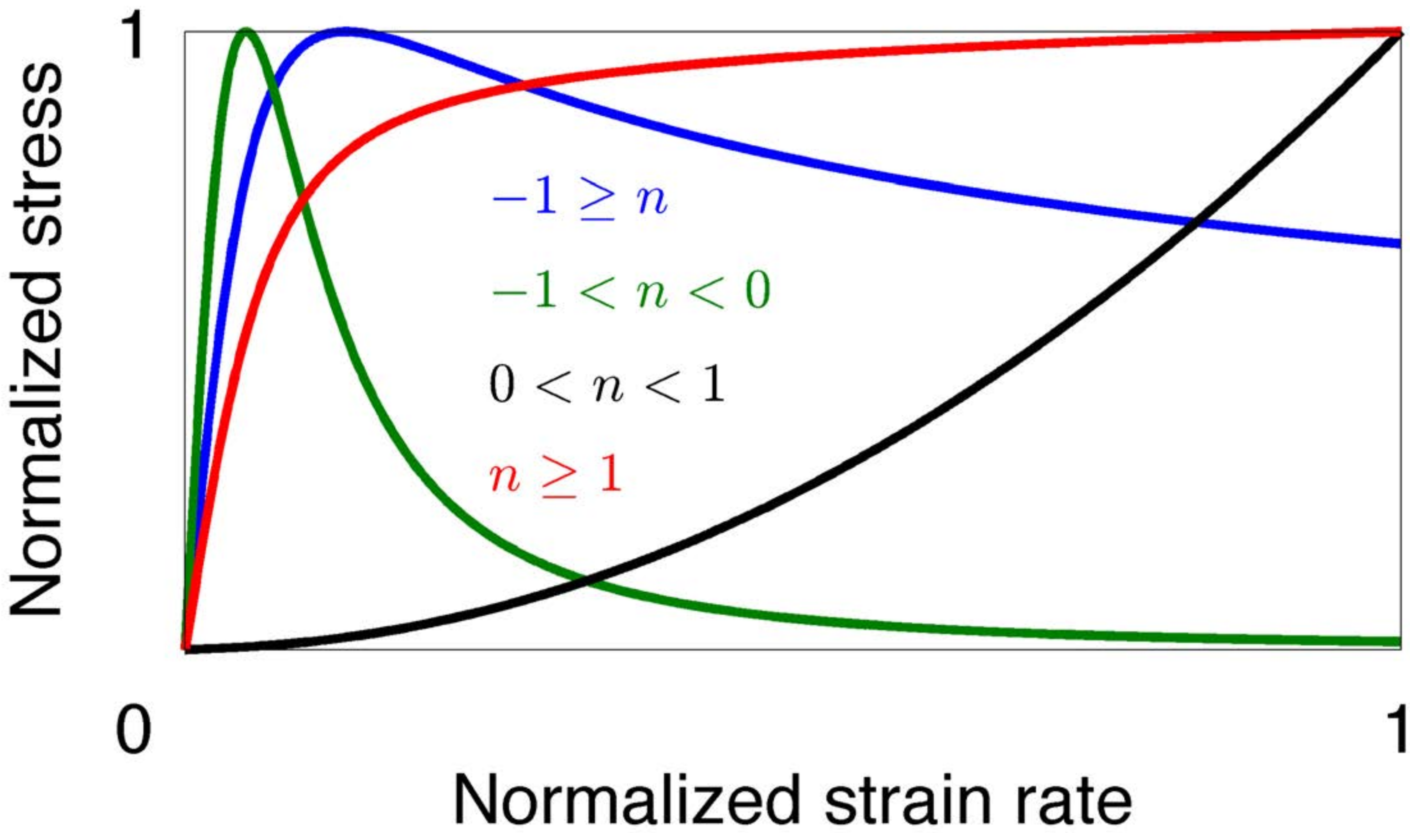
Generalised power-law rheology in MCMs

$$\sigma(\dot\epsilon) = \mu(\dot\epsilon, T, z)\cdot\dot\epsilon = (A\dot\epsilon)\cdot e^{\frac{B+C\cdot z}{T}}\cdot(\gamma+\dot\epsilon^2)^{\frac{1-n}{2n}}$$

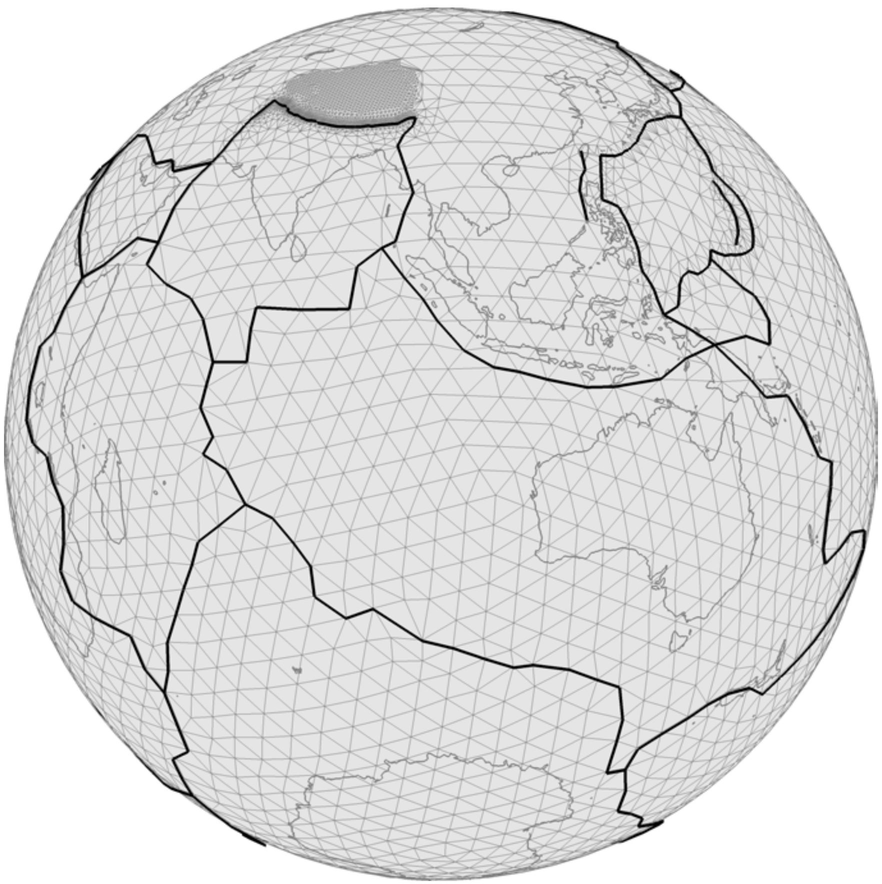
$$\sigma(\dot\epsilon) \propto \dot\epsilon \qquad \text{if } \dot\epsilon \to 0$$

$$\sigma(\dot\epsilon) \propto \dot\epsilon^{\frac{1}{n}} \qquad \text{if } \dot\epsilon \to +\infty$$

See Bercovici, 1993



Modelling PLATENESS and the dynamics of plates with SHELLS



✓SHELLS is a finite-element model that solves the instantaneous torque balance in the THIN-SHELL limit. It compute plate forces and associated velocities at equilibrium.

✓It includes lateral variations of the geotherm and therefore of the effective viscosity in the ductile regime.

✓It includes topography/bathymetry as well as crust/lithosphere thicknesses.

✓Tectonic plates are built explicitly into the computational grid.

✓Present-day plate boundaries feature dip angles constrained from seismological observations.

✓They also feature laterally-varying friction coefficients in range 0.01 to 0.07, as opposed to continuum elements featuring 0.6 to 0.85 friction coefficients.

✓**The main shortcoming of this class of models is the inability to compute mantle buoyancies**. An important component of the plate torque-balance is therefore missing.

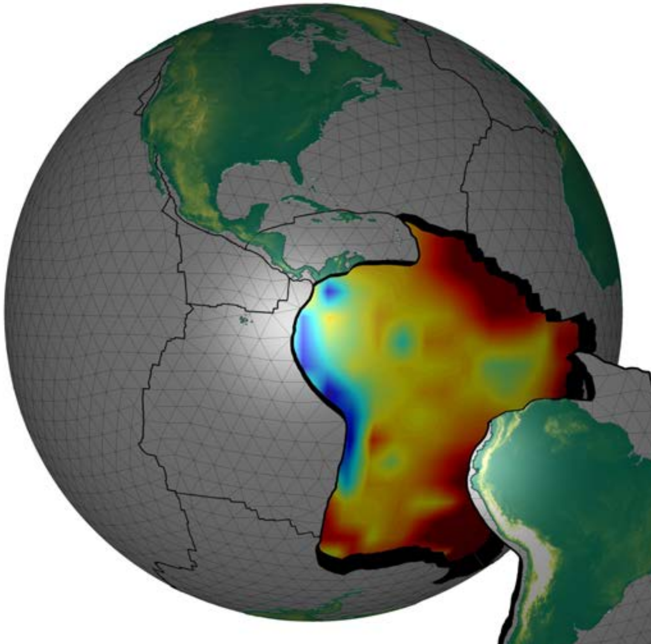
Global models of the coupled mantle/plates system

✓ MCMs or FE thin-shell models alone are not capable to account properly for the torque-balance or the rheological features of the plates/mantle system.

✓ The logical step is merging these two classes of models. Realistic buoyancy forces predicted by MCMs are included in the torque-balance of lithospheric plates, computed through the SHELLS global model.

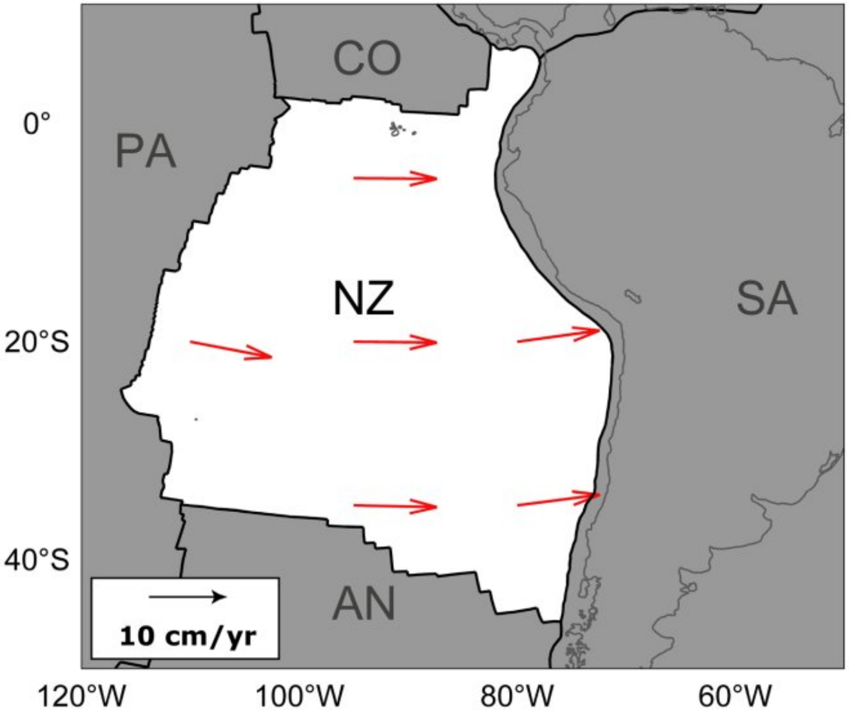
✓ In these joint simulations of mantle/plates dynamics, global plate velocities and tectonic forces at equilibrium are computed.

✓ Building on this technical advance, one can use global models of the coupled mantle/plates system to reproduce observed geological record of plate kinematics, and **efficiently reconstruct budgets of forces driving and resisting plate motions.**



Observed Nazca plate motion relative to South America: A prominent example of plate-motion change

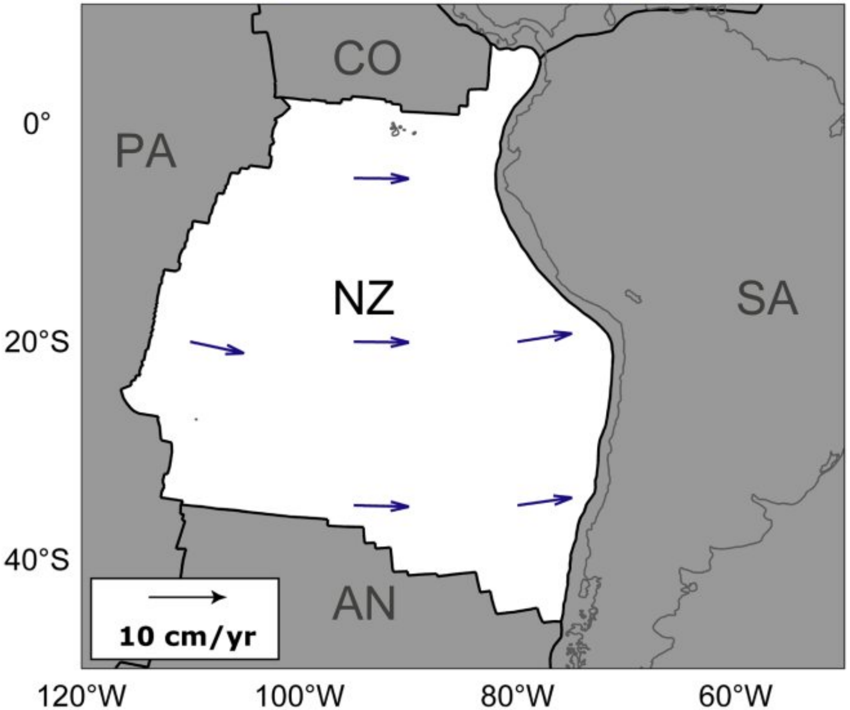
10 Myrs ago



10.3 cm/yr

Gordon and Jurdy, 1986

present day

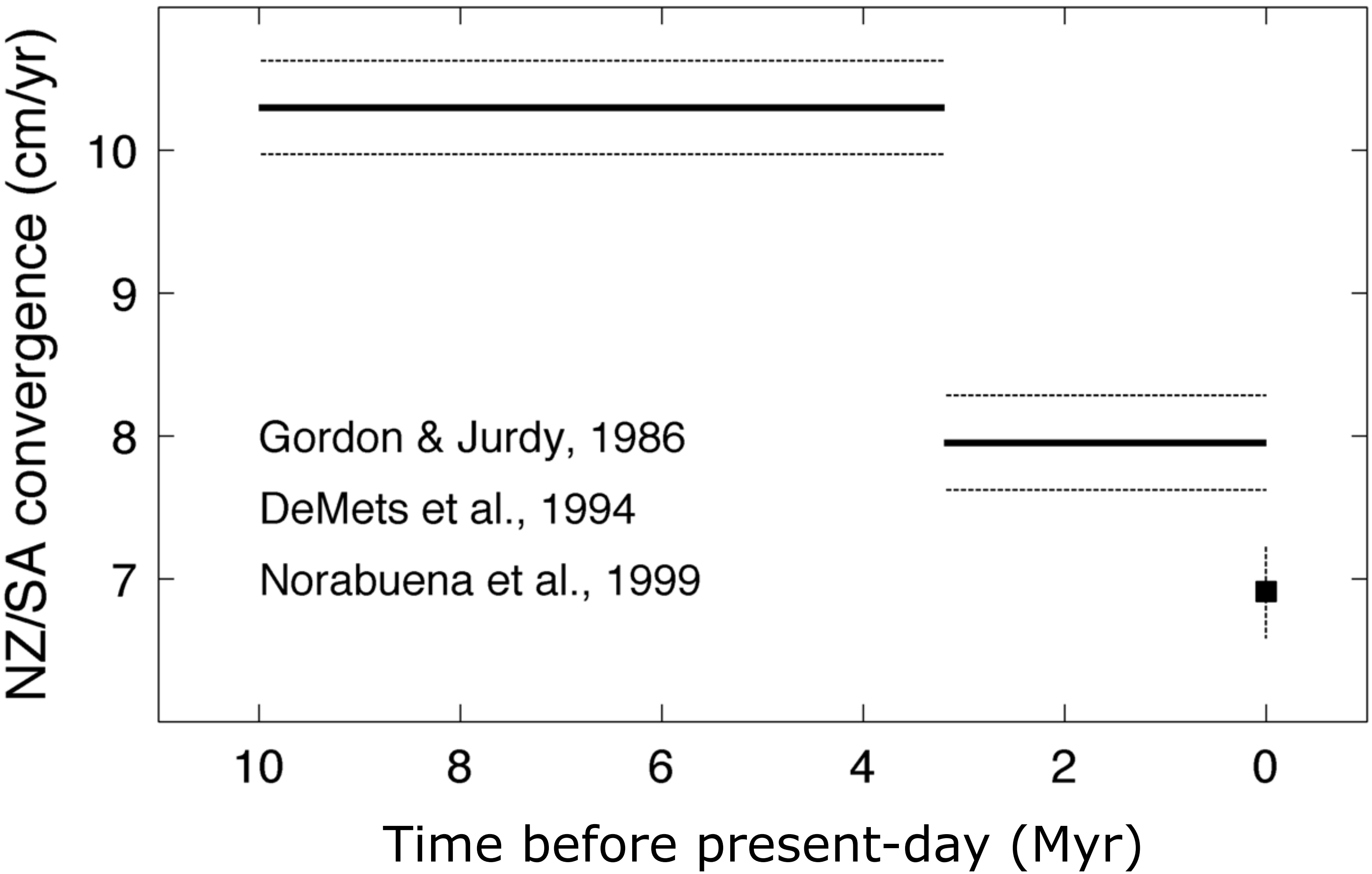


6.7 cm/yr

Norabuena et al., 1999

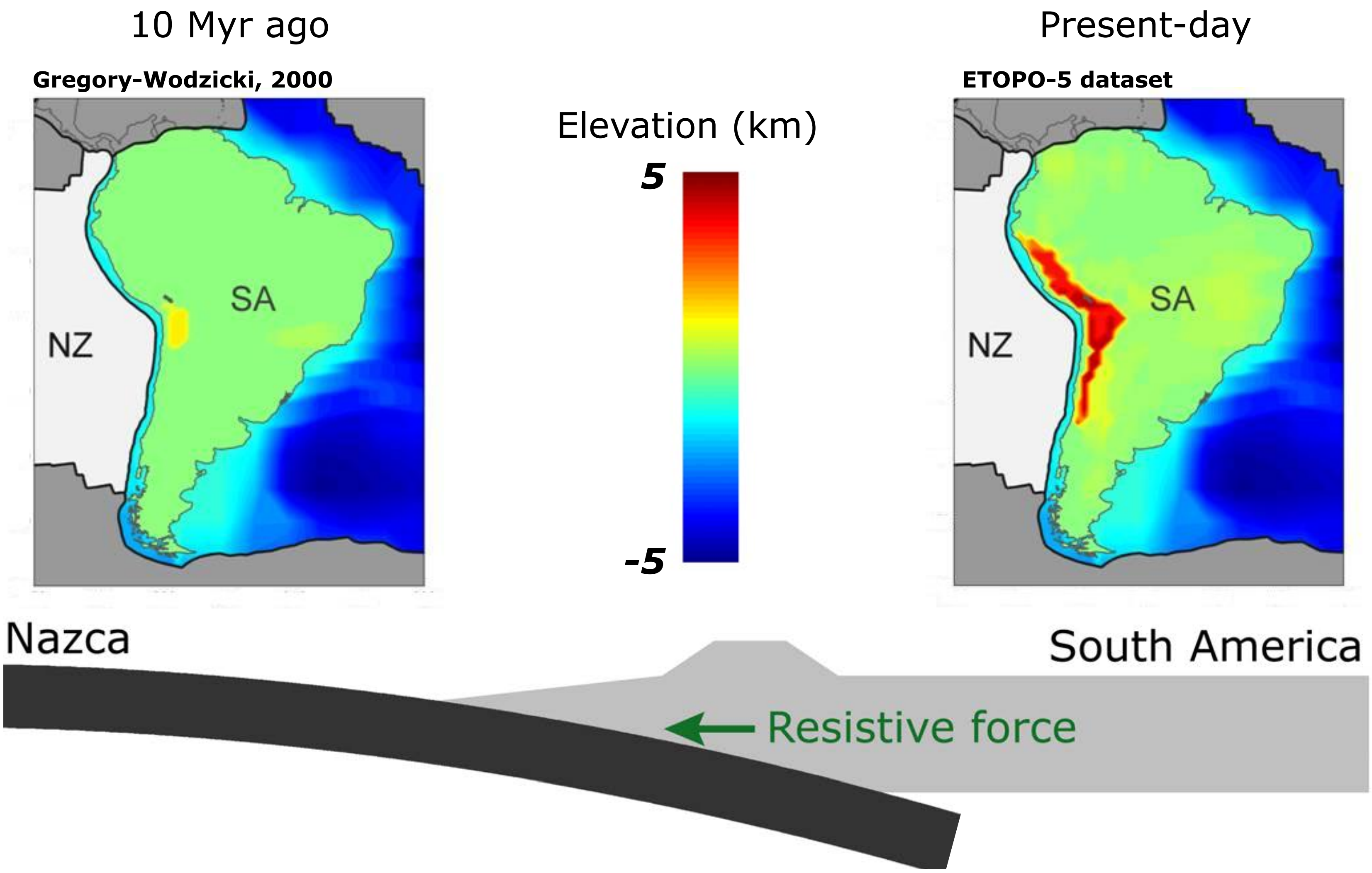
30% reduction of NZ/SA convergence rate

History of Nazca/South America convergence since 10 Ma



Note continuous reduction of convergence rate

Major tectonic event at NZ/SA boundary: Uplift of the Andes

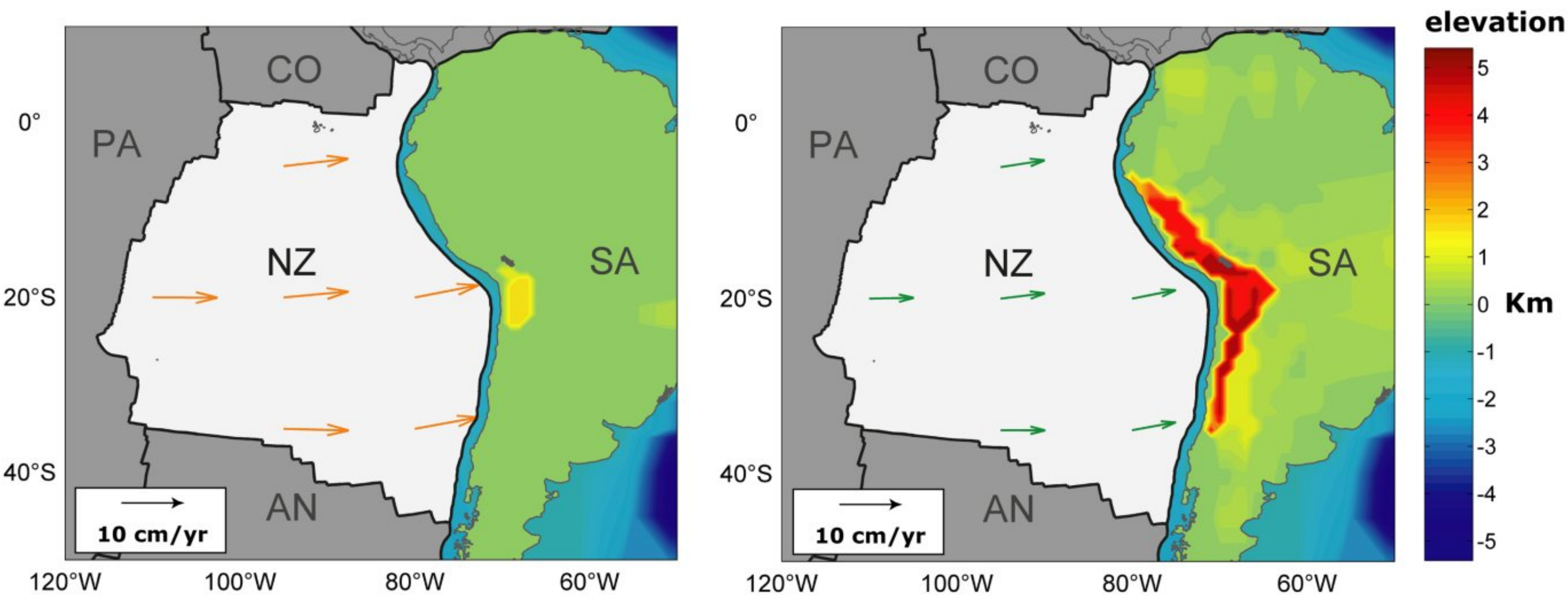


Are resistive forces provided by the Andes capable of slowing down the Nazca/South America convergent motion?

Computed Nazca plate motion relative to South America

Iaffaldano et al., 2006

10 Myr ago | **Present-day**

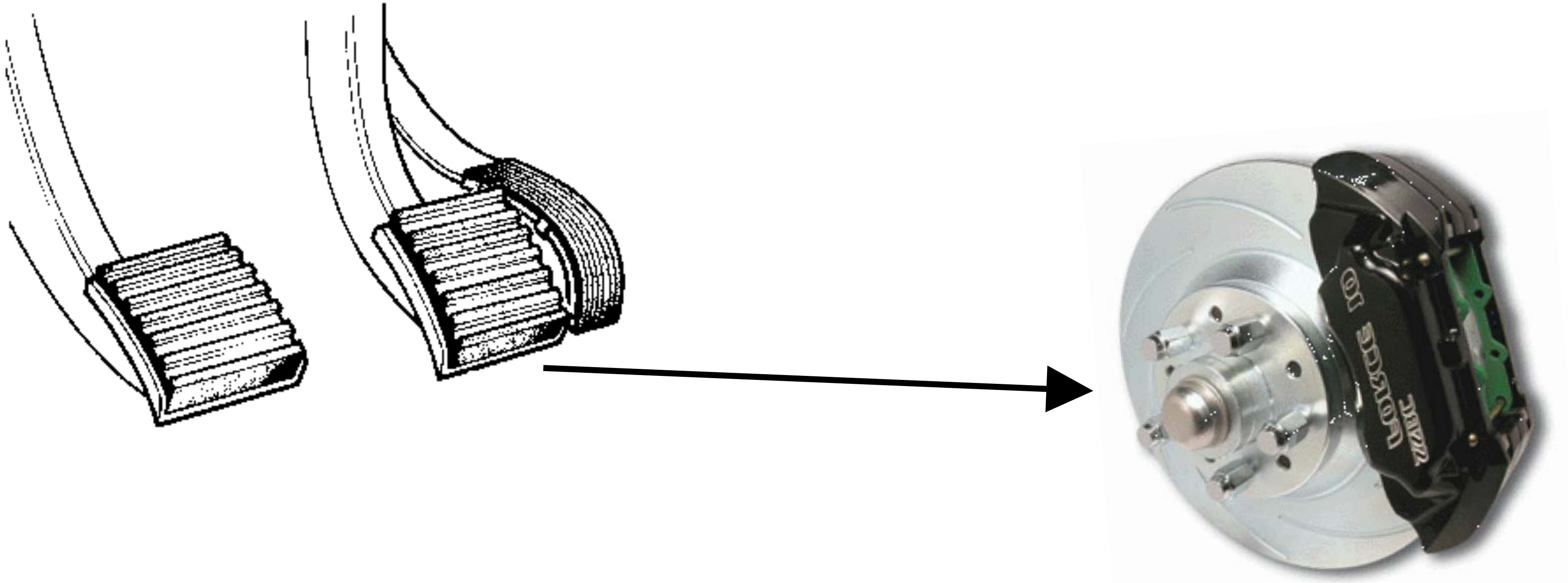


10.1 cm/yr | **6.9 cm/yr**

Observed 10.3 cm/yr | **Observed 6.7 cm/yr**

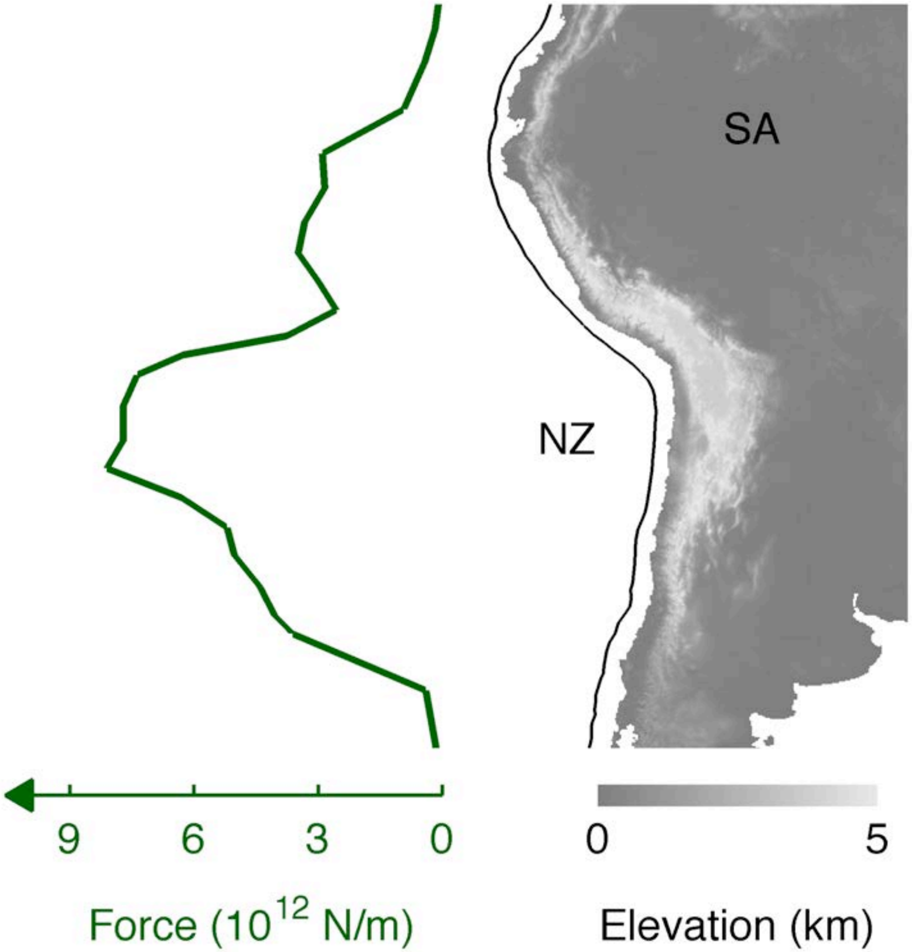
Modelled plate motions compare well with observations

Slowdown due to orogeny works much like car brakes



- ✓ Your car progressively slows down because you push the brake-pedal stronger, increasing the resistance against which the engine works. **Frictional properties of brakes remain the same though!**
- ✓ In fact, one can show in quantitative terms that friction-coefficient variations are of second-order importance in controlling NZ/SA convergence variations (e.g. Iaffaldano & Bunge, 2009).
- ✓ Similarly, one can link the recent convergence history of other major tectonic settings (i.e. Tibet and Zagros) to their history of orogeny, erosion and continental deformations, which are inferred from geological observations (e.g. Iaffaldano et al., 2011; Austerman & Iaffaldano, 2013).

Increase of resisting forces in the brittle plate boundary following Andean orogeny



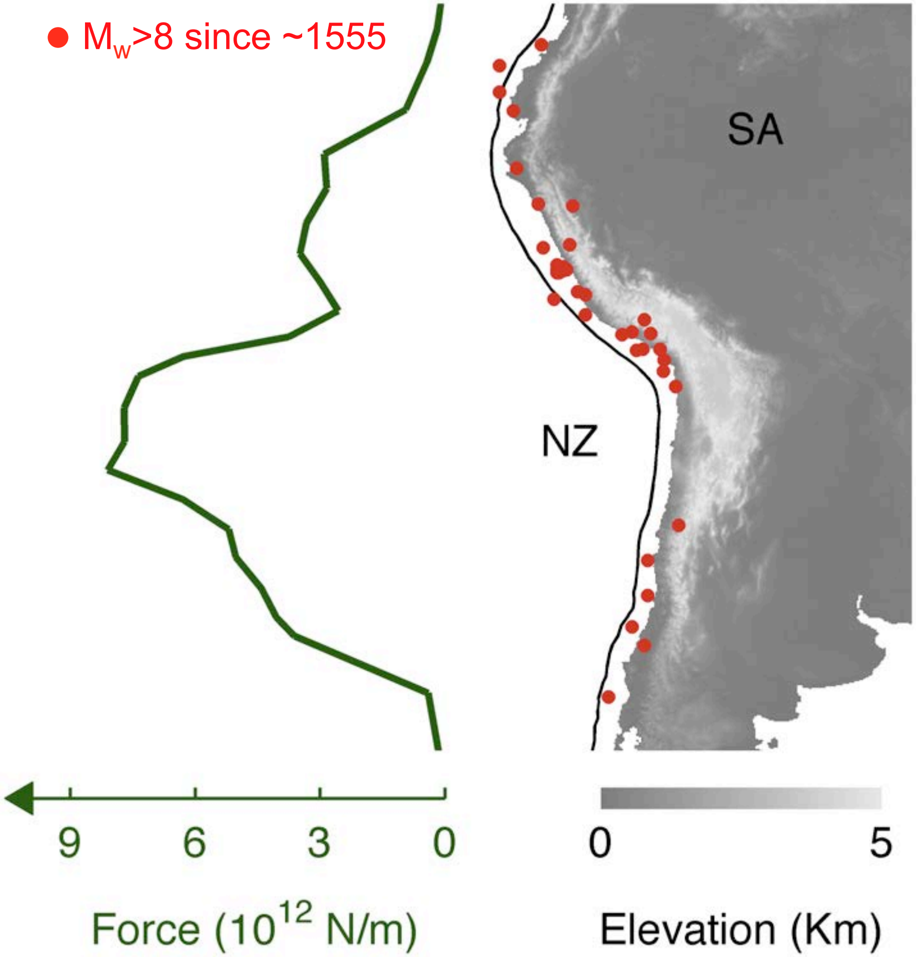
✓ Tectonically significant forces, on the order of 10**12 N/m.

✓ Trend of force magnitudes reflects Andean morphology.

✓ By 3rd Newton's law, forces act mutually on overriding and subducting plates.

✓ **These forces are a measure of the increase of mechanical coupling between NZ and SA over the past ~10 Myr.**

Increase of resisting forces in the brittle plate boundary following Andean orogeny



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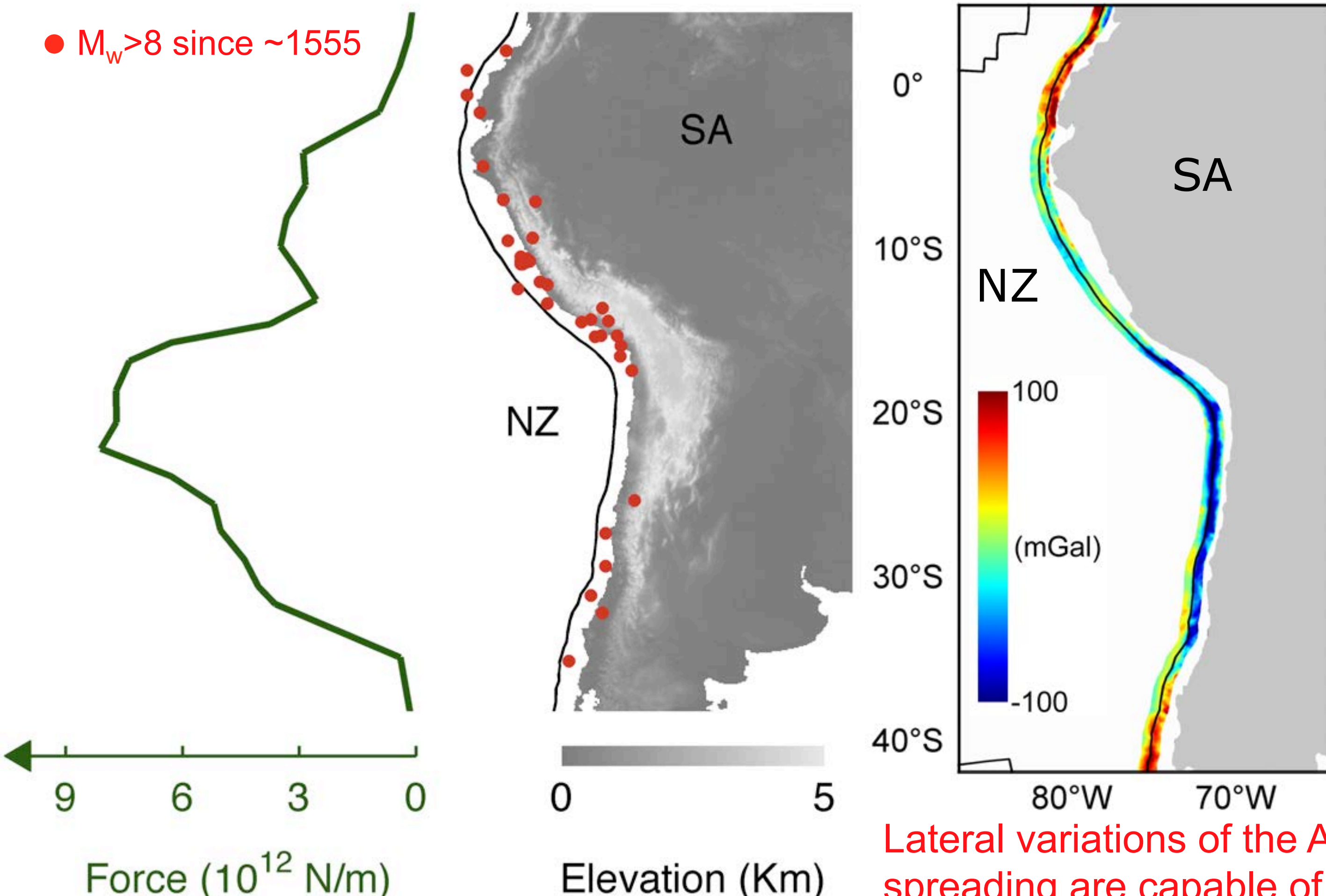
Some correlation exists between the occurrence of great earthquakes at the NZ/SA margin, and the emplacement of lateral plate-coupling variations following Andean orogeny.

The seismic record is admittedly short. However, one plausible, qualitative explanation is that seismic rupture over large areas is inhibited when plate-coupling is stronger.

Increase of resisting forces in the brittle plate boundary following Andean orogeny



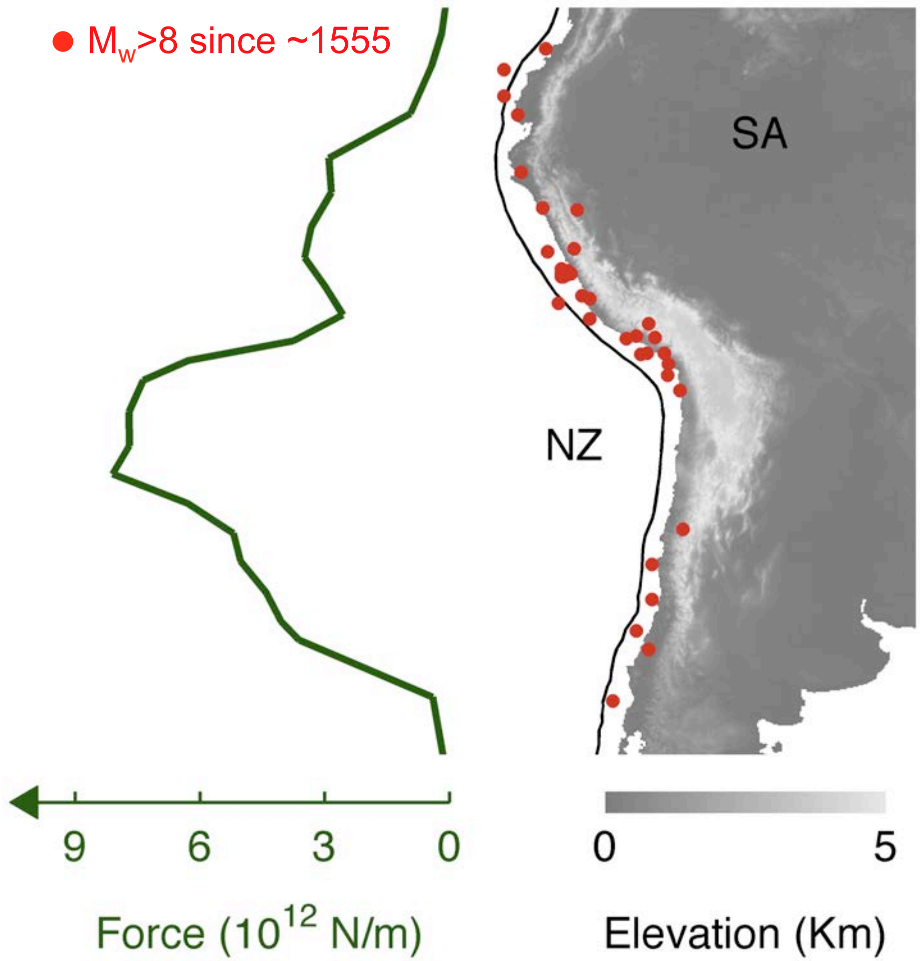
Trench-parallel gravity anomalies, indicating vertical deformation of the trench region.

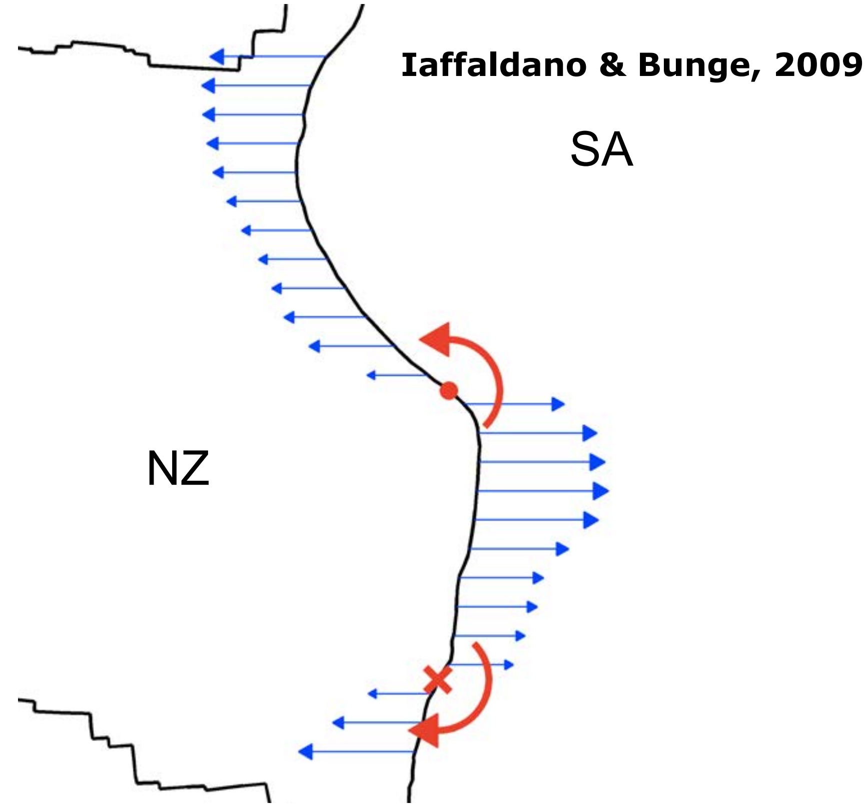
Iaffaldano & Bunge, 2008

Lateral variations of the Andean gravitational spreading are capable of deflecting the Nazca plate to different degrees along the trench.

This results in trench-depth lateral variations, and therefore in gravity anomalies along the trench.

Increase of resisting forces in the brittle plate boundary following Andean orogeny

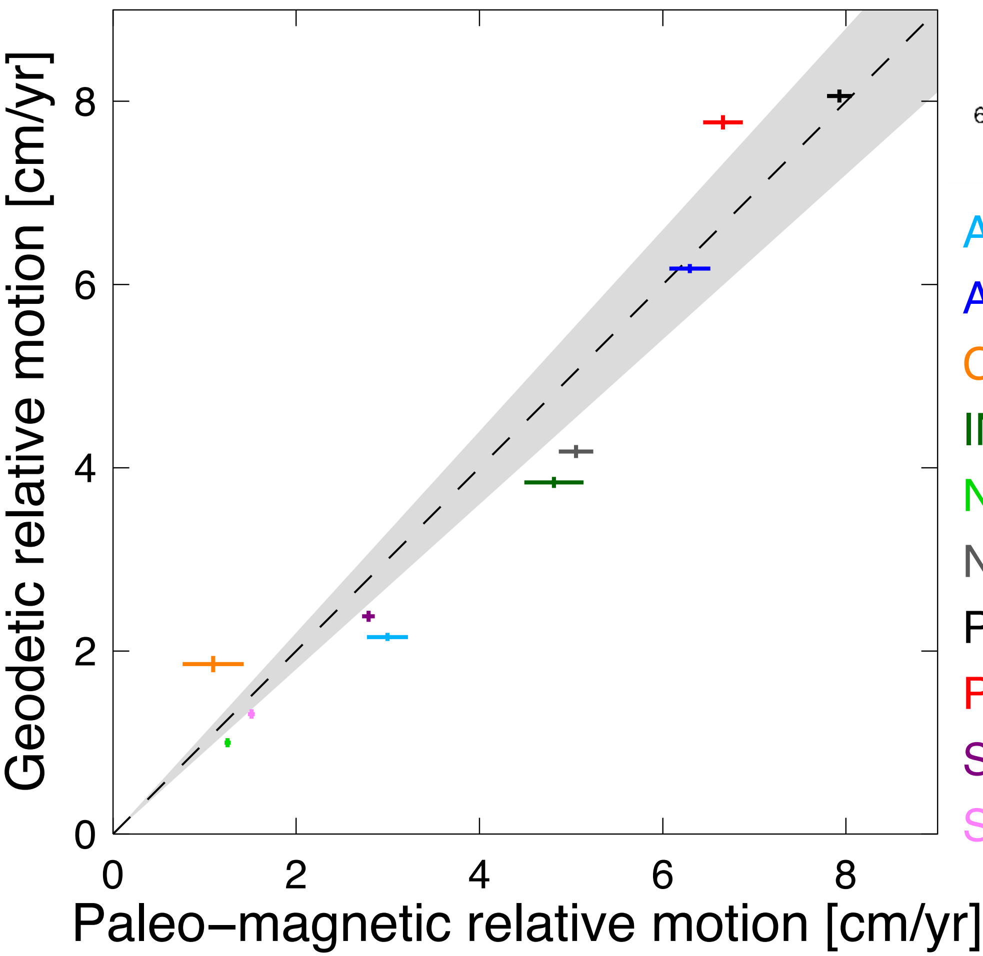


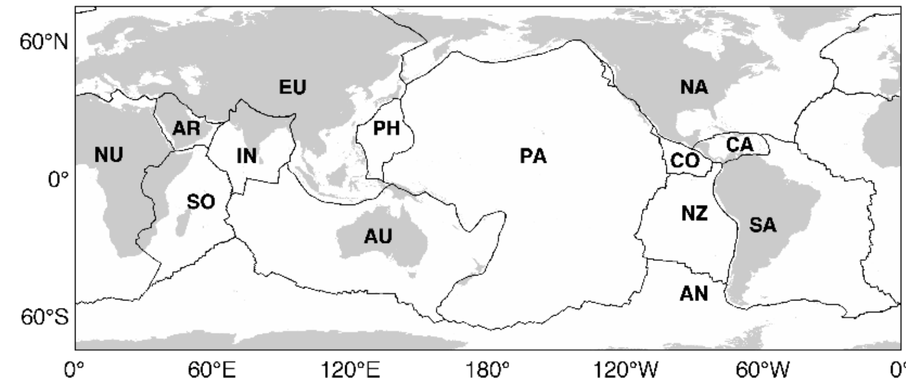


Paleo-magnetic and geodetic observations at the regional-scale indicate that the peculiar curvature of the margin has been acquired coevally with Andean orogeny.

The geological record could be explained by noting that at the large-scale the ability of SA to override NZ is reduced in the central margin due to stronger mechanical coupling.

Comparison of past-3.2-Myr and present-day plate motions





AR/EU [Austermann & Iaffaldano, 2013]

AU/AN

CA/NA

IN/EU [Iaffaldano et al., 2009; 2013]

NU/AN [Stamps et al., 2013]

NZ/AN [Iaffaldano et al., 2006]

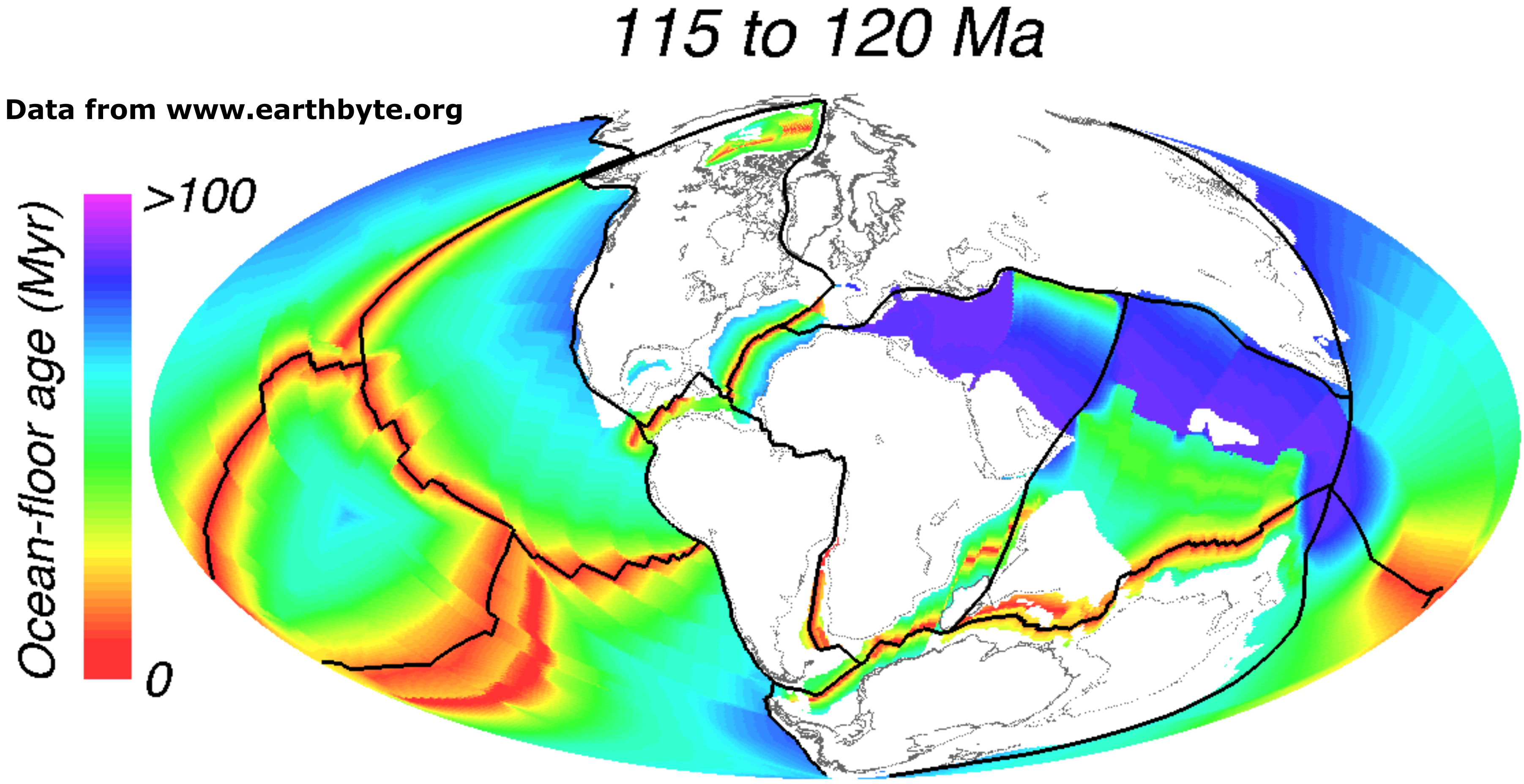
PA/AN

PH/EU [Iaffaldano, 2012]

SA/AN [Iaffaldano et al., 2007]

SO/AN [Stamps et al., 2013]

Reconstructed plate motions for the past 120 Myr



Each of the reconstructed plate-motion changes is a signal to interpret, in order to translate the history of plate kinematics into the history of plate dynamics.