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Testing geophysical hypotheses with global models of the coupled mantle-lithosphere system

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Aknowledgments

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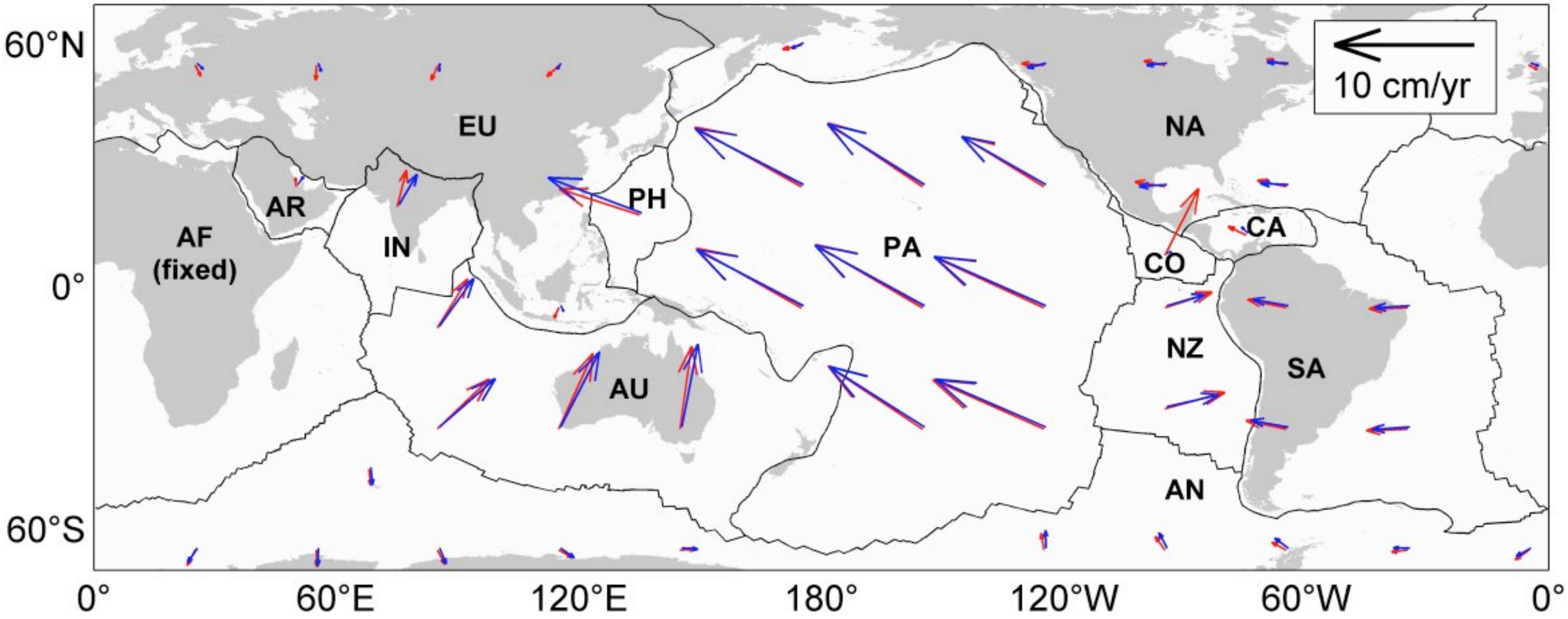
Tim Dixon - RSMAS, Miami

Comparison of recent (3.2 Myrs) and present-day plate motions



NUVEL-1A (3.2 Myrs ago, Paleomagnetic reconstruction)

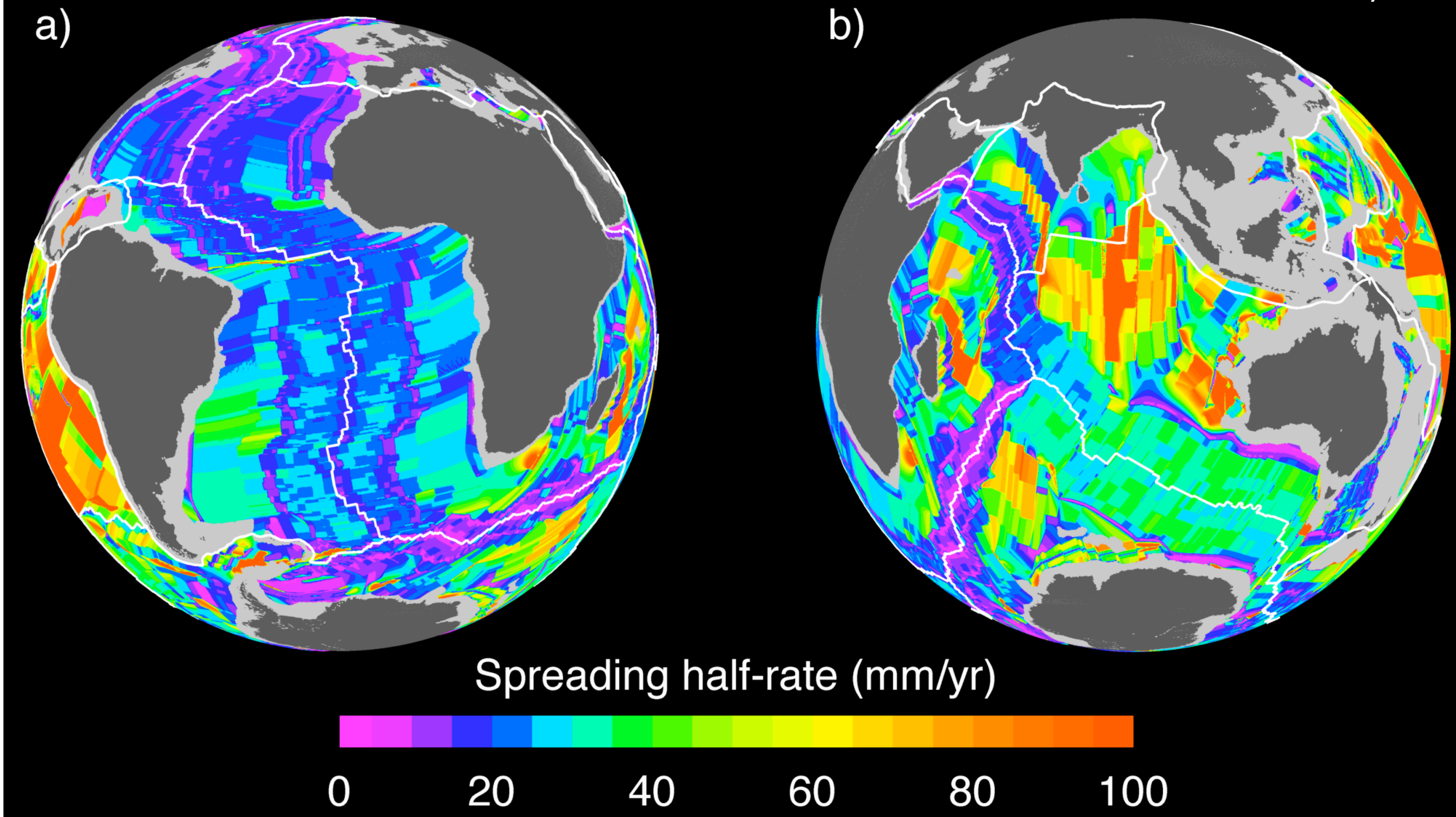
REVEL (Present-day, Geodetic estimate)

Iaffaldano et al., 2007

Plate motions show variations occurring on a time scale of few Myrs

History of ocean-floor spreading for the past 180 Myrs

Müller et al., 2008

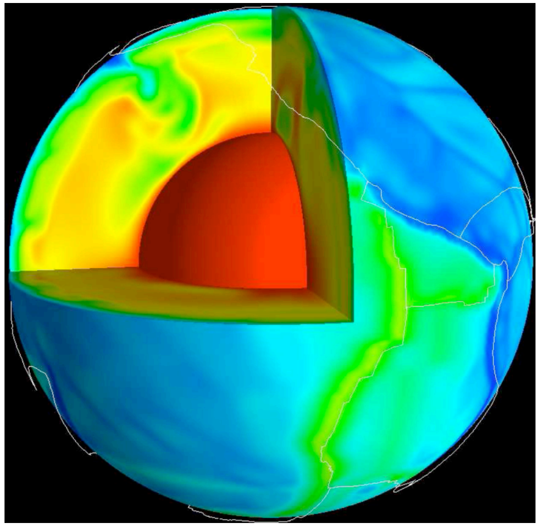


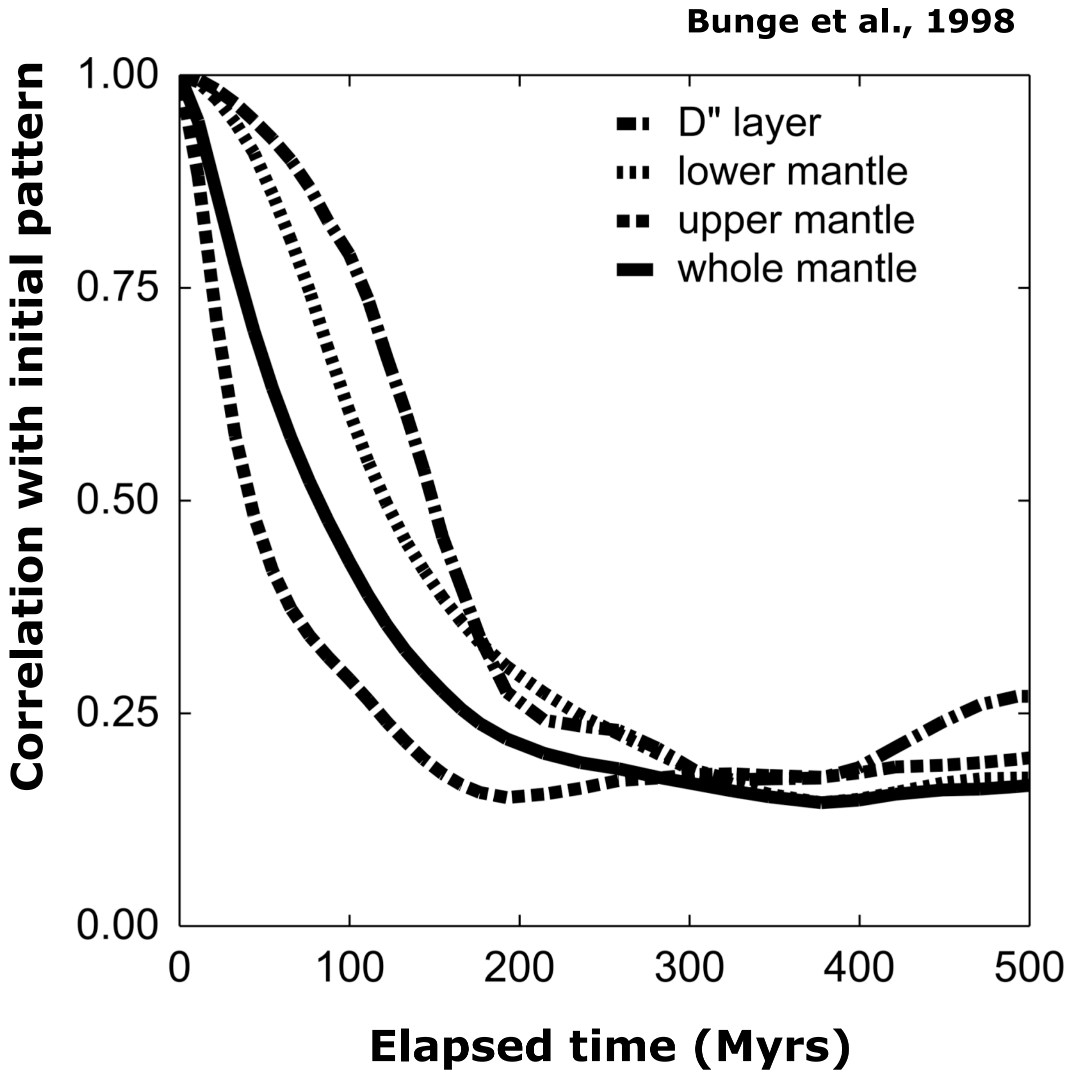
Abrupt changes in spreading-rate reveal short time-scale variations (few Myrs) even in past plate motions

Time evolution of mantle flow pattern from 3D circulation models

Mantle temperature distribution

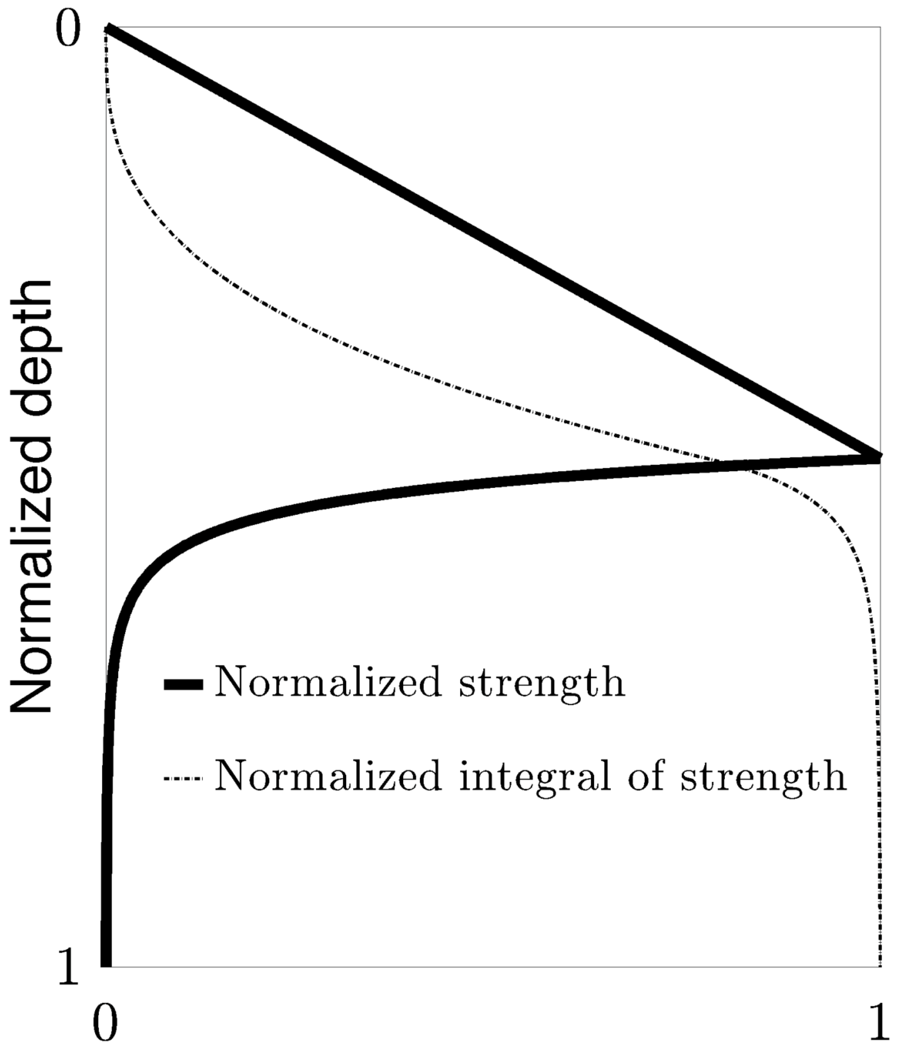
(**red=hot**, **blue=cold**)





Significant changes in flow pattern occur during the first 150 Myrs

Strength of the lithosphere



✓ In faulted material, strength represents the stress level to achieve and maintain in order to sustain sliding between parts.

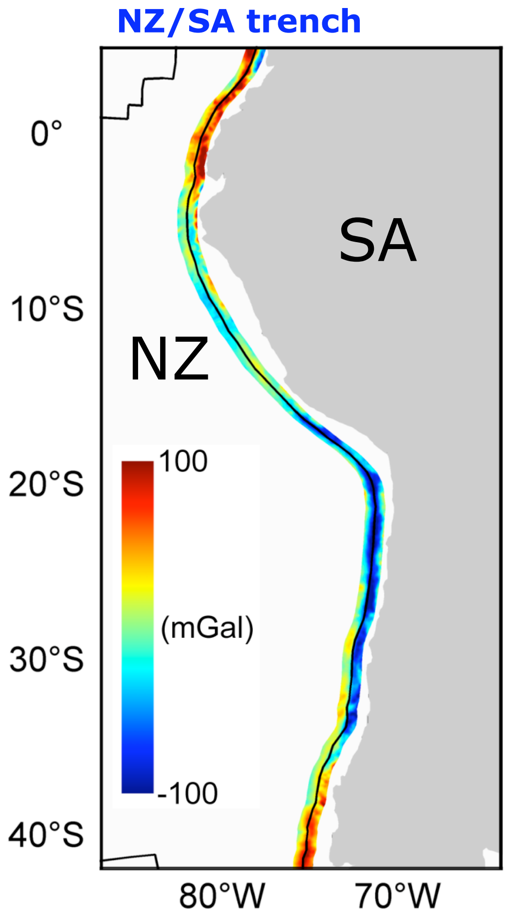
✓ Strength increases linearly with overburden pressure in the upper portion of lithosphere (**brittle**), and decreases exponentially with temperature in the deeper part (**ductile**).

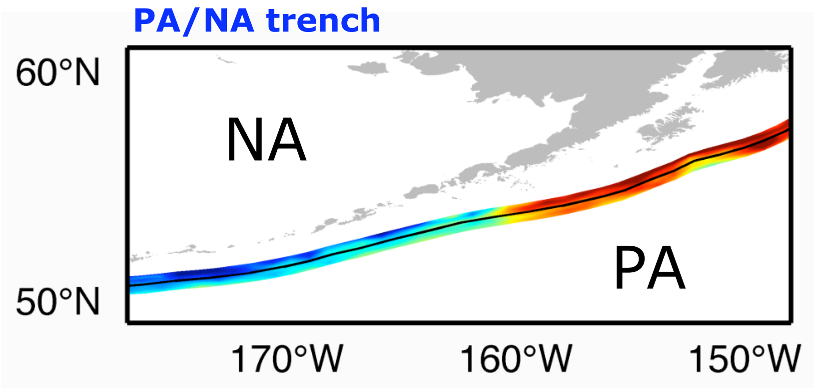
✓ The brittle part contributes **~80%** of the total strength. **Such inference holds within the ranges of friction coefficients and strain rates typical of plate tectonics**.

Other independent observations point to shallow-seated forces:

Observed free-air gravity anomalies along convergent margins

Sandwell & Smith, 1997





- ✓ Anomalies with respect to the regional-average cross profile.
- ✓ Large magnitudes, as high as 100 mGal.
- ✓ Short-wavelength variations along the margin.

This is suggestive of shallow-seated forces at plate boundaries, responsible for ocean-floor deformation and gravity anomalies

Modeling the lithosphere: the ***SHELLS*** code (Peter Bird)

$$g\rho + \frac{\partial \sigma_{ij}}{\partial x_j} = 0$$ momentum conservation

$$div(\bar{v}) = 0$$ mass conservation

✓ It computes **plate velocities and associated forces at equilibrium** in the THIN-SHELL limit.

✓ Note the instantaneous nature of the momentum equation: **Time evolution is not considered**.

✓ This is an advantage, as we don‵t understand well time evolution of plate boundaries (for instance dip-angle).

Global computational grid for present-day lithosphere models

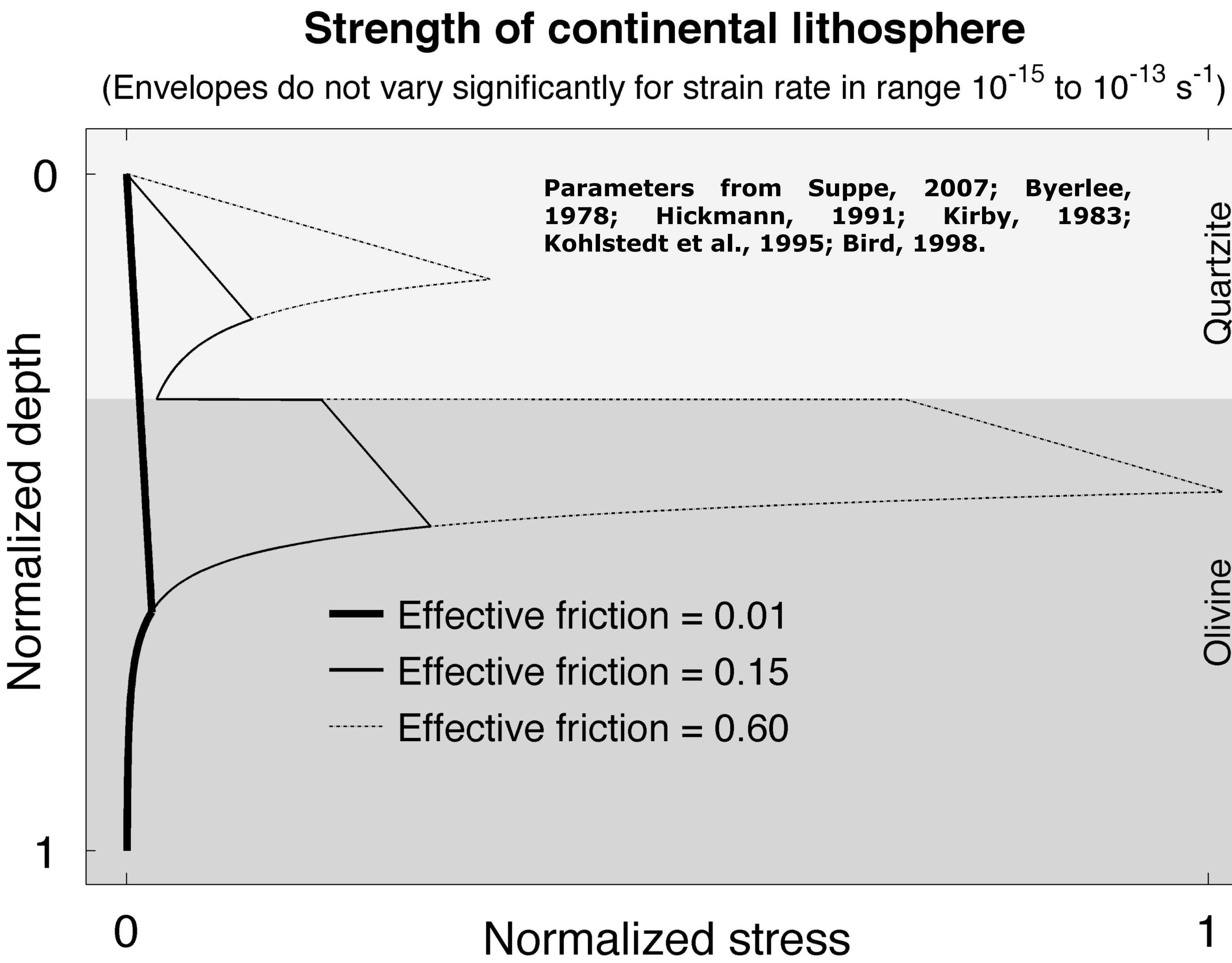
✓It includes lateral variations of the geotherm and therefore of the effective viscosity in the ductile portion.

✓It includes topography and crust/lithosphere thicknesses.

✓Tectonic plates are built explicitly into the computational grid.

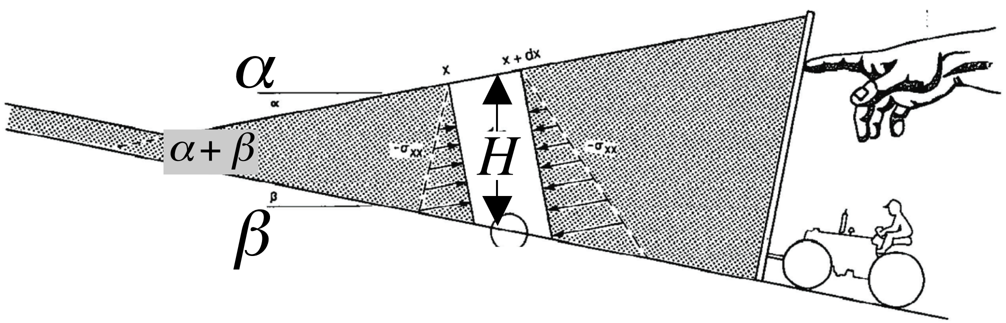
✓Plate boundaries feature dip angle from seismological observations.

✓They also feature friction in range 0.01 to 0.1, as opposed to continum elements featuring 0.6 to 0.85 friction.



Strength of continental lithosphere
(Envelopes do not vary significantly for strain rate in range 10^{-15} to 10^{-13} s^{-1})
Parameters from Suppe, 2007; Byerlee, 1978; Hickmann, 1991; Kirby, 1983; Kohlstedt et al., 1995; Bird, 1998.
Quartzite
Olivine
Effective friction = 0.01
Effective friction = 0.15
Effective friction = 0.60
Normalized depth
0
1
Normalized stress
0
1

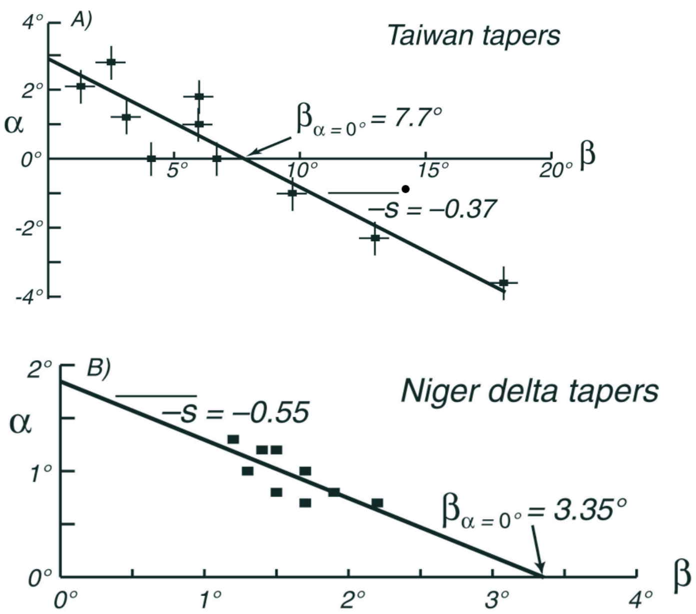
Plate-boundary friction from critical taper model and in-situ measurements



Suppe (2007) assumes mechanical homogeneity of the wedge in the critical taper theory (Dahlen, 1990).

This leads to alpha and beta being linearly related, while slope and intercept provide values for internal and basal strength.

Data from the field



Taper measurements indicate basal strength 10, possibly 20 times less than internal strength.

Ingredients for standard Mantle Circulation Models (MCMs)

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

✓ **Plate motion history for past 120 Myrs or so** (Lithgow-Bertelloni & Richards, 1998). Note also the recent ***Earthbyte*** initiative.

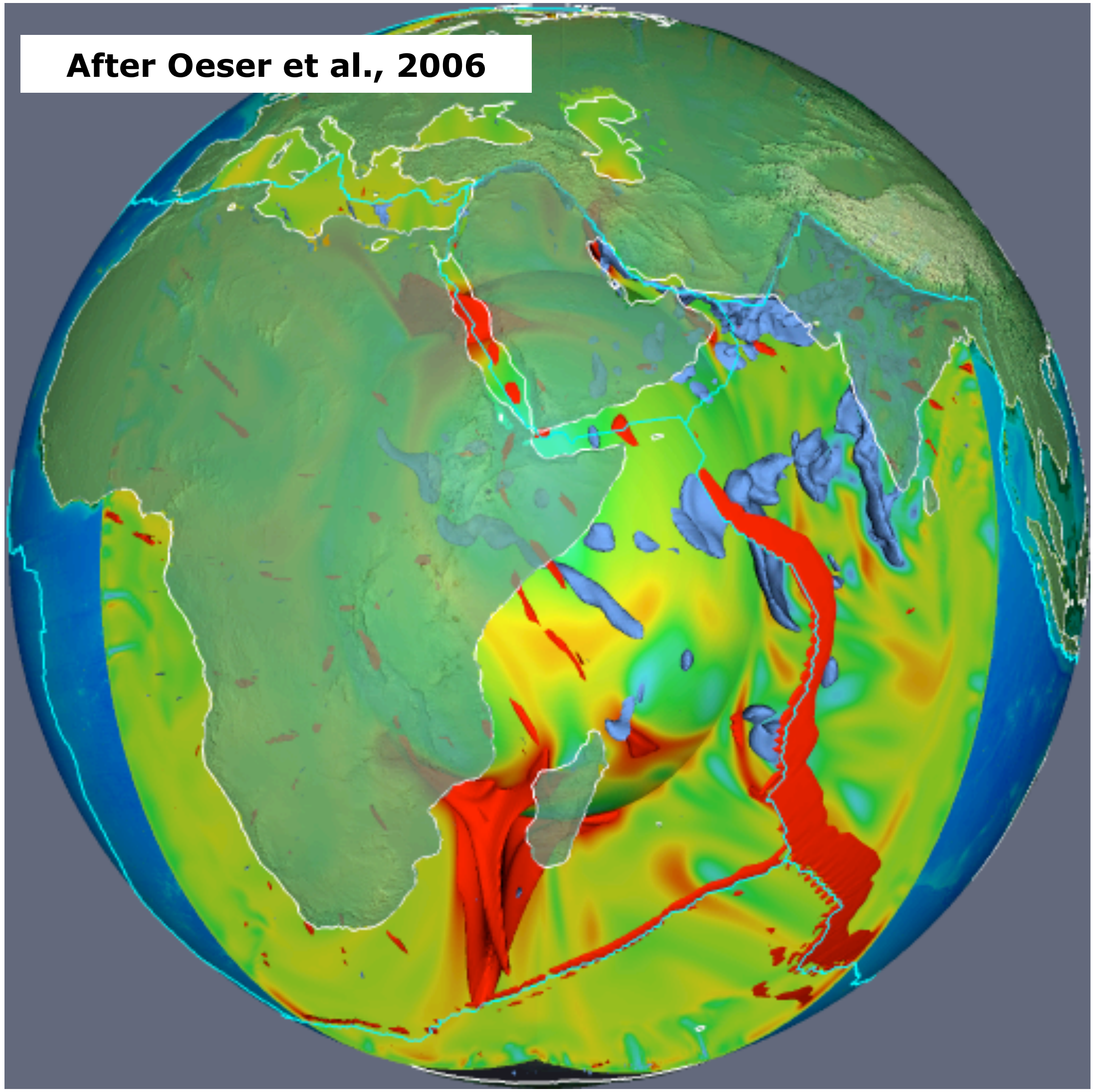
✓ **Depth-dependent viscosity** (Richards & Hager, 1984; Mitrovica, 1996).

✓ **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** (Stixrude, 2005/2007; Piazzoni et al., 2007)

Temperature isosurfaces from global MCMs



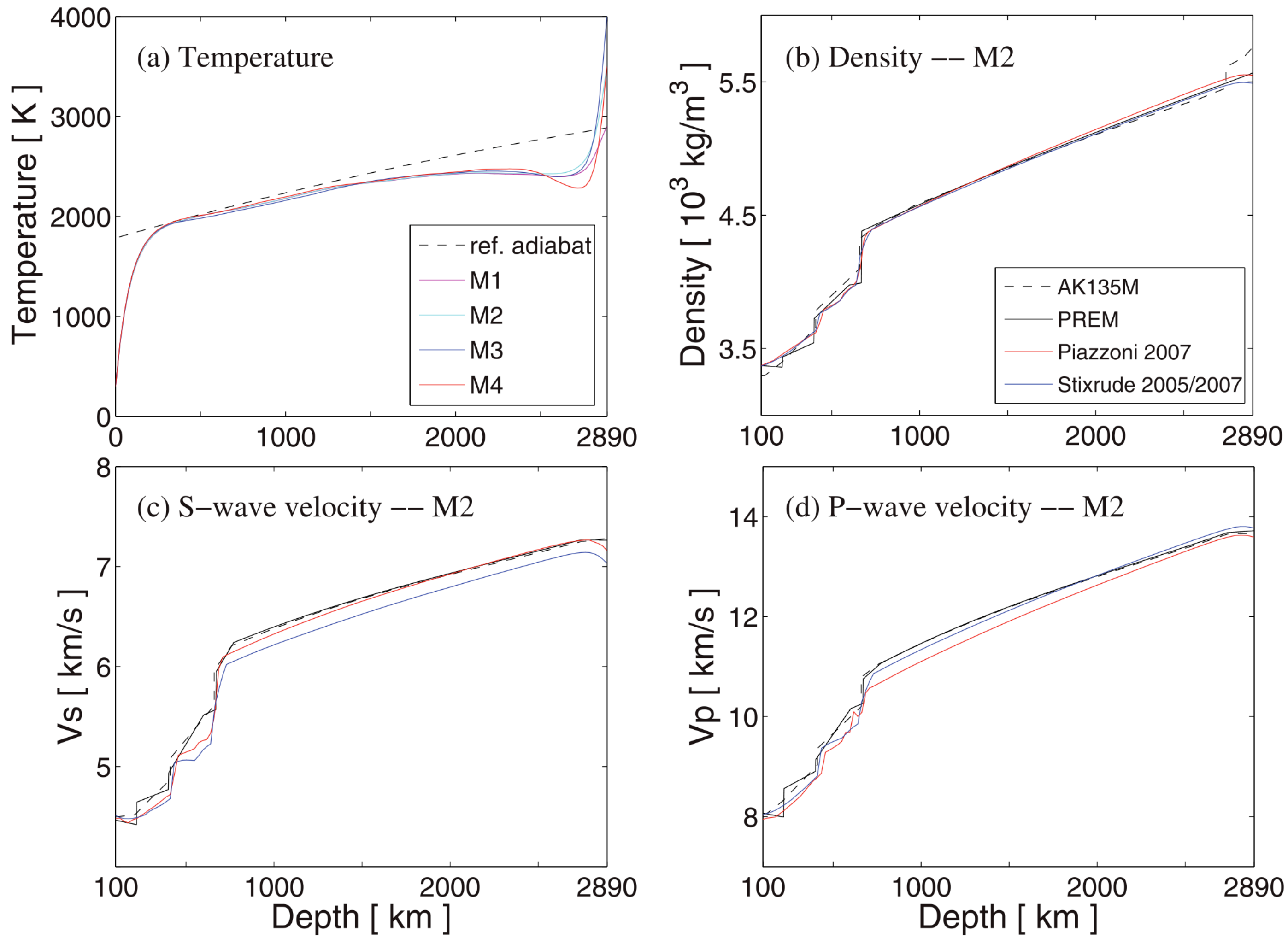
Red = hot, buoyant

Blue = cold, sinking

Realistic density anomalies drive convection in the Earth mantle and generate shear tractions at the base of lithosphere

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

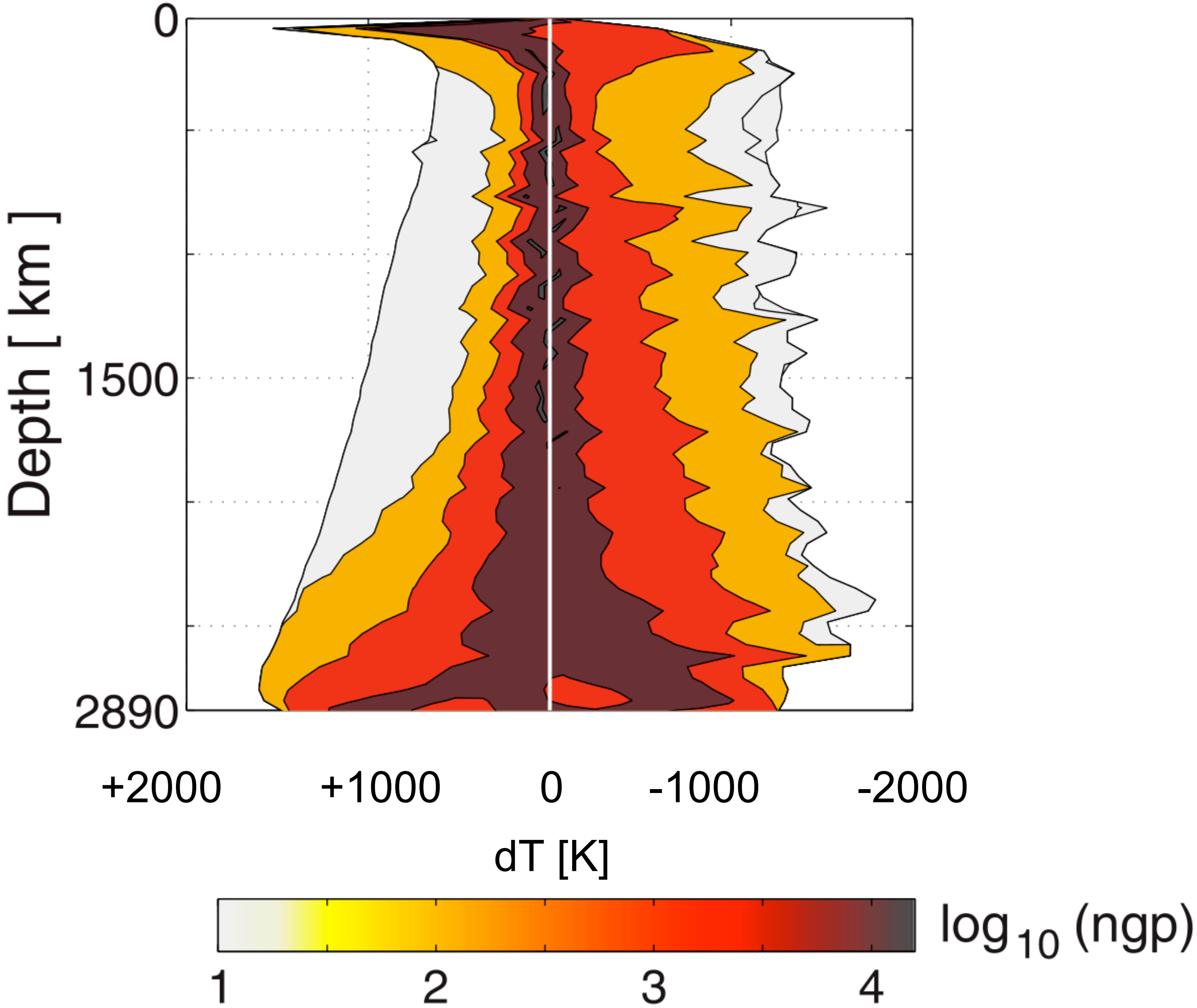
Schuberth et al., 2009



While there are small but relevant differences in seismic-velocity profiles, subject to a series of ongoing investigations [Cammarano et al. 2003, Deschamps & Trampert 2003/2004, Farnetani & Samuel 2005, Ricard et al. 2005, Mattern et al. 2005], **MCMs reproduce well density and therefore buoyancy in the Earth's mantle.**

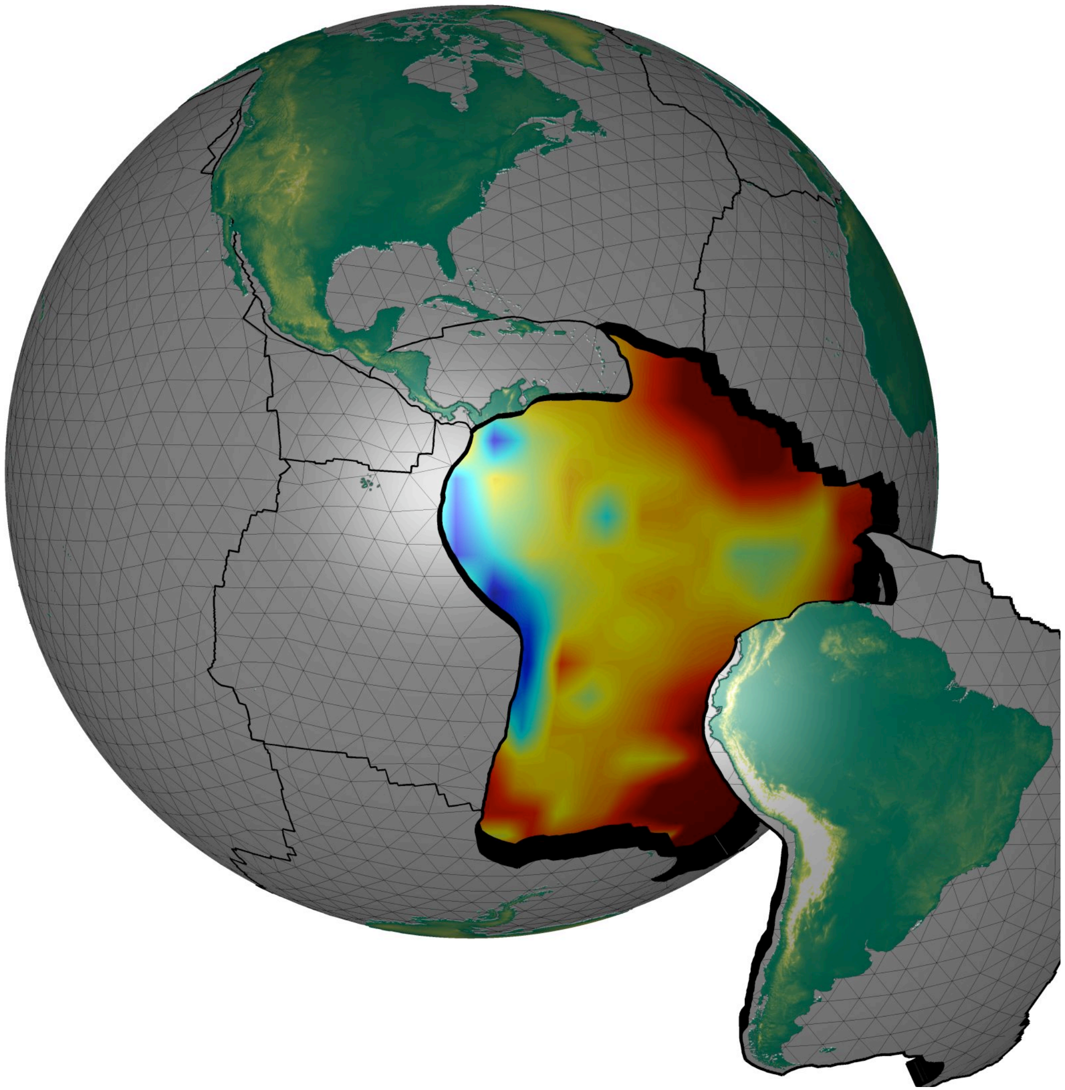
Depth histograms of lateral temperature-variations from MCMs

Schuberth et al., 2009



Realistic buoyancy forces from MCMs are included into the momentum-balance computed through the lithosphere numerical model

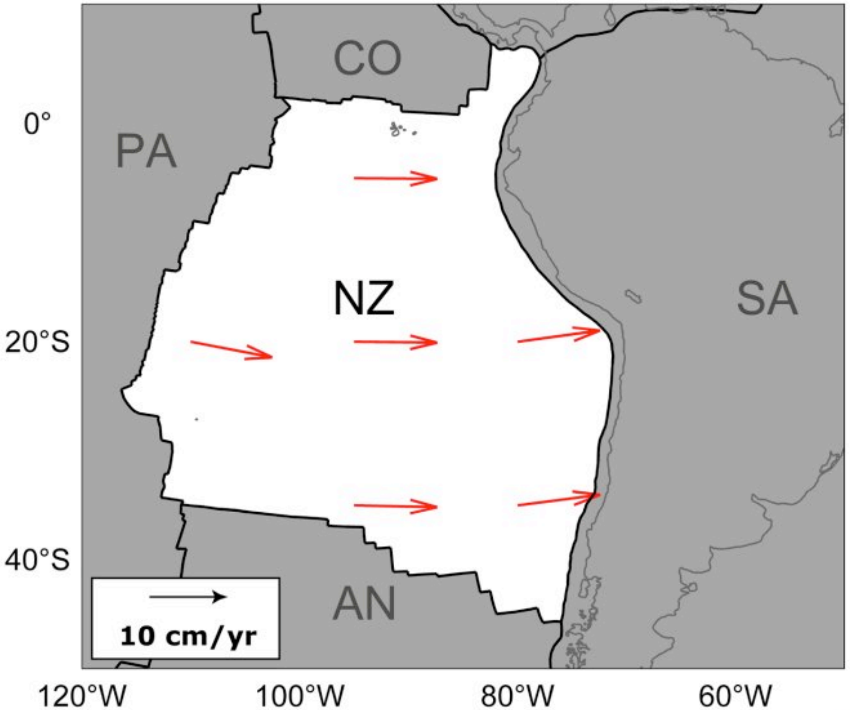
When used to reproduce observed plate-kinematics, global models of the coupled mantle/lithosphere system become a tool to compute **budgets of forces in lithosphere dynamics.**



Observed Nazca plate motion relative to South America:

a prominent example of plate motion change over time

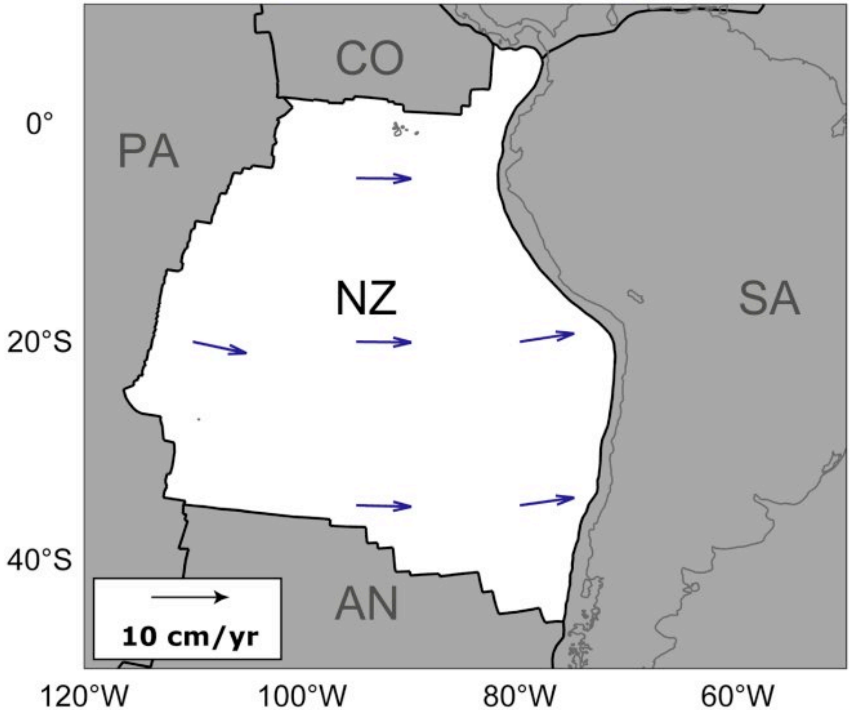
10 Myrs ago



10.3 cm/yr

Gordon and Jurdy, 1986

present day

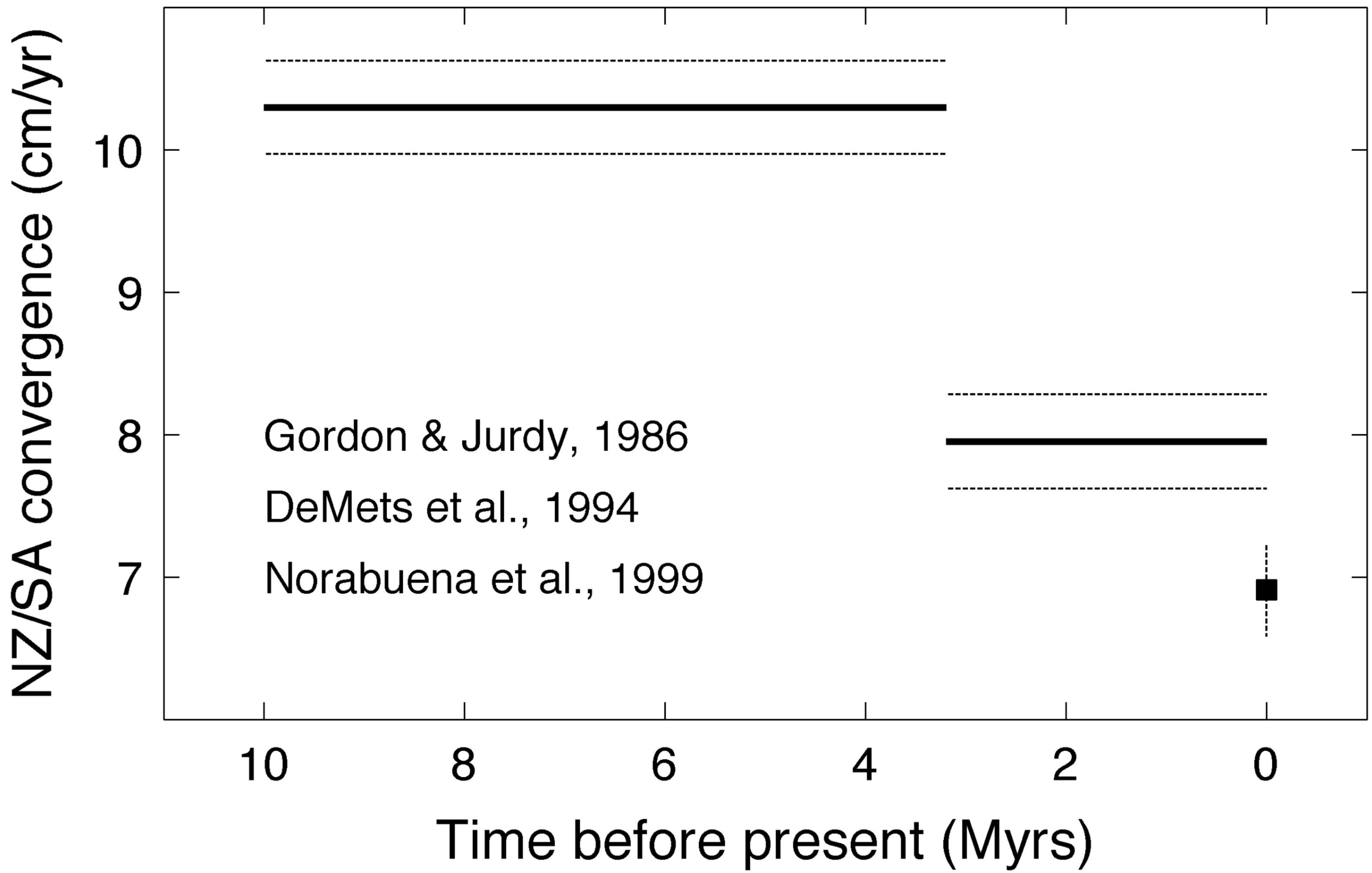


6.7 cm/yr

Norabuena et al., 1999

30% reduction of NZ/SA convergence rate

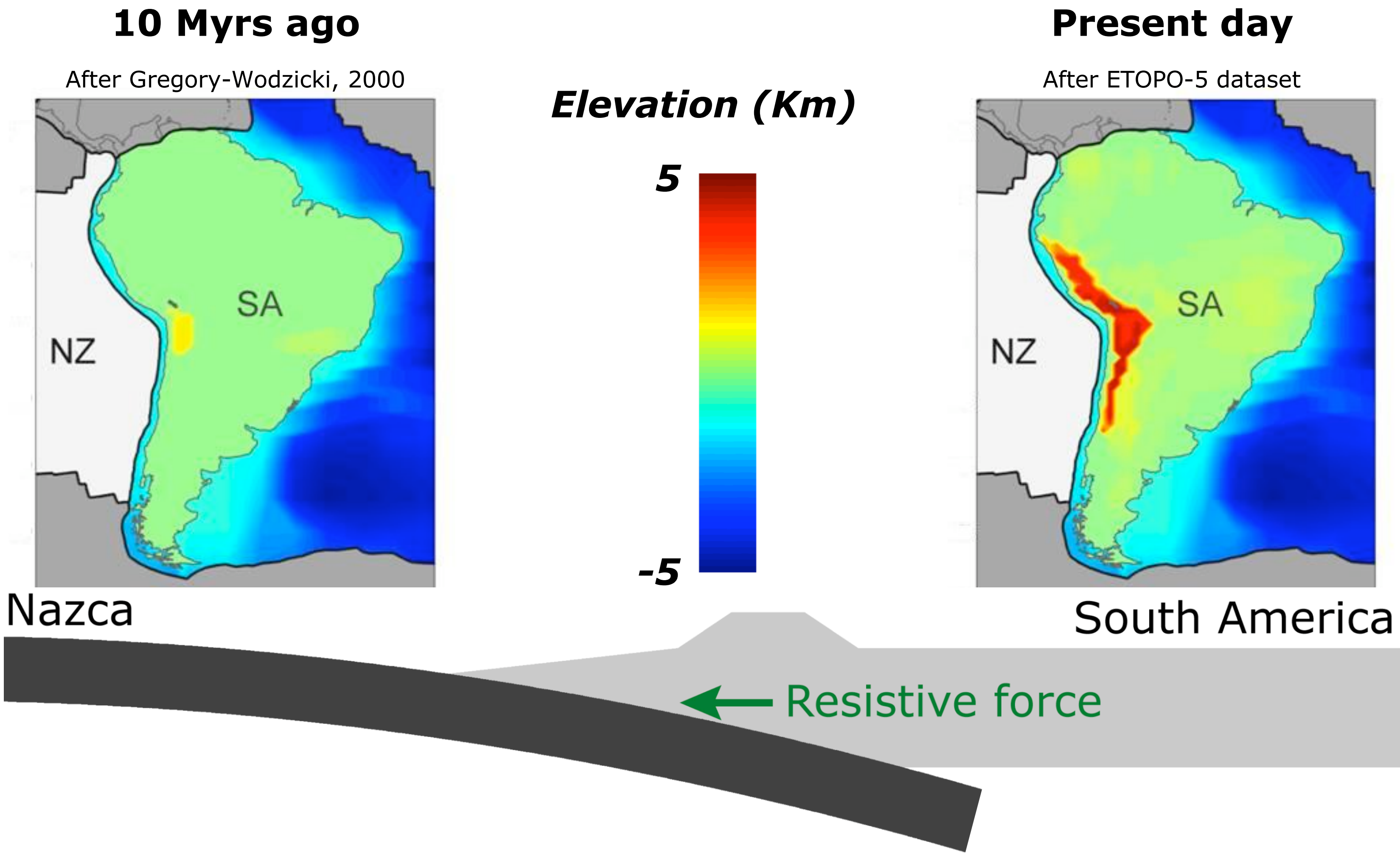
History of Nazca/South America convergence



Note continuous reduction of convergence rate over the past 10 Myrs

Most important tectonic change at NZ/SA boundary:

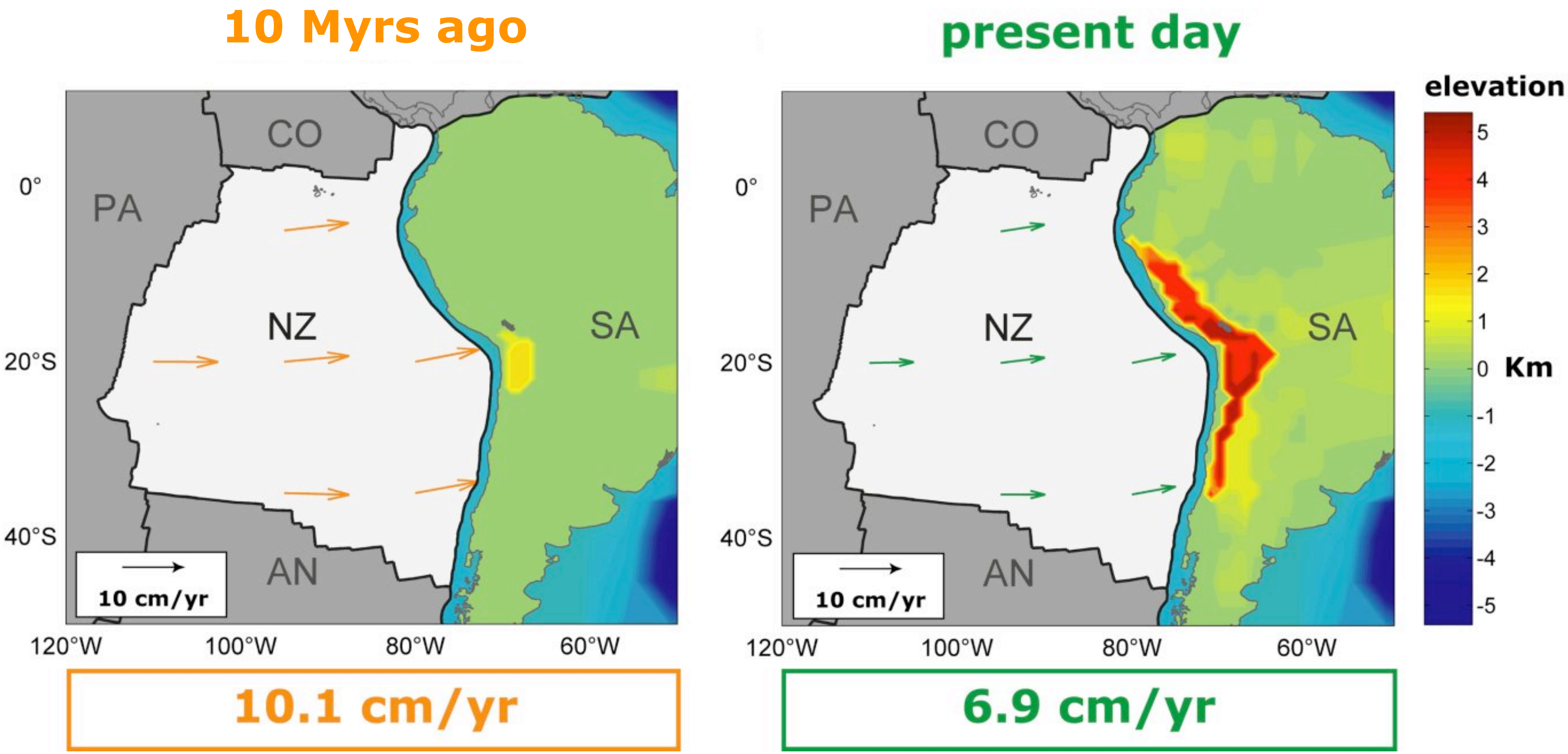
Uplift of the Andes



Can resistive forces slow down the convergent motion?

Computed Nazca plate motion relative to South America

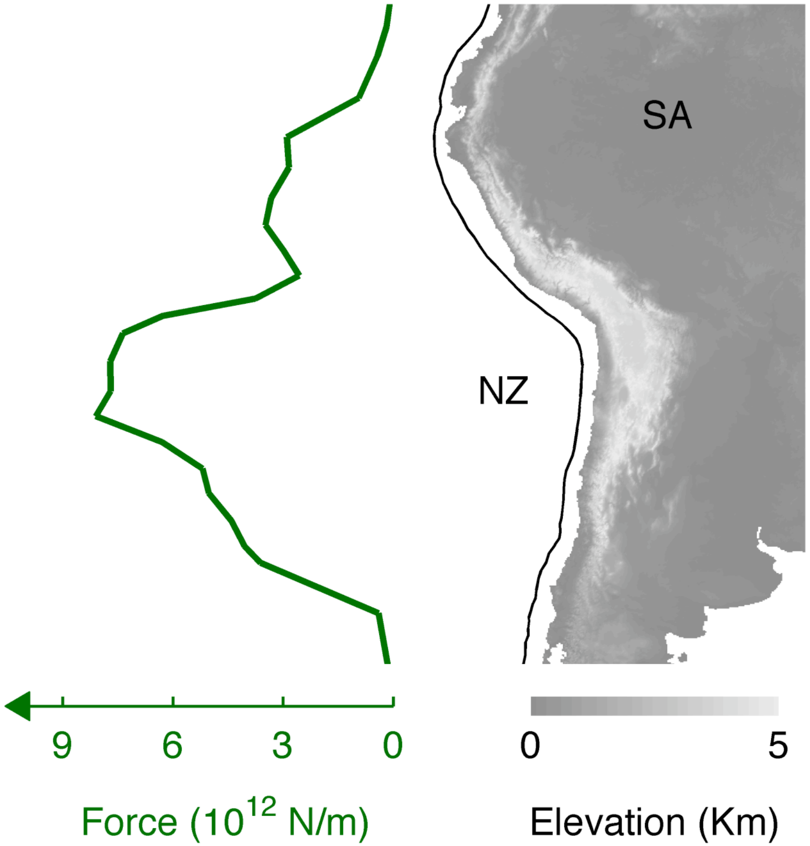
Iaffaldano et al., 2006



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

Computed motions compare remarkably well with observations

Increase of resistive forces in the upper portion of plate boundary from global mantle/lithosphere models

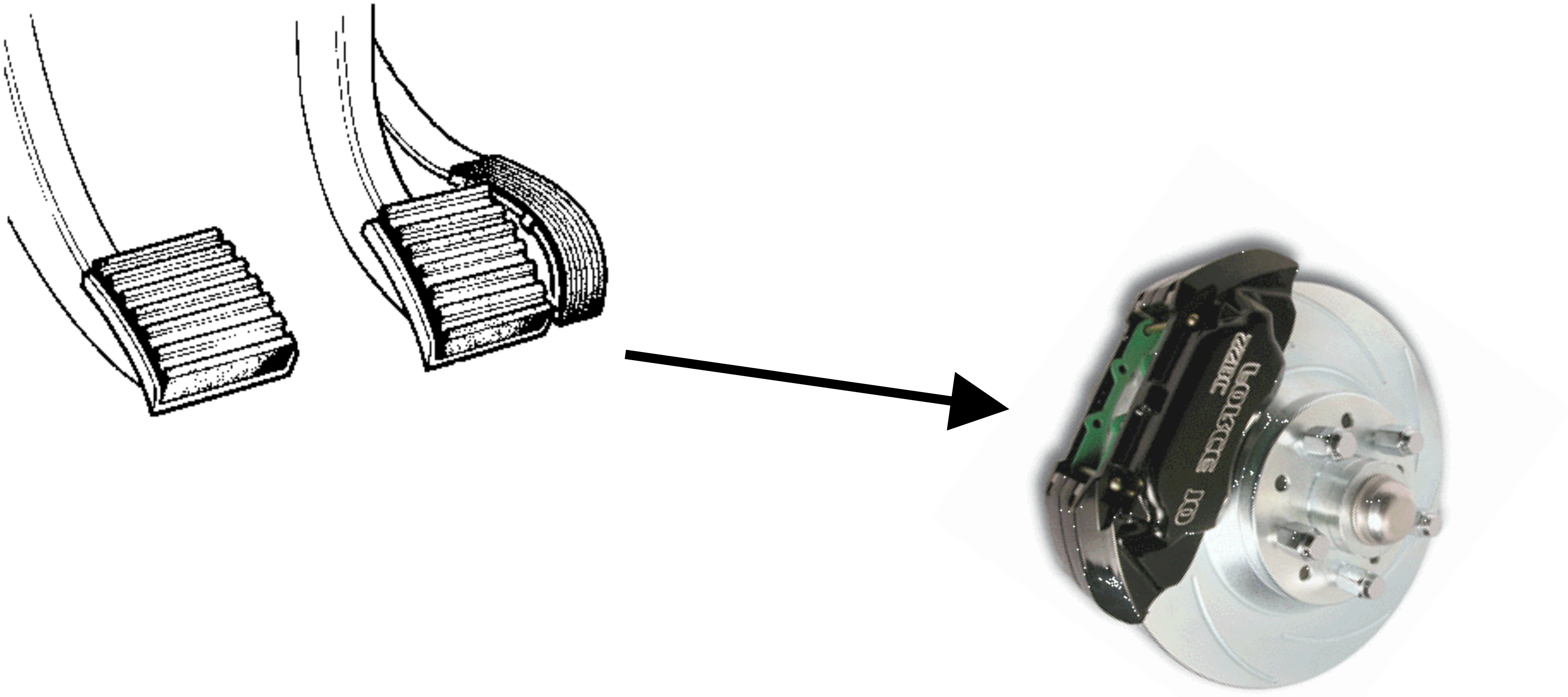


✓ Tectonically significant forces on the order of 10**12 N/m.

✓ Trend of force magnitudes reflects Andean morphology.

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

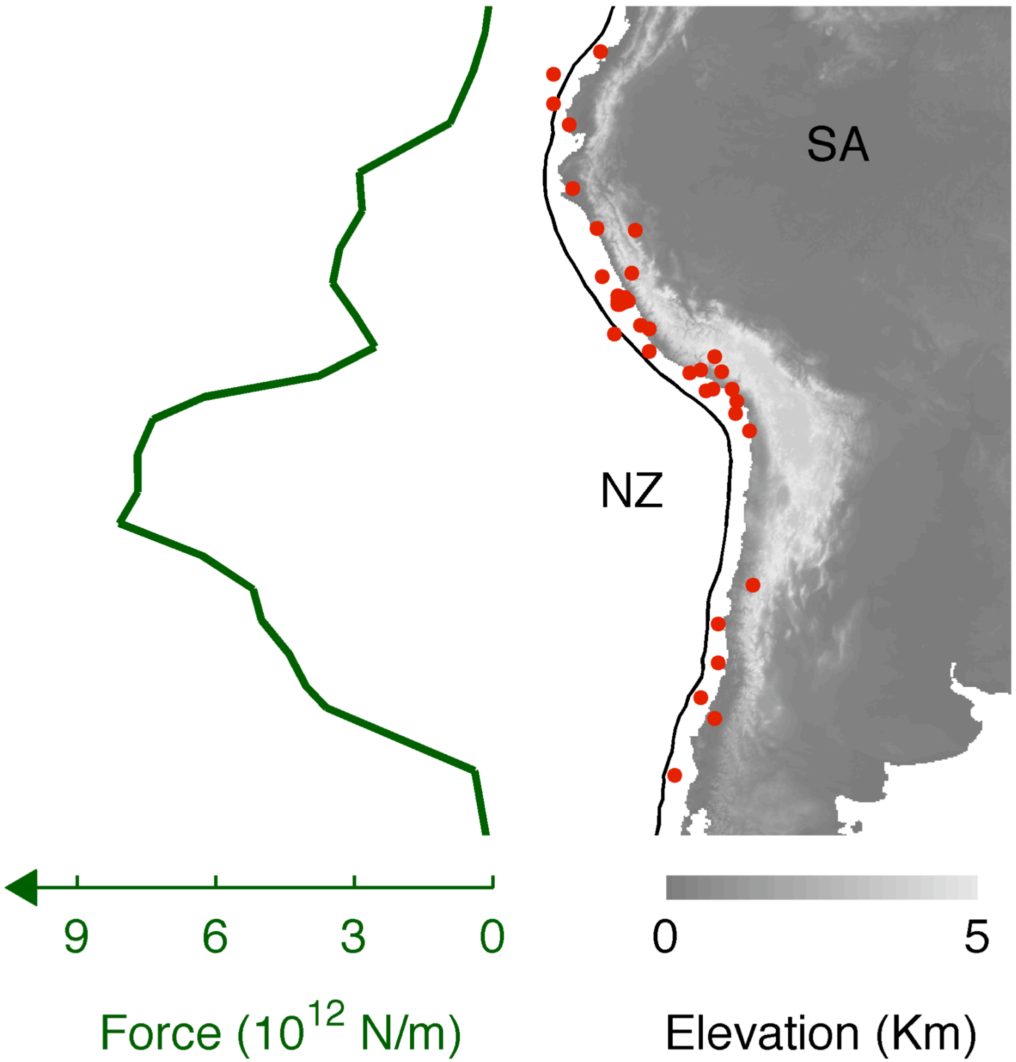
It works like a car brake



Your car slows down because you push the pedal stronger and increase the resistance against which the engine works.

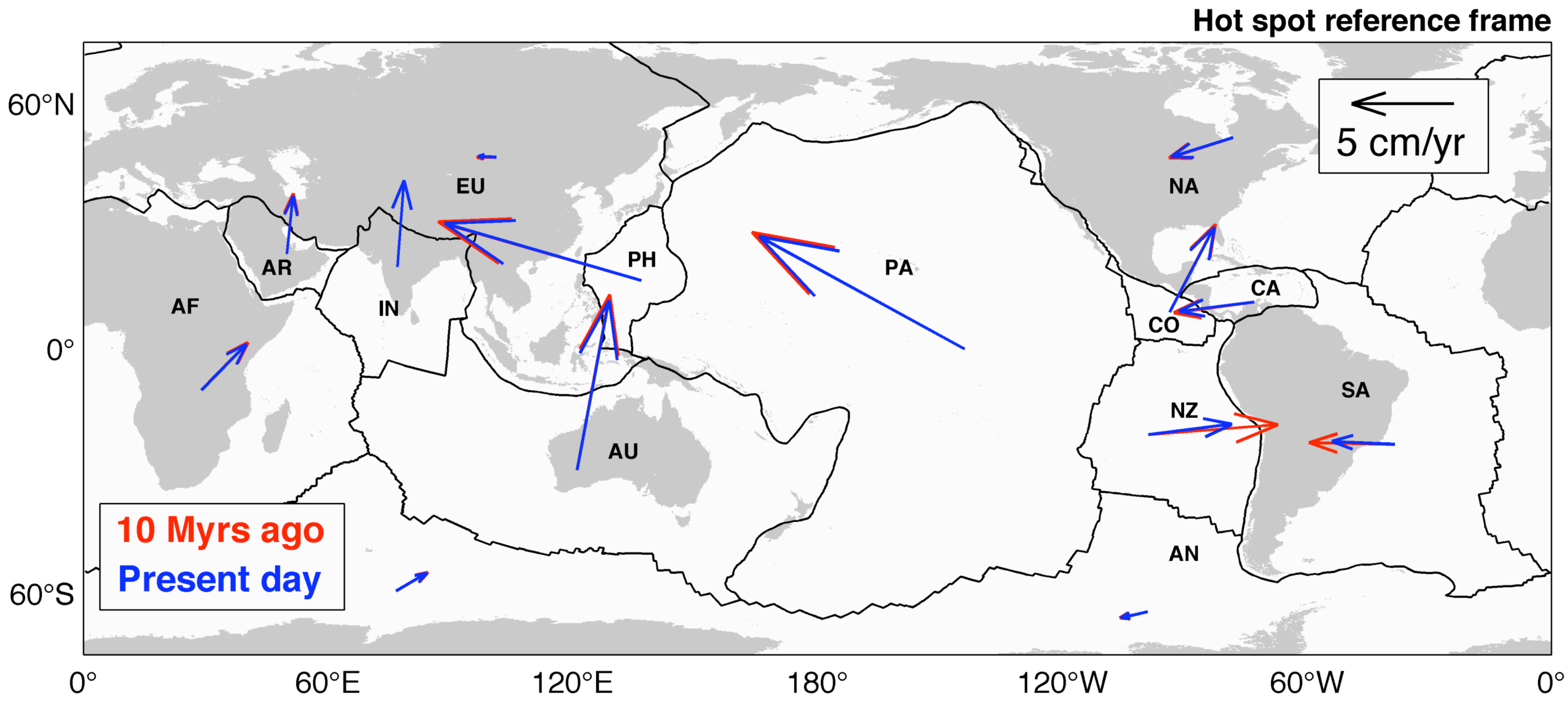
Frictional properties remain the same though.

- Budget of convergence-resisting forces due to Andean topography, located in the brittle NZ/SA plate interface.
- Locations of great (Mw>8) earthquakes reported along the NZ/SA plate interface since 1555.



While the earthquake record is admittedly shorter than the typical recurrence time, it could also be that strong plate coupling inhibits great earthquakes along convergent margins.

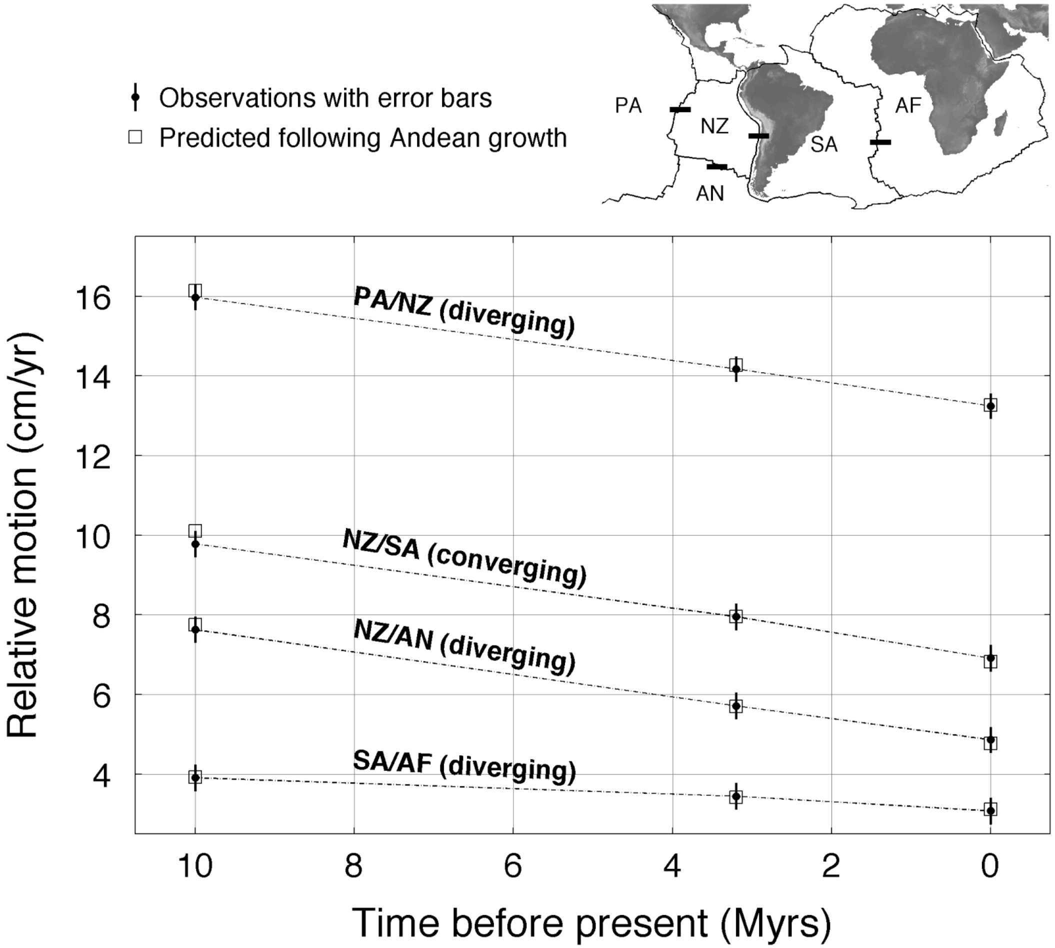
Predicted global plate motions before (red) and after (blue) Andean growth



Velocity reduction is confined to plates sharing the convergent boundary, where resisting forces increase due to Andean growth.

Is the reduction evident also in the isochron-record of surrounding ridges?

Plate motion history in South Pacific and South Atlantic



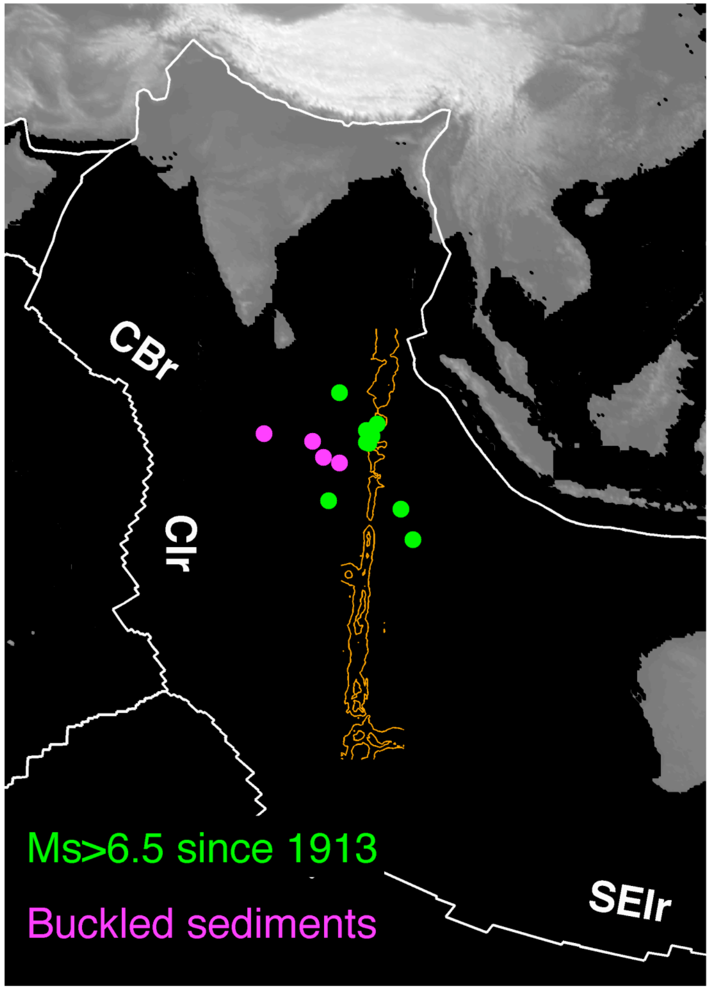
✓ Resisting forces arising from Andean growth account for the recent history of motion in South Pacific and South Atlantic.

✓ Fit at 3.2 Myrs results from numerical inversion (via automatic differentiation) of the forward tectonic problem.

✓ This corroborates the existence of a link between evolution of continental topography and sea-floor spreading.

Iaffaldano & Bunge, in press.

Evidences of separation between India and Australia plates



Wiens et al. [1985] suggested that a boundary between India and Australia plates did form, initiating possibly in late Miocene. Such inference is supported by

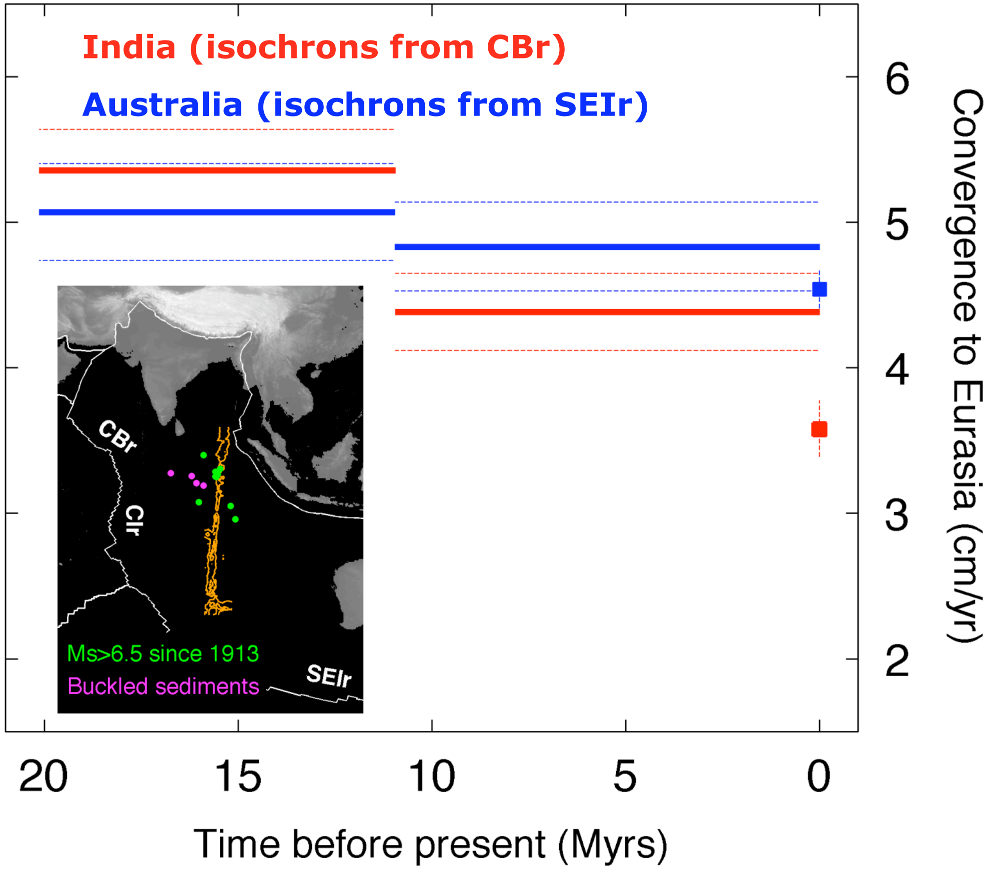
✓ Significant (Ms>6.5) intraplate seismicity along the northern Ninety East Ridge (in orange), indicating left-lateral strike-slip mechanisms [Stein and Okal, 1978].

✓ Imaged unconformities of sea-floor sediments in the Indian Ocean suggestive of a compression event some 8 Myrs ago [Weissel et al., 1980], when Tibet had attained most of its present-day elevation [Tapponier et al., 2001].

Any such events would most likely trigger a change in plate motion, as the budget of momentum has to be repartitioned

History of observed convergence relative to stable Eurasia plate

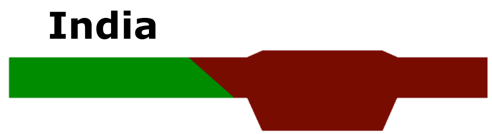
Iaffaldano & Bunge, in press



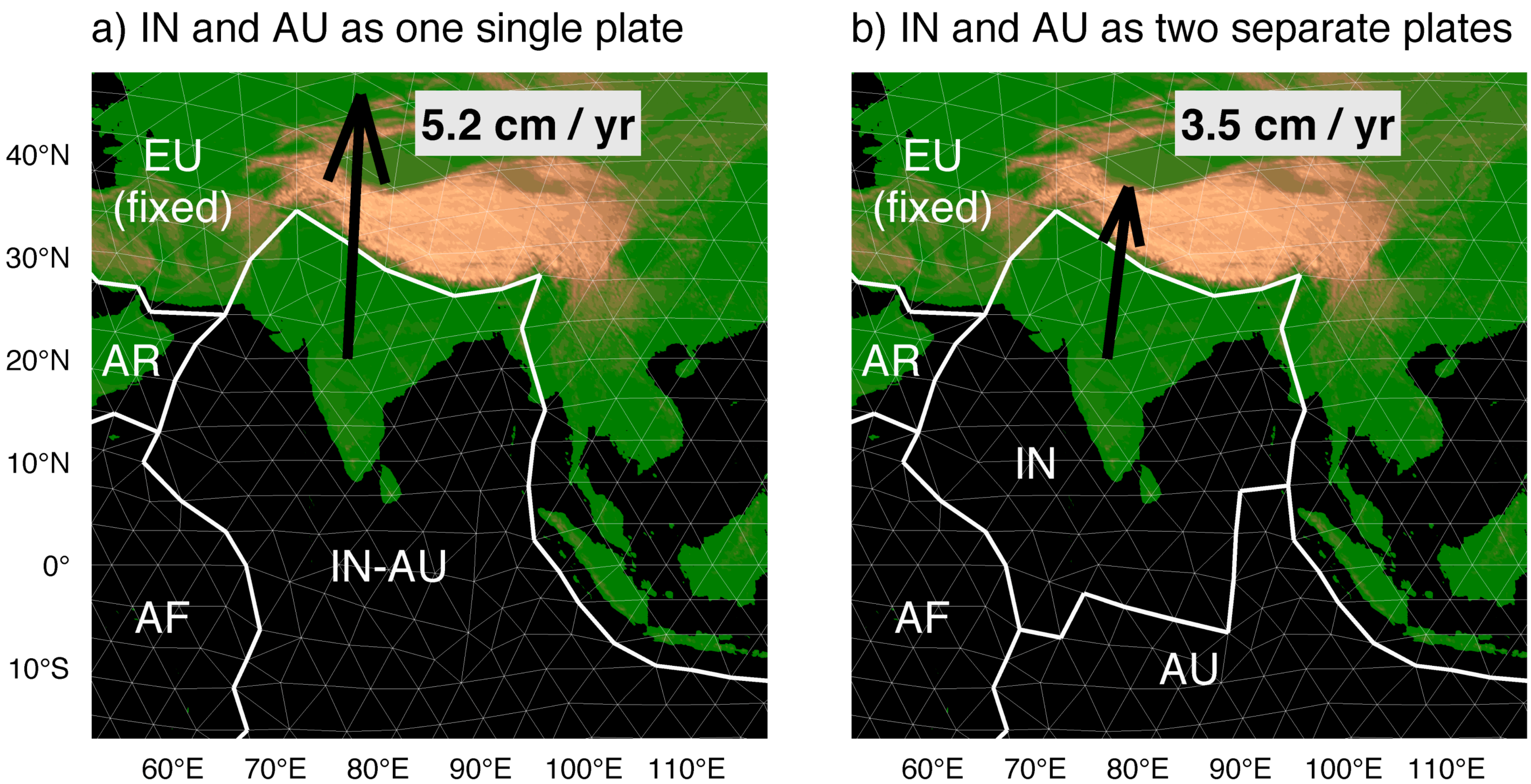
Data from Cande & Stock, 2004; Merkouriev & DeMets, 2006; Sella et al., 2002.

Upon plate separation, equal resisting forcing from gravitational spreading of gross Tibet acts more efficiently against a smaller India plate.

This ultimately results in a slow down of convergence towards Eurasia.



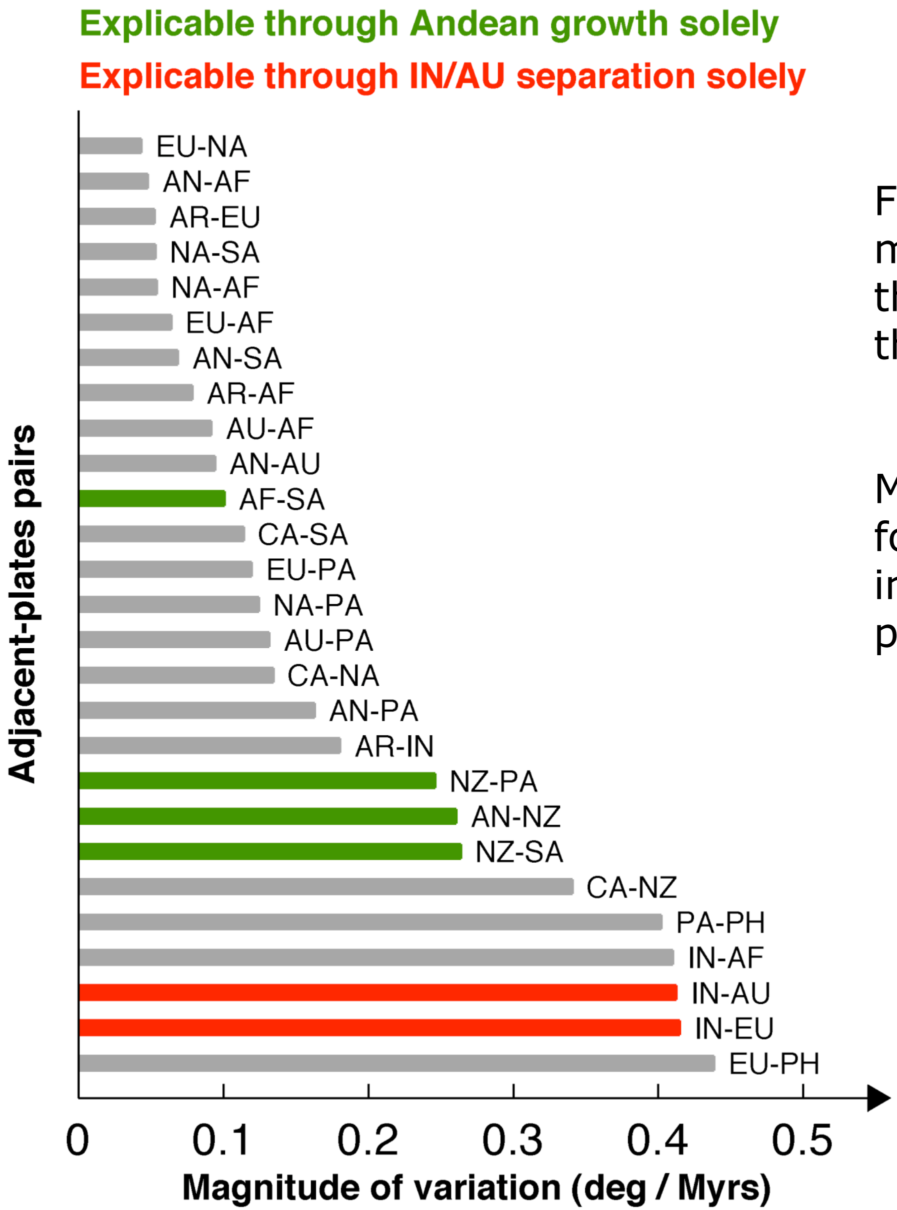
Predicted plate motion of India relative to Eurasia



Iaffaldano & Bunge, in press

Separation between India and Australia plates around 10 Myrs ago best explains the observed record of convergence towards Eurasia

Observed variations of adjacent-plates motions for the past 10 Myrs



Forward and inverse models of the coupled mantle/lithosphere system explain ~30% of the recent kinematic changes occurring on the Earth's surface.

Models have proved to be an effective tool for computational geosciences. The ability to include realistic plate configurations allows predictions of plate motion changes that

- ✓ can be explicitly tested against the geologic and geodetic records.
- ✓ are associated to budgets of shallow- as well as deep-rooted forces acting upon plates.