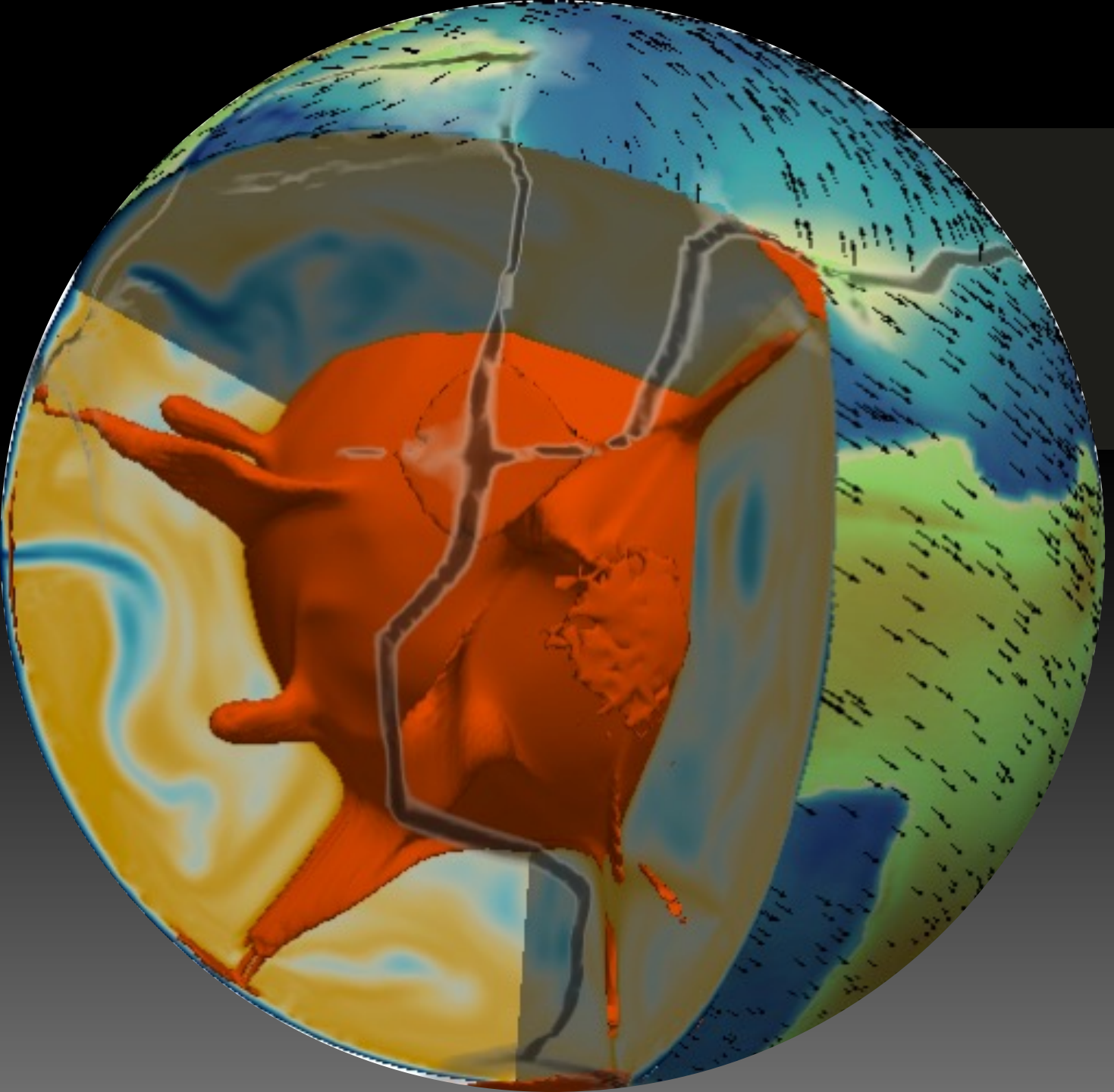


LITHOSPHERE AND MANTLE INTERACTIONS

MAËLIS ARNOULD

maelis.arnould@univ-lyon1.fr

ÉCOLE DOCTORALE DES HOUCHES

12 JULY 2021

Draw / write whatever comes first to your mind when you think about :

« Plate tectonics »

1 min

A SMALL SUMMARY OF THE LECTURE

- **A bit of history…**
- **The theory of plate tectonics and its limitations**
- **What drives plate tectonics?**
- **How to create new plates and plate boundaries?**
- **Dynamic topography: what does that mean?**

A BIT OF HISTORY

- **Before 1930, geologists already had a good knowledge of:**

  - **Geological mapping**
  - The **geometry of geological units**
  - **Paleontology**
  - **Geophysics** (gravimetry, seismology, fluid mechanics)

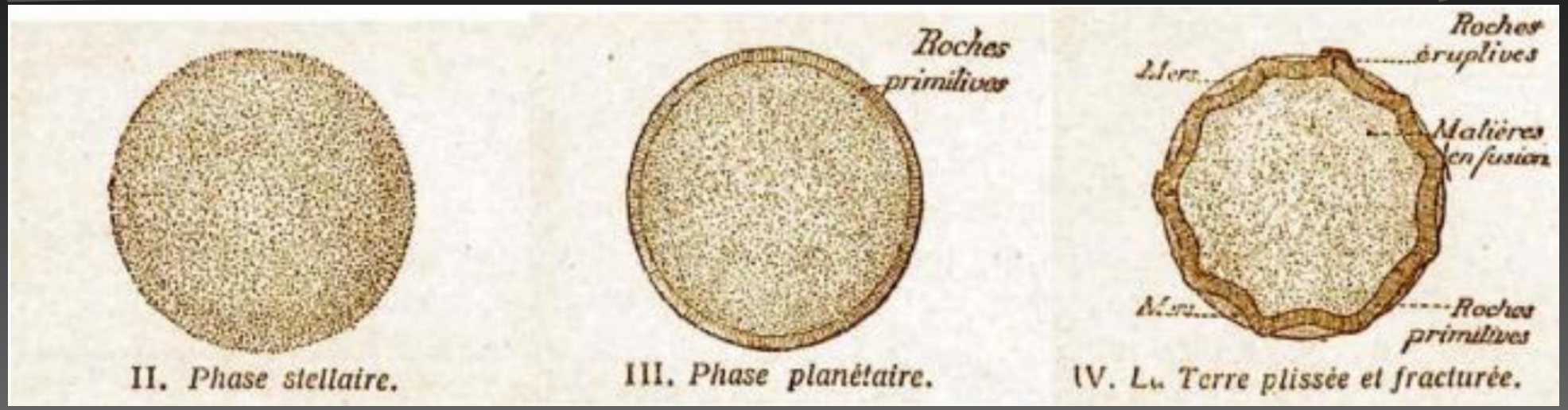
BUT no global model of how the internal Earth works!

A BIT OF HISTORY

- **Theory of the thermal contraction of the Earth (<1930)**

Éduard Suess (1831-1914), "*les bassins océaniques sont des aires d'affaissement, […] reproduisant les affaissements que nous avons reconnus dans l'intérieur des continents.*"

Cooling of the Earth's interior

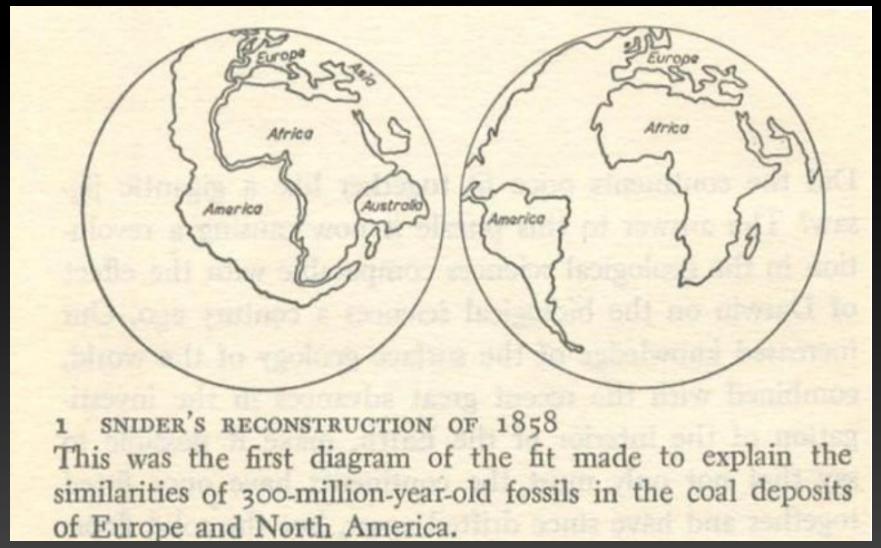


Geology school book, 9th grade (4ème), V. BOULET, 1925

A BIT OF HISTORY

- **Some intriguing observations…**

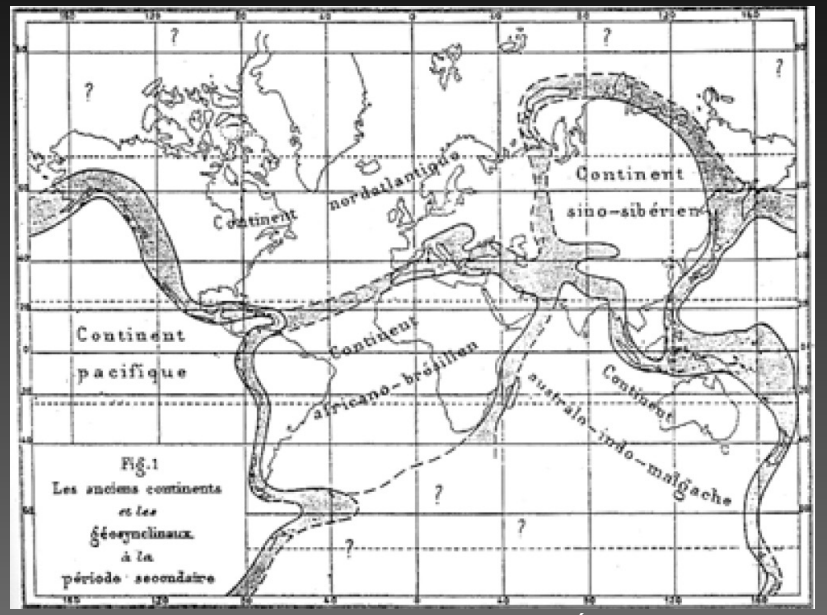
Correspondance of the shapes of Africa and South-America



1 SNIDER'S RECONSTRUCTION OF 1858
This was the first diagram of the fit made to explain the similarities of 300-million-year-old fossils in the coal deposits of Europe and North America.

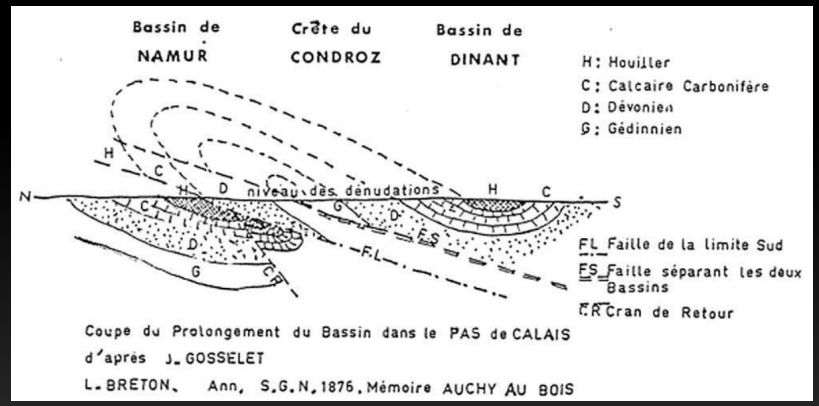
Snider-Pellegrini, 1858

Tectonic deformation confined within "geosynclines" and continental bridges to explain the **coexistence of fauna-flora on separate continents**



Émile Haug, 1900

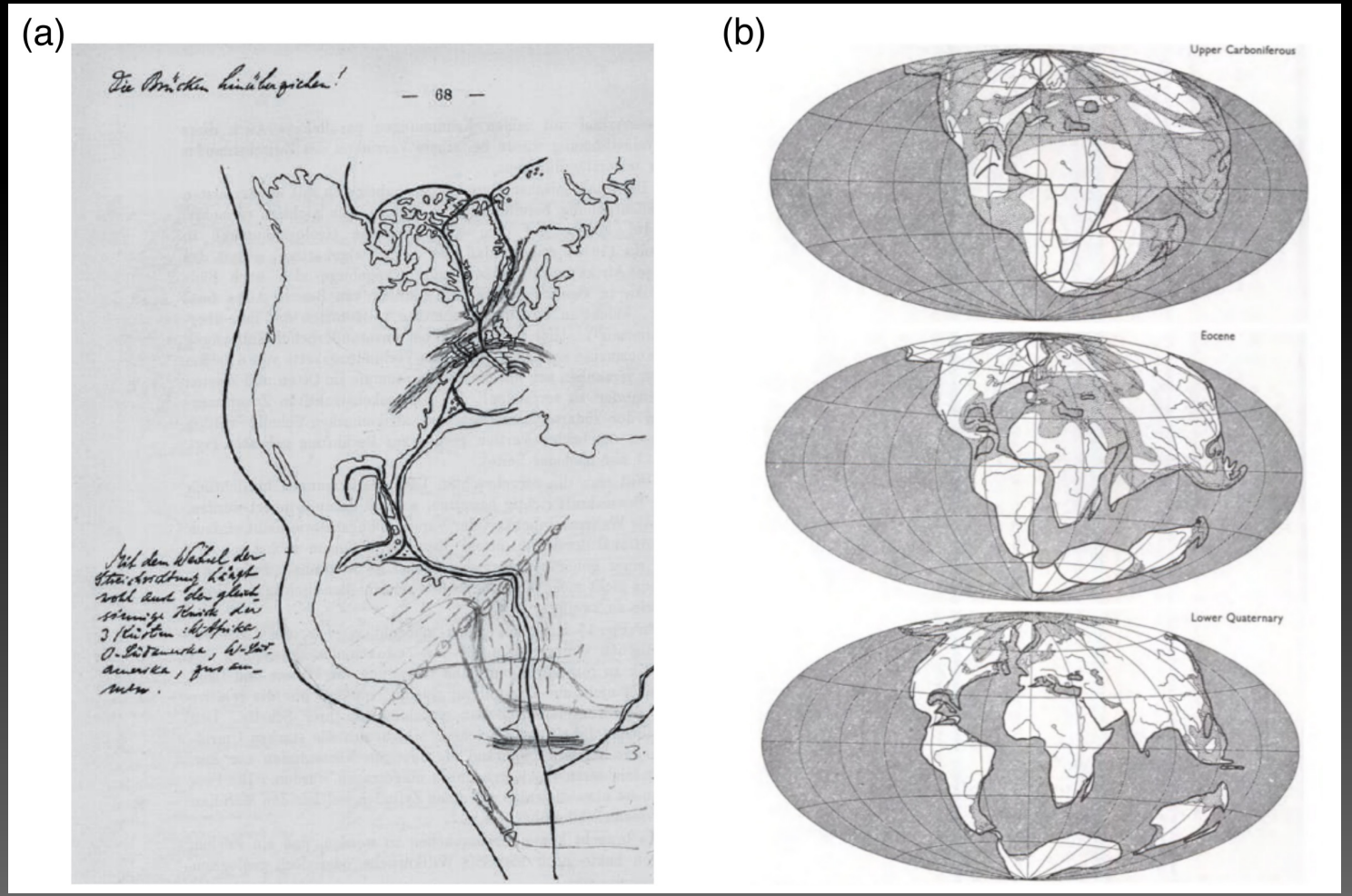
Nappes with different ages and nature dansin mountains explained by **important lateral motions**



Marcel Bertrand, 1884

A BIT OF HISTORY

- **From continental drift…**



Alfred Wegener, 1915-1924

Alfred Wegener (1880-1930)

A BIT OF HISTORY

- **From continental drift…**

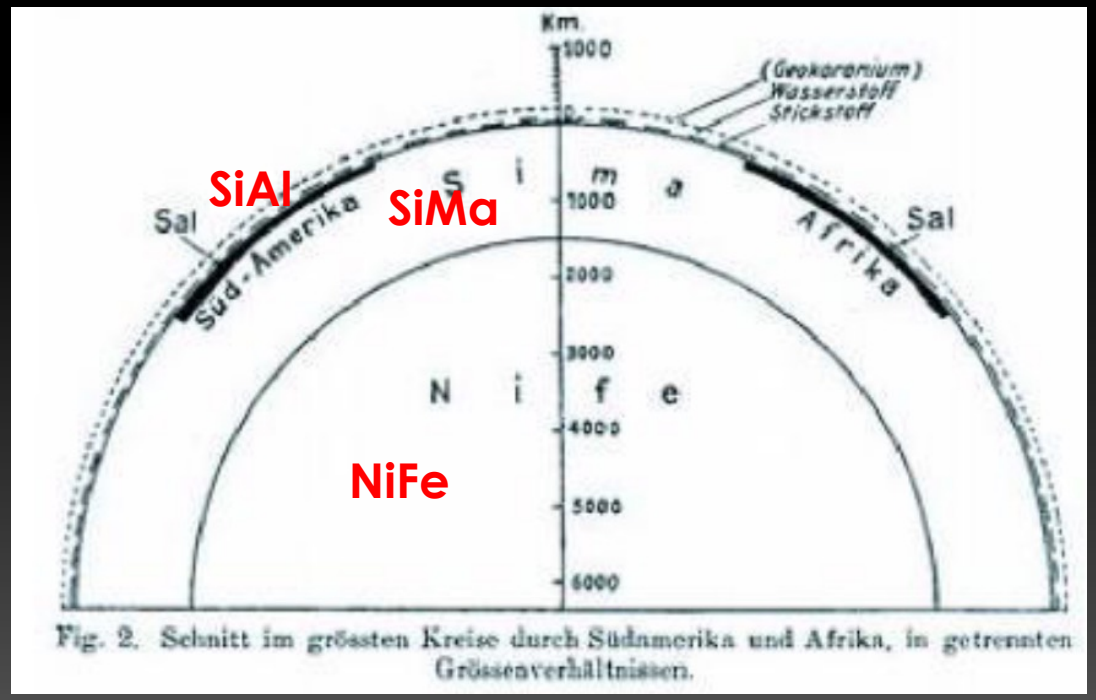
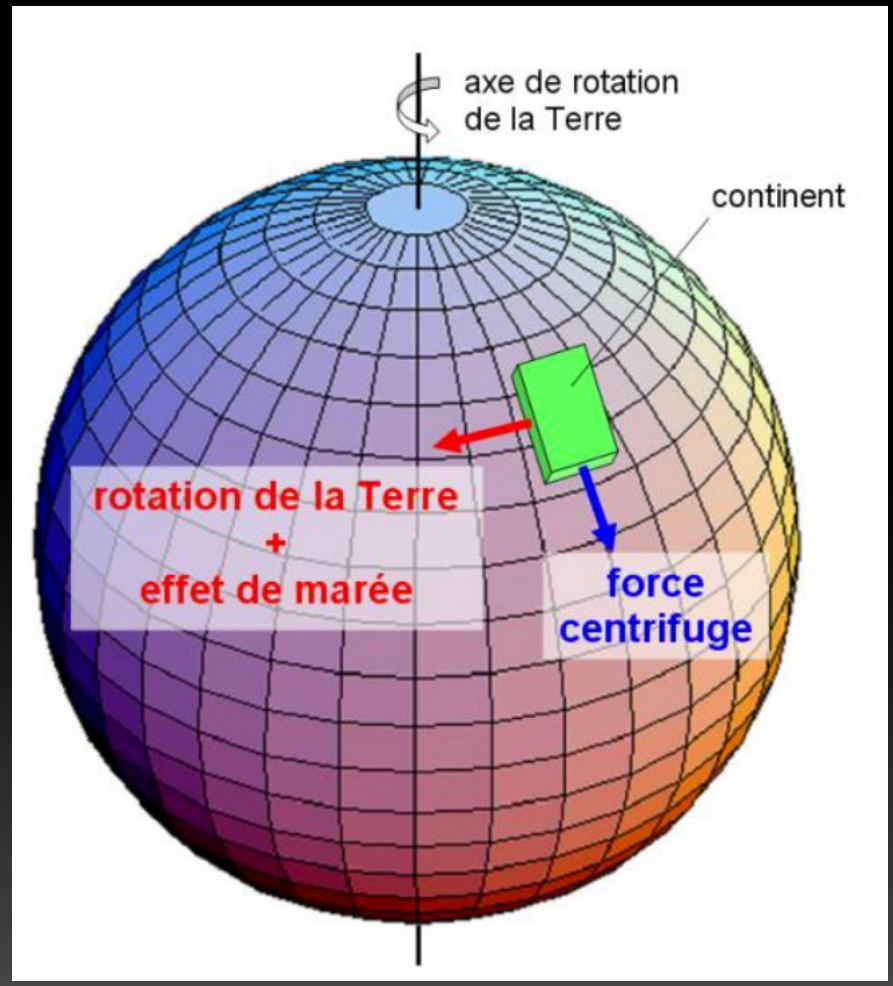


Fig. 2. Schnitt im grössten Kreise durch Südamerika und Afrika, in getrennten Grösseverhältnissen.

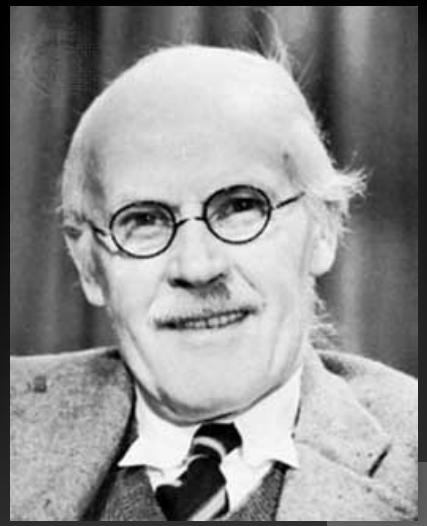
Oceanic rocks are different from continental rocks. Continents(**sial**) drift over the solid mantle (**sima**)
⇒ **Isostasy**



The **centrifugal force** (linked to Earth's rotation) would induce a **drift of continents towards the equator** and the combined action of **the Earth's rotation** and **the tidal force** would induce a **drift of continents toward the West.**

A BIT OF HISTORY

- … to the theory of plate tectonics



Harold Jeffreys (1891-1989)

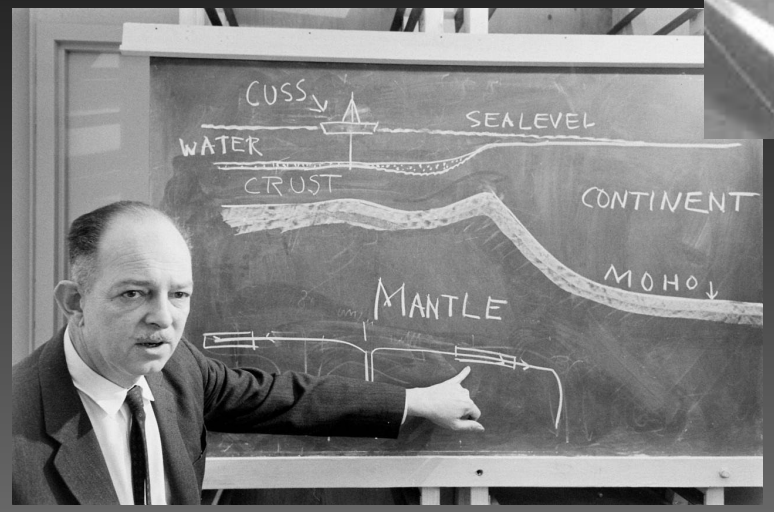
Keith Runcorn (1922-1995)

Marie Tharp (1920-2006)

Tuzo Wilson (1908-1993)

Frederick Vine and Drummond Matthews

Arthur Holmes (1890-1965)



Harry Hess (1906-1969)

… and many more …

A BIT OF HISTORY

- … to the theory of plate tectonics

Xavier Le Pichon

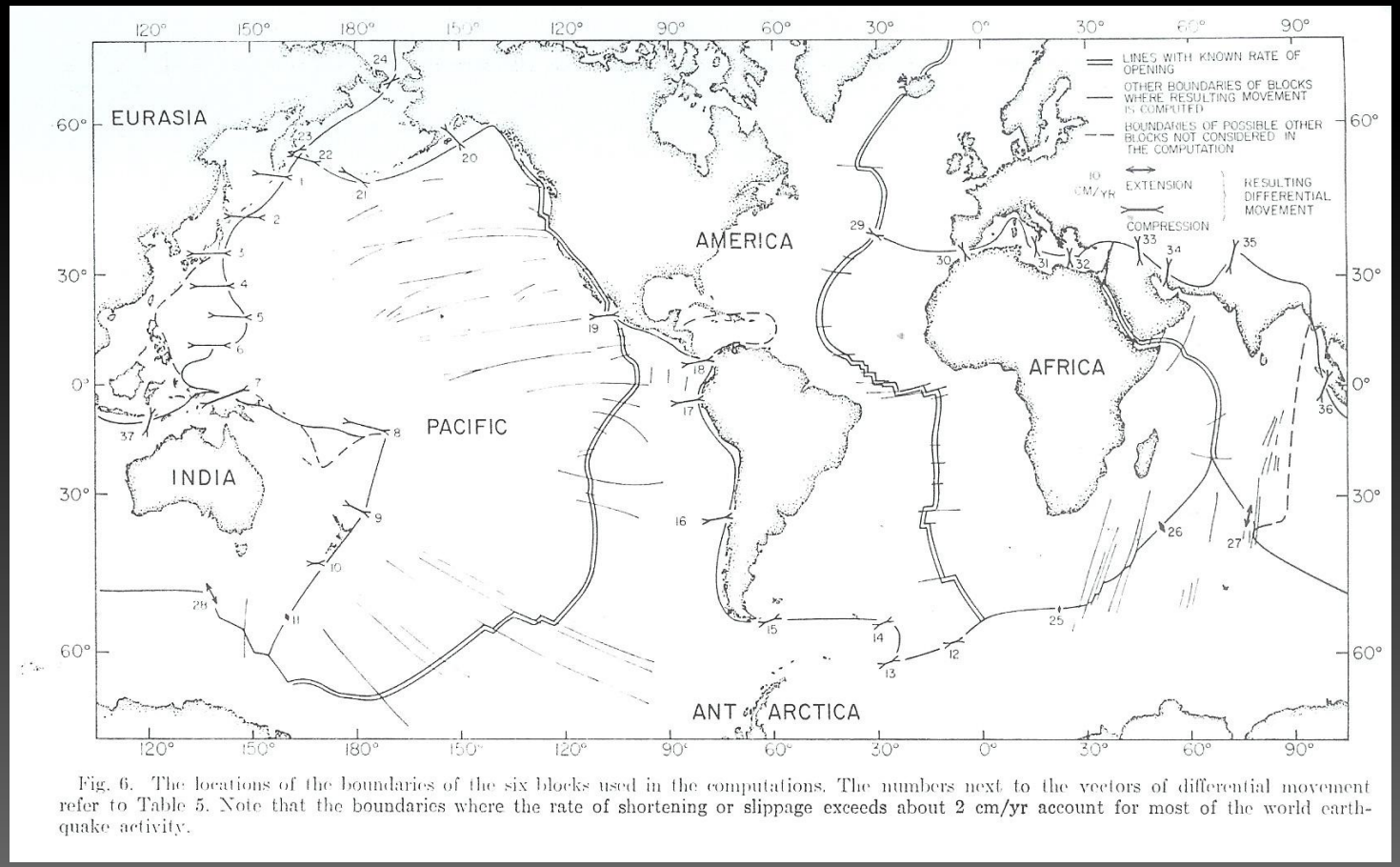
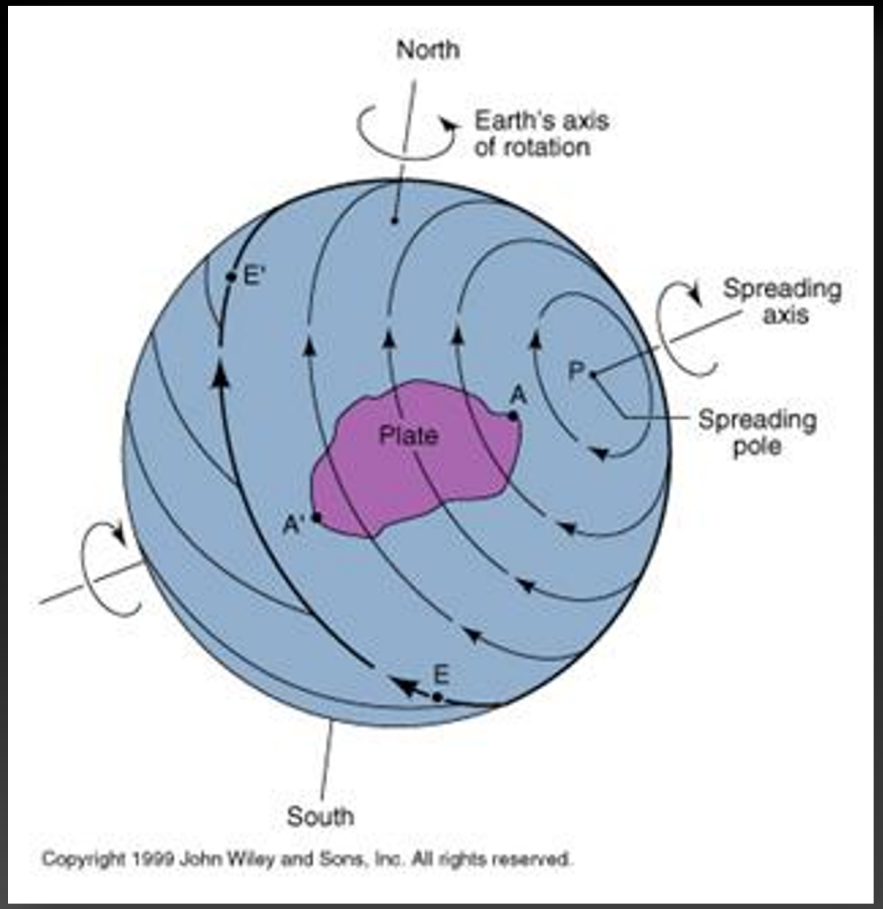


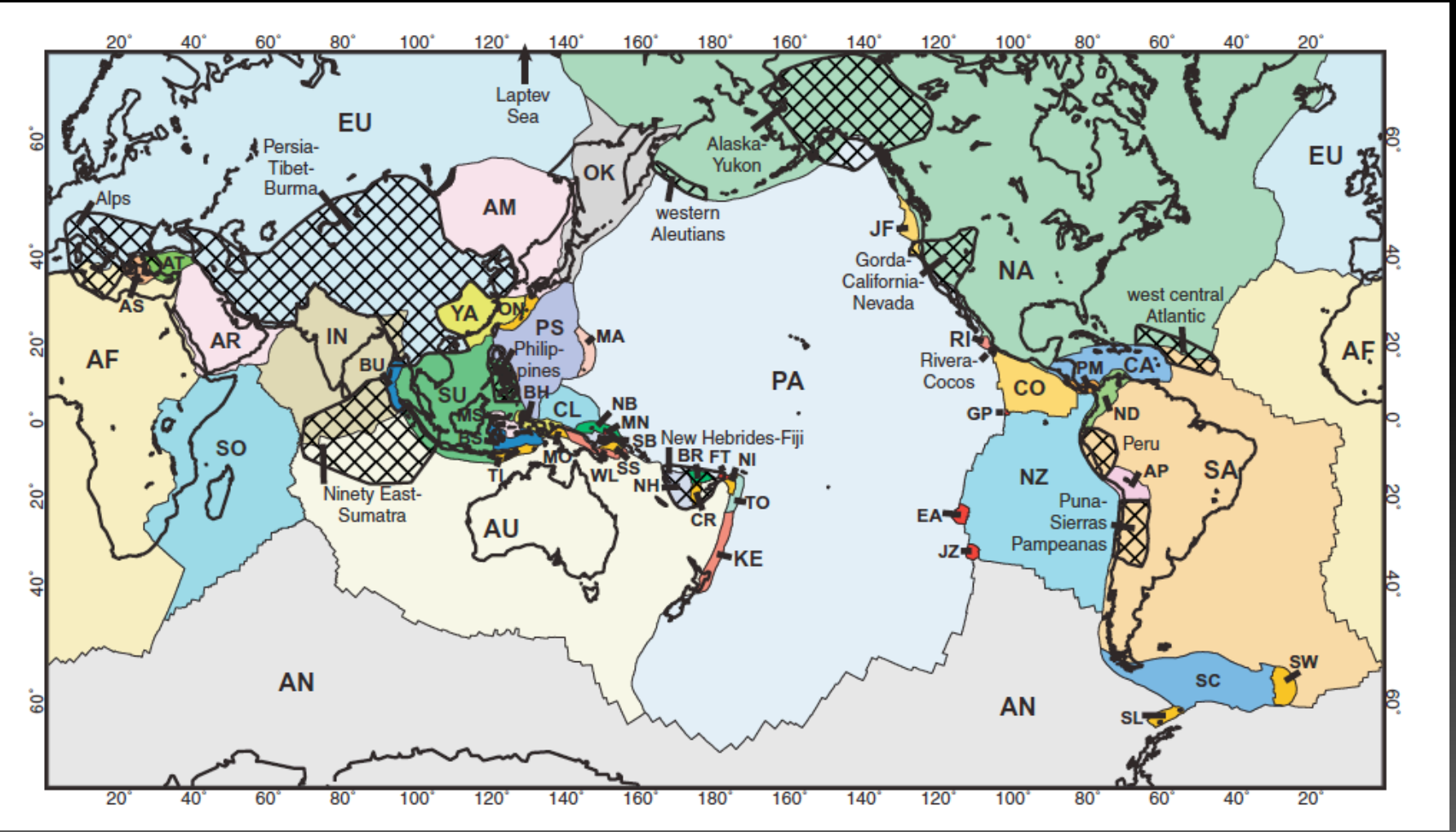
Fig. 6. The locations of the boundaries of the six blocks used in the computations. The numbers next to the vectors of differential movement refer to Table 5. Note that the boundaries where the rate of shortening or slippage exceeds about 2 cm/yr account for most of the world earthquake activity.

Xavier Le Pichon, 1968



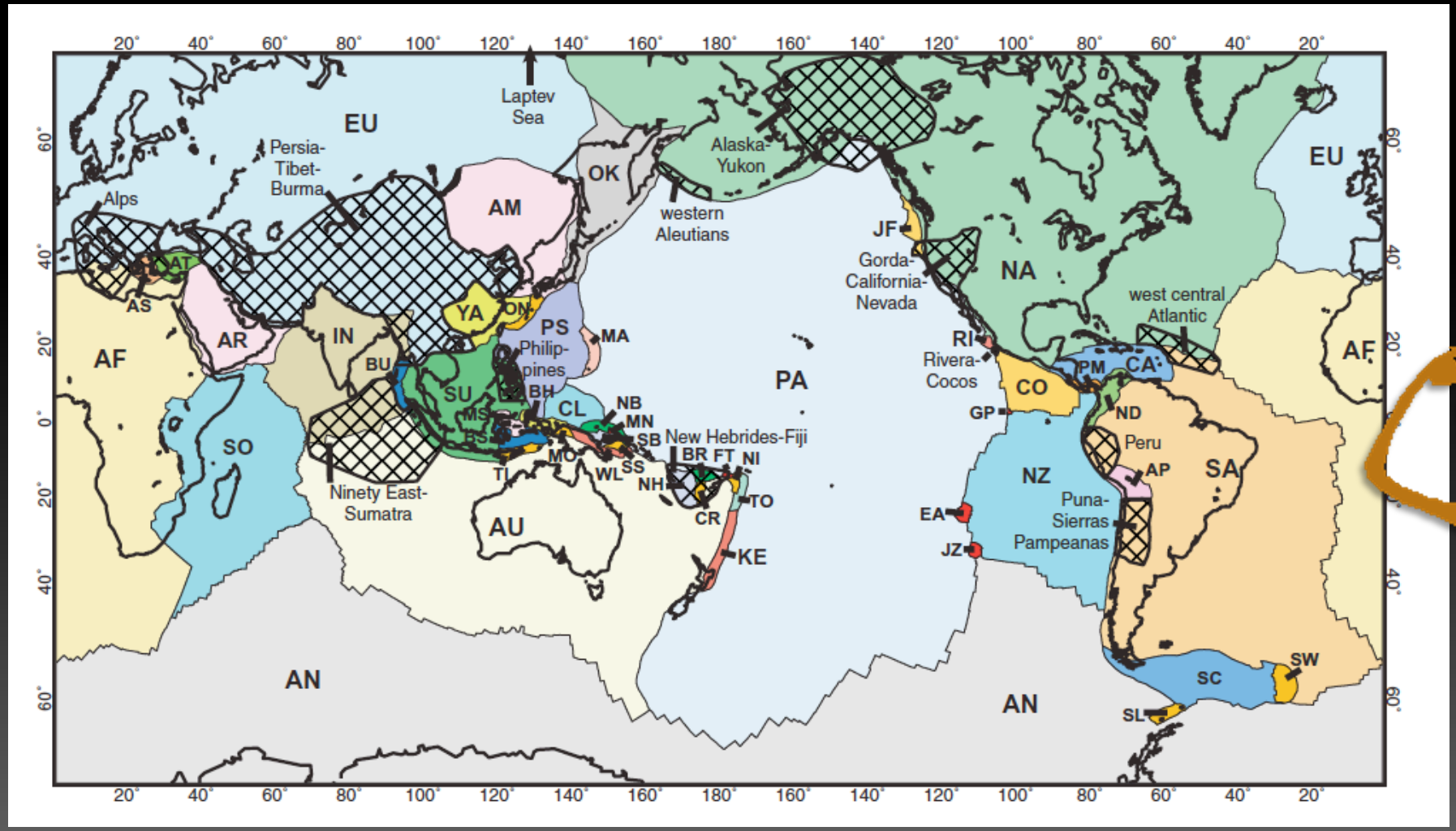
The Euler theorem

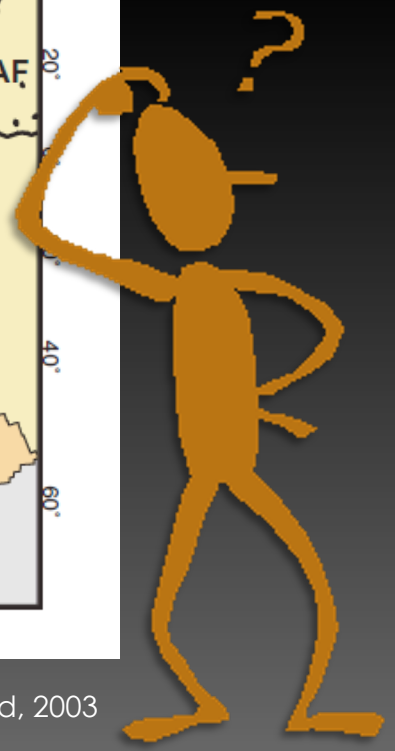
THE PLATE TECTONICS' THEORY TODAY



Bird, 2003

What are the *manifestations* of plate tectonics?

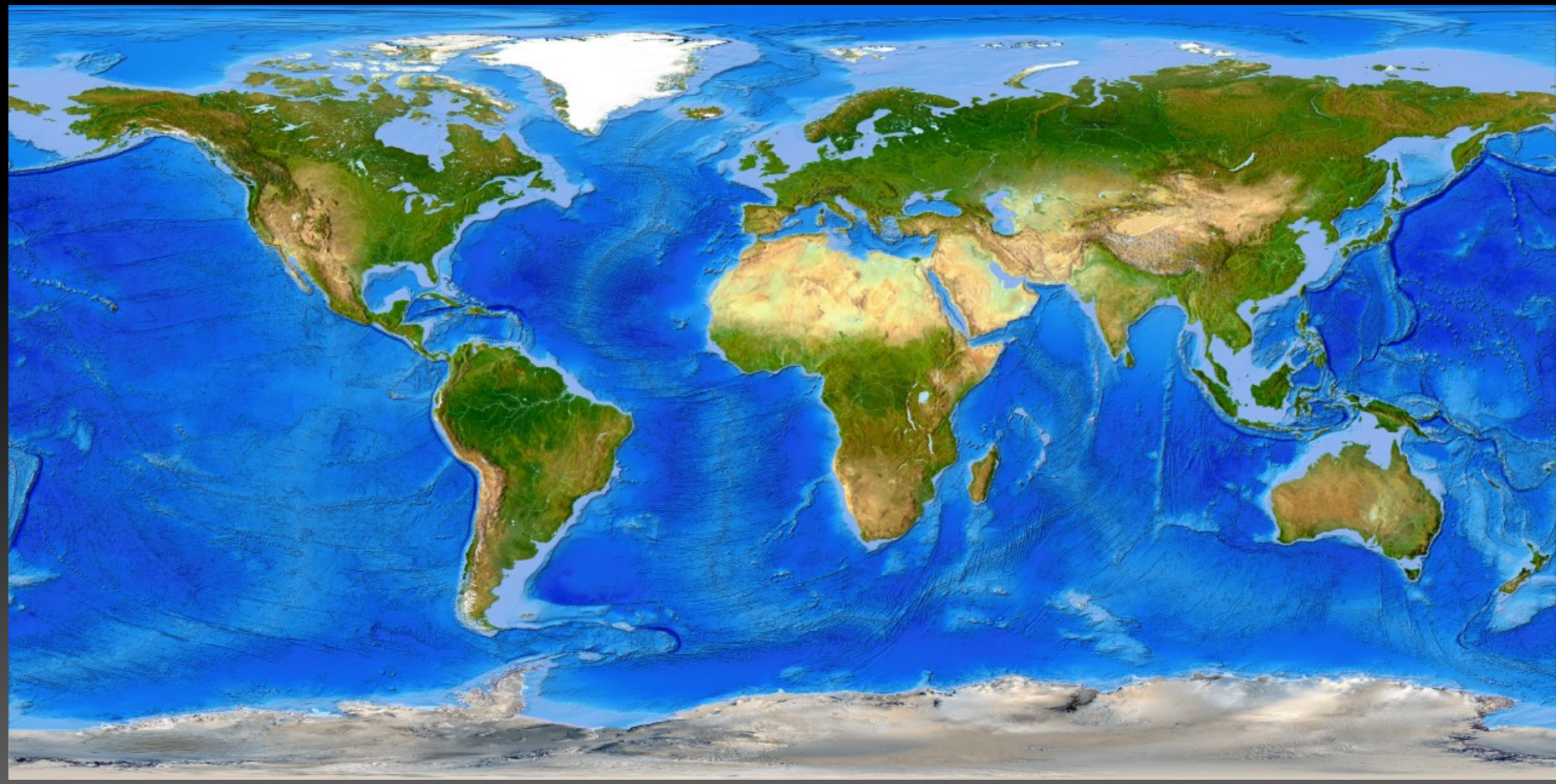




Bird, 2003

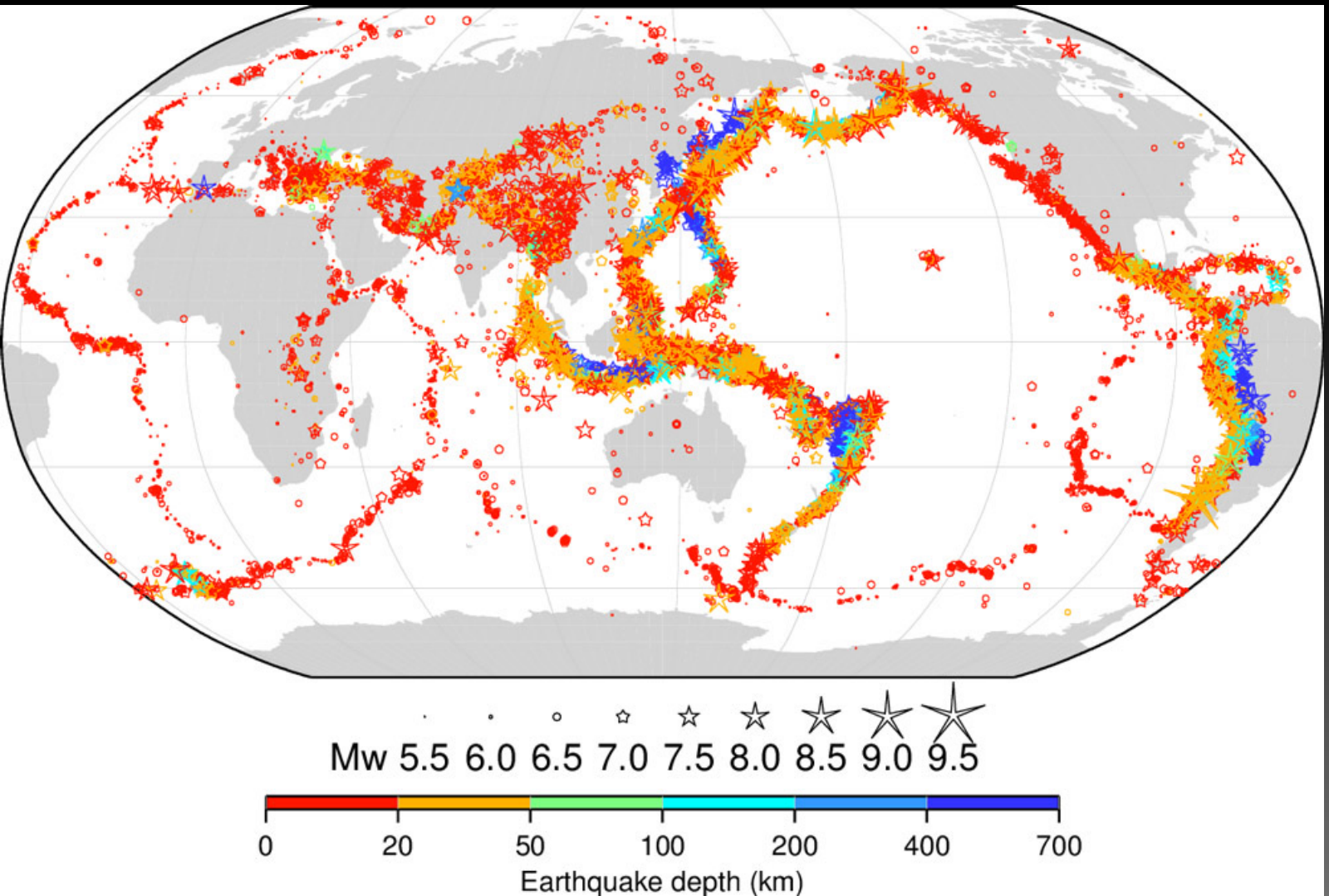
SOME EXAMPLES OF EVIDENCE OF PLATE TECTONICS

Surface topography

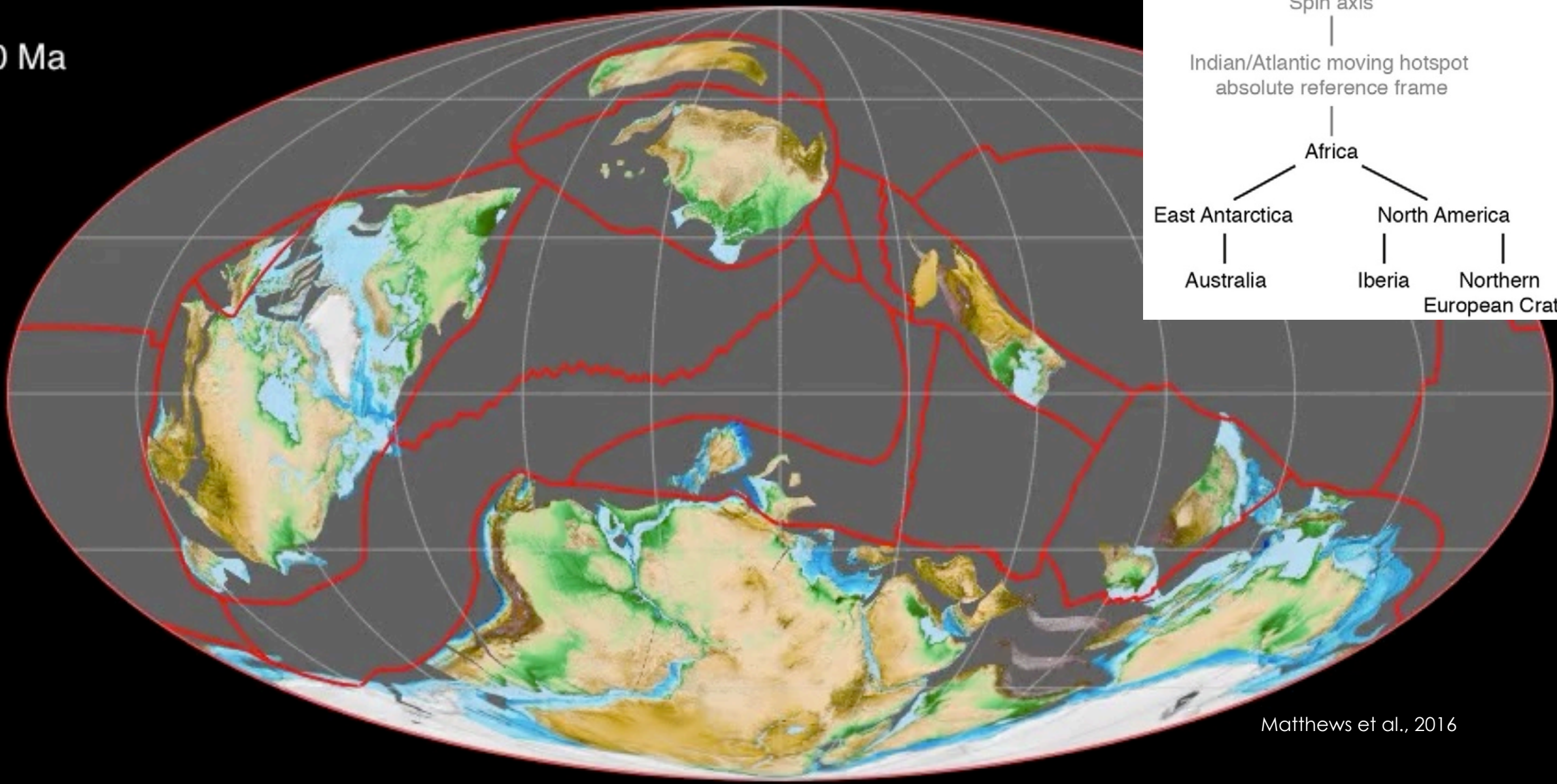


SOME EXAMPLES OF EVIDENCE OF PLATE TECTONICS

World seismicity



ONE EXAMPLE OF APPLICATION OF THE THEORY

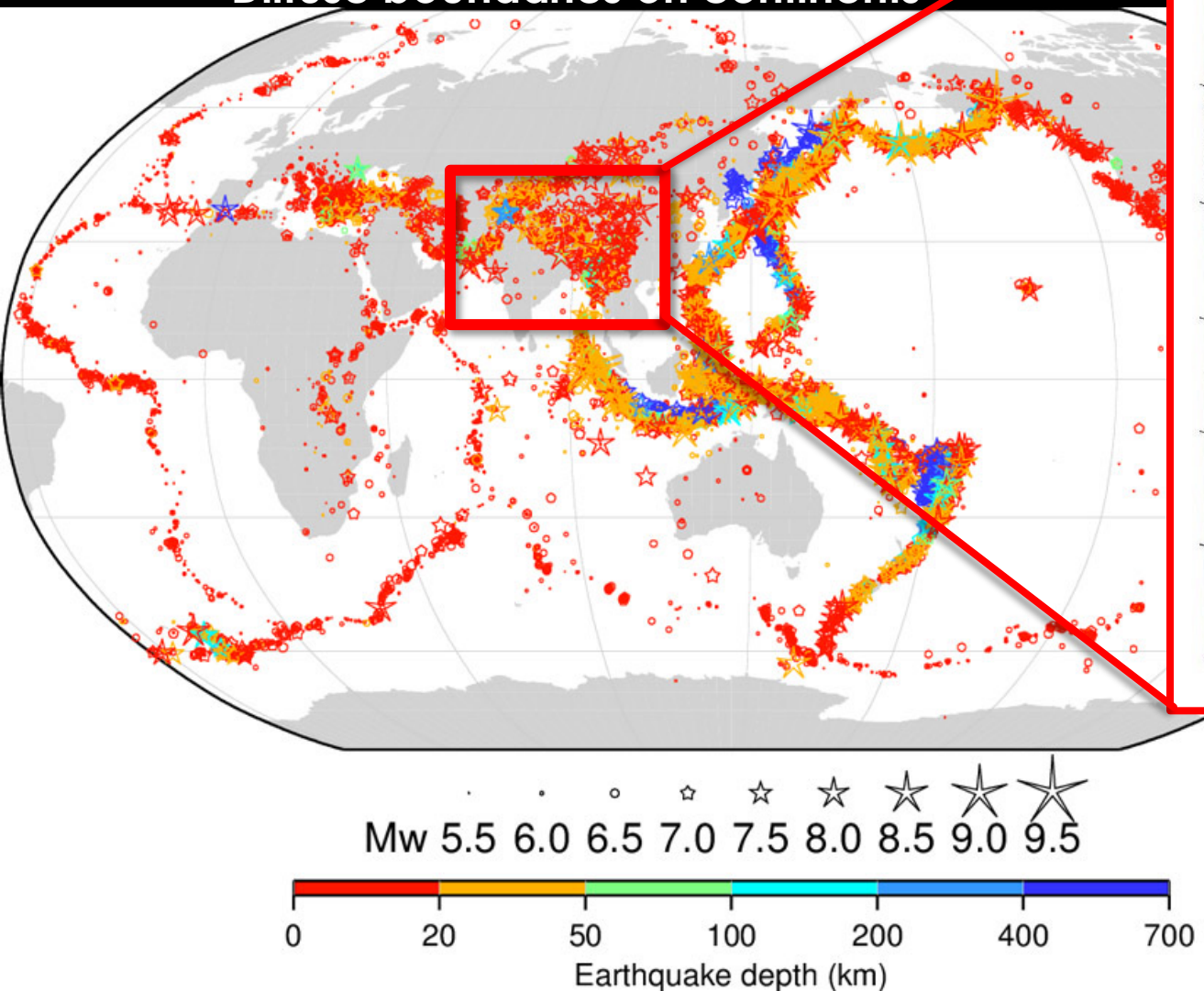


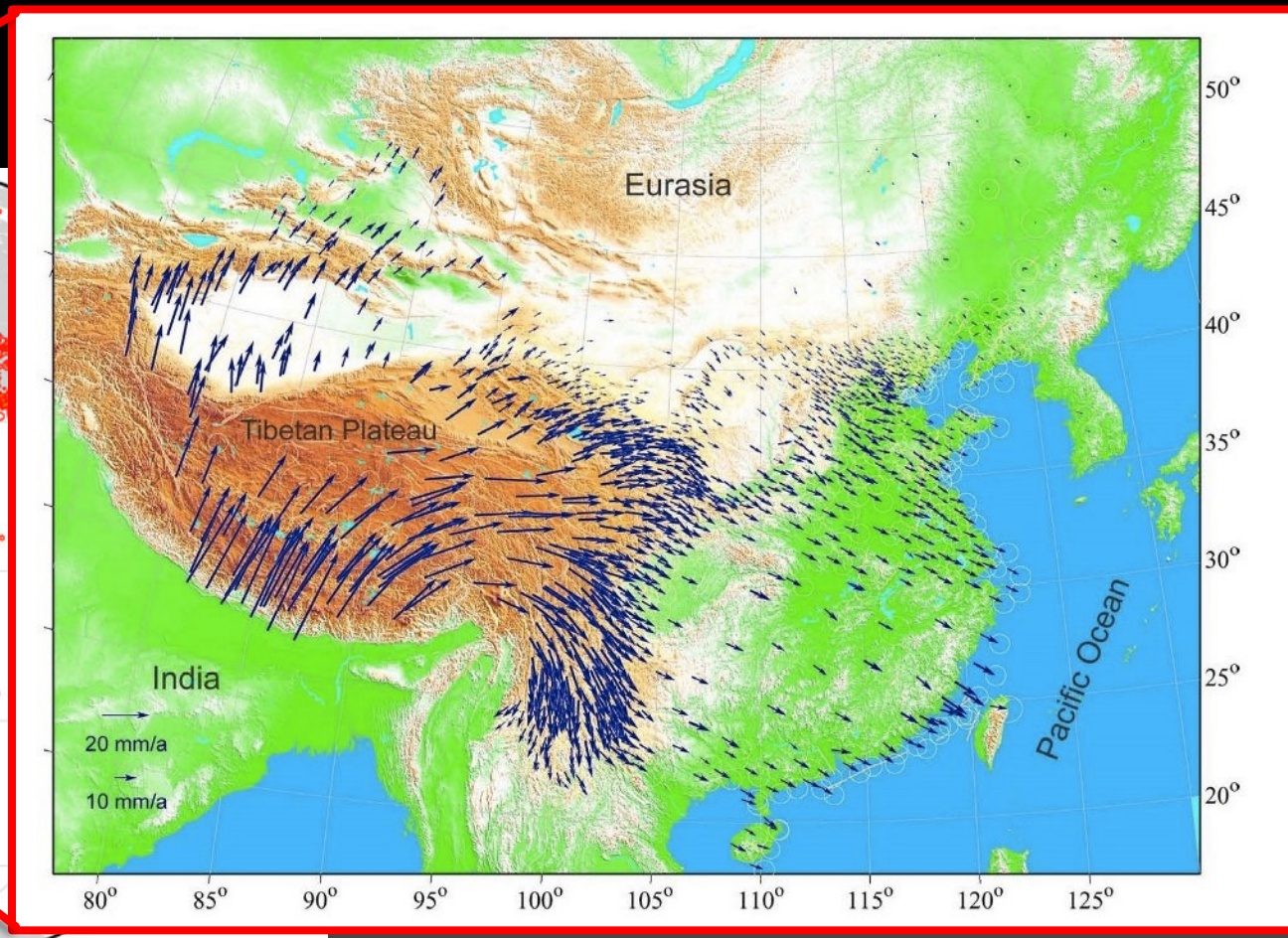
Matthews et al., 2016

What are the limitations of the theory of plate tectonics?

WHERE ARE THE PLATE BOUNDARIES?

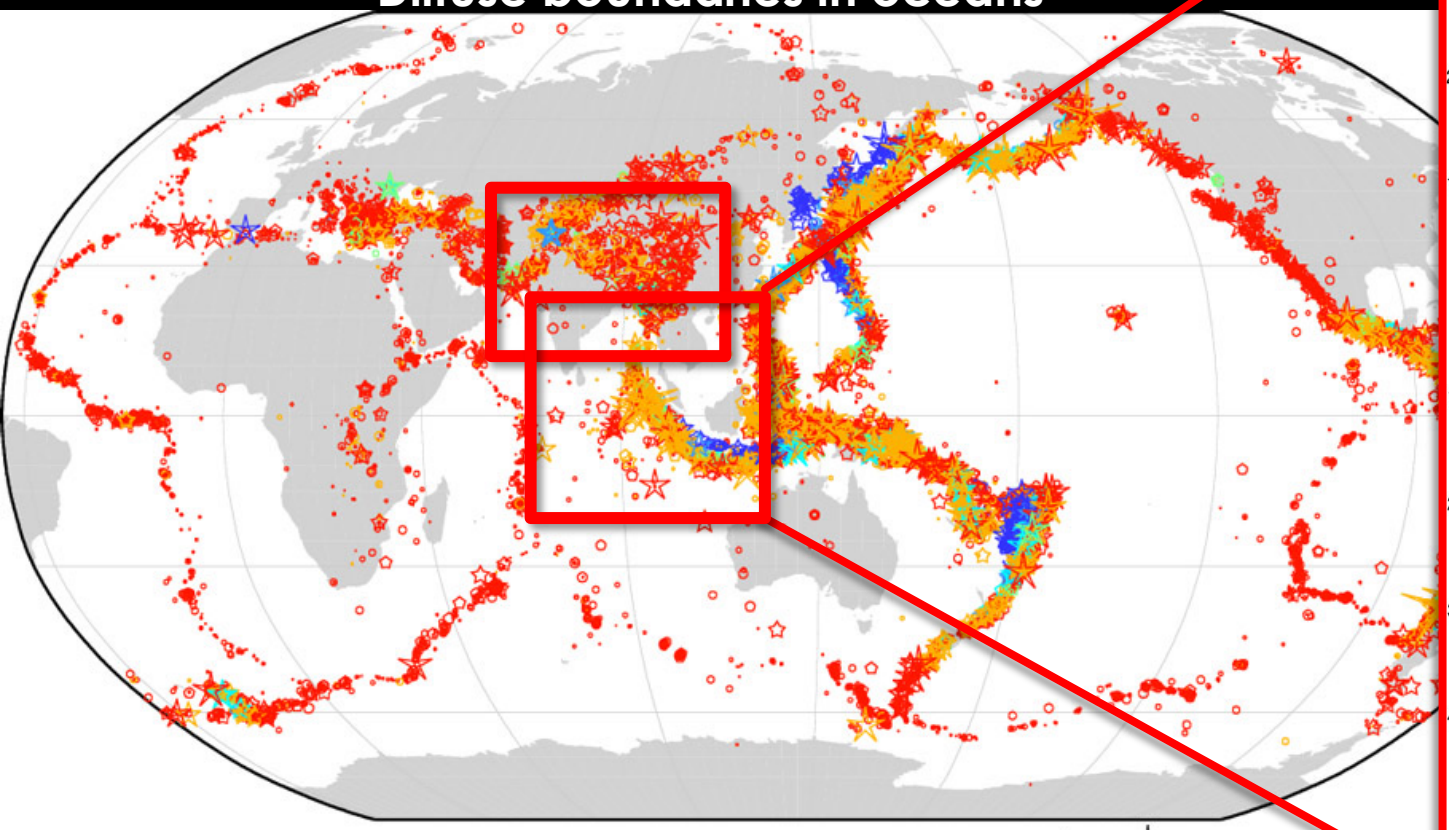
Diffuse boundaries on continents

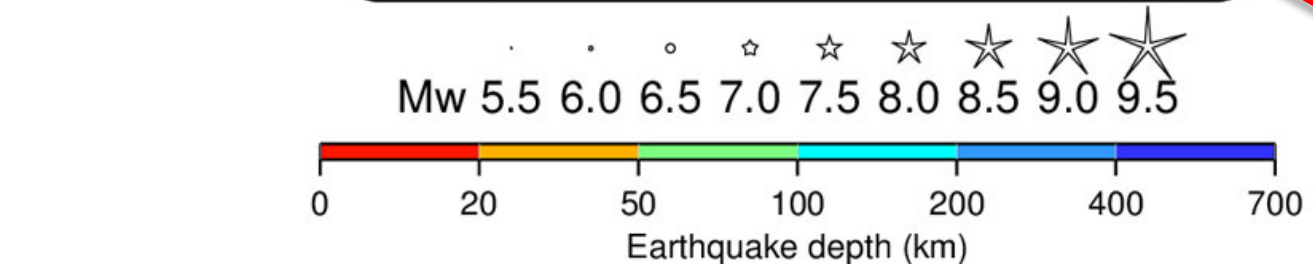


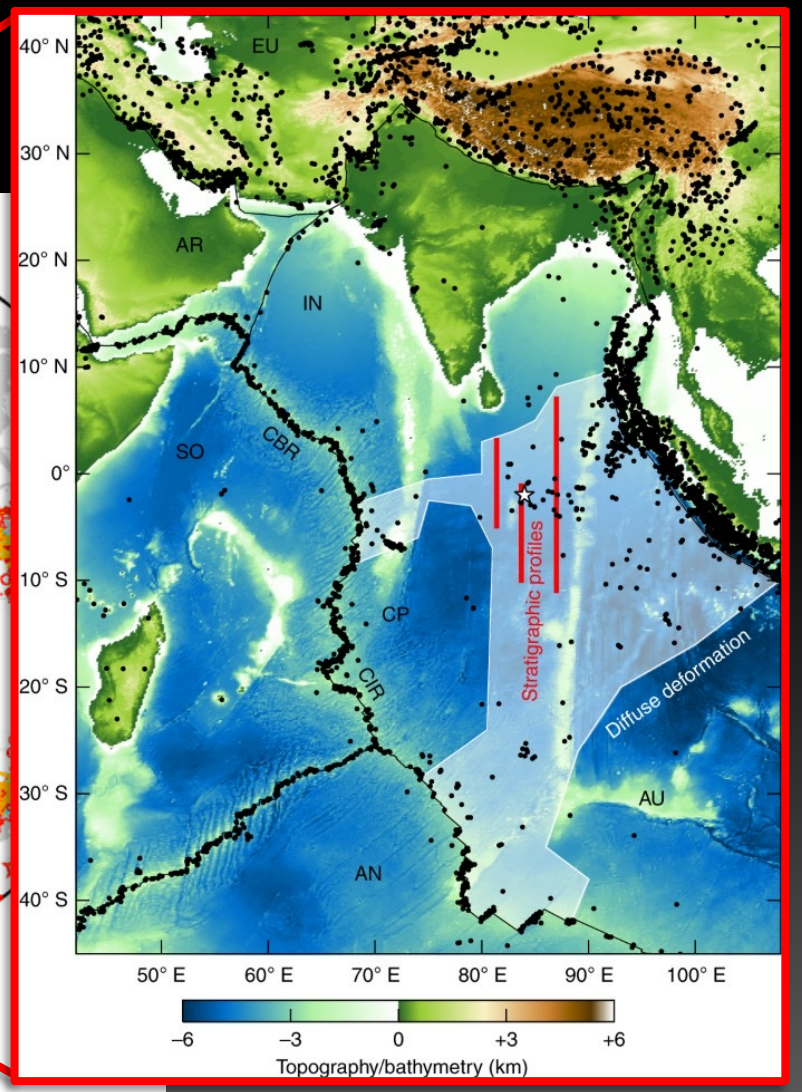


WHERE ARE THE PLATE BOUNDARIES?

Diffuse boundaries in oceans



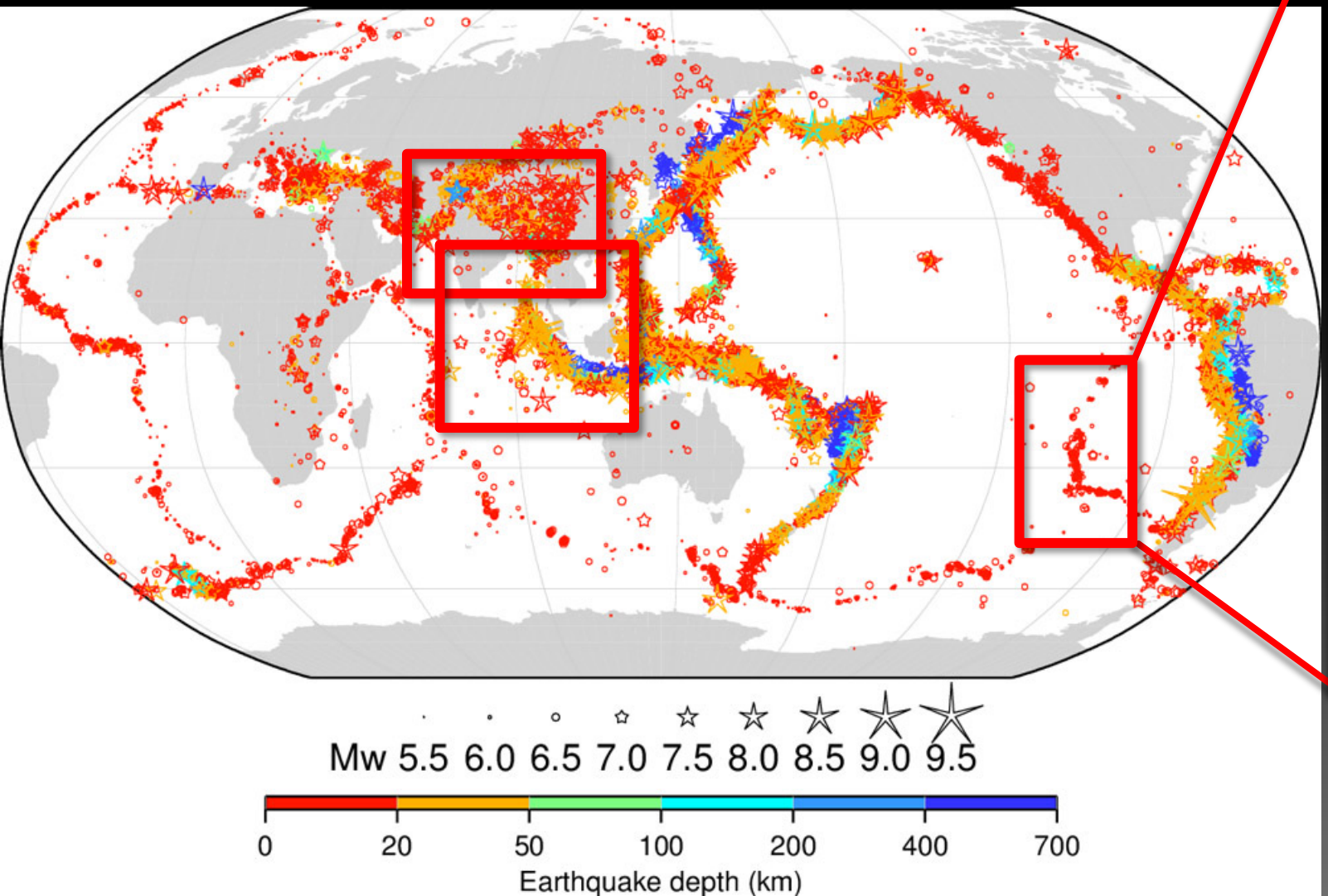


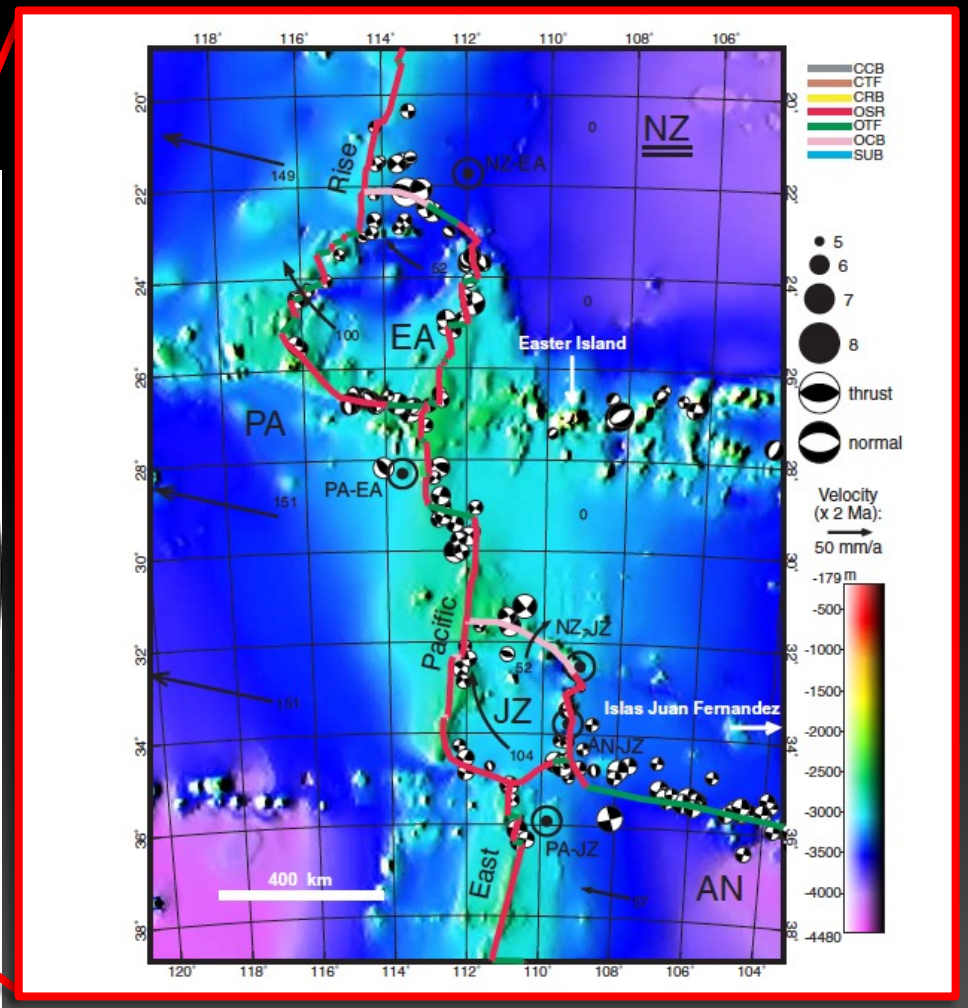


Iaffaldano et al., , 2018

WHERE ARE THE PLATE BOUNDARIES?

Microplates



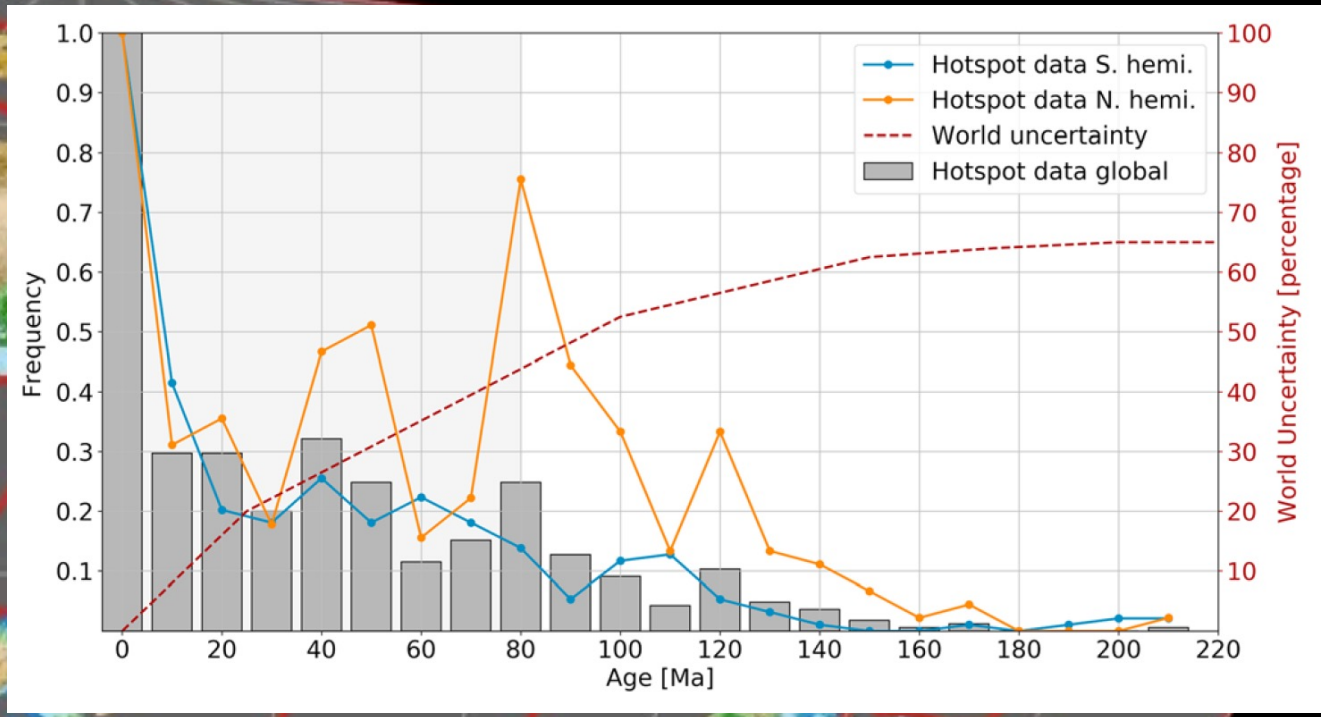


Bird, 2003

RECONSTRUCTING PAST PLATE TECTONIC MOTIONS

Tetley et al., 2019

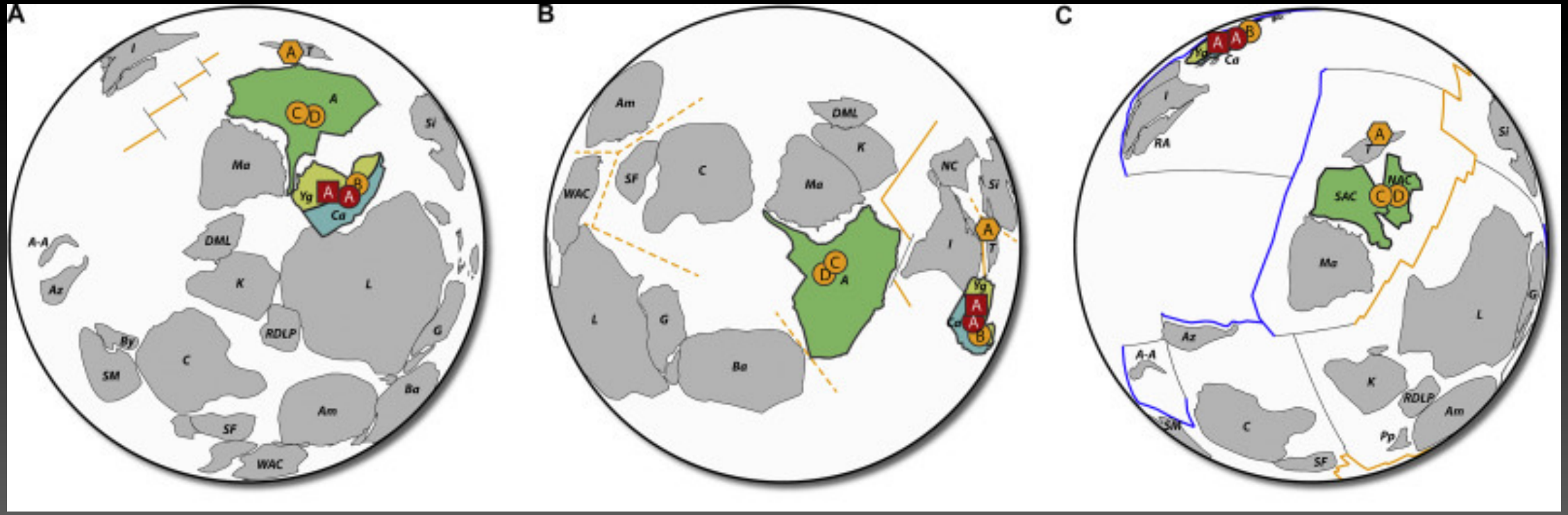
410 Ma



Matthews et al., 2016

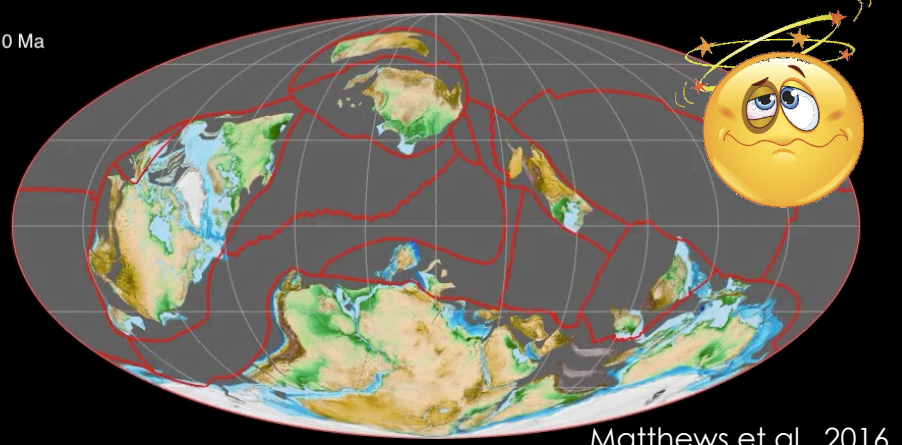
RECONSTRUCTING PAST PLATE TECTONIC MOTIONS

Comparison of 3 models of tectonic recontructions of the position of continents 780 Ma ago

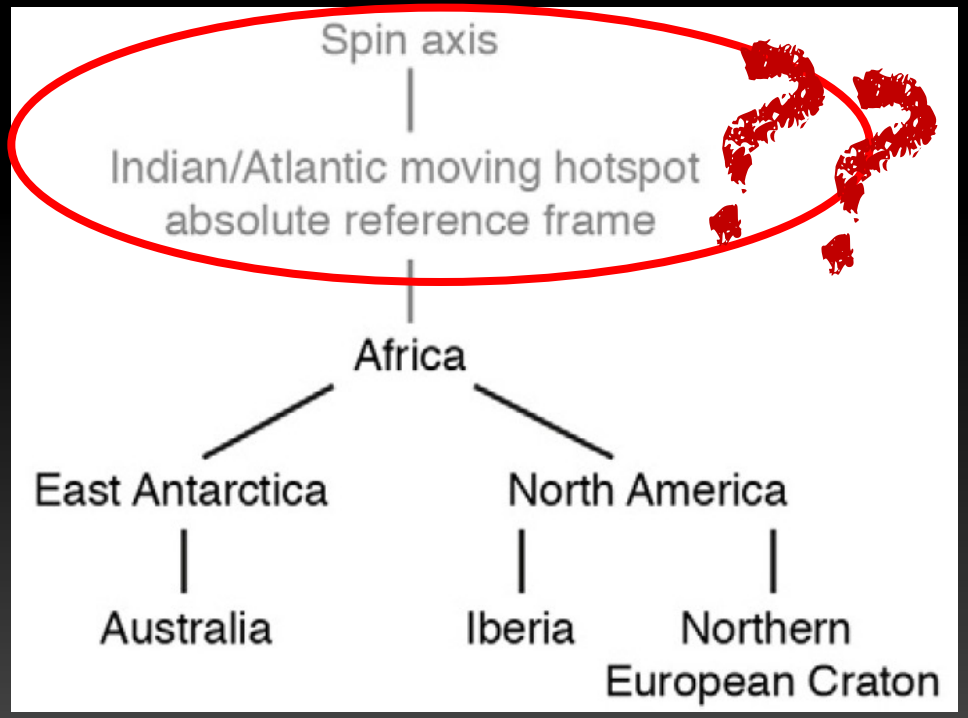


Tetley et al., 2019

MOVING PLATES RELATIVE TO… WHAT?



Matthews et al., 2016



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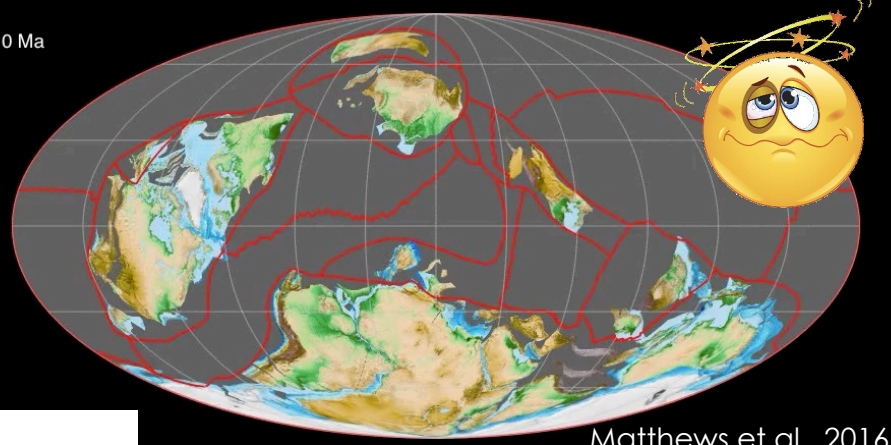
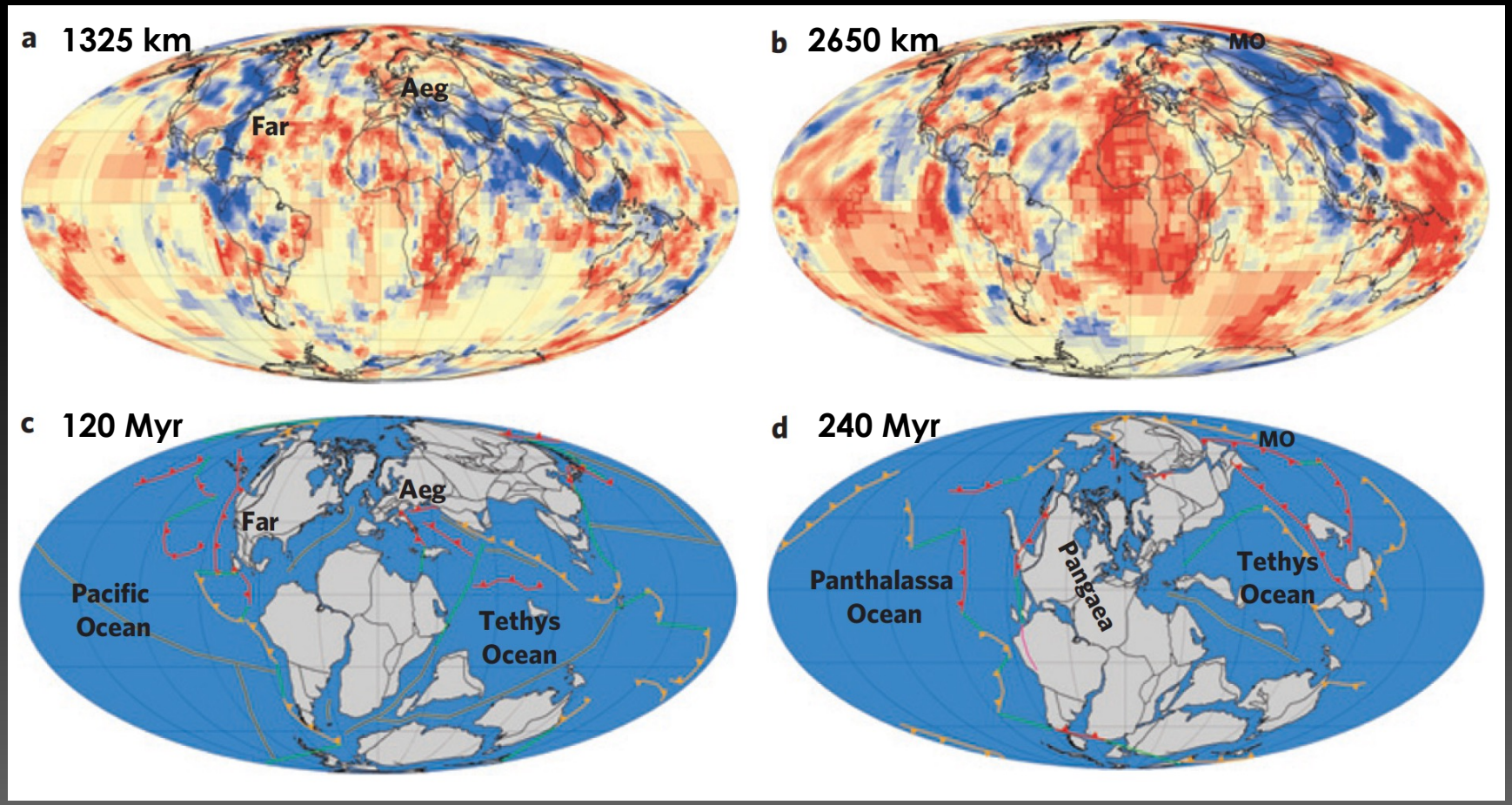


Matthews et al., 2016

- **Use of lower-mantle slab remnants?**



Van der Meer et al., 2010

MOVING PLATES RELATIVE TO… WHAT?

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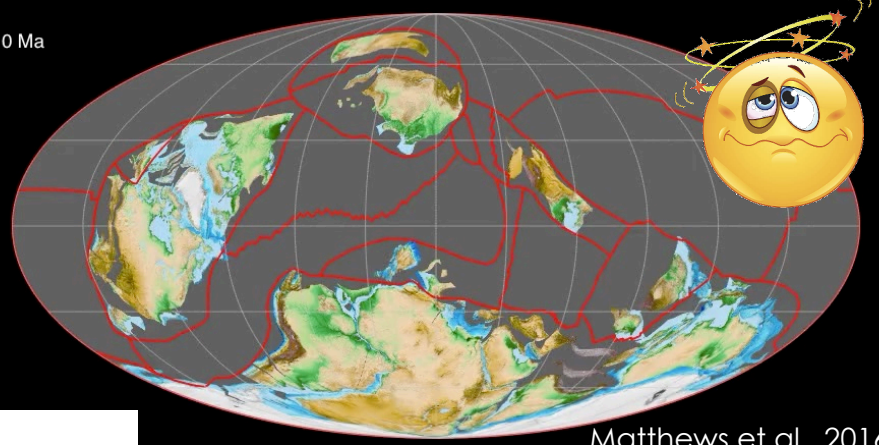
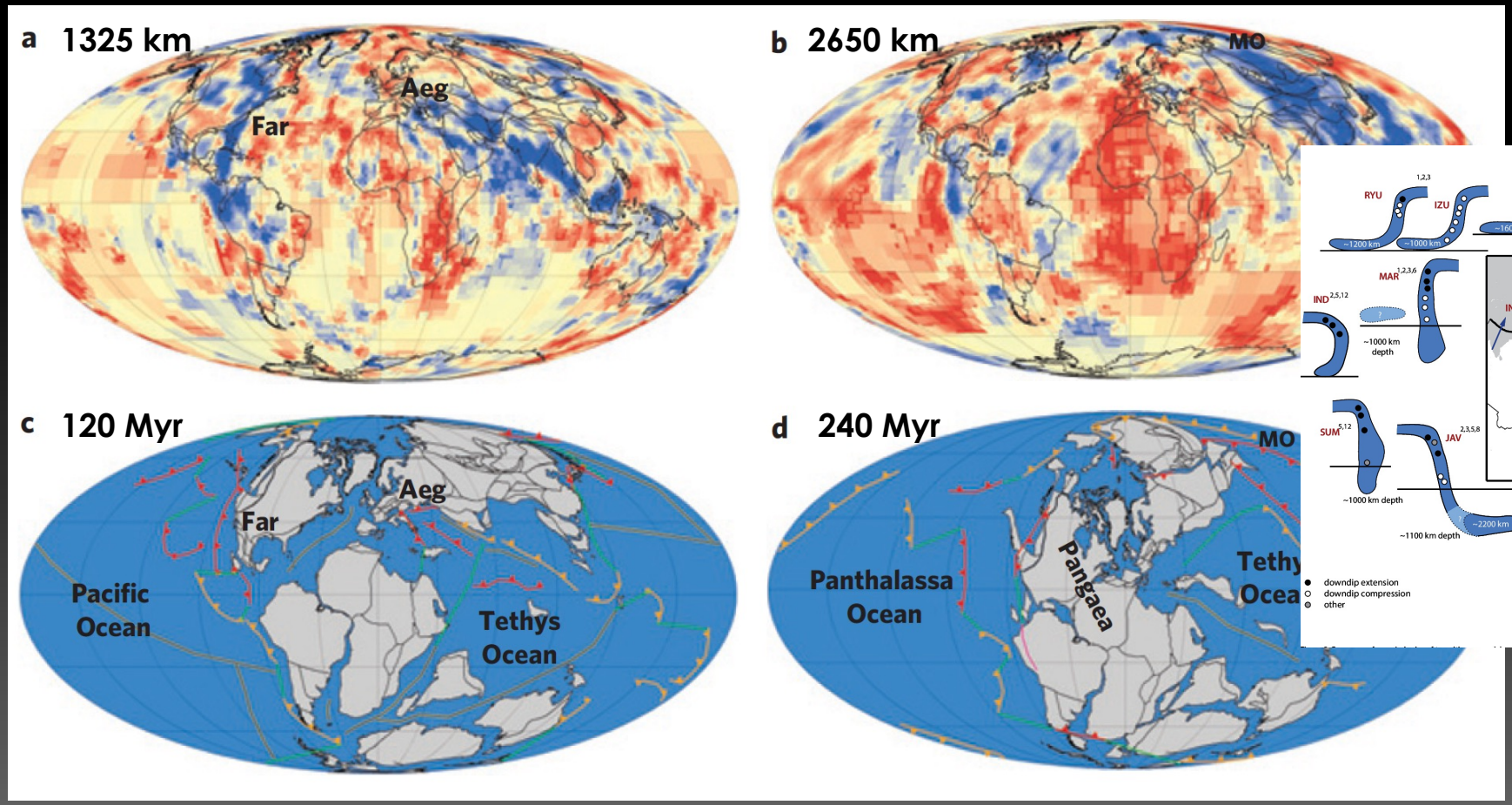
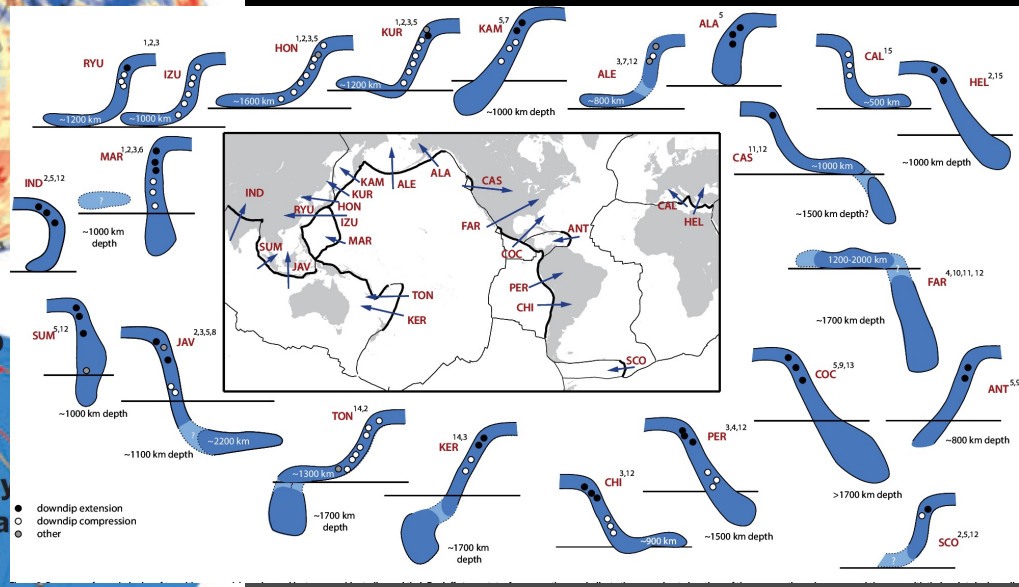


Matthews et al., 2016



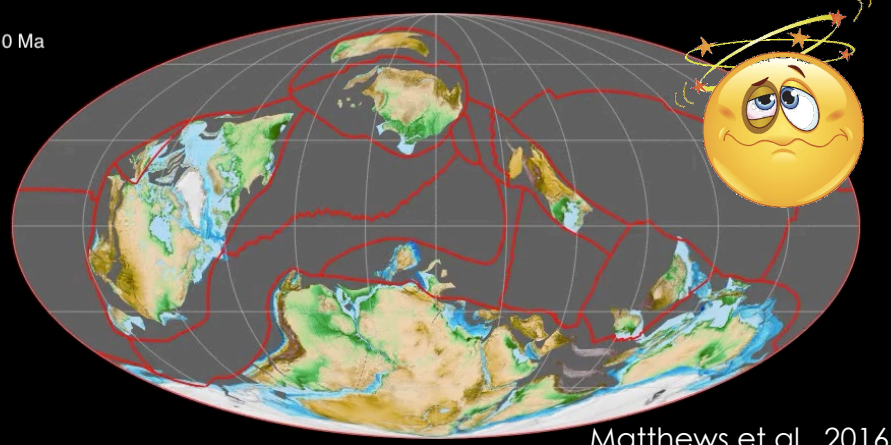


Goes et al., 2017

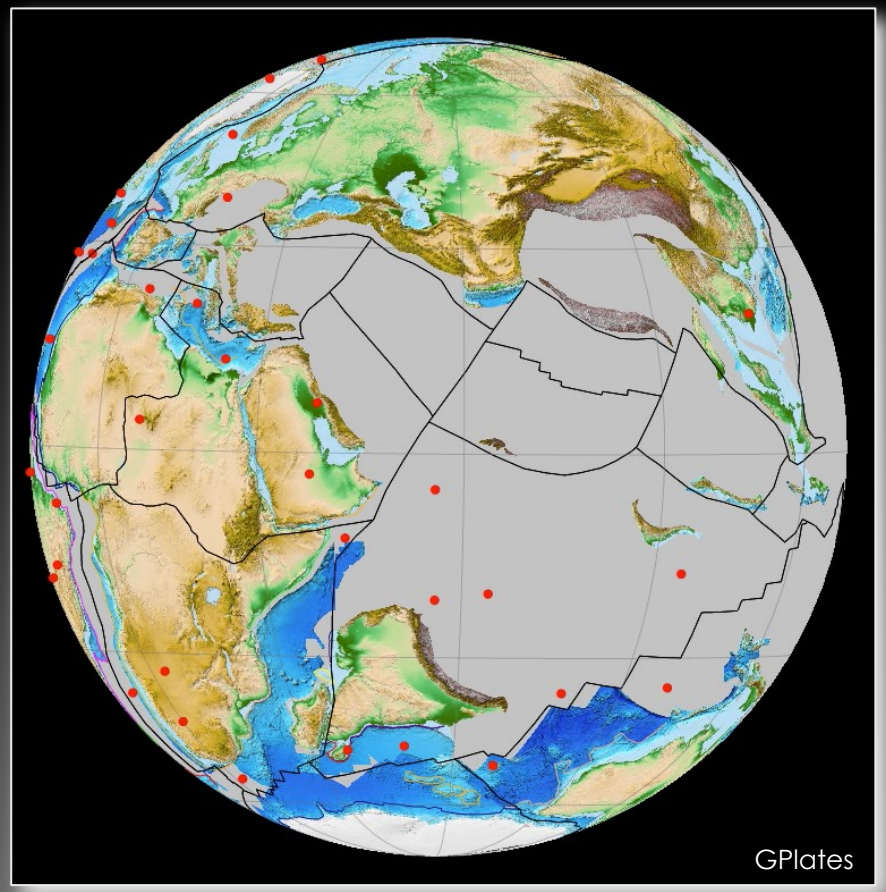
Van der Meer et al., 2010

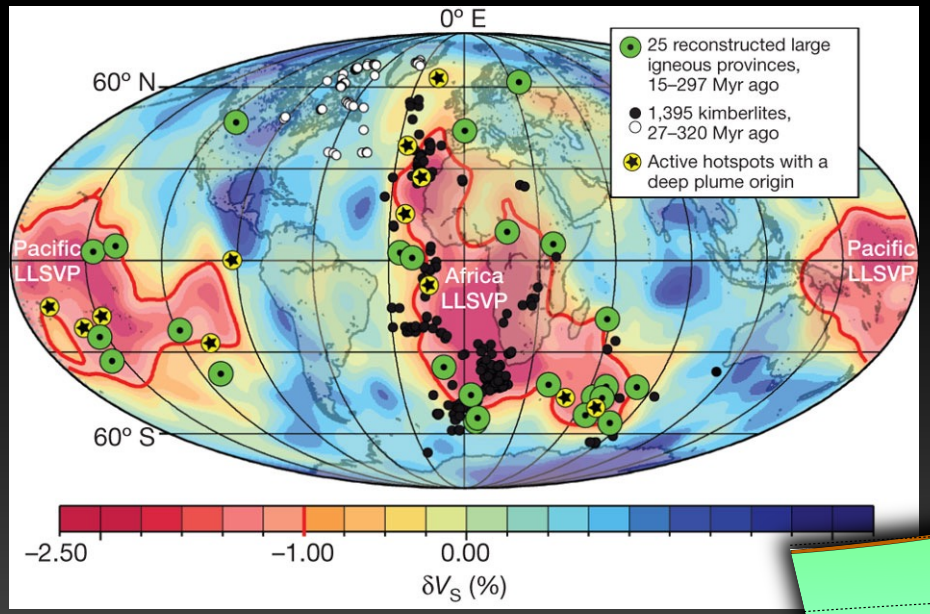
MOVING PLATES RELATIVE TO… WHAT?

- **Fixed mantle plumes?**

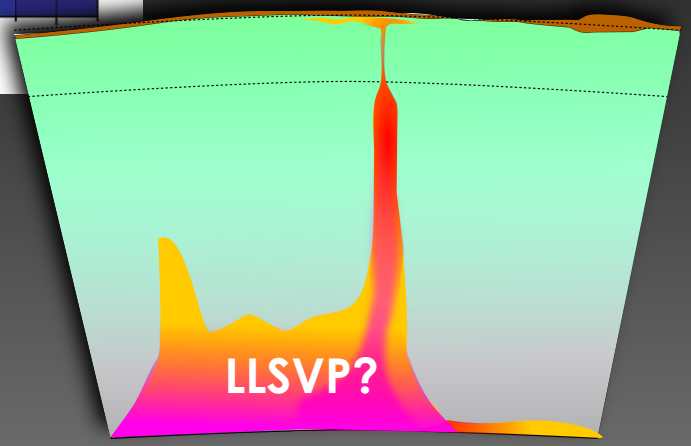


Matthews et al., 2016

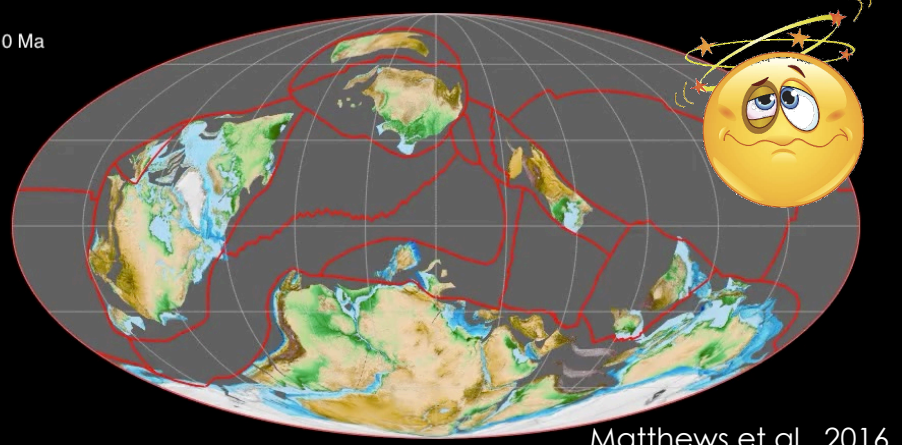




Torsvik et al., 2010

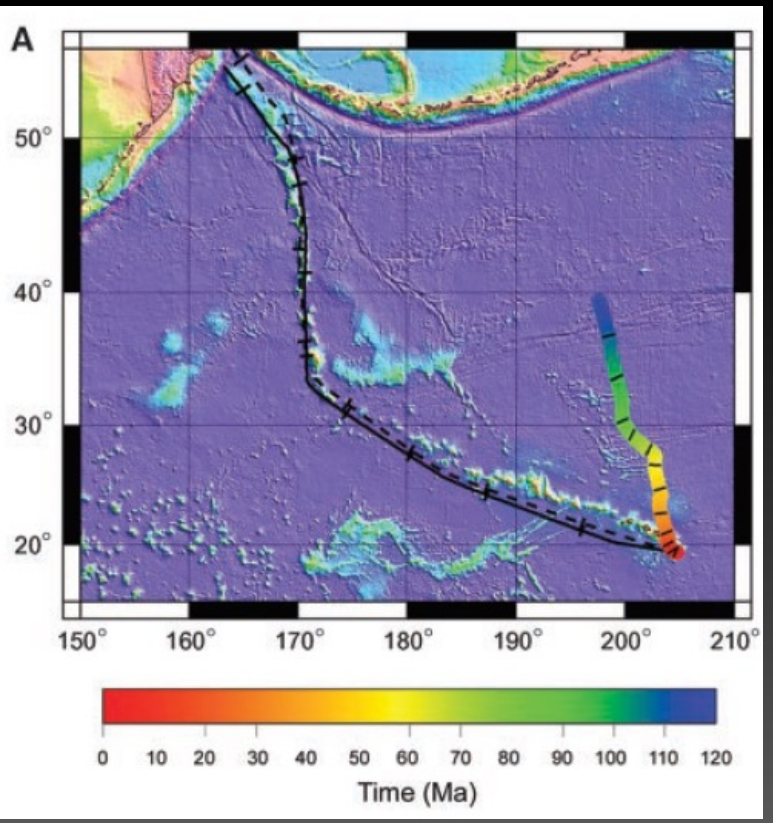


MOVING PLATES RELATIVE TO… WHAT?



Matthews et al., 2016

- **Is everything moving?**



Tarduno et al., 2003

Moving plumes?

MOVING PLATES RELATIVE TO… WHAT?

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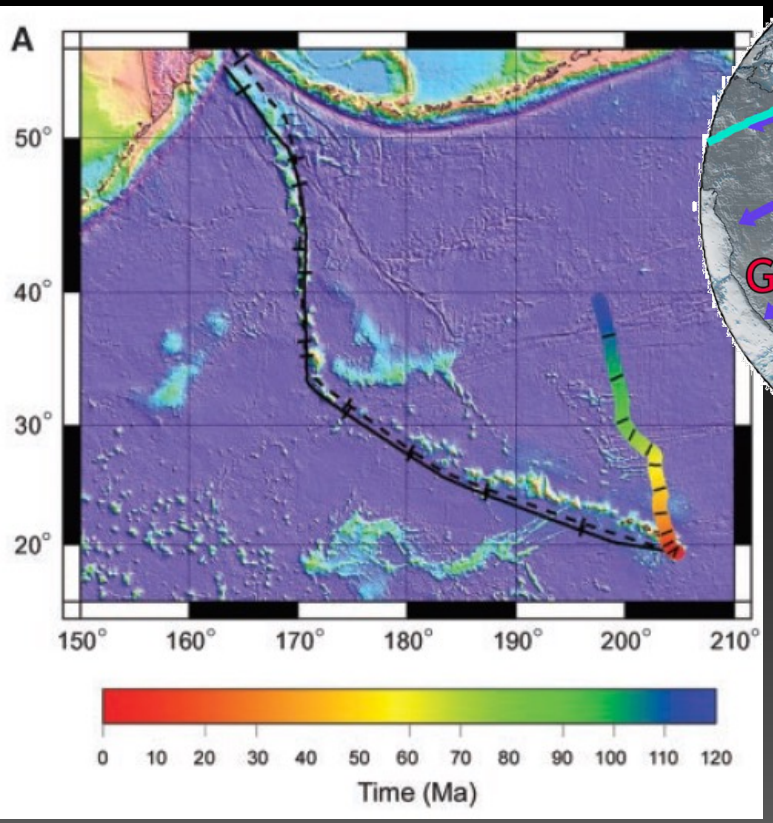

Tarduno et al., 2003

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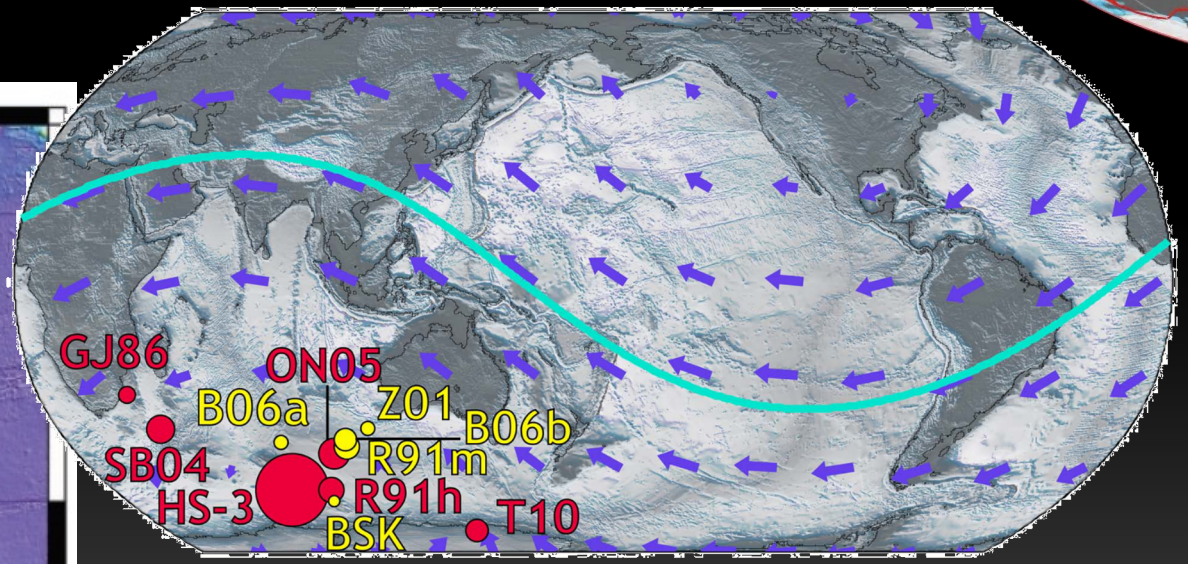
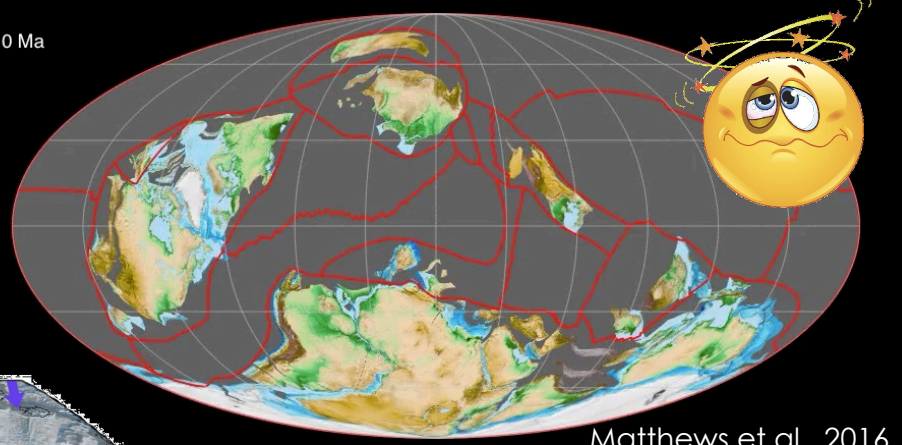


Gérault et al., 2012

Net rotation?



Matthews et al., 2016

MOVING PLATES RELATIVE TO… WHAT?

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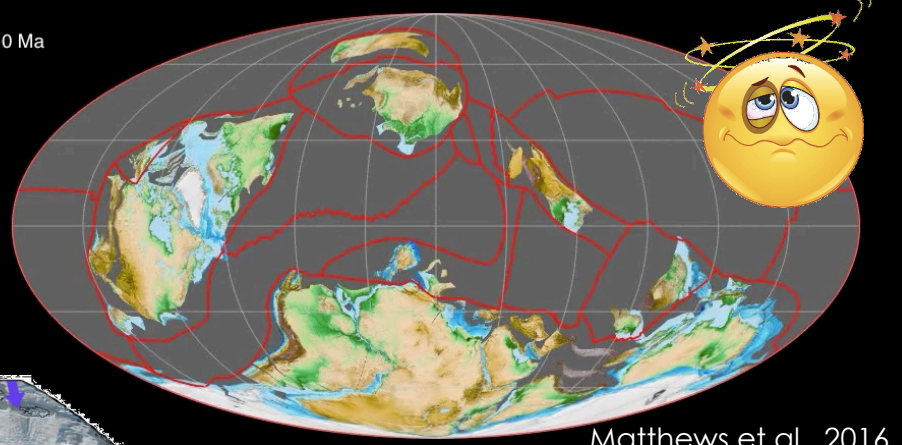
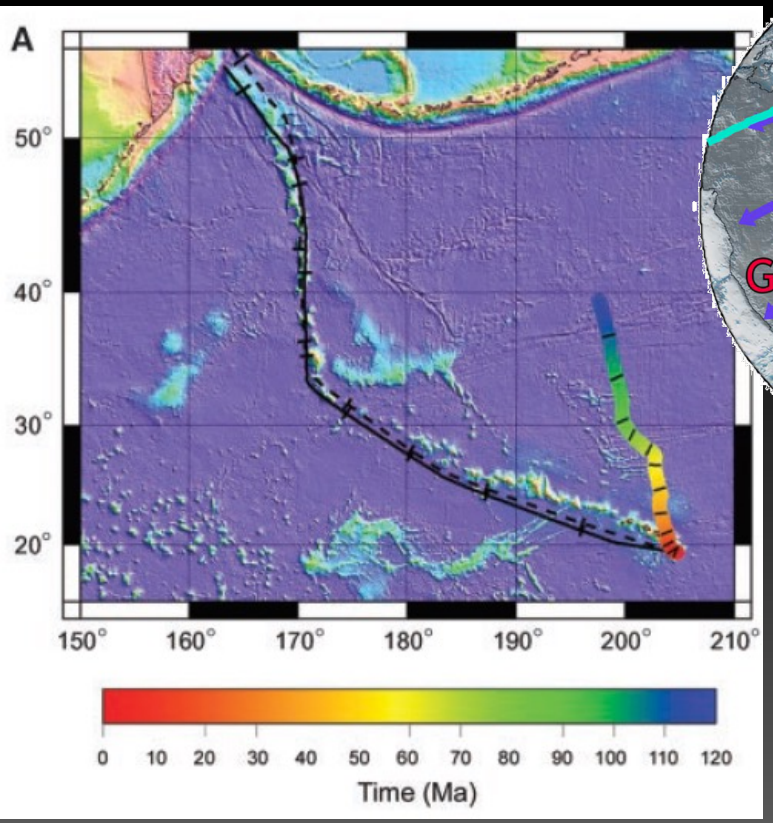


Matthews et al., 2016



Tarduno et al., 2003

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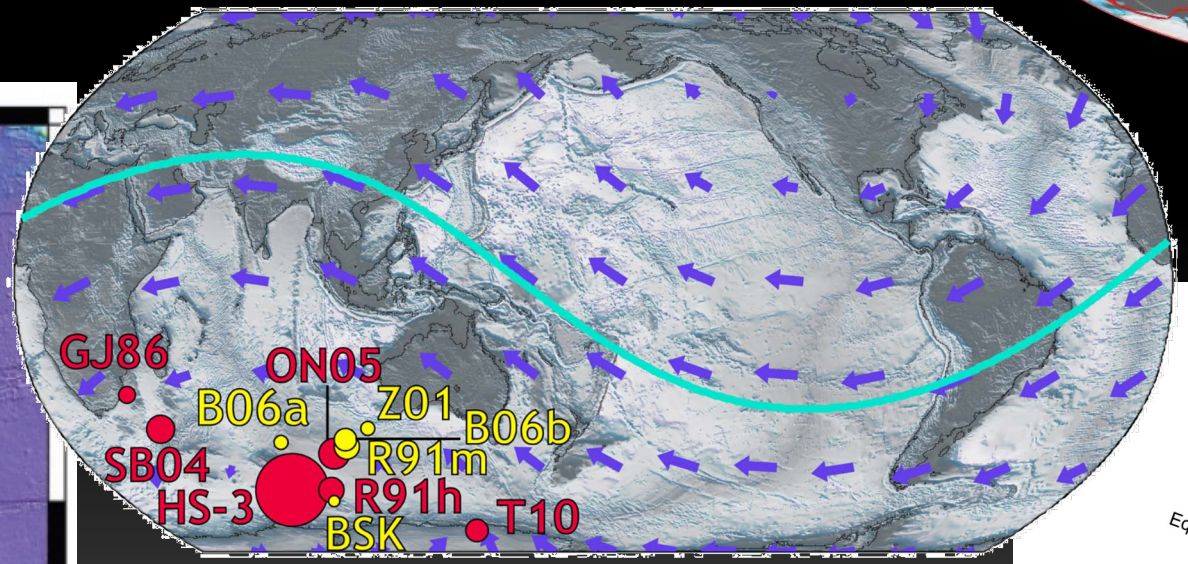

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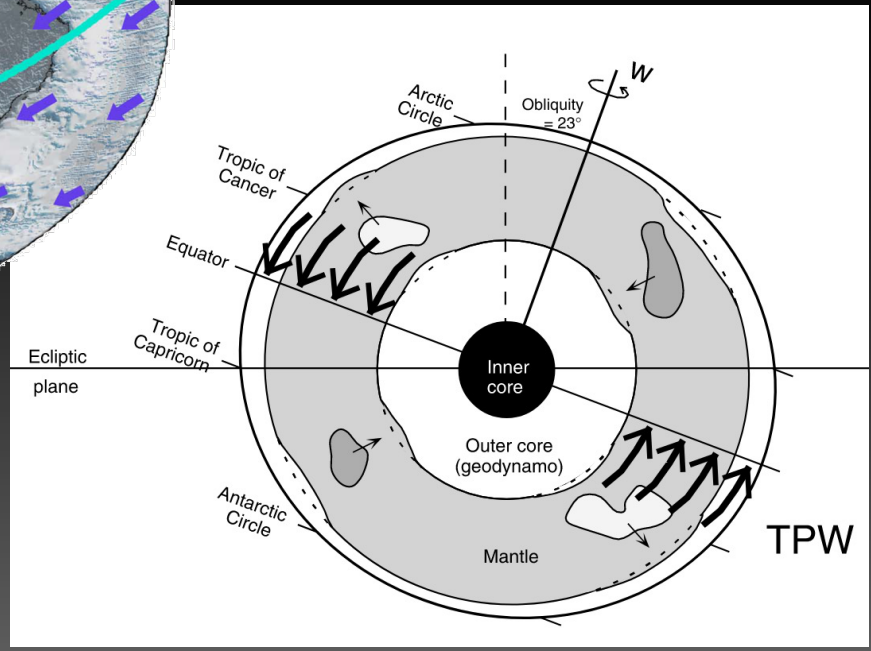
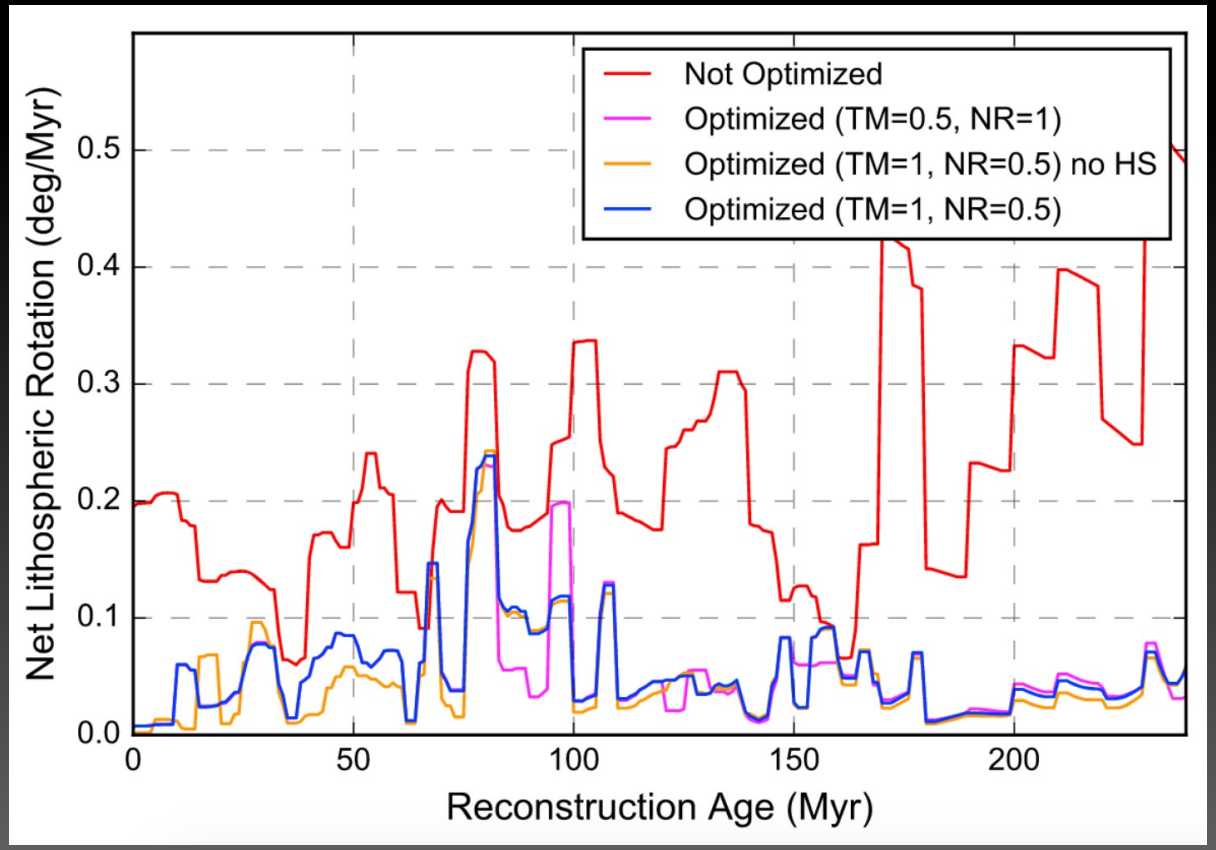


Evans, 2003

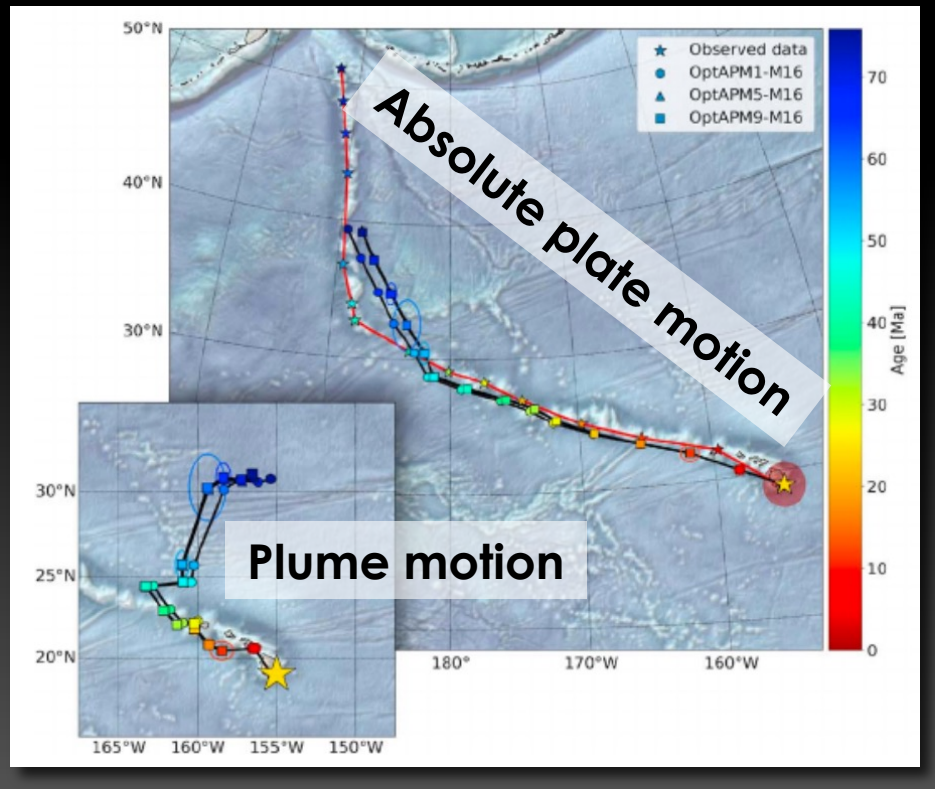
True Polar Wander?

MOVING PLATES RELATIVE TO… WHAT?

- **"Geodynamic" optimization of plate tectonic reconstructions?**

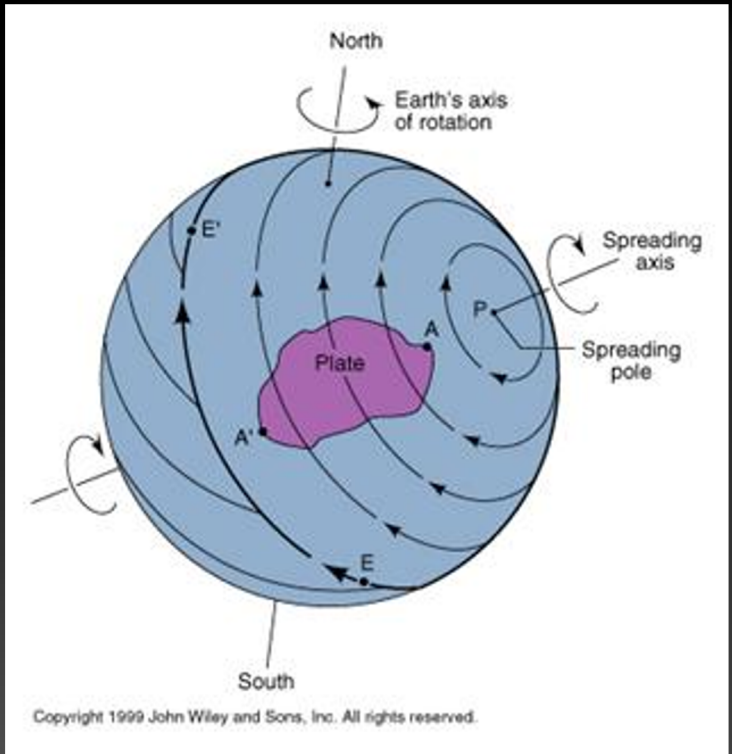


Müller et al. 2019



e.g. Tetley et al., 2019

WHAT ABOUT THE DRIVERS OF PLATE TECTONIC MOTIONS?



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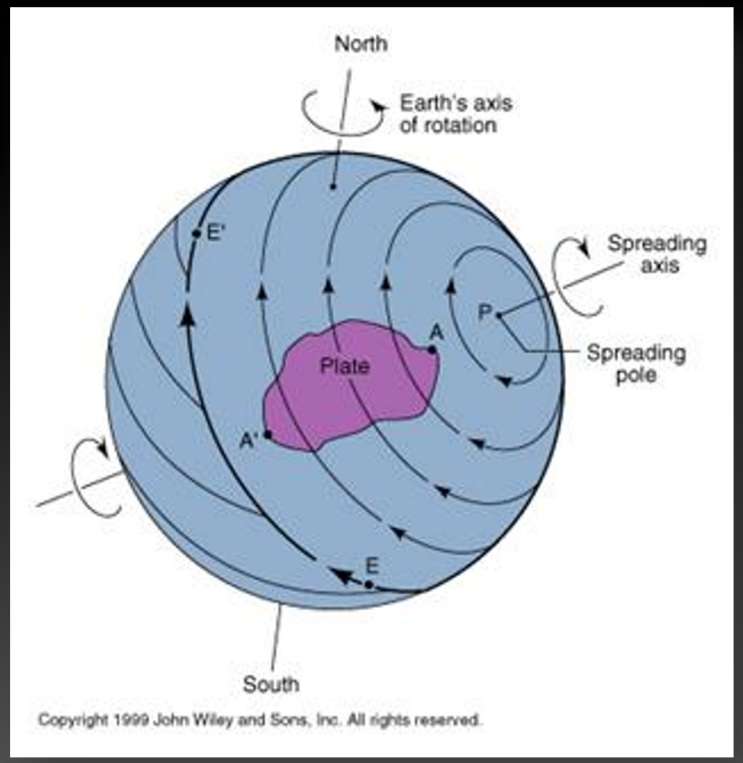


VS

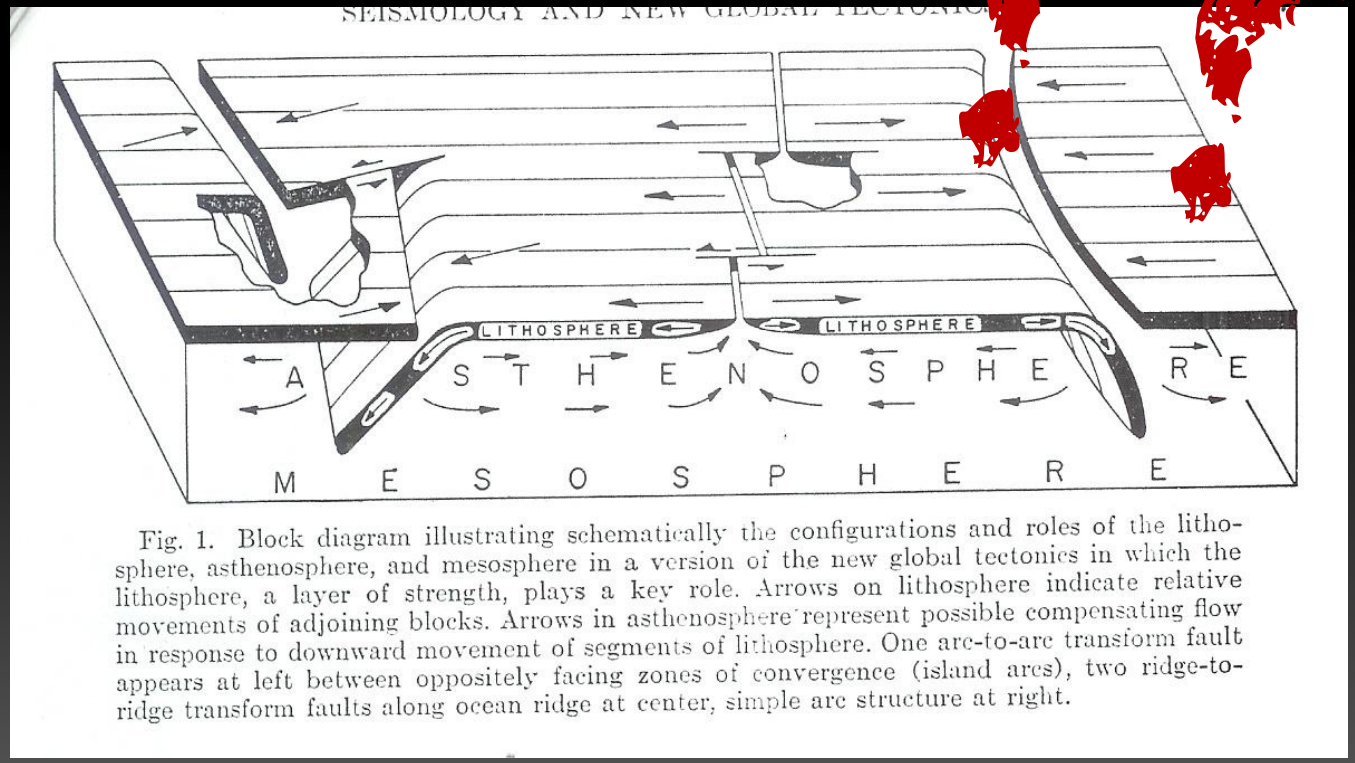
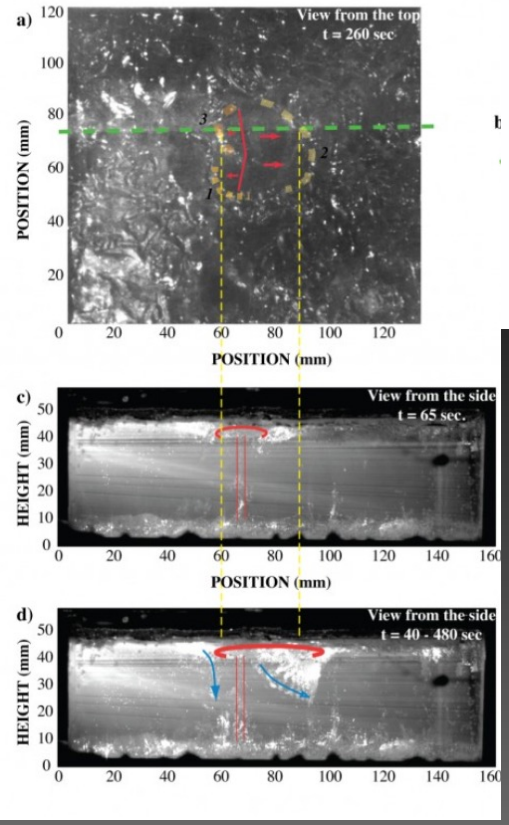


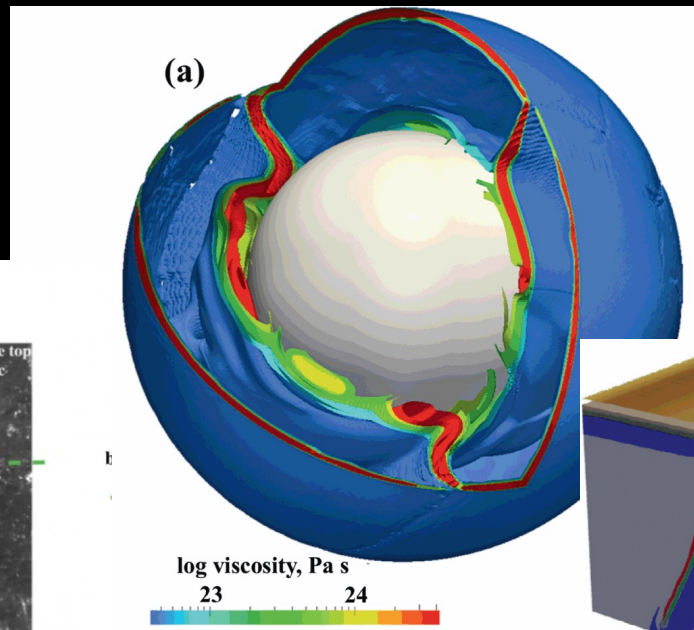
Fig. 1. Block diagram illustrating schematically the configurations and roles of the lithosphere, asthenosphere, and mesosphere in a version of the new global tectonics in which the lithosphere, a layer of strength, plays a key role. Arrows on lithosphere indicate relative movements of adjoining blocks. Arrows in asthenosphere represent possible compensating flow in response to downward movement of segments of lithosphere. One arc-to-arc transform fault appears at left between oppositely facing zones of convergence (island arcs), two ridge-to-ridge transform faults along ocean ridge at center, simple arc structure at right.

Isacks et al., 1968

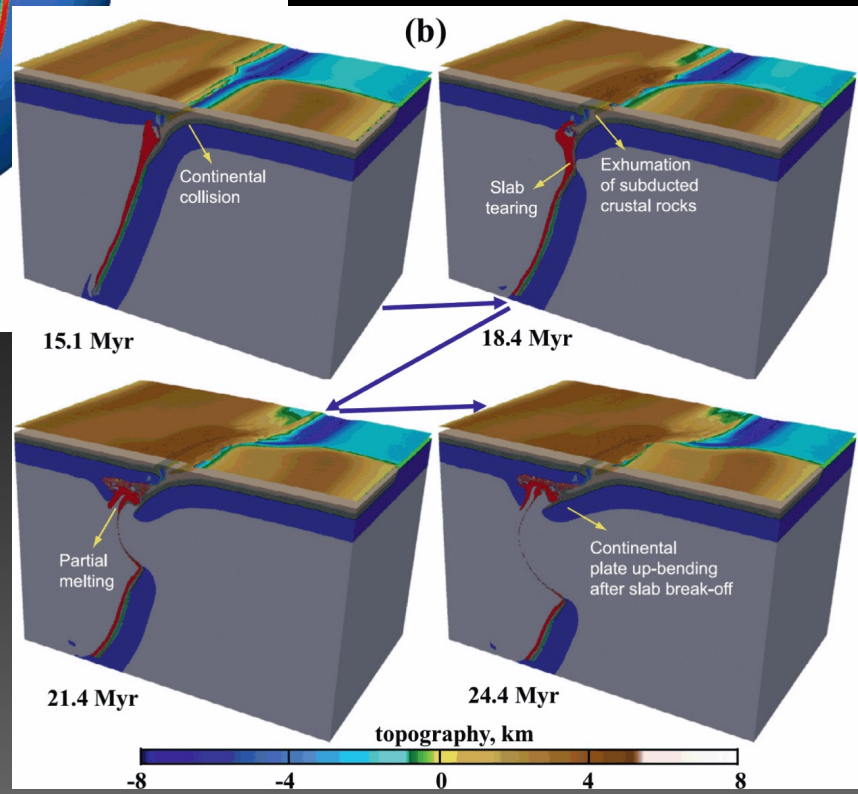
WHAT ABOUT THE DRIVERS OF PLATE TECTONIC MOTIONS?



Davaille et al., 2017



Crameri et al., 2012



What drives plate tectonics?

WHAT DRIVES MANTLE CONVECTION?

- **Forces implied in mantle convection:**

Viscous dissipation

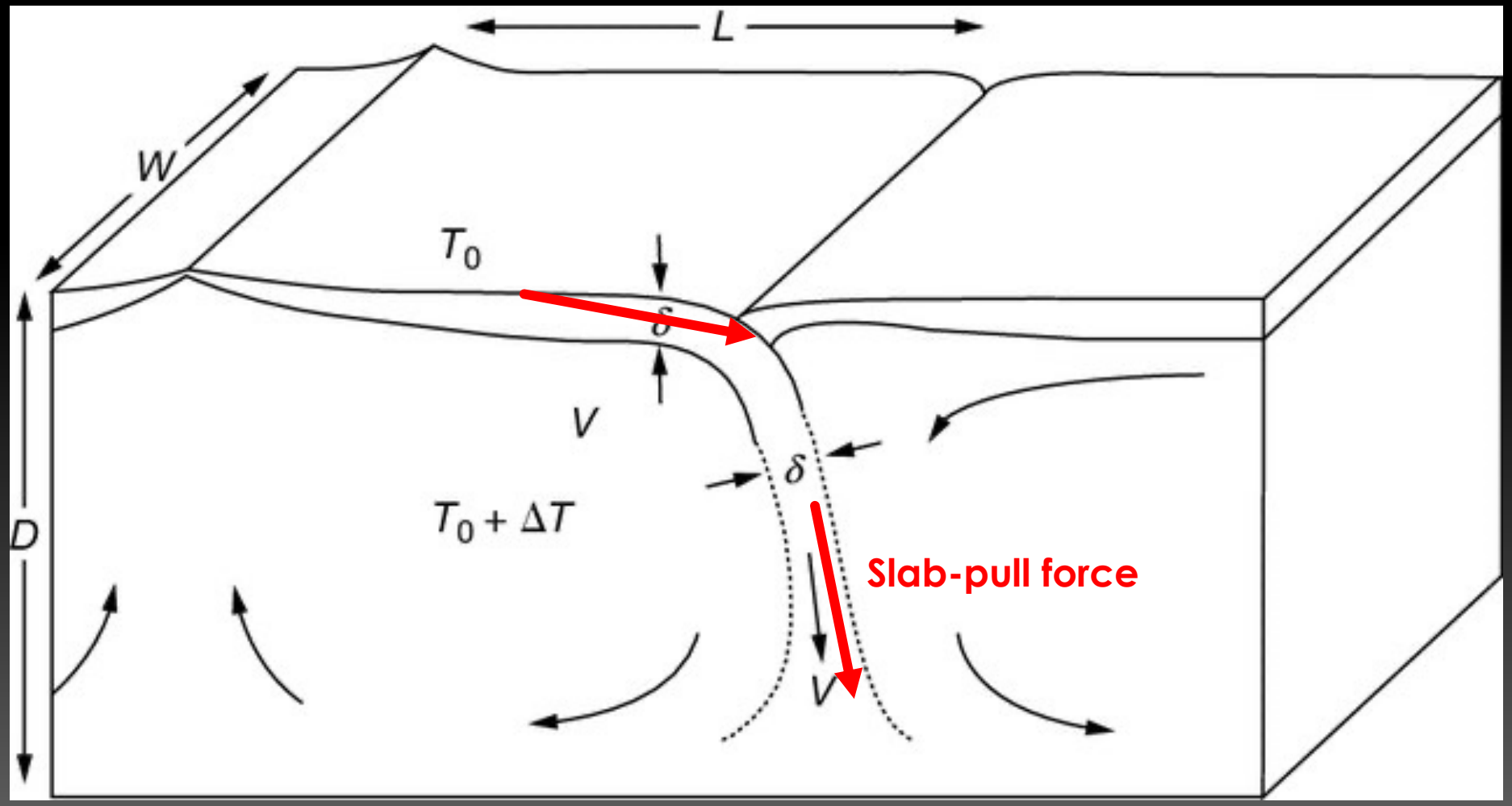
Buoyancy forces

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

Thermal dissipation

THE ROLE(S) OF SUBDUCTION?

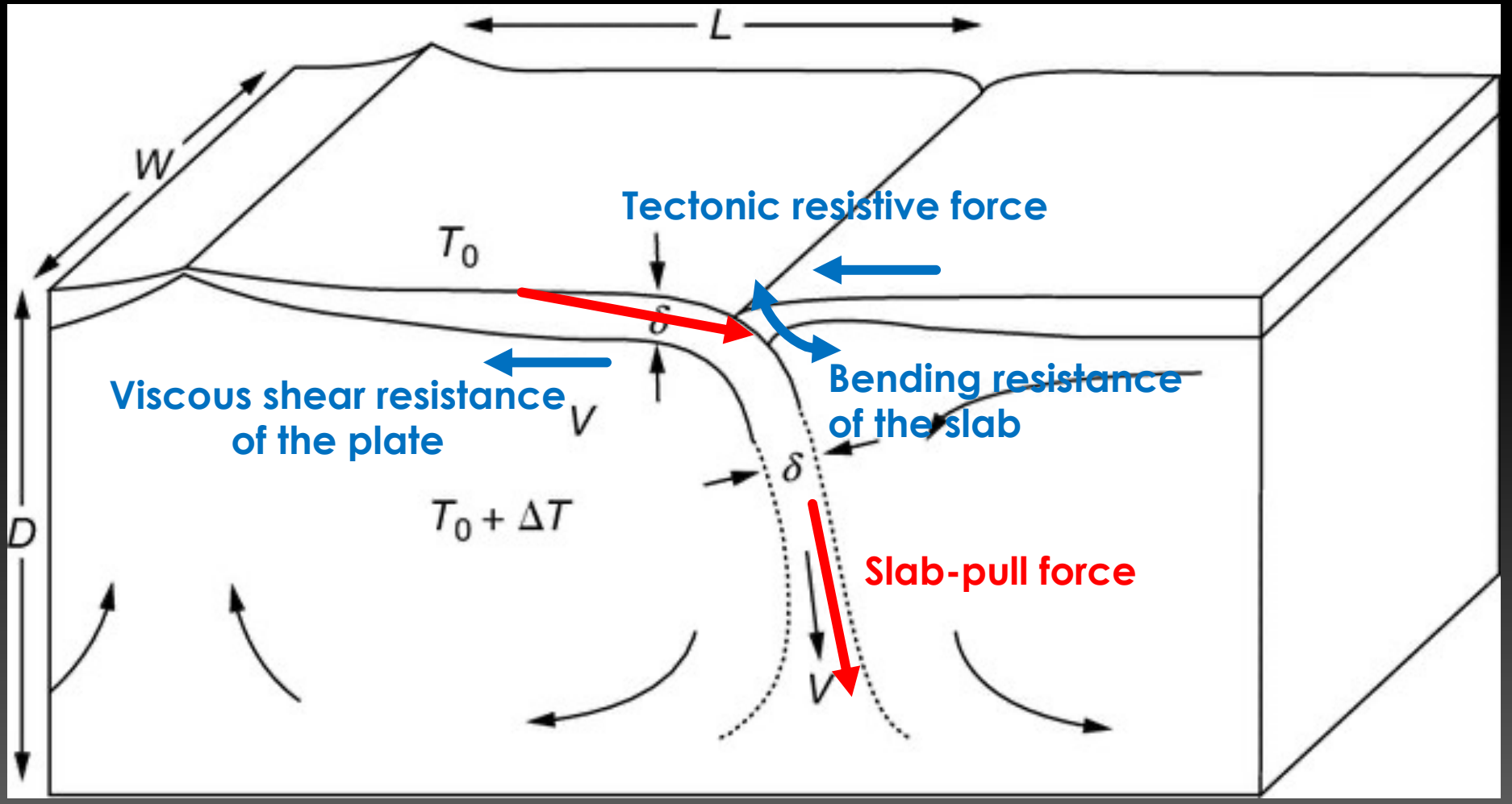
- **Slab pull**



Davies and Richards, 1992

THE ROLE(S) OF SUBDUCTION?

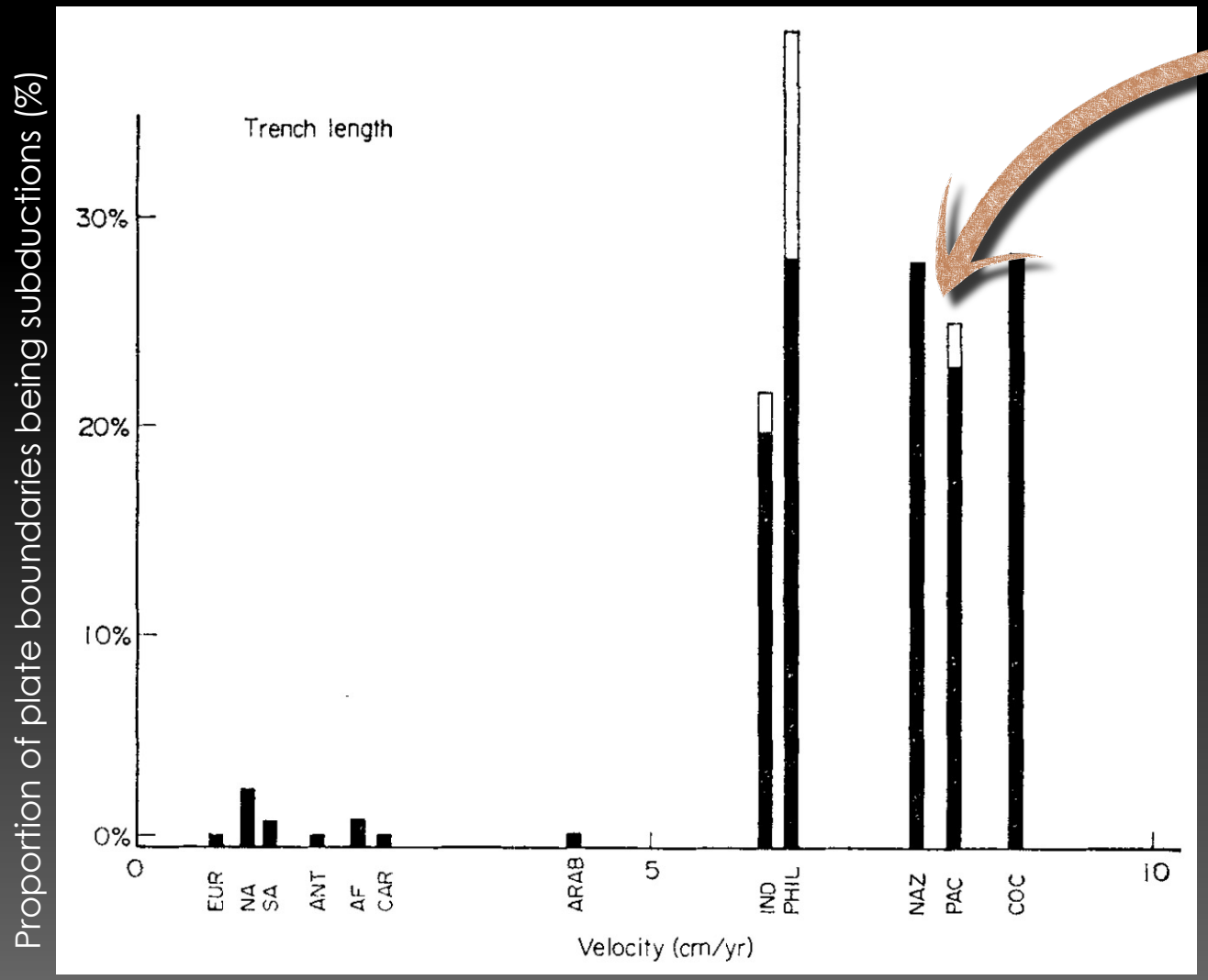
- **Slab pull**



Davies and Richards, 1992

THE ROLE(S) OF SUBDUCTION?

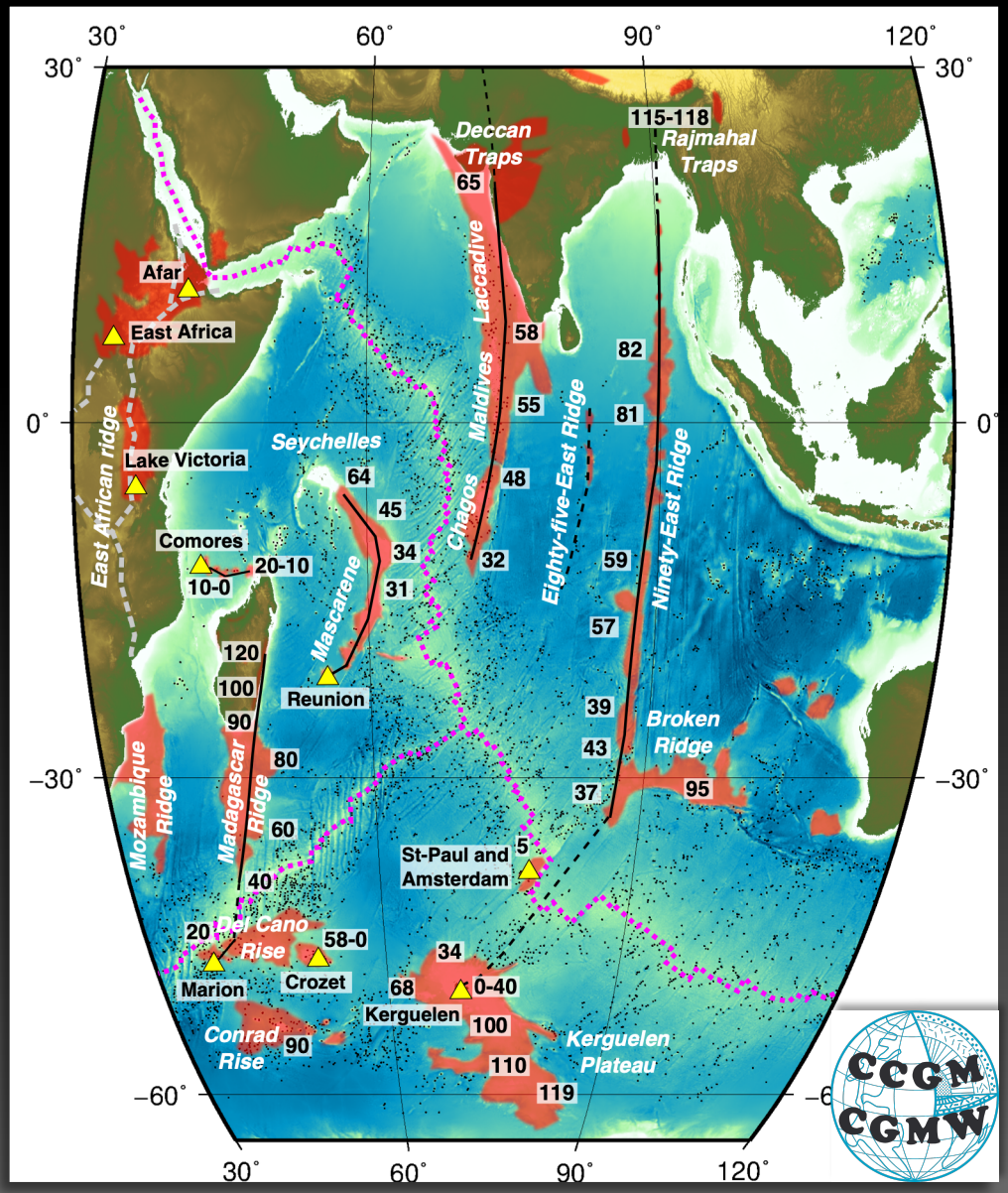
- **Slab pull**



The **Pacific Plate** is for example surrounded by **numerous subduction zones**

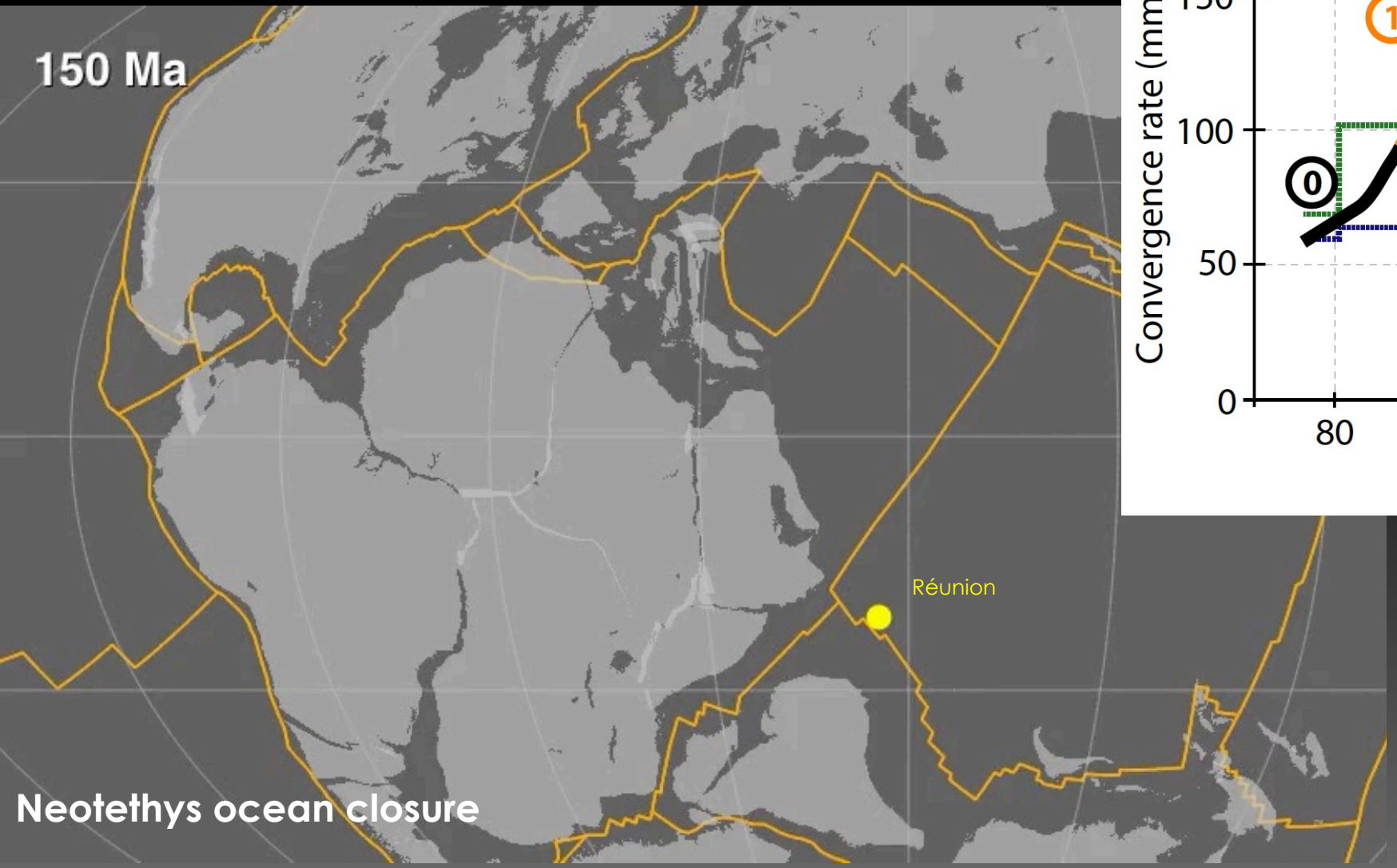
Forsyth and Uyeda, 1975

THE INDIAN OCEAN BASIN



Arnould, Seton and Tsekhmistrenko, 2020

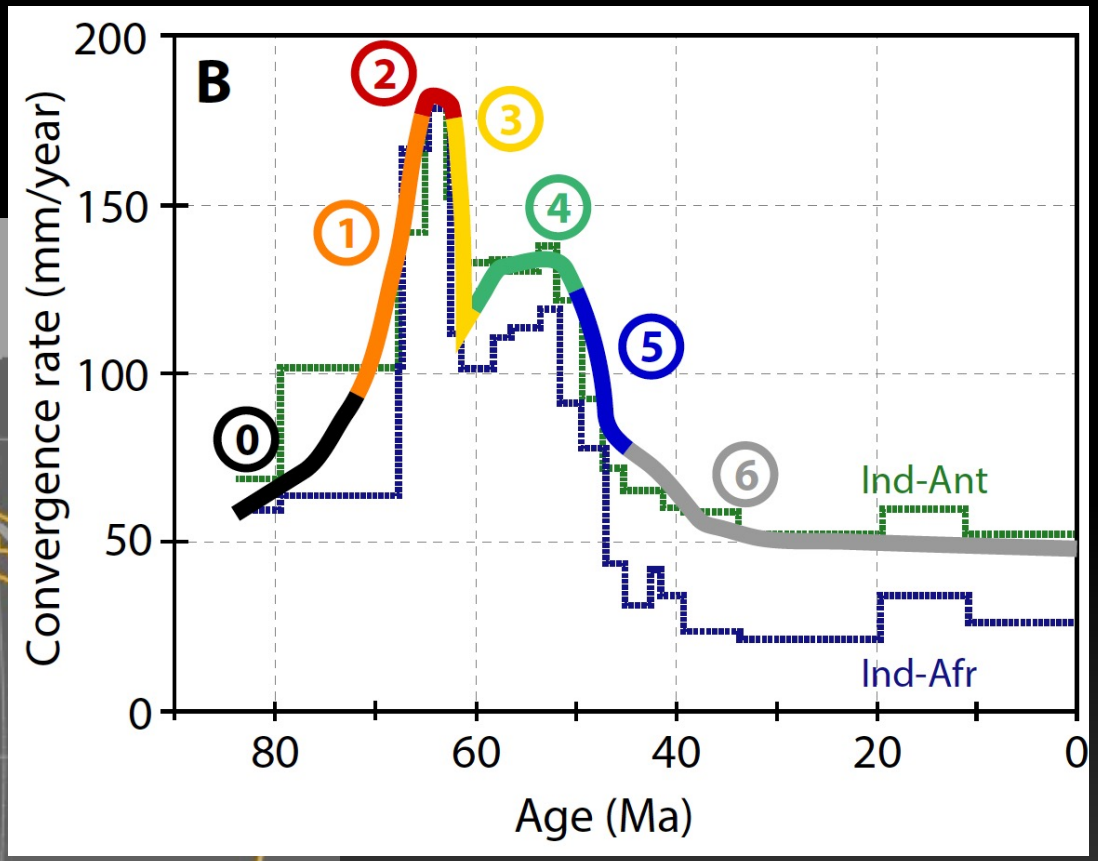
THE INDIAN OCEAN BASIN



Neotethys ocean closure

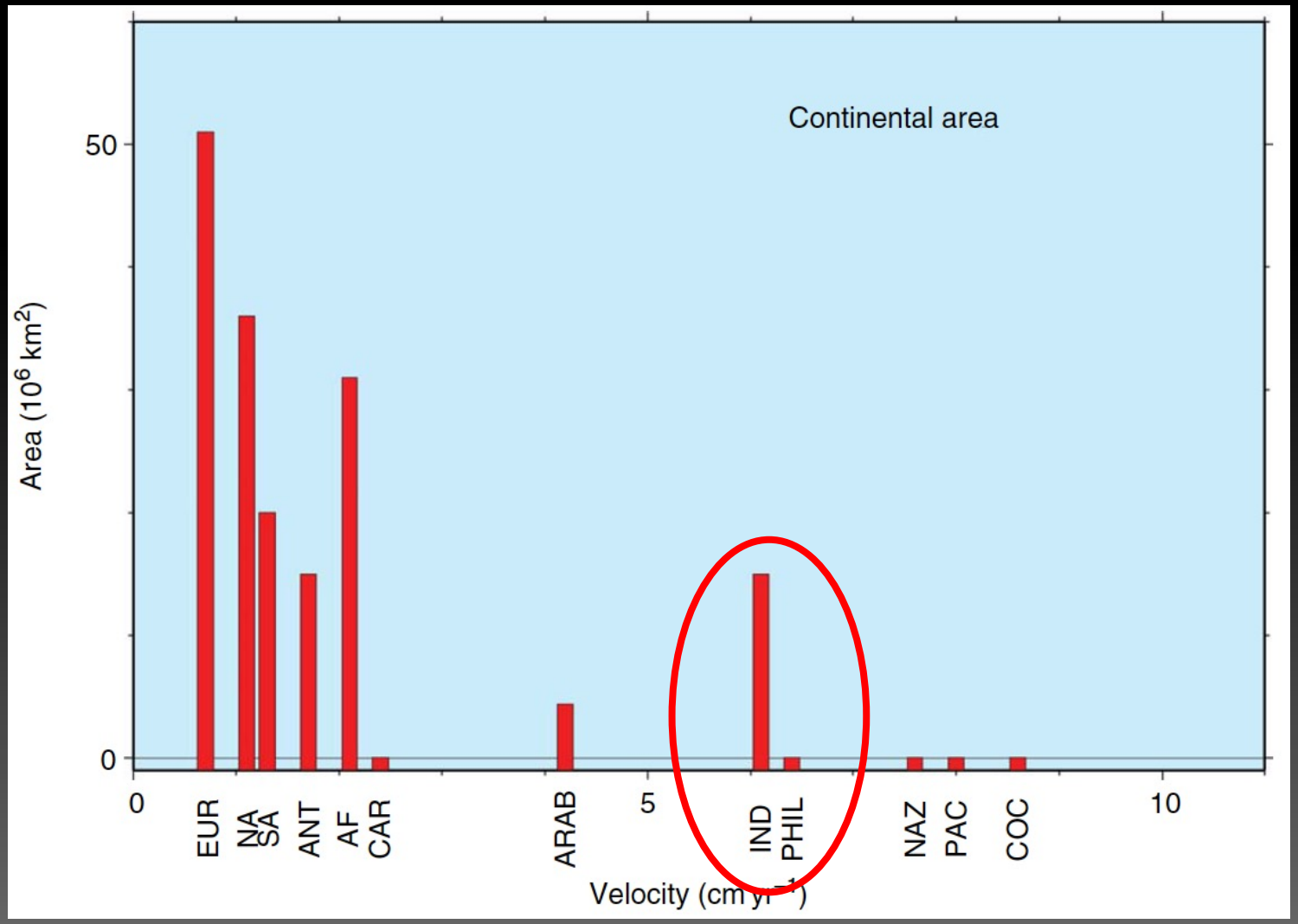
Seton et al., 2012

Indian plate relative acceleration (> 15 cm/yr)



Pusok and Stegman, 2020

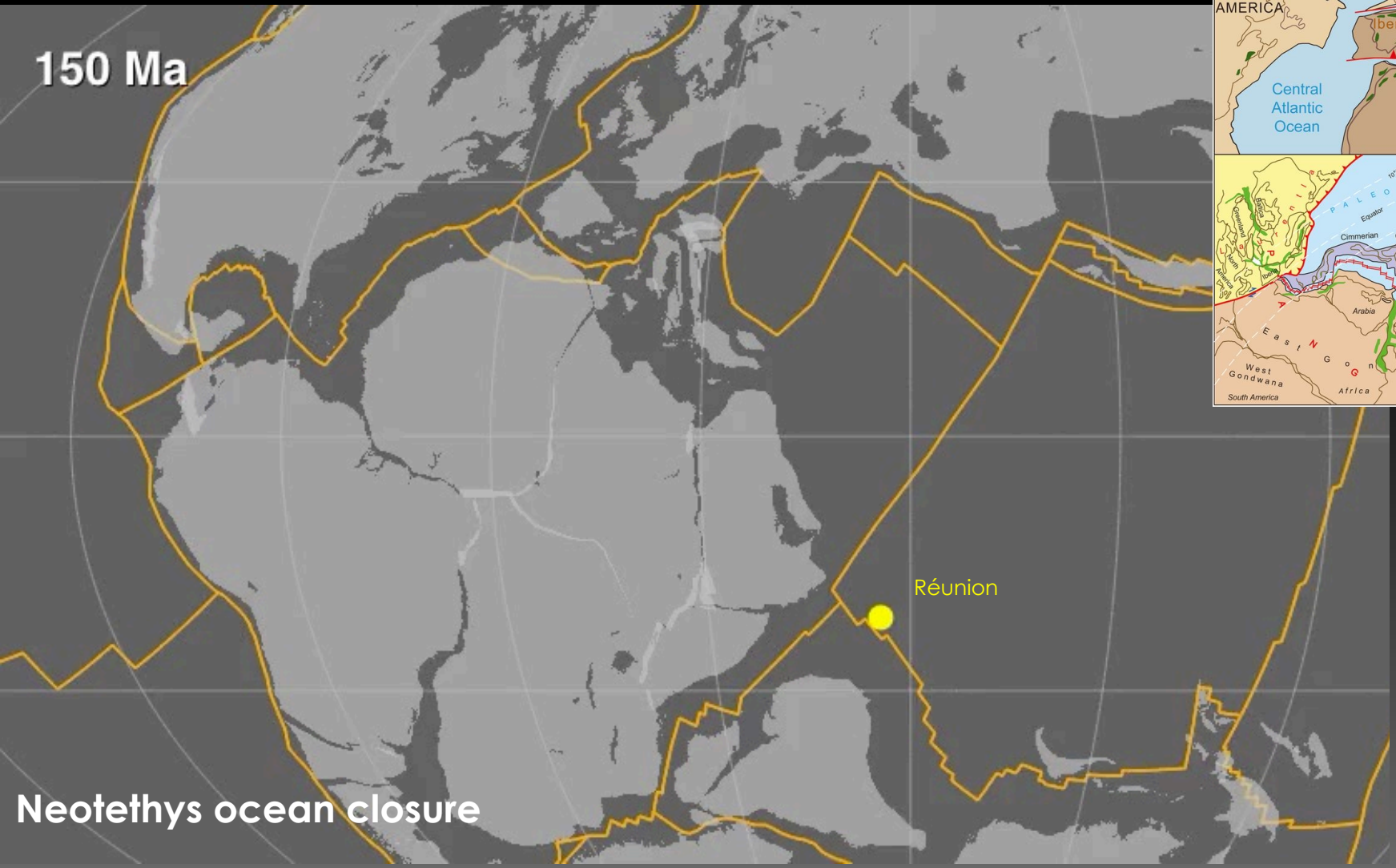
THE INDIAN OCEAN BASIN



From Forsyth and Uyeda, 1975

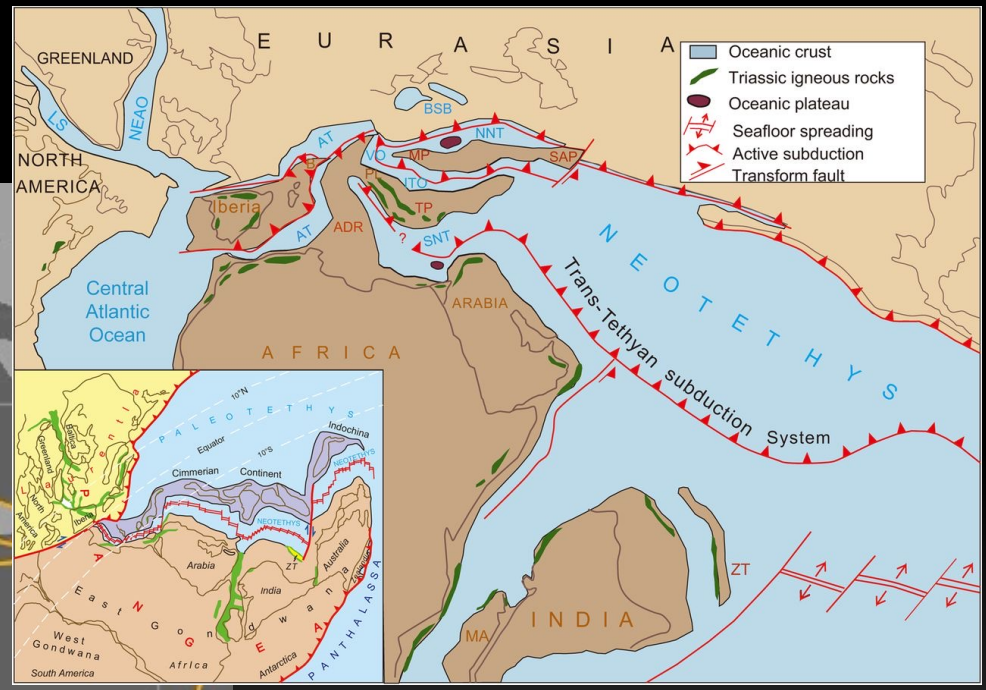
THE ROLE(S) OF SUBDUCTION?

- **Slab pull and double-subduction**



Seton et al., 2012

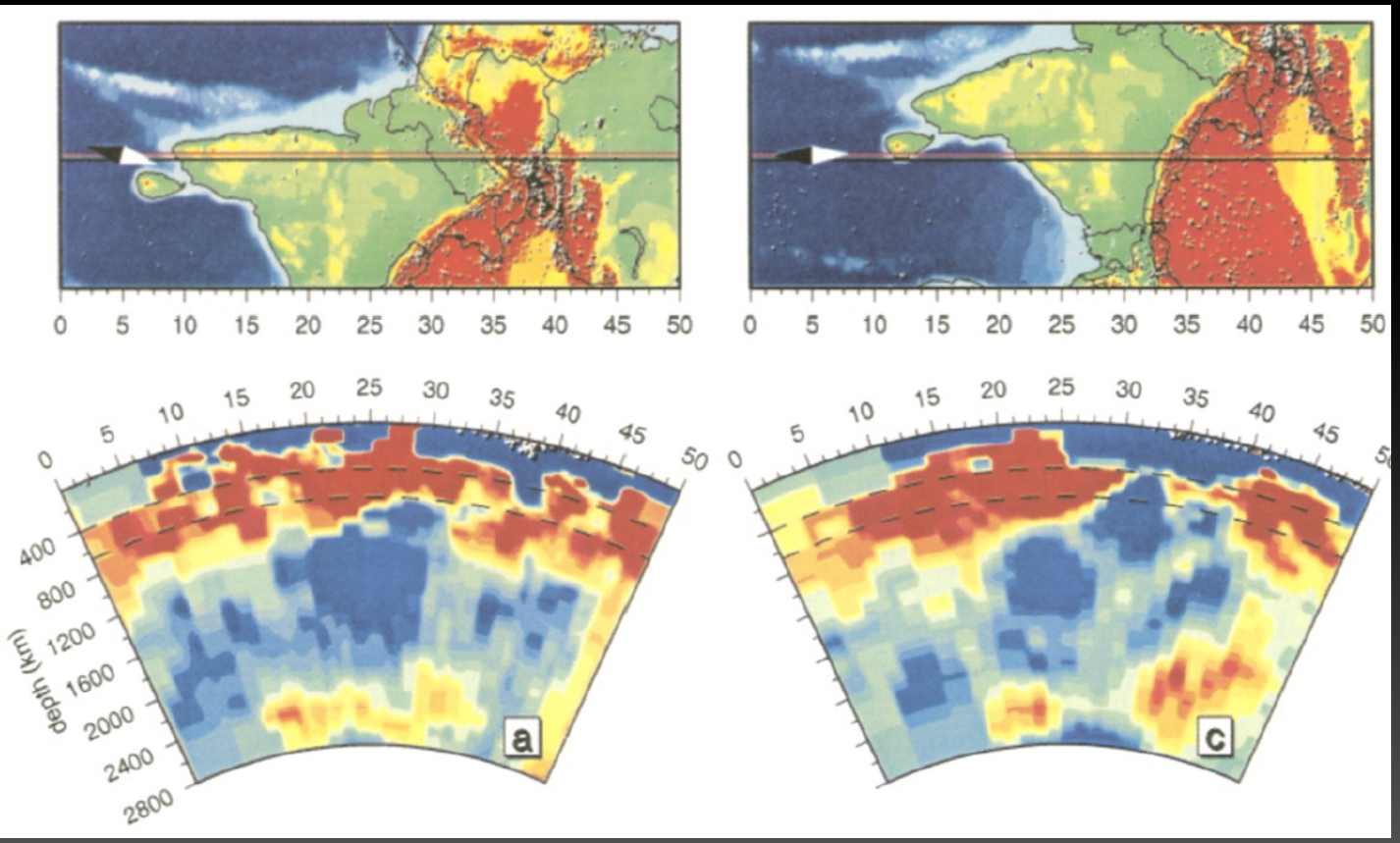
Late Cretaceous



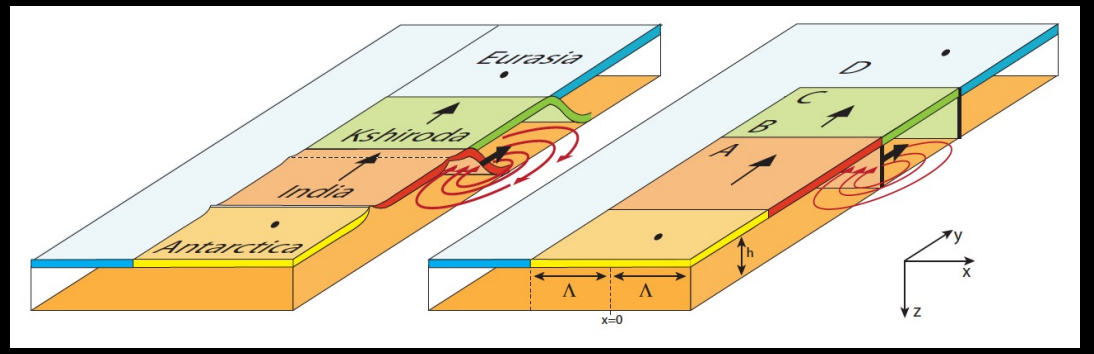
Dilek and Furnes, 2019

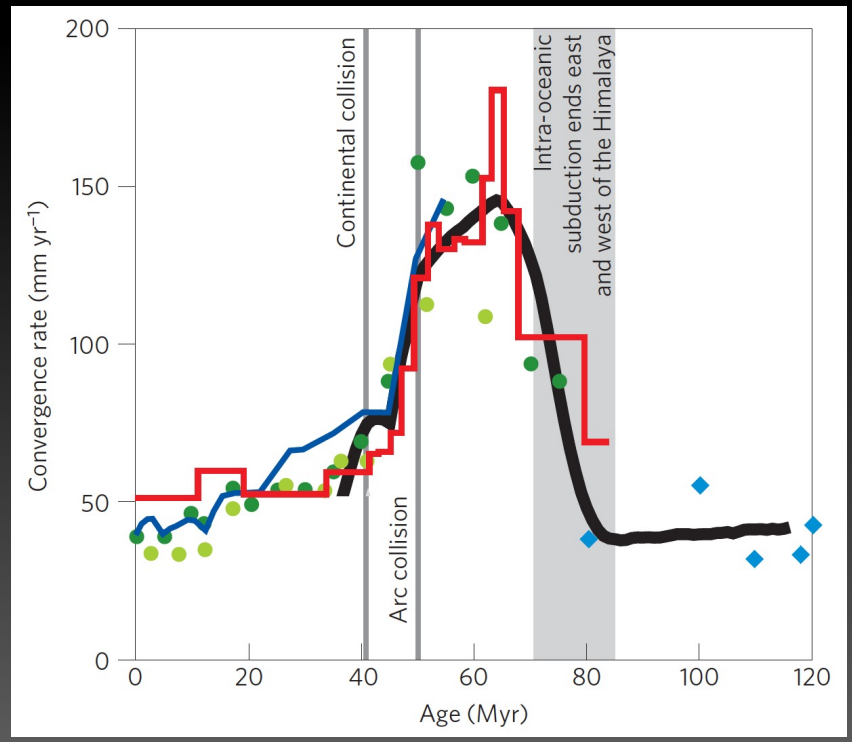
THE ROLE(S) OF SUBDUCTION?

- **Slab pull and double-subduction**



Van der Voo et al., 1999

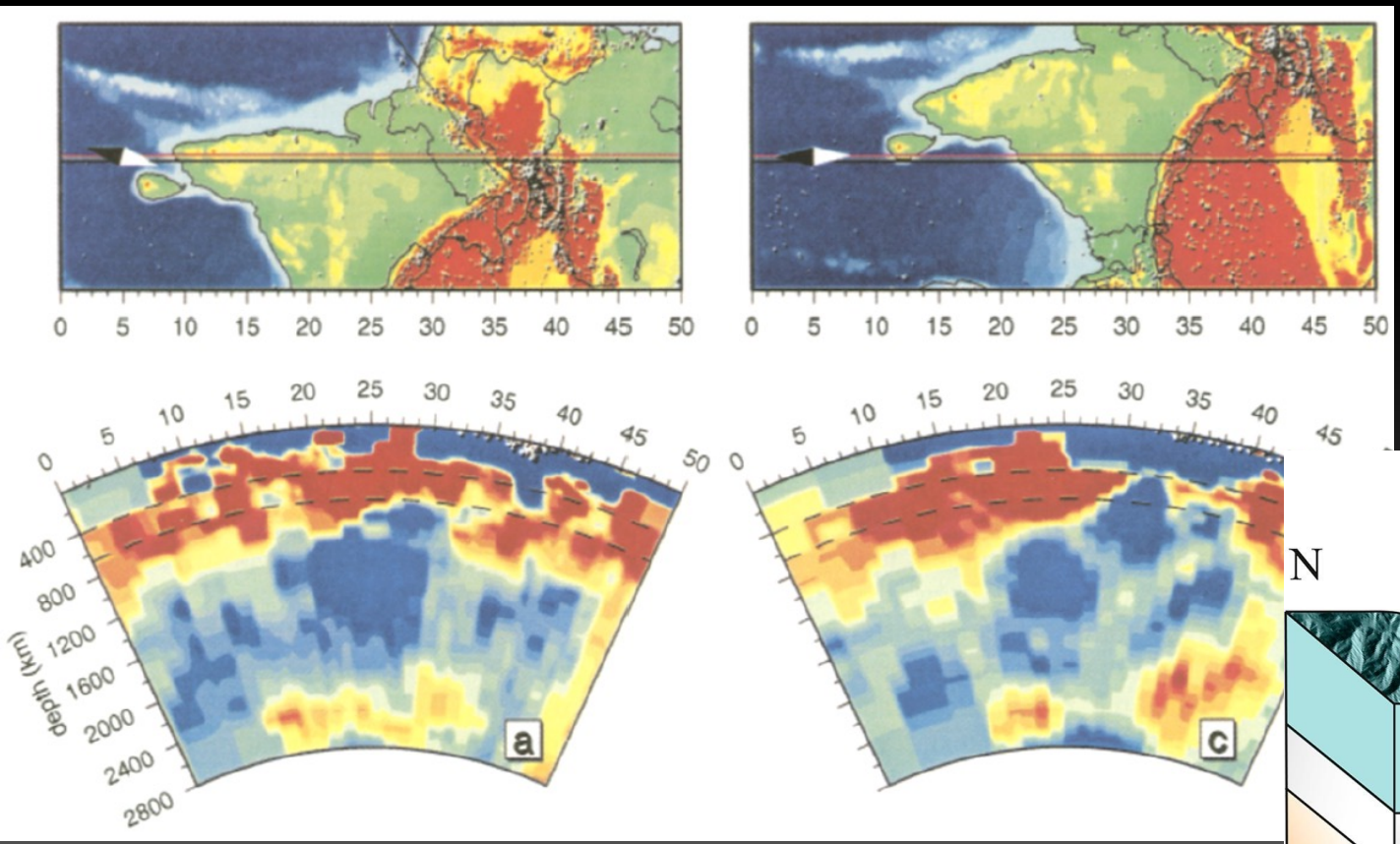




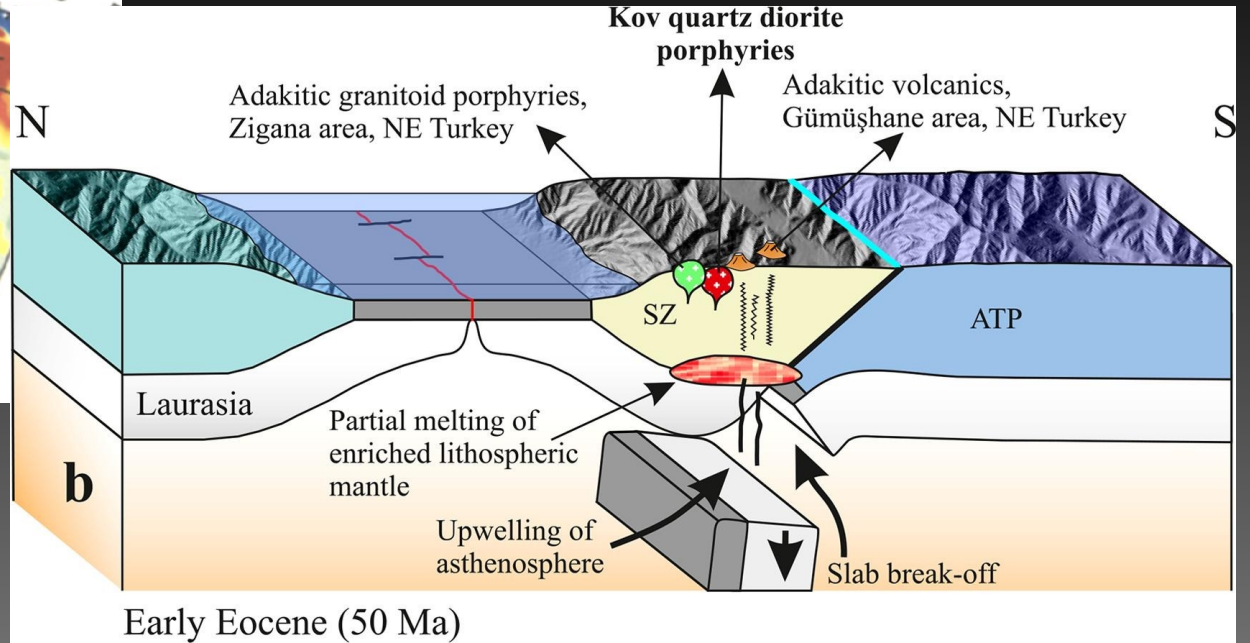
Jagoutz et al., 2015

THE ROLE(S) OF SUBDUCTION?

- **Problem: evidence of slab breakoff ?**



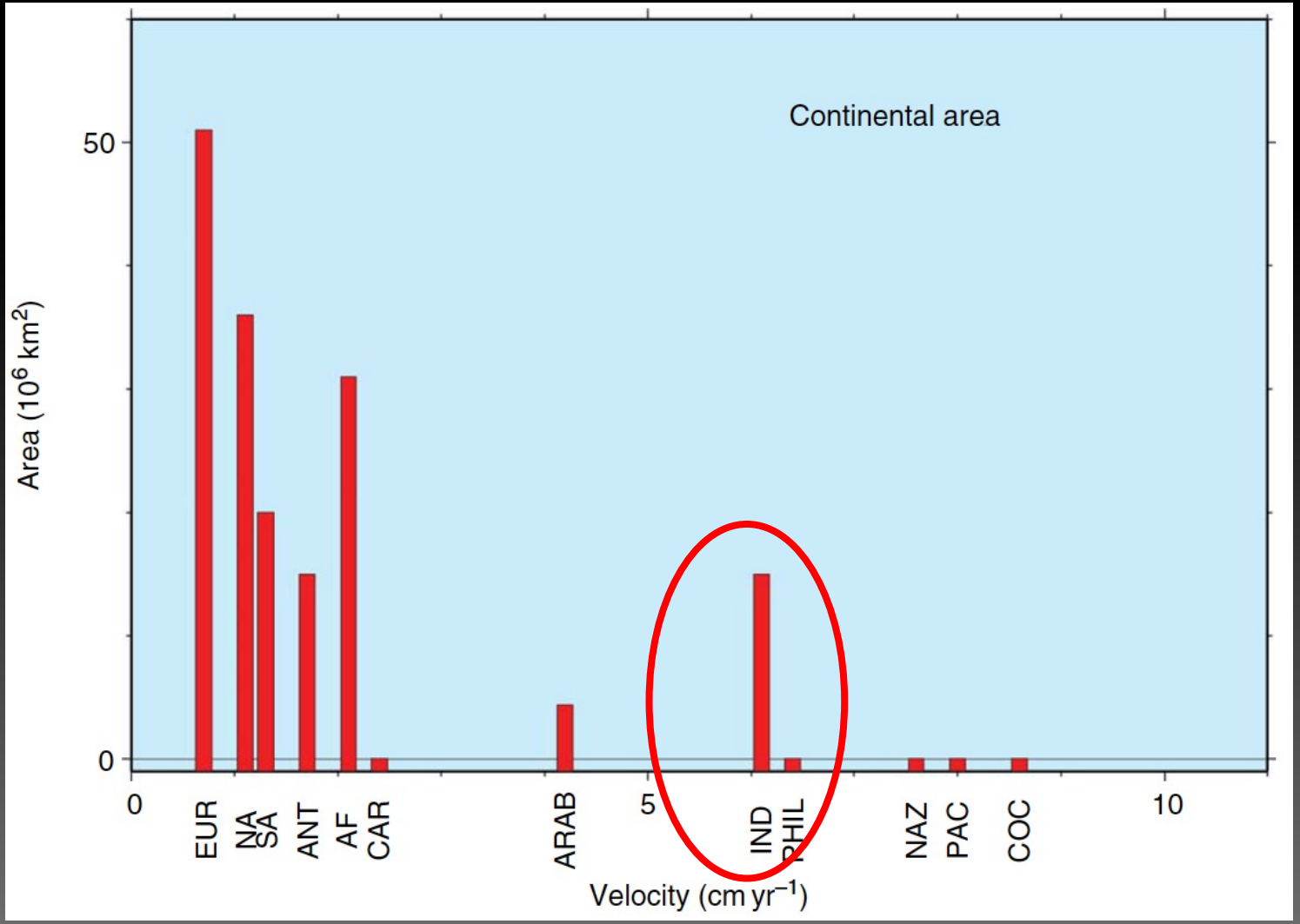
Van der Voo et al., 1999

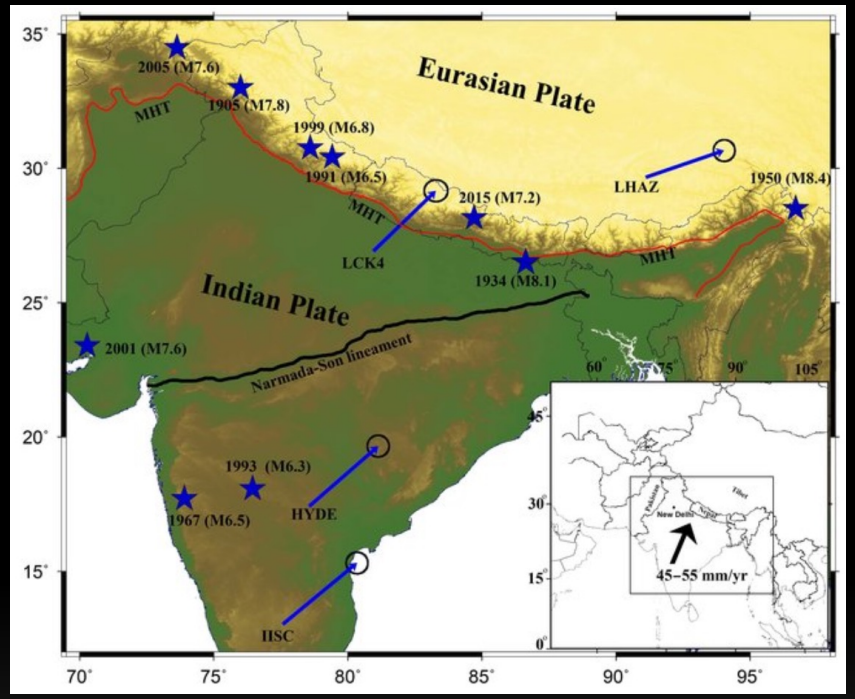


Early Eocene (50 Ma)

THE ROLE(S) OF SUBDUCTION?

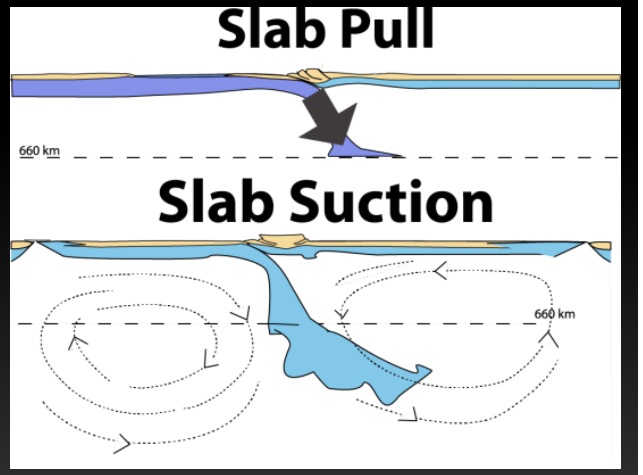
- **The Indian Plate: an anomaly?**

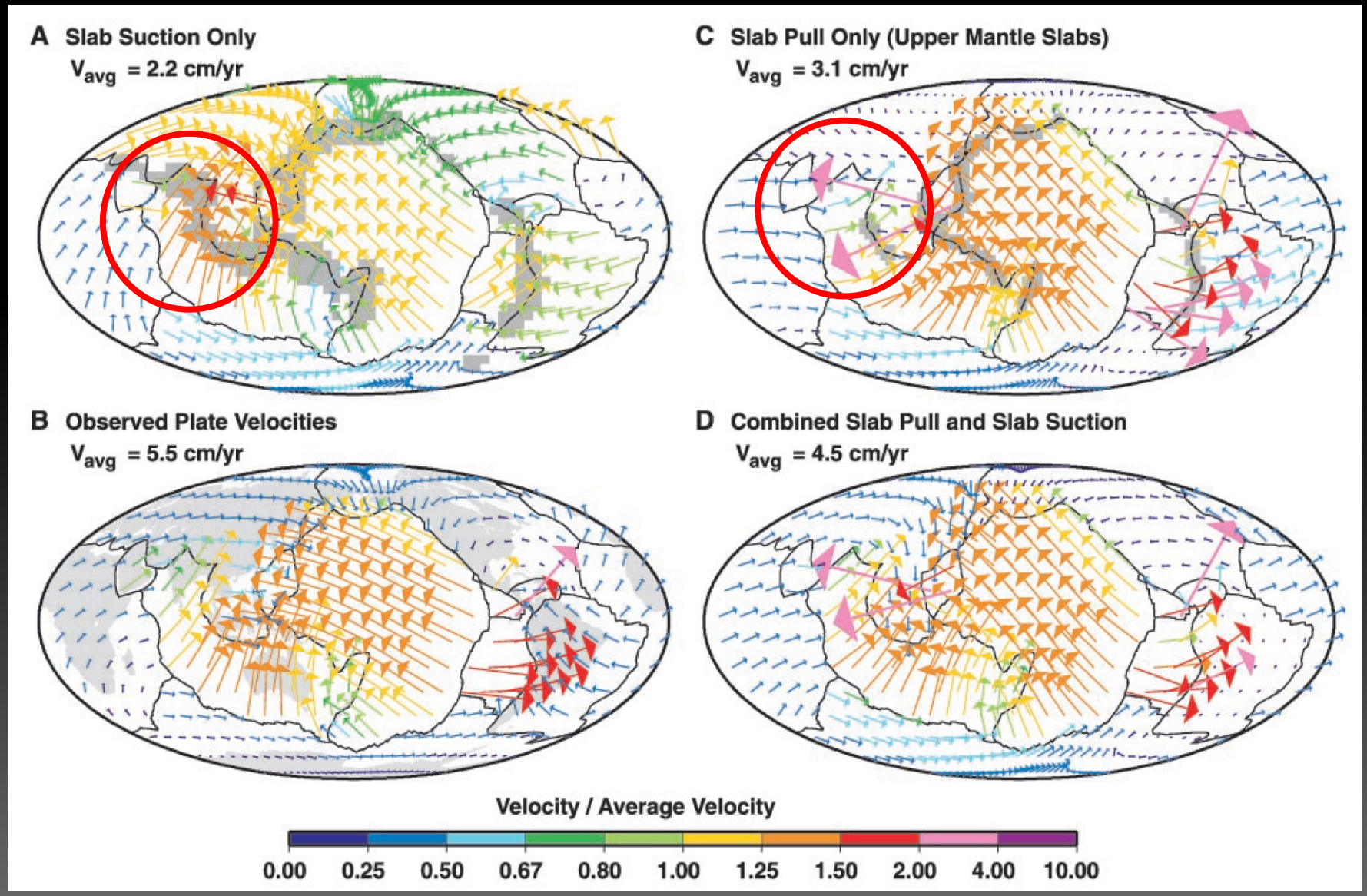




From Forsyth and Uyeda, 1975

THE ROLE(S) OF SUBDUCTION?



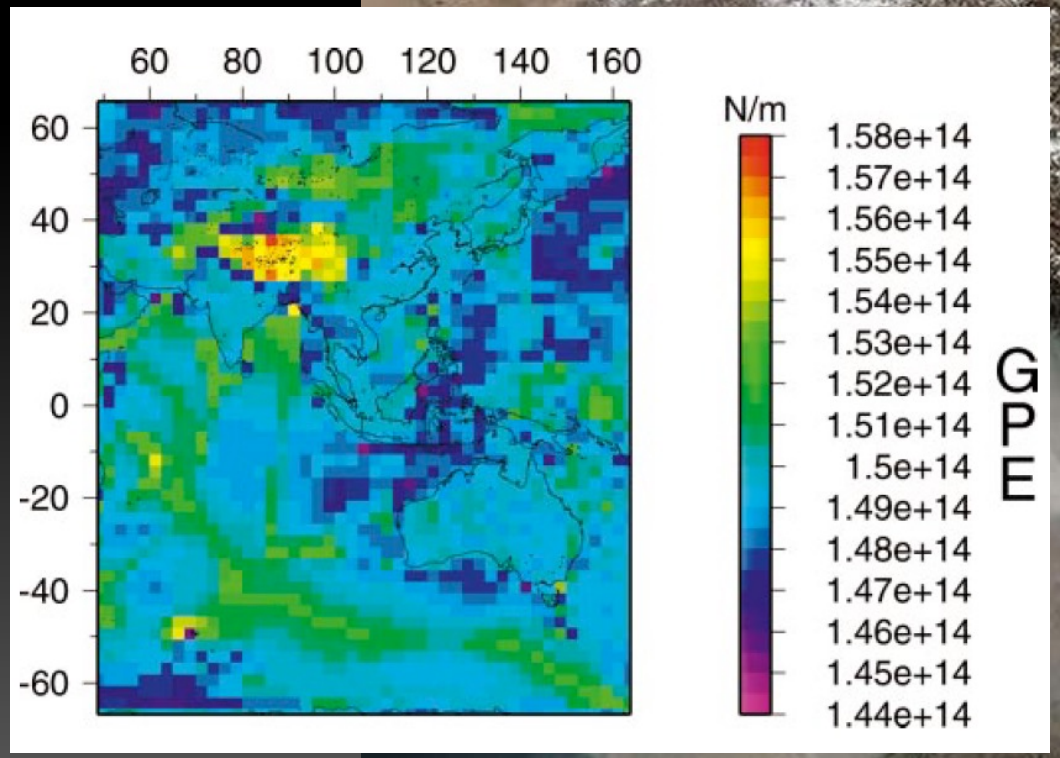


Conrad and Lithgow-Bertelloni, 2002

GRAVITATIONAL POTENTIAL ENERGY

- **The effect of mountains**

Typical reblochon from les Houches

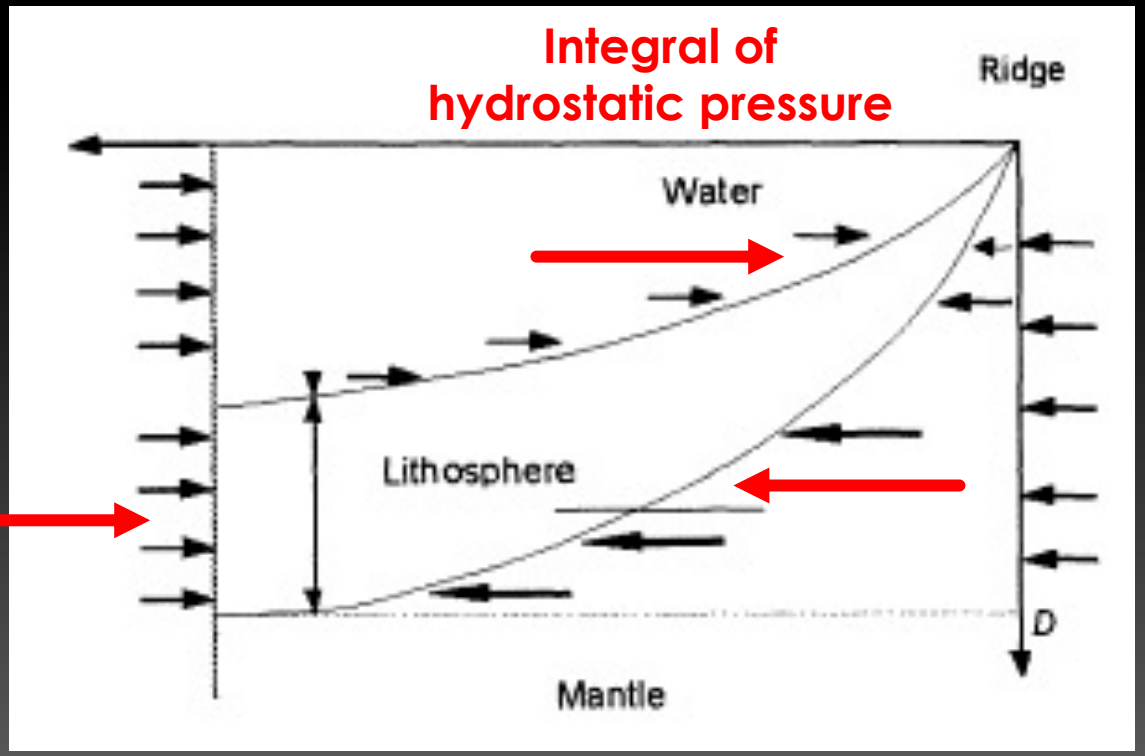


Gosh et al., 2006

GRAVITATIONAL POTENTIAL ENERGY

- **The effect of ridge push**

Integral of pressure in the lithosphere (depends on lithosphere age and thermal diffusivity)

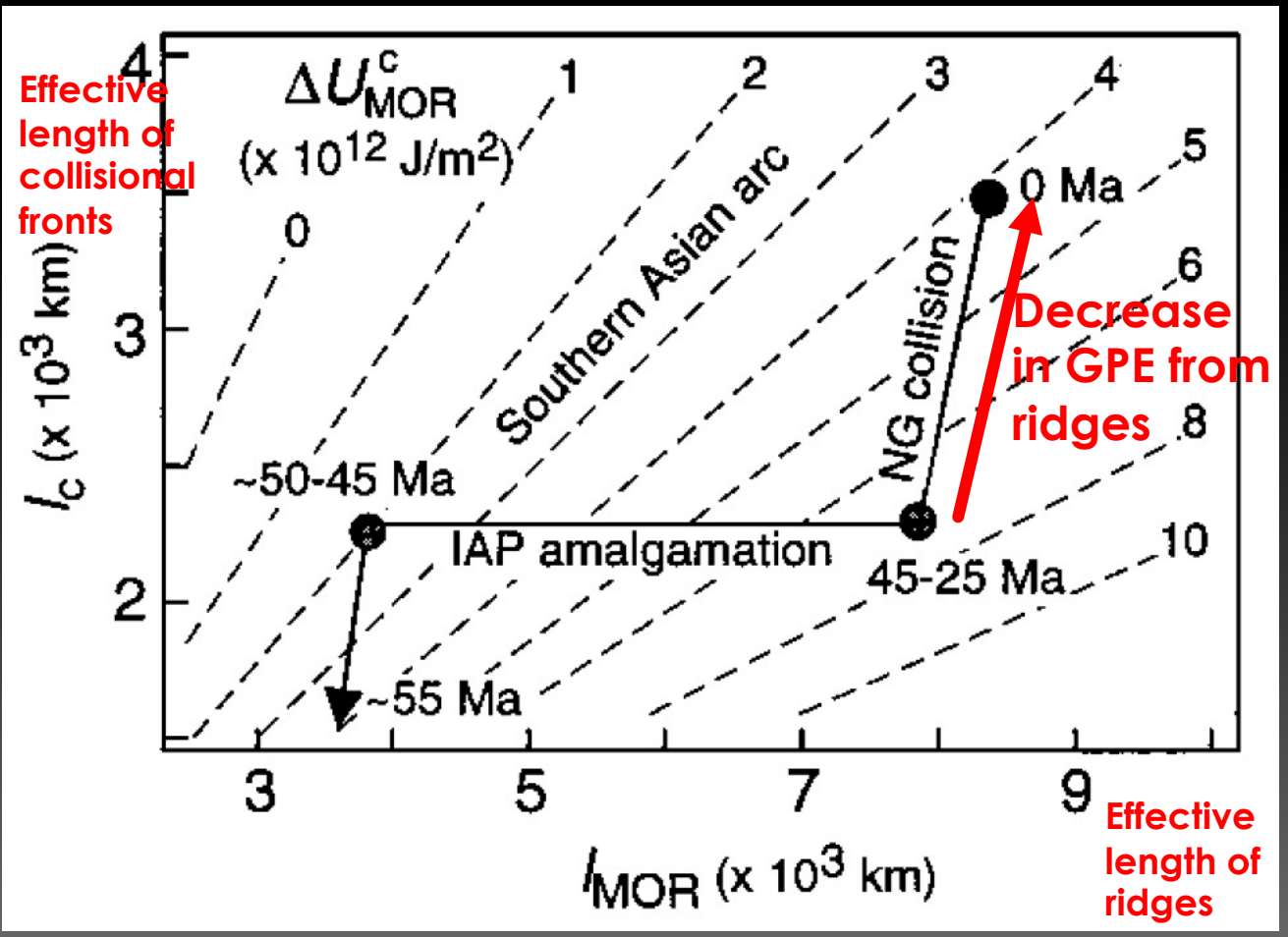


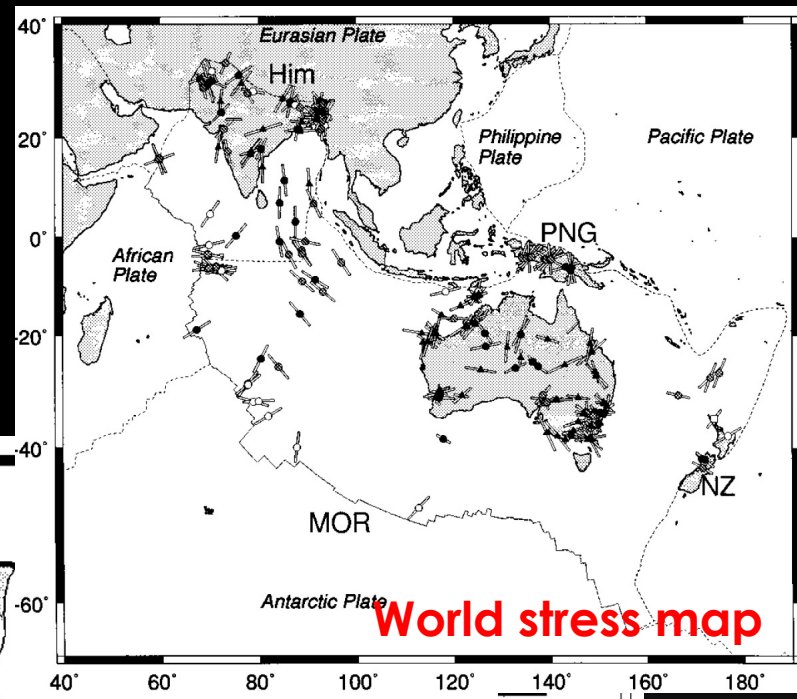
Integral of lithostatic pressure

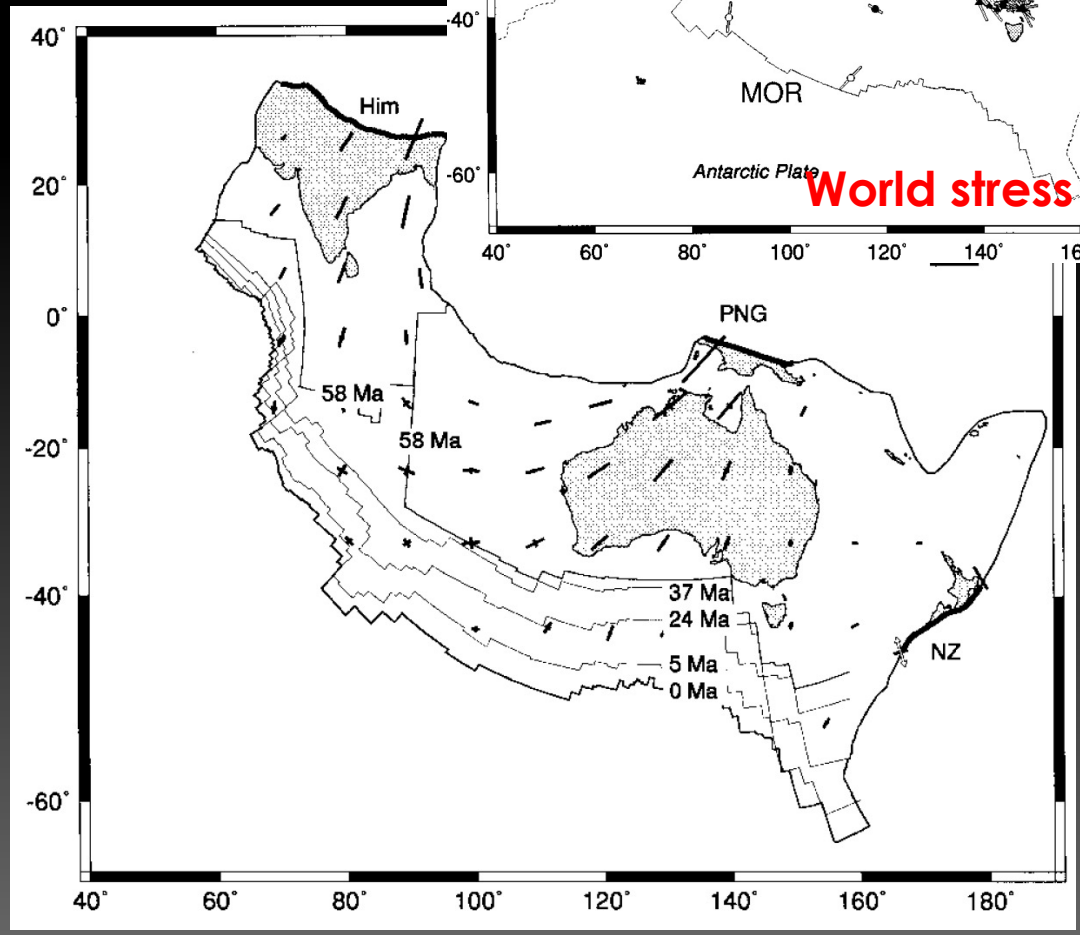
Turcotte and Schubert, 1982

GRAVITATIONAL POTENTIAL ENERGY

- **Evolution of the focusing of ridge torque?**

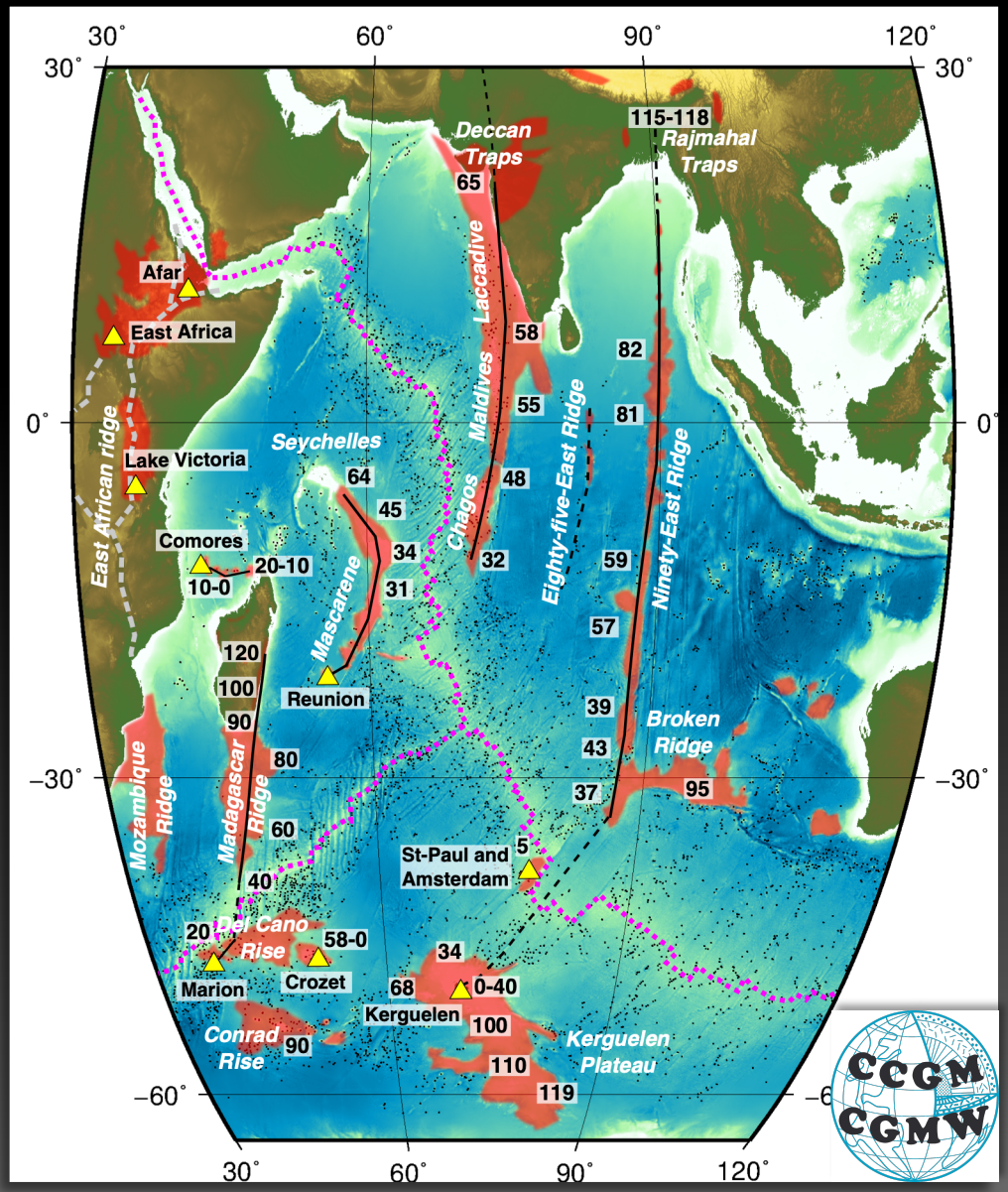






Sandiford et al., 1995

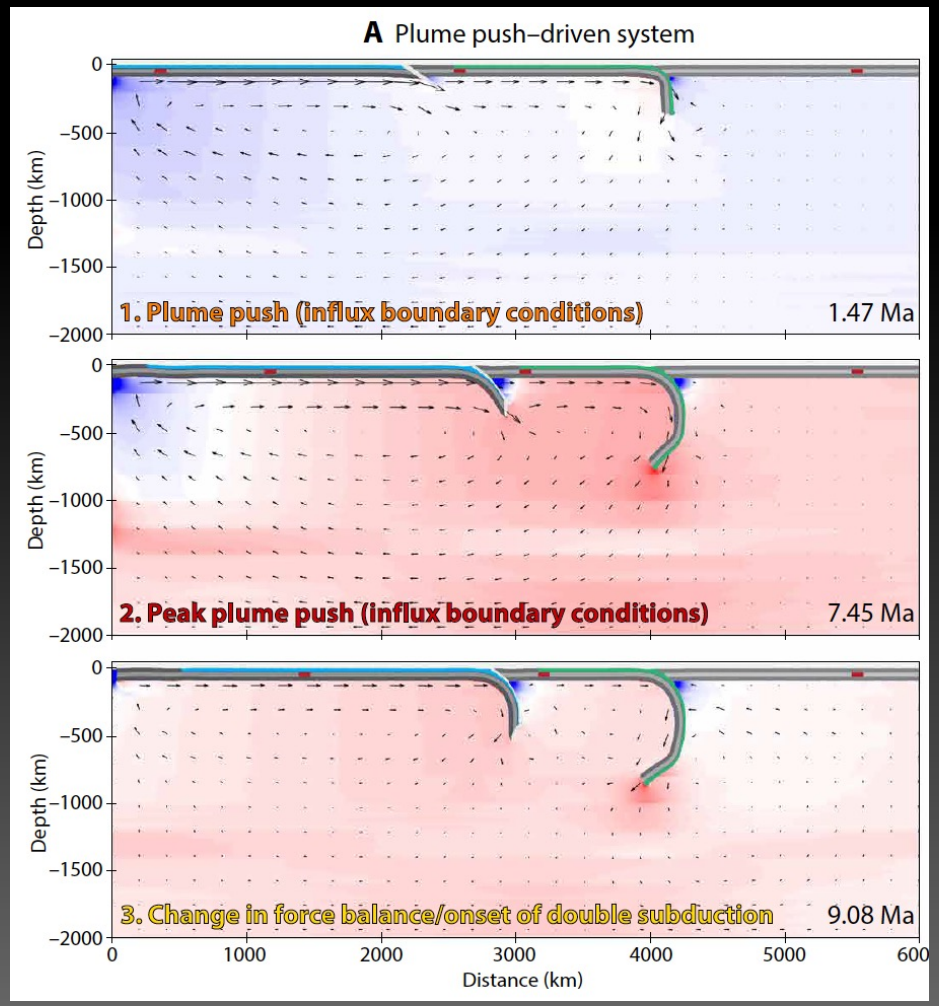
A ROLE FOR MANTLE PLUMES?

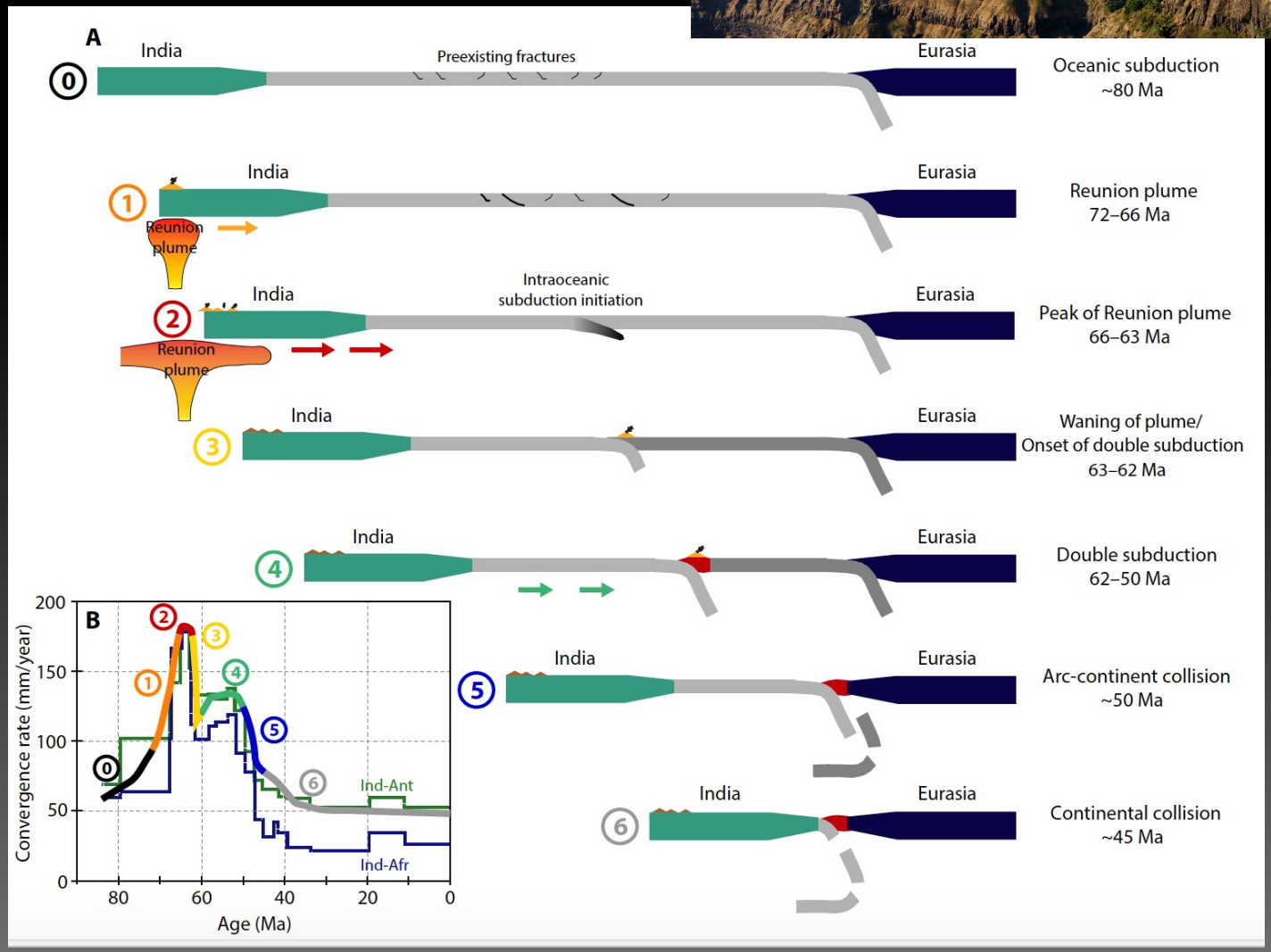


Arnould, Seton and Tsekhmistrenko, 2020

A ROLE FOR MANTLE PLUMES?

- **Plume push?**



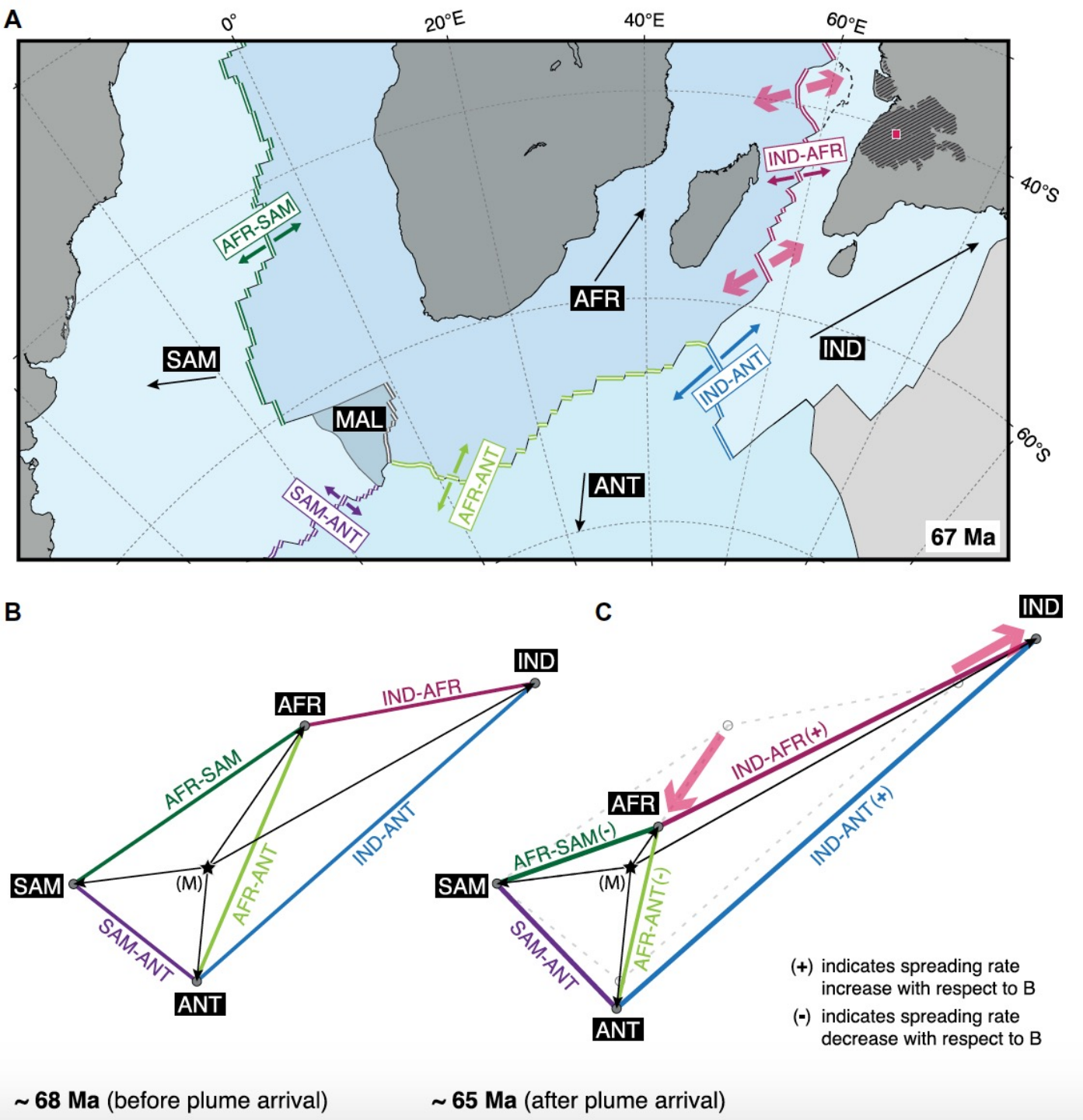


Pusok and Stegman, 2020

BACK TO PALEOMAG

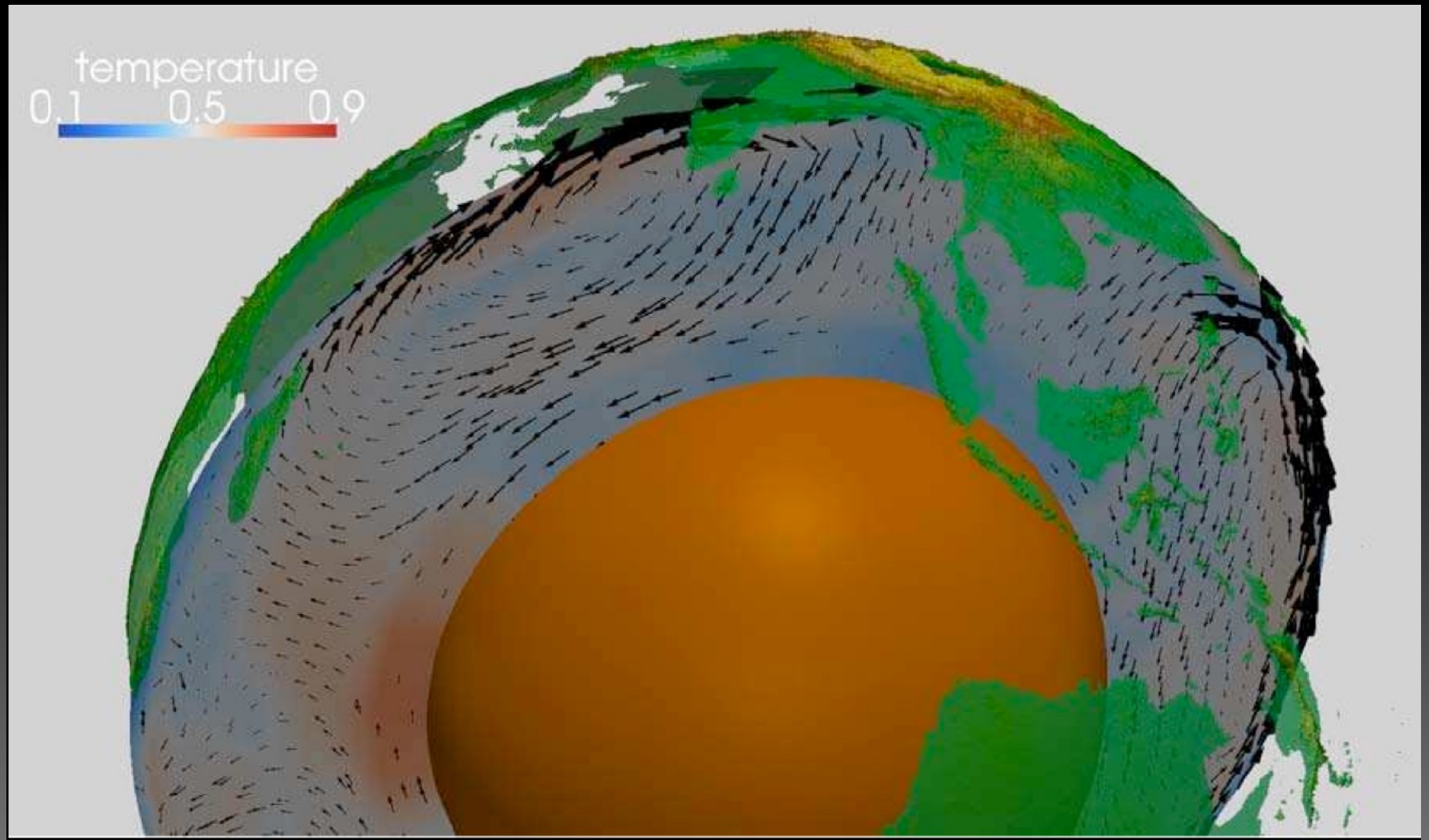
"We propose that this circuit-wide spike in divergence rates is best explained as the artifact of a magnetic reversal time-scale error around the much studied Cretaceous- Tertiary boundary, and that the period spanning chrons C29–C28 lasted 70% longer than currently assumed. "

Perez-Diaz et al., 2021



GOING GLOBAL…

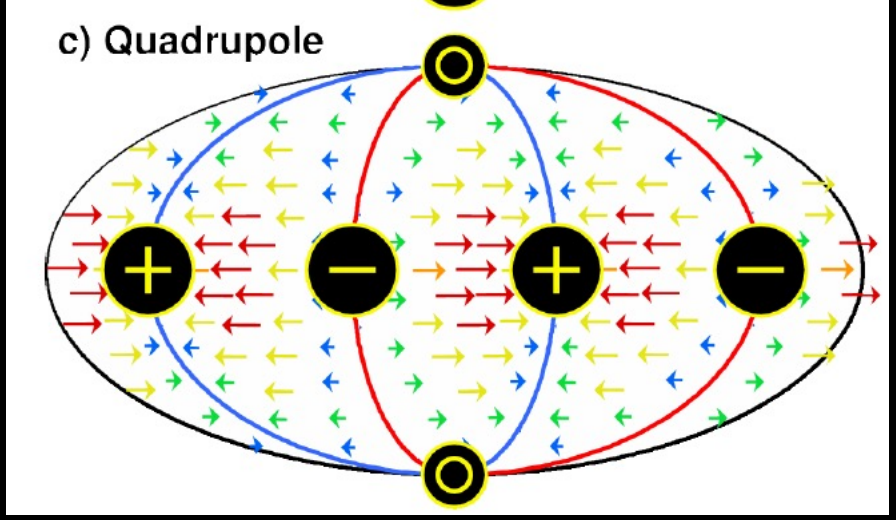
- **A conveyor belt?**

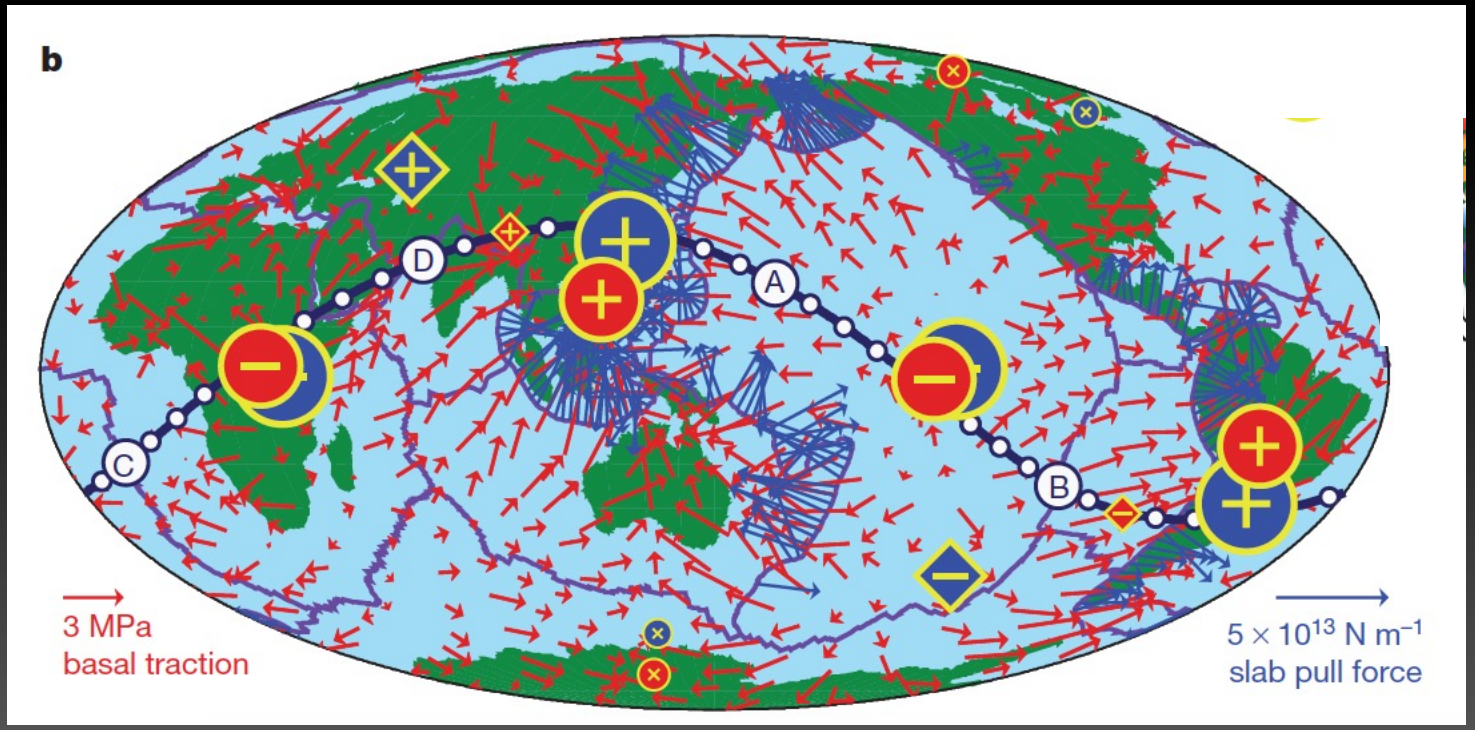


T. Becker

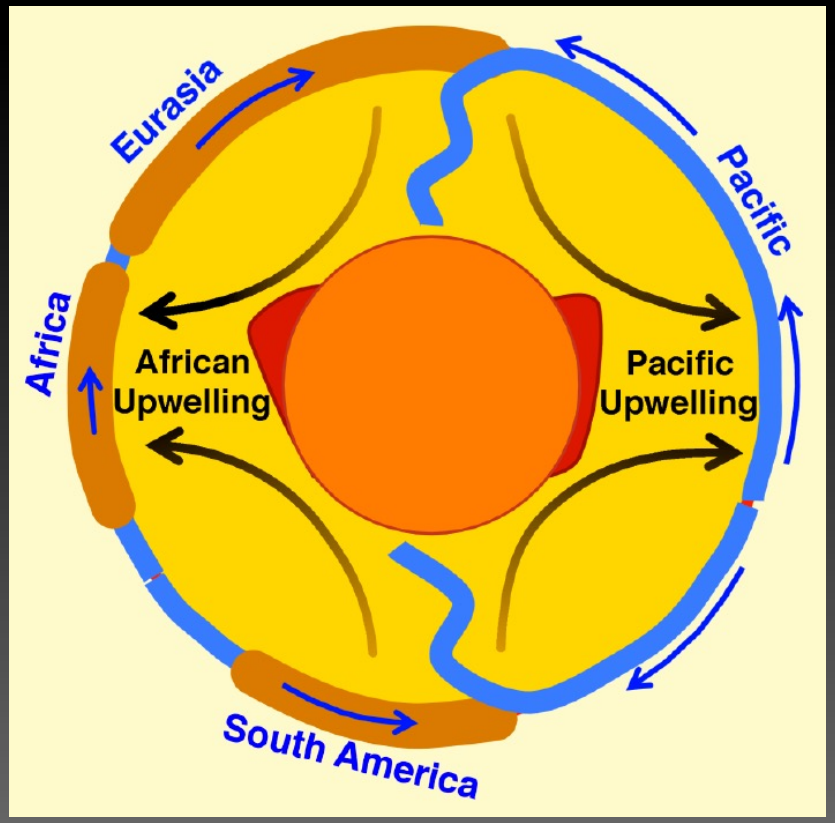
GOING GLOBAL…

- **Surface plate velocities as an expression of degree 2 convection?**

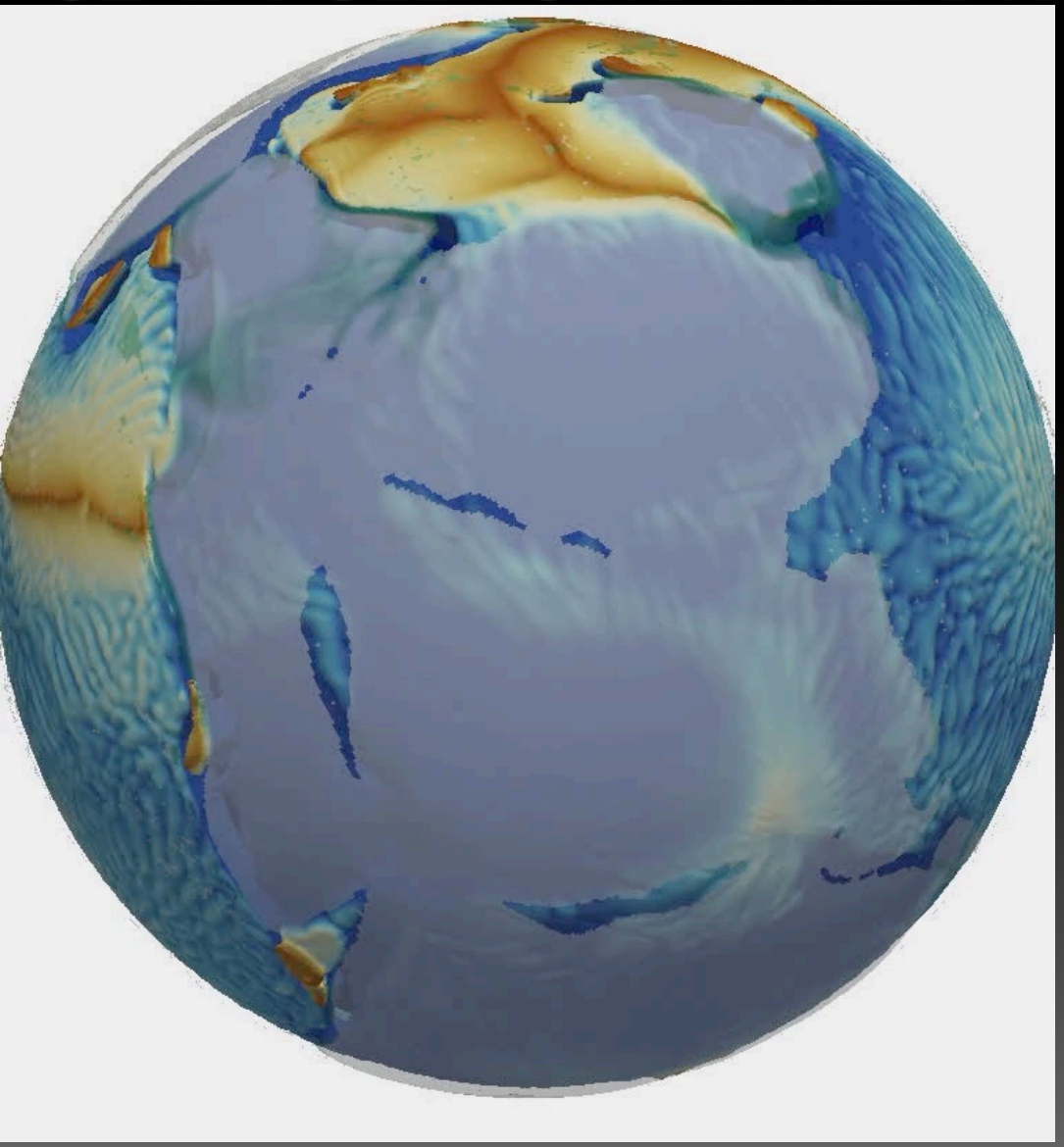




Conrad et al., 2013



SLAB PULL VS MANTLE DRAG



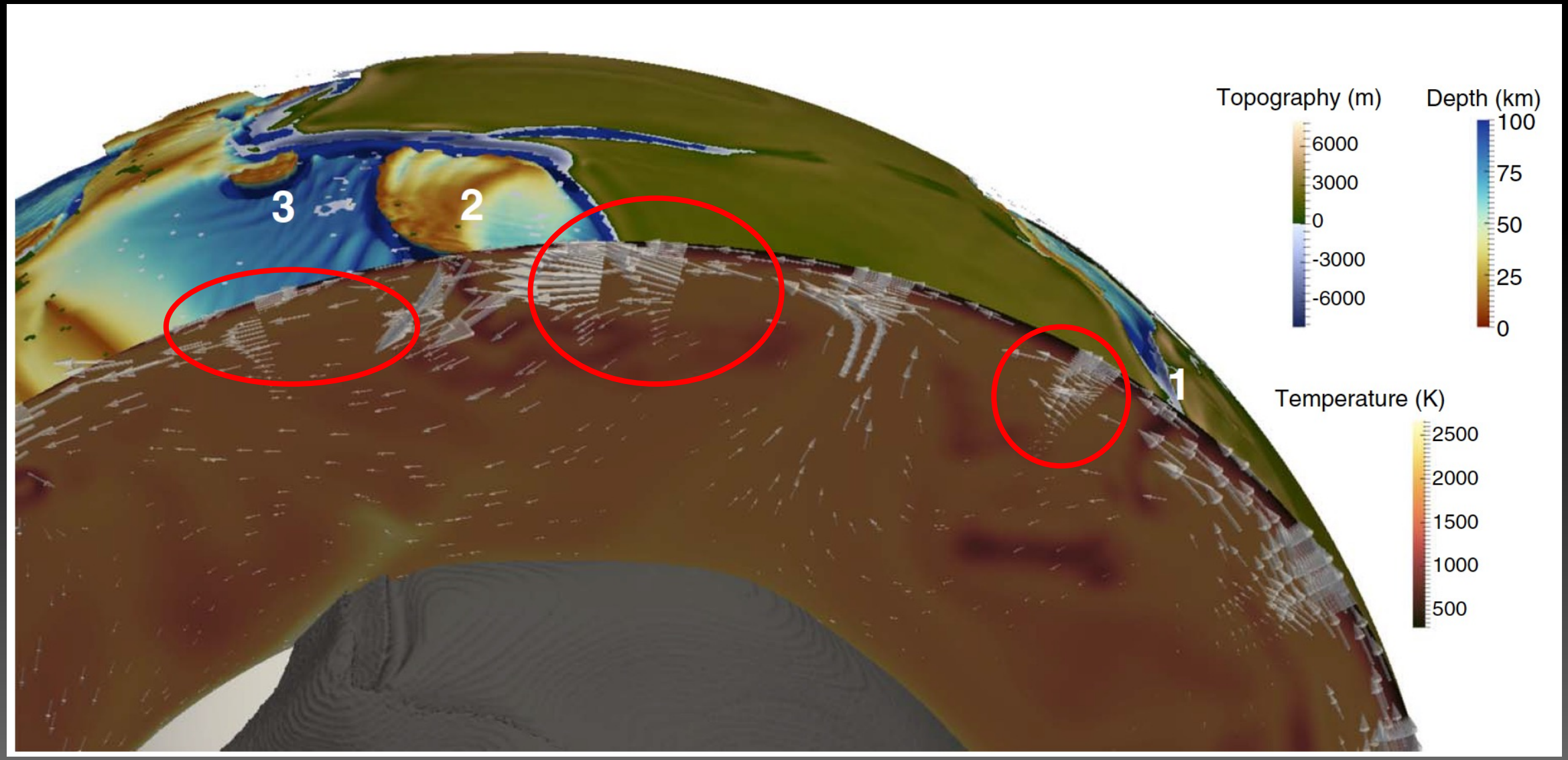
Surface

Interior

Coltice et al., 2020

SLAB PULL VS MANTLE DRAG

1 : collision zone
2 : back-arc bassin
3 : newly-formed subduction zone



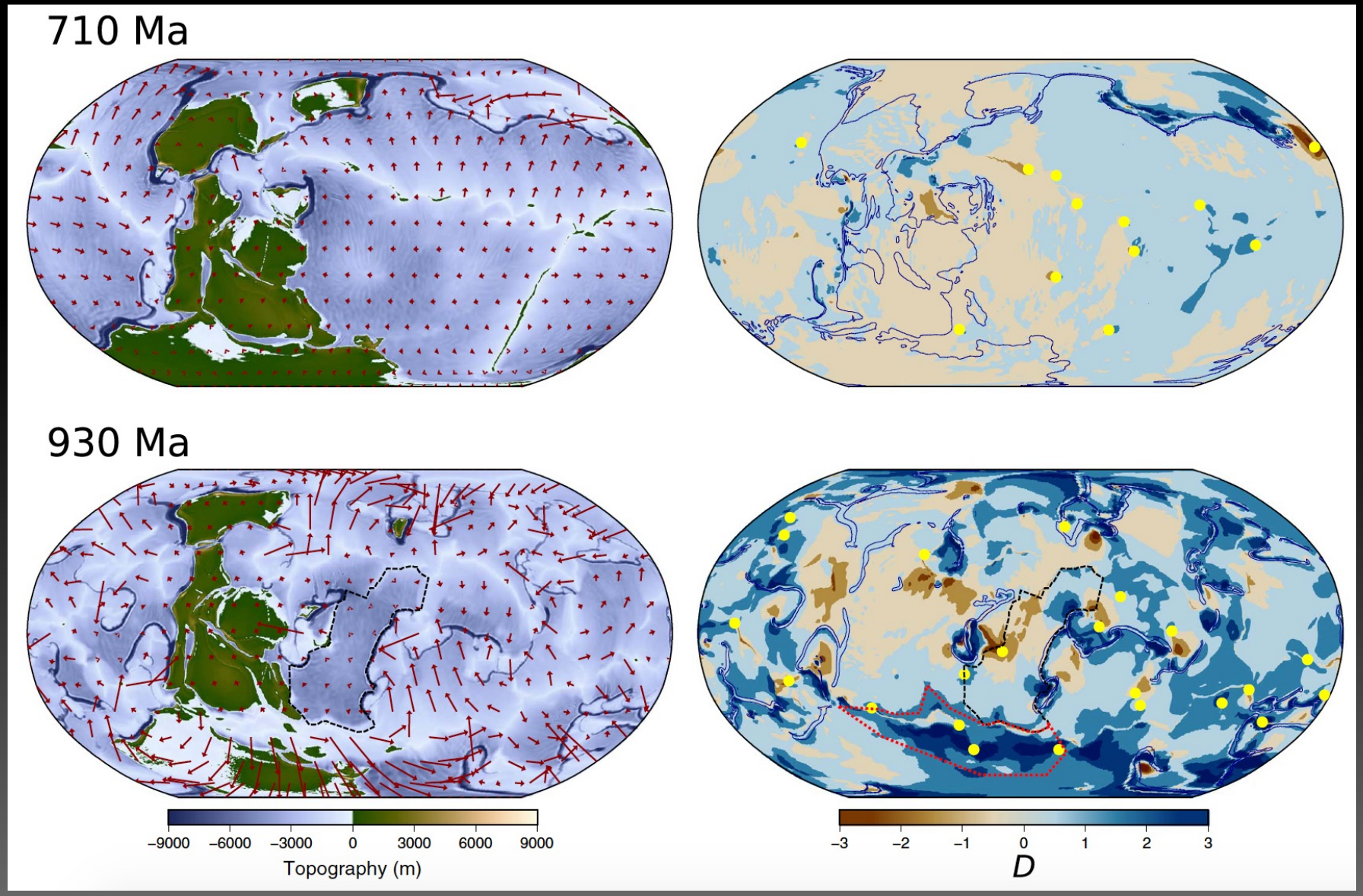
Coltice et al., 2020

SLAB PULL VS MANTLE DRAG

* D = drag coefficient
D<0 => mantle drag dominates
D>0 => slab pull dominates

Collision

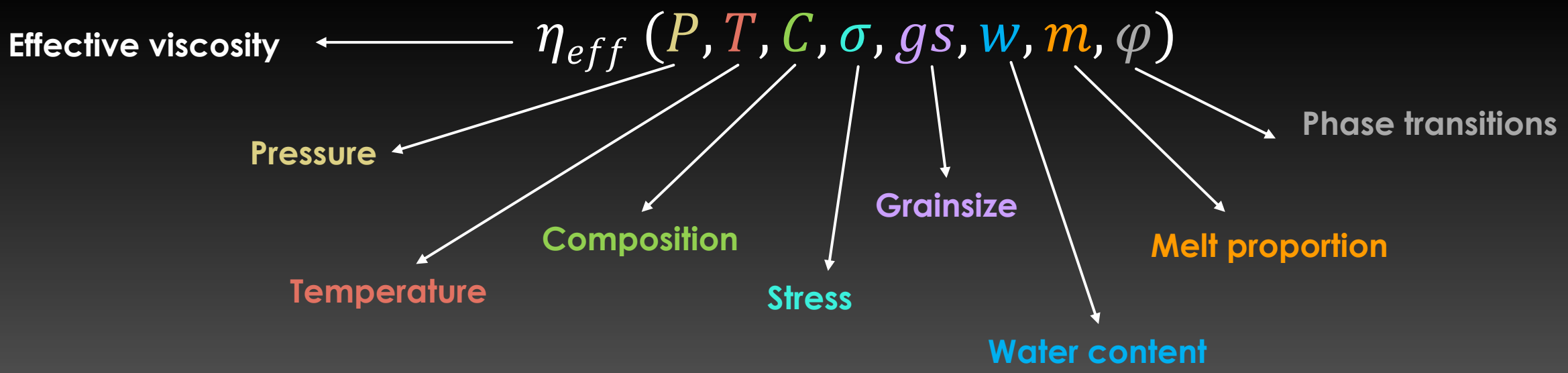
Break-up



Coltice et al., 2020

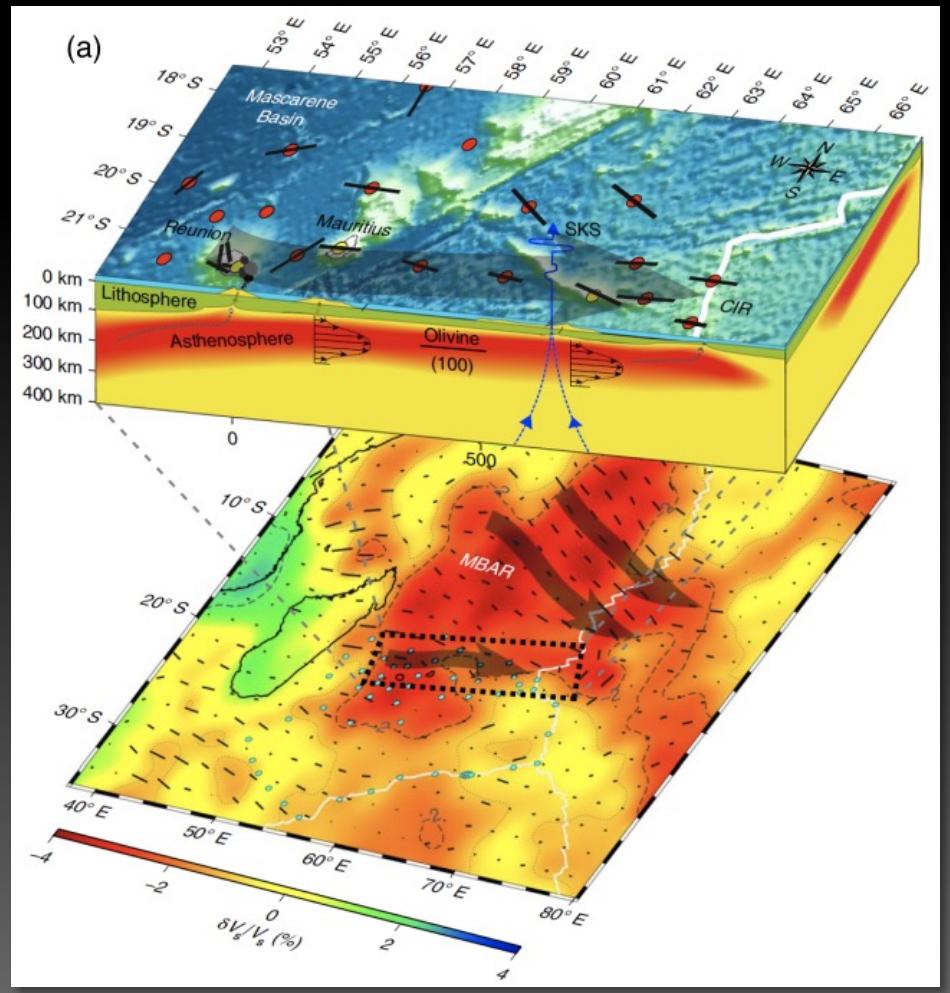
WHAT CONTROLS THE LITHOSPHERE-MANTLE COUPLING?

- **Rheology, the clue? But also our big problem… (as often…)**

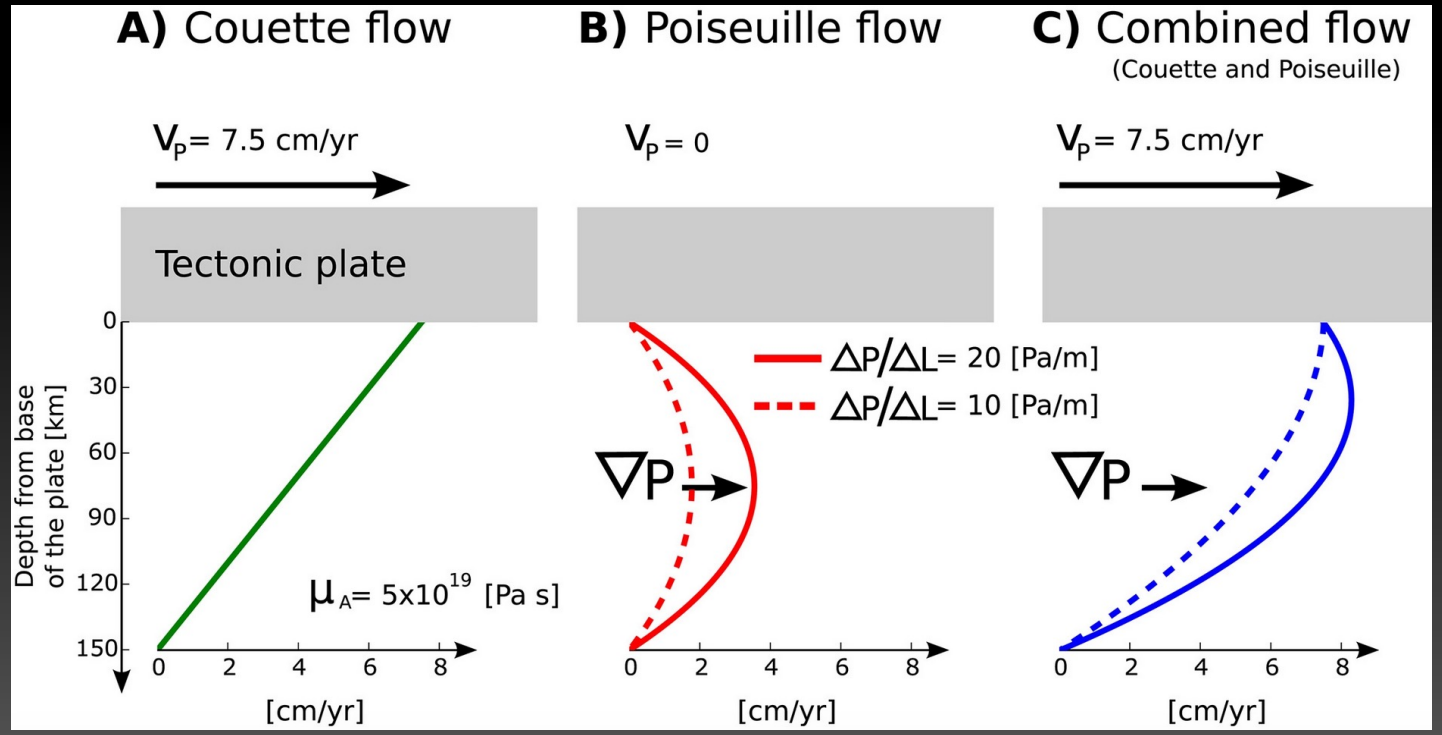


WHAT CONTROLS THE LITHOSPHERE-MANTLE COUPLING?

- **Pressure gradients and shear stresses:**



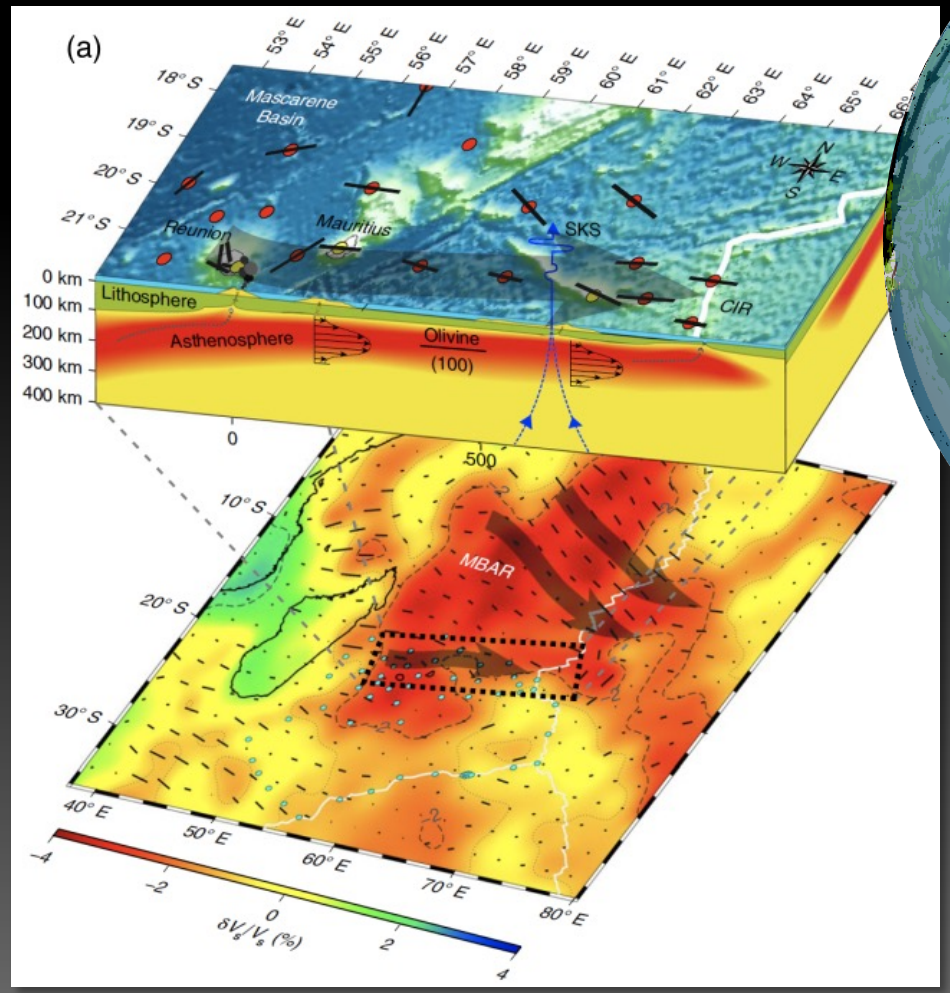
Barruol et al., 2019

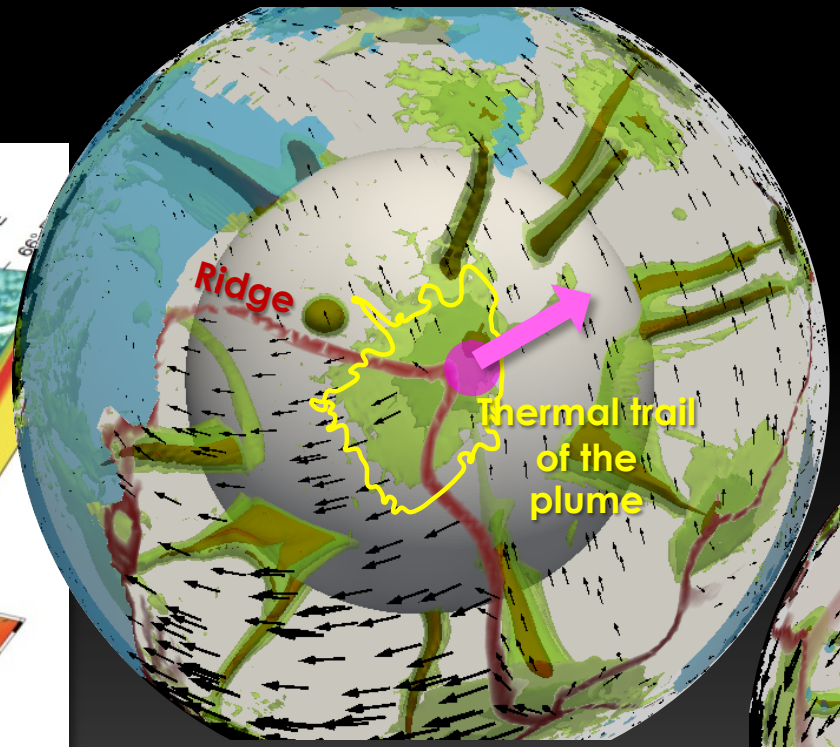


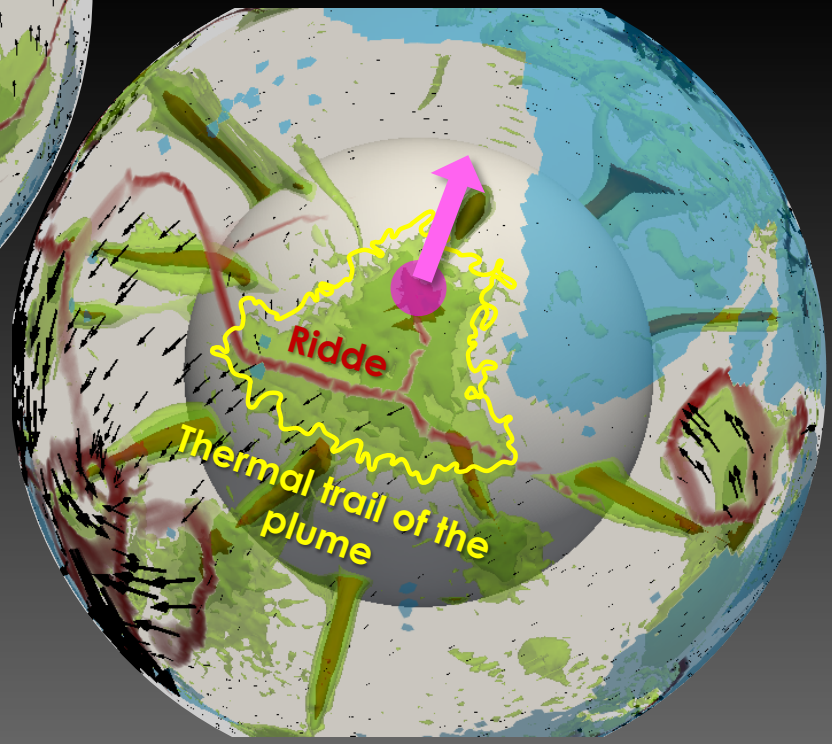
Stotz et al., 2018

WHAT CONTROLS THE LITHOSPHERE-MANTLE COUPLING?

- **Integration over time?**



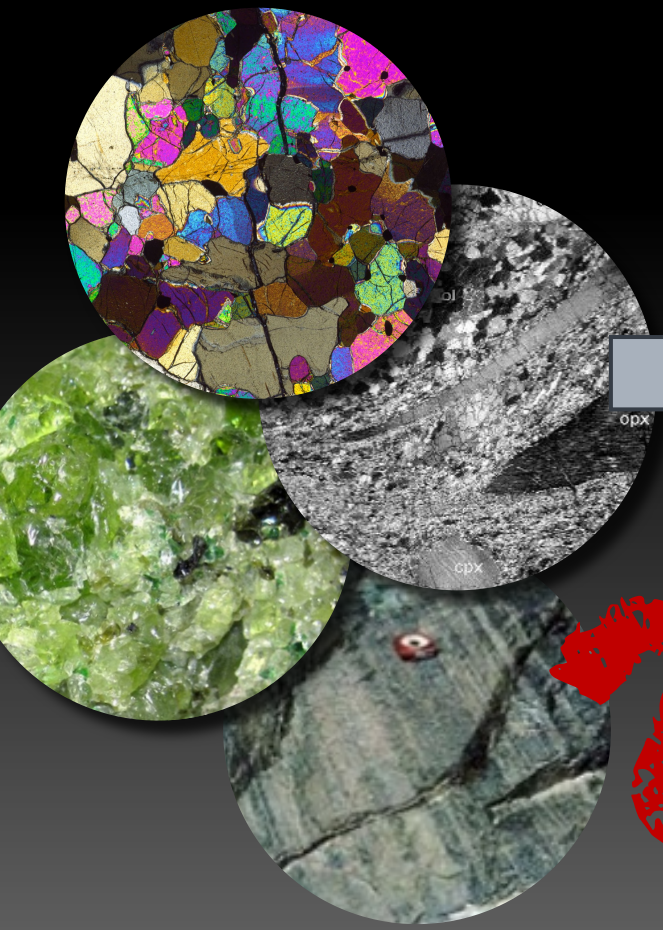


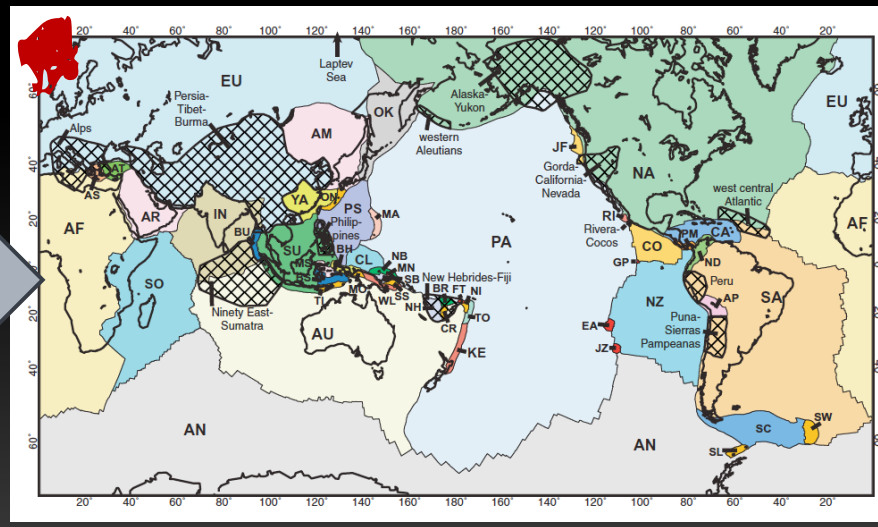


Barruol et al., 2019

How to initiate new splate boundaries?

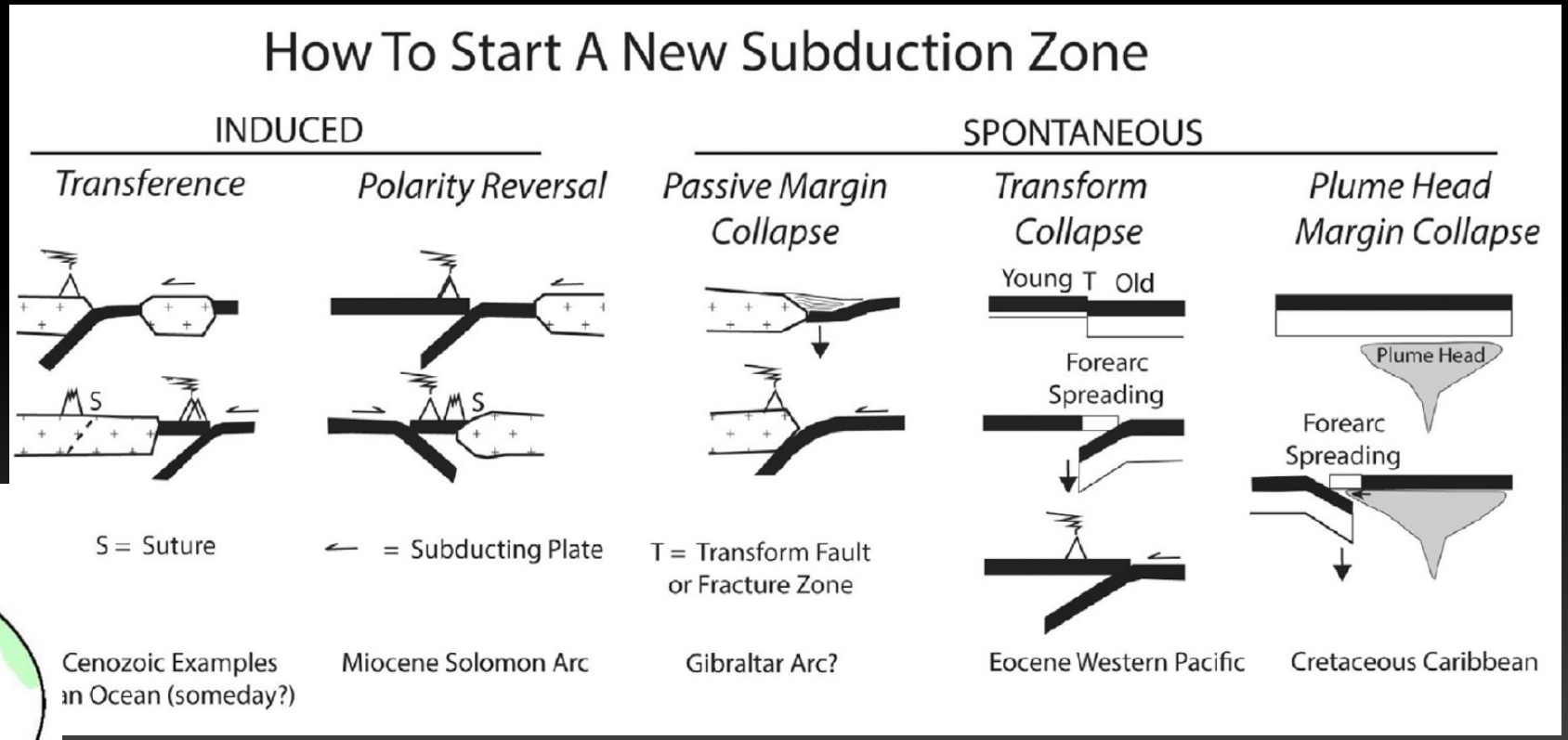
A MULTI-SCALE PROBLEM

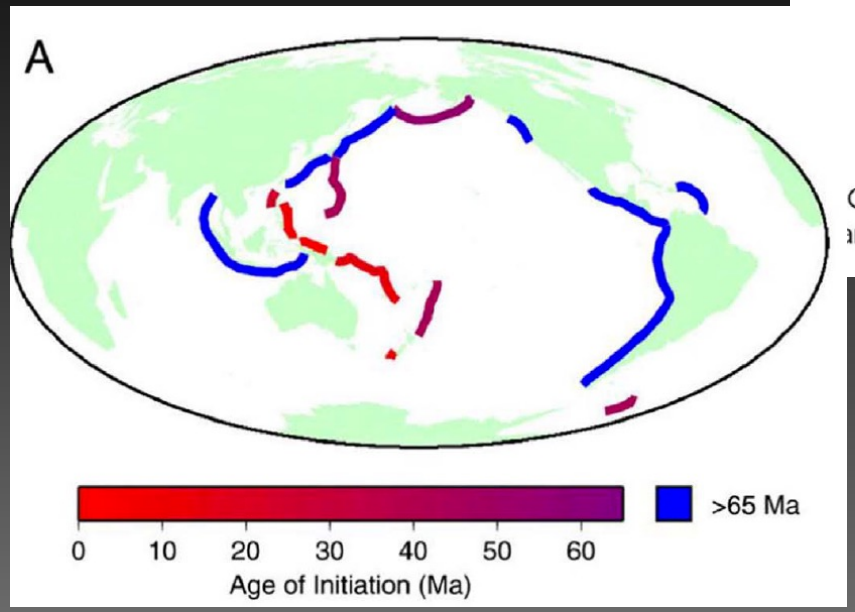




How to initiate new subductions?

SPONTANEOUS OR FORCED INITIATION?

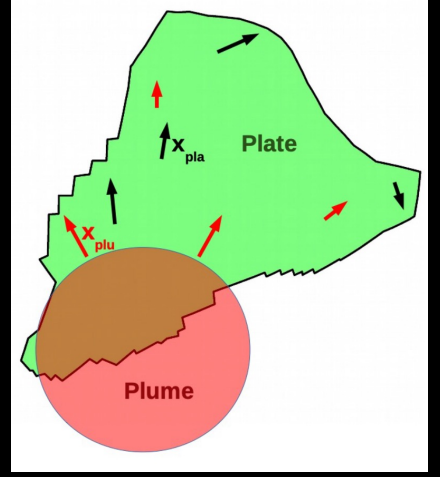


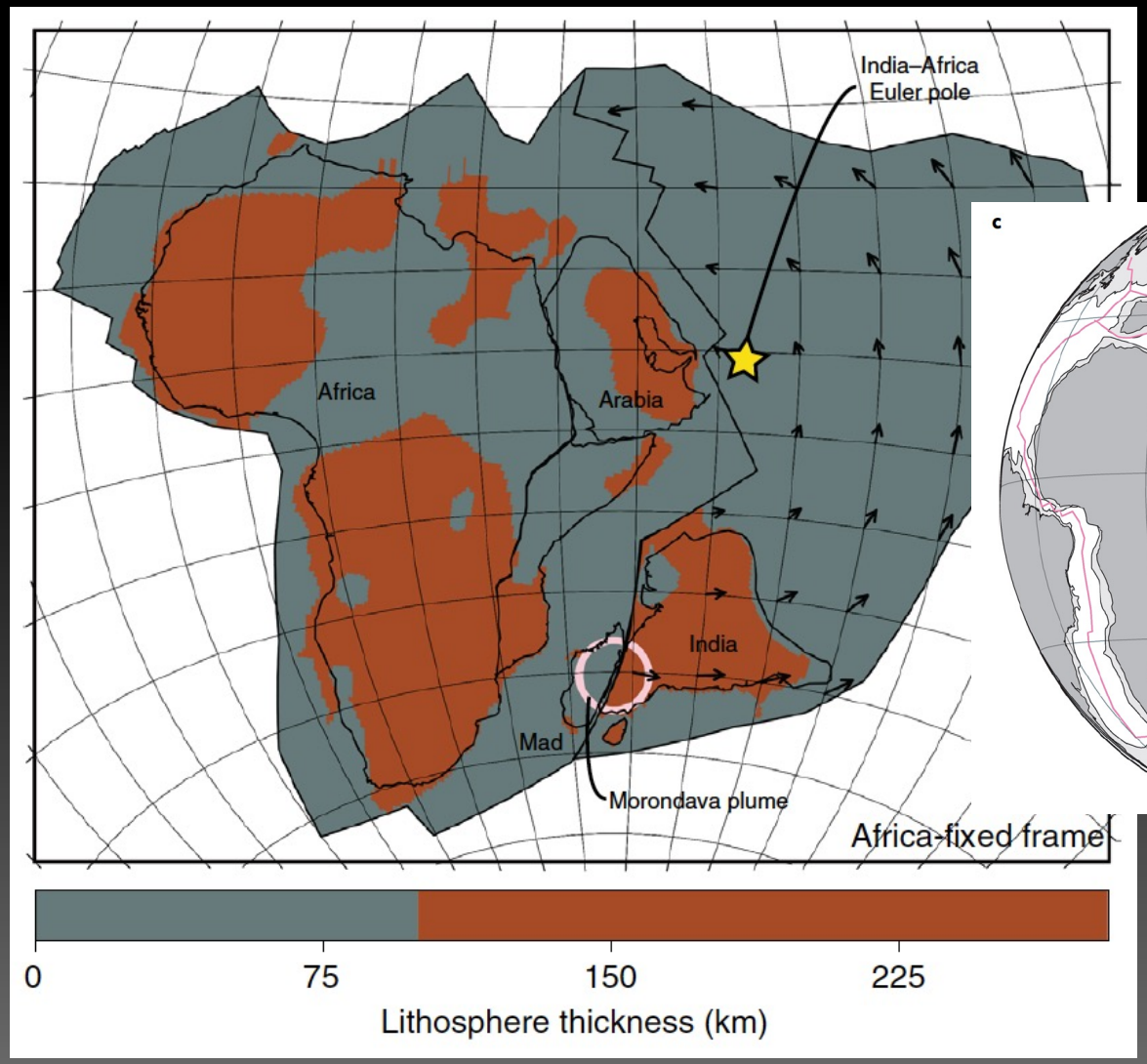


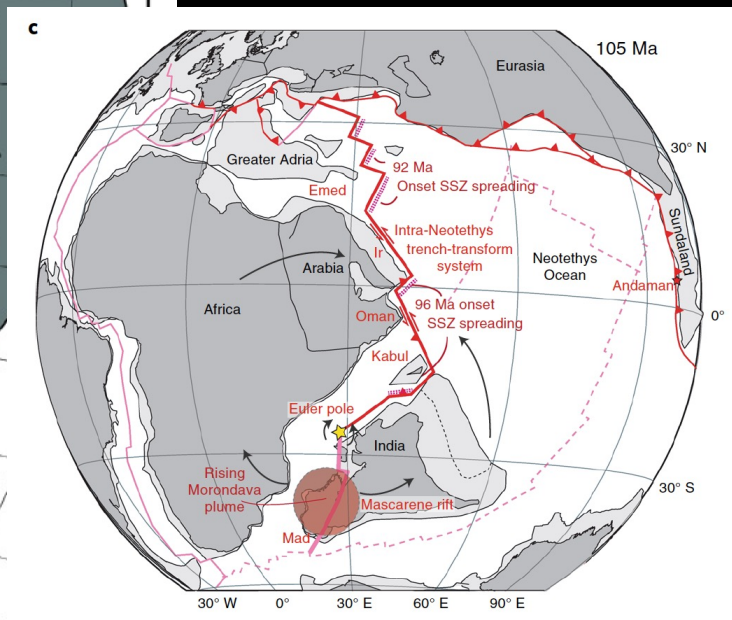
Stern and Gerya, 2017

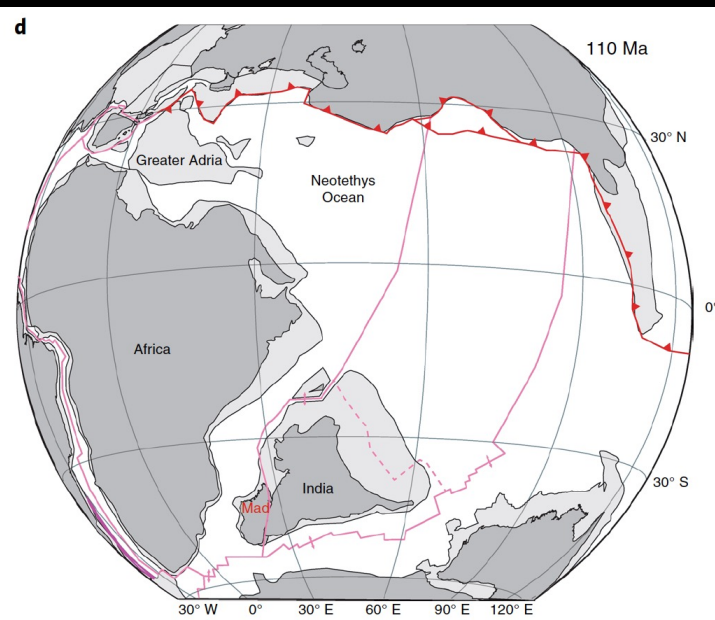
Also, visit the SZI database: https://www.szidatabase.org/

MANTLE PLUMES AND SLAB INITIATION?



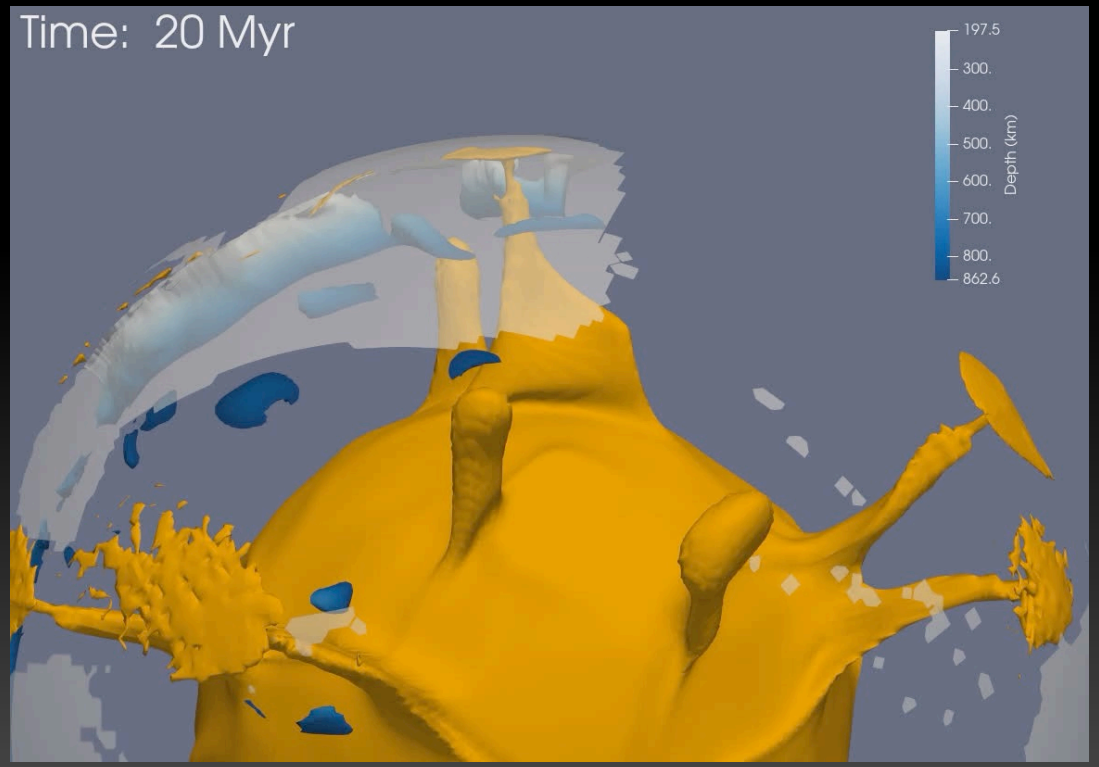


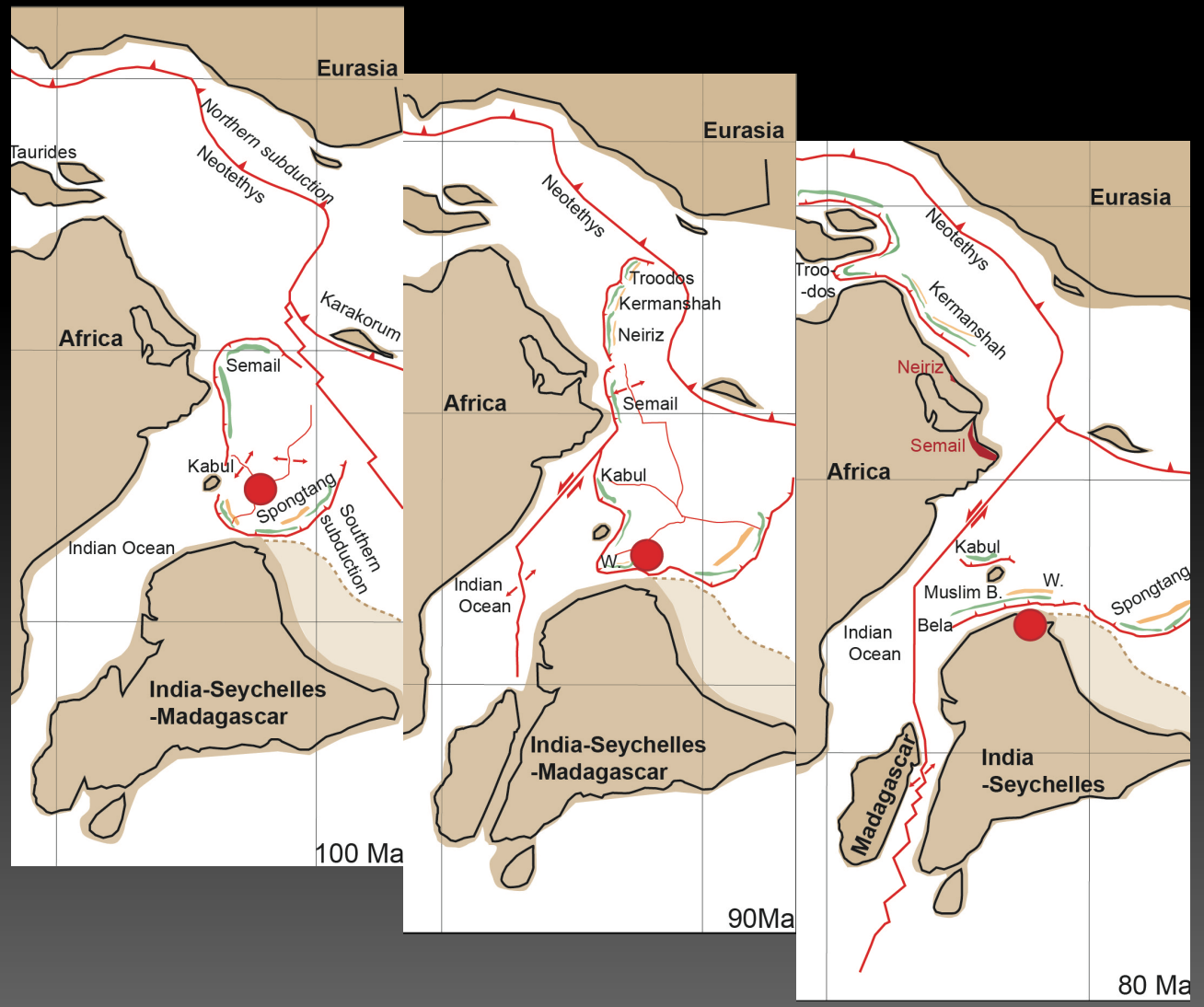




Van Hinsbergen et al., 2021

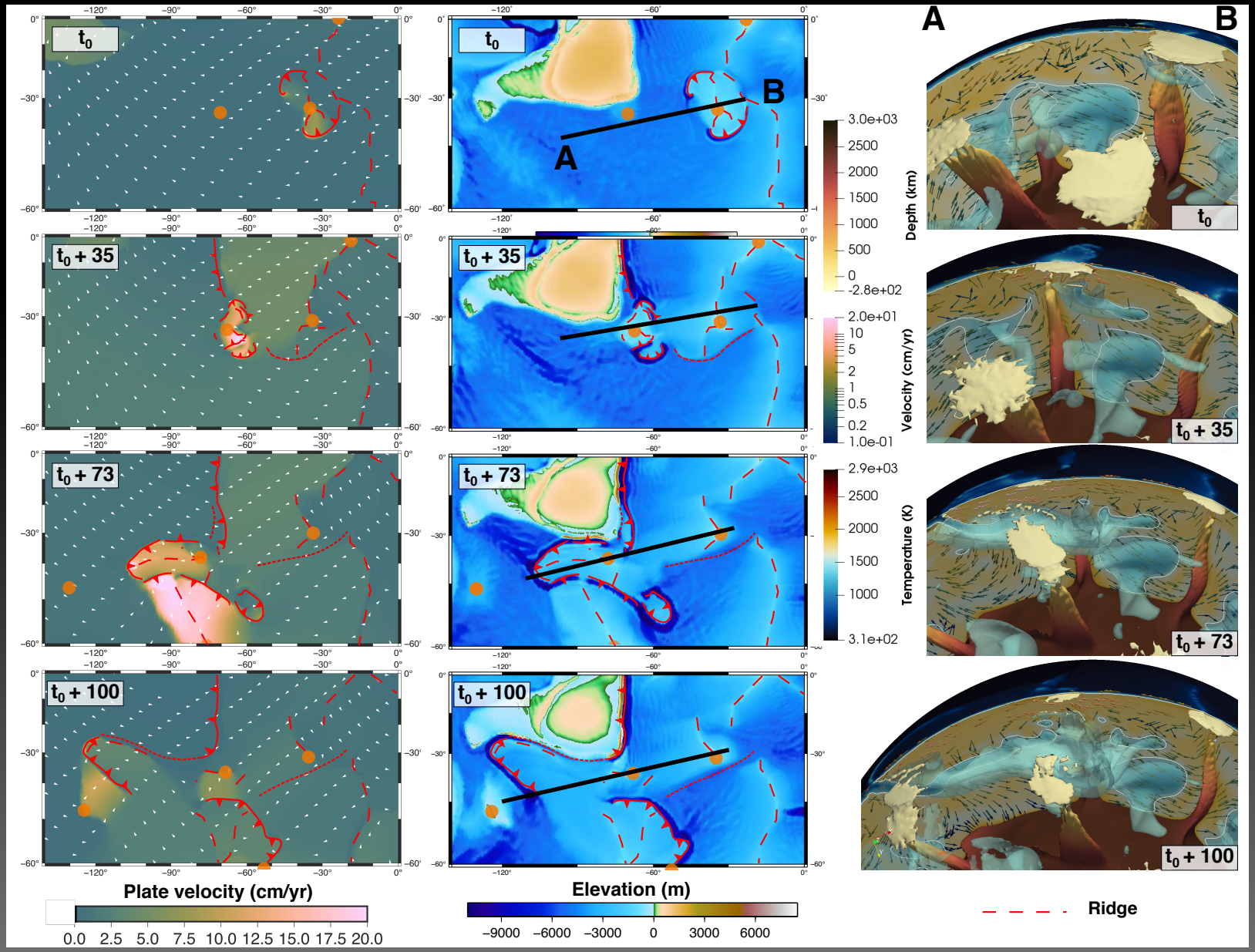
MANTLE PLUMES AND SLAB INITIATION?

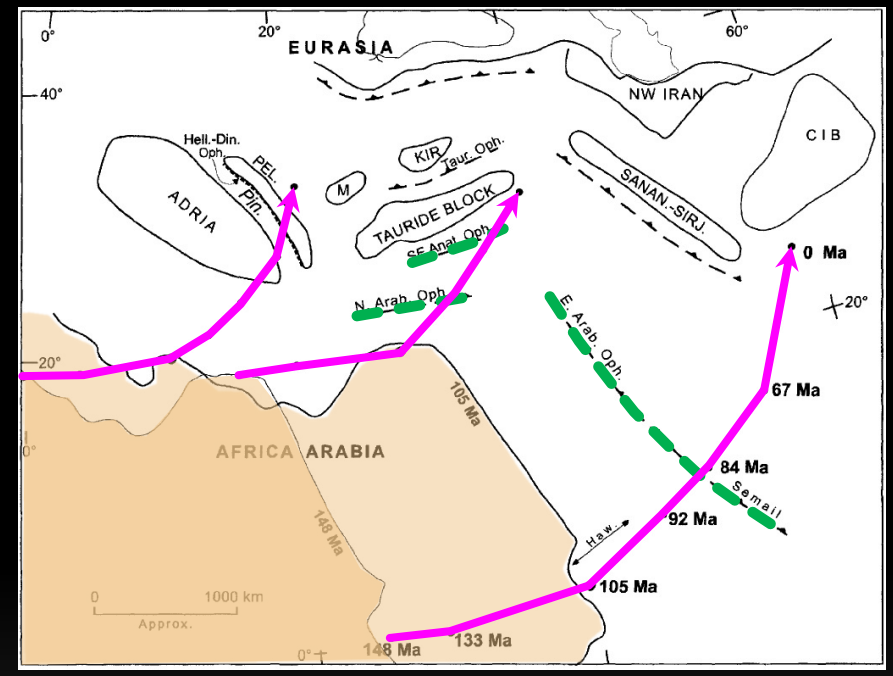




Rodriguez et al., *2021*

MANTLE PLUMES AND SLAB INITIATION?



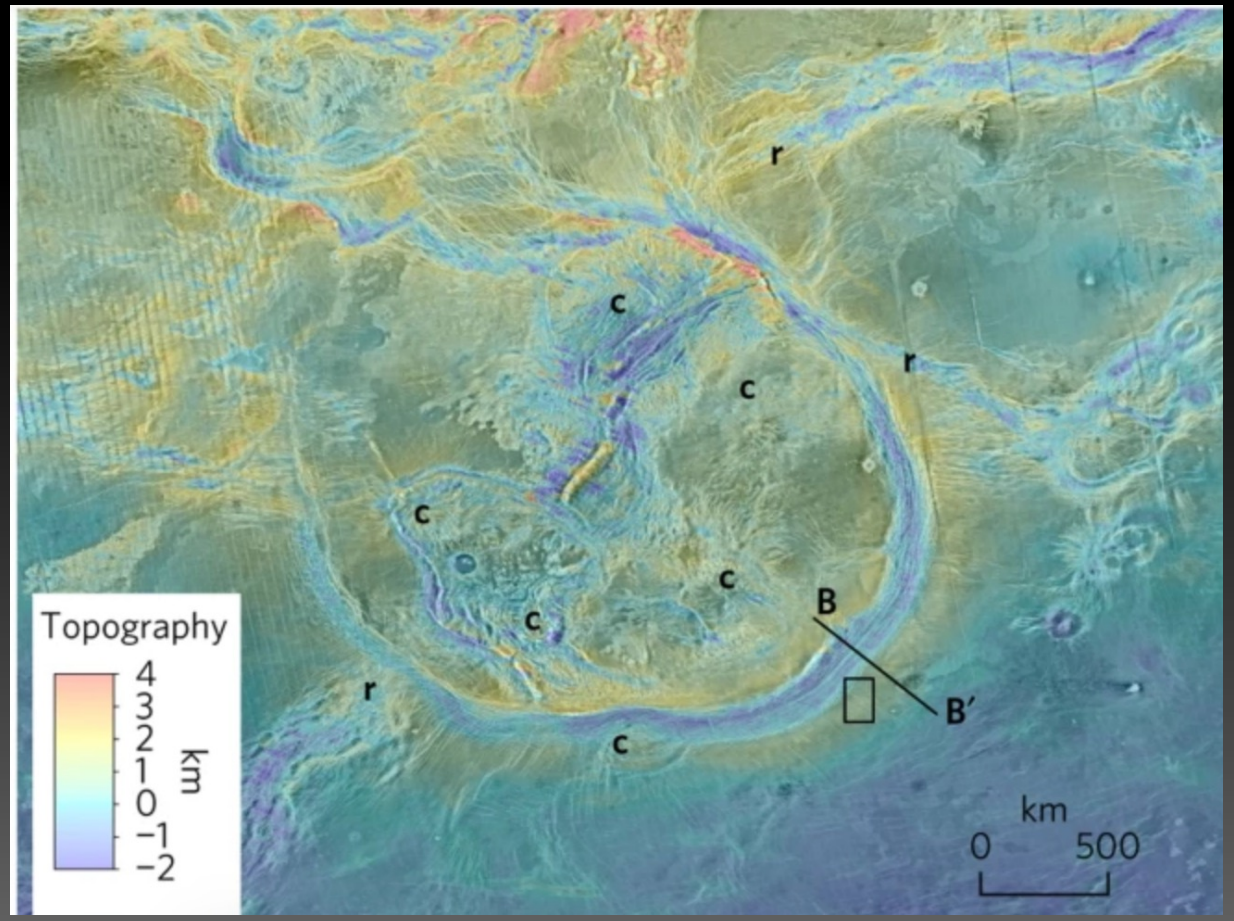


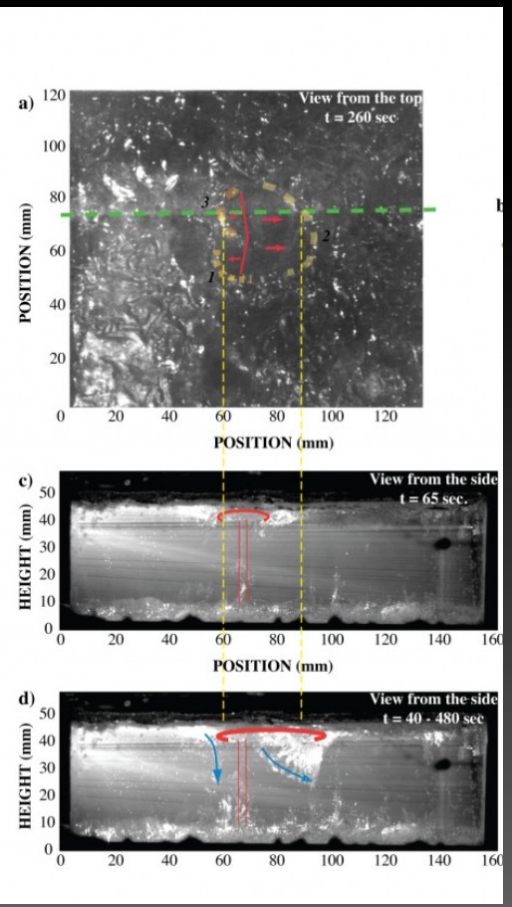
Garfunkel, 2006

- **Plumes as the driver of Global Plate Reorganization events?**

MANTLE PLUMES AND SLAB INITIATION?

- **On other planets? Example of Venus**

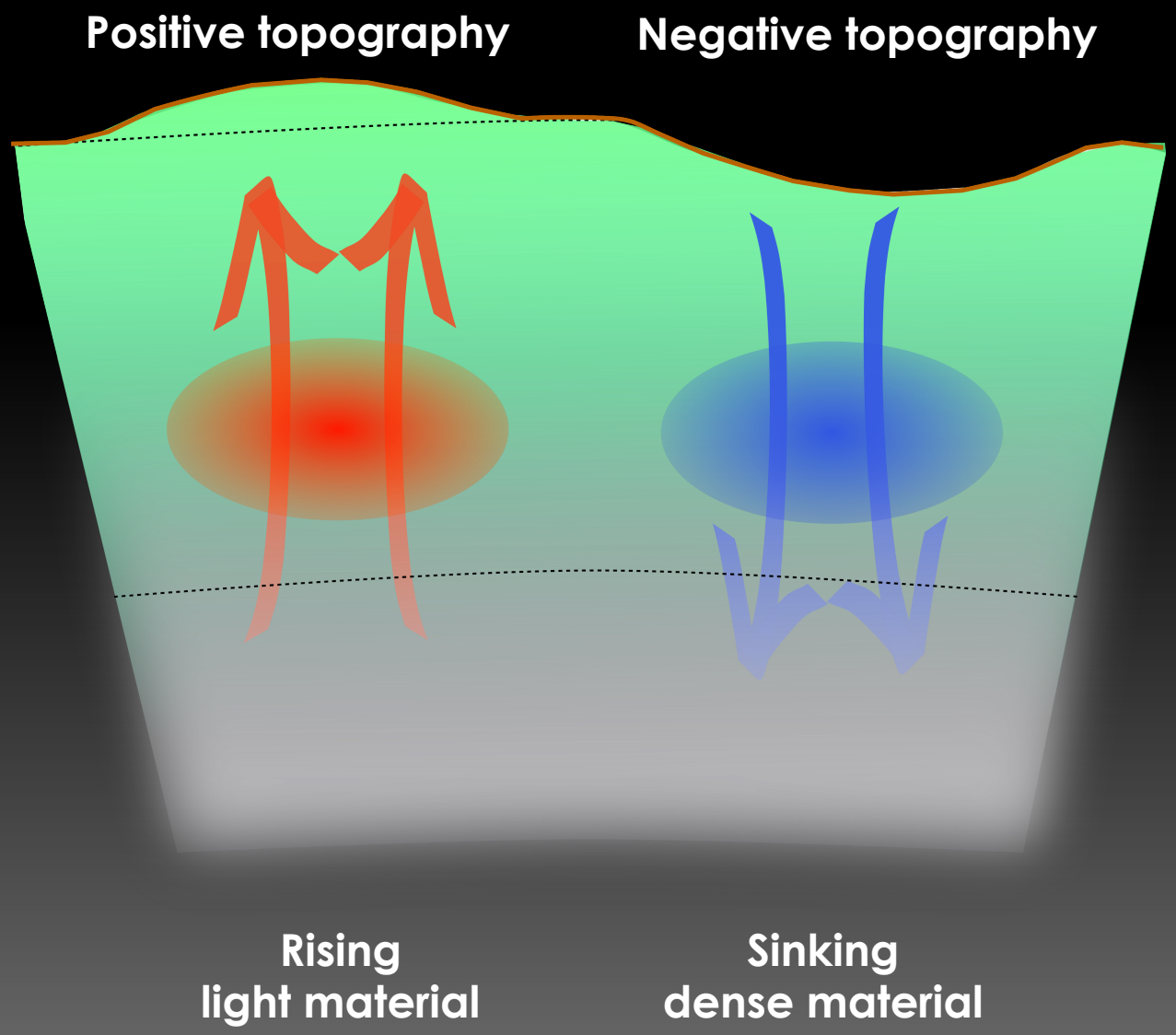




Davaille et al., 2017

Mantle convection and surface topography

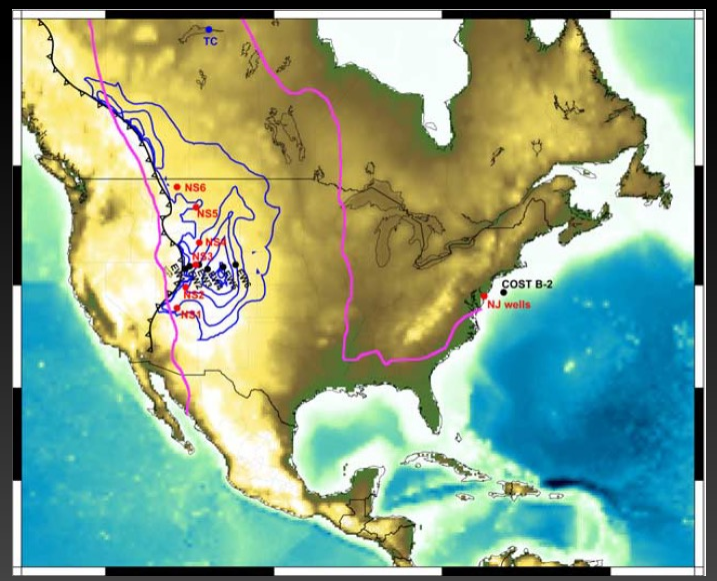
WHAT IS DYNAMIC TOPOGRAPHY?



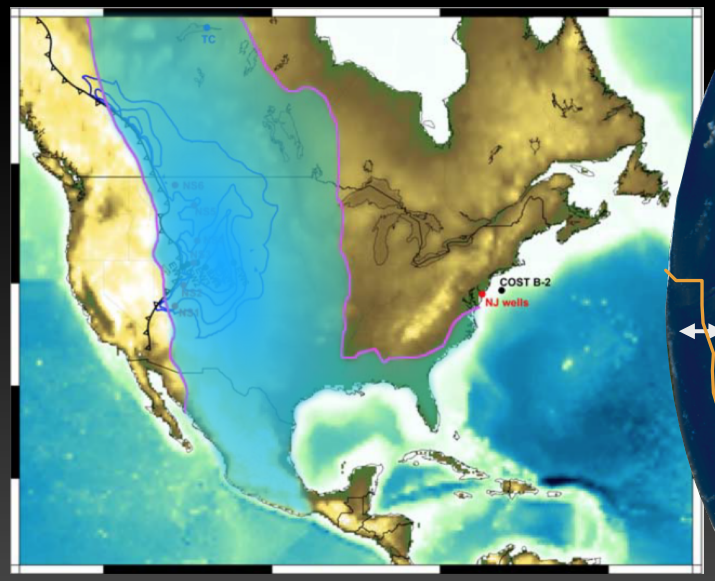
IMPORTANCE OF DYNAMIC TOPOGRAPHY

- **Paleogeographic/paleotopographic reconstructions**

Present-day



95 Ma ago

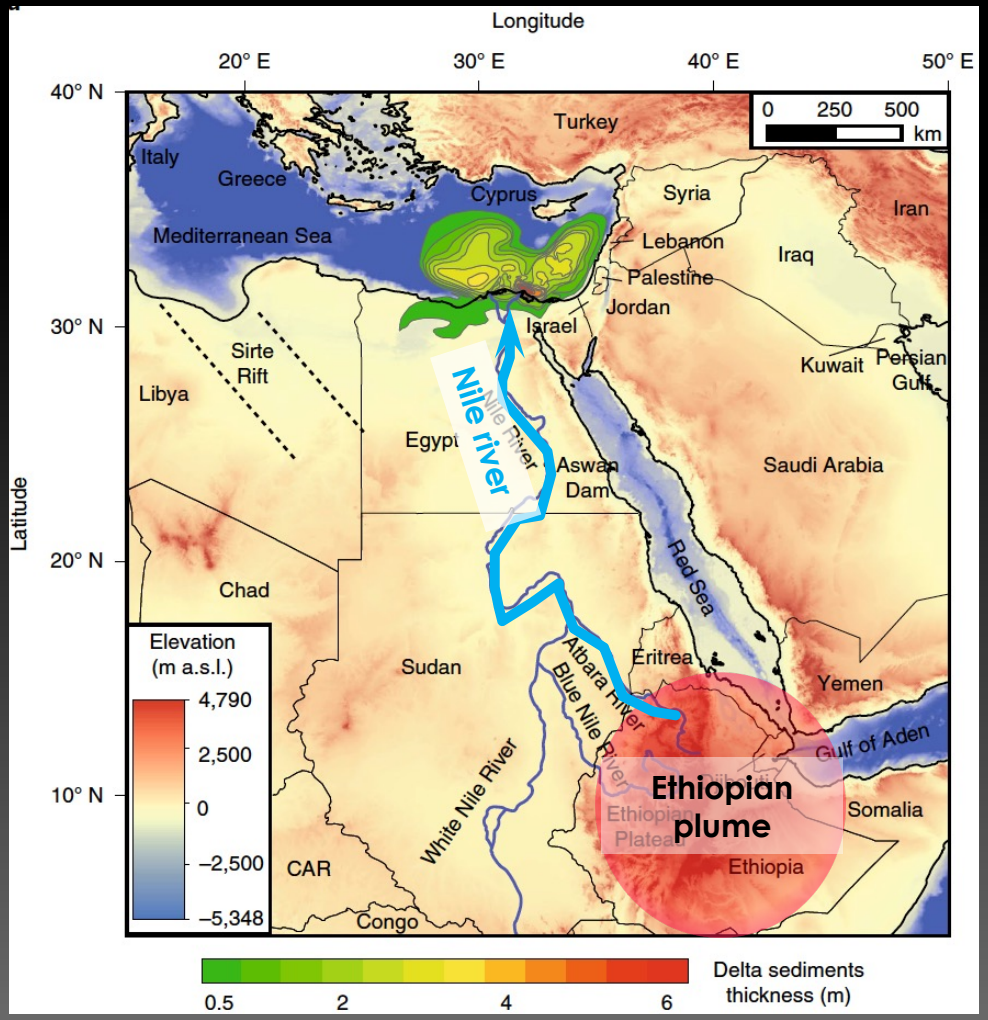


Spasojevic et al., 2009

Etopo_2

IMPORTANCE OF DYNAMIC TOPOGRAPHY

- **Paleogeographic/paleotopographic reconstructions**

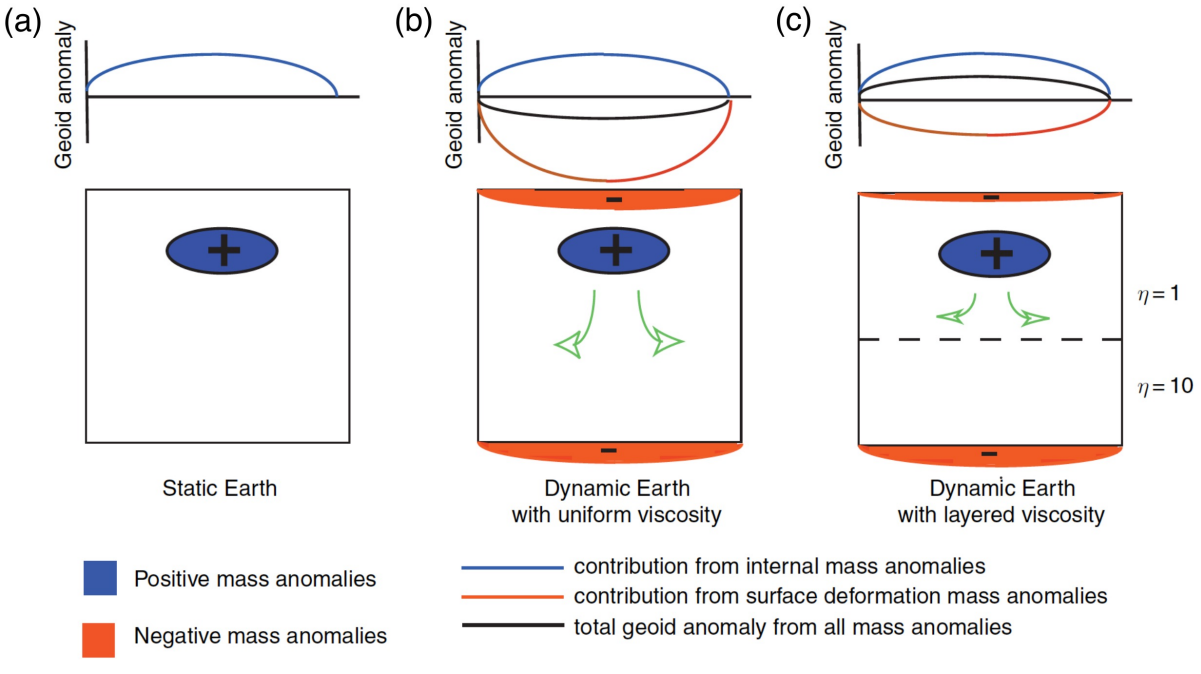


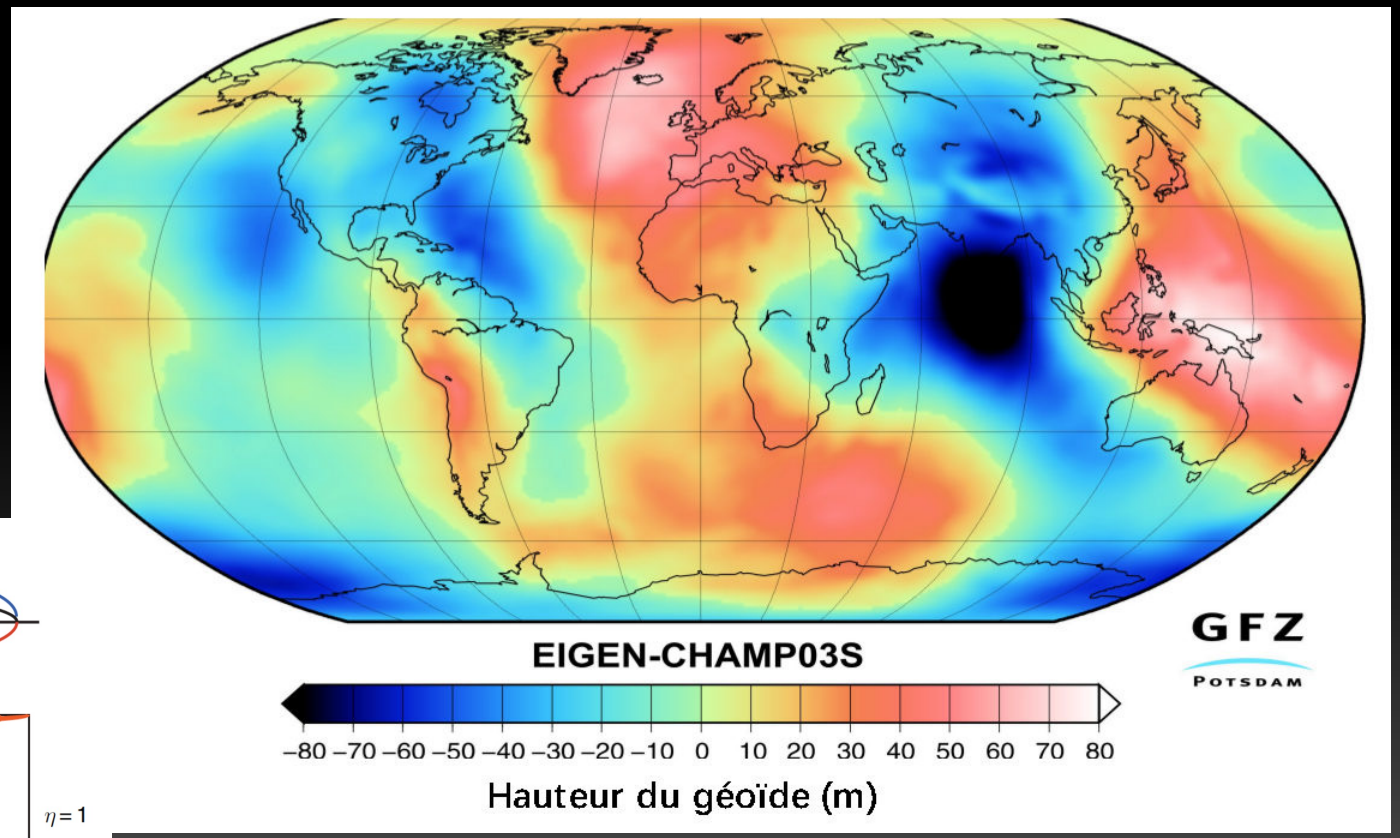
Faccenna et al., 2019

IMPORTANCE OF DYNAMIC TOPOGRAPHY

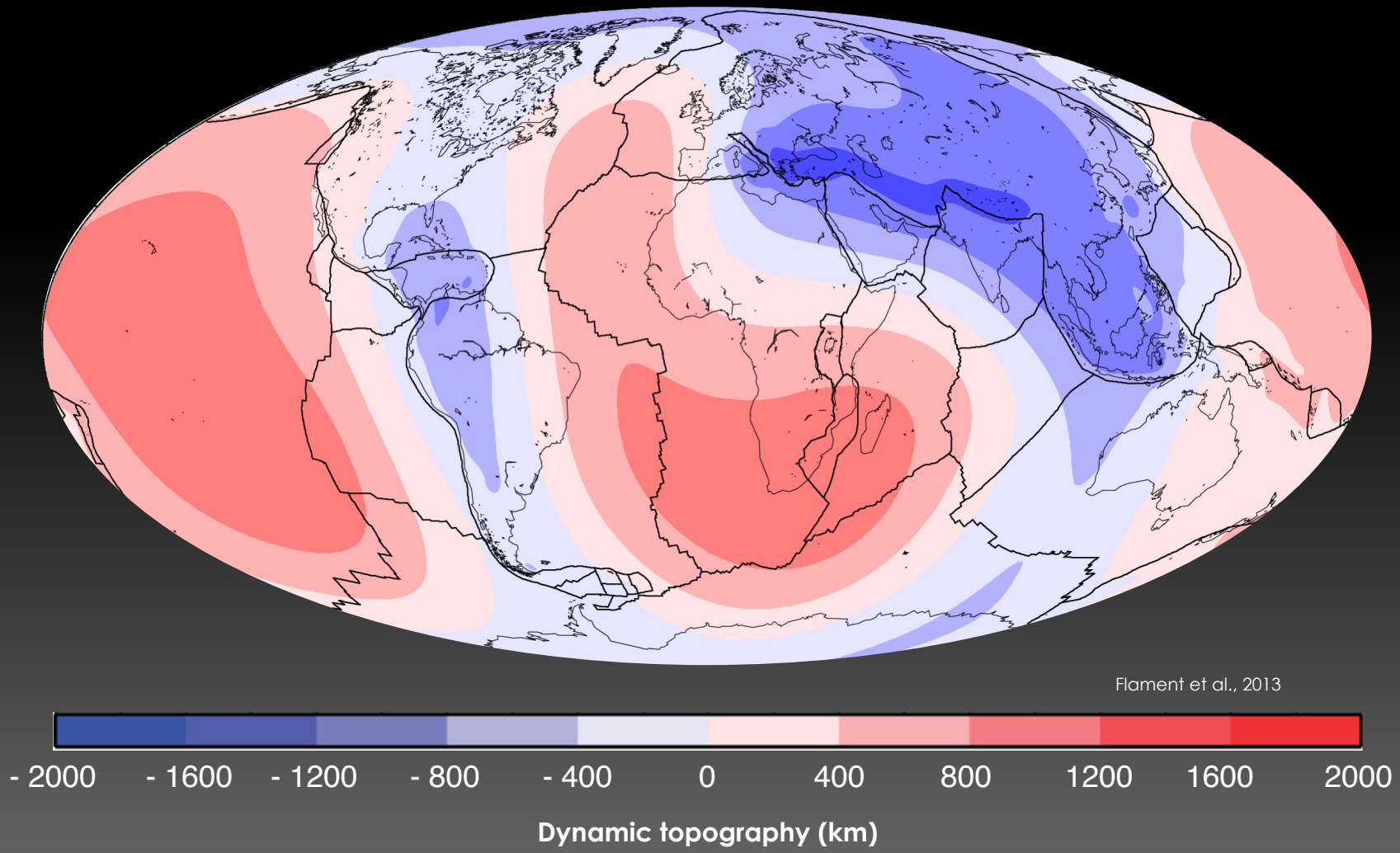
- **Past geoid and TPW:**

King, 2007

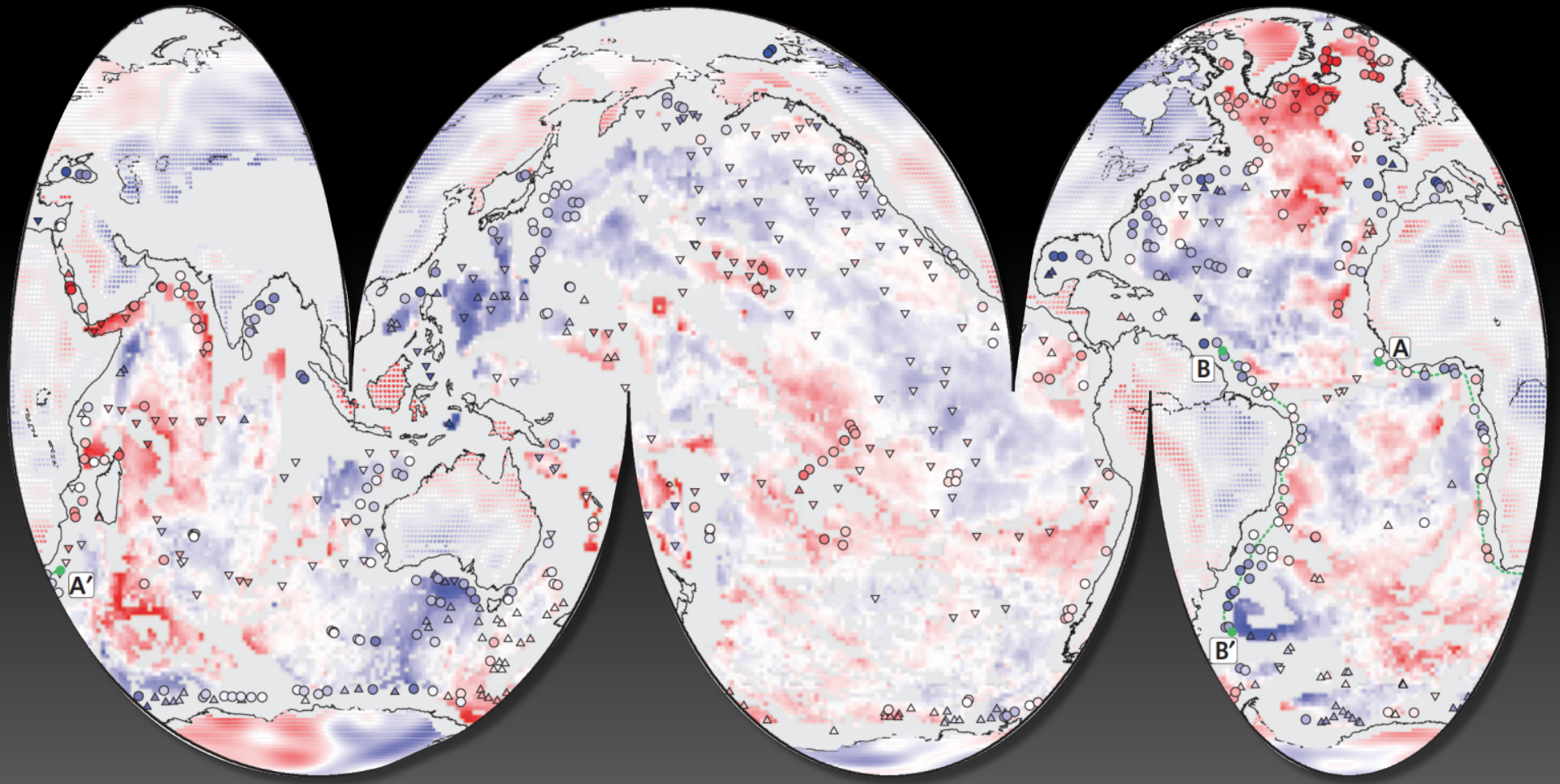




MODELS OF DYNAMIC TOPOGRAPHY

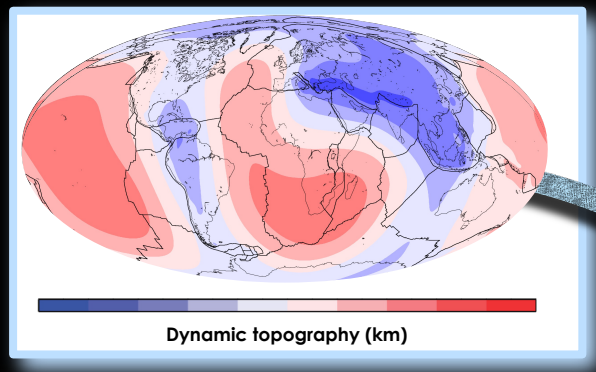


OBERVATION-BASED DYNAMIC TOPOGRAPHY

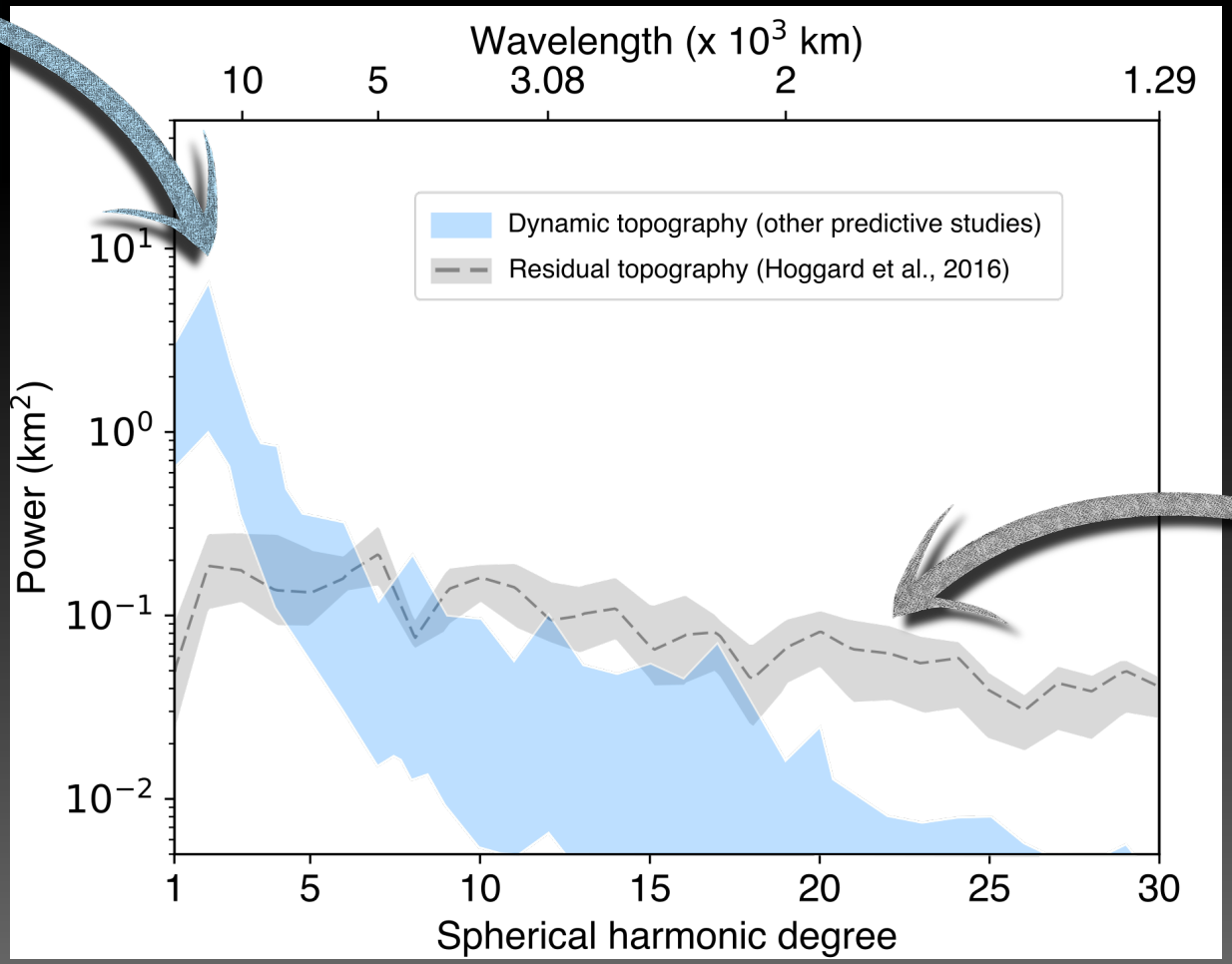


Hoggard et al., 2016

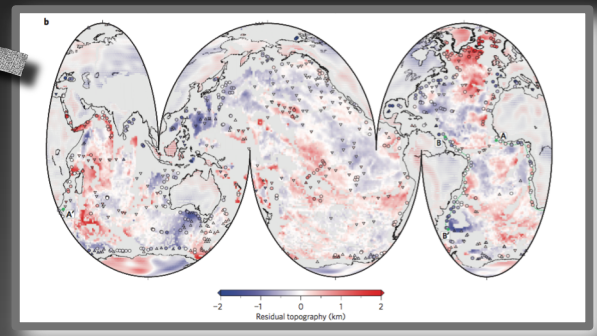
POWER SPECTRUM OF DYNAMIC TOPOGRAPHY



Flament et al., 2013



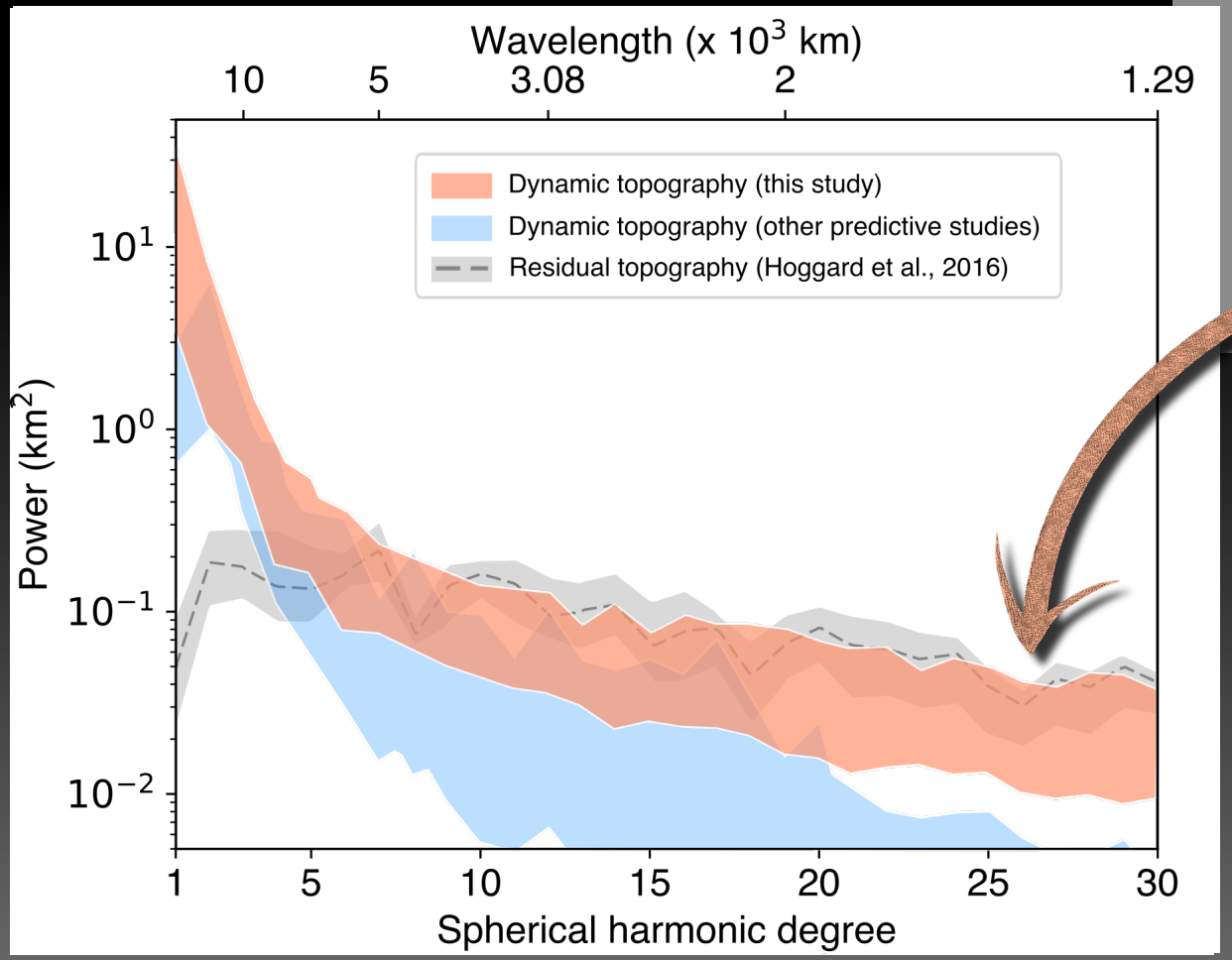
Hoggard et al., 2016

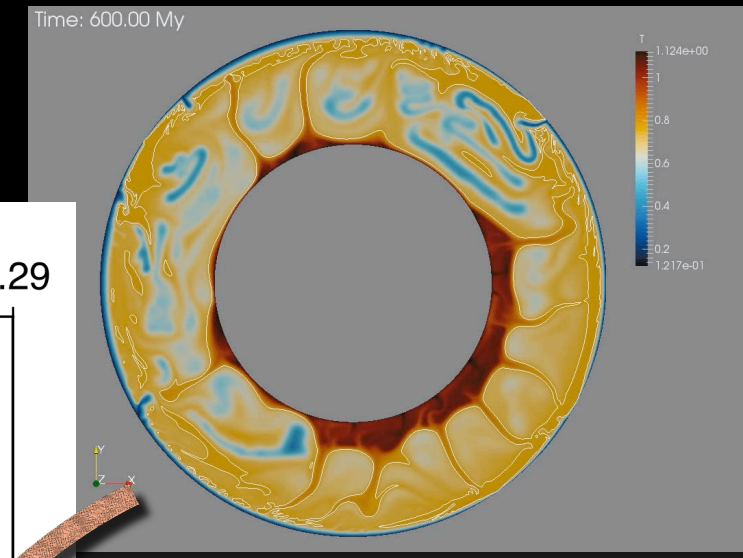


Large-scale

Intermediate-scale

POWER SPECTRUM OF DYNAMIC TOPOGRAPHY

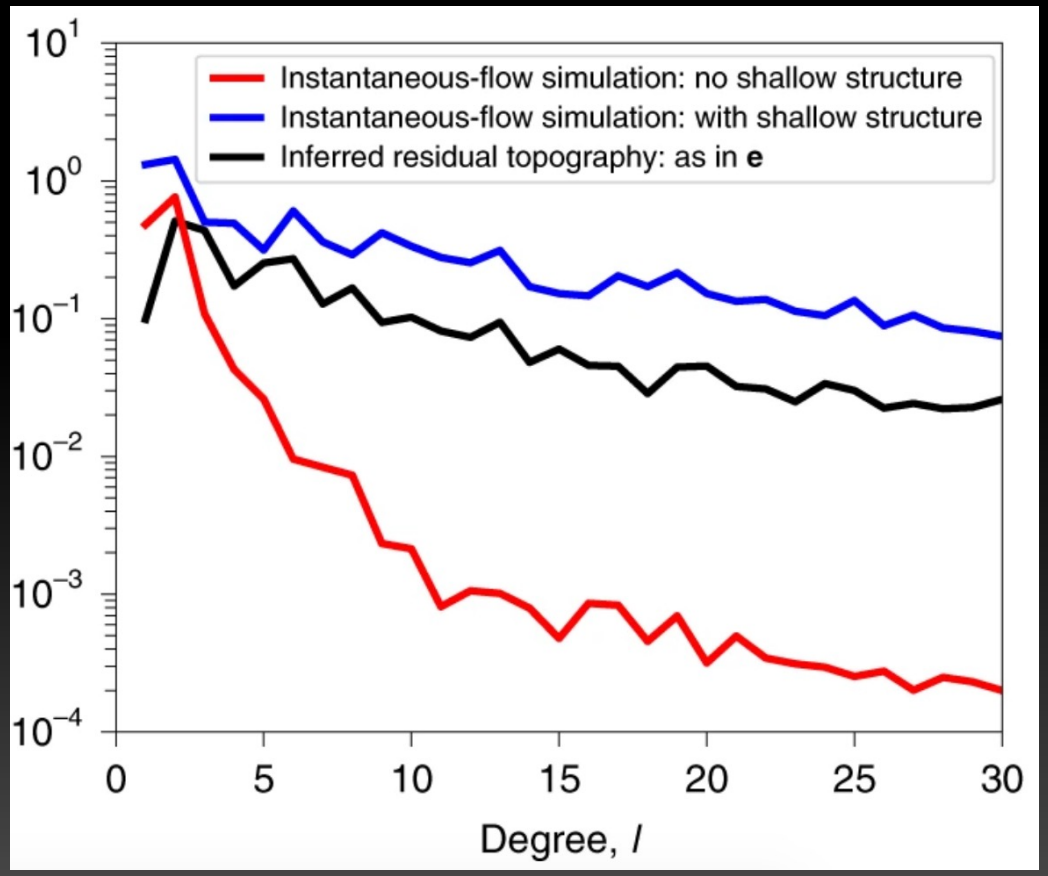




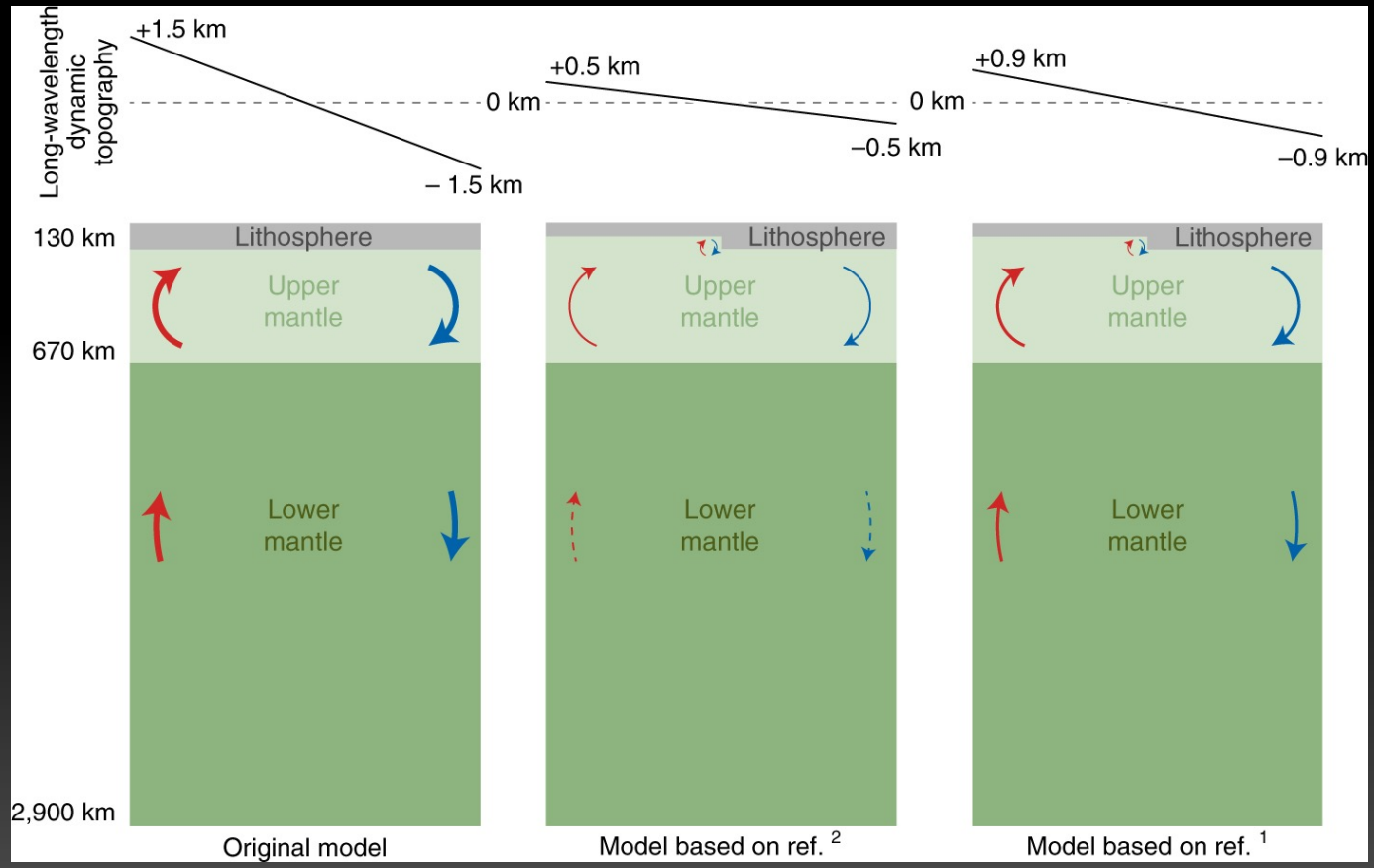
Large-scale

Intermediate-scale

POWER SPECTRUM OF DYNAMIC TOPOGRAPHY



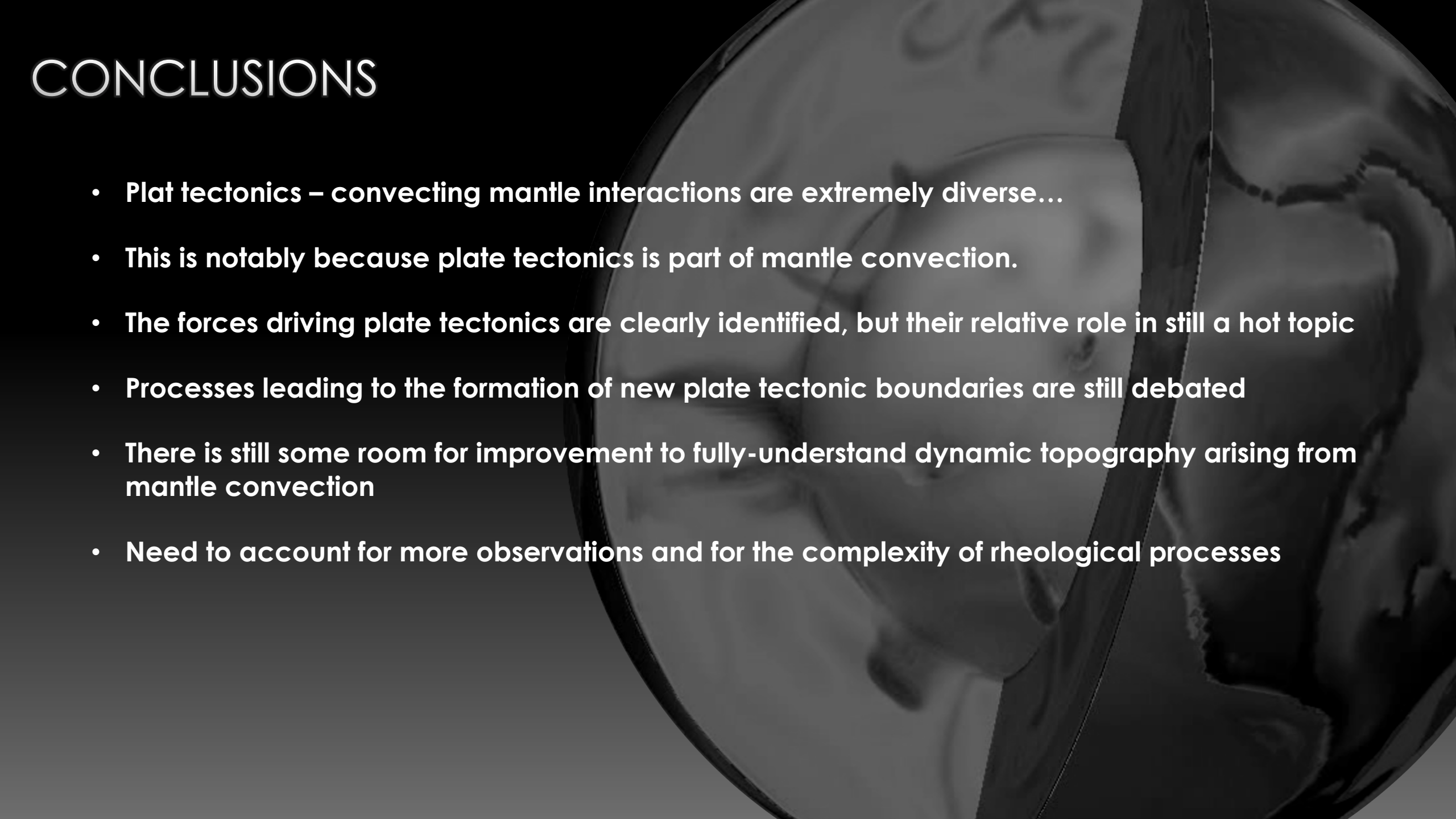
Davies et al., 2019



Flament, 2019

To be continued..

CONCLUSIONS



- Plat tectonics – convecting mantle interactions are extremely diverse…
- This is notably because plate tectonics is part of mantle convection.
- The forces driving plate tectonics are clearly identified, but their relative role in still a hot topic
- Processes leading to the formation of new plate tectonic boundaries are still debated
- There is still some room for improvement to fully-understand dynamic topography arising from mantle convection
- Need to account for more observations and for the complexity of rheological processes

CONCLUSIONS

- Plat tectonics – convecting mantle interactions are extremely diverse…
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- Need to account for more observations and for the complexity of rheological processes

- *"Scientific debate" is a driver of new knowledge!*
- *The key(s) probably reside(s) in multi-disciplinary synergy*

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Alice Adenis

Lucia Perez-Diaz

https://didthisreallyhappen.net