Mantle geodynamics

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with materials from lectures by Stéphane Labrosse, Maëlis Arnould, Yanick Ricard, Maylis Landeau, Catherine Thoraval

Deep Earth Doctoral School - Les Houches - Autumn 2022

ÉCOLE DE PHYSIQUE DES HOUCHES

Mantle geodynamics

1. Evidence for surface (plate) and deep (mantle) motions

+ orders of magnitude

2. Dynamic models to understand the mantle (past & present)

3. Mantle and plate dynamics : modelling diversity and recipes

4. Progress and perspectives

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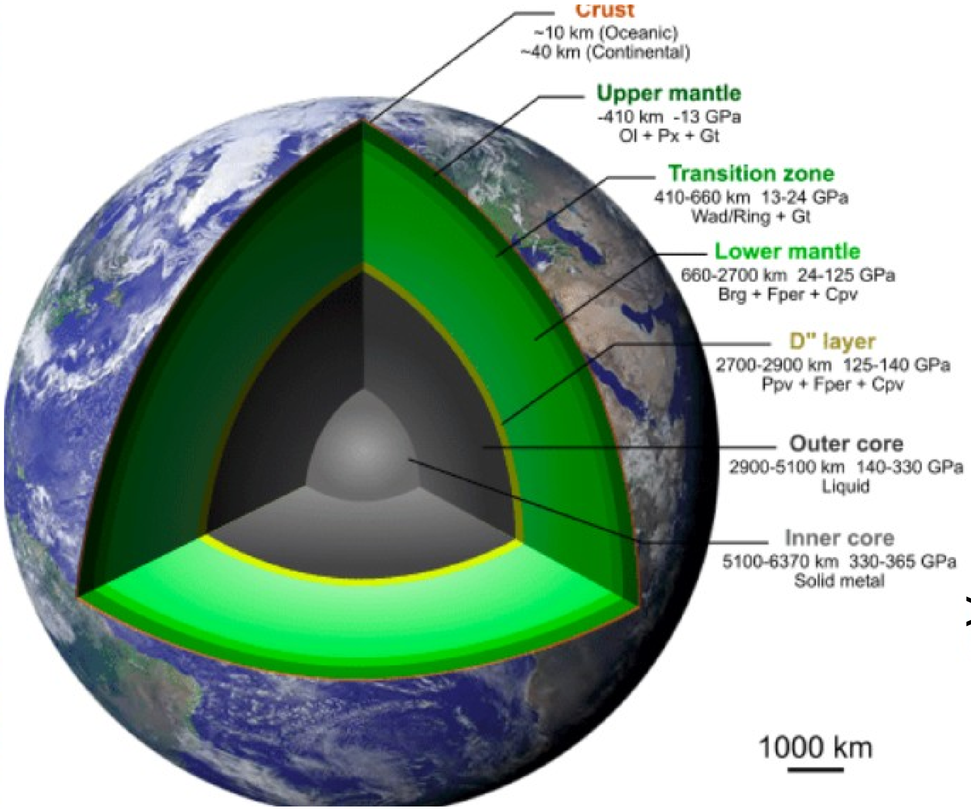
Although we cannot feel or see it… solid Earth moves…!?

Mantle from 10 to 2900 km - deepest borehole on Earth = ???

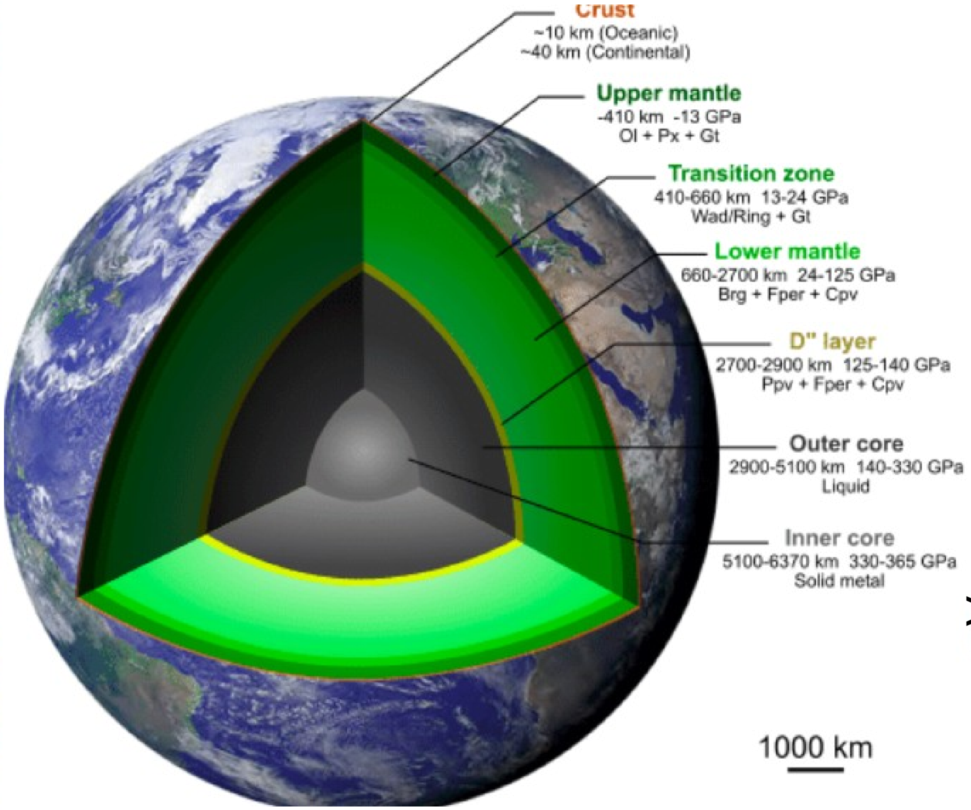


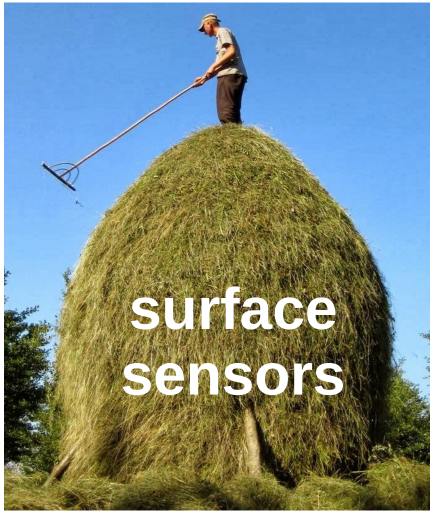
> we *barely* measure
the **surface (slow) motions**

Yoshizaki & McDonough 2021

Although we cannot feel or see it… solid Earth moves…!?

Mantle from 10 to 2900 km - deepest borehole on Earth = 12 km





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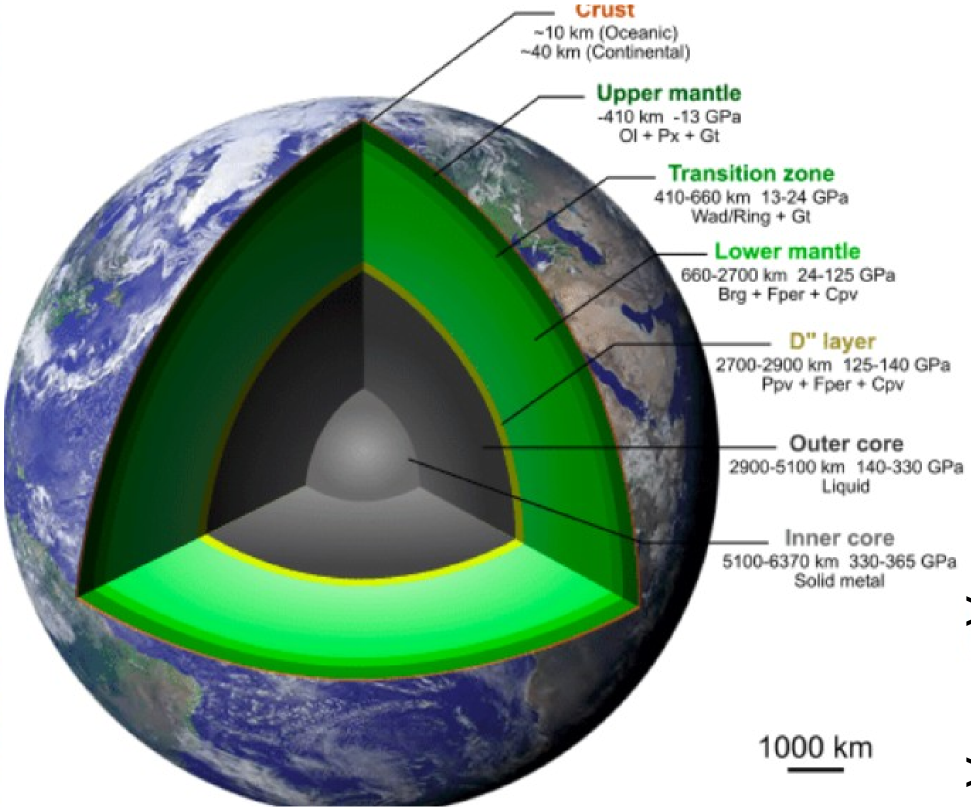

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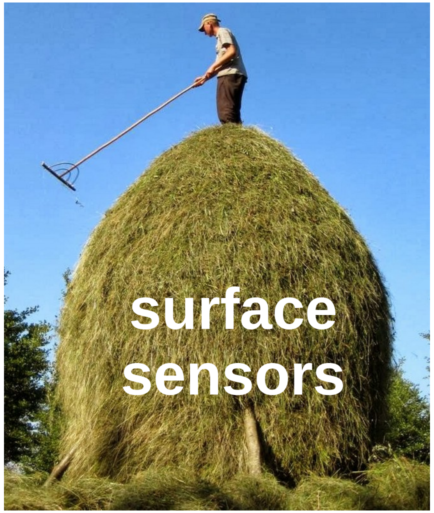

> we *barely* measure
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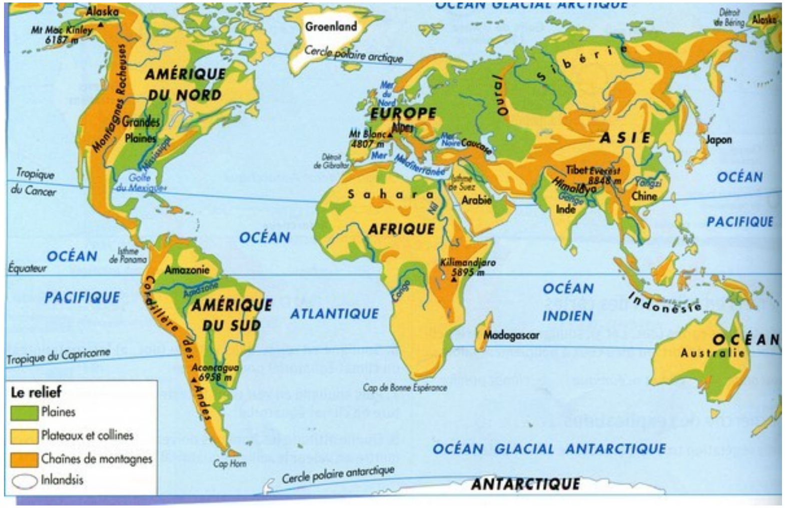
> inacessible deep Earth : argument for deep dynamics is necessarily **<u>indirect</u>**

Argument for surface motions : ocean topography

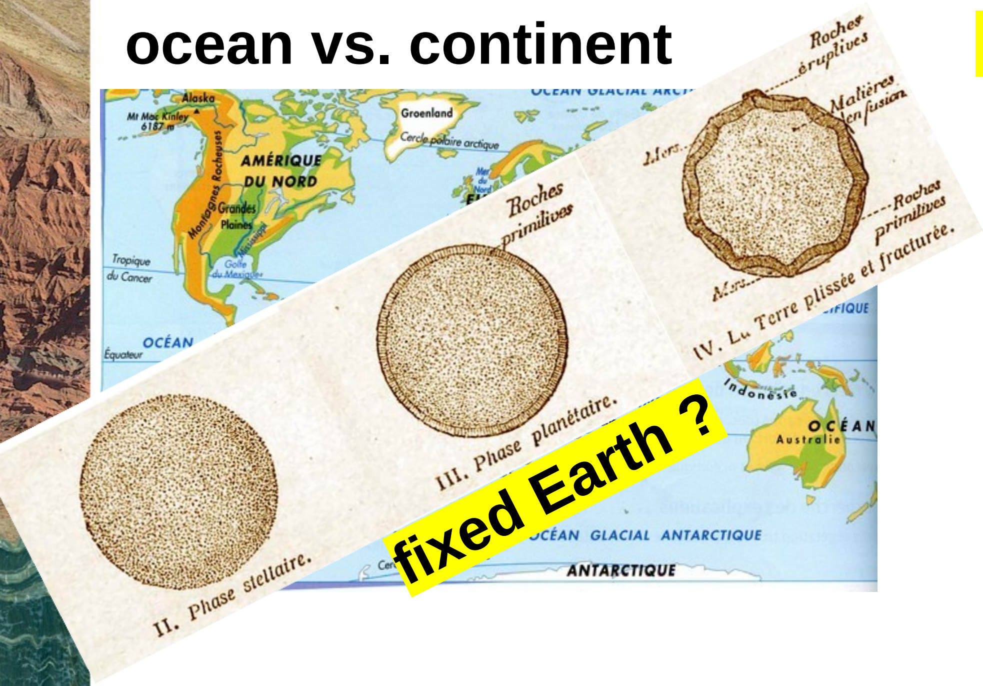
ocean vs. continent



Argument for surface motions : ocean topography

ocean vs. continent

… but is the sea floor uniform ?



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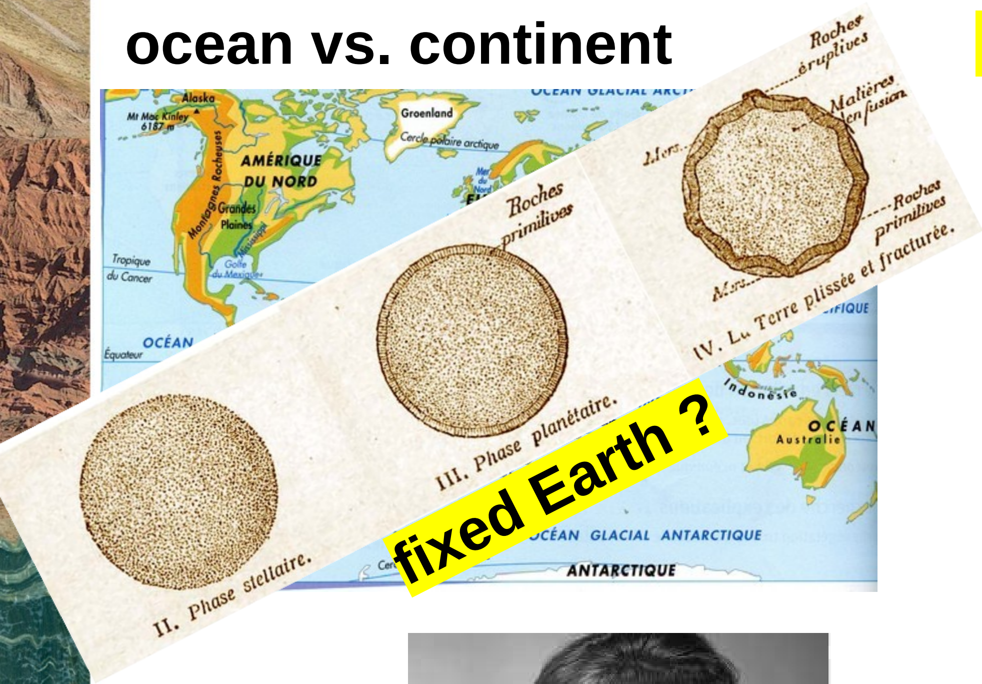


Mary Tharp, Bruce Heezen - 1957

… but is the sea floor uniform ?

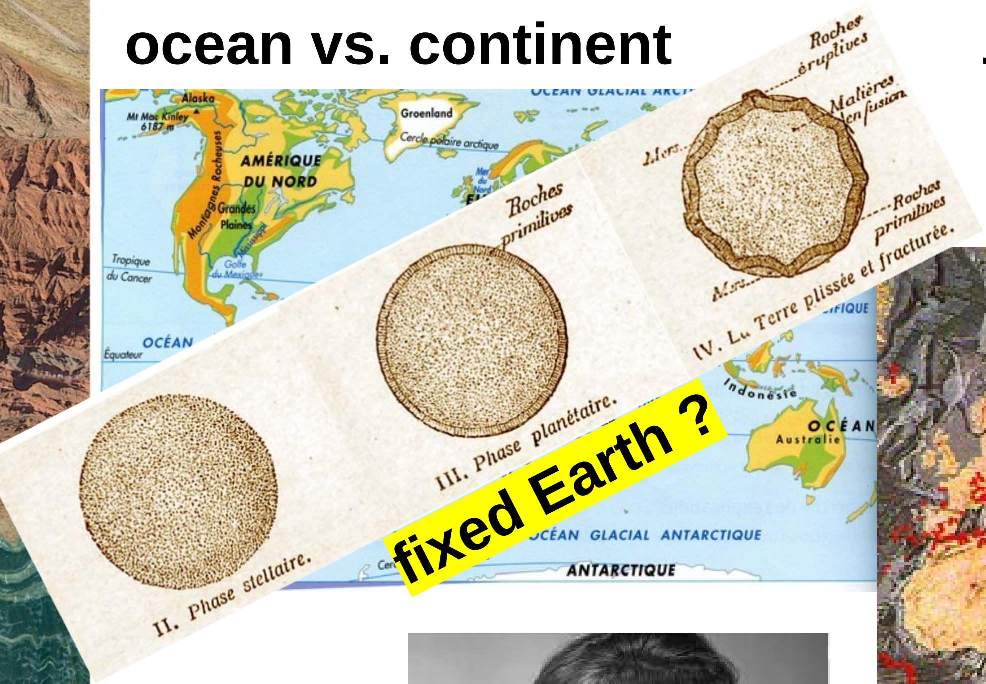
NO !!!

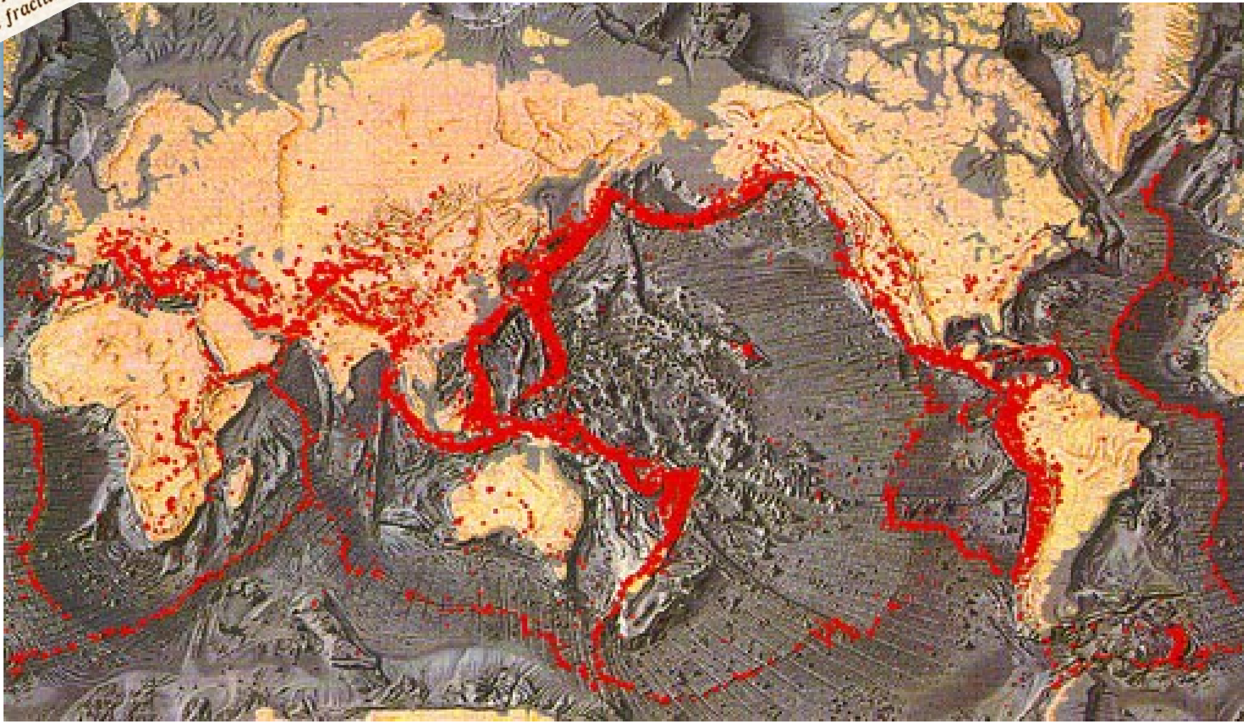
Argument for surface motions : ocean topography

ocean vs. continent

… but is the sea floor uniform ?

NO > plate boundaries vs. plates !





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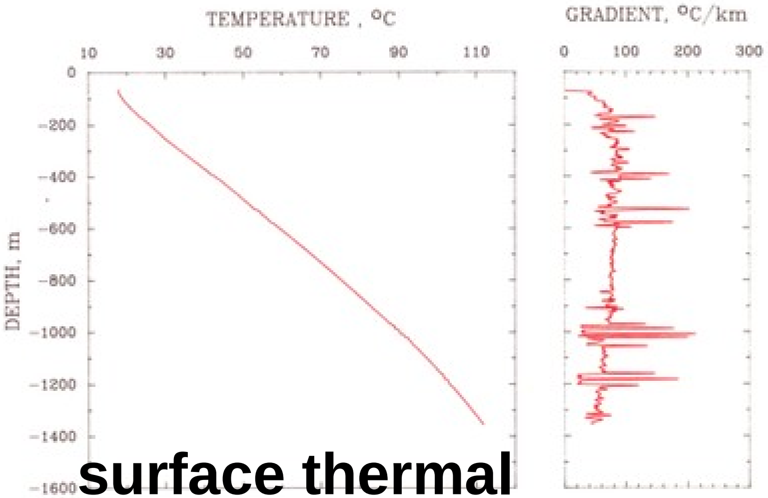
Argument for solid Earth motions :
Earth's internal temperature & surface heat flow



surface thermal gradient ~ 30°C/km

extrapolation to 6400 km depth
= 200 000°C ??? gas ?!

Argument for solid Earth motions :
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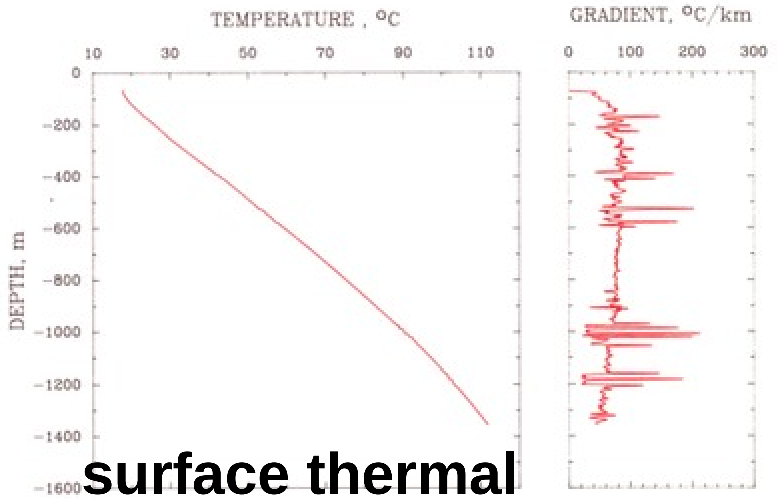

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→ need a reduced thermal gradient
> **convective heat transport**
and motion of Earth’s interior ?

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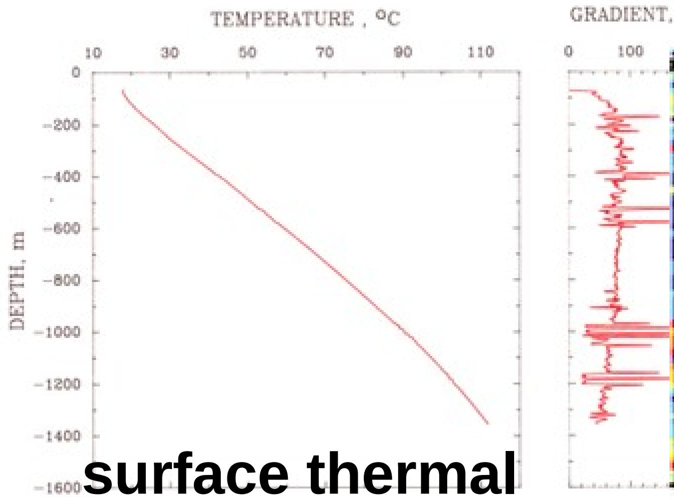

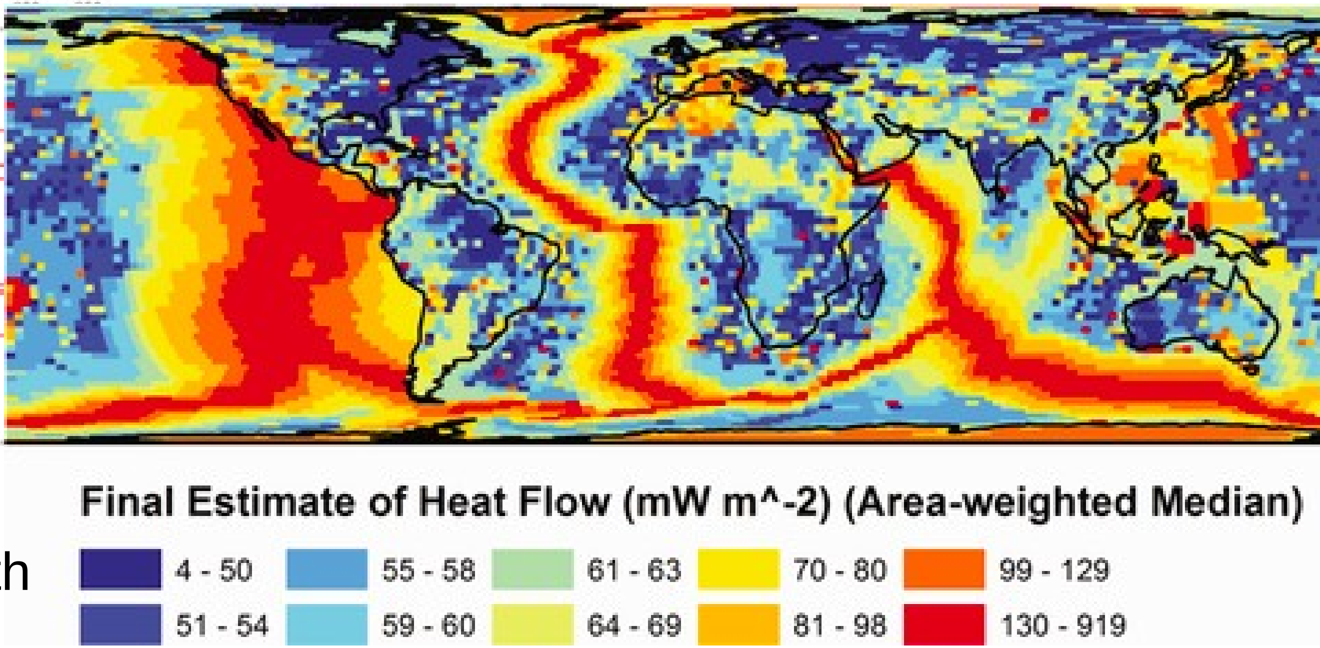

Davies G³ 2013

surface thermal gradient ~ 30°C/km

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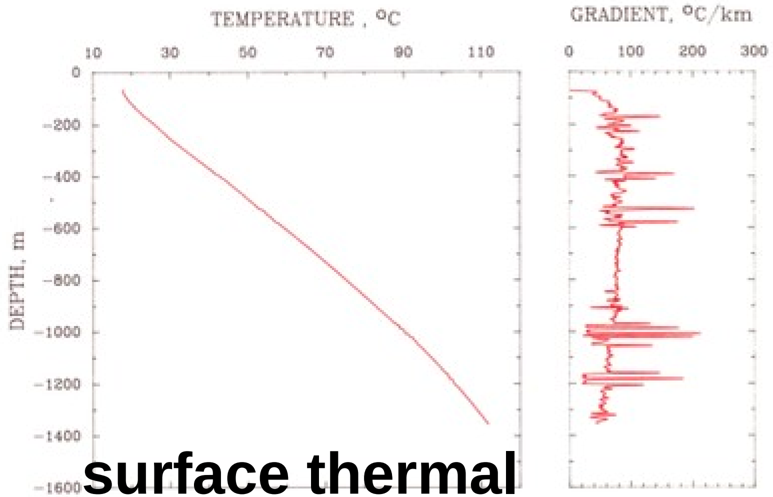
regions of large heat flux :
magmatism, **hot upwelling** ?

Argument for solid Earth motions :
Earth’s internal temperature & surface heat flow



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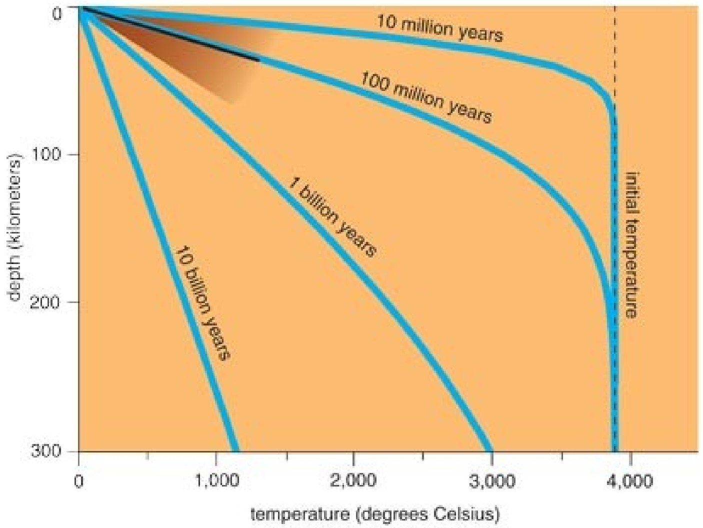


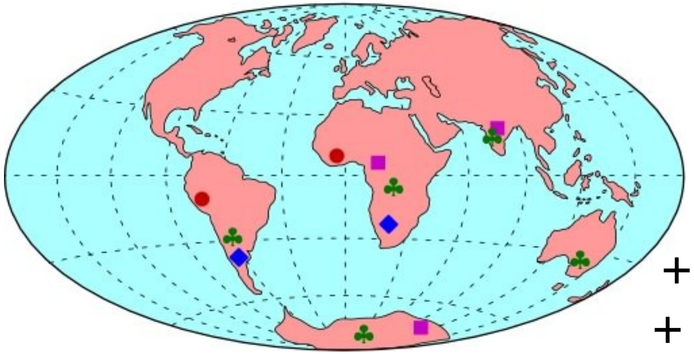
from cooling to Earth’s age
> Buffon, Fourier, Kelvin, Perry…

https://www.americanscientist.org/article/kelvin-perry-and-the-age-of-the-earth

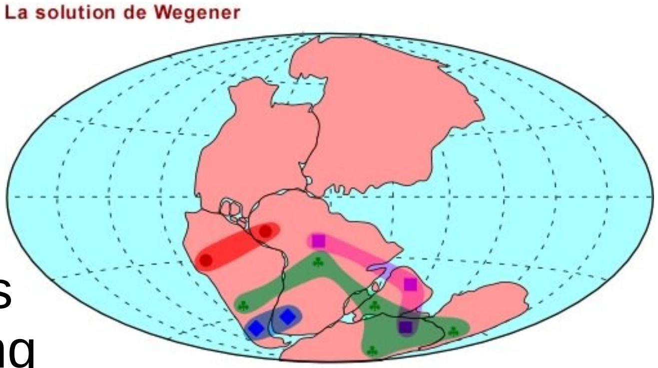
https://planet-terre.ens-lyon.fr/ressource/age-Terre-histoire.xml

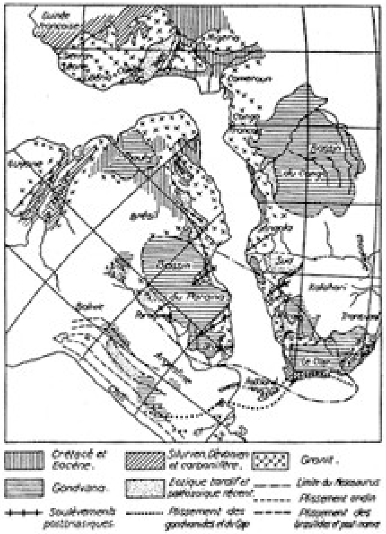
Evidence of surface motions : geological and paleontological records

Wegener
1912



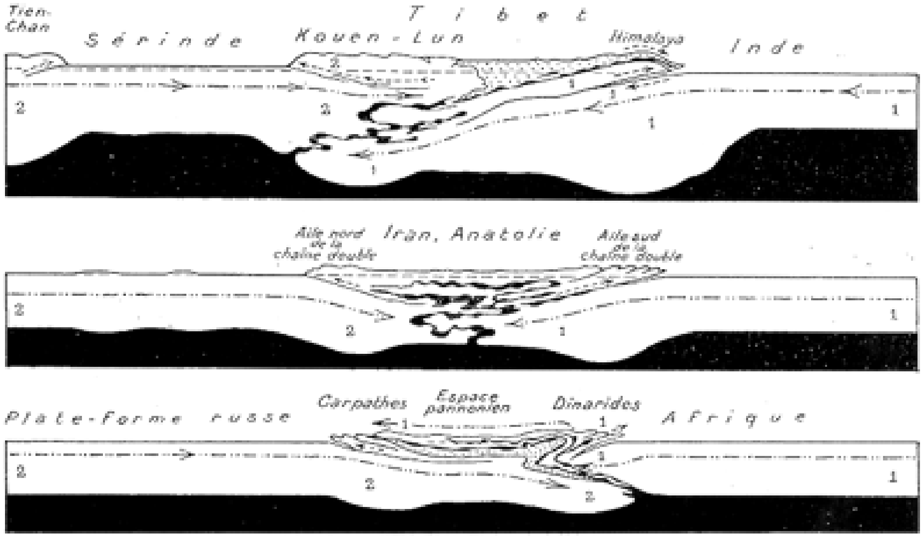
permian fossils
+ glacial striations
+ coast interlocking



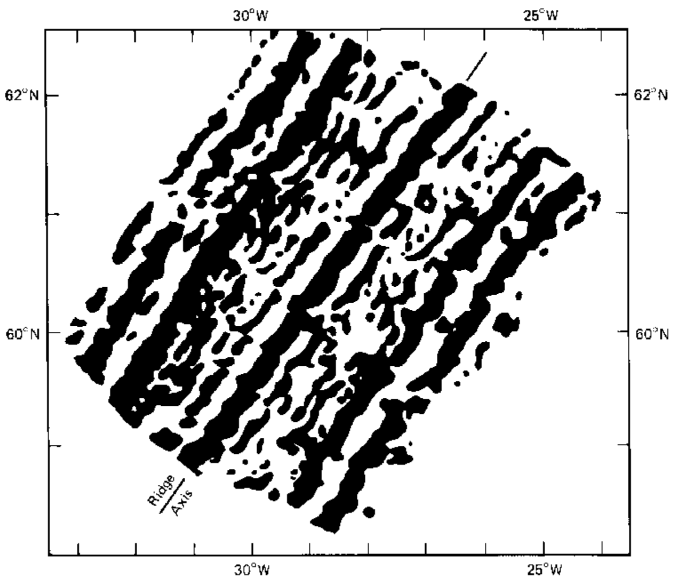


Bertrand + Haug + Du Toit + Argand

https://planet-terre.ens-lyon.fr/ressource/derive-continents-wegener.xml

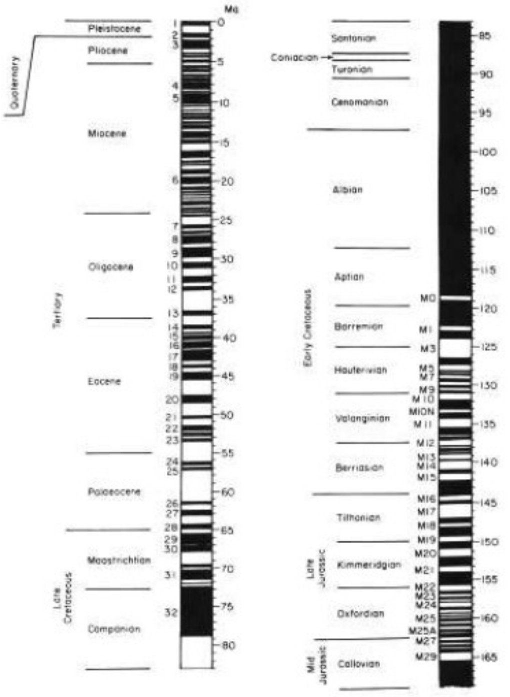


Evidence of surface motions : paleomagnetism

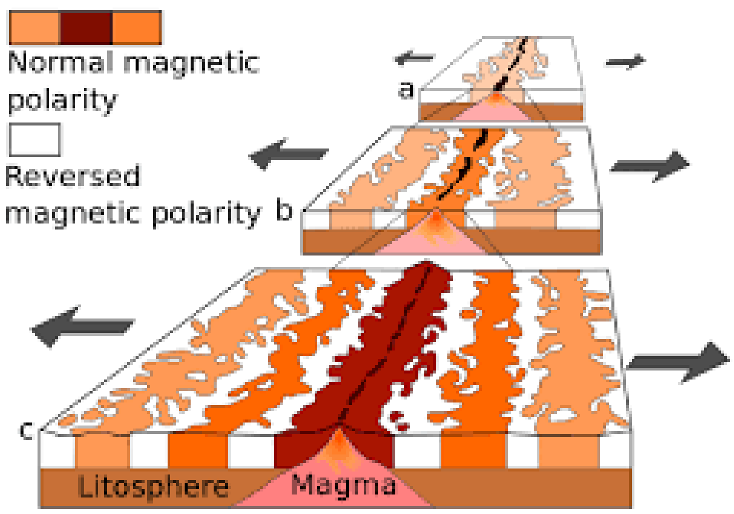


magnetite (Fe_3O_4) of basalt and gabbro record the magnetic field polarity during its cooling at ridge (magnetization below 730°C)

Figure 3.6 Chronométrie des polarités du champ magnétique depuis 165Ma

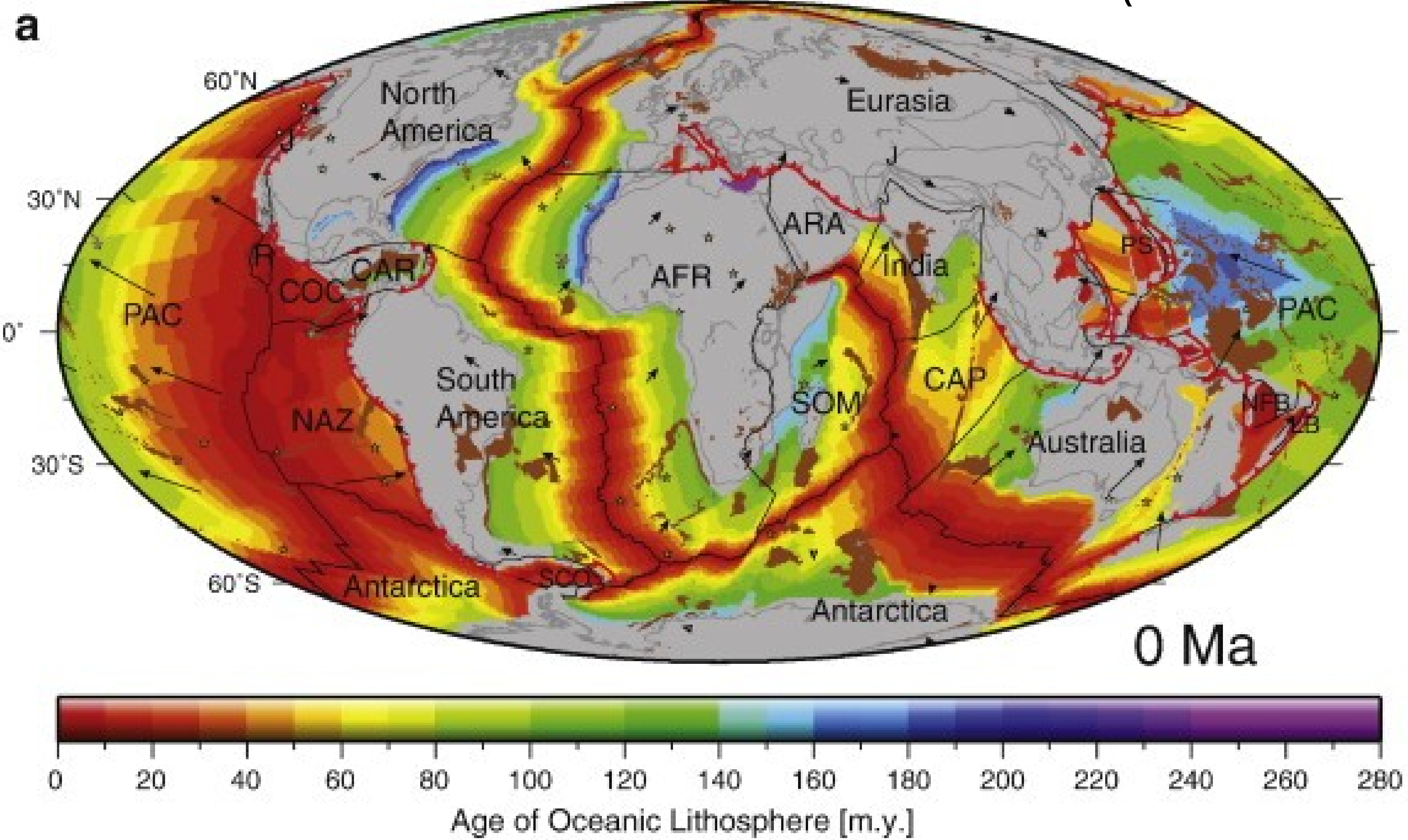


300 geomagnetic reversals these last 200 Myr

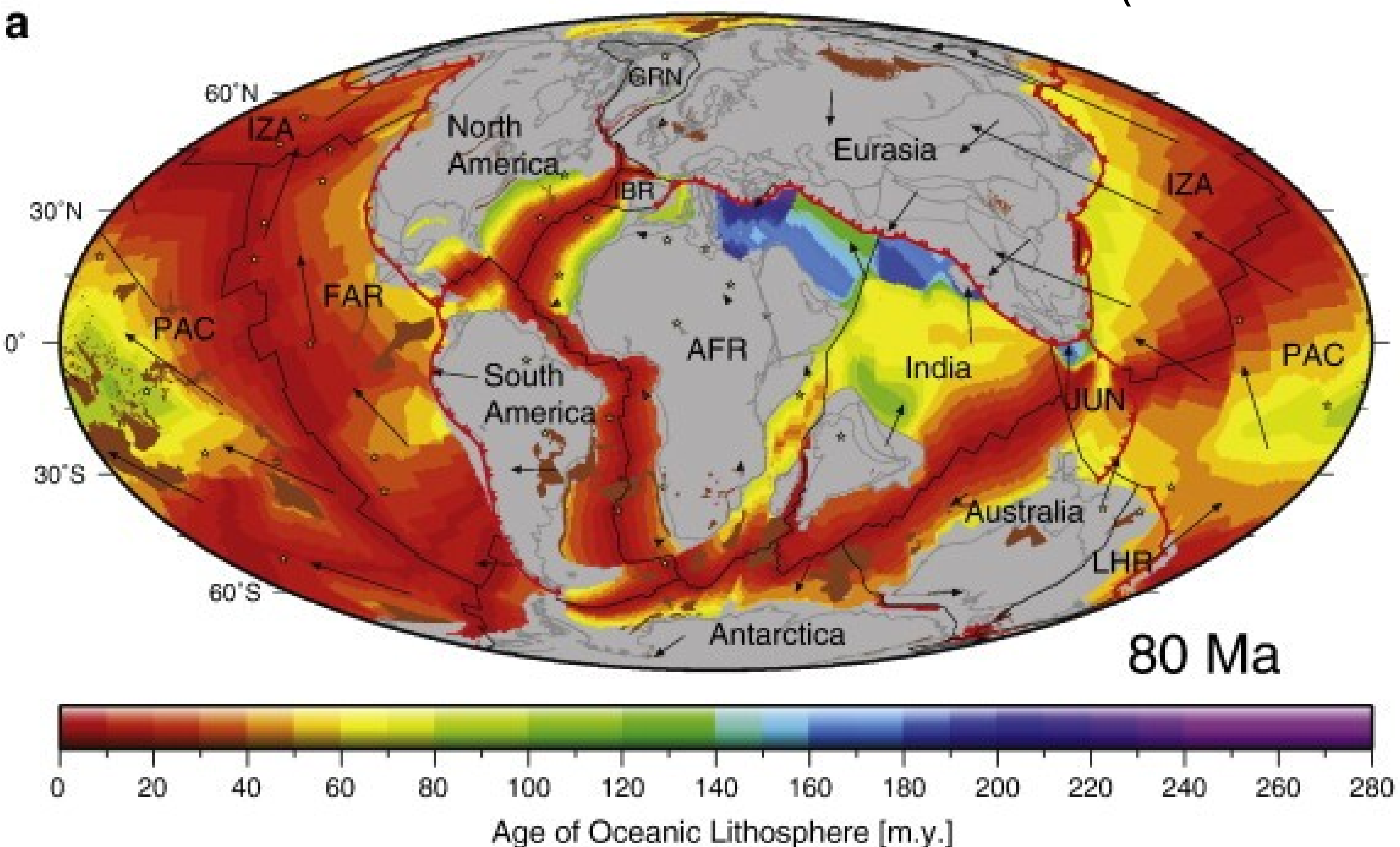


Seafloor spreading
(Morley, Vines, Matthews - 1963)

(Seton et al. 2012)



(Seton et al. 2012)



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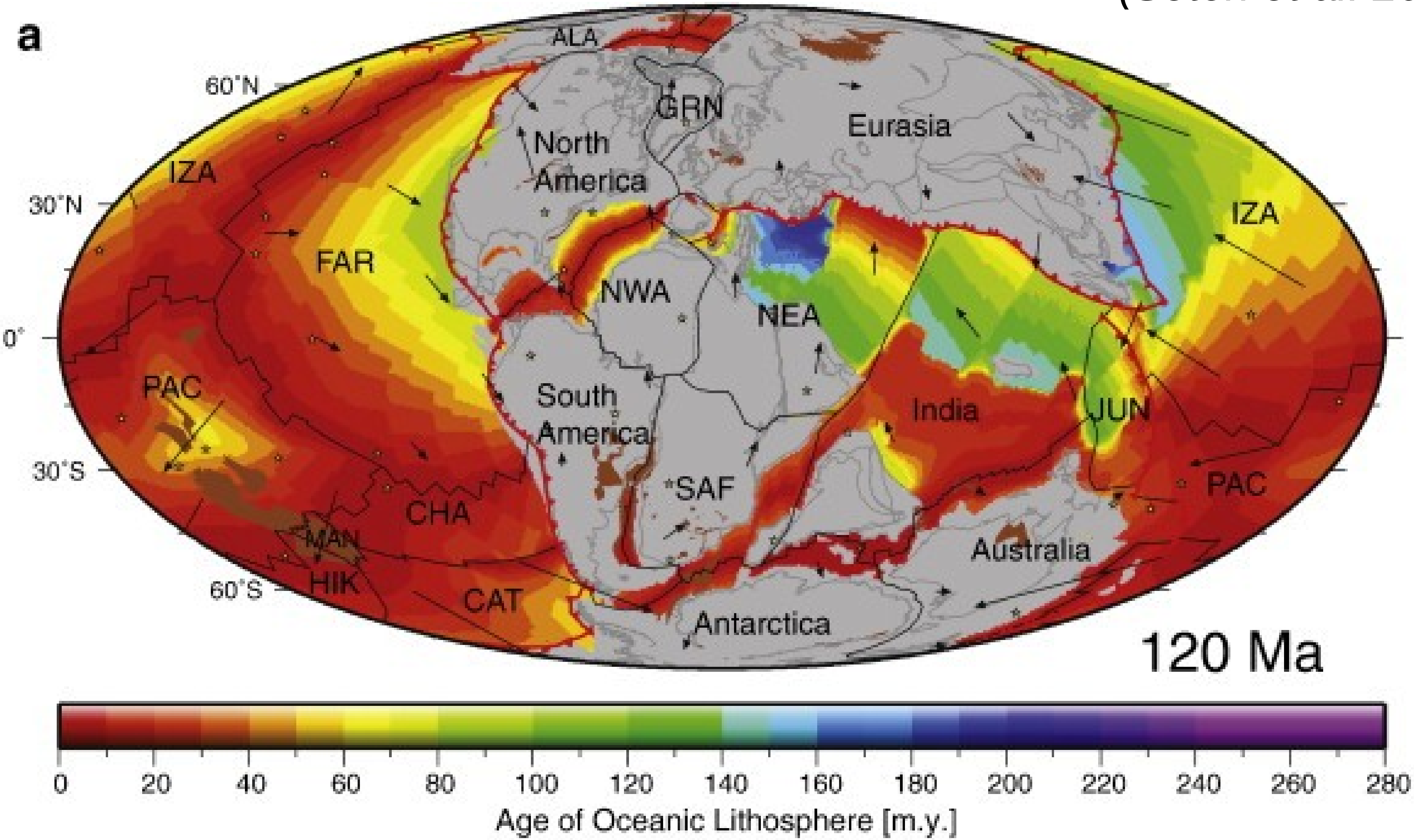

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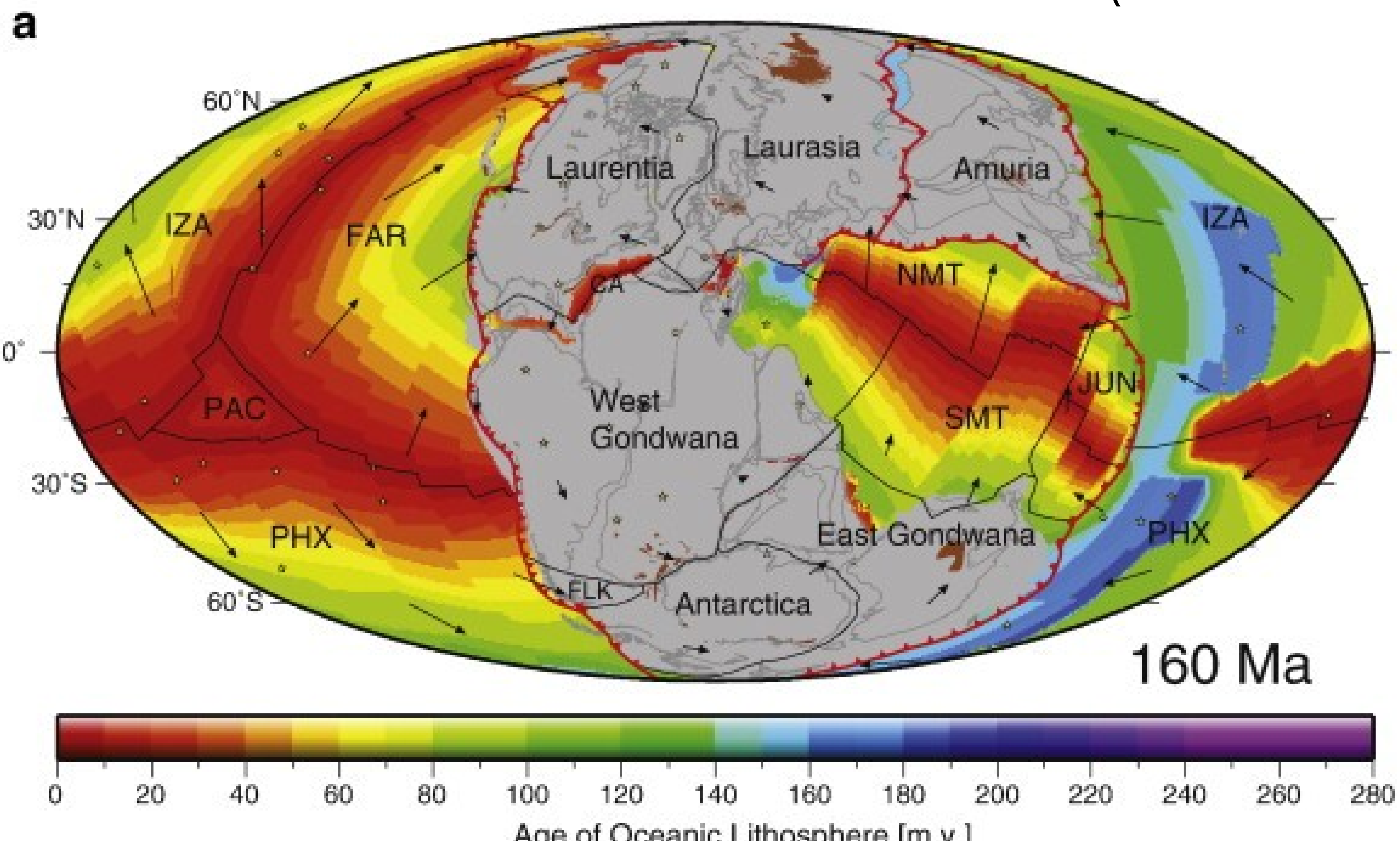

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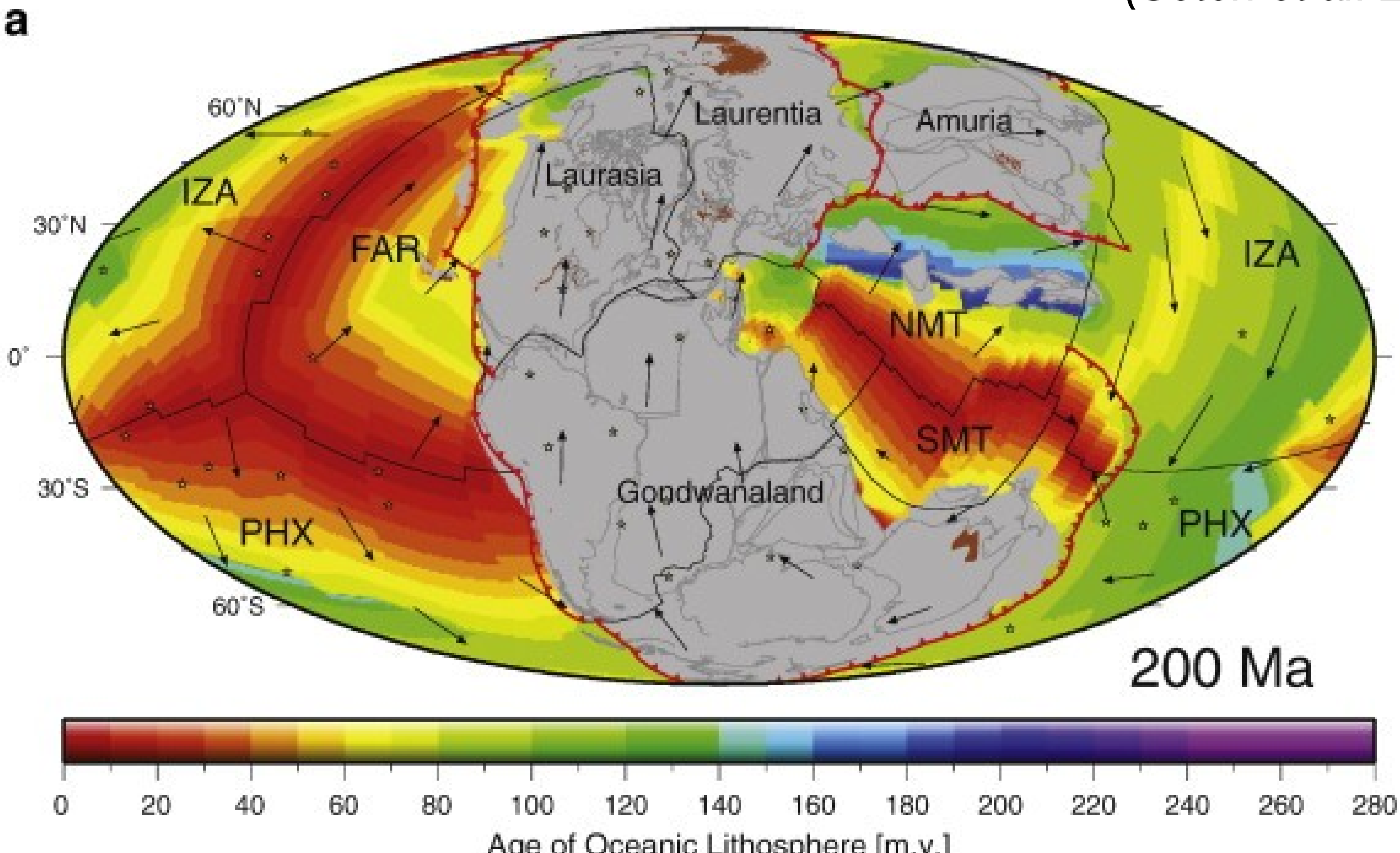
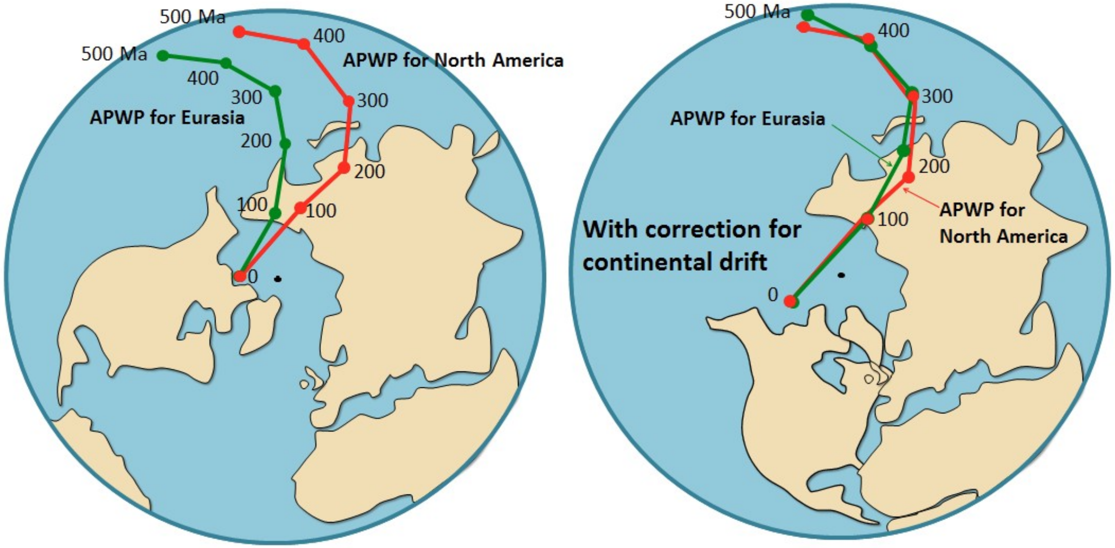
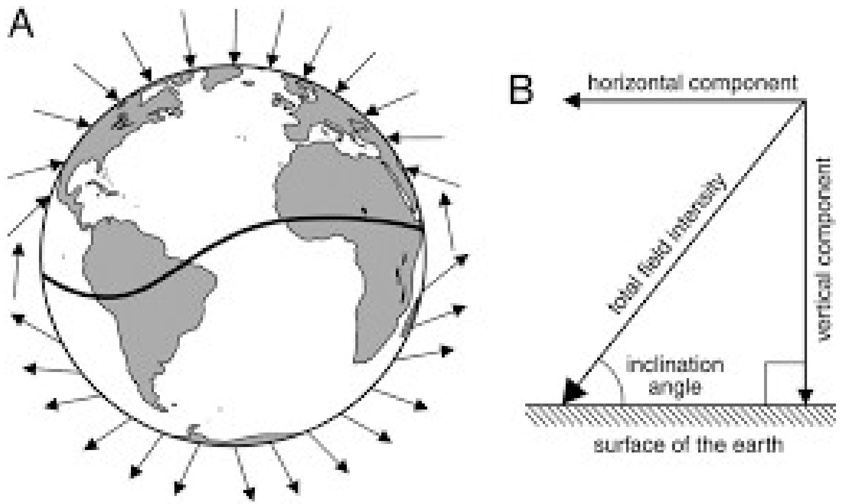


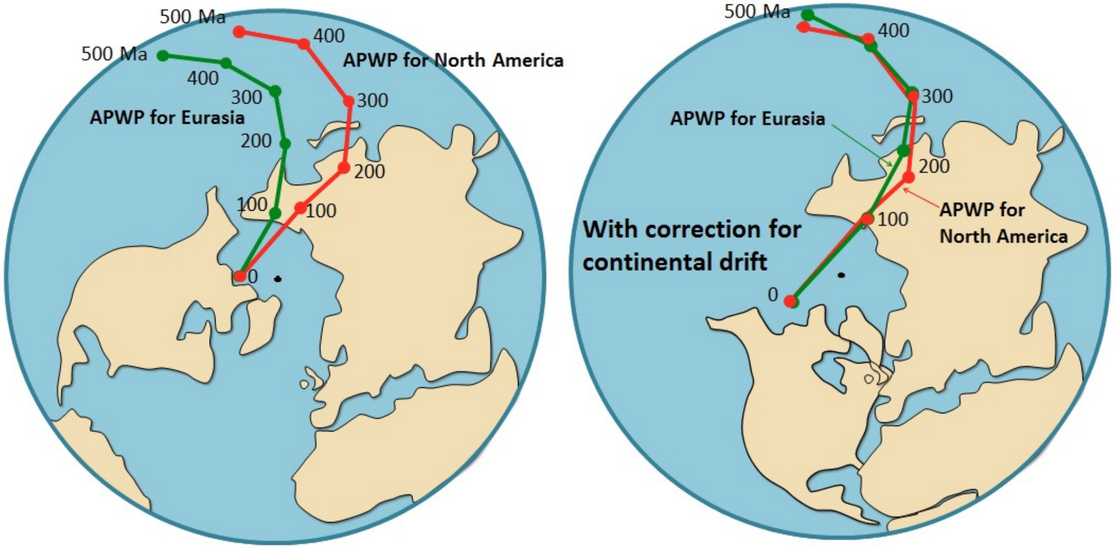
Evidence of surface motions : paleomagnetism

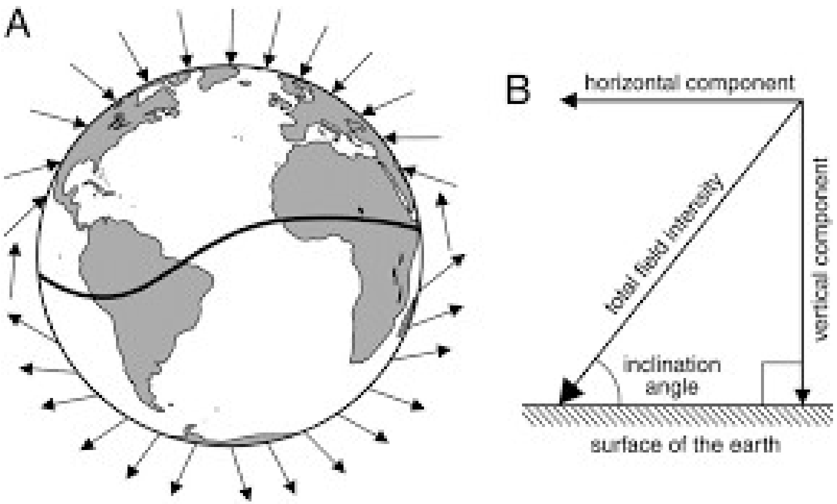




Apparent polar wander
path (APWP) due to
continents motion

Evidence of surface motions : paleomagnetism



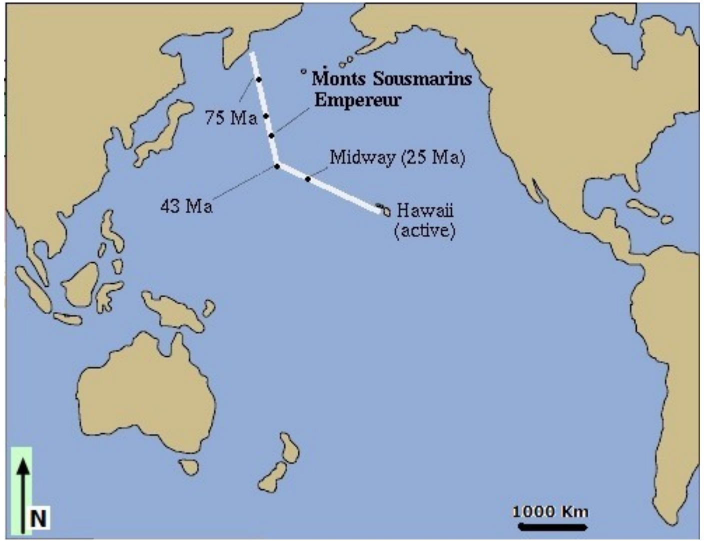


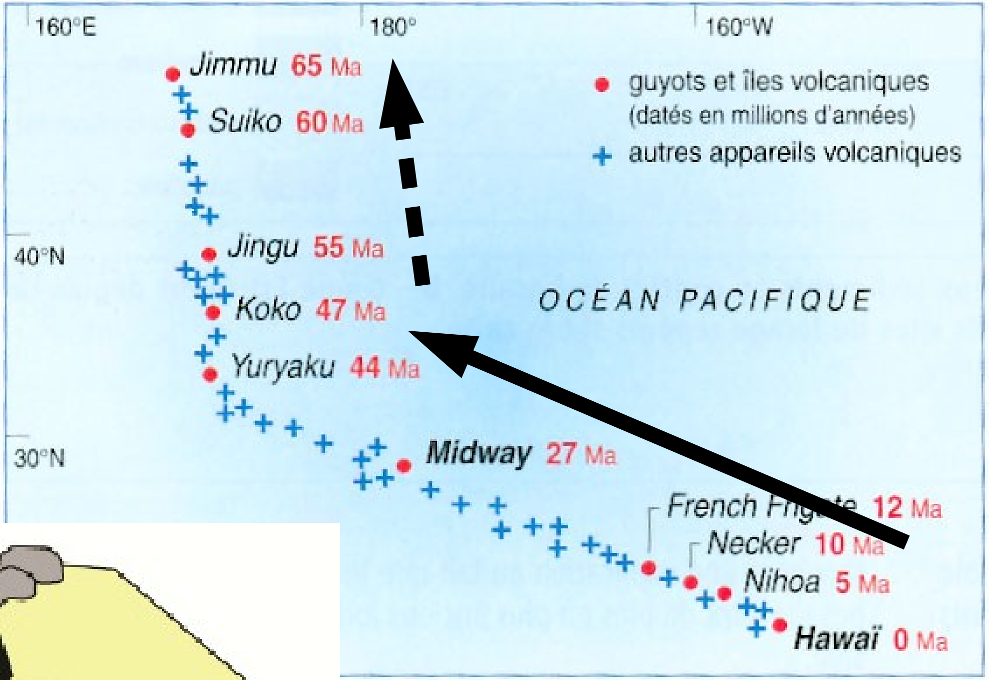
Apparent polar wander path (APWP) due to continents motion

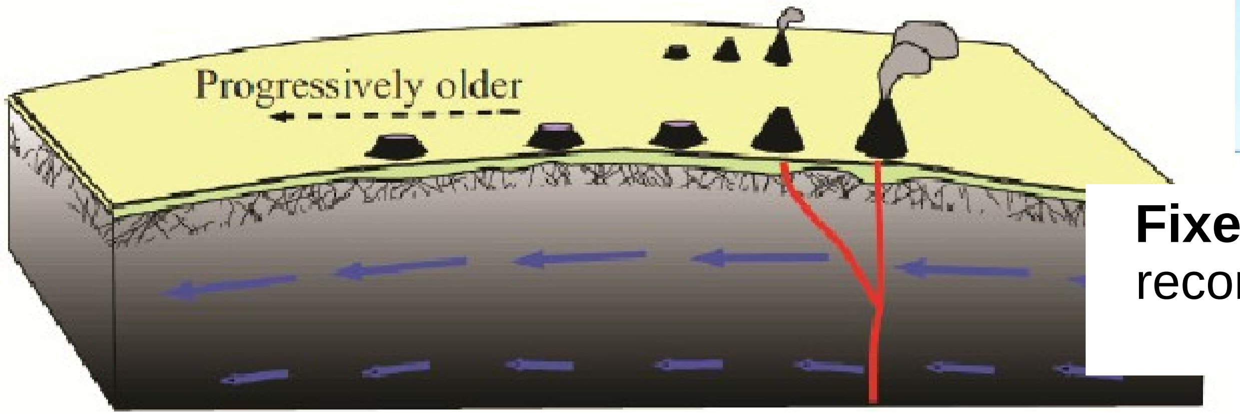
paleolatitude deduced from **paleo-magnetic inclination**

Rodina supercontinent ?

Evidence of surface motions : hotspot volcanic alignement



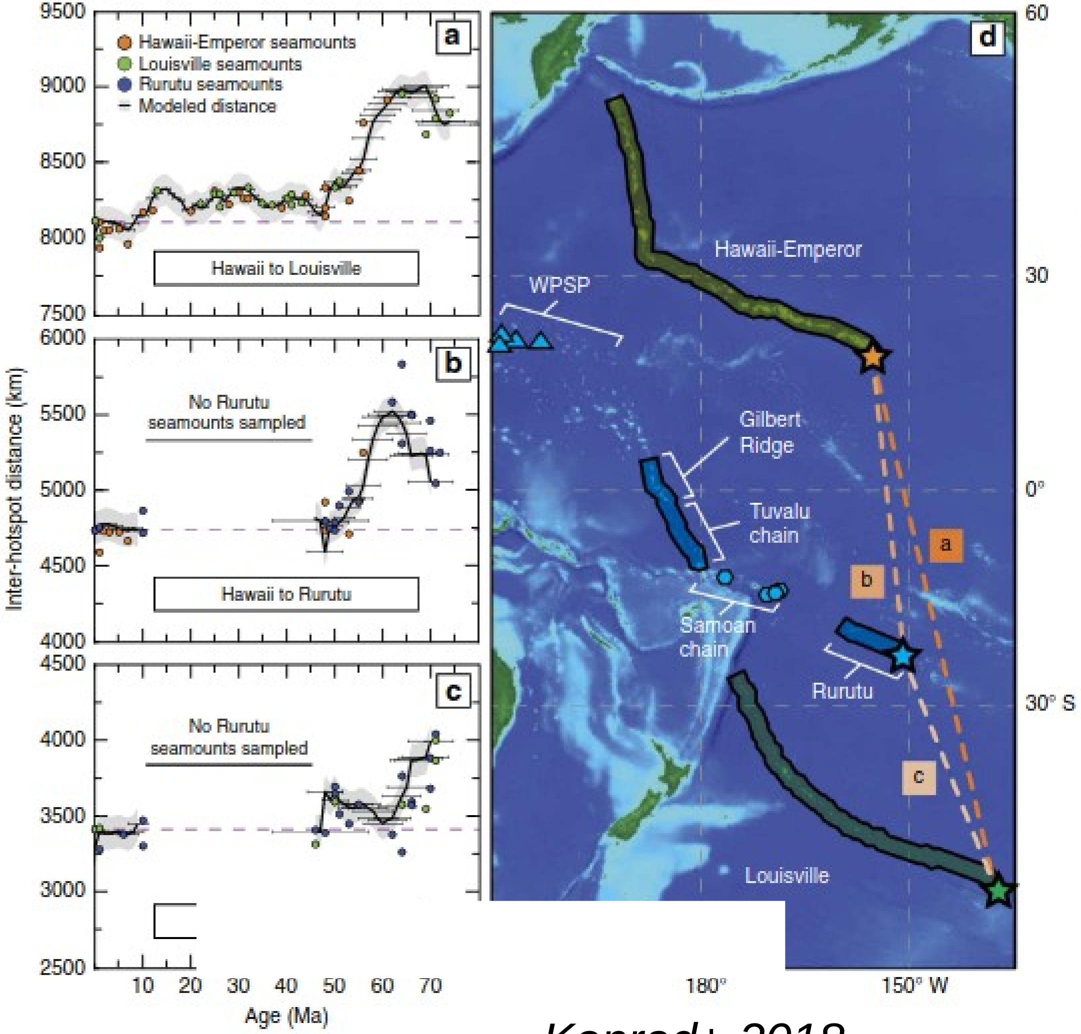




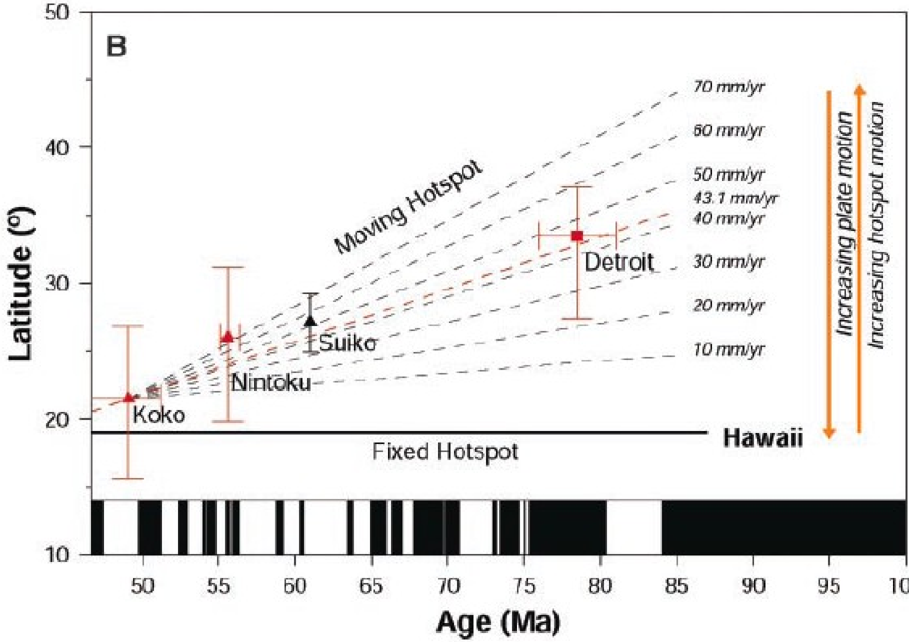
Fixed plume and moving plate > reconstruction of velocity magnitude and direction back in time

Adam 2012

Evidence of surface motions : hotspot volcanic alignement



Konrad+ 2018

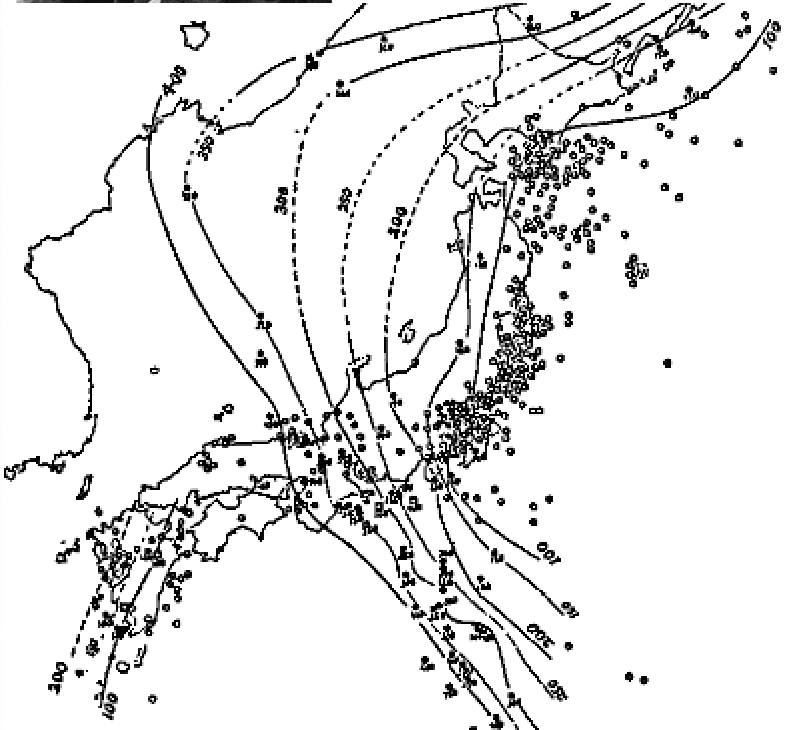


Tarduno+ Science 2003

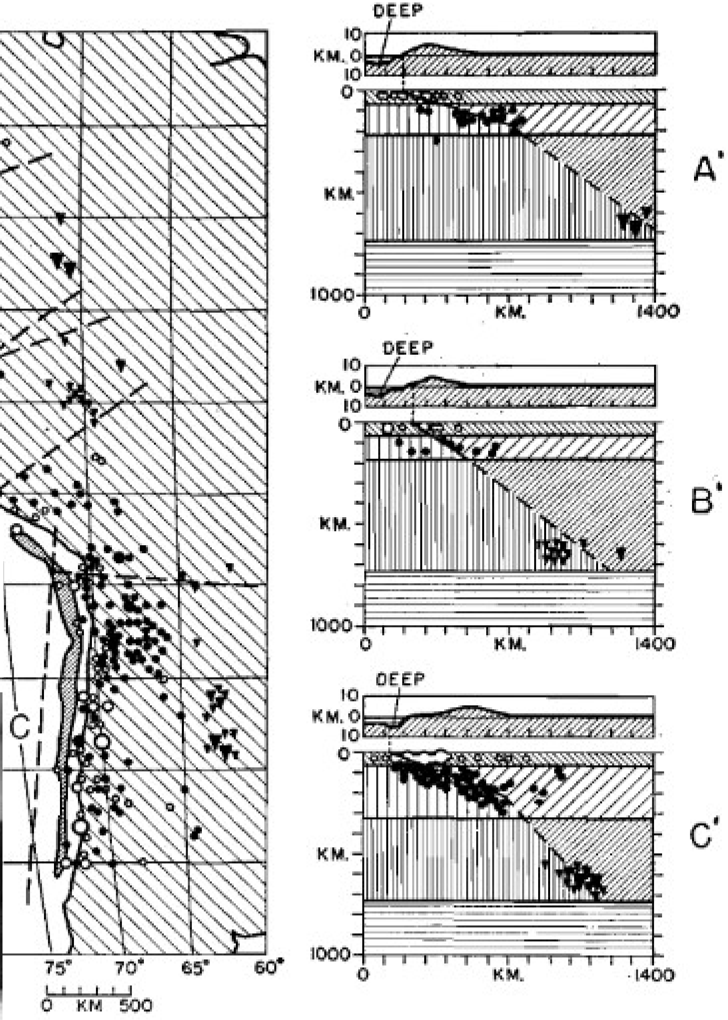
Not so fixed plumes… ?

Evidence of surface motions : faults and earthquakes

Kiyoo Wadachi
(1928-1935)

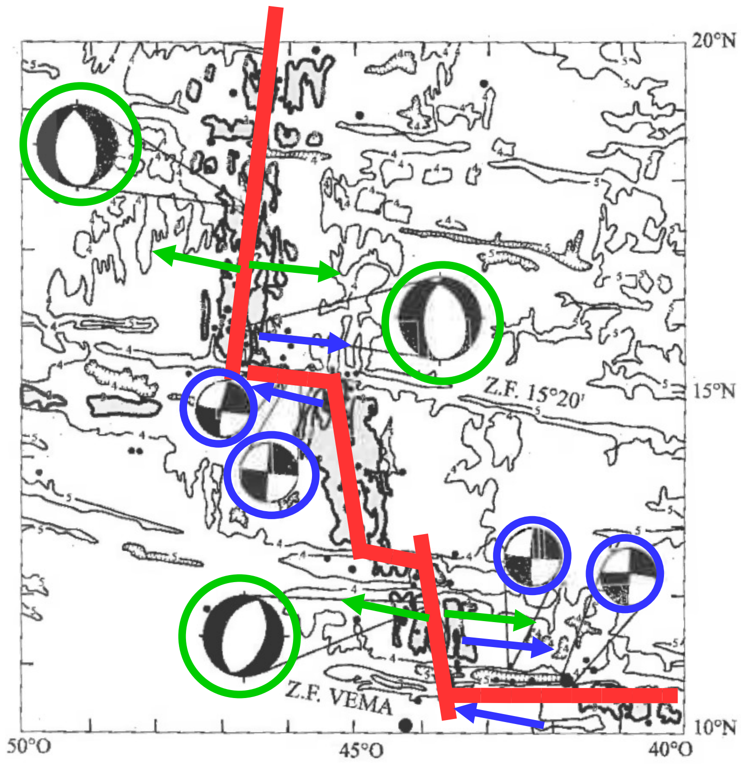


Hugo Benioff
(1949)

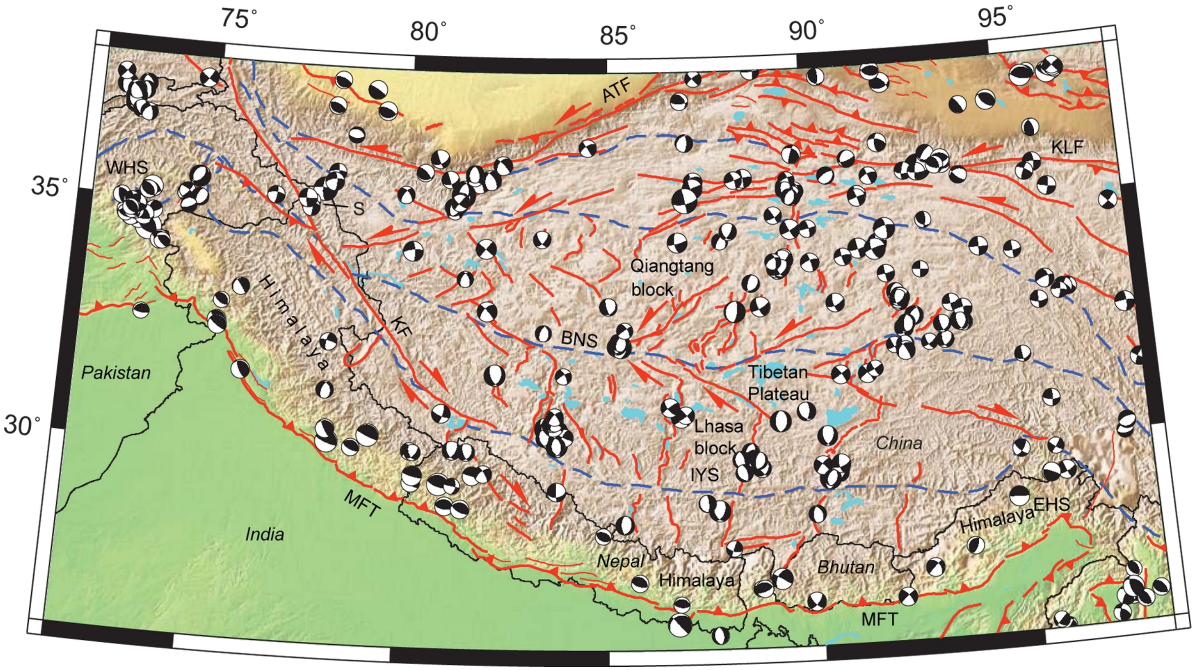


Evidence of surface motions : faults and earthquakes

Focal mechanisms of large (plate boundary) faults



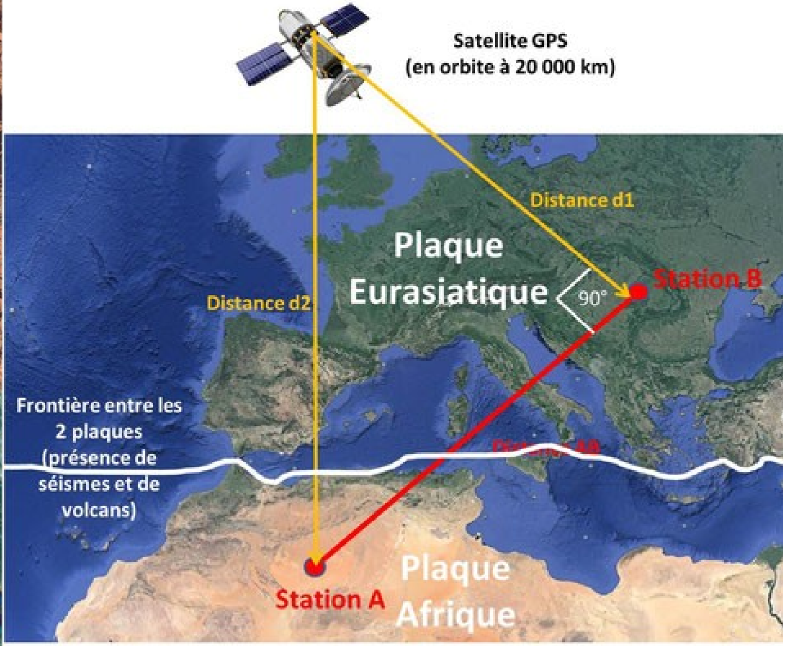
Normal and transform faults at mid-Atlantic ridges



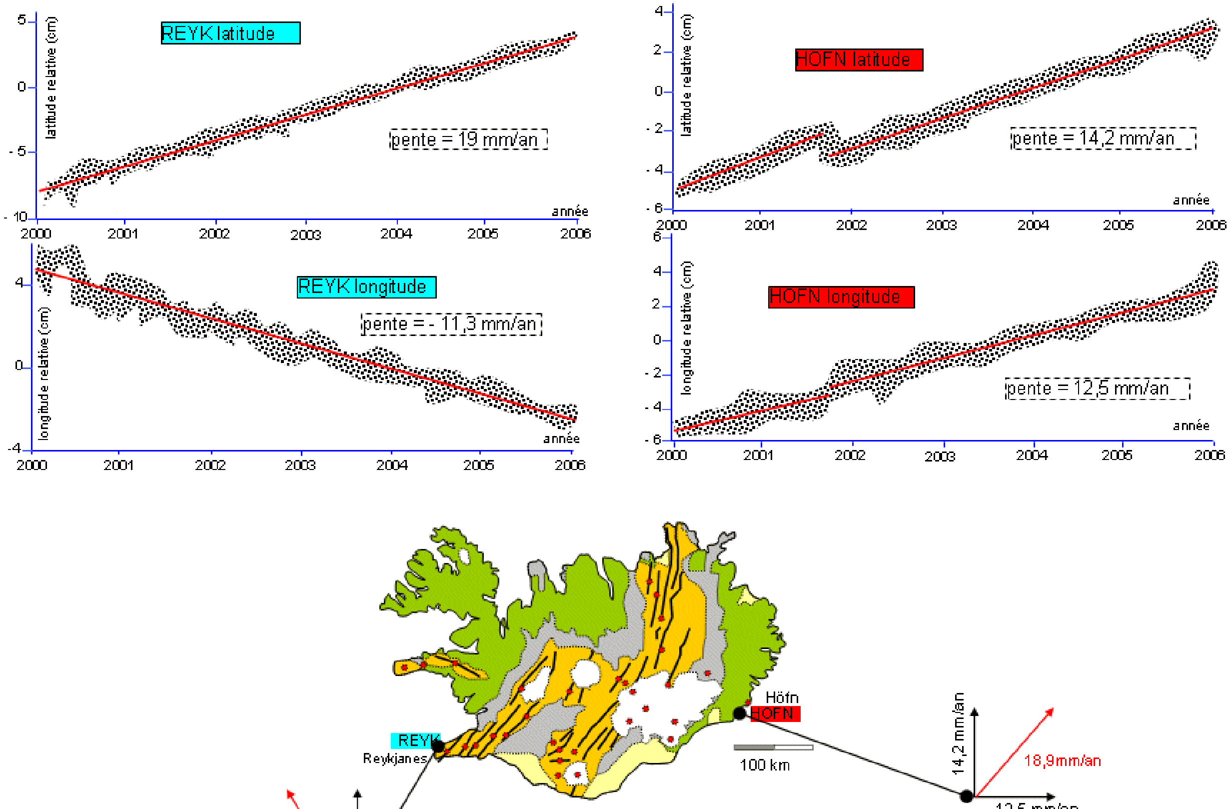
Inverse (thrust) faults in Himalaya + intraplate deformations
(plates are not fully rigid)

Evidence of surface motions : geodesy

<u>GPS,</u> DORI, VLBI > displacements inferred at human time scales (10s years)



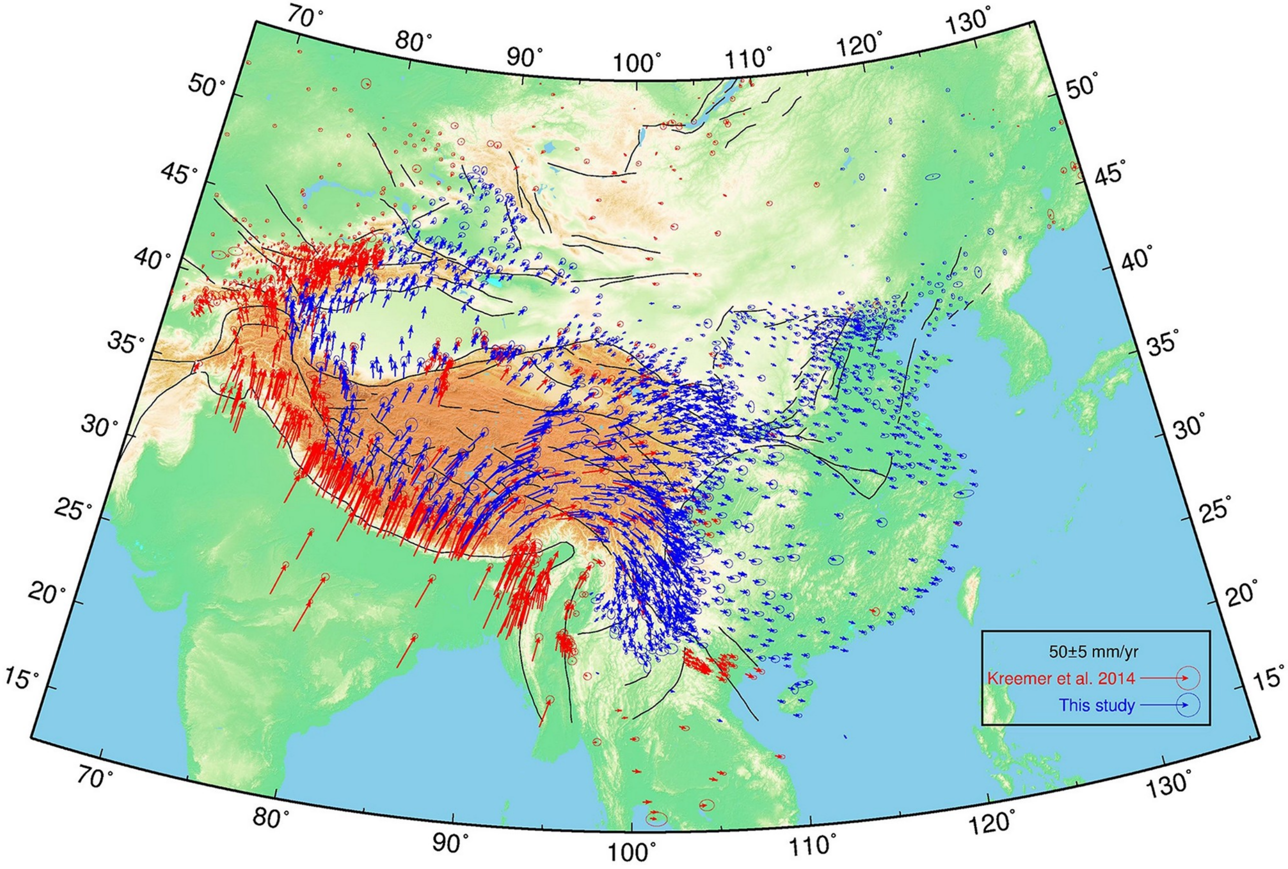
GPS Islande



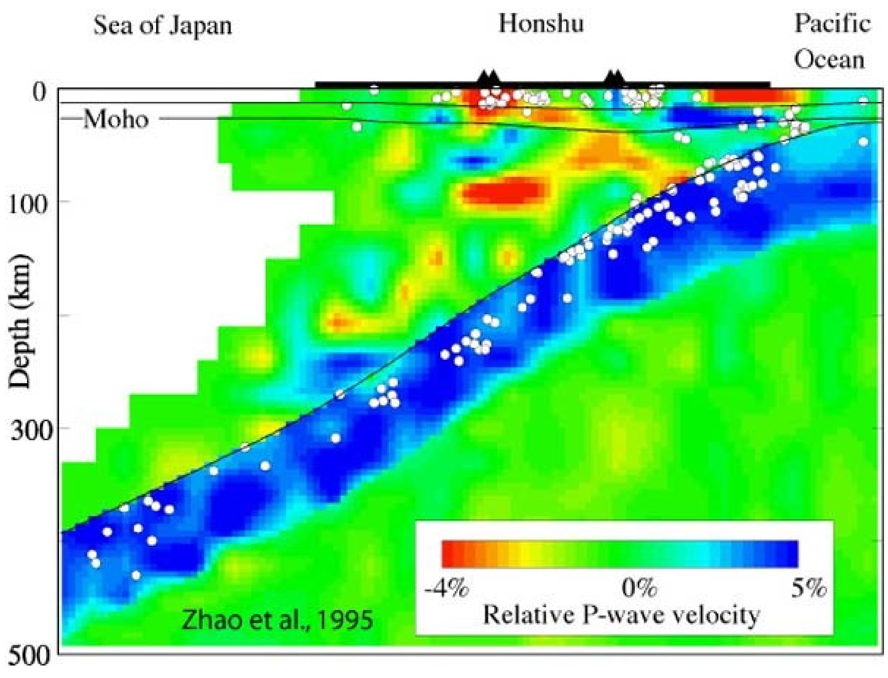
Evidence of surface motions : geodesy

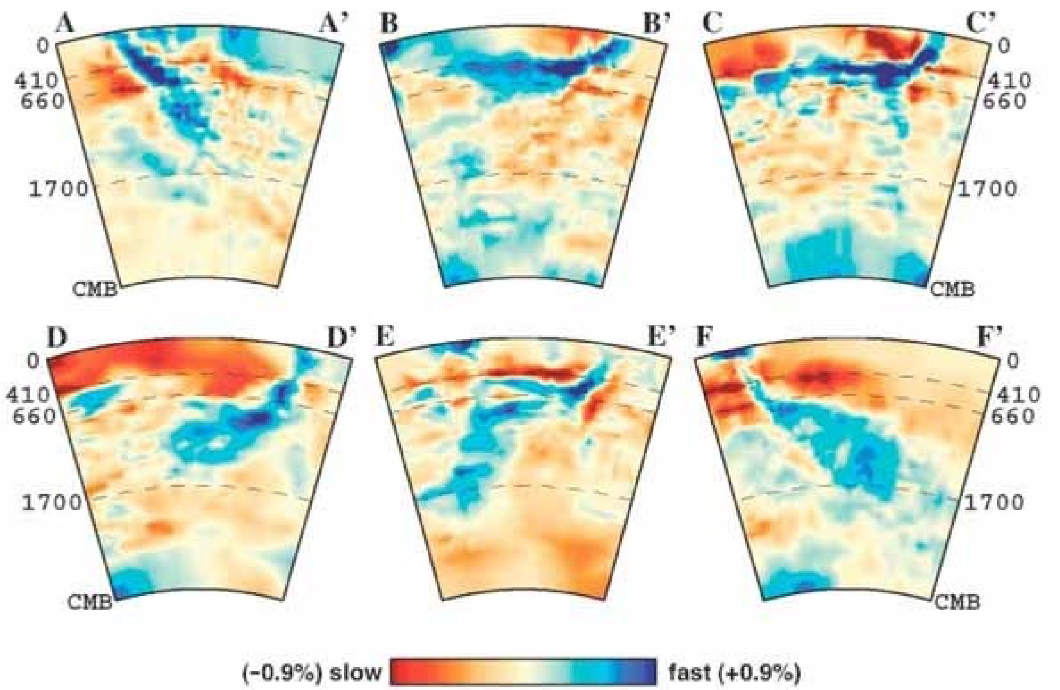
GPS, DORI, VLBI > displacements inferred at human time scales (10s years)

differential surface motions
→ **intraplate deformation !**



Argument for <u>deep</u> motions : slabs in seismic tomography



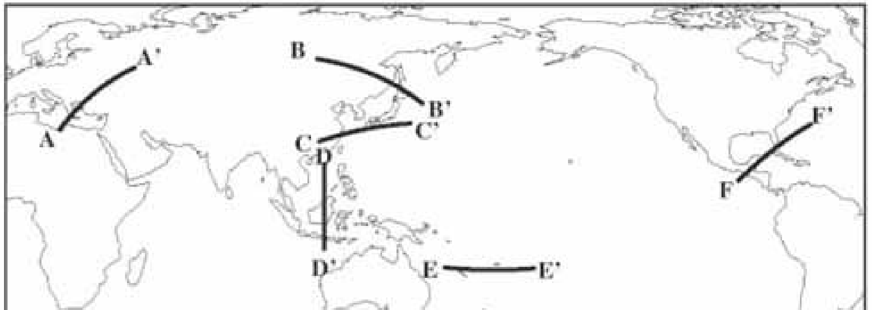


wave velocity anomaly

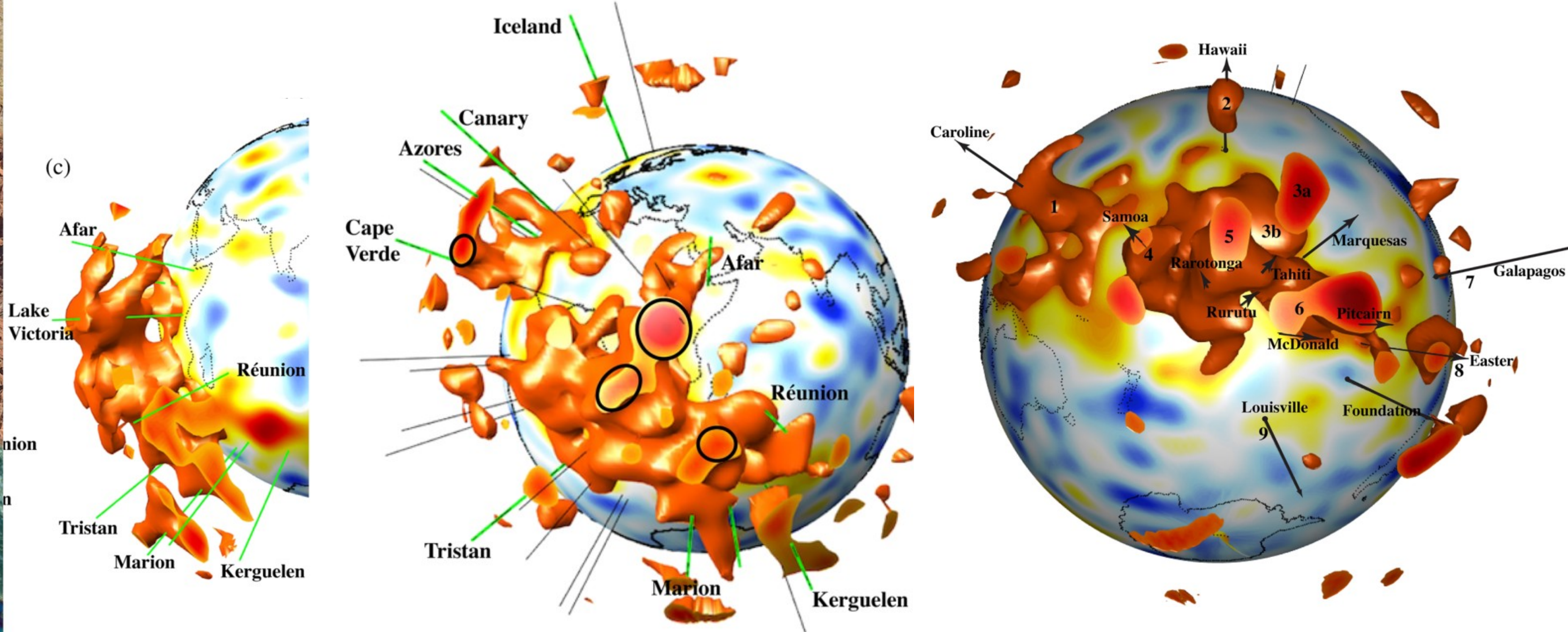
> density anomaly (motion)

> temperature anomaly

Karason & van der Hilst, 2000

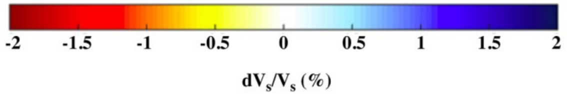


Argument for deep motions : plumes in seismic tomography



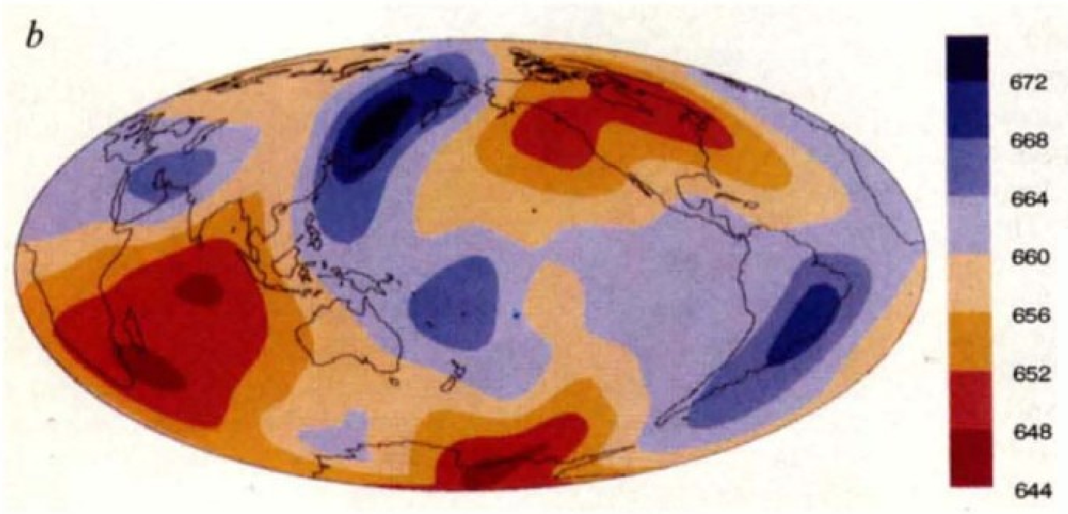
bundles of mantle (thermochemical) plumes
between 1500 and 2800 km deph

-0.8 to -1 % isosurface

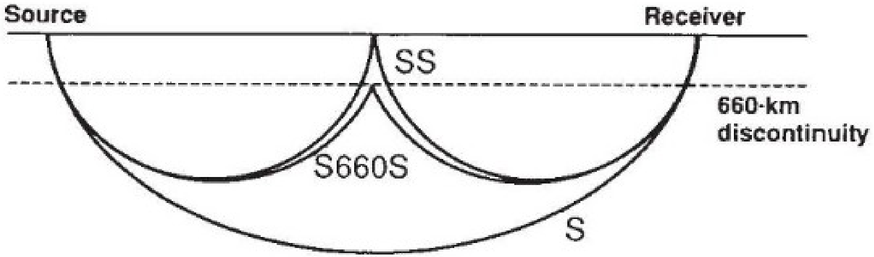


Davaille & Romanowicz, 2020

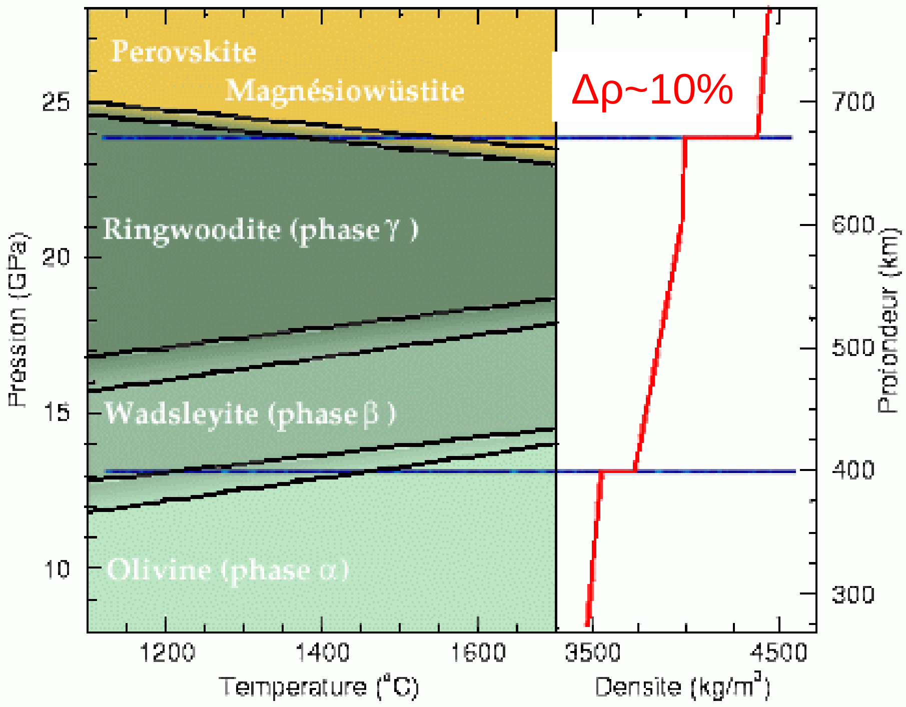
Argument for deep motions : deflection of seismic discontinuities



Shearer & Masters, Nature, 1992



topography of phase transitions
> **temperature anomalies**



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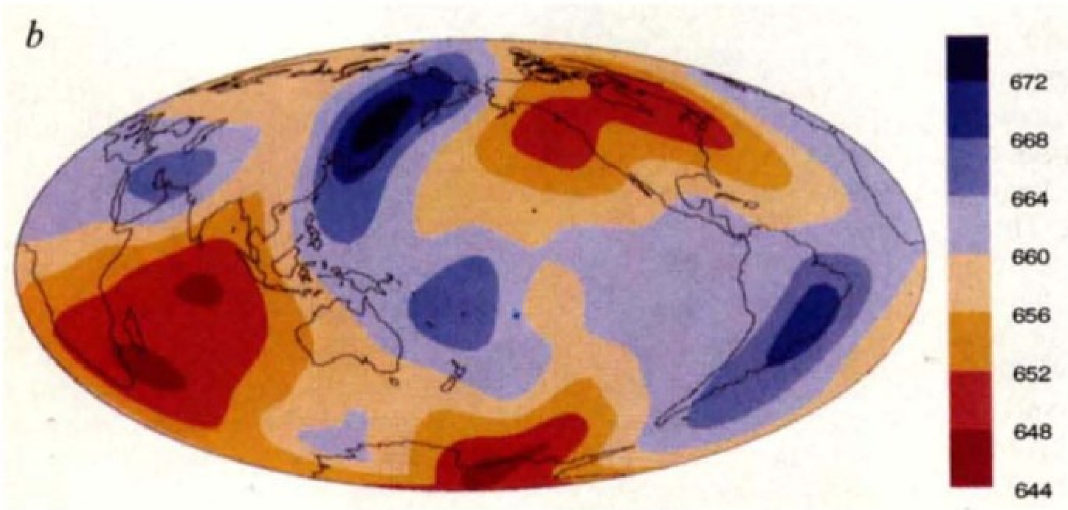

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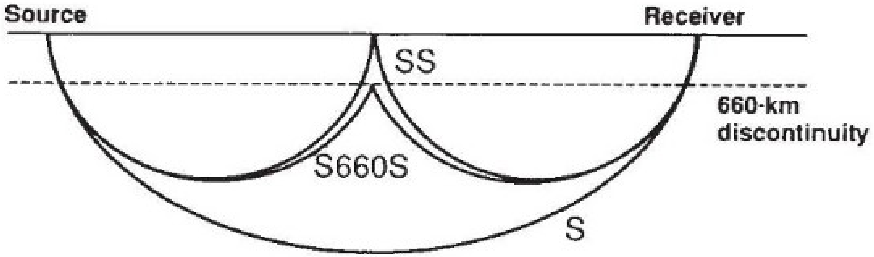

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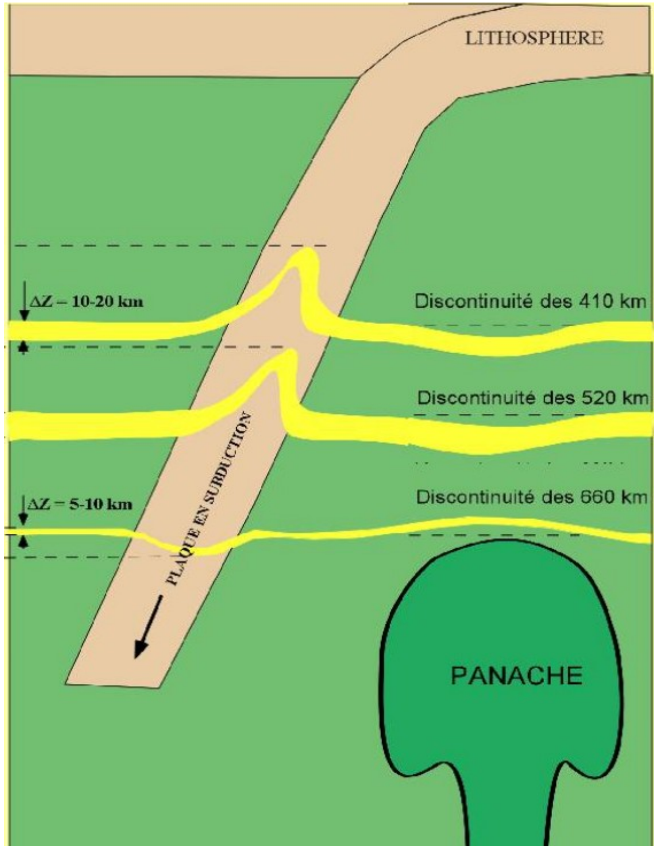
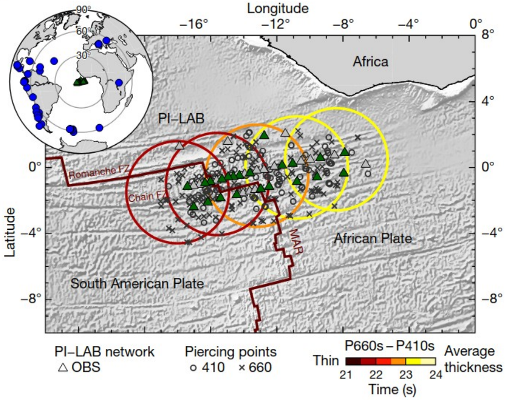
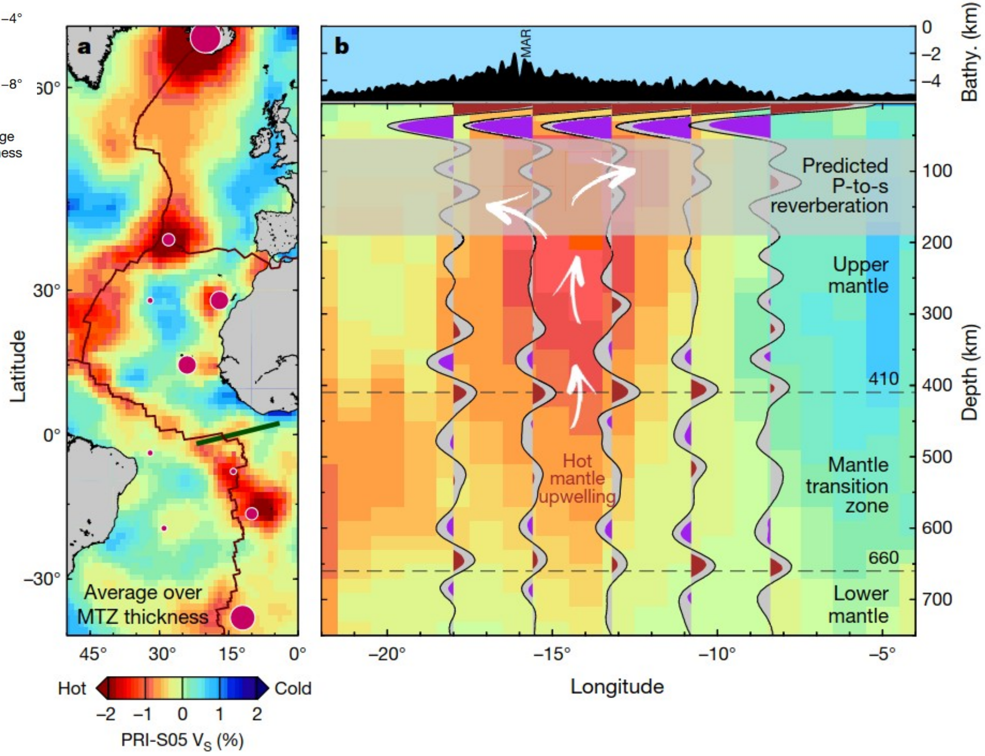
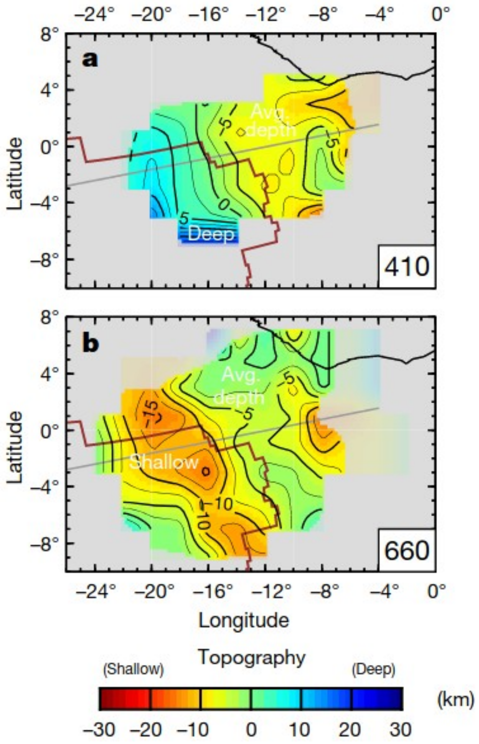


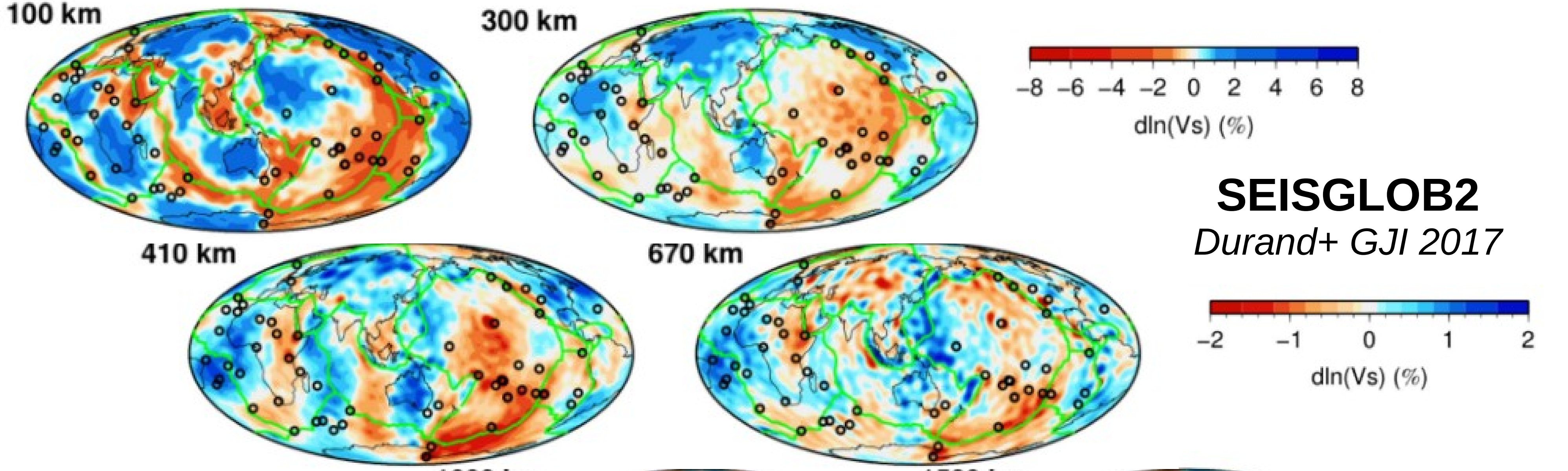
Deep motions also below mid-ocean ridges ?!



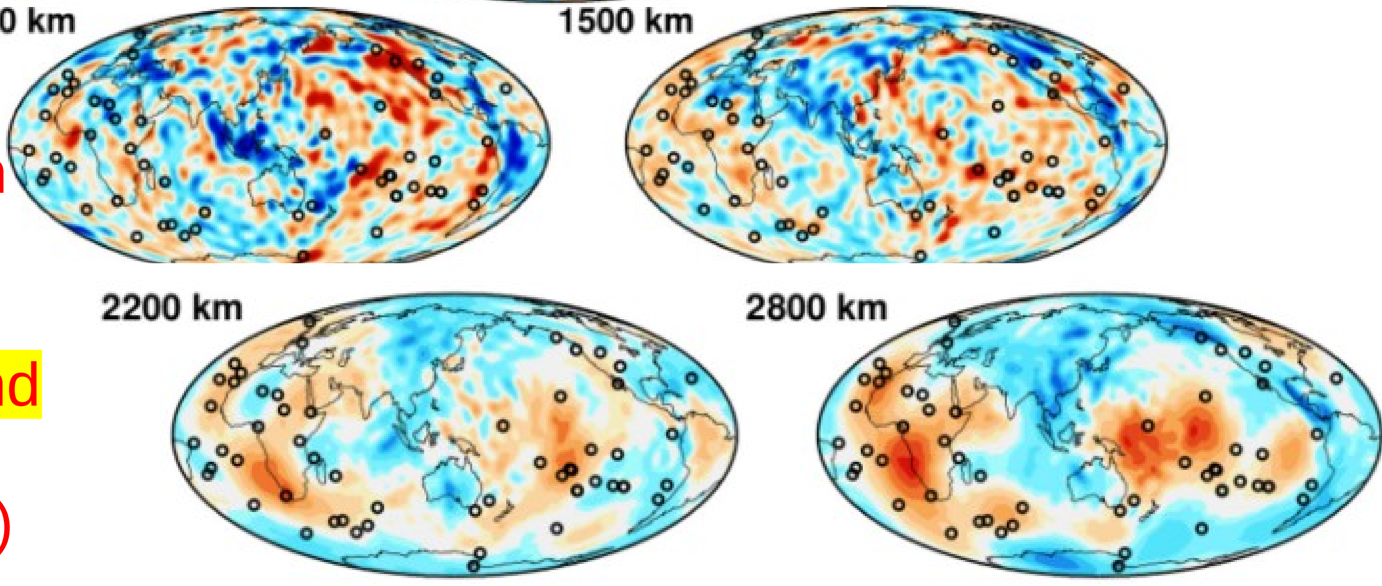




Agius+ Nature 2021



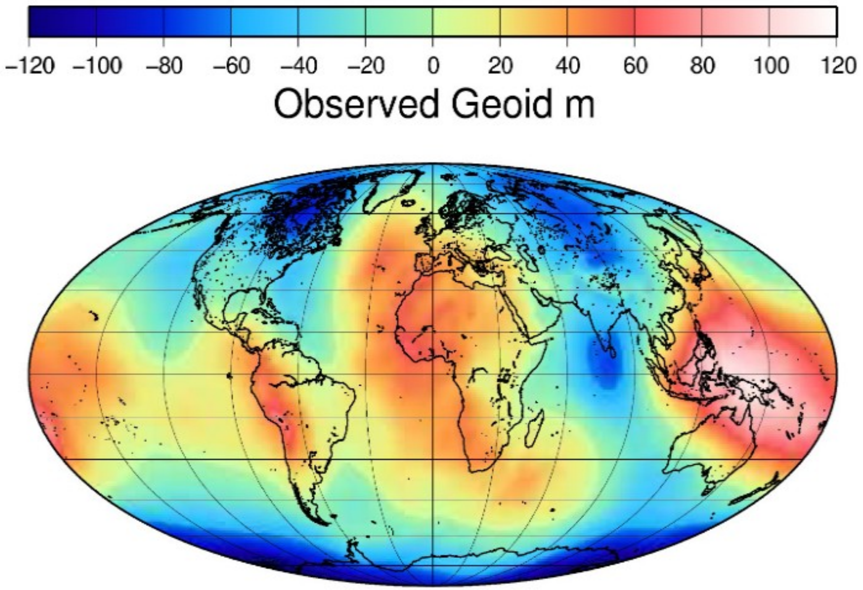
SEISGLOB2
Durand+ GJI 2017



Several scales
of mantle convection

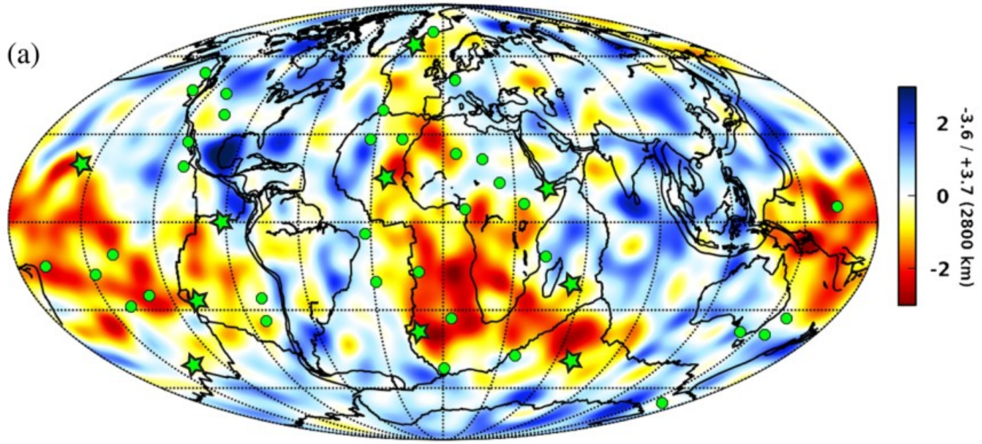
what happens around
1000 km depth ?
(short wavelengths)

Argument for <u>deep</u> motions : geoid vs. seismic tomography



F. Chambat

Shear velocity relative anomaly
at 2800 km depth



French & Romanowicz GJI 2014

Why does lighter material induces a geoid high ?

Why does denser material indues a geoid low ?

MOTION
> "flow-induced" deformation of density interfaces (surface, mantle phase transitions, CMB)

Argument for deep motions : geoid vs. seismic tomography

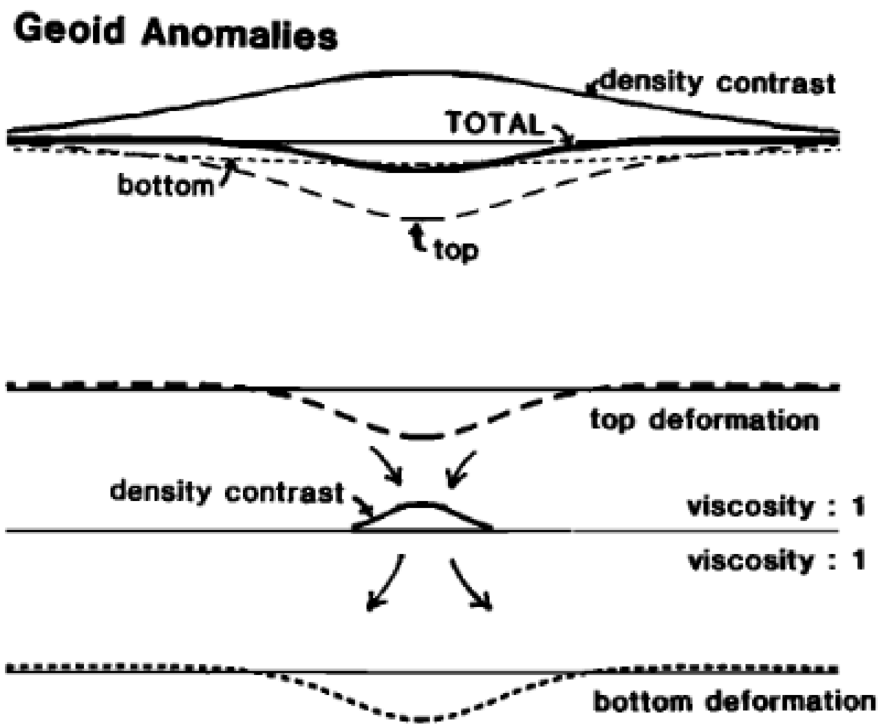


Fig. 1. Illustration of the components of the geoid anomaly from a cosine bell density contrast at the midpoint of a layer of uniform viscosity η. The total anomaly (heavy solid line) is the sum of the contributions from the density contrast itself (light solid line), from dynamic deformation of the upper boundary (long dashes), and from dynamic deformation of the lower boundary (short dashes). The total geoid anomaly is negative for a positive density anomaly.

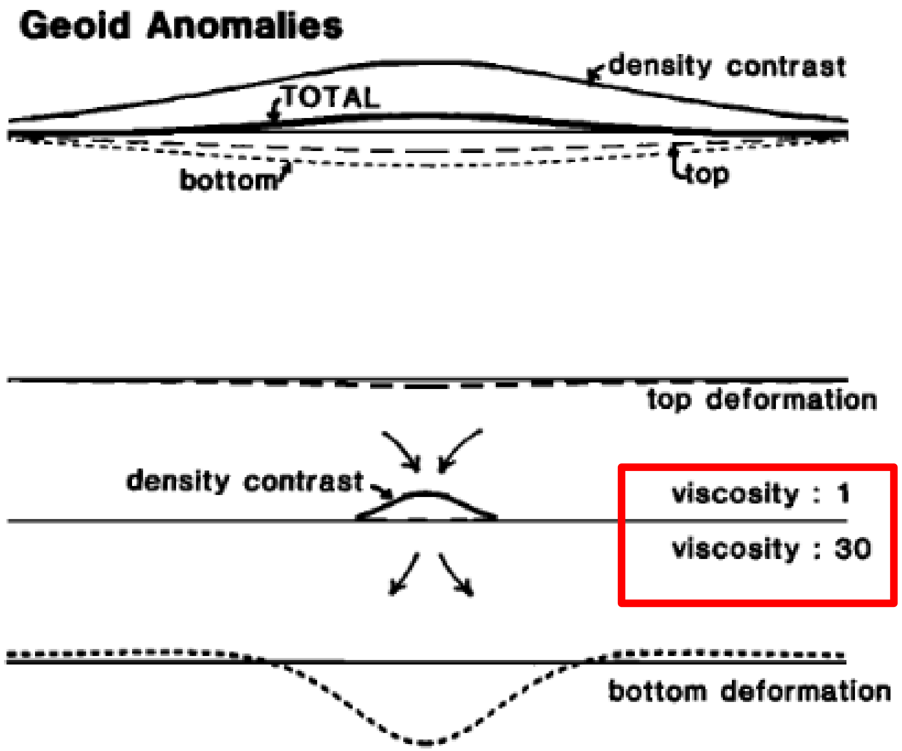
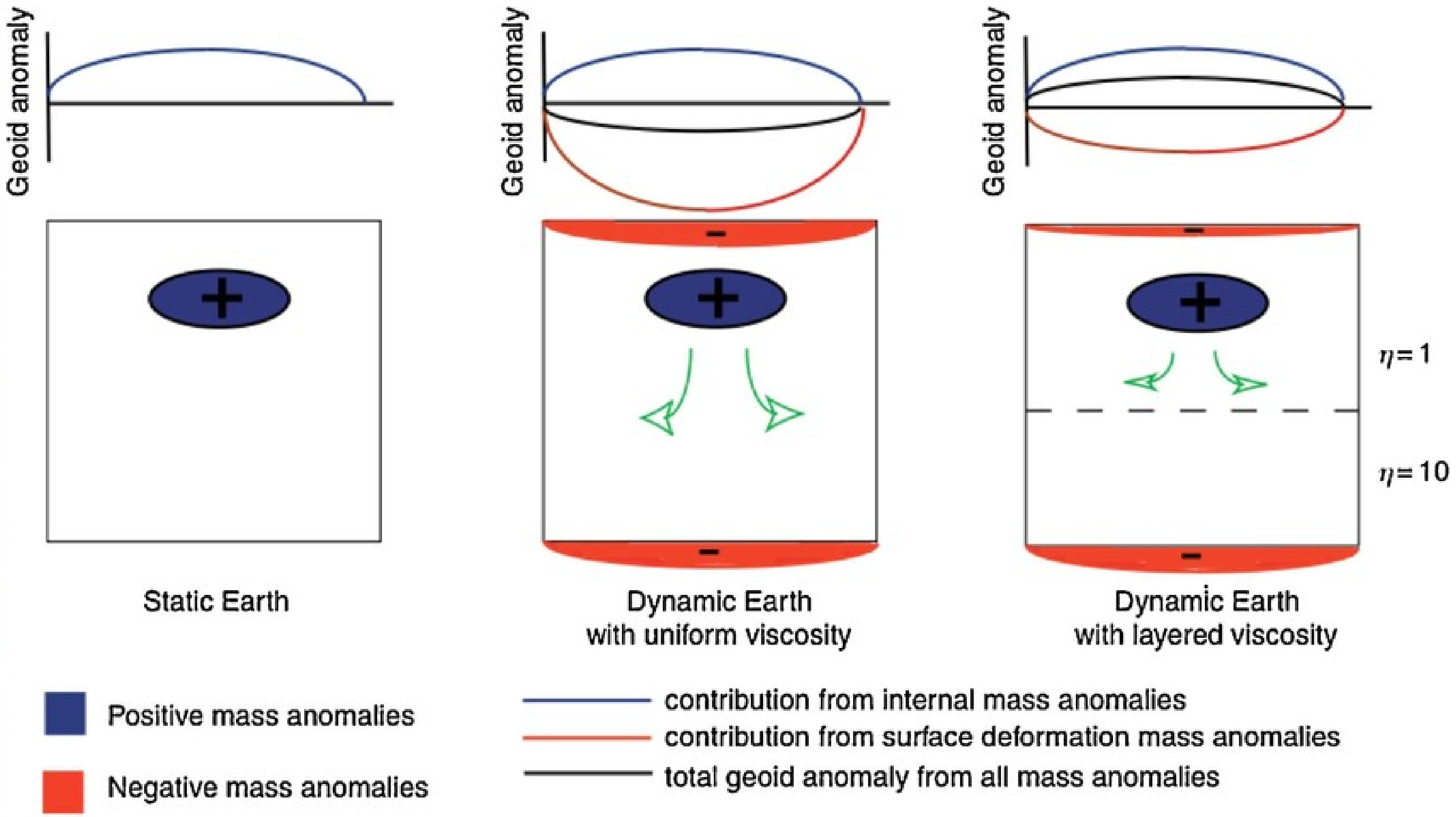


Fig. 2. As in Figure 1, but now the bottom half of the layer has a viscosity η a factor of 30 larger than the upper half. The sign of the total geoid anomaly is now positive.

Hager JGR 1984

Argument for <u>deep</u> motions : geoid vs. seismic tomography

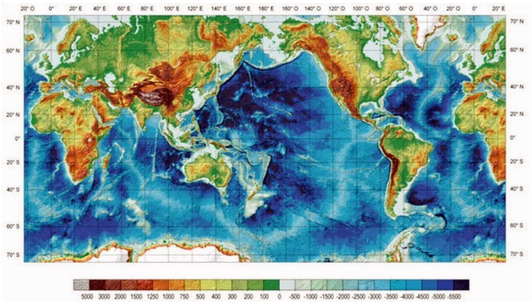


Reconciling geoid and seismic tomography gives contraints on the **viscosity variation with depth**

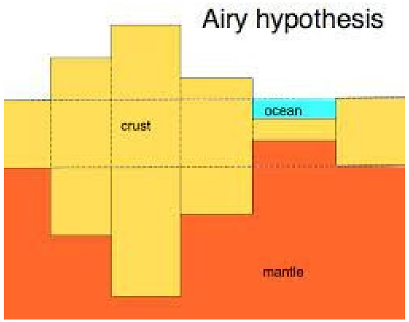
(e.g. Ricard+ JGR 1993)

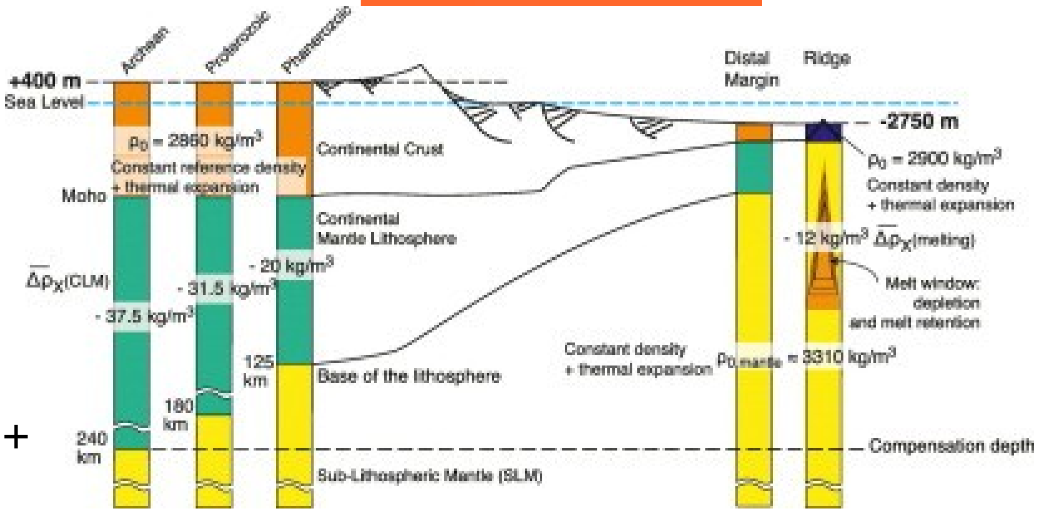
Argument for deep motions : dynamic (non-isostatic) topography

Topography = statically-equilibrated density distribution + “residual”
(dynamic component ?)



Sea floor topography map (from Calmant et al., 2002)





Theunissen+ 2022

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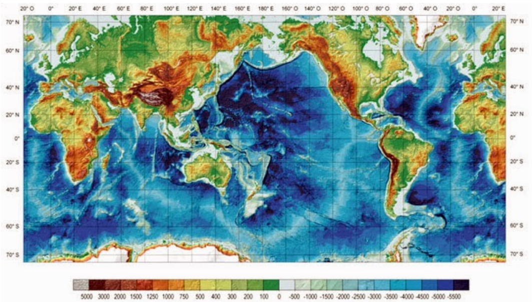
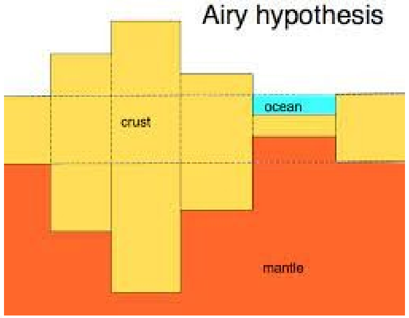
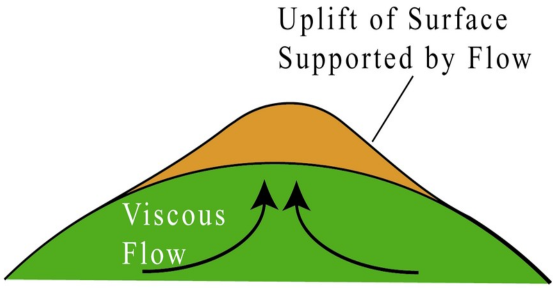
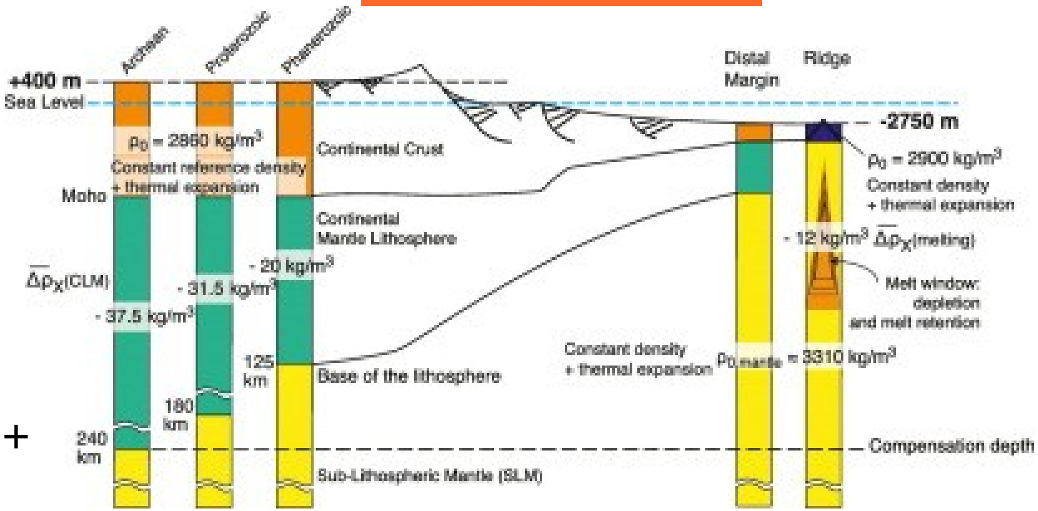
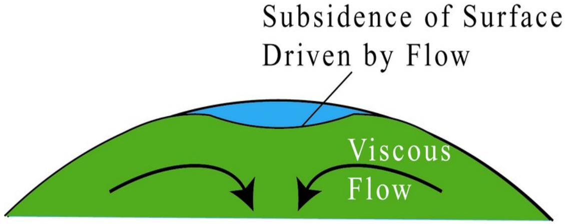

Sea floor topography map (from Calmant et al., 2002)







Theunissen+ 2022



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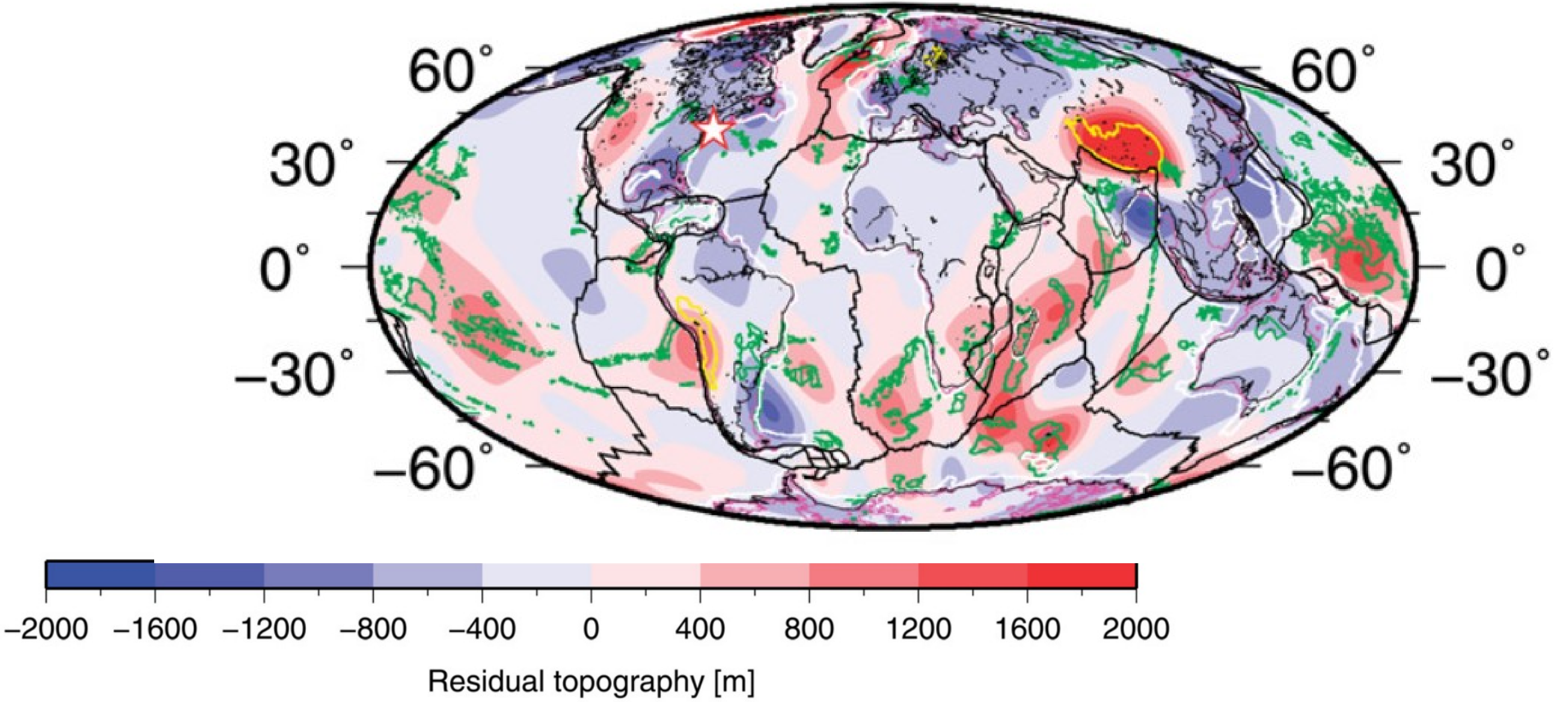
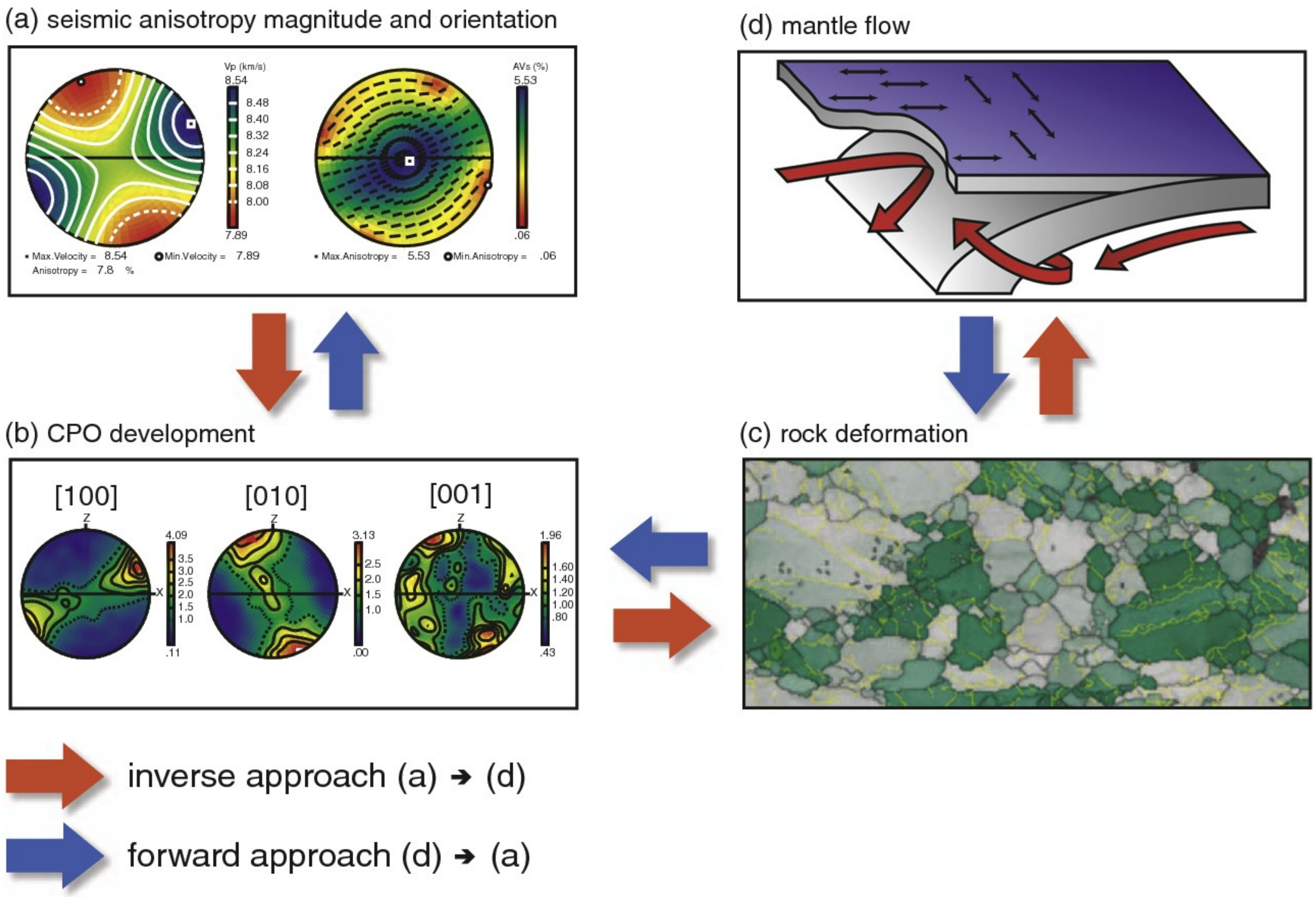


- green > large igneous provinces
- yellow > continental crust thicker than 50 km

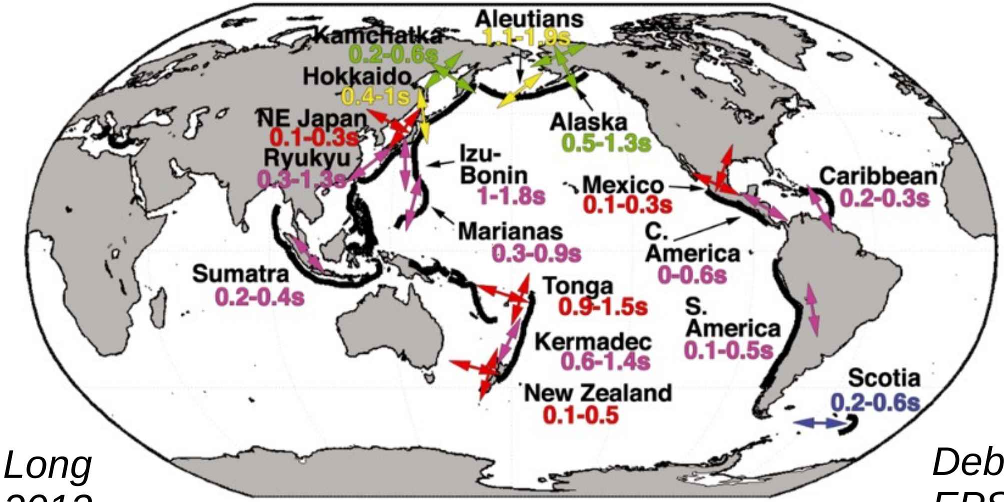
Flament+ Lithosphere 2013

Argument for <u>deep</u> motions : seismic anisotropy (UM + D'')



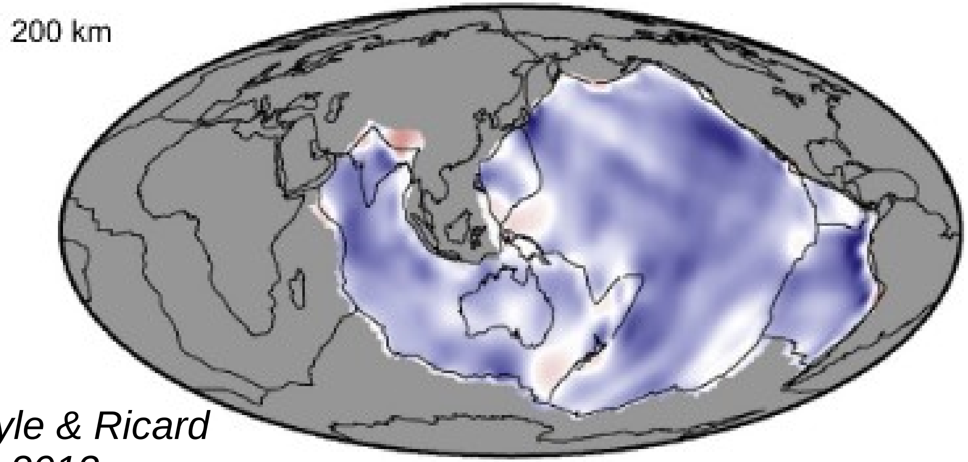
Argument for <u>deep</u> motions : seismic anisotropy (UM)

Fast direction in subduction wedges



Long
2013

agreement between fast direction and present-day plate motion



Debayle & Ricard
EPSL 2013

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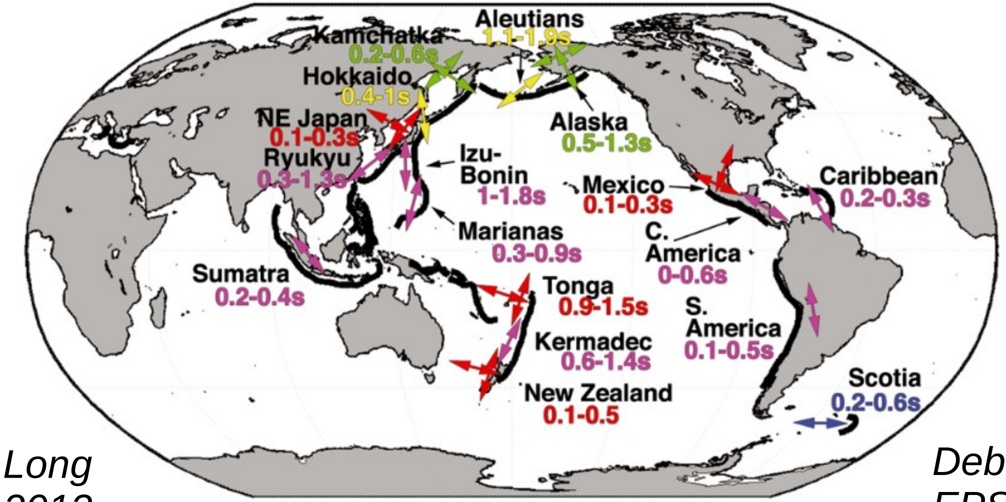

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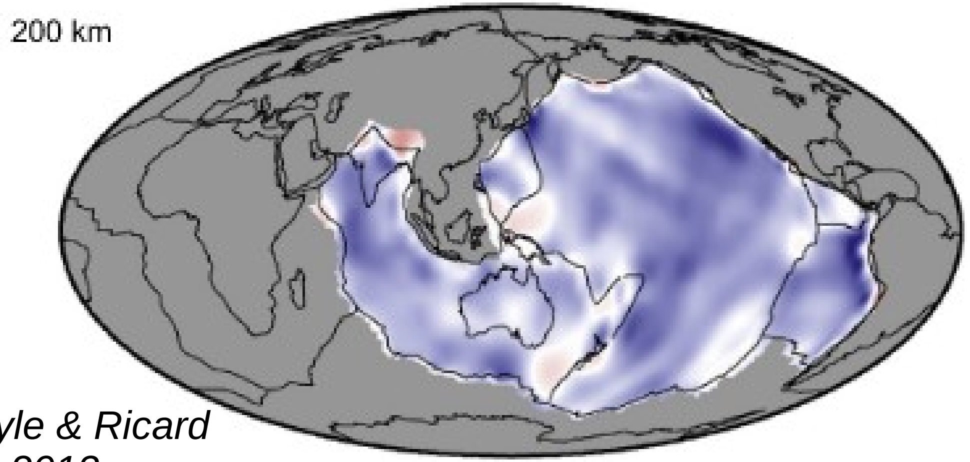
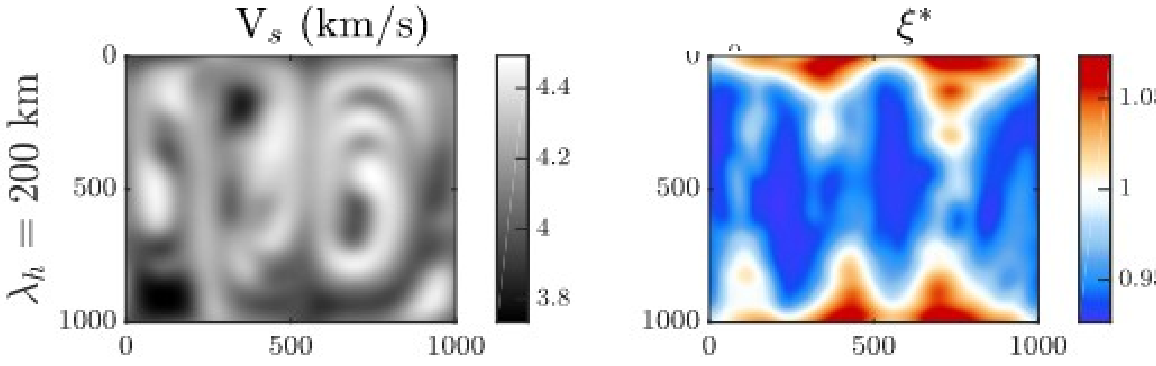


Debayle & Ricard EPSL 2013

… but **small-scale heterogeneities**

> "caution should be taken when interpreting observed anisotropy in terms of LPO and mantle deformation"

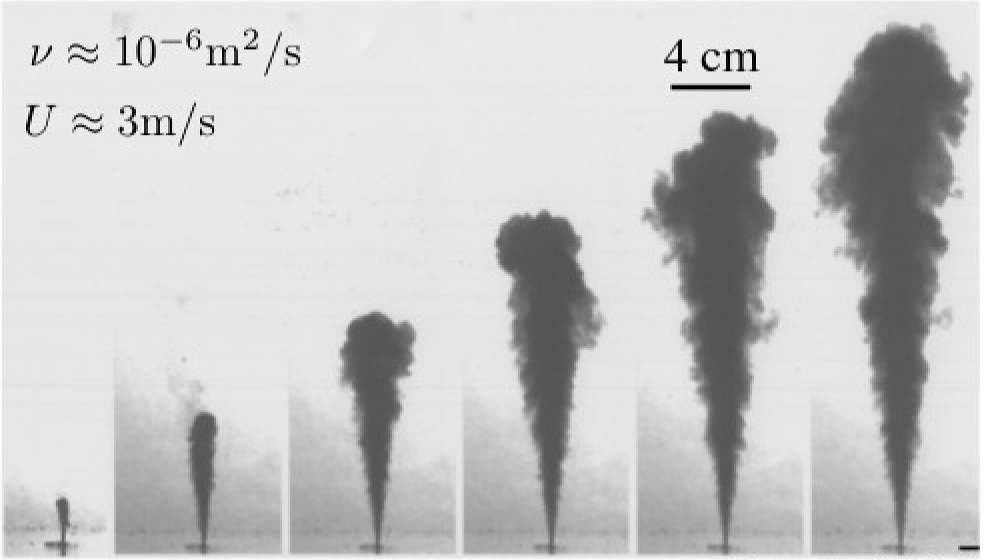
Alder+ GJI 2017



Dimensionless numbers

- Reynolds number $Re = \dfrac{\text{inertia}}{\text{viscous forces}} = \dfrac{\text{viscous time}}{\text{advective time}} = \dfrac{UL}{\nu}$

$Re \approx 9000$ Turbulent plume



Diez et al., 2003

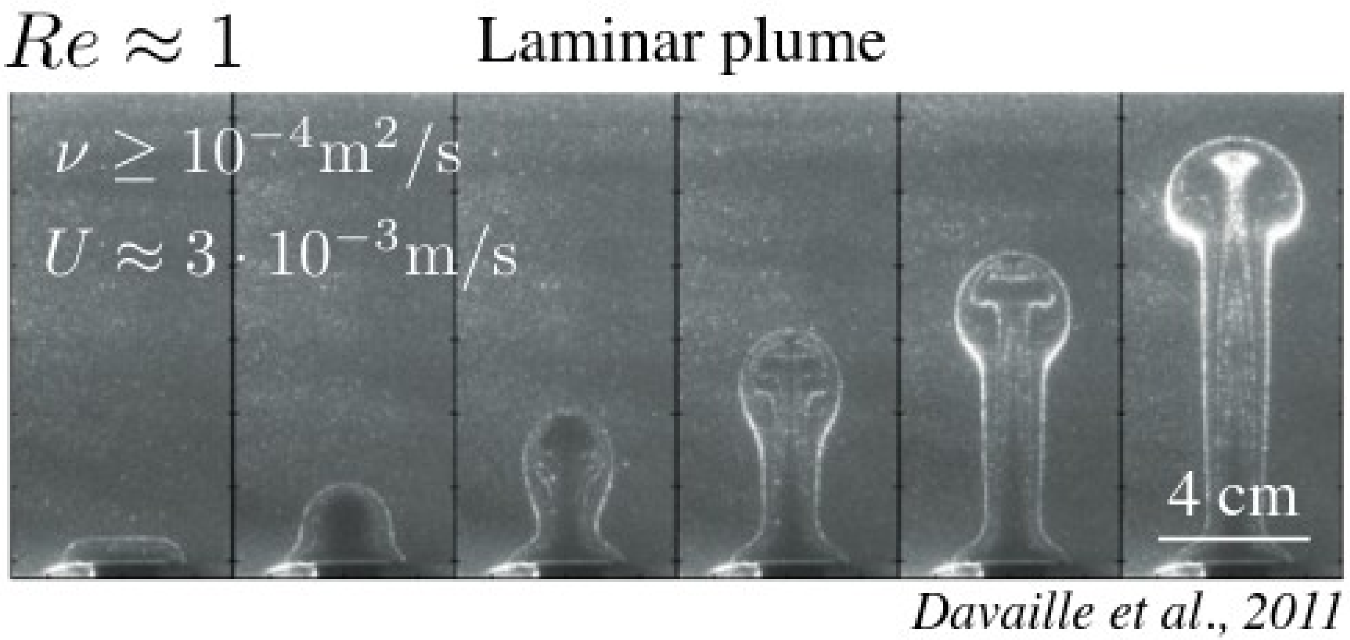
Dimensionless numbers for mantle dynamics

- Reynolds number $Re = \dfrac{\text{inertia}}{\text{viscous forces}} = \dfrac{\text{viscous time}}{\text{advective time}} = \dfrac{UL}{\nu}$

kinematic viscosity $\nu \sim 10^{18}$ m^2/s

Re << 1

laminar flow



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- Rayleigh number $Ra = \dfrac{\alpha \, \Delta T \, g \, H^3}{\nu \, k}$

- buoyancy vs. momentum + thermal diffusivities
- time scales : thermal diffusion vs. convection

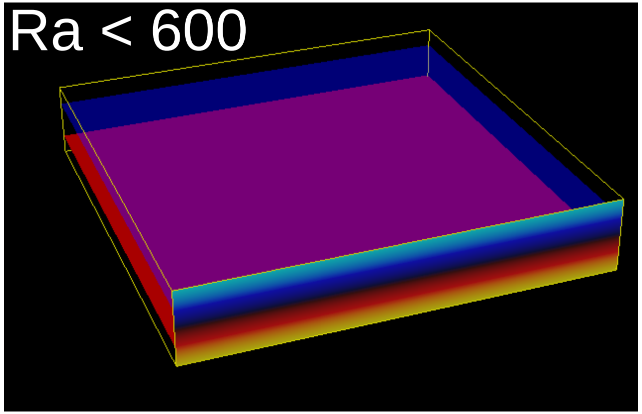
upper mantle viscosity ~ 10^{20} Pa.s
lower mantle viscosity ~ 10^{22} Pa.s
sub-plate low viscosity layer (?) ~ 10^{18} Pa.s

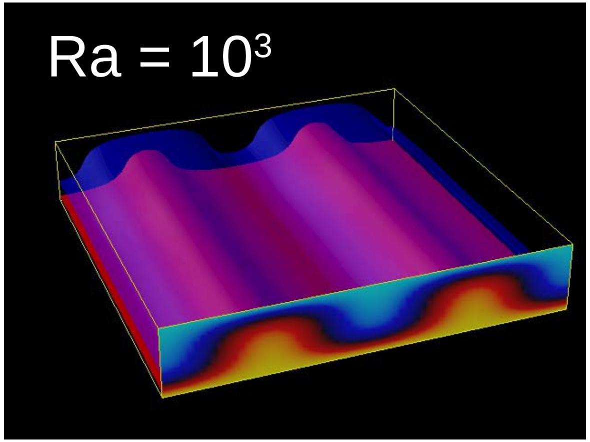
H = 200 km (sub-plate SSC ?)
H = 660 km (upper mantle)
H= 2900 km (whole mantle)

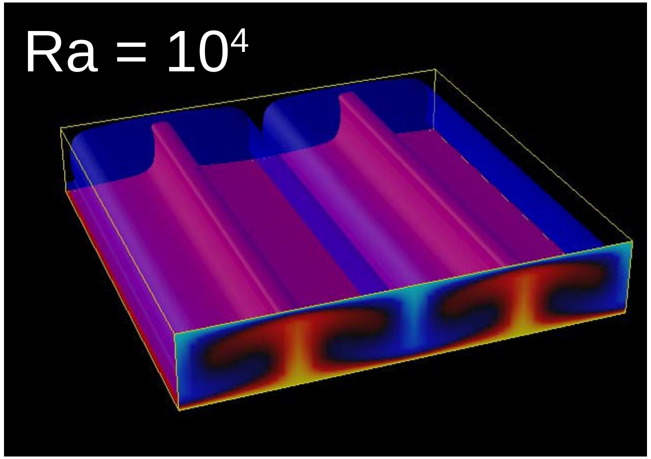
$\Delta T_{\text{subplate-surface}} \sim 1000$ K
$\Delta T_{\text{660-surface}} \sim 2000$ K
$\Delta T_{\text{CMB-surface}} \sim 3000$ K

Ra ~ 10^6 – 10^8
convecting mantle

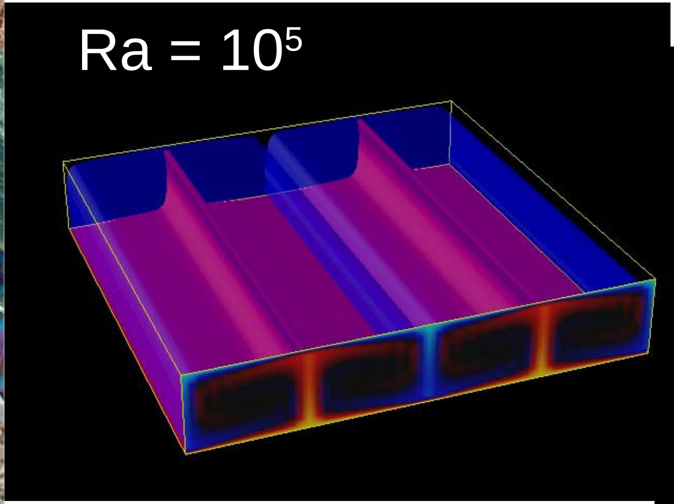
Increasing the Rayleigh number and changing the pattern of convection

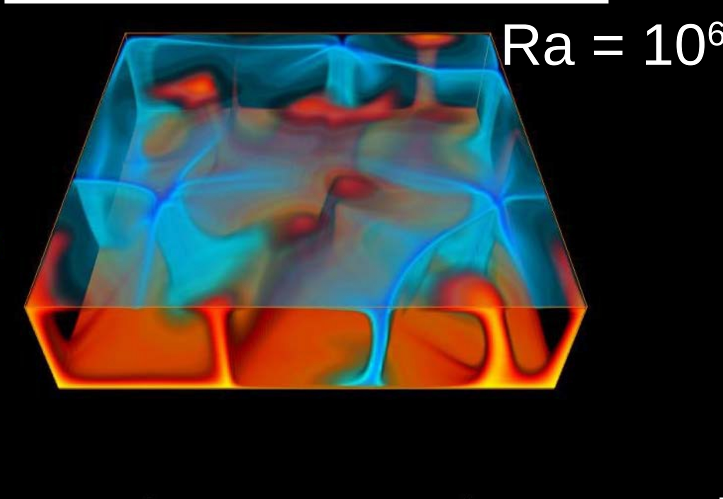


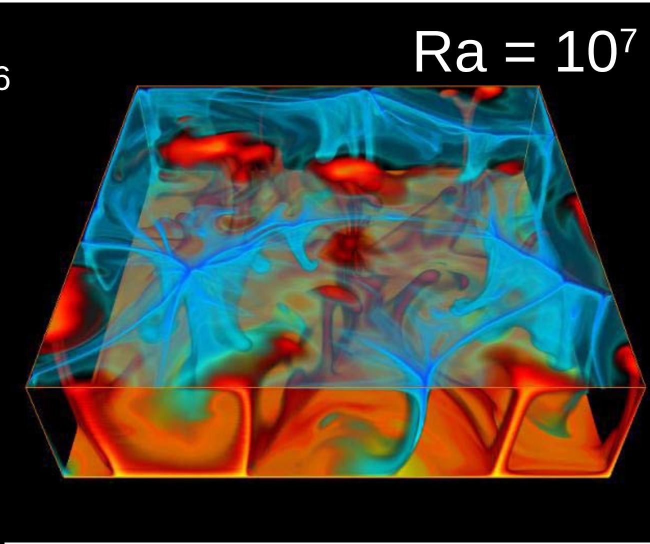




Dubuffet, 2005







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convecting mantle

- Prandtl number $$Pr = \frac{\nu}{k}$$

momentum diffusivity
to thermal diffusivity

Pr > 10^{23} - *"infinite"*
thermal anomalies trigger motions

Dimensionless numbers for mantle dynamics

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Ra ~ 10^6 – 10^8
convecting mantle

large Ekman number
viscous/creeping flow
(no Earth's rotation effect)

- Prandtl number $Pr = \frac{\nu}{k}$

momentum diffusivity
to thermal diffusivity

Pr > 10^{23} - *"infinite"*
thermal anomalies trigger motions

Orders of magnitude : 0-D mantle dynamics

- Surface plate motions ~ 0.1-10 cm/yr - Deep mantle motions ~ **1 cm/yr**
  time to travel through the mantle (plume up, slab down) ~ **???**

- Ratio between surface (R=6400 km) and CMB (R=2800 km) ~ **???**

  surface of a sphere = $4\pi R^2$

- **Strain rate** in the upper mantle ~ **???**

  2 cm/yr plate shearing the upper mantle (Couette)

- Thermal anomalies ~ +300 / -1000 K → **relative density anomalies** ~ **???**

  thermal expansivity α ~3 10^{-5} K

1 yr ~ 3.10^7 s

- Length scale of **thermal diffusion** over 100 Myr ~ **???**
- Length scale of **chemical diffusion** over 100 Myr ~ **???**
- Diffusive time to transport heat through a 10 or 100-km lithosphere ~ **???**

  $d = (\kappa t)^{1/2}$ - thermal diffusivity ~ 10^{-6} m^2/s - chemical diffusivity 10^{-9}-10^{-13} m^2/s

- **Heat flux** advected by slabs : $Q = \delta x L \rho C_p w \delta T$ ~ **???**

  L_{trench} ~ 50 000 km - δT~600 K - w~ 10 cm/yr – slab thickness δx~ 100 km

  density ρ ~ 3300 kg/m^3 – specific heat C_p ~ 1000 J/K/kg

Orders of magnitude : 0-D mantle dynamics

- Surface plate motions ~ 0.1-10 cm/yr - Deep mantle motions ~ **1 cm/yr**

  time to travel through the mantle (plume up, slab down) ~ **300 Myr**

- Ratio between surface (R=6400 km) and CMB (R=2800 km) ~ **5**

  surface of a sphere = $4\pi R^2$

- **Strain rate** in the upper mantle ~ $\mathbf{10^{-15}\ s^{-1}}$

  2 cm/yr plate shearing the upper mantle (Couette)

- Thermal anomalies ~ +300 / -1000 K → **relative density anomalies** ~ **1-3 %**

  thermal expansivity α *~3* 10^{-5} *K*

1 yr ~ 3.10^7 s

- Length scale of **thermal diffusion** over 100 Myr ~ **60 km**
- Length scale of **chemical diffusion** over 100 Myr ~ **20 m – 2 km**
- Diffusive time to transport heat through a 10 or 100-km lithosphere ~ 3 / 300 Myr

  $d = (\kappa t)^{1/2}$ - *thermal diffusivity ~* 10^{-6} m^2/s *- chemical diffusivity* 10^{-9}*-*10^{-13} m^2/s

- **Heat flux** advected by slabs : $Q = \delta x L \rho C_p w \delta T$ ~ **30 TW** (plumes ~ 2 TW)

  L_{trench} *~ 50 000 km -* δT*~600 K - w~ 10 cm/yr – slab thickness* δx*~ 100 km*

  density ρ *~ 3300 kg/*m^3 *– specific heat* C_p *~ 1000 J/K/kg*

Mantle geodynamics

1. **Evidence for surface (plate) and deep (mantle) motions**

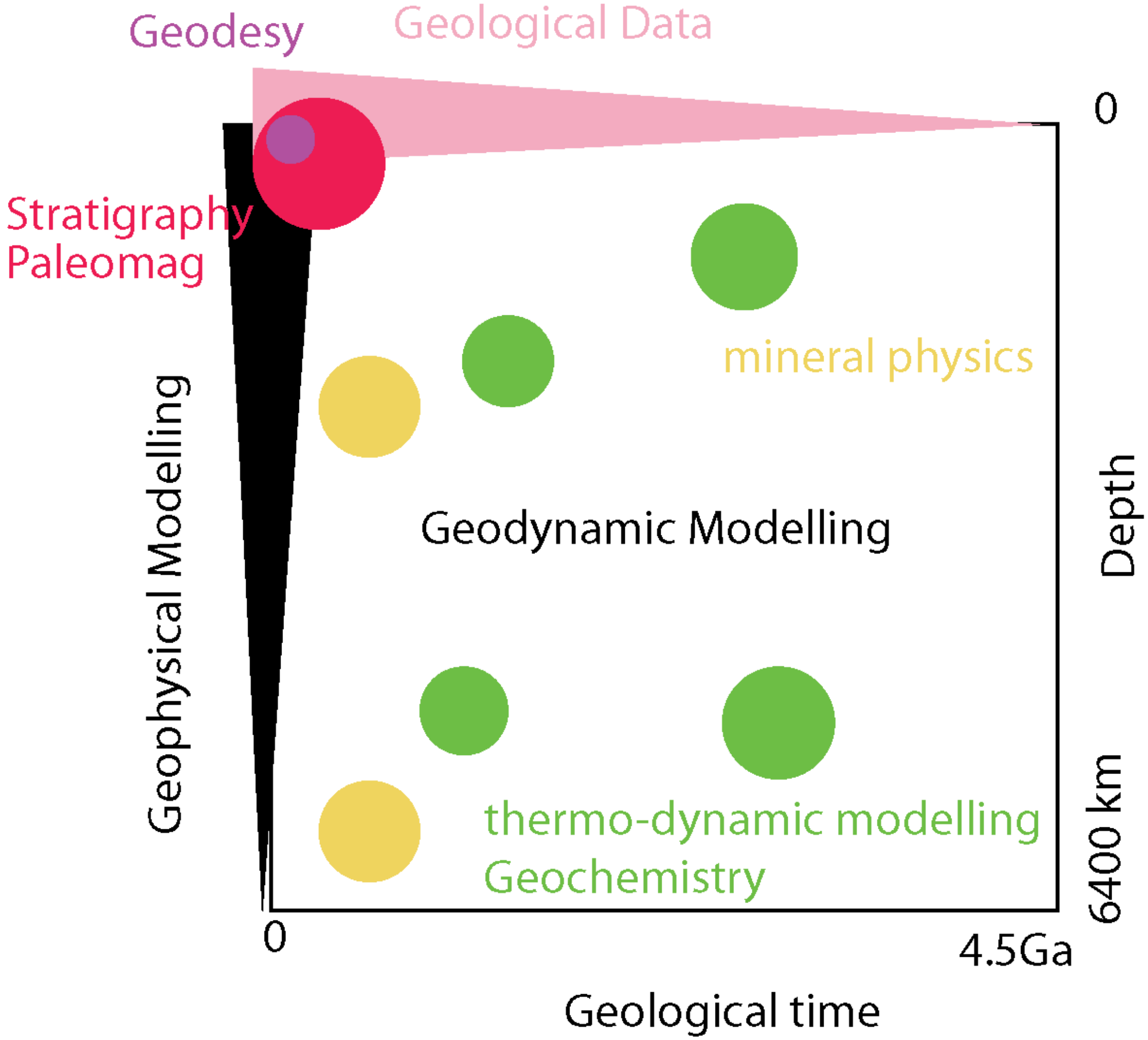
   \+ *orders of magnitude*

2. **Dynamic models to understand the mantle** (past & present)

3. **Mantle and plate dynamics : modelling diversity and recipes**

4. **Progress and perspectives**

Discrete data in time and space



- Measurement
  (displacement, geol. history)

  ≠ physical state
  (stress, temperature, strength, fluid pressure)

- A pure “data-driven” approach not based on physics has little chance to help us understand past or deep earth

after Taras Gerya & Laëtitia le Pourhiet

Models (simplified representation of reality) **of solid Earth dynamics**

- **Conceptual models** – “cartoons” (intuition + data)

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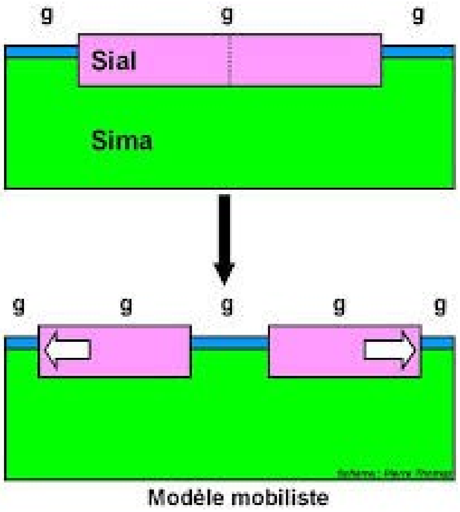
continental drift
(Wegener – 1912)

physical explanation :
~~tidal force~~



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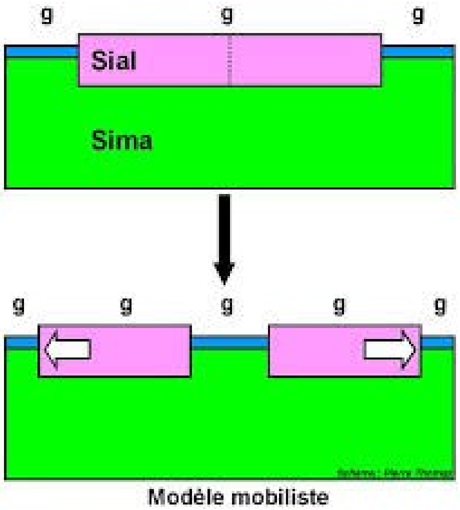

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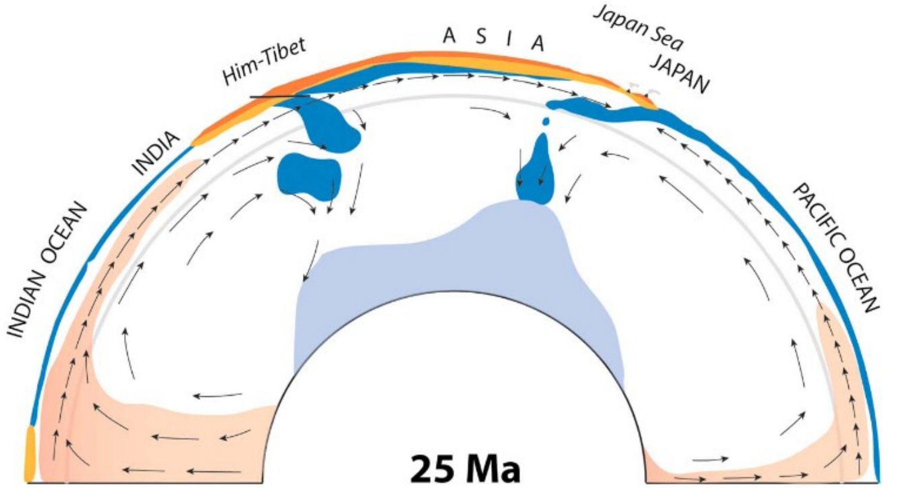
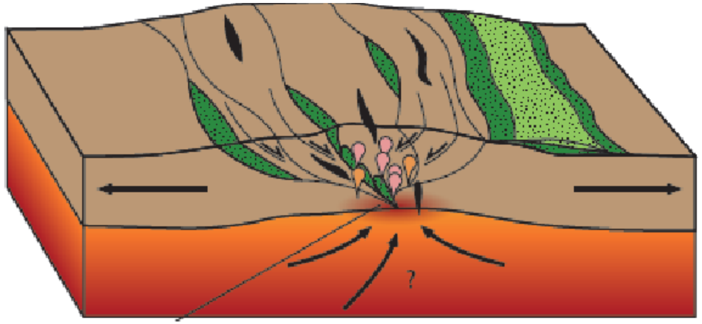


Scenario of past mantle flow from geology + seismic tomography/anisotropy
Jolivet+ 2018



Craton evolution from isotope geochemistry
Albert+ 2016

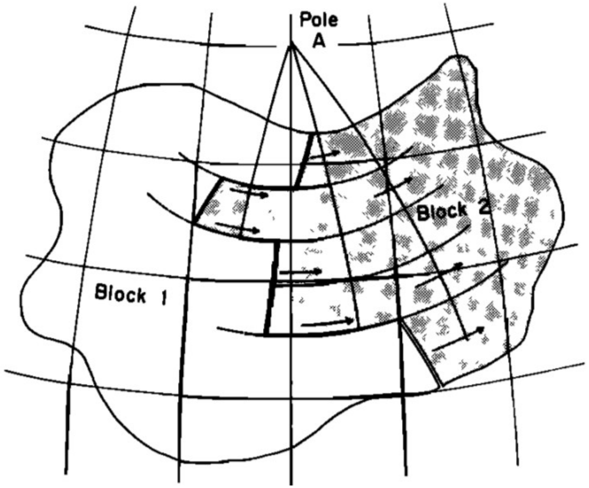
Models (simplified representation of reality) **of solid Earth dynamics**

- **Conceptual models** – “cartoons” (intuition + data)

- **Quantitative models**

> instantaneous models

* plate tectonics models



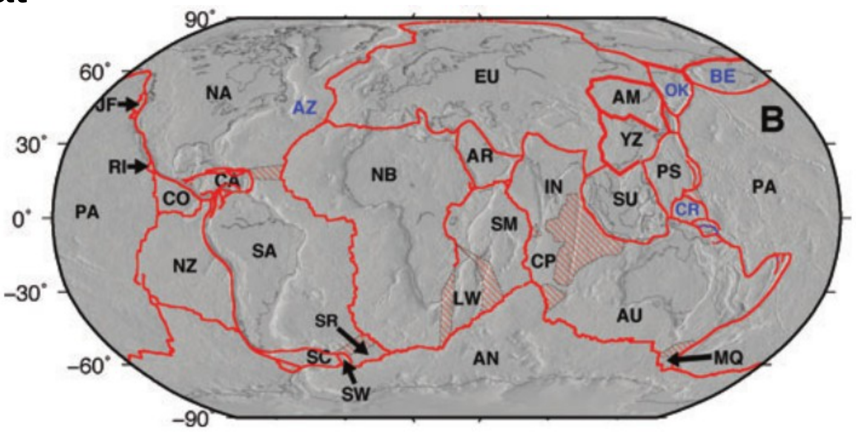
Morgan, 1968

- **rigid blocks** moving at the surface of a spher

- eulerian formalism

- minimizing surface variations

- oceanic expansion rates since 3 Ma
+ focal mechanisms
(+GPS)



25 plates’ model MORVEL
(DeMets+ 2010)

Model<u>s</u> (simplified representation of reality) **of solid Earth dynamics**

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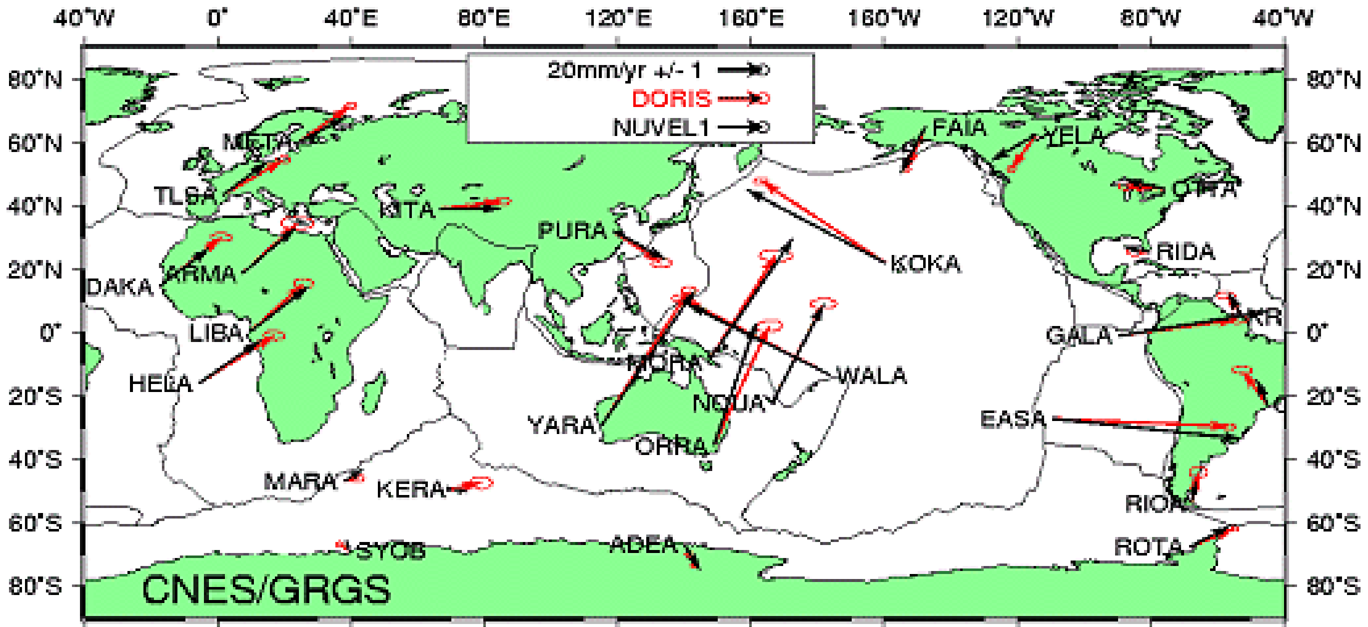


Models (simplified representation of reality) of solid Earth dynamics

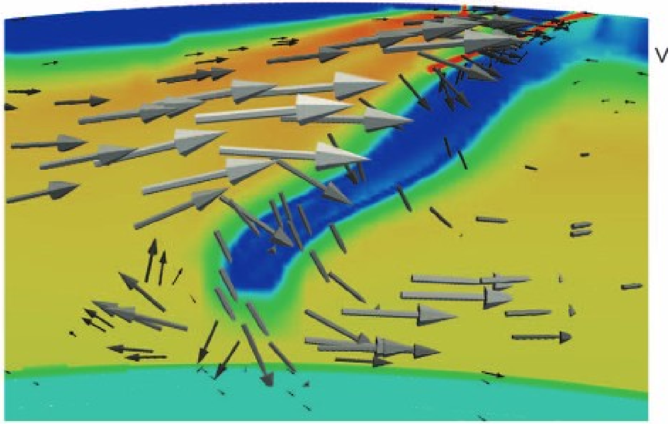
- **Conceptual models** – “cartoons” (intuition + data)

- **Quantitative models**

> instantaneous models

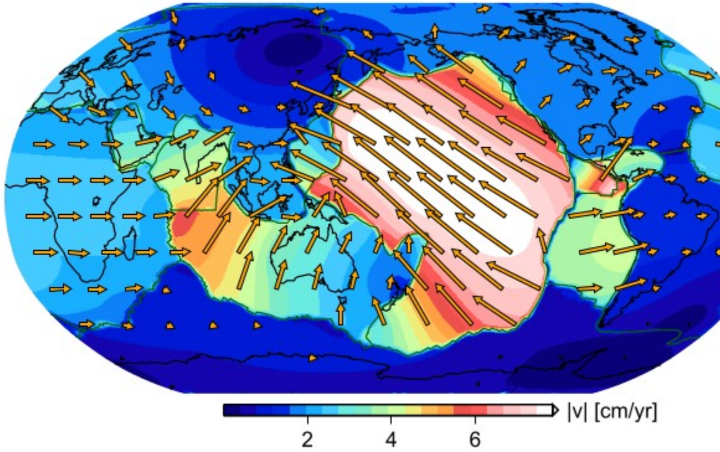
* plate tectonics models

* instantaneous mantle flow models



Stadler+ Science 2010

instantaneous Stokes solution
from present-day density anomalies (seismology)
+ viscosity model
+ plate boundaries...



Becker G³ 2017

Model<u>s</u> (simplified representation of reality) **of solid Earth dynamics**

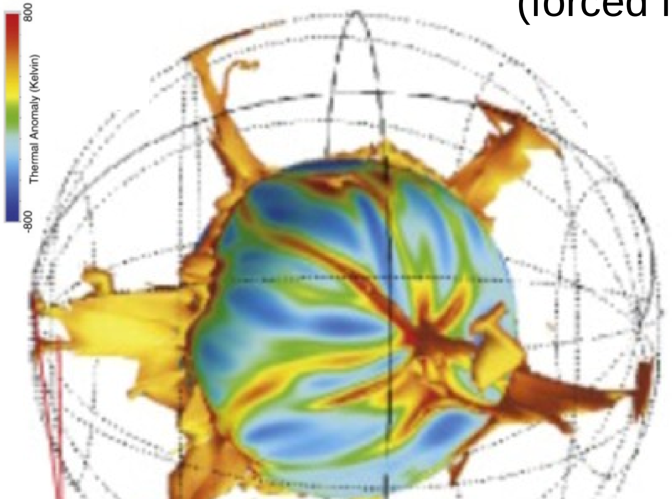
- **Conceptual models** – “cartoons” (intuition + data)

- **Quantitative models**

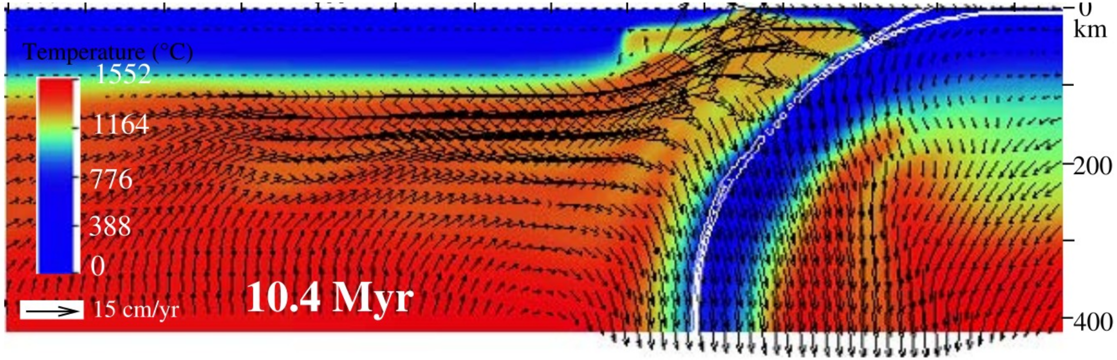
> instantaneous models

> **time-dependent models**

= evolution in space and time starting from an initial state outside equilibrium
(forced flow, density anomalies, basal heat...)



Davies & Davies EPSL 2009



Arcay+ G^3 2008

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+ *orders of magnitude*

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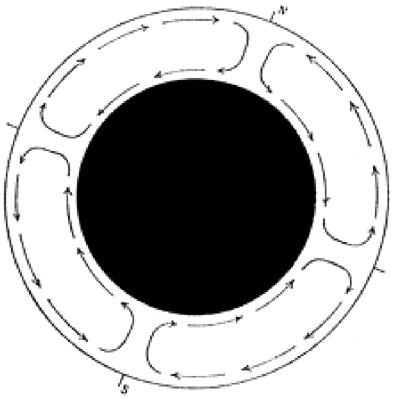
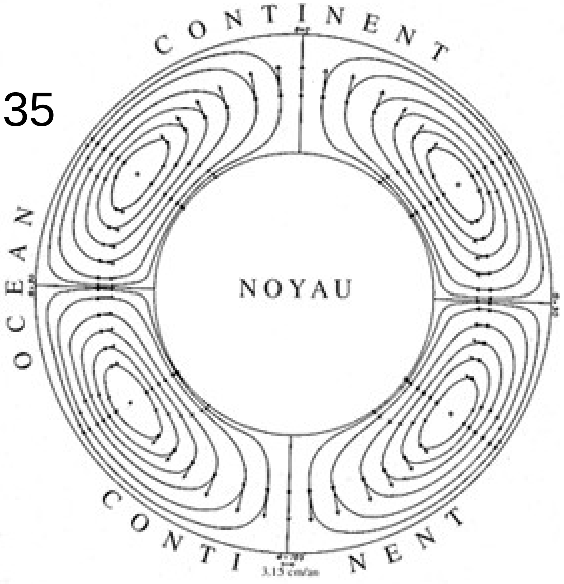
Thermal convection to explain mantle and surface dynamics

Models of mantle convection have been around for a long time... before plate tectonics theory !



Holmes 1931

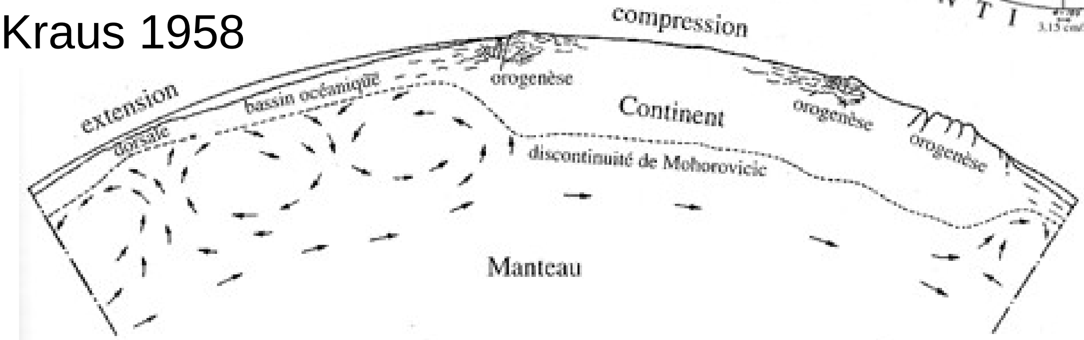
Pekeris 1935

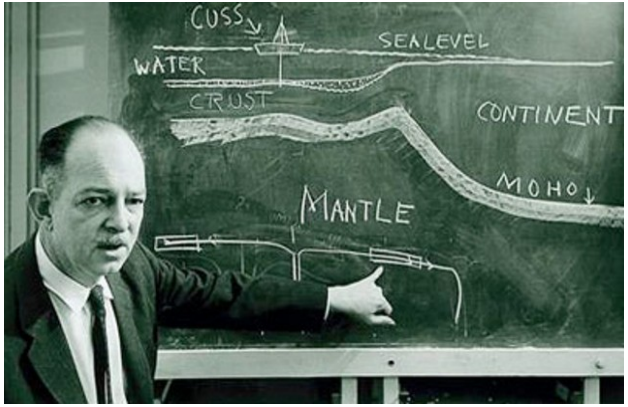


+ Vening Meinesz
+ Griggs + Urey...

https://planet-terre.ens-lyon.fr/ressource/histoire-convection.xml

Kraus 1958





Hess, 1962

Temperature-dependent mantle viscosity

mantle viscosity $$\eta \propto \exp\left(\frac{E}{RT}\right)$$

Arrhenius law

HOT

COLD

(cold) lithosphere 1000x more viscous than (hot) asthenosphere

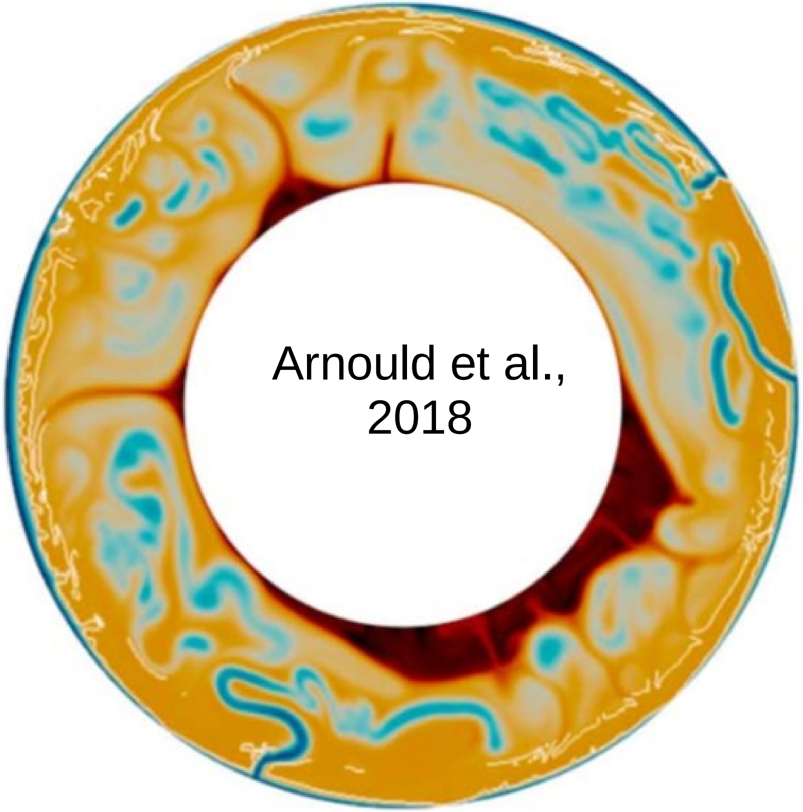
How does the mantle convect ?

- Spherical shell

- **Secular cooling**

- **temperature-dependent viscosity**

- **Ra > 10^6** : “chaotic” convection
  at several scales



Arnould et al., 2018

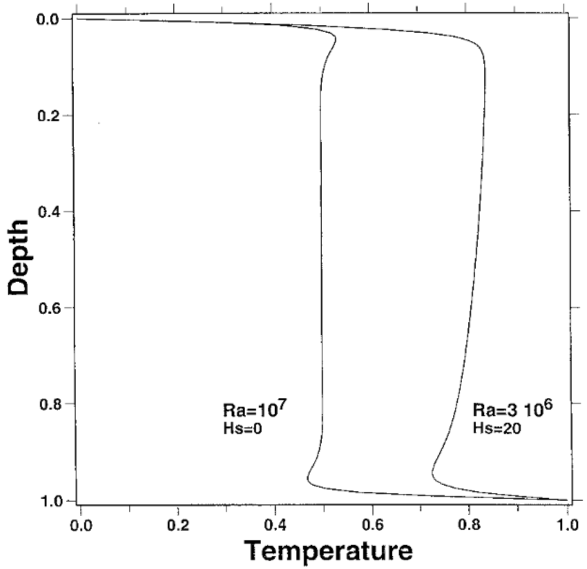
How does the mantle convect ?

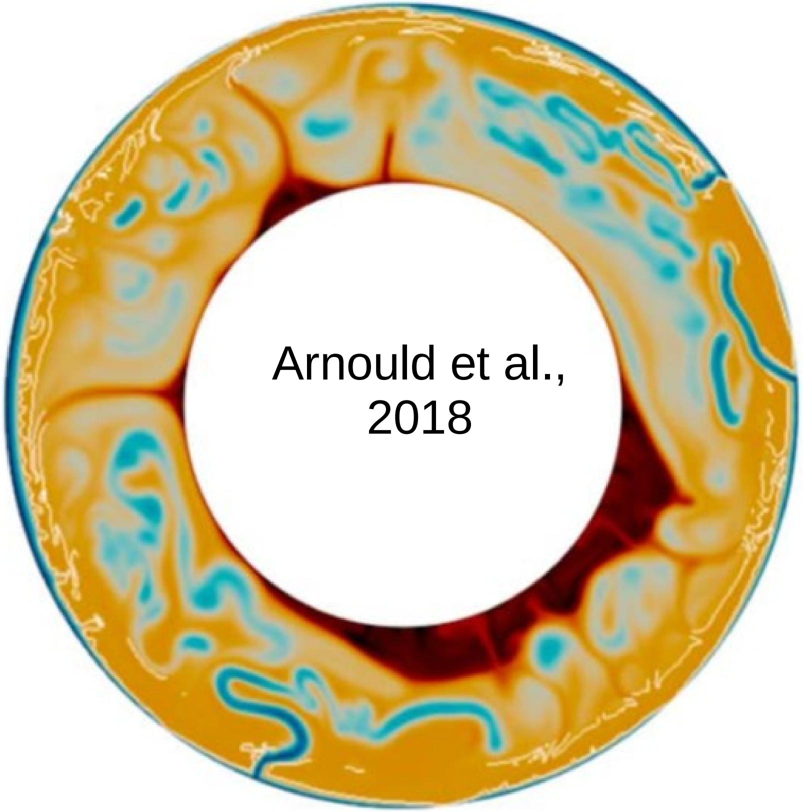
- Spherical shell
- **Secular cooling**
- **temperature-dependent viscosity**
- **Ra > 10^6** : “chaotic” convection at several scales
- Internal heating from radioactive elements

$$\frac{\partial T}{\partial t} + u\nabla T = \nabla^2 T + H_s$$

prominent **cold boundary layer** (lithosphere)

Sotin & Labrosse PEPI 1999

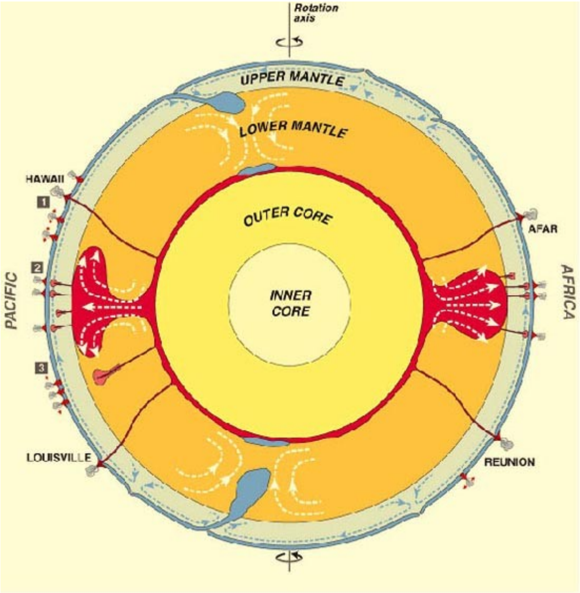




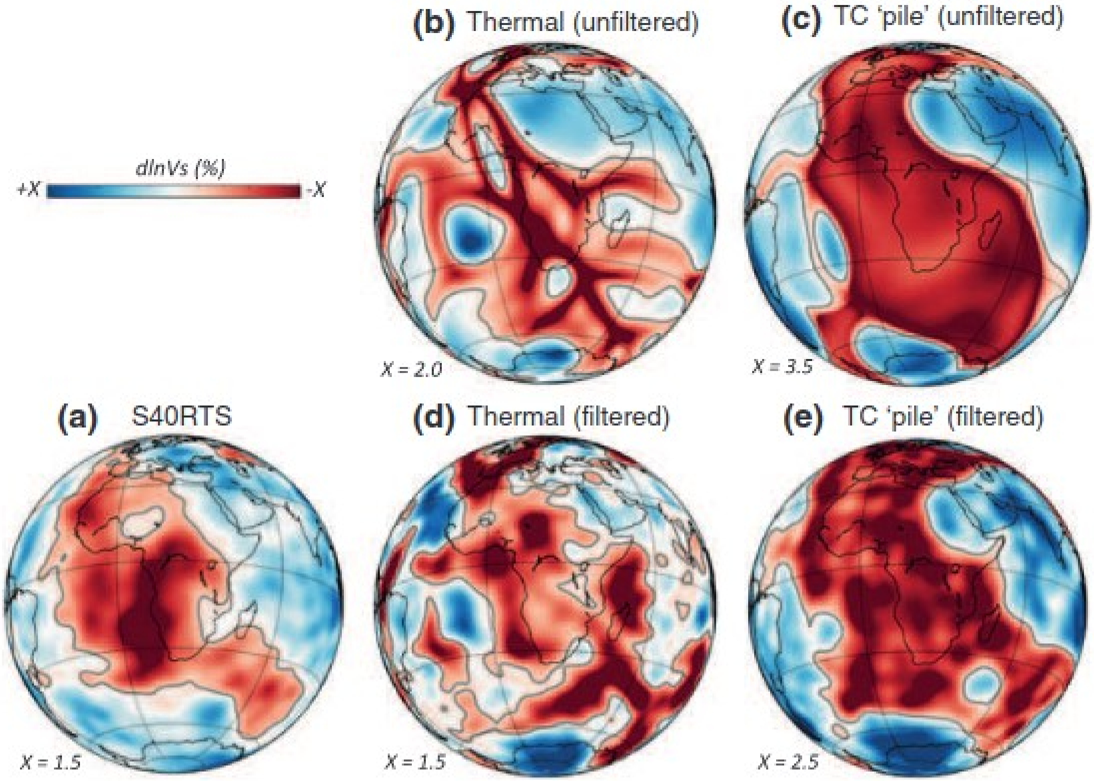
Arnould et al., 2018

Persistence of degree-2 mantle convection ?

Stability of degree-2 throughout Earth's history ?



two antipodal denser equatorial regions > stable configuration for Earth's moments of inertia *(Dziewonski+ EPSL 2010)*

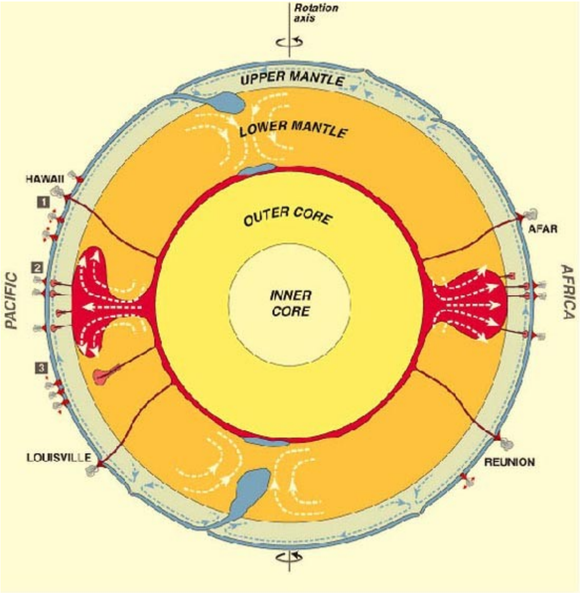


… what is the density anomaly of LLSVP ?

Davies + 2015

Persistence of degree-2 mantle convection ?

Stability of degree-2 throughout Earth's history ?



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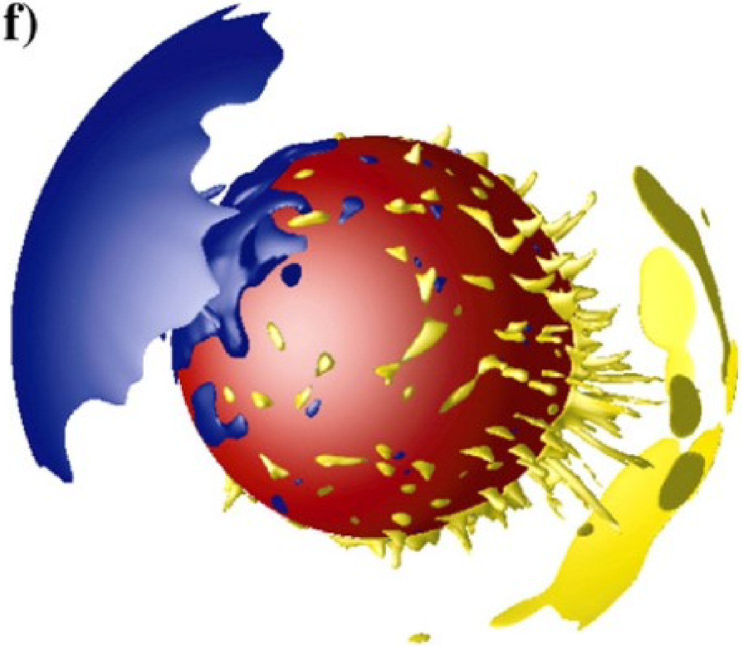
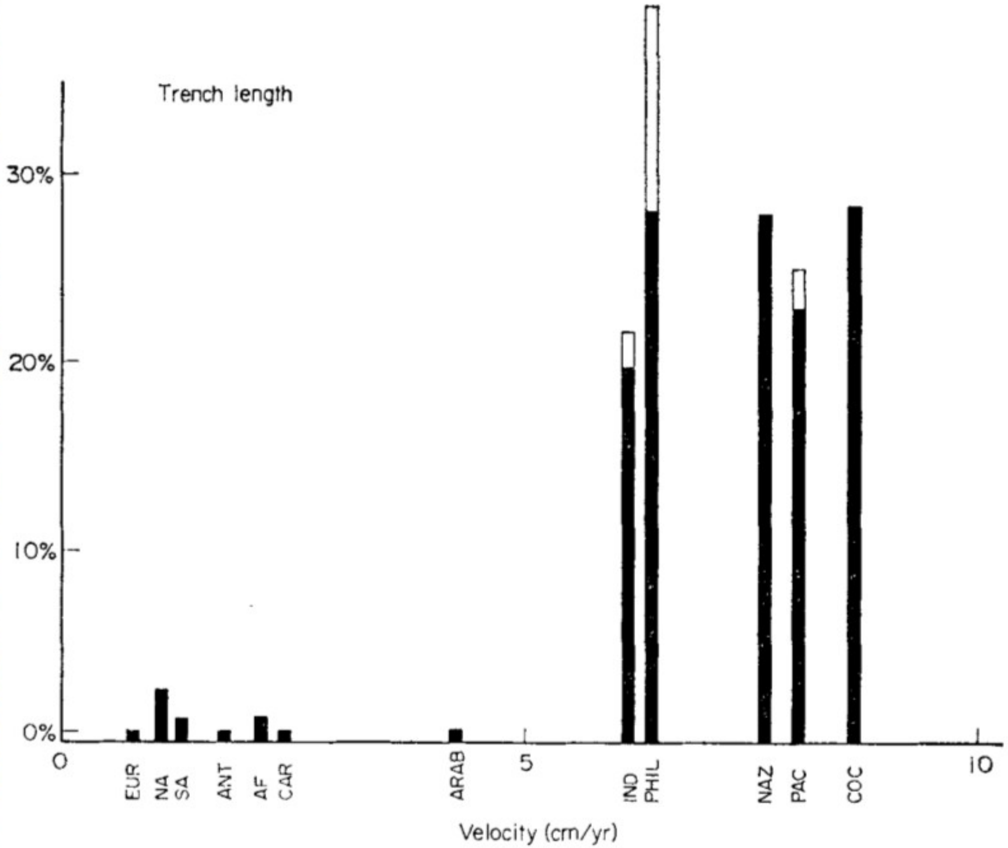
f)



Stable degree-1 configuration with supercontinent assembly
(Zhong+ EPSL 2007)

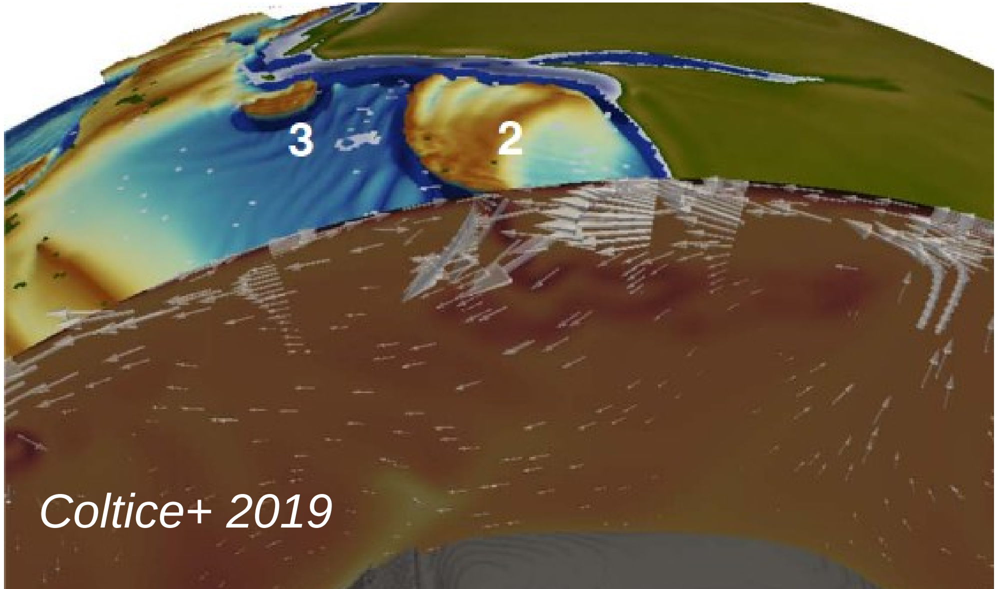
Driving forces of plates motions

Slab pull is a major driving force of surface plate motions



Forsythe & Uyeda, GJI, 1975

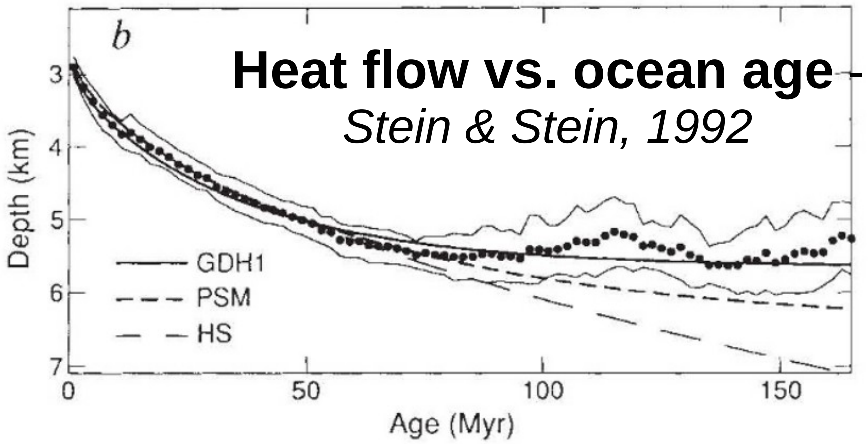
… but **basal drag from asthenosphere** can also play a role (“conveyor belt”)

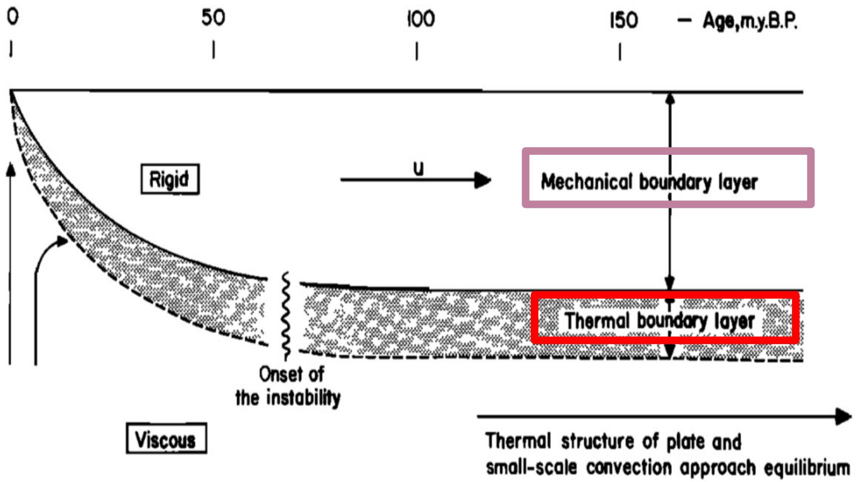


Coltice+ 2019

Several scales of convection

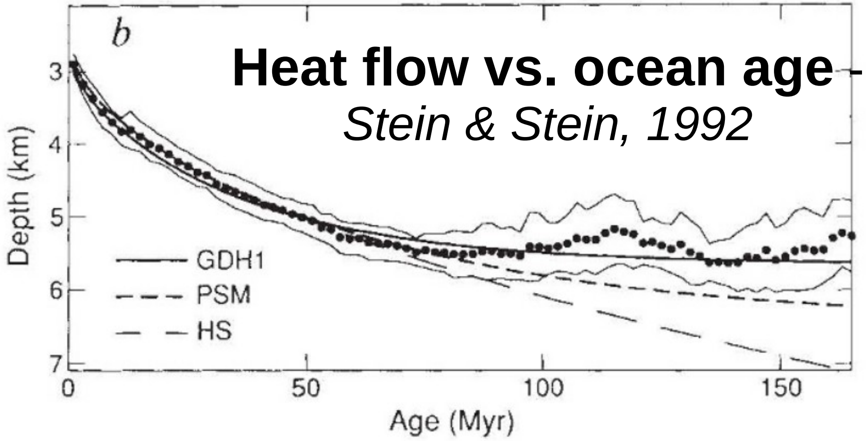
Heat flow vs. ocean age - *Stein & Stein, 1992*





Parsons & McKenzie, 1978

Several scales of convection



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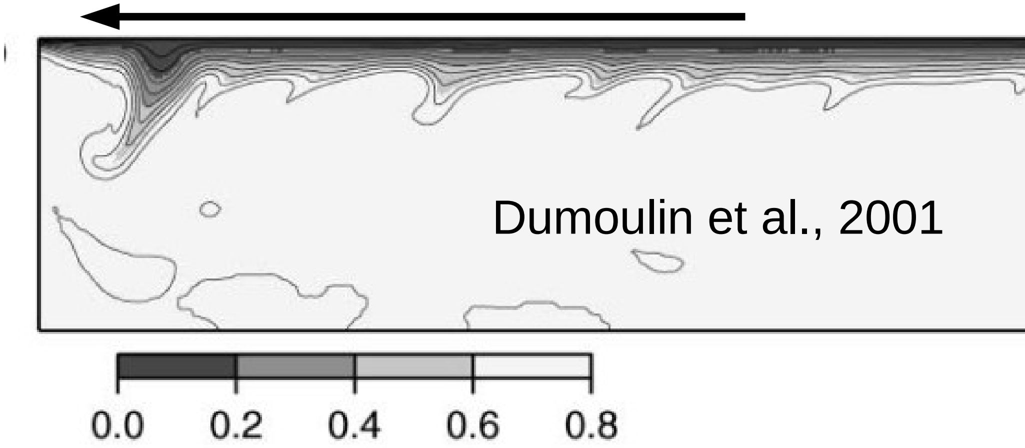
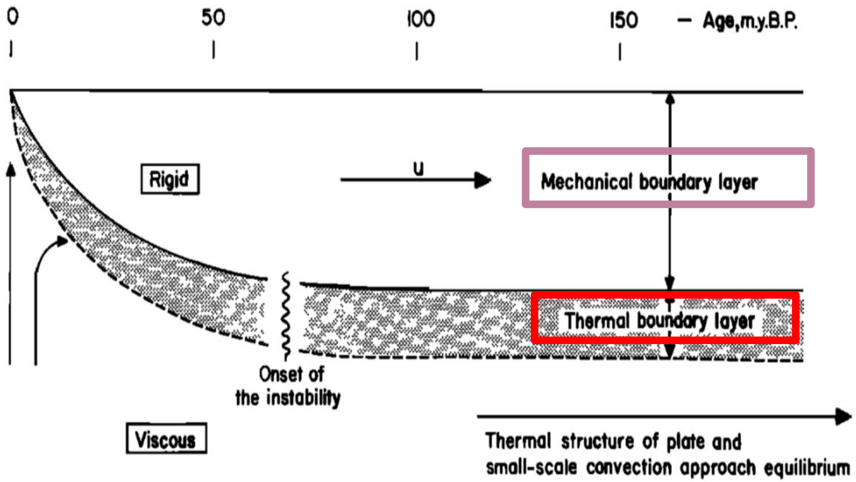
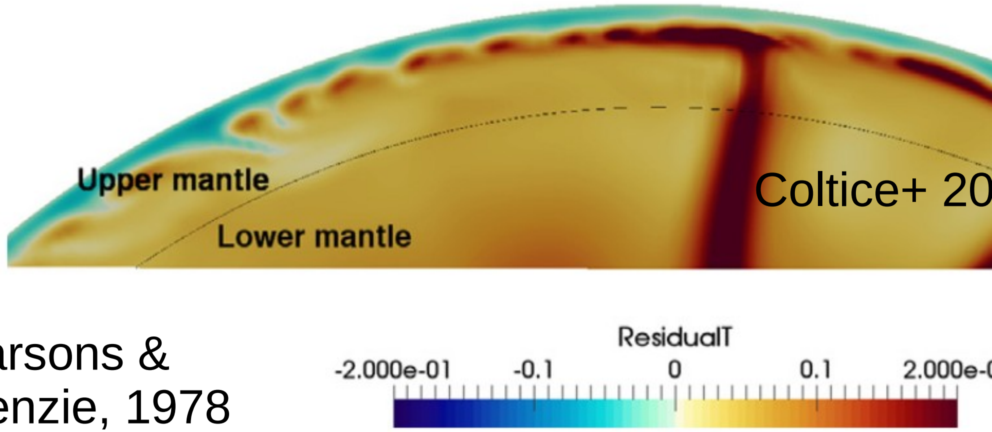


Dumoulin et al., 2001



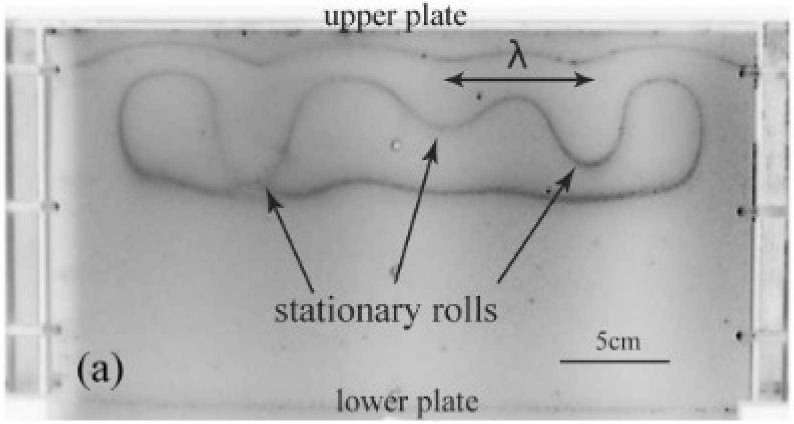
Parsons & McKenzie, 1978

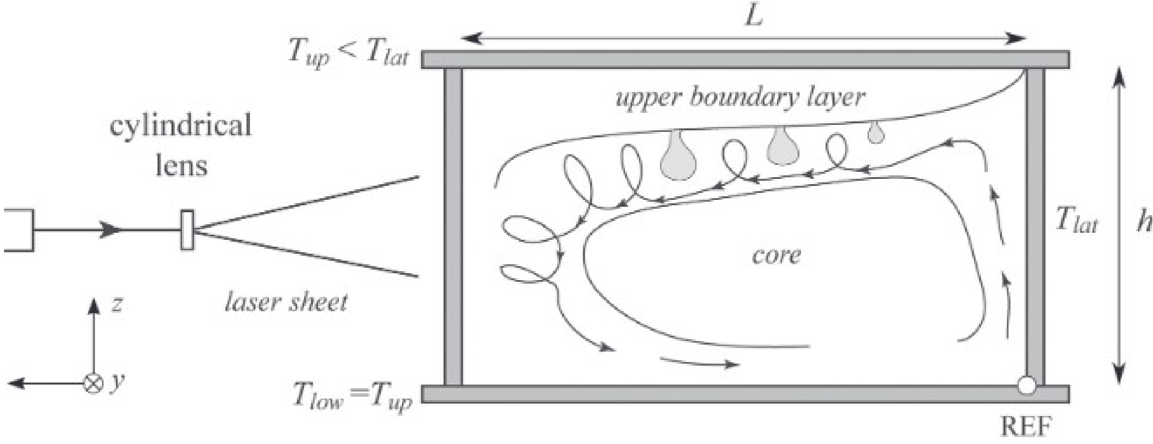
small-scale convection ?

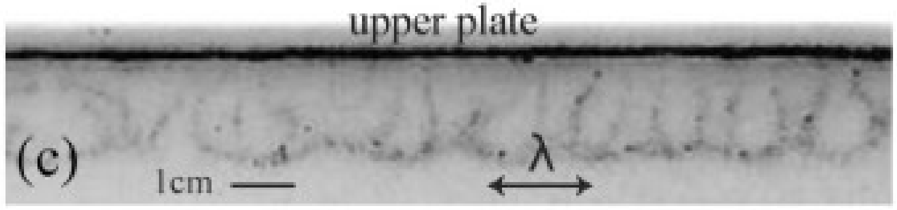


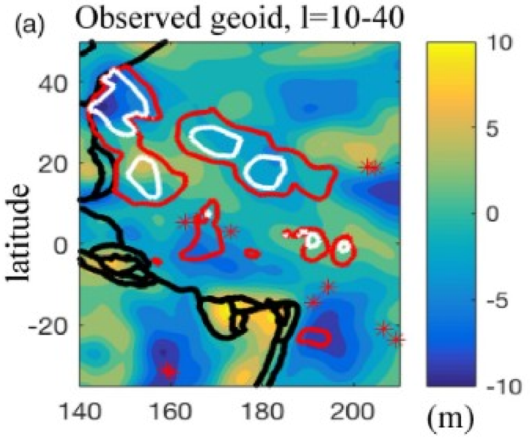
Coltice+ 20

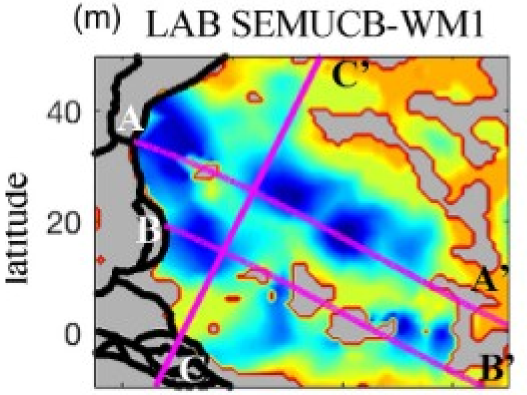
Several scales of convection – 1000-km scale cells ?









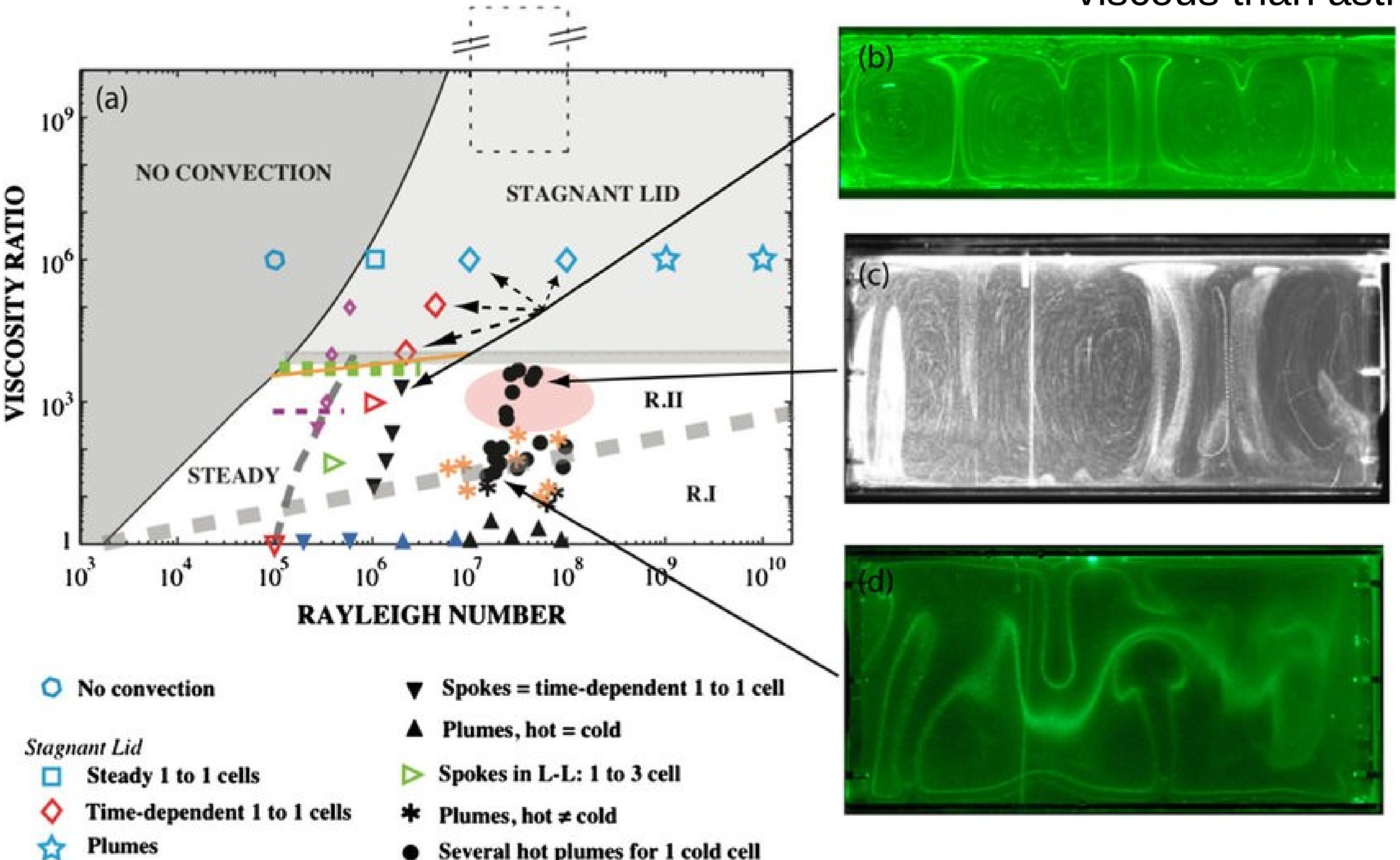


Analogue experiment (glucose syrup)
+ geoid & seismic data

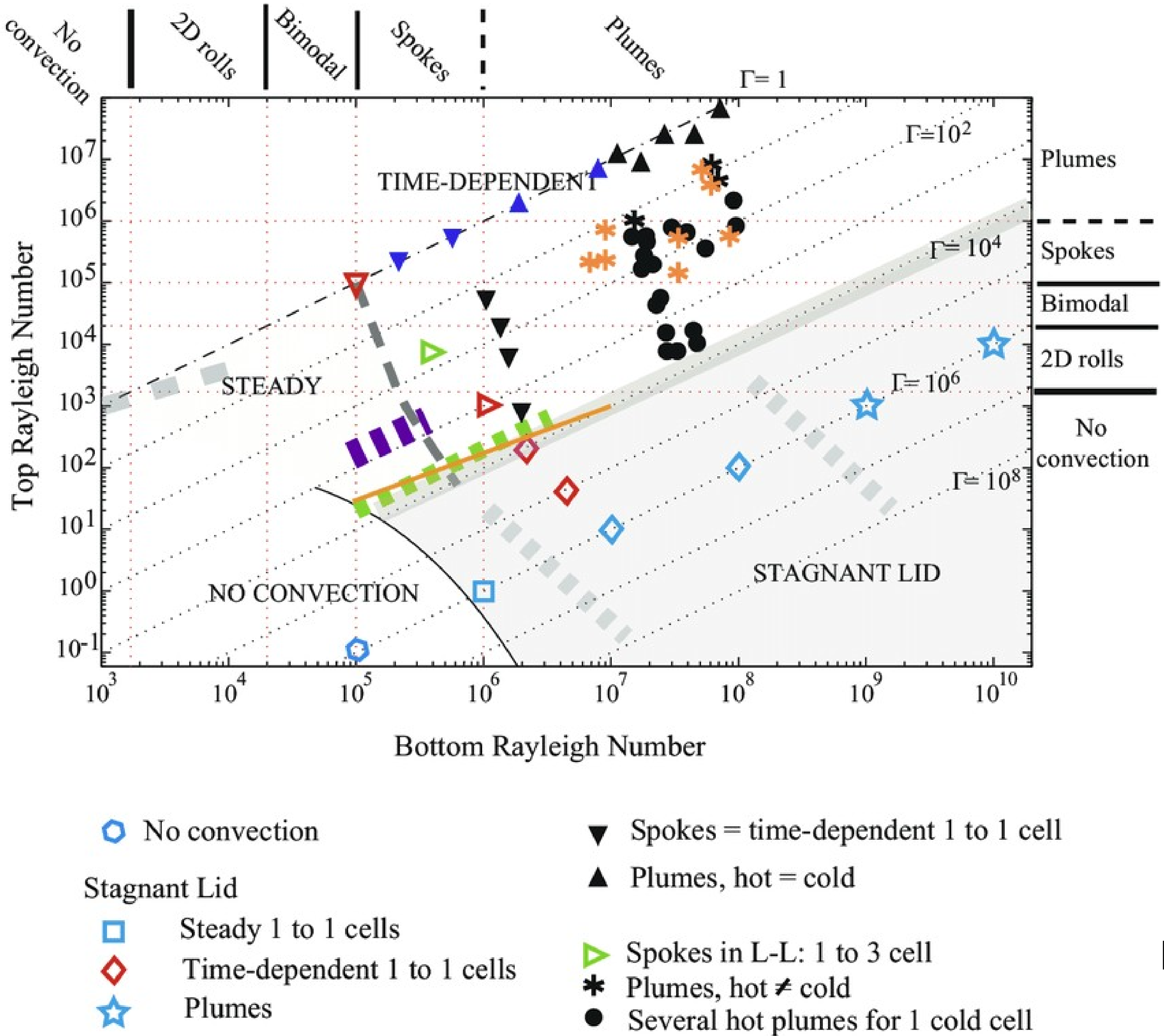
Adam, Vidal + G3 2021

How does the mantle convect ?

- Strongly **temperature-dependent viscosity** > lithosphere 1000x more viscous than asthenosphere



Smrekar+ 2018

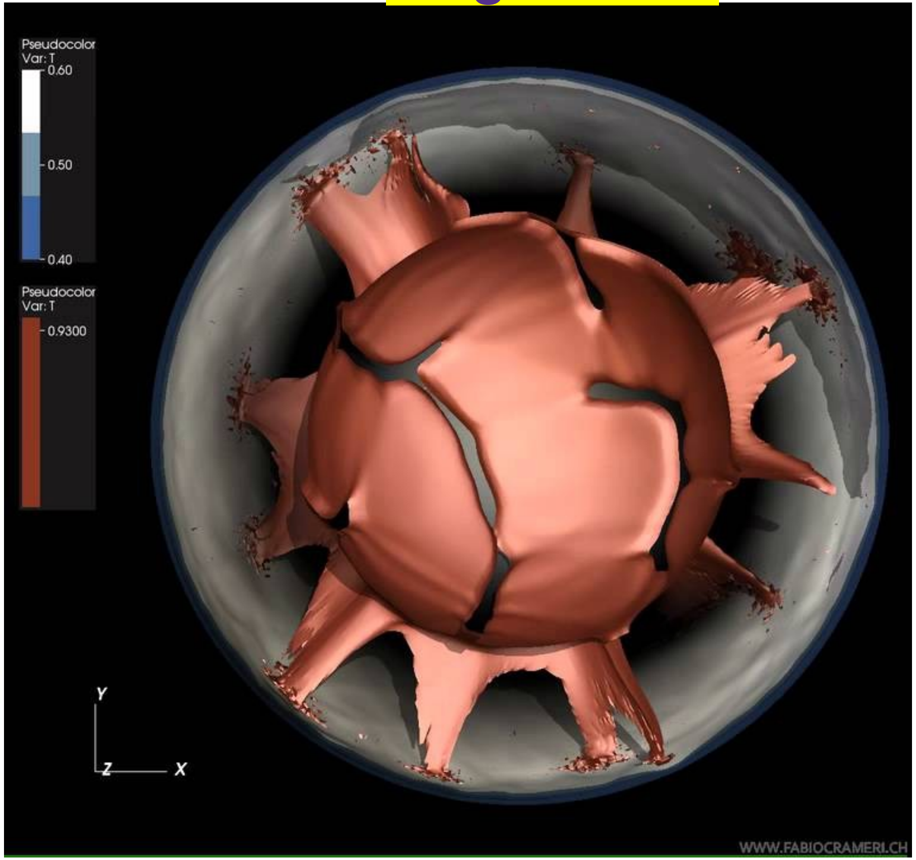


Davaille+ 2011

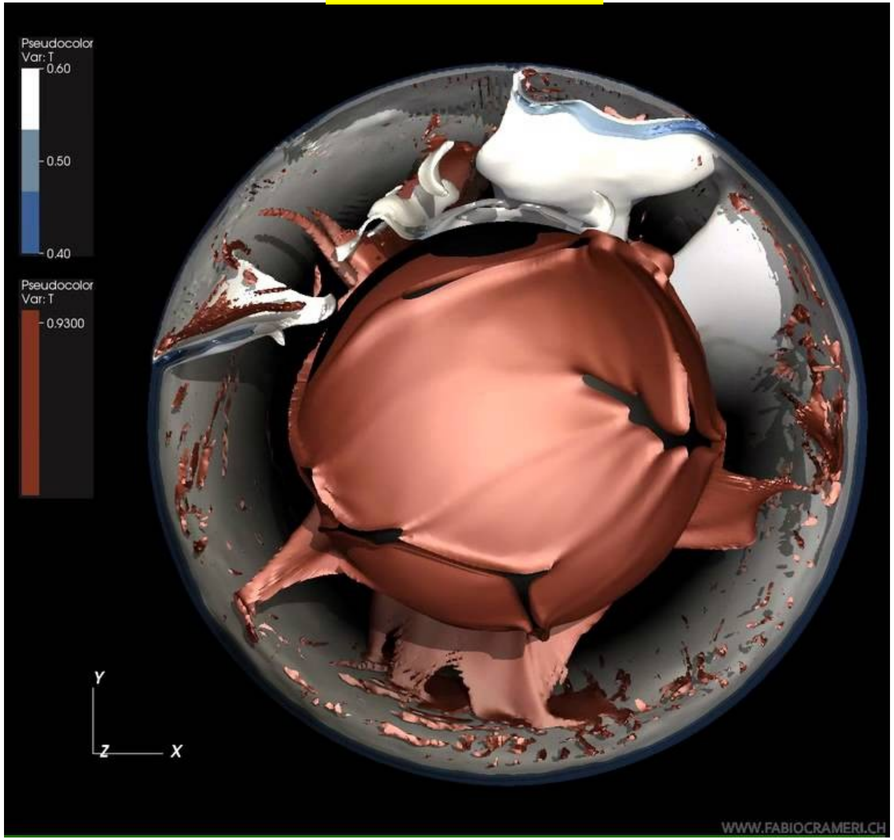
Importance of viscosity parameterization

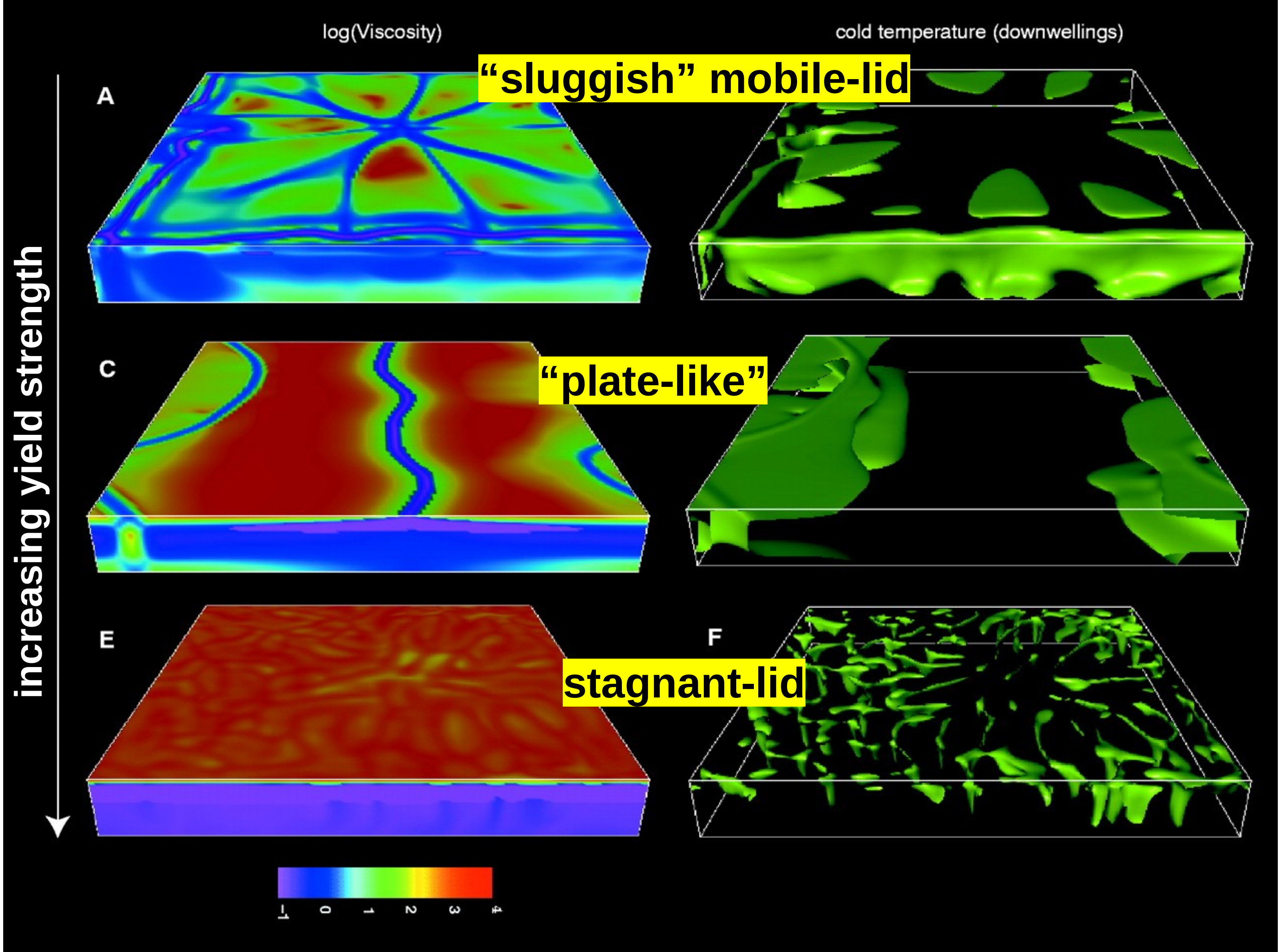
- Strongly **temperature-dependent viscosity**

stagnant-lid



mobile-lid



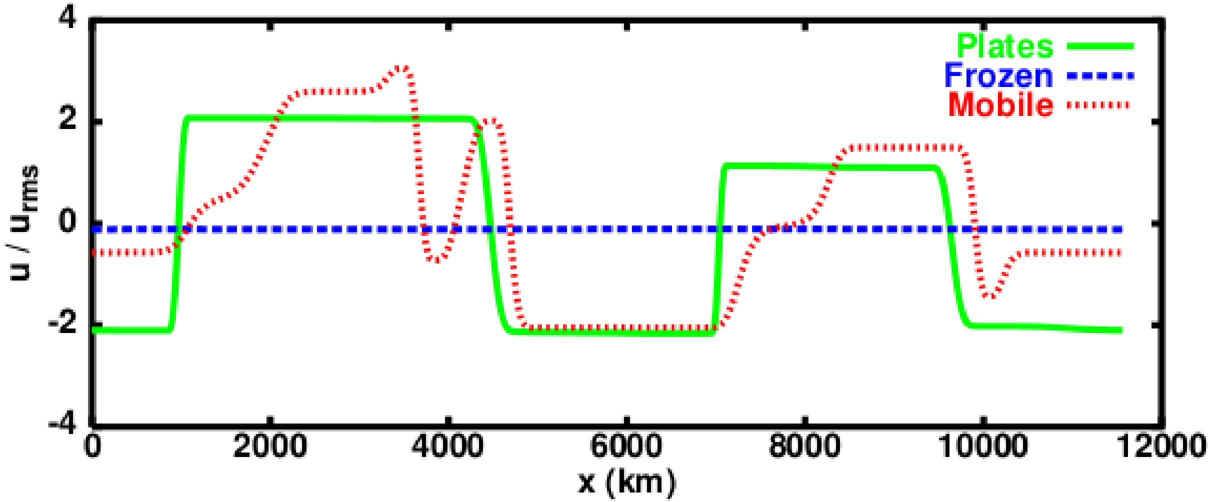


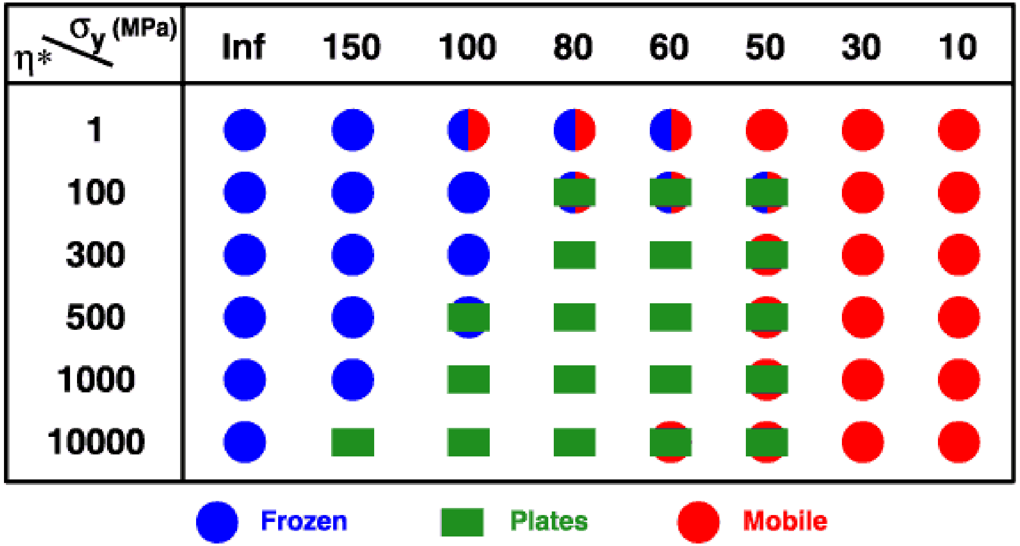
yield strength = mechanical resistance of the cold lithospheric boundary layer

Tackley Science 2000

Importance of viscosity parameterization

localizing deformation at plate boundary

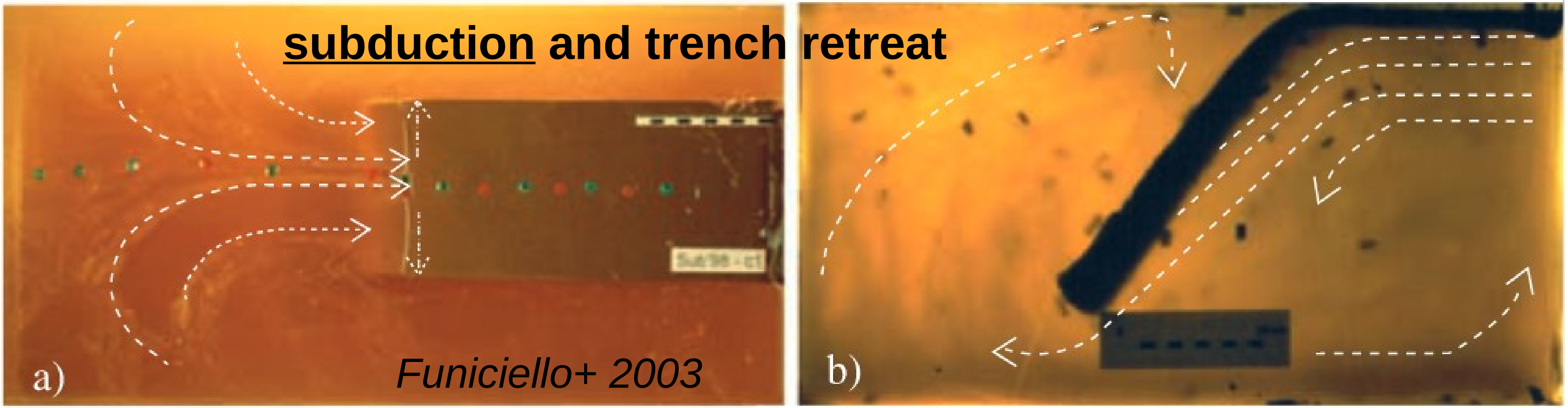




lithosphere mobility as a function of **yield stress** σ_y and viscosity contrast η^* for a **sub-plate low-viscosity layer**

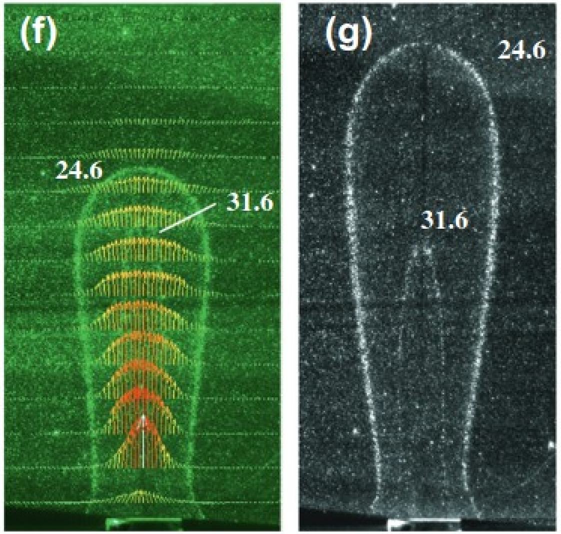
Richards G[3] 2001

Ingredients of numerical/analogue experiments



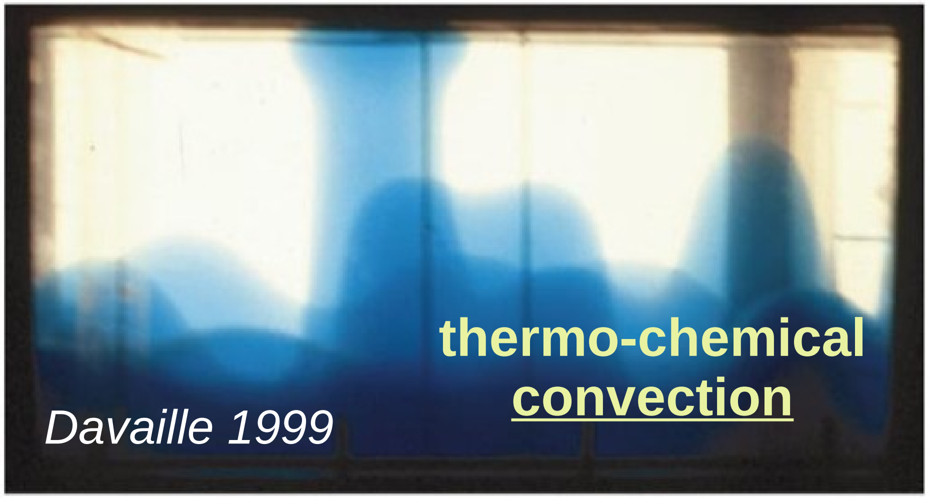
subduction and trench retreat

Funiciello+ 2003



plume in a yield-stress fluid

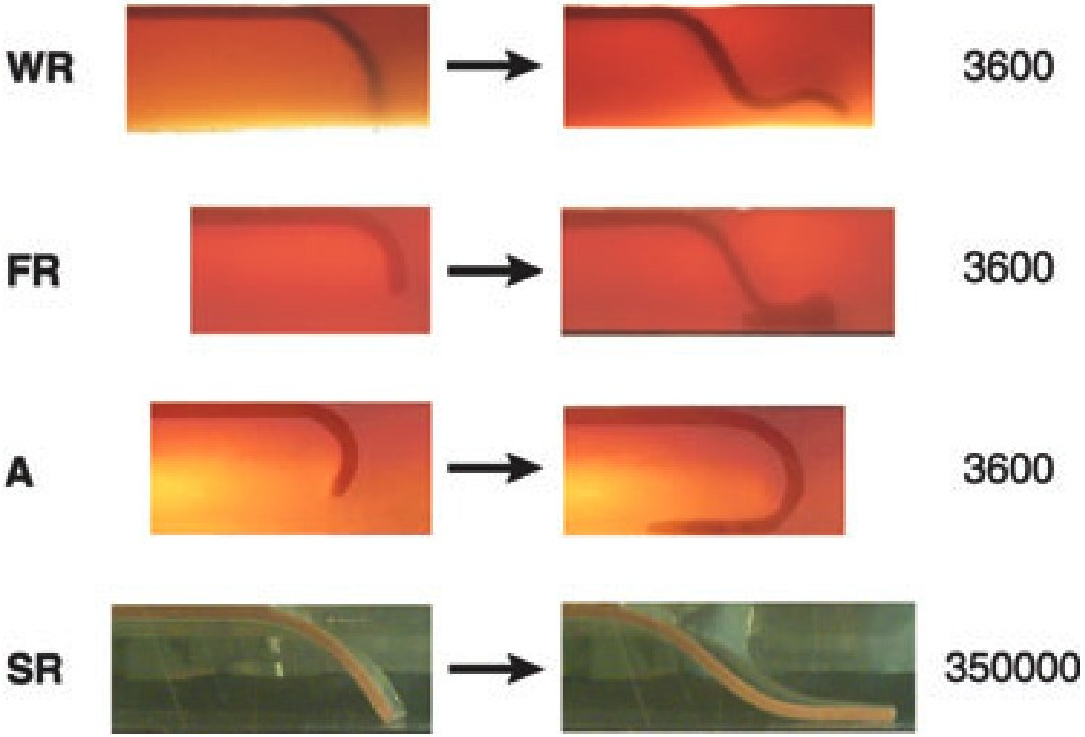
Davaille+ 2013



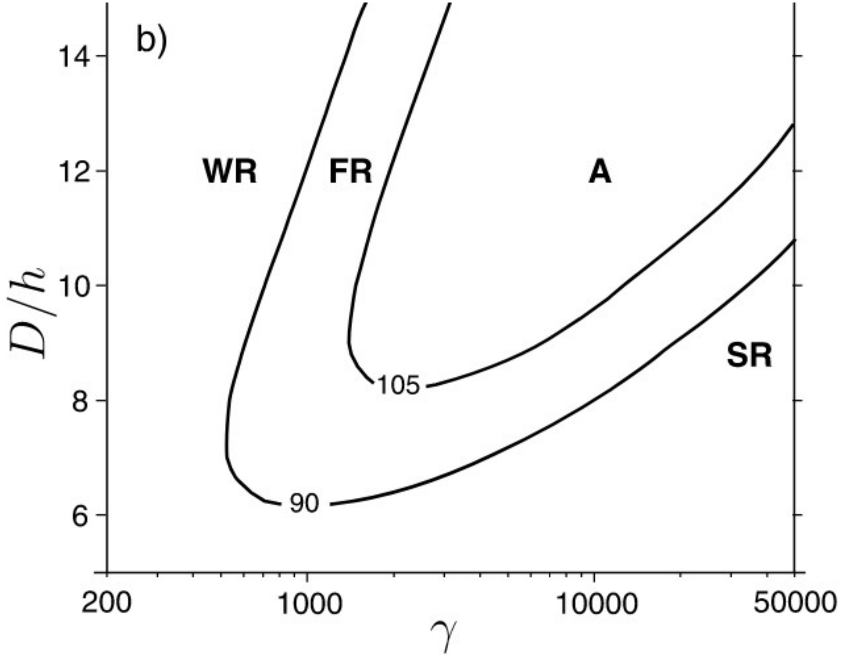
thermo-chemical convection

Davaille 1999

Slab shape : influence of viscosity contrast



theoretical isocontours of the dip of slab tip when it reaches the bottom



WR: weak retreating mode.
FR: folding retreating mode.
A: advancing mode.
SR: strong retreating mode.

Ribe
GJI 2010

modes of free subduction as a function of the viscosity contrast γ and the ratio D/h of the layer depth to the sheet thickness

Mantle convection layering : radial viscosity profile ?

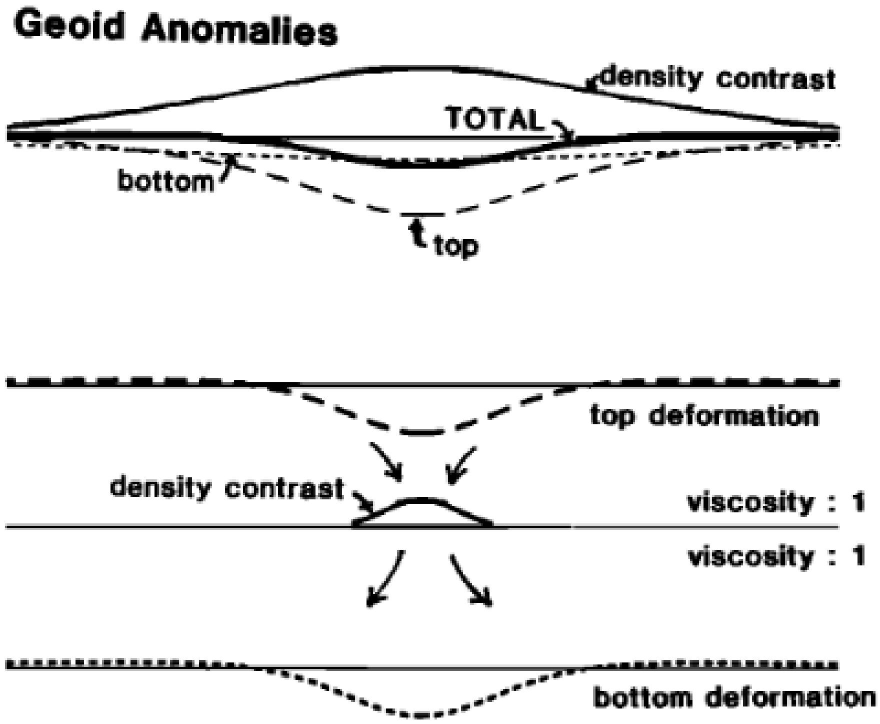


Fig. 1. Illustration of the components of the geoid anomaly from a cosine bell density contrast at the midpoint of a layer of uniform viscosity η. The total anomaly (heavy solid line) is the sum of the contributions from the density contrast itself (light solid line), from dynamic deformation of the upper boundary (long dashes), and from dynamic deformation of the lower boundary (short dashes). The total geoid anomaly is negative for a positive density anomaly.

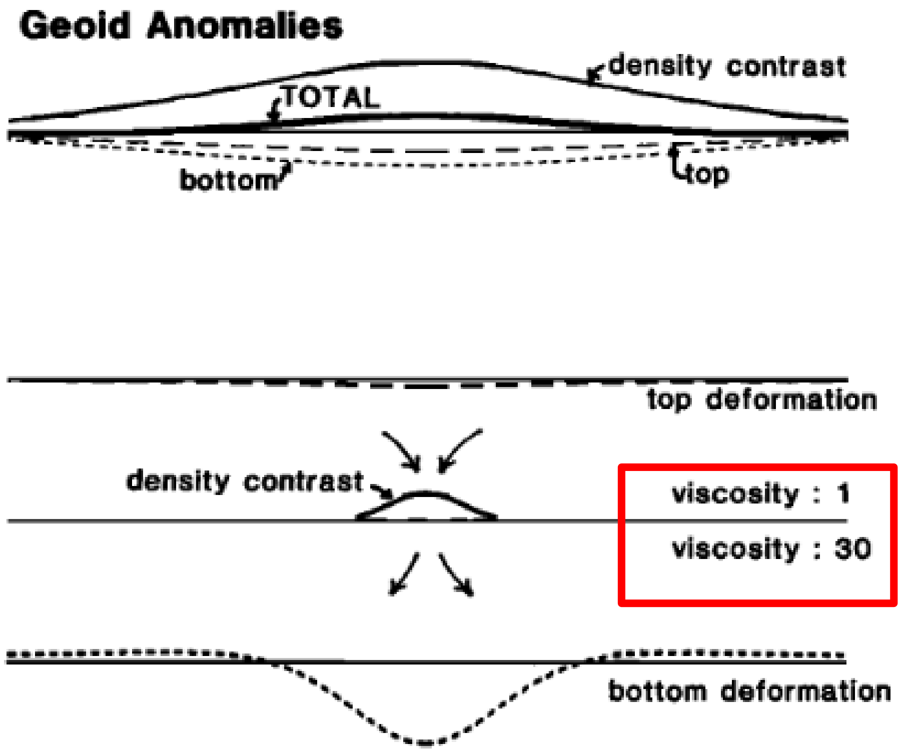
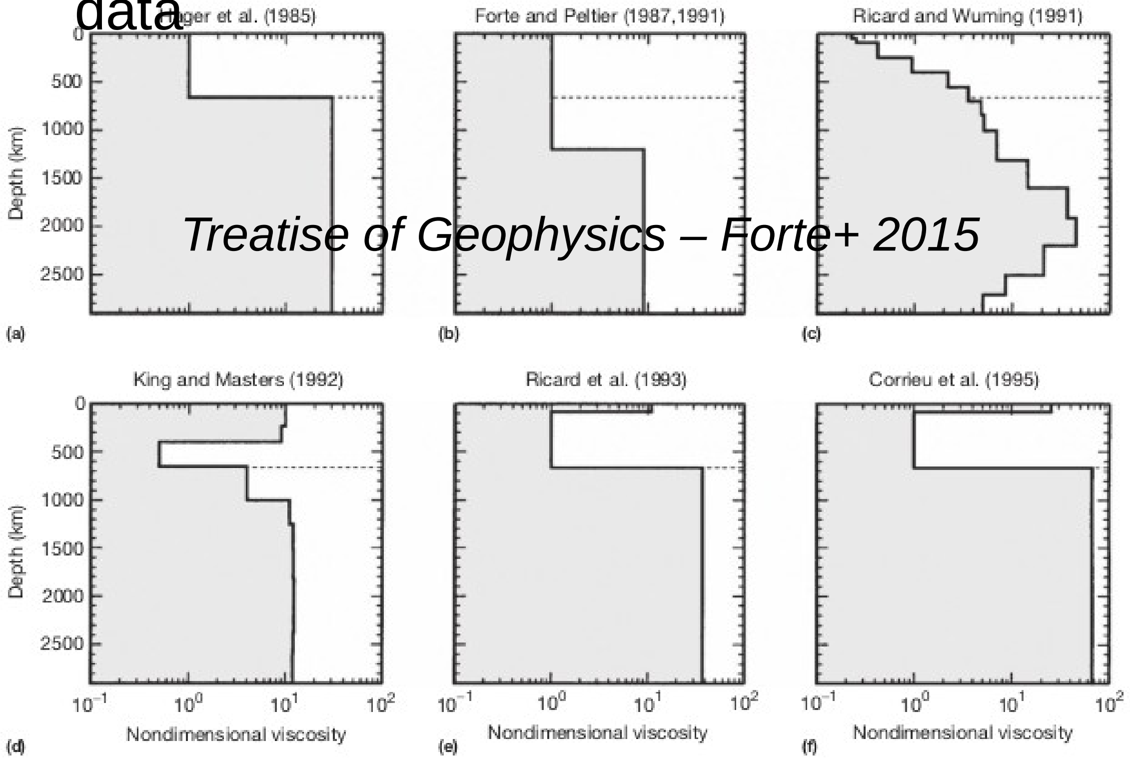


Fig. 2. As in Figure 1, but now the bottom half of the layer has a viscosity η a factor of 30 larger than the upper half. The sign of the total geoid anomaly is now positive.

Hager JGR 1984

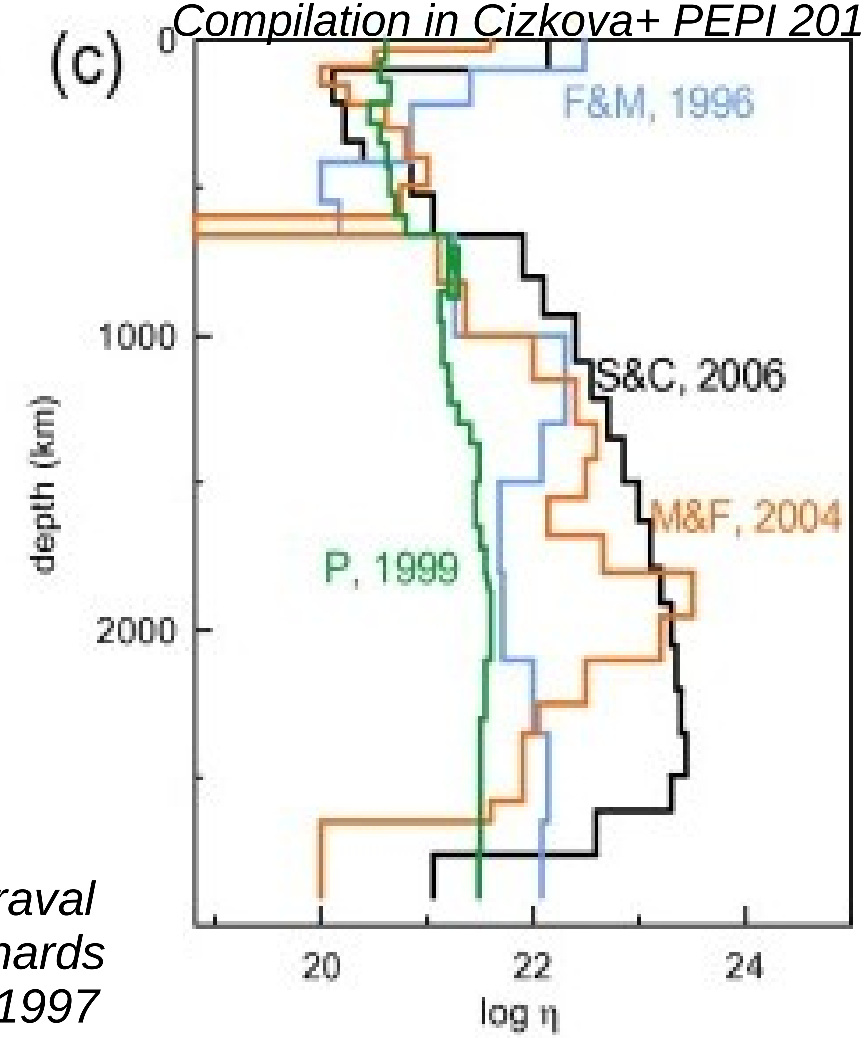
Mantle convection layering : radial viscosity profile ?

inversion of geoid, postglacial rebound data



Treatise of Geophysics – Forte+ 2015

Compilation in Cizkova+ PEPI 201



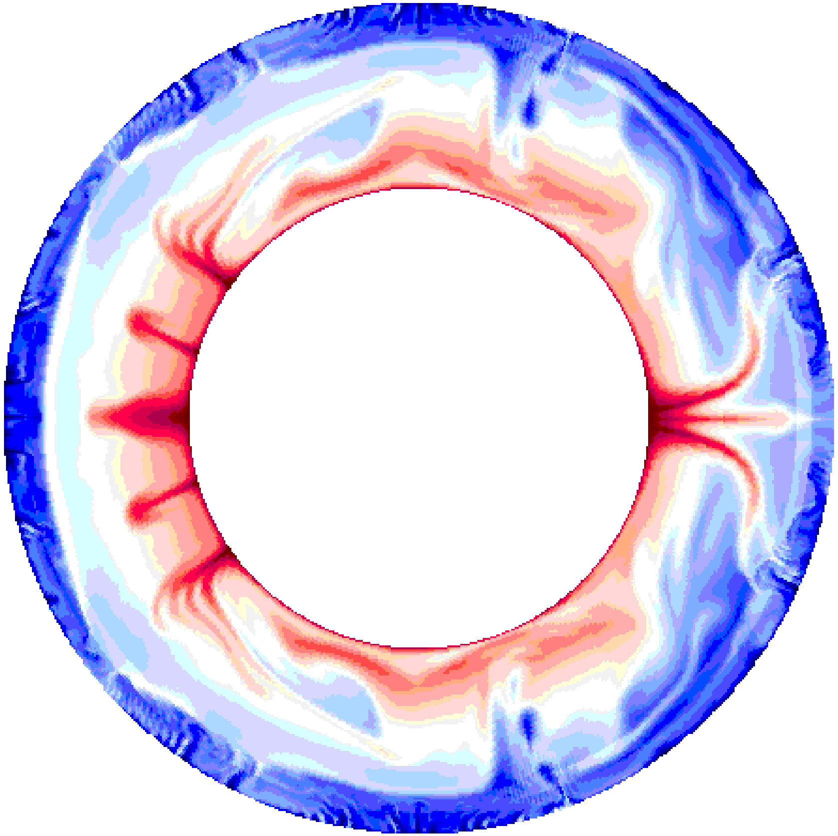
Thoraval &Richards GJI 1997

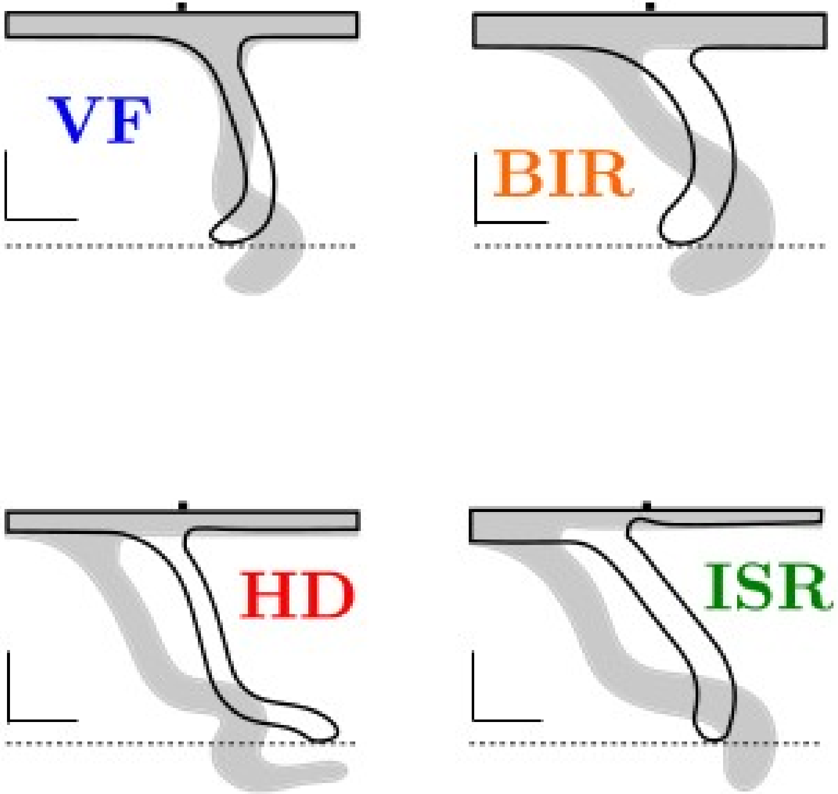
… but large uncertaintites on Bcs =

→ can we solve for more than 3 layers ?

Mantle convection layering and slab deformation

1.5-layer ?

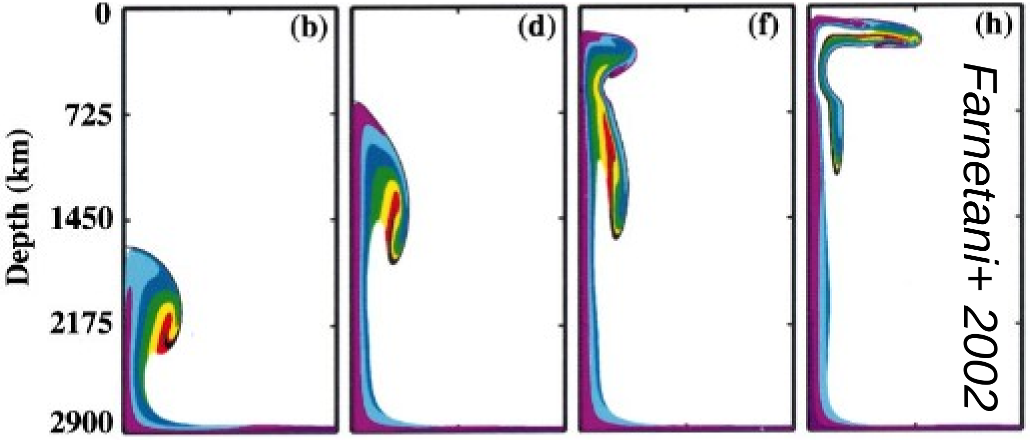




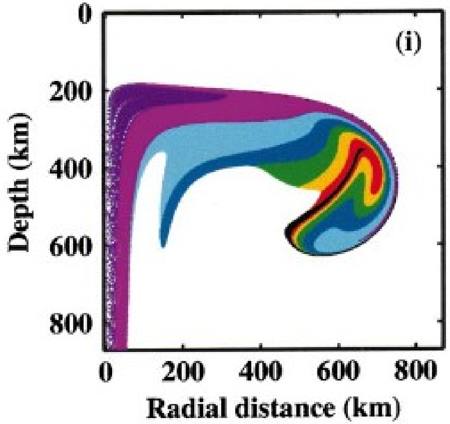
Garel+ G3 2014

Ingredients of numerical/analogue experiments

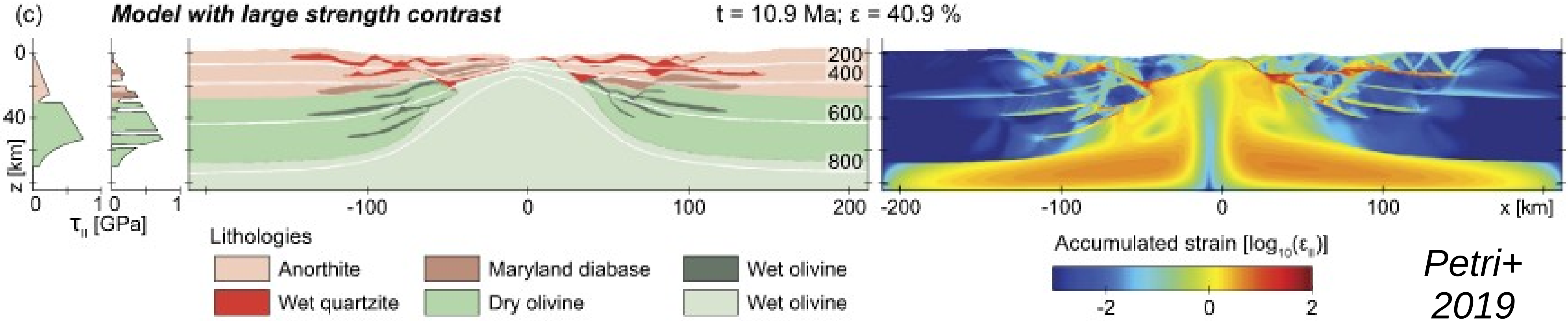
mixing and deformation in mantle plumes



Farnetani+ 2002



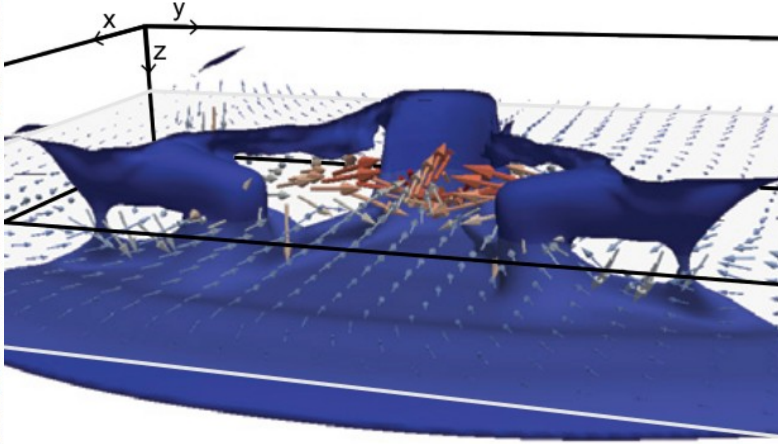
rifting of heterogeneous continental lithosphere



Petri+ 2019

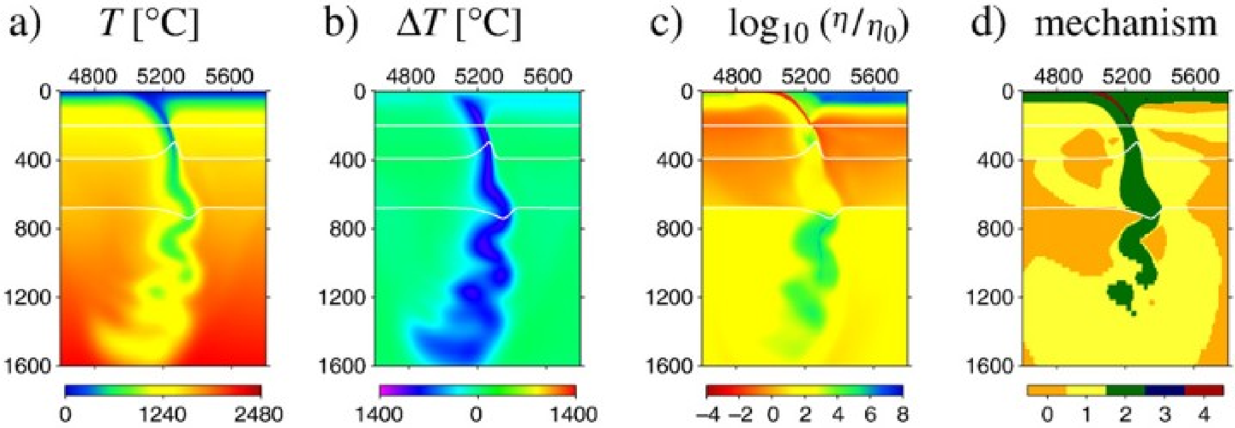
Ingredients of numerical/analogue experiments

3-D toroidal flow through slab tear



Magni+ Geology 2014

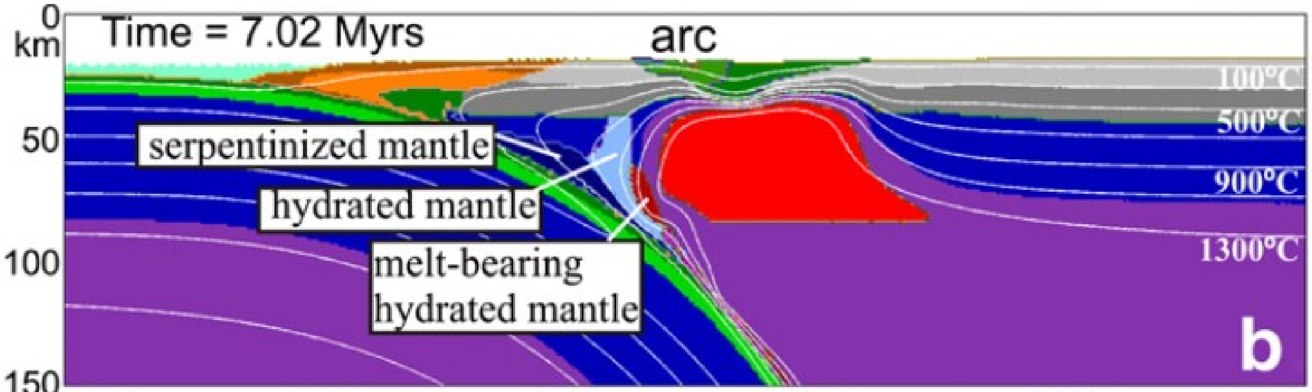
slab piling (viscosity jump + phase transitions)



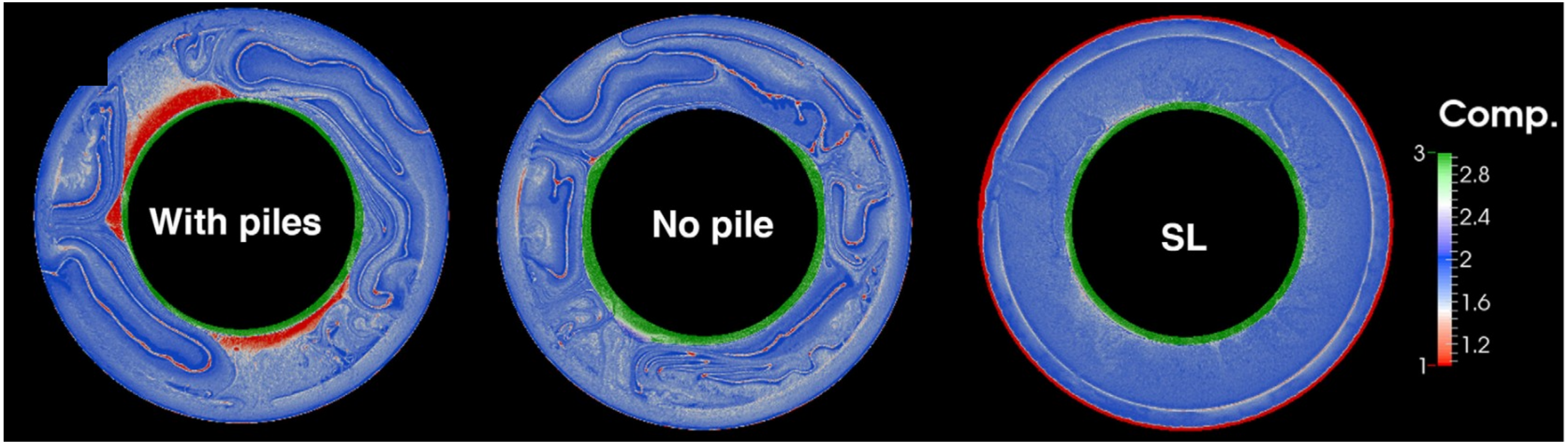
Cizkova & Behoukova EPSL 2008

subduction
+ water transfer
+ partial melting
+ erosion & sedimentation

Sizova, Gerya+ 2010

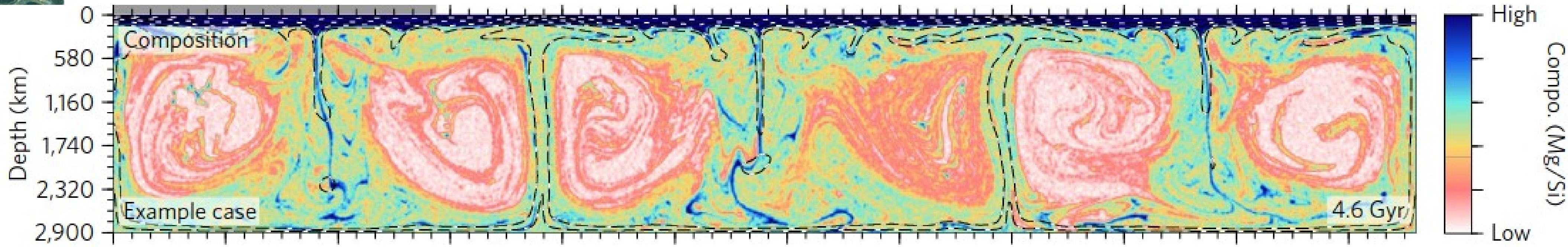


Ingredients of numerical/analogue experiments



Nagakawa & Tackley G3 2015

Chemical differentiation + various yield strength



persistent **BEAMS** (bridgmanite-enriched ancient mantle structures) if viscosity contrast > 30

Ballmer+ NatGeo 2017

Ingredients of numerical/analogue experiments

Analogue models,
numerical models

DOMAIN - A + N

- **dimension** > 2-D (no toroidal flow), 3-D
- domain geometry > cartesian, spherical / upper mantle only vs. whole mantle
- **boundary conditions** : closed (no-slip, free-slip, free-surface, surface-driven)
  or open (periodic, imposed) - heat flux, temperature
- **initial conditions**: thermal field ; continents, chemical reservoirs

PROPERTIES – A + N

- **state equation** ρ = f (T, z, chemistry, material) ⇒ density anomalies
- **viscosity** η = f (T, z, chemistry, material, grain size, strain rate, CPO...)
- parameters and dependencies (rad. heat production, thermal cond., thermal expansivity...)
- chemical partitioning coefficients

EQUATIONS - N

- **conservation equations** : mass, momentum (energy)

- simplifications : Boussinesq
  + inifinite Pr

NUMERICAL RESOLUTION - N

Recipes for solving the conservation equations

- Finite difference, finite-element or finite-volume approximations
- Marker in cells (e.g. evolutive composition, grain size) or passive tracers
- Possible auto-adaptive meshing

examples of thermo-mechanical codes :

Citcom & **ASPECT** (US-CIG community codes), **StagYY** (Tackley, Coltice), I3/I2ELVIS (Gerya+), pTatin (May & Le Pourhiet), **Underworld** (Moresi+), LaMEM (Kaus+), Fluidity (Davies+)...

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Coupling to other codes for other processes

- PerpleX, MAGEMIN - **mineral assemblage evolution**
- Badlands, Fastscape – **erosion, incision & sedimentation**
- D-REX **– evolution of anisotropy...**

The “good use” of models

“All models are wrong but some are useful”

G. Box, *Robustness in the strategy of scientific model building*, 1979

The "good use" of models

"All models are wrong but some are useful"

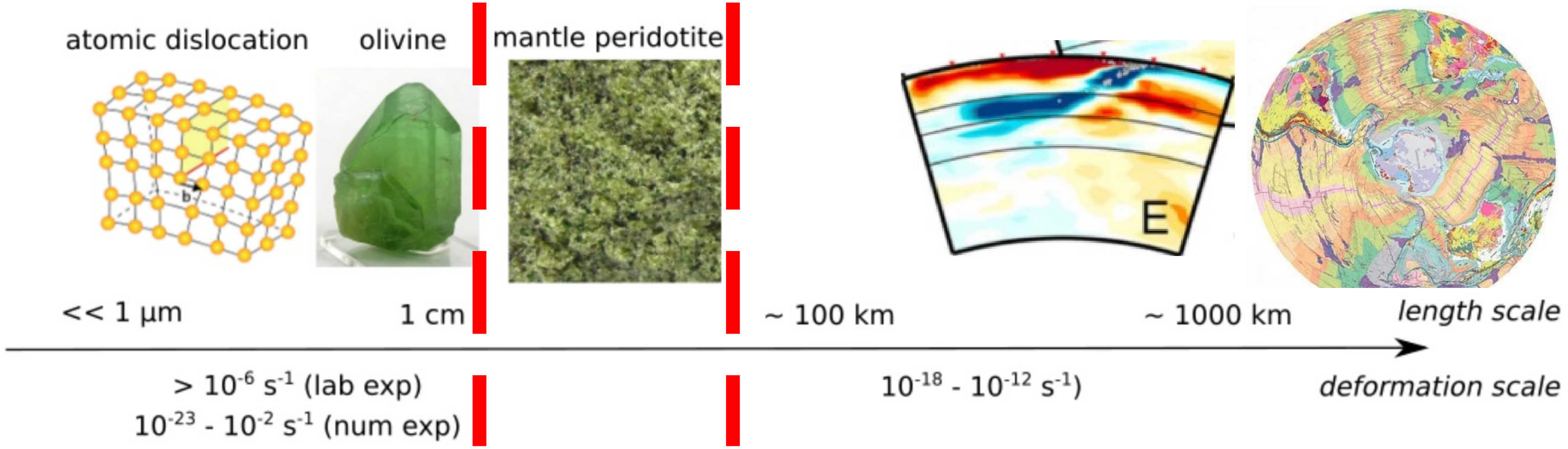
G. Box, *Robustness in the strategy of scientific model building*, 1979

→ ***of course the model is not the truth***

→ ***but the model can be "illuminating and useful"***

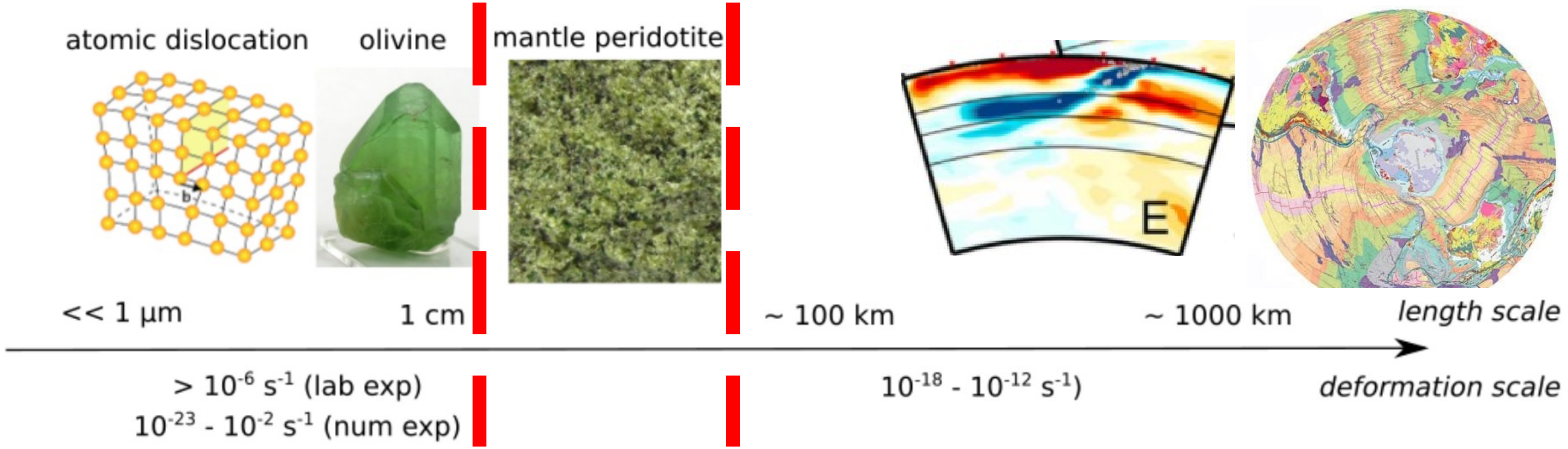
A lot of different models can be useful – <u>even simple ones, even very complex ones</u> – depending on the science question and the data to compare with !

Dynamical models : input and outputs relative to data



Small-scale data
Acquiring / Upscaling

Dynamical models : input and outputs relative to data



Small-scale data

Acquiring / Upscaling

INPUT **Parameterizing**

Numerical models

- **dynamical evolution**
- self-consistent **feedbacks**

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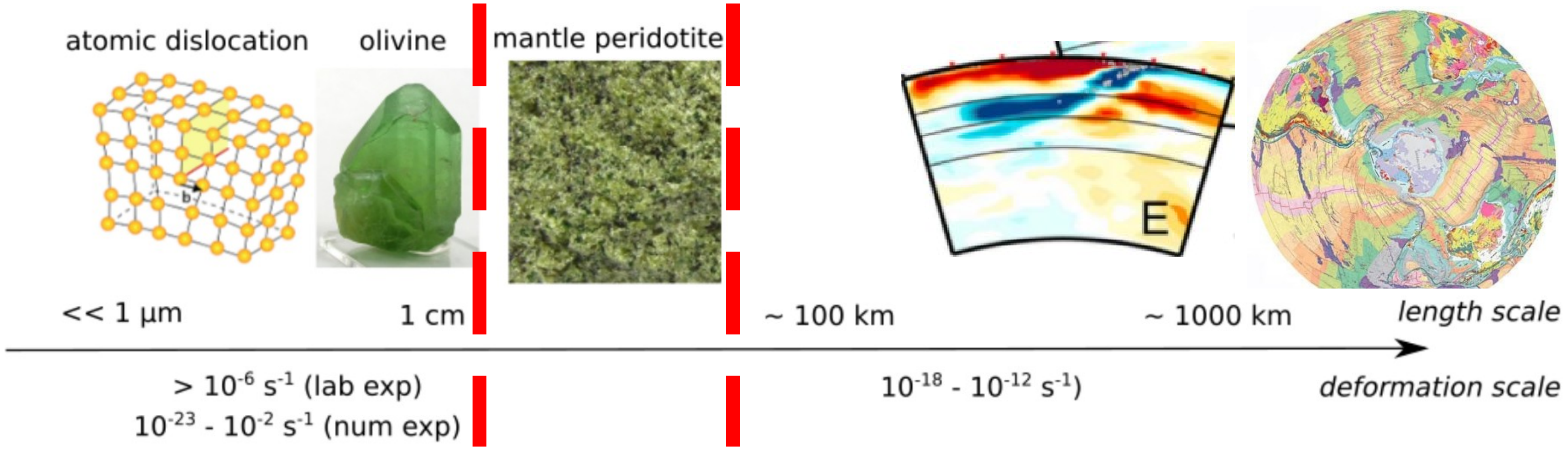


Small-scale data
Acquiring / Upscaling

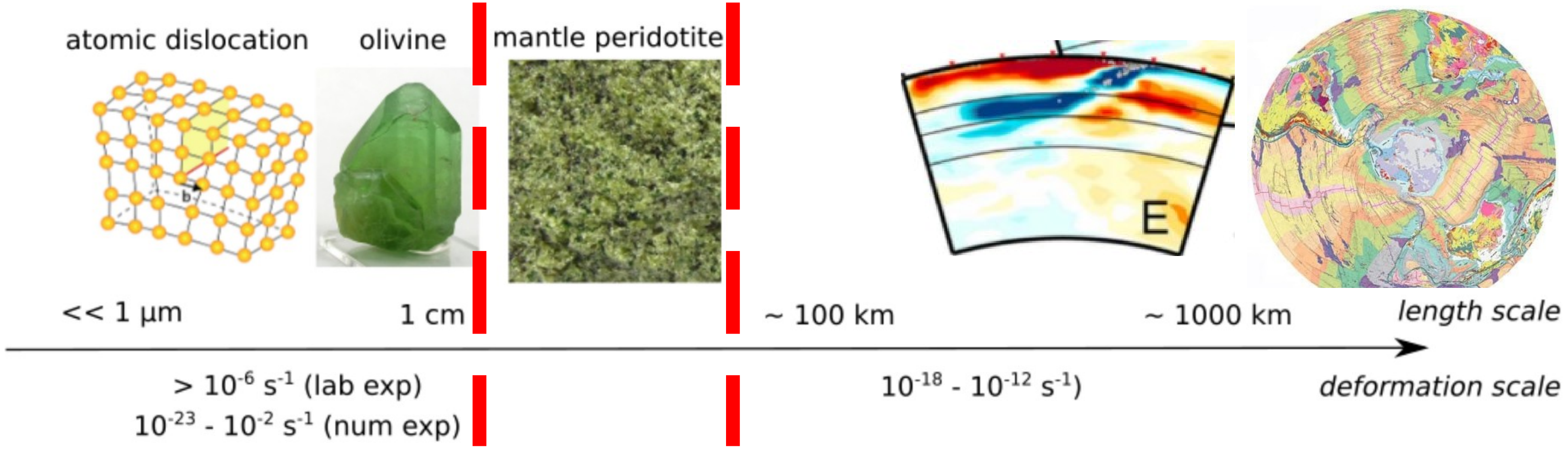
Geological and geophysical DATA

INPUT **Parameterizing**

Numerical models
- **dynamical evolution**
- self-consistent **feedbacks**

PREDICTIONS
SYNTHETICS

Dynamical models : input and outputs relative to data



Small-scale data
Acquiring / Upscaling

INPUT **Parameterizing**

Numerical models
- **dynamical evolution**
- self-consistent **feedbacks**

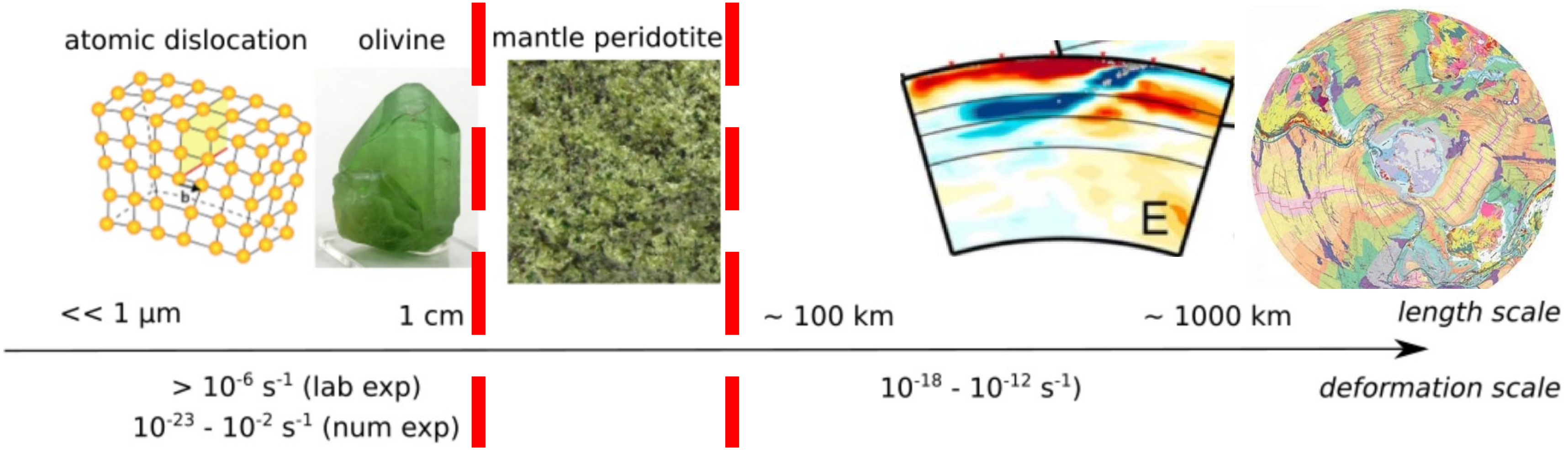
PREDICTIONS SYNTHETICS

COMPARISON

Geological and geophysical DATA

- inversion: what for ? a priori ?
- probabilistic input (uncertainties)
- **data can integrate a long history of mantle evolution**
  (e.g. anisotropy, thermal structure)

Dynamical models : input and outputs relative to data



Small-scale data

Geological and geophysical DATA

Numerical models
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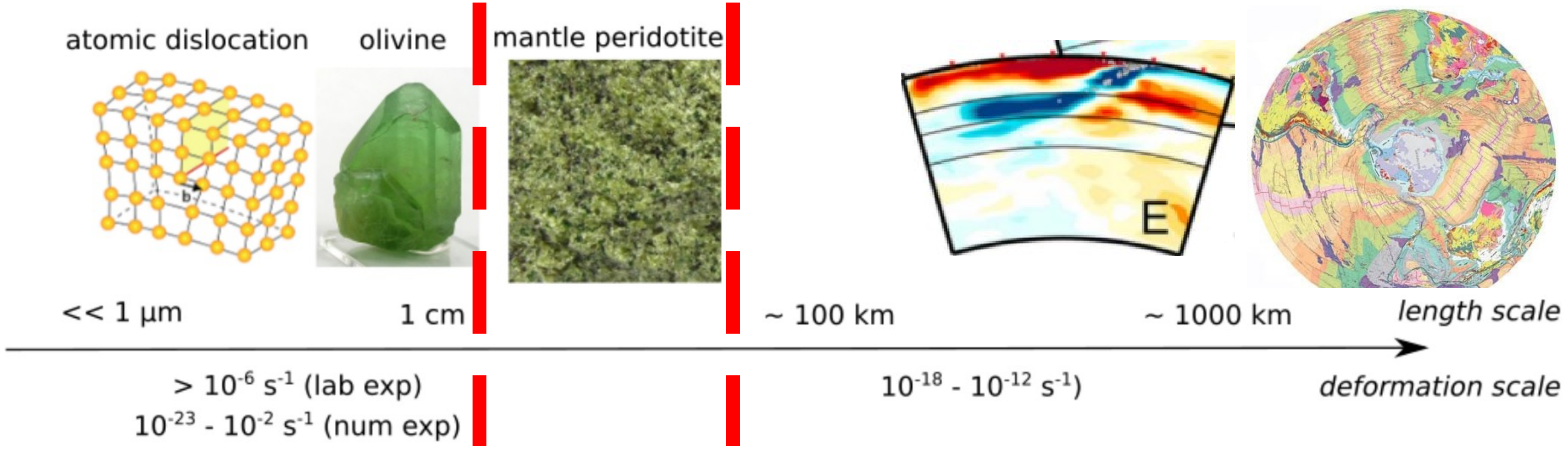


Small-scale data

INPUT

effective parameterization

Numerical models

- **dynamical evolution**
- self-consistent **feedbacks**

PREDICTIONS SYNTHETICS

COMPARISON

Geological and geophysical DATA

constraints on physical fields and their temporal evolution : *viscosity, stress state, velocity, deformation rate*

Mantle geodynamics

1. Evidence for surface (plate) and deep (mantle) motions

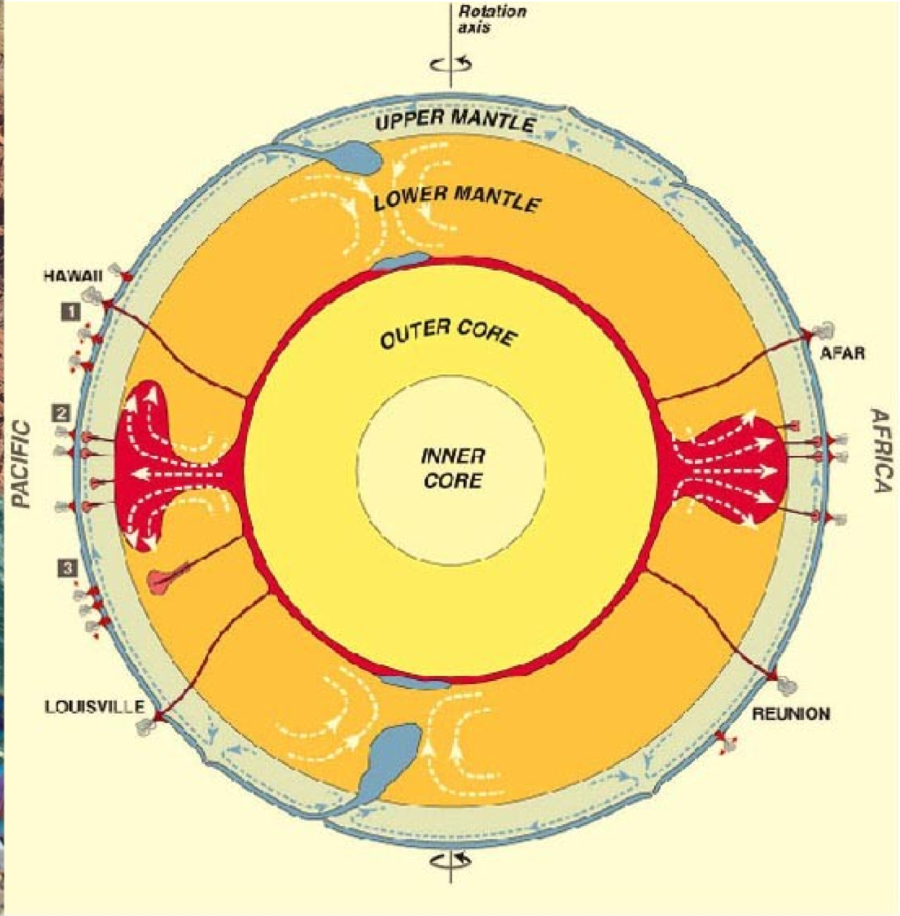
+ *orders of magnitude*

2. Dynamic models to understand the mantle (past & present)

3. Mantle and plate dynamics : modelling diversity and recipes

4. Progress and perspectives

Mantle convection



- The mantle convects, with **several** coexisting **length scales**

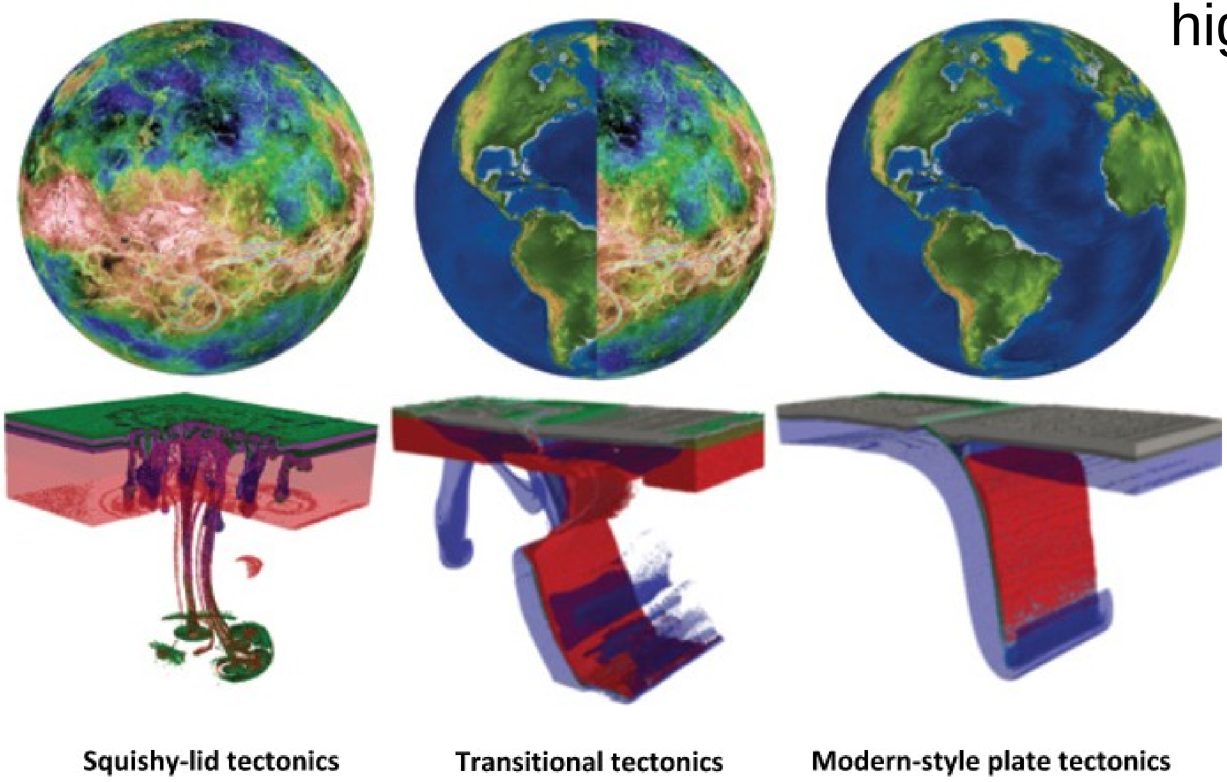
- Conv. models can exhibit self-consistent plate tectonics : one-sided subduction, subd. initiation, strike-slip faulting, continental break-up...

- Mantle convection is **time-dependent**, with possible “catastrophic events” : slab avalanching, drastic change in plate direction (Hawaiian bend), resurfacing of Venus

- mantle convection influences Earth secular cooling + heat flux at CMB (> core dynamics)

A big challenge

How <u>did</u> the mantle convect in the **hot early Earth** ?



Gerya 2019

higher temperature
> lower viscosity
> higher Ra number

> more plumes
> Venus-like ?

> faster microplates ?
> weak slabs ?

> ++ partial melt
> plutonic-squishy-lid ?

Lourenço+ G³ 2020

Future challenges

- what happens in the **outer zone / transition zone** above 1800 km ?

  water, melt, oc.crust ?

- what is the **rheology** of the lithospheric mantle ? of the lower mantle ?

  1-D *effective* viscosity of the mantle?

- where/how are **chemical anomalies** still preserved after 4.5 Gyr of convection ?

- how did a basal magma ocean transition to a solid convective mantle ?

  Chemical signatures at D'' ?

- when did "modern" plate tectonics start ?

- coupling btn external Earth **(atmosphere/hydrosphere)** and solid Earth for water and carbon cycles ?

  for paleoclimate periodicity ?

- convection of super-Earths ?

- multiphysics models, scale transfers

....

$$\textbf{disappointment} = \frac{\textbf{hope}}{\textbf{reality}}$$