What is a (lithospheric) plate ?

Fanny Garel

Géosciences Montpellier
University of Montpellier

Summer school – Les Houches
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LABEX LIO
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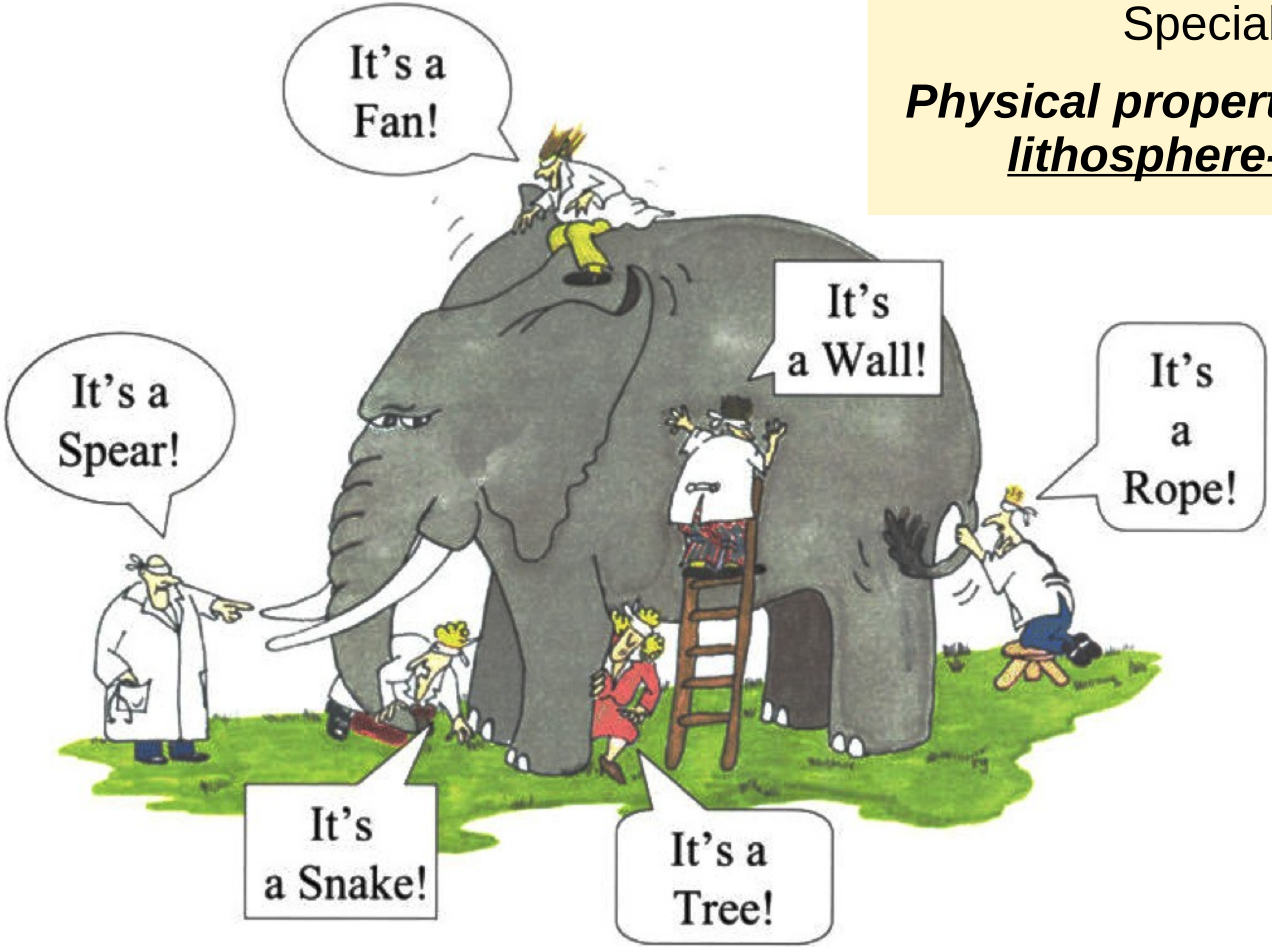
The “lithosphere” elephant



Special issue – PEPI 2021

Physical properties and observations of the <u>lithosphere-asthenosphere system</u>

- seismology, heat flow
- electrical conductivity
- gravimetry
- mineral physics
- geotherms
- rheology, melting
- dynamics

...

Source: Himmelfarb et al 2002 (artist: G. Renee Guzlas)

What is a plate ?

Plate tectonics vs. tectonic plate

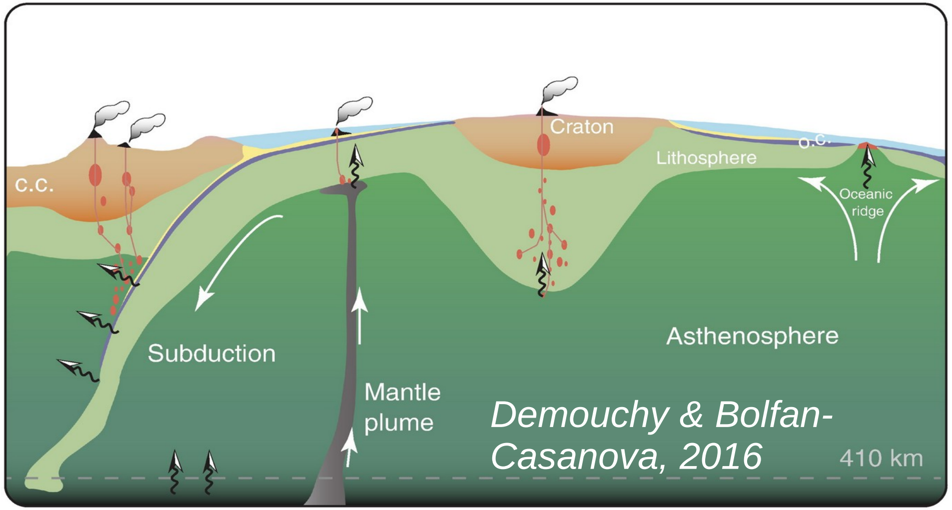
1. Multiple definitions of lithospheric plates

2. Chasing a LAB in dynamical models

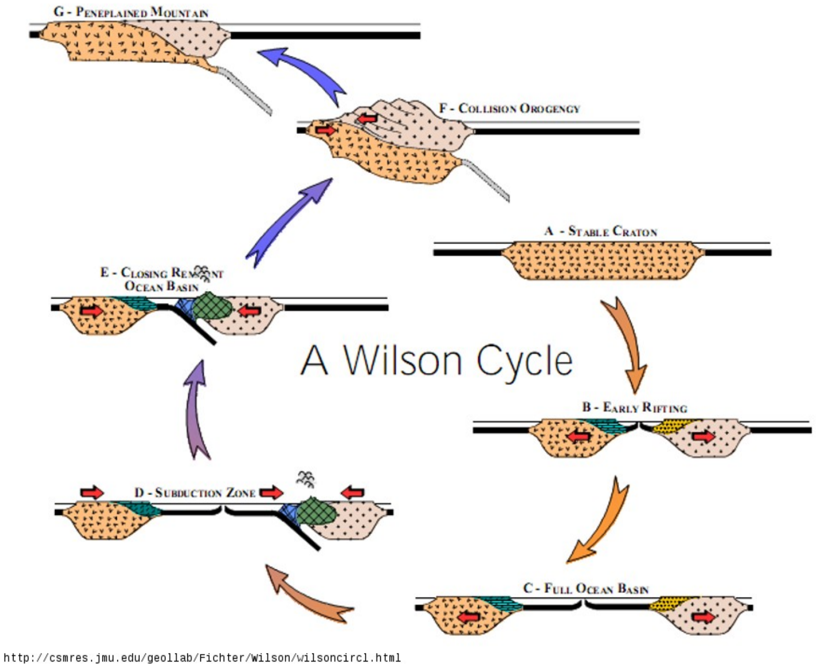
3. Geophysical proxieS of an elusive LAB

Is the plate concept still relevant ?

"Plate tectonics" (theory) ≠ dynamics of plates (obs., reconstruct.)



All the things we put behind "plate tectonics" lato sensu...



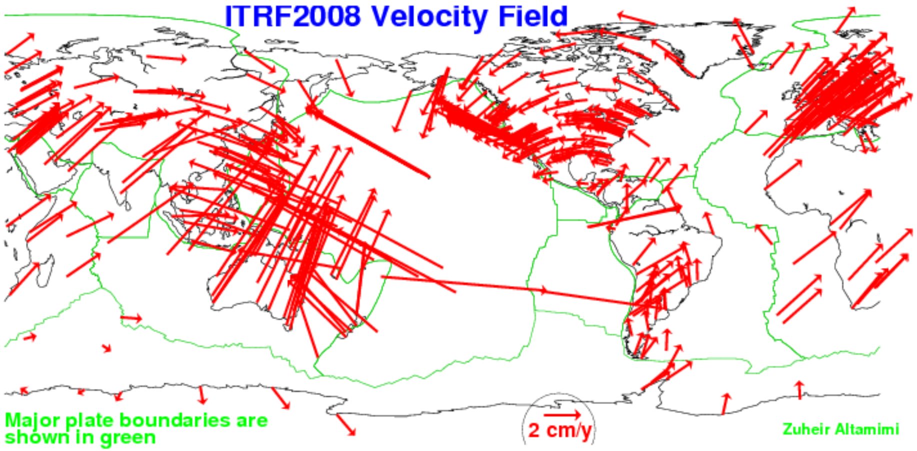
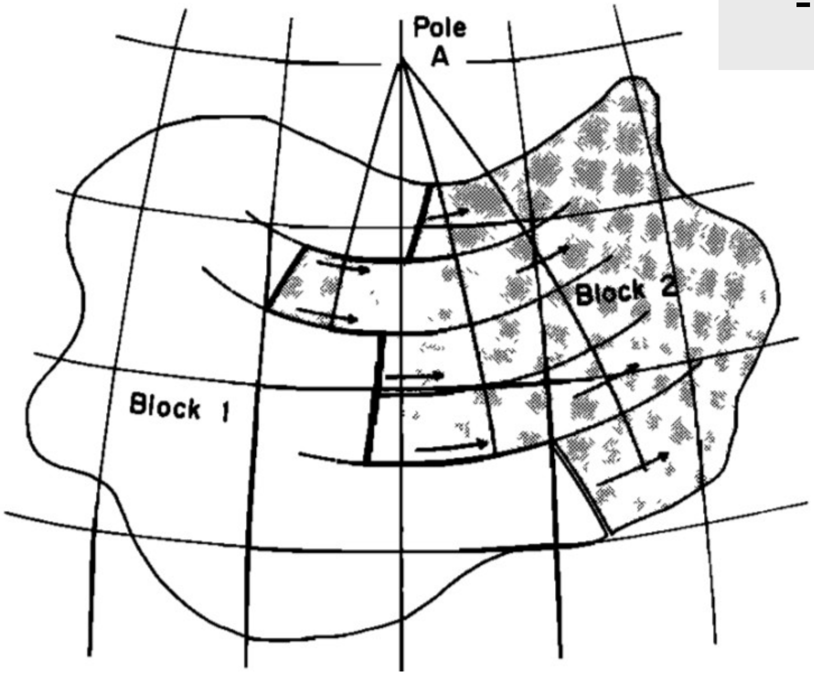


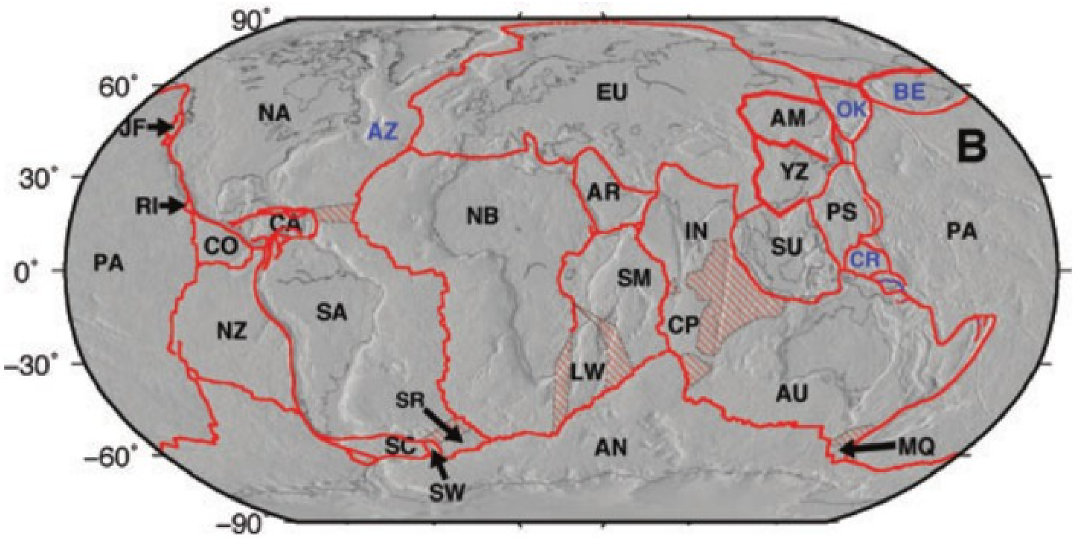
Plate tectonics sensu stricto = a map-view theory

Morgan, McKenzie, Parker, Le Pichon...
(late 1970s)

- **rigid blocks moving** at the surface (2-D) of a sphere
- eulerian formalism
- minimizing surface variations
- paleomagnetic rates (+GPS)



Morgan, 1968



25 plates' model MORVEL (DeMets et al., 2010)

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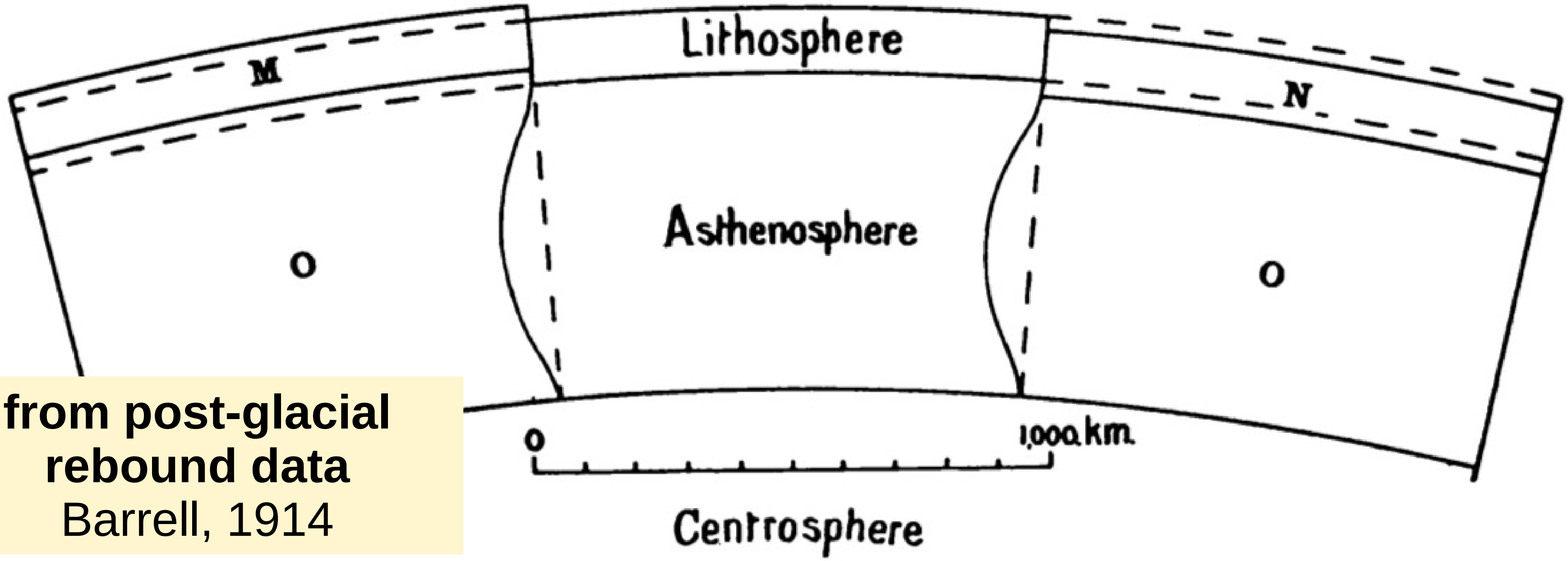
Strong “lithosphere” vs. soft “asthenosphere”



from post-glacial rebound data
Barrell, 1914

LITHOSPHERE

rigid layer
(crust + uppermost mantle)

ASTHENOSPHERE

relatively “softer” mantle layer

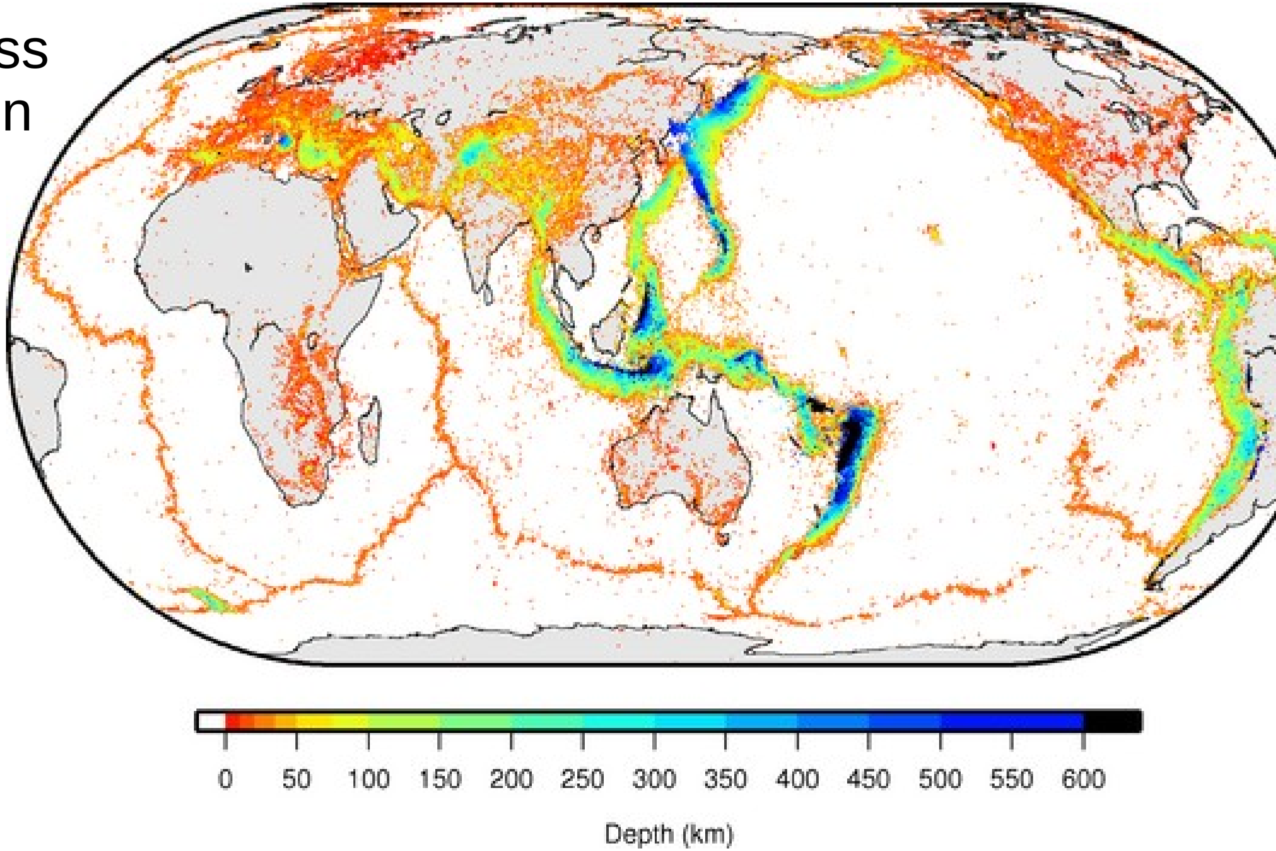
Strong plates vs. weak plate boundaries

- earthquakes
  < mechanical rupture
  < accumulated stress
  and deformation

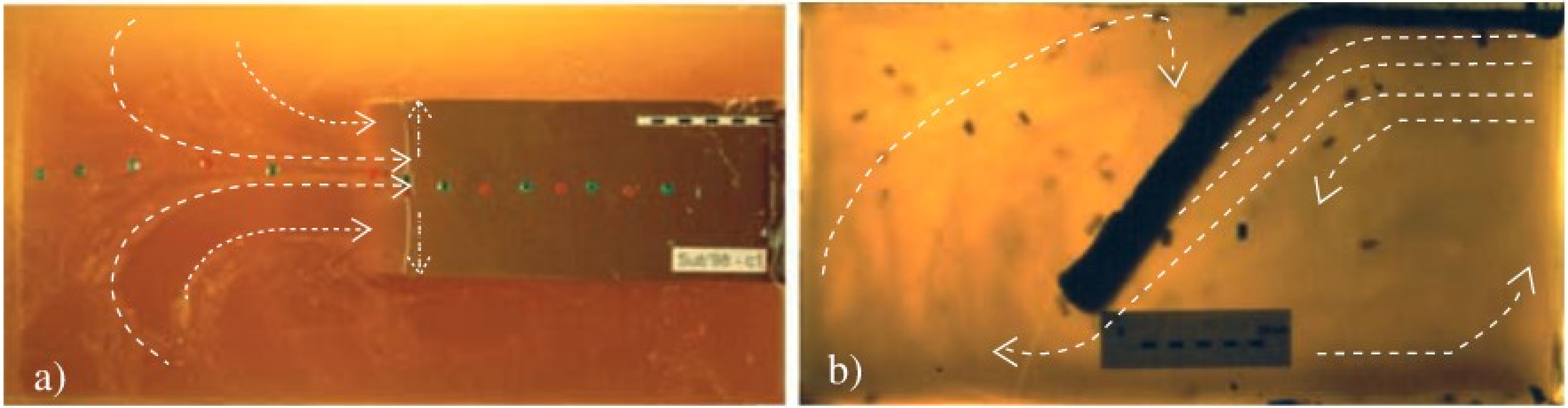
- no EQ > undeformed
  plate interiors

- but intraplate seismicity...

Seismicity 1964 – present
International Seismological Centre



Strong “lithosphere” vs. soft “asthenosphere”



Funiciello et al., 2003

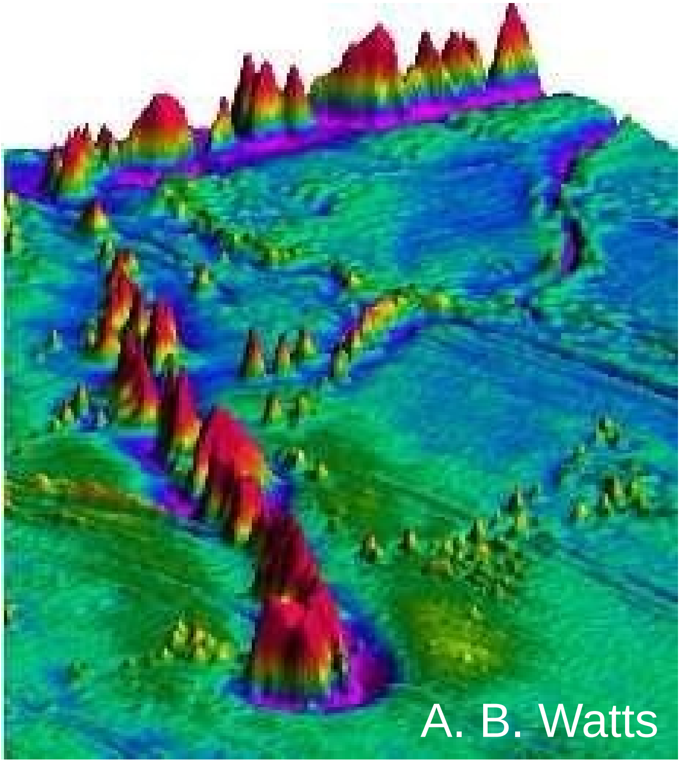
Analogue experiments

- lithosphere ≡ silicone putty
- asthenosphere = glucose syrup

Viscosity ratio > 1000

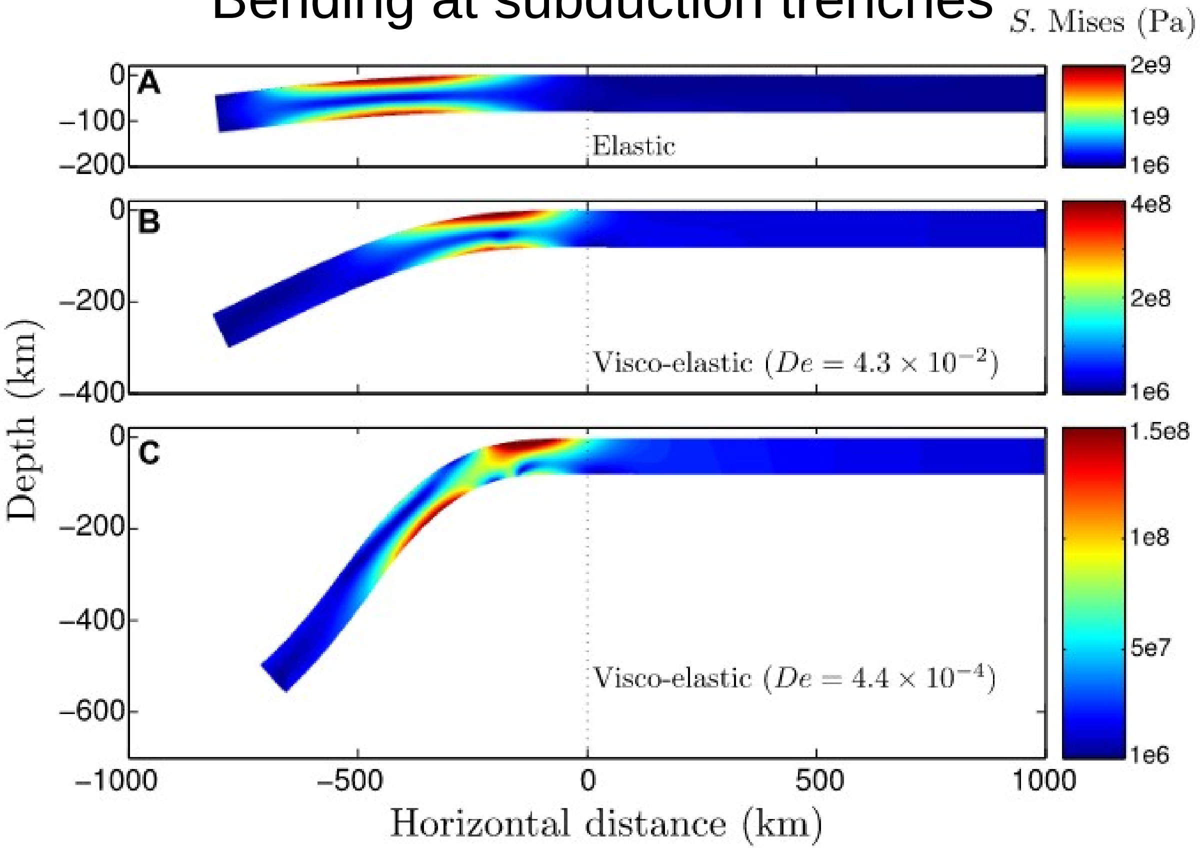
“Compositional” numerical models

Strong... but nevertheless deforming plates



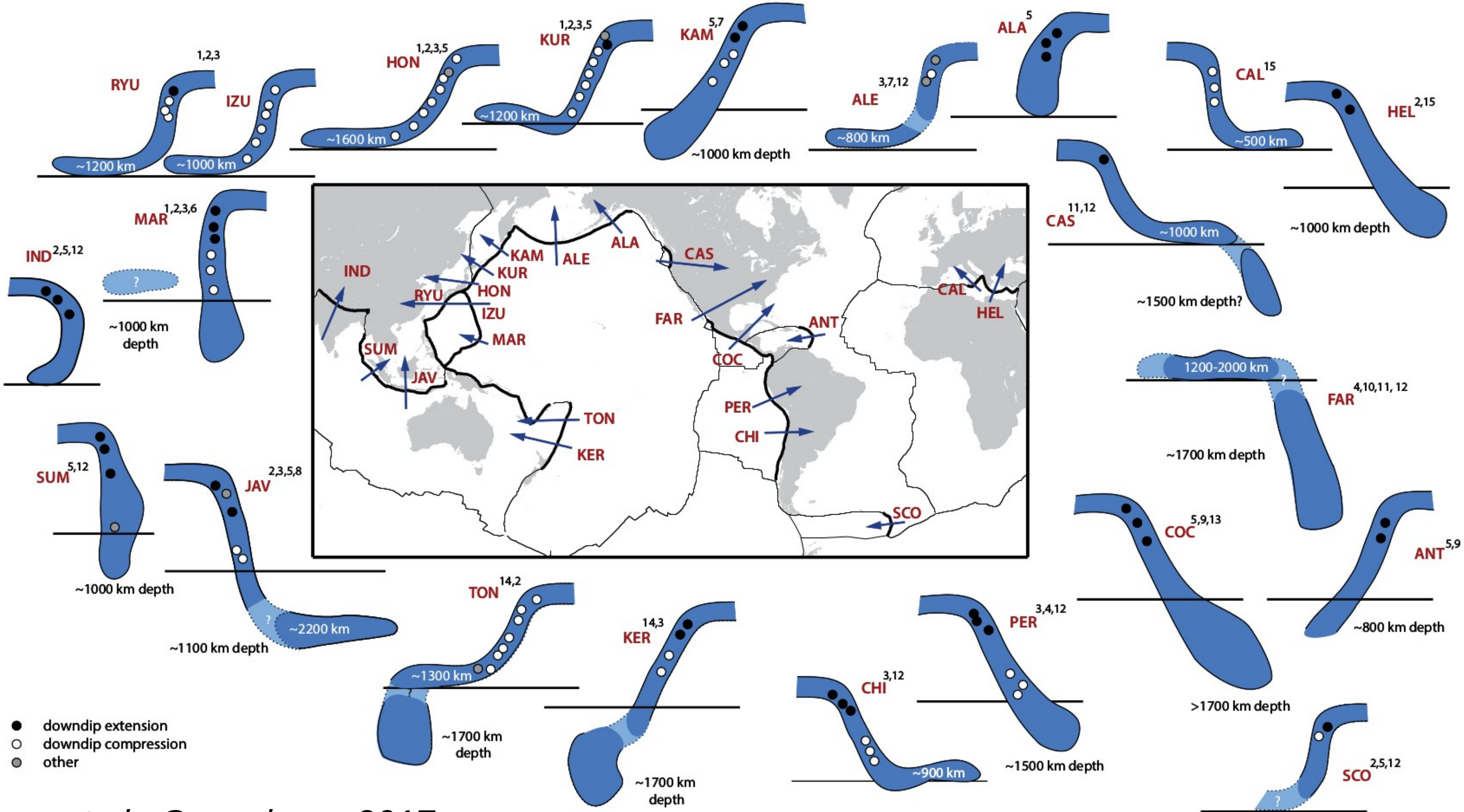
Flexure around Hawaii-Emperor seamounts

Bending at subduction trenches



Fourel et al., 2014

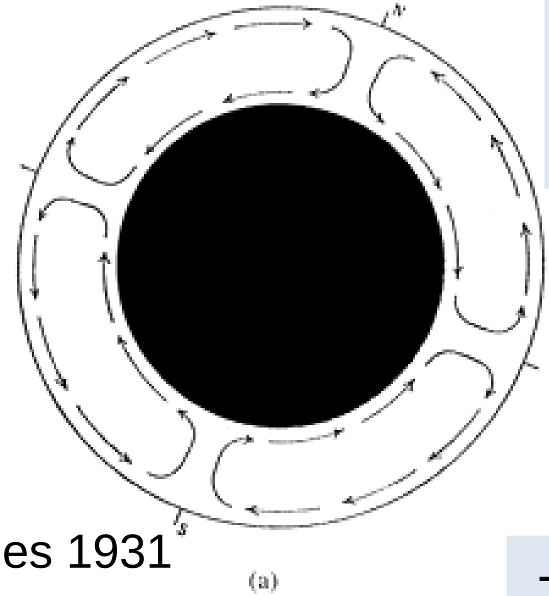
Strong... but nevertheless deforming plates



Goes et al., Geosphere, 2017

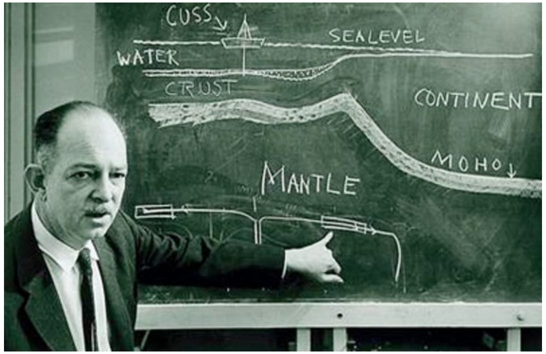
Cold lithosphere vs. hot asthenosphere

Lithosphere as the conducting and **moving cold boundary layer of convective mantle**

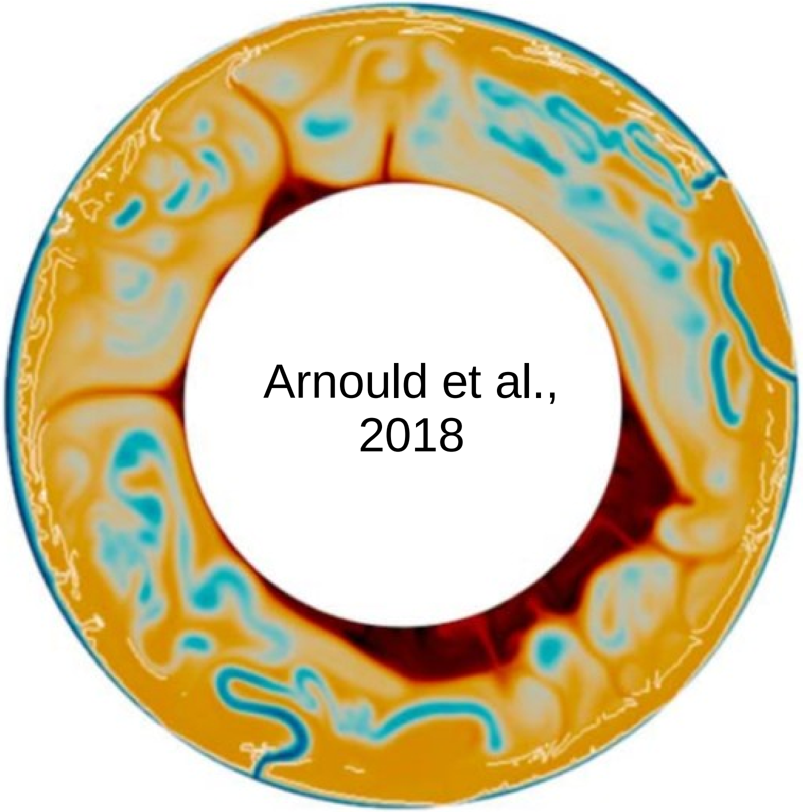


Holmes 1931

+ lithospheric plates sinking in the mantle



Hess, 1962

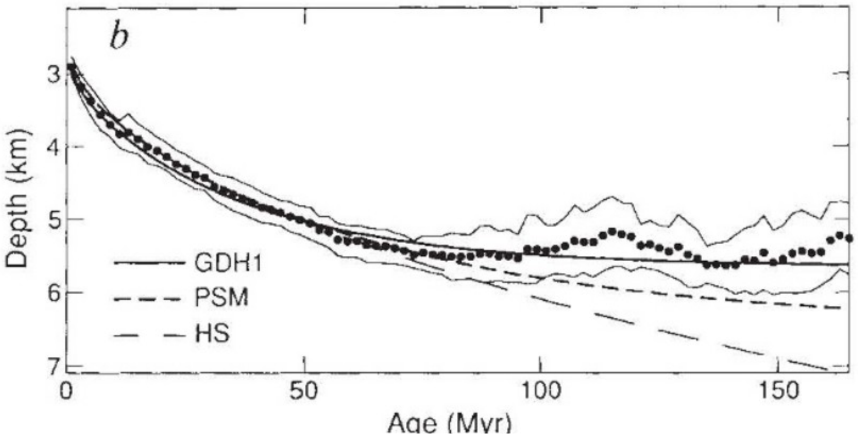


Arnould et al., 2018

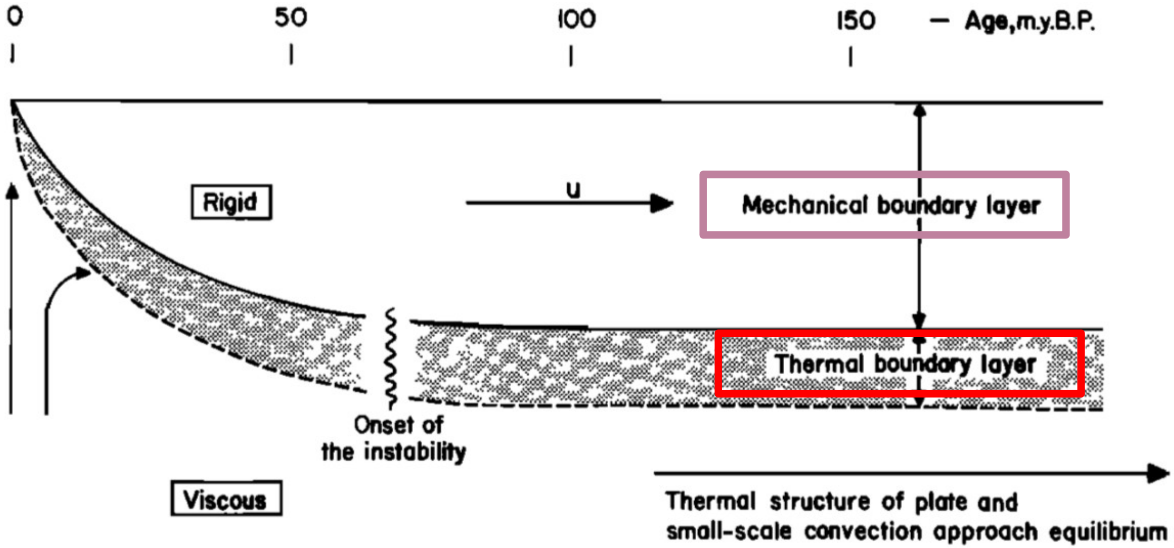
Cold lithosphere vs. hot asthenosphere

Heat flow & bathymetry

$\Delta T \rightarrow \Delta\rho \rightarrow \Delta h$



Stein & Stein, 1992



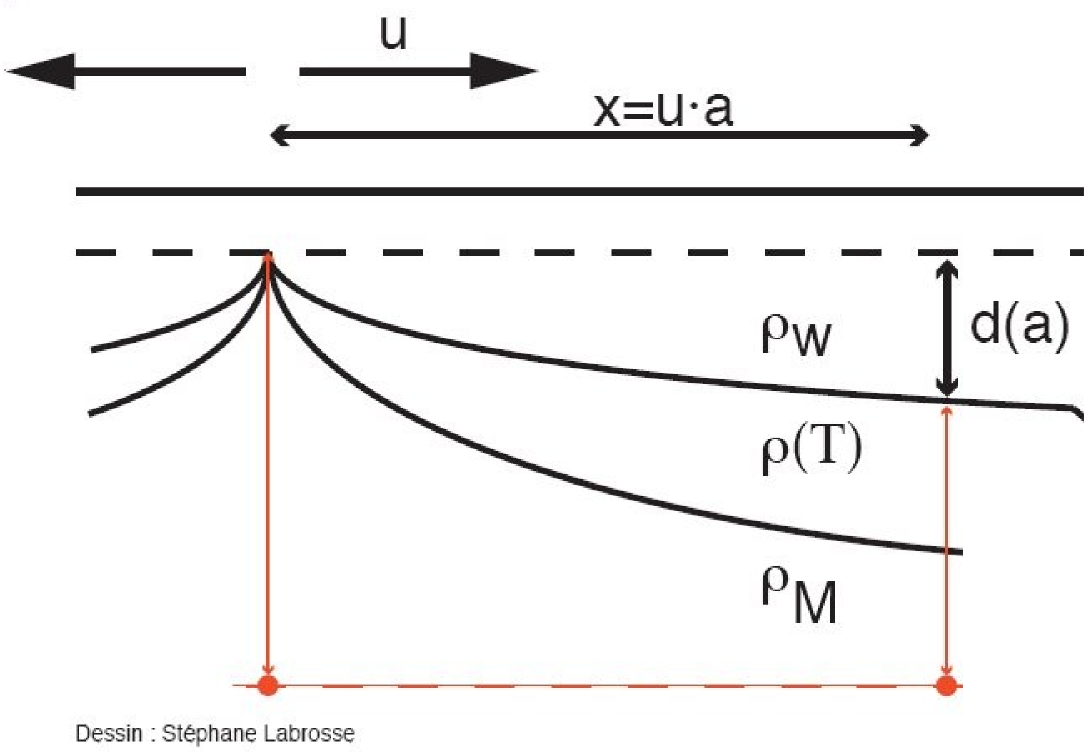
Parsons & McKenzie, 1978

Cold lithosphere vs. hot asthenosphere

Half-space cooling model of oceanic mantle, cooling from above as it spreads away from the ridge

$$\frac{\partial T}{\partial a} = \lambda \frac{\partial^2 T}{\partial z^2}$$

$$T = T_M \operatorname{erf}\left(\frac{z}{2\sqrt{\lambda a}}\right)$$



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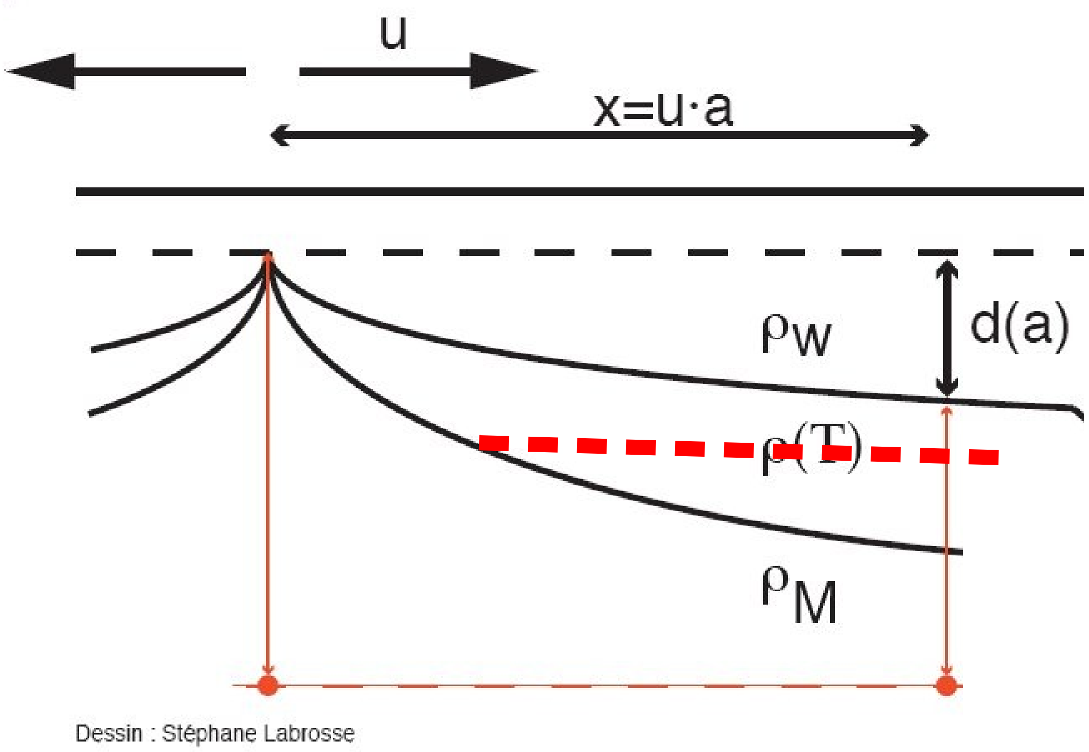

Plate model with base of the plate at a constant temperature (1300°C)
(McKenzie, 1967)
(Parsons & Sclater, 1977)

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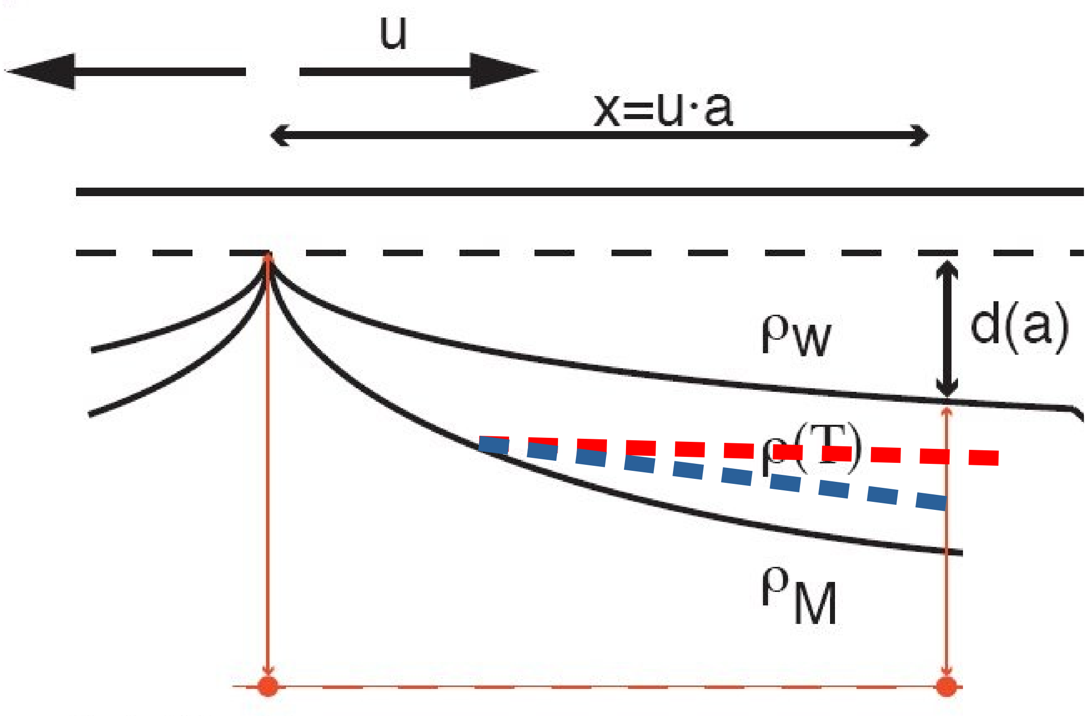
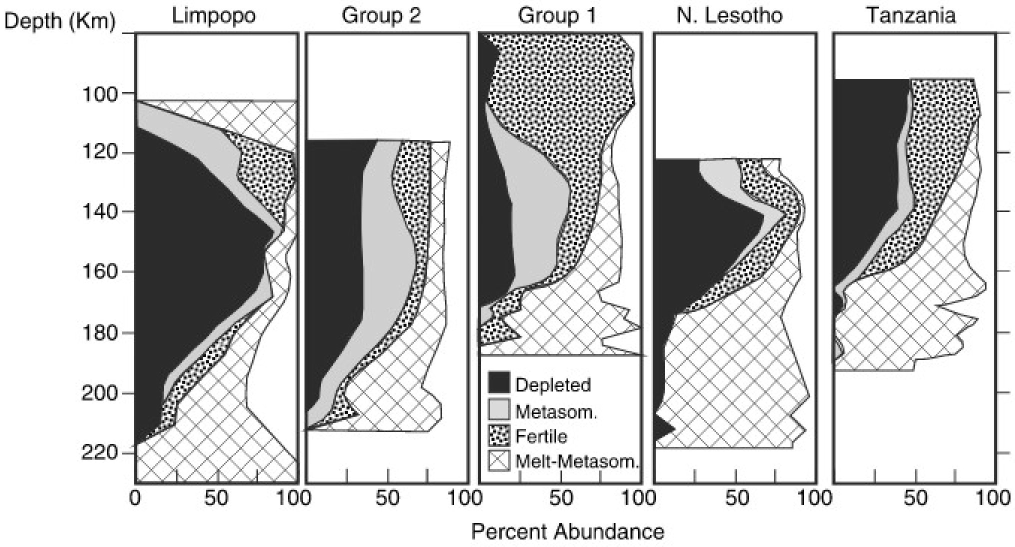


Dessin : Stéphane Labrosse

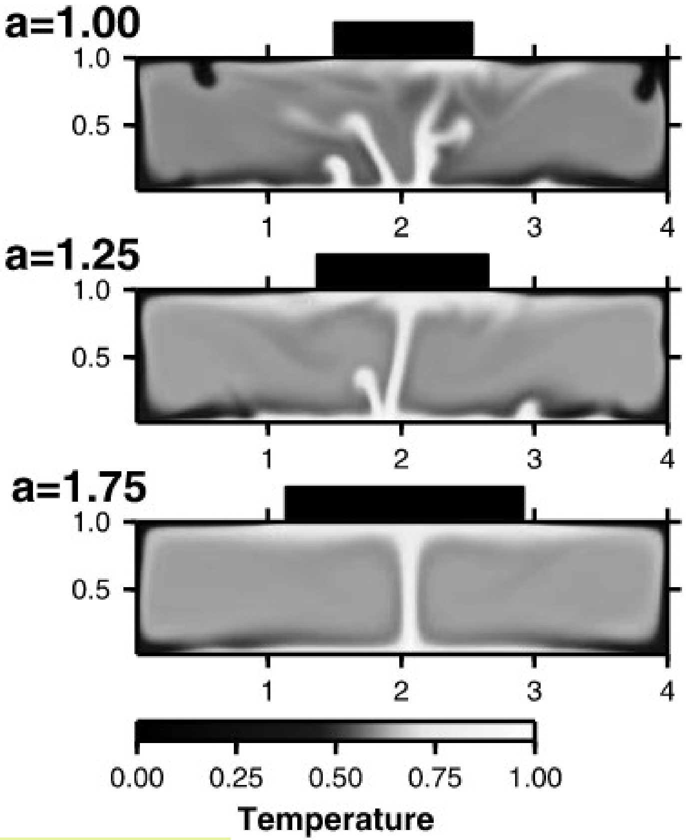
Plate model with base of the plate at a constant temperature (1300°C)
(McKenzie, 1967)
(Parsons & Sclater, 1977)

CHABLIS model with bottom lithosphere isotherm imposed with a constant-heat flow
(Doin & Fleitout, 1996)

Continental lithosphere



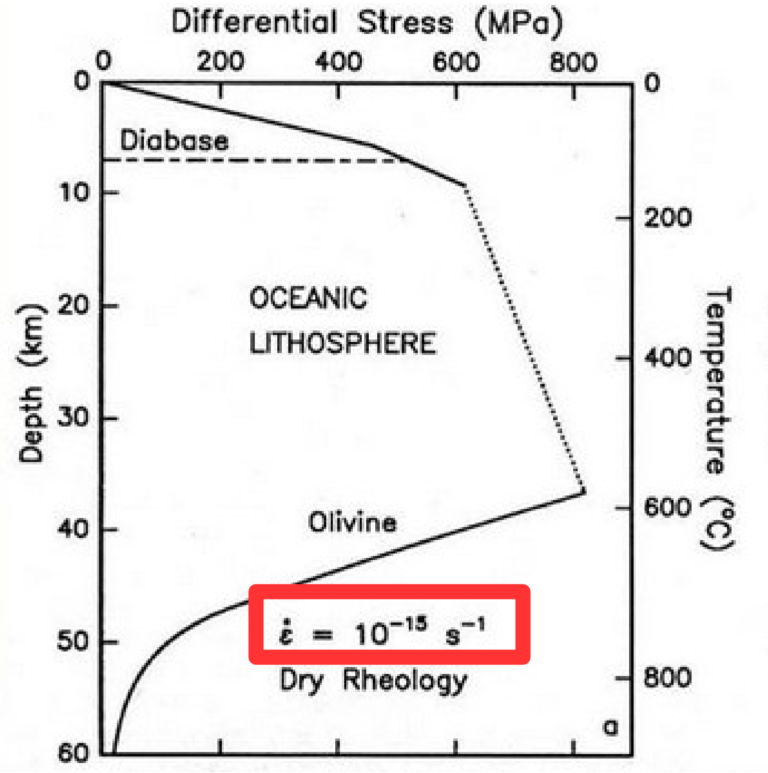
Mantle type in the African lithosphere
as interpreted from xenoliths
Carlson et al., 2005



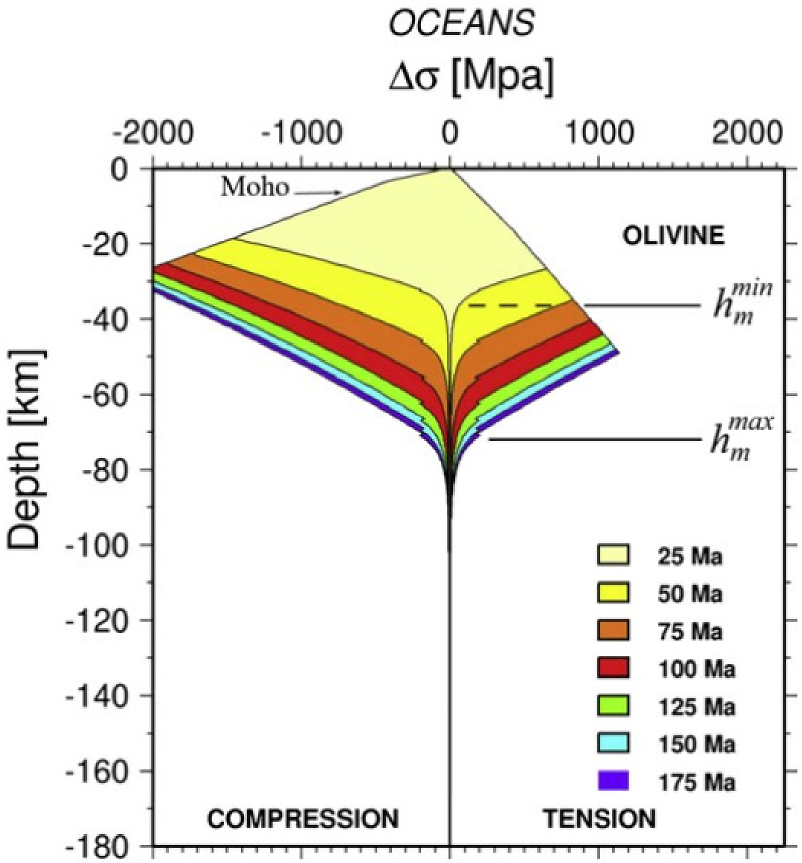
Grigné et al., 2007

Possible melt-depleted / dehydrated continental lithosphere
→ variable viscosity and conductivity
→ effects on flow pattern and surface heat flux
→ cratonic keels ?

Reconciling temperature and strength through rheology

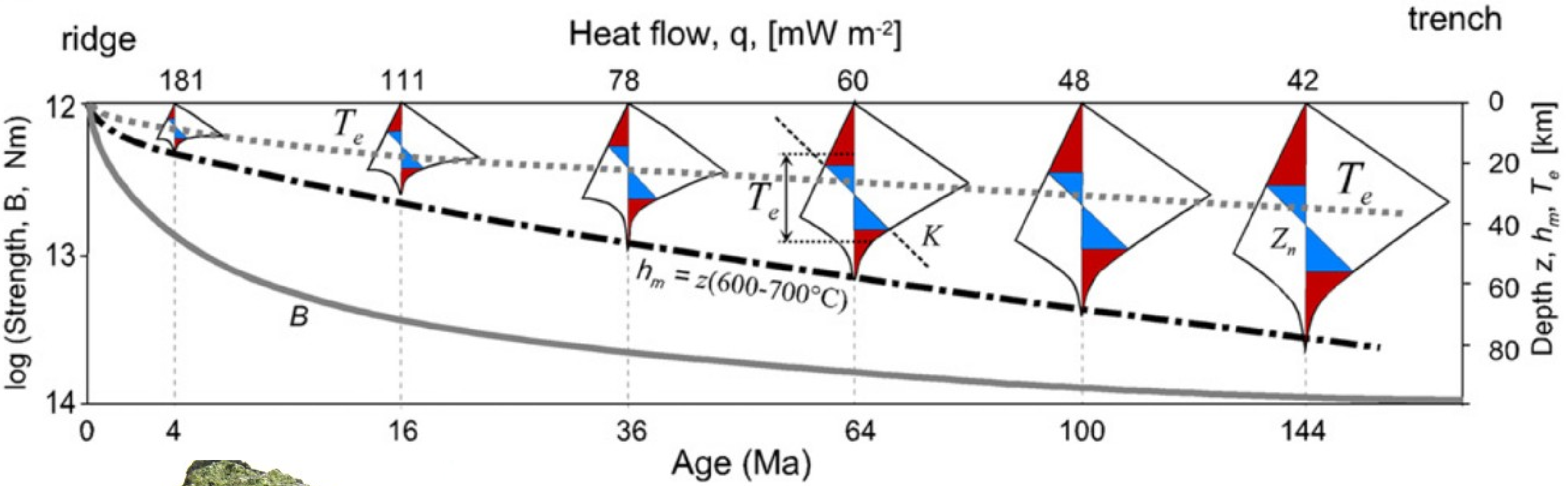


Kohlstedt et al., 1995



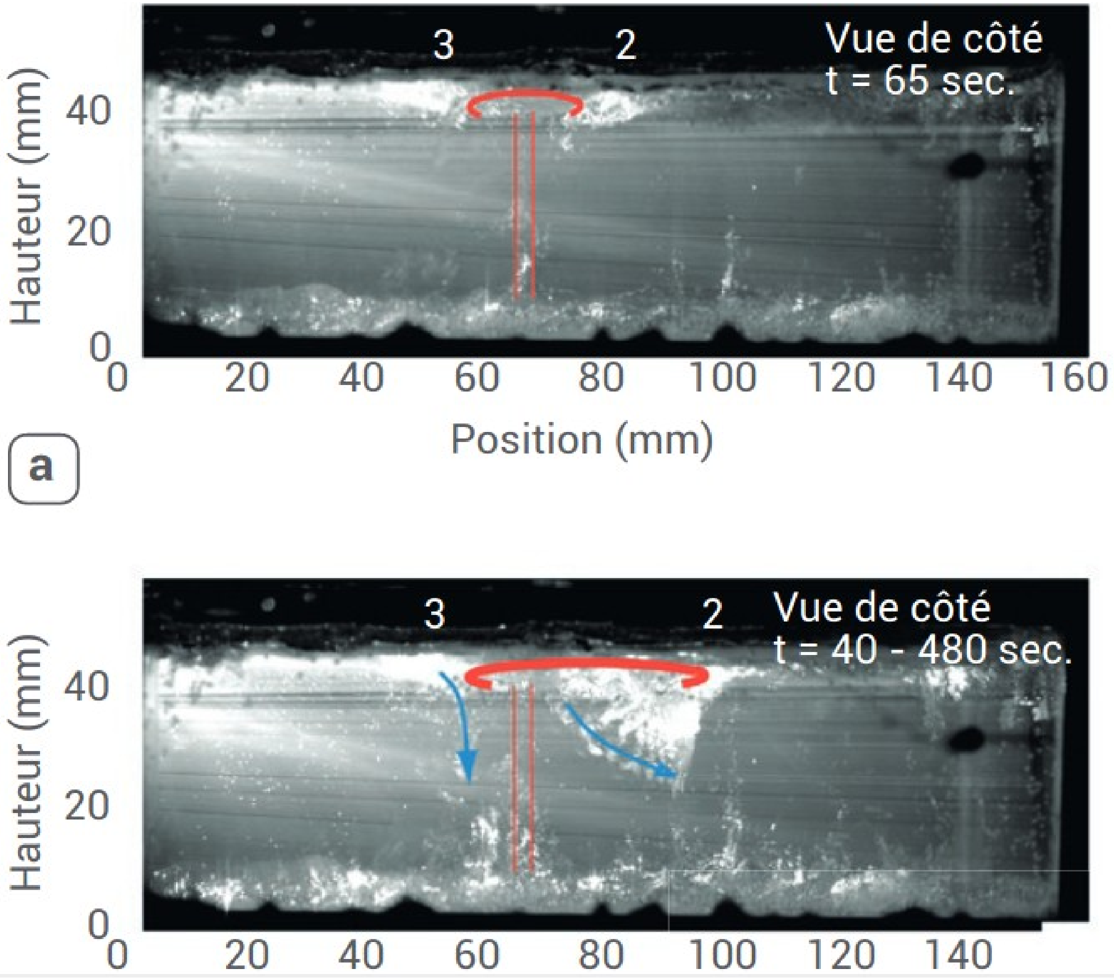
Burov, 2011

Reconciling temperature and strength through rheology



Burov, 2011

Analogue material with temperature-like dependent rheology



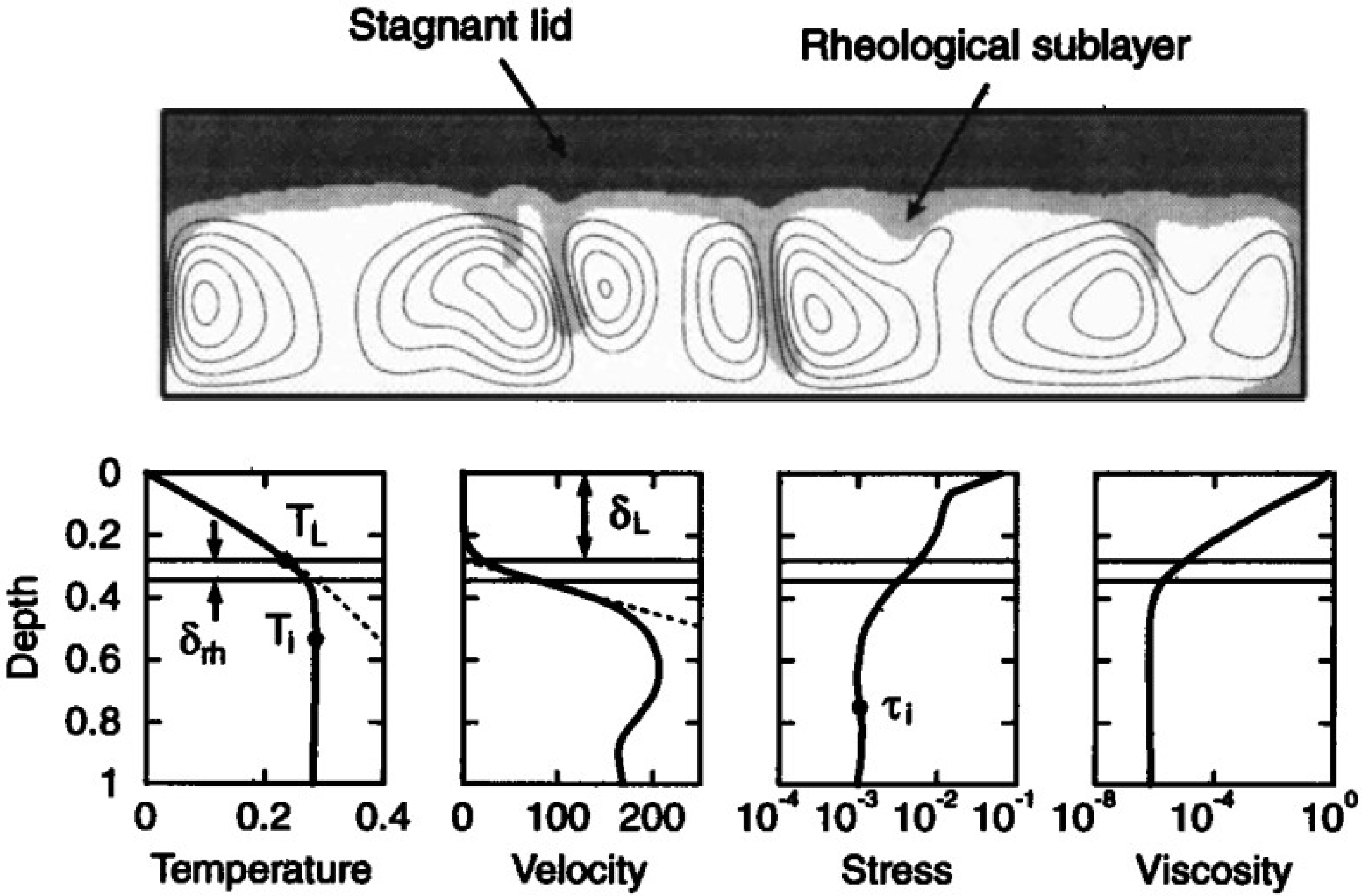
- Surface evaporation in the lab = surface cooling of the Lo

- Ludox material (silica particle suspension) +/- dried

  > newtonian
  > shear-thinning
  > elastic
  > brittle

Davaille et al., 2020

Thermal, mechanical, rheological lithosphere



Stagnant-lid simulation

→ what happens in a system with a moving surface ?

Solomatov & Moresi, 2000

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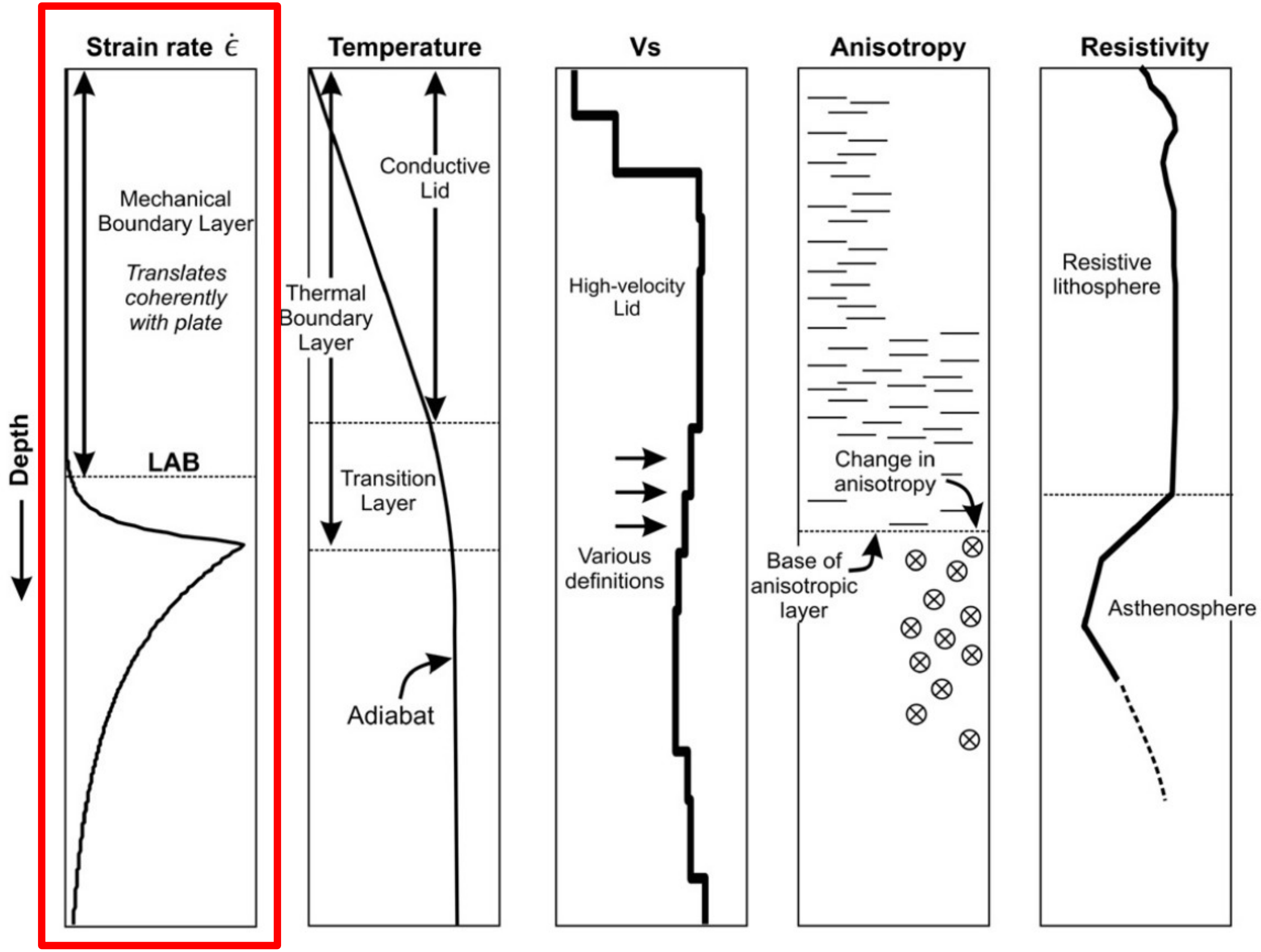
Is the plate concept still relevant ?

Interpretation of data require info on deformation and motion

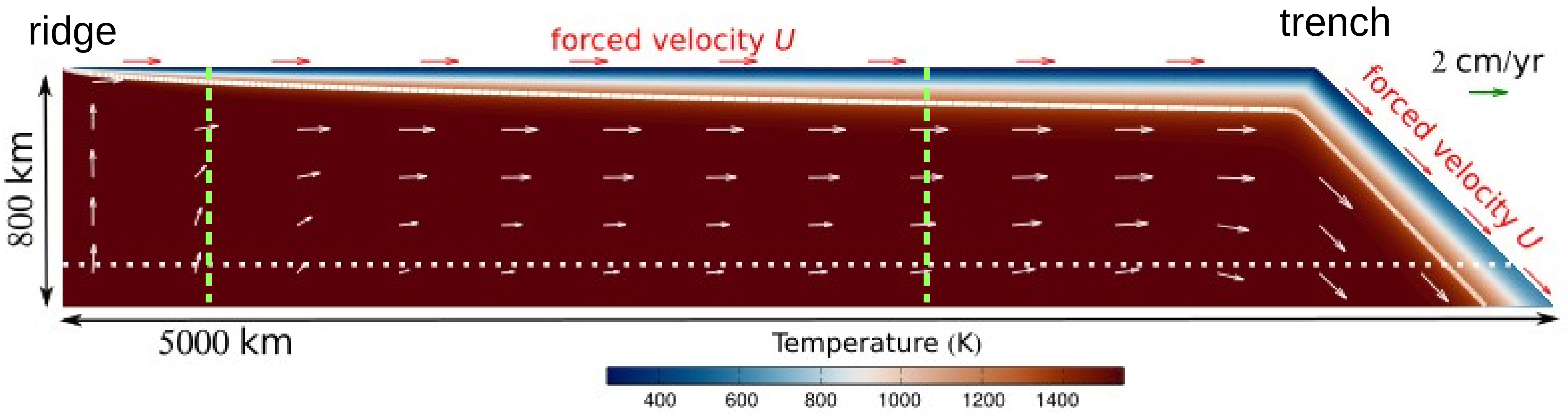
More complex strain rate profile ?

What is the velocity profile ?



Eaton et al., 2009

Asthenospheric flow driven by surface plate



Forced velocity U : 1-2-5-10-20 cm/yr

Vertical profiles at different ages

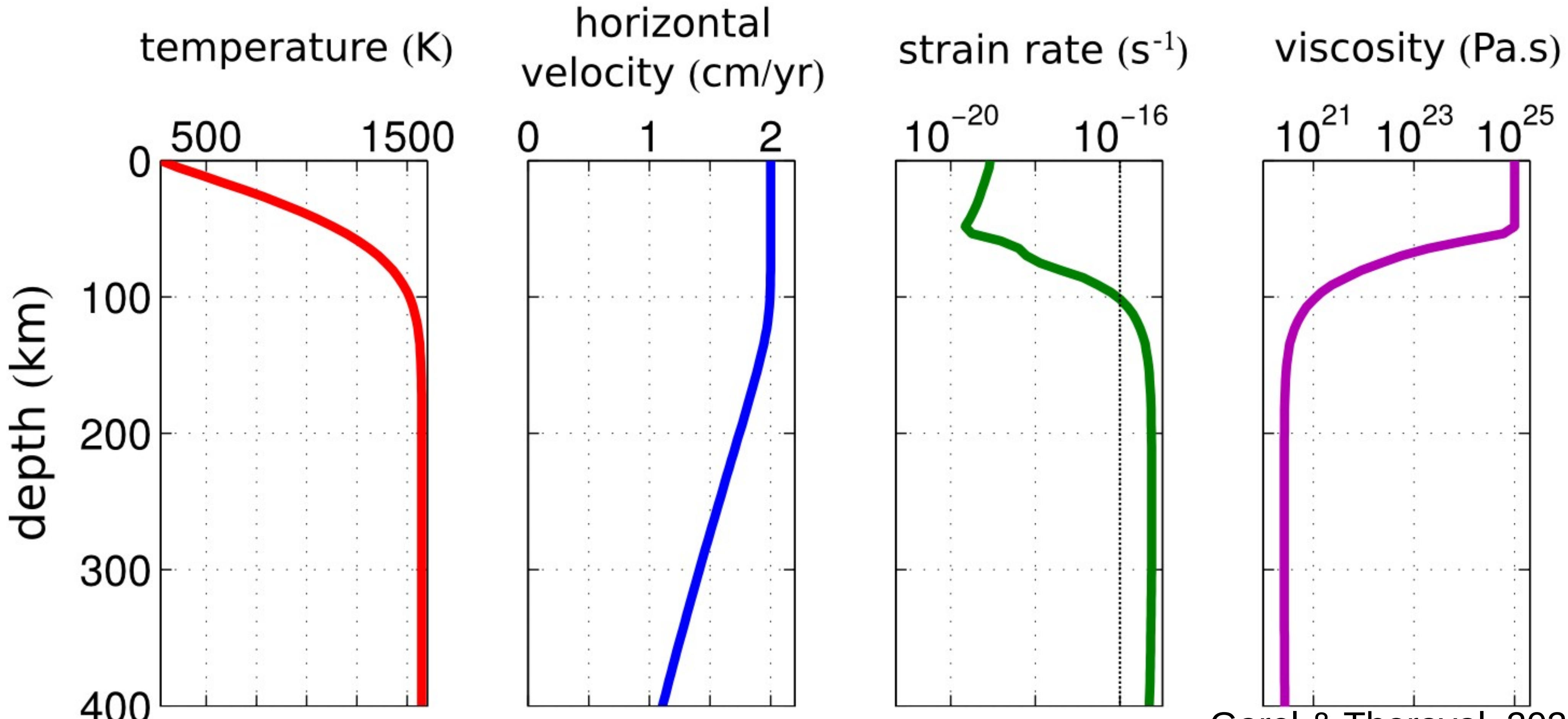
- one <u>single</u> material for both lithosphere and asthenophere

(no pre-imposed discontinuity)

- steady-state

Garel & Thoraval, 2021

Vertical profiles below a moving plate (2 cm/yr)



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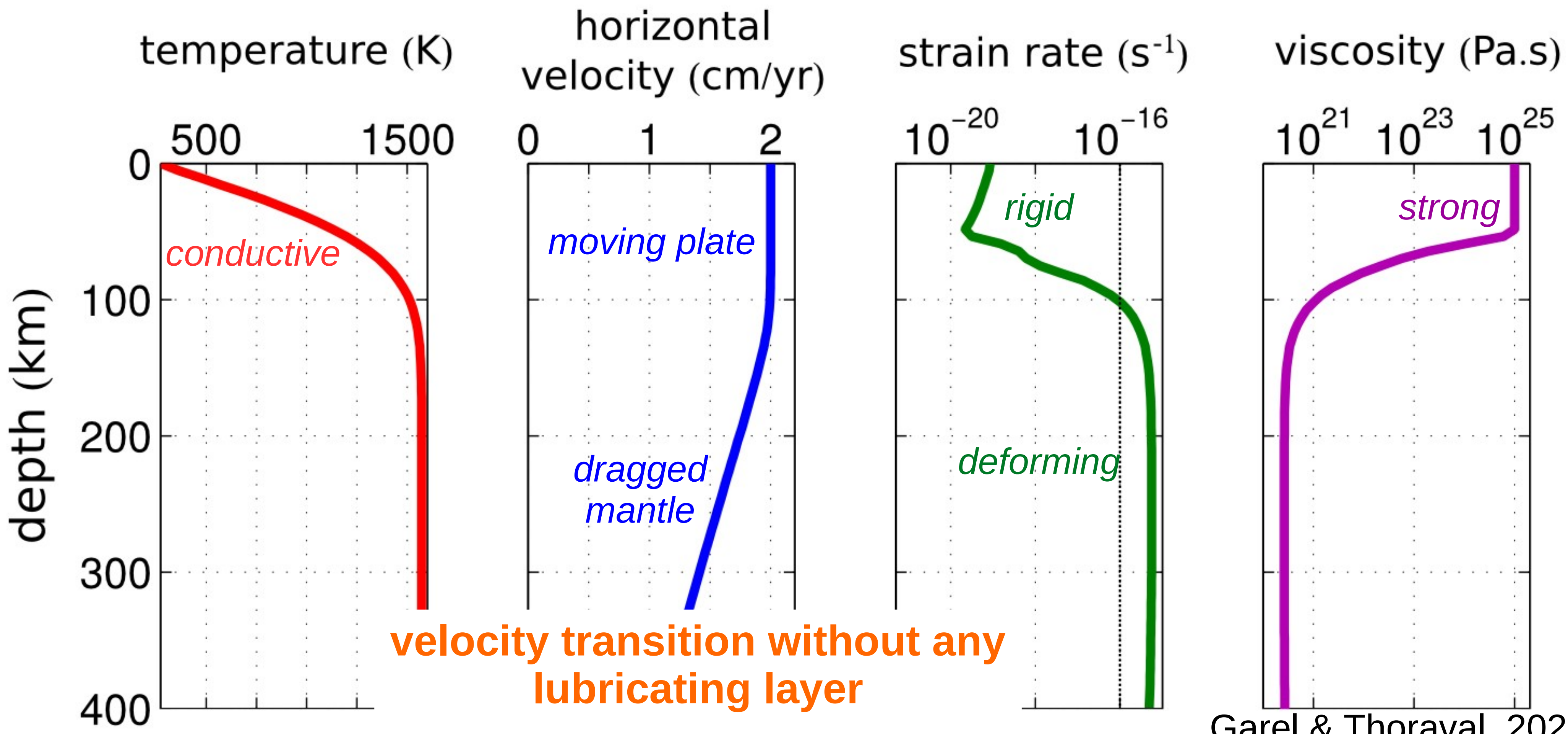
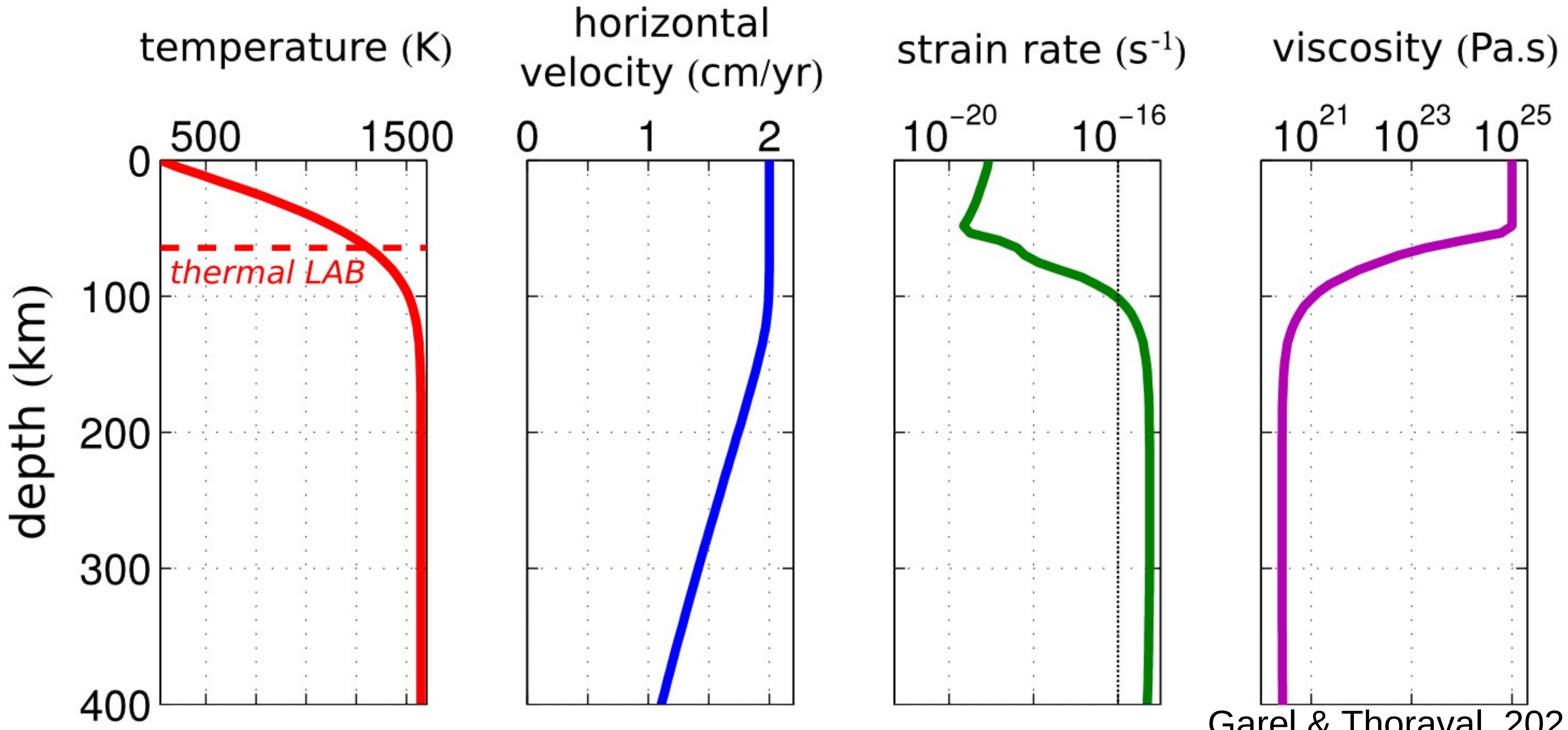


velocity transition without any lubricating layer

Garel & Thoraval, 2021

Vertical profiles below a moving plate (2 cm/yr)



Garel & Thoraval, 2021

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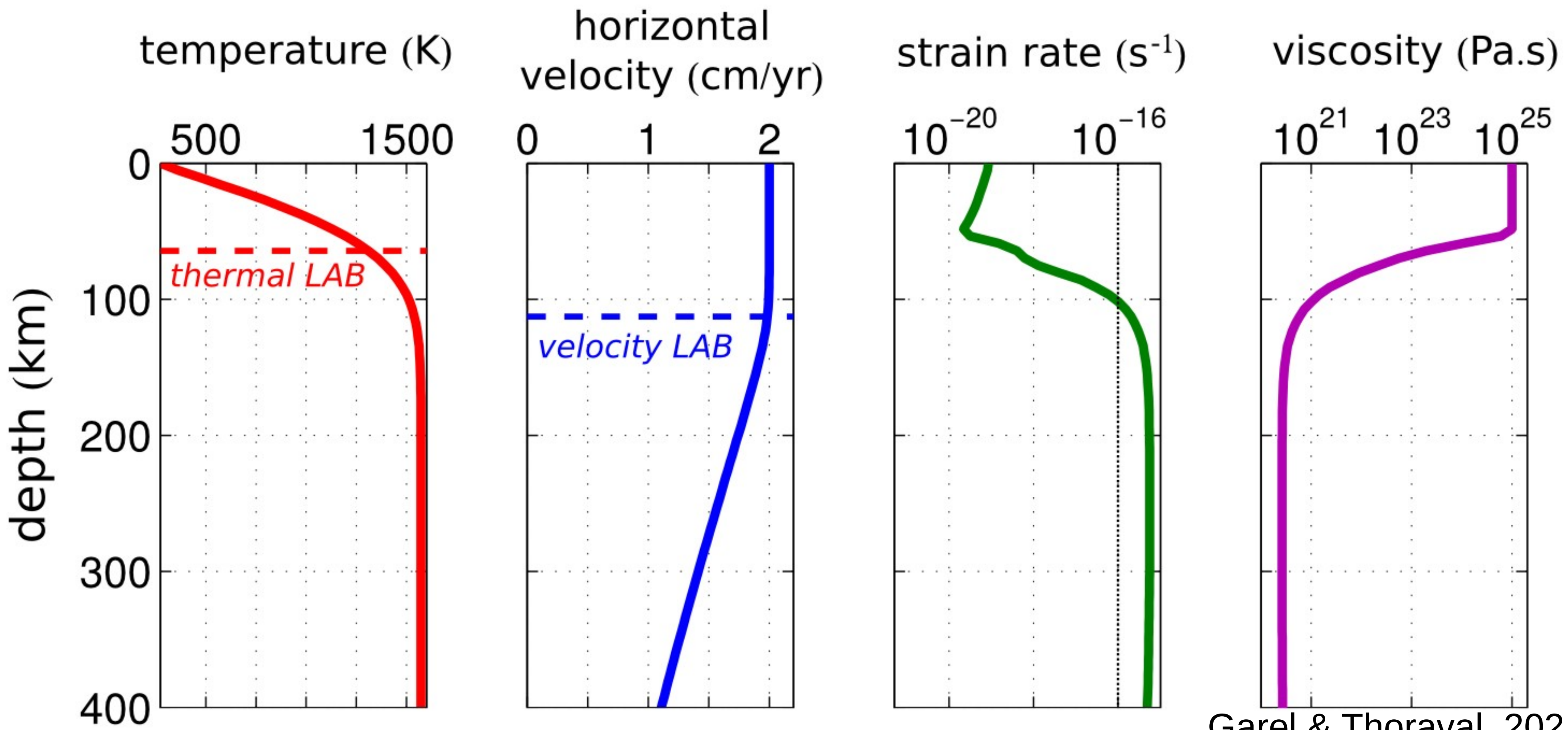

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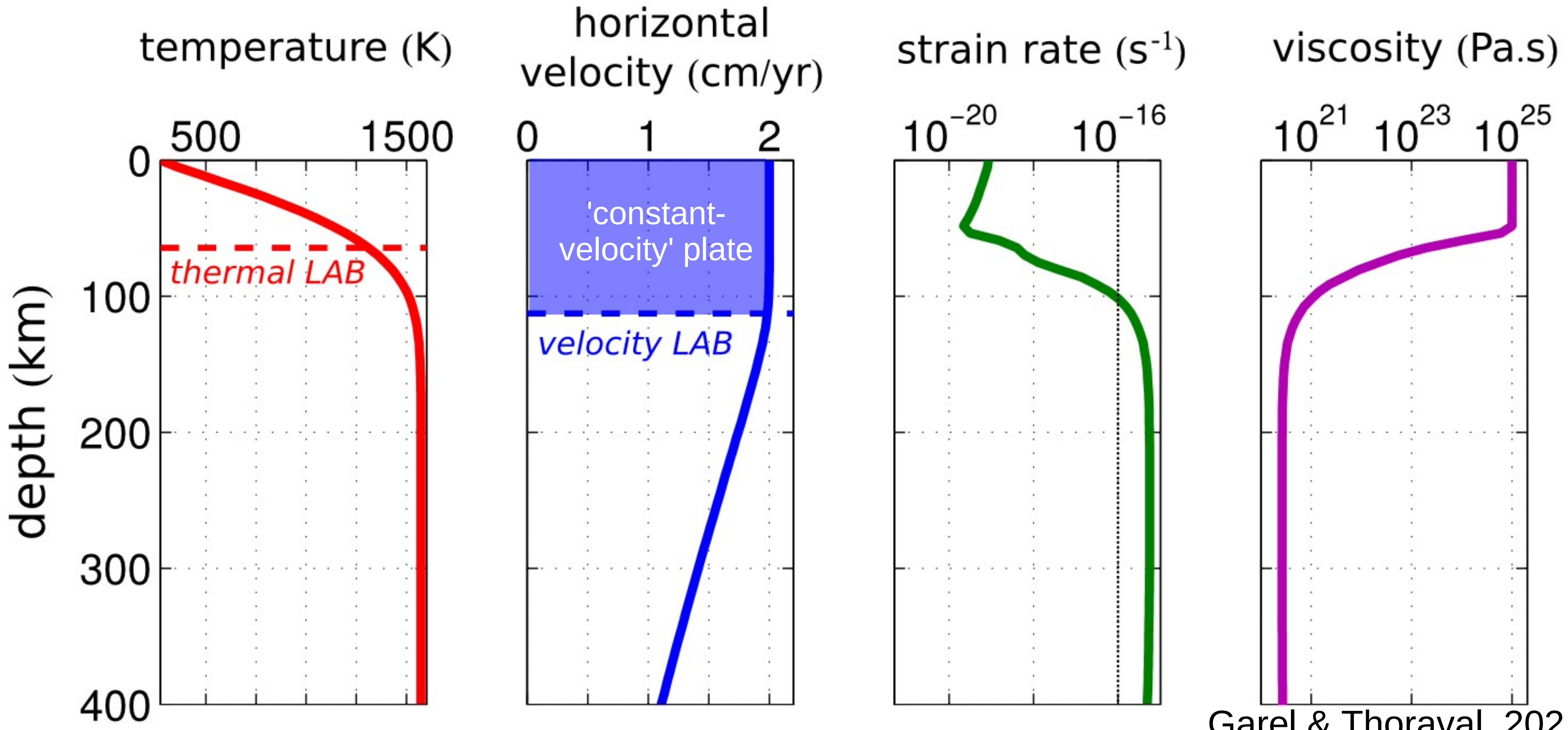

Garel & Thoraval, 2021

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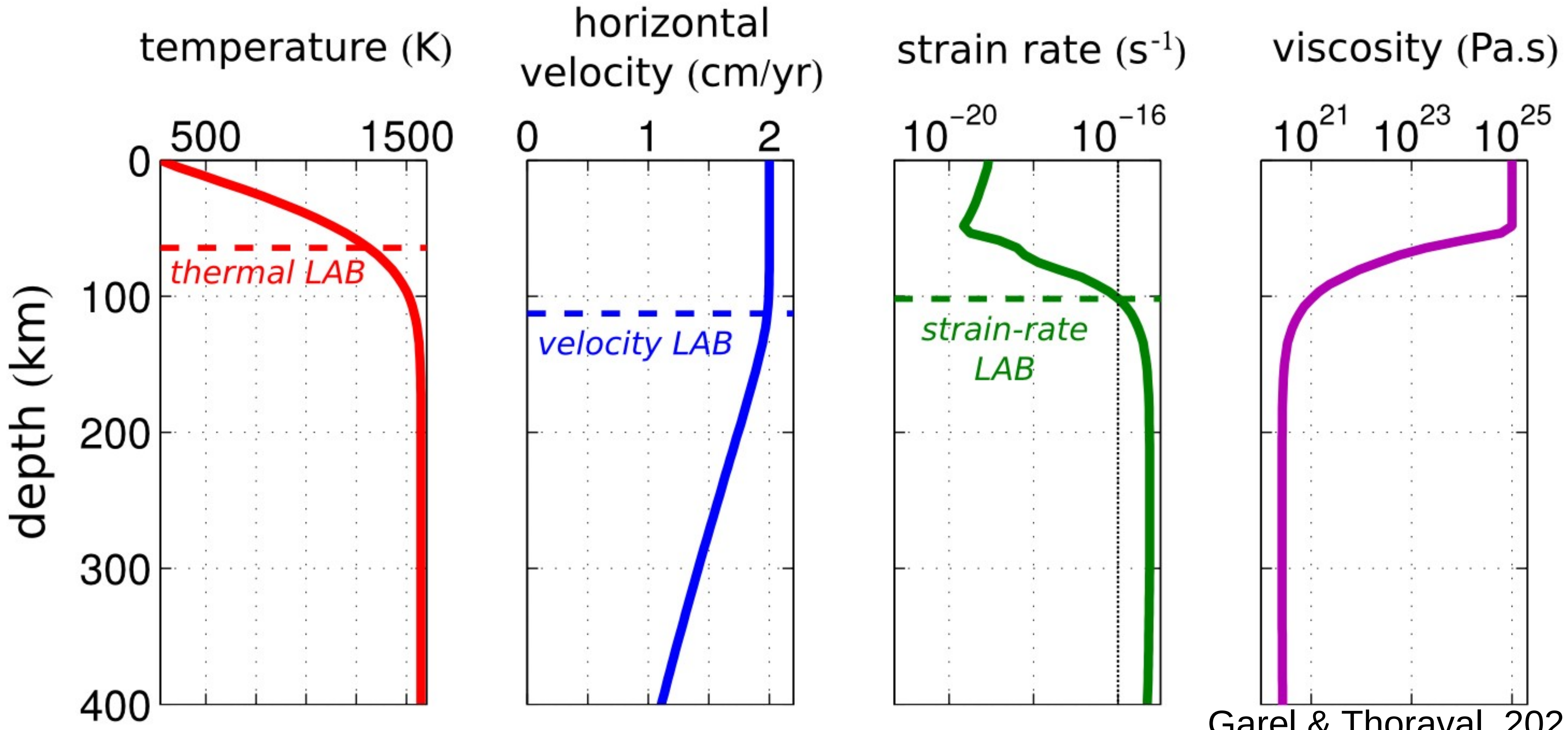
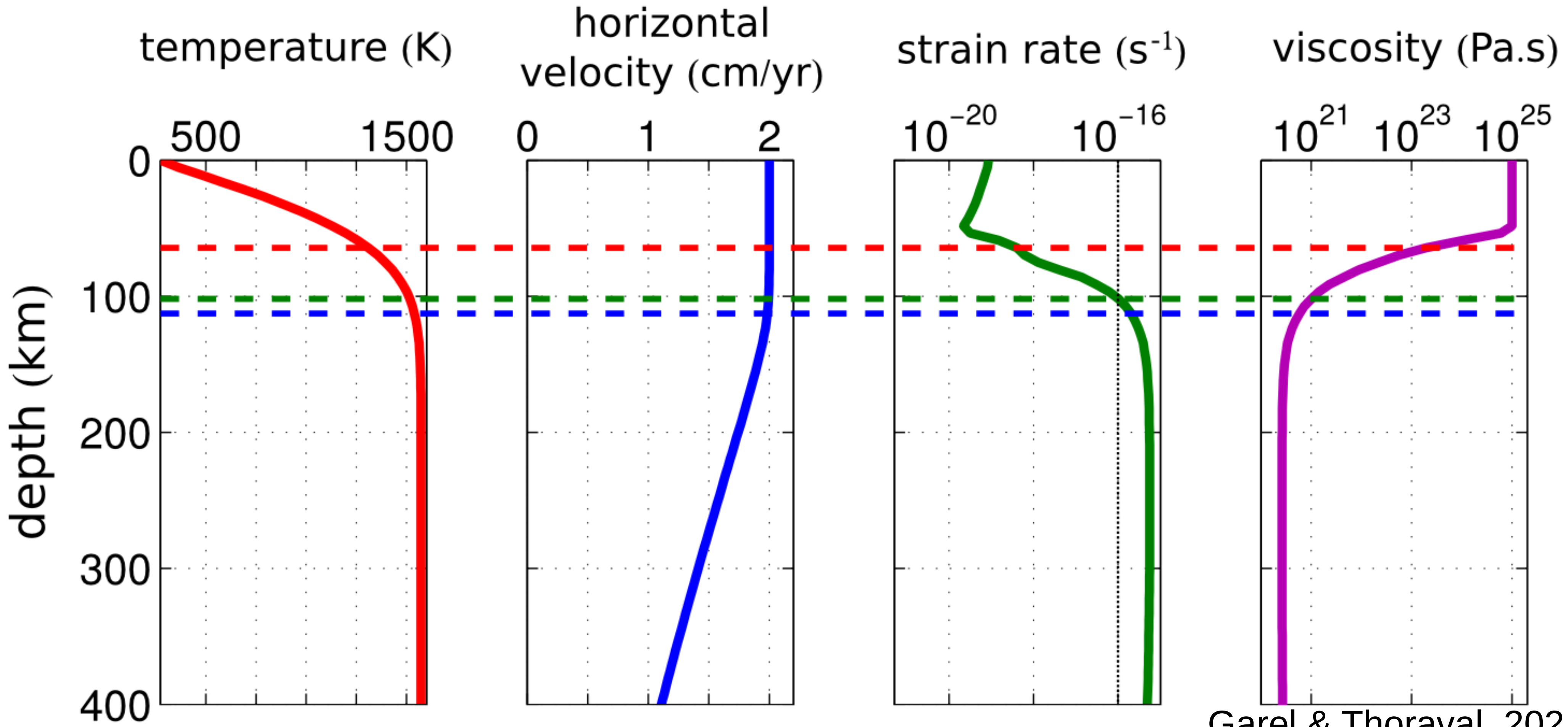


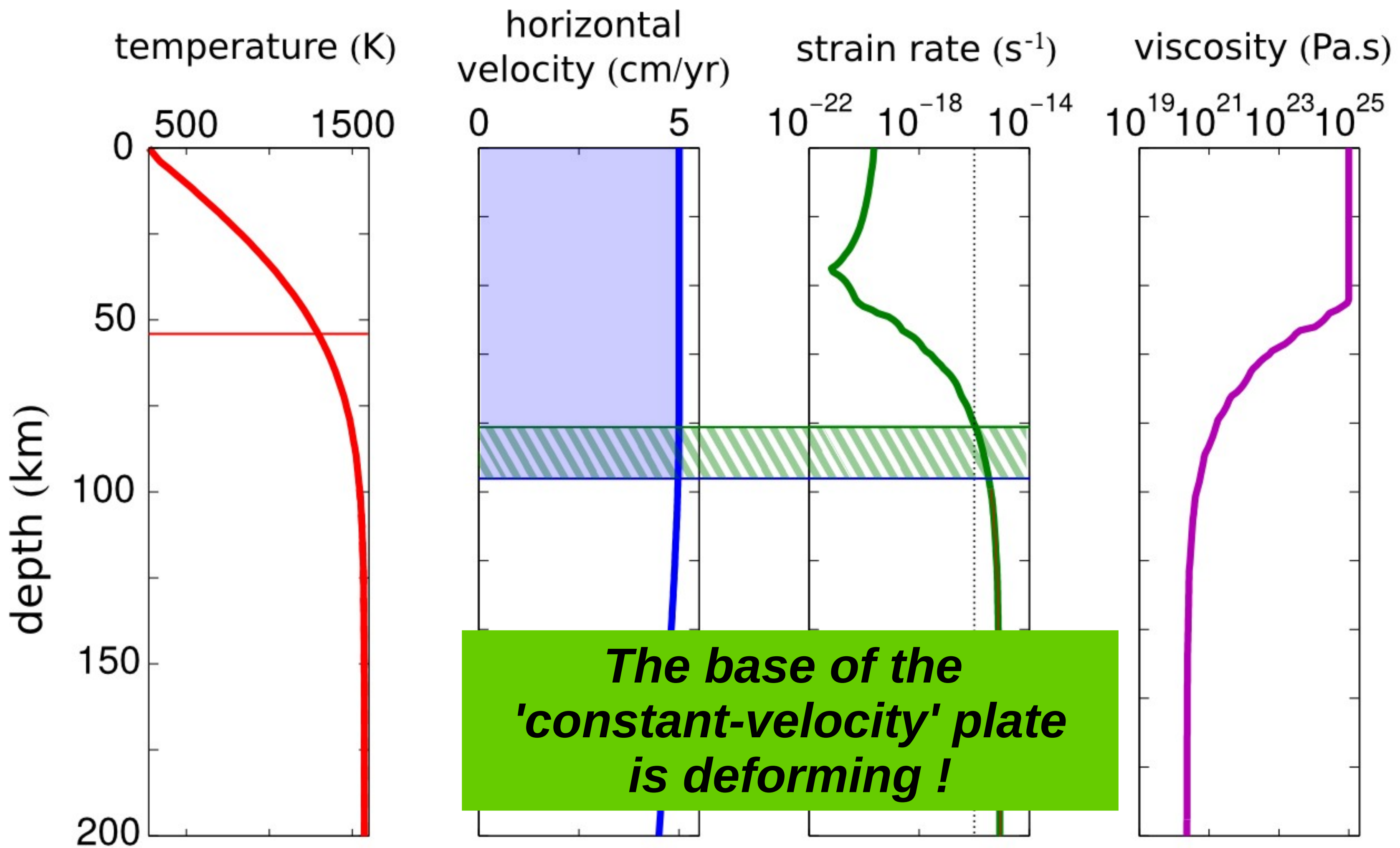
Garel & Thoraval, 2021

Vertical profiles below a moving plate (2 cm/yr)

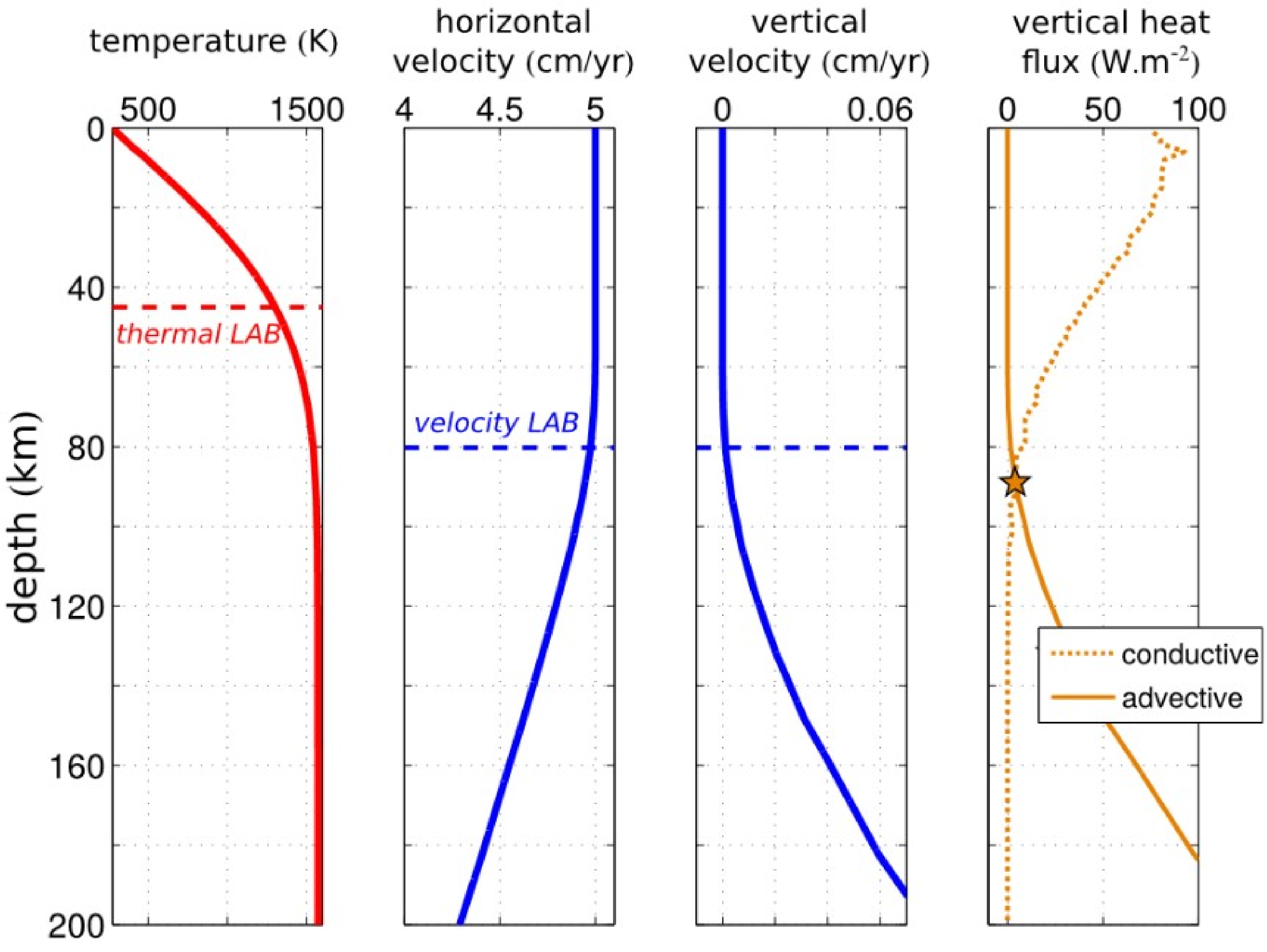


Garel & Thoraval, 2021

Vertical profiles below a moving plate (5 cm/yr)

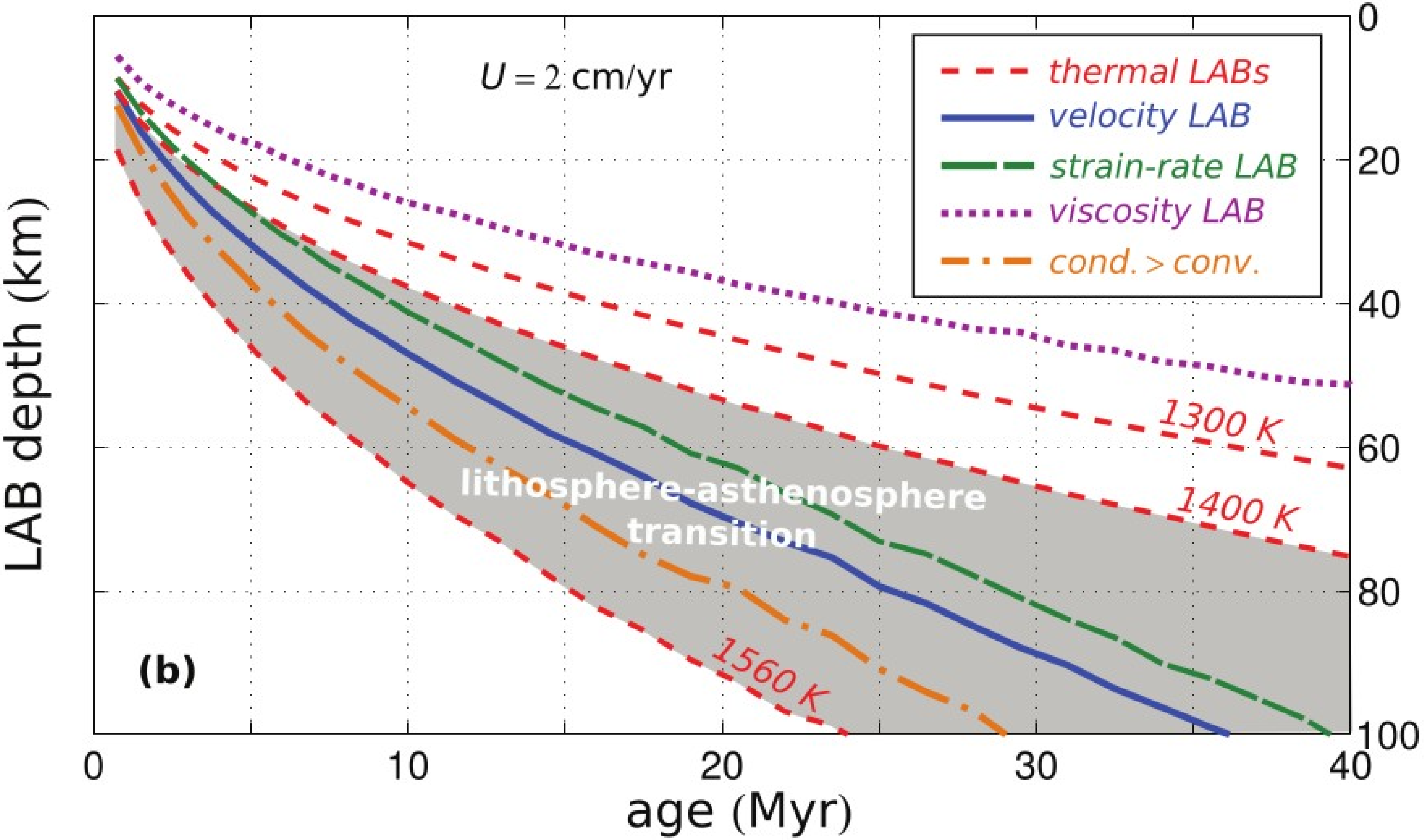


The base of the 'constant-velocity' plate is deforming !



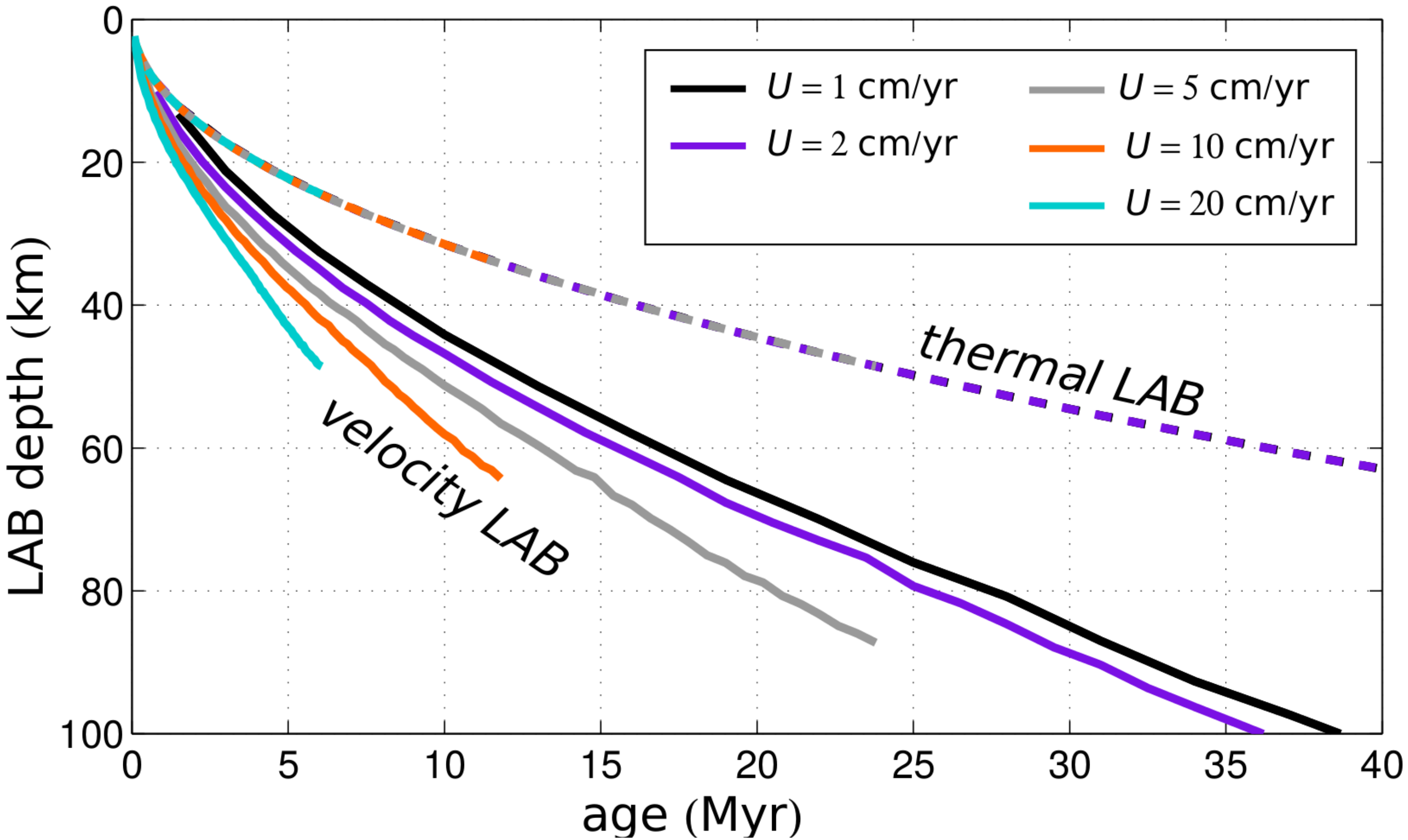
Garel & Thoraval, 2021

Progressive transition from lithosphere to asthenosphere



Garel & Thoraval, 2021

Variation of LAB depth for steady-state plate-driven flow



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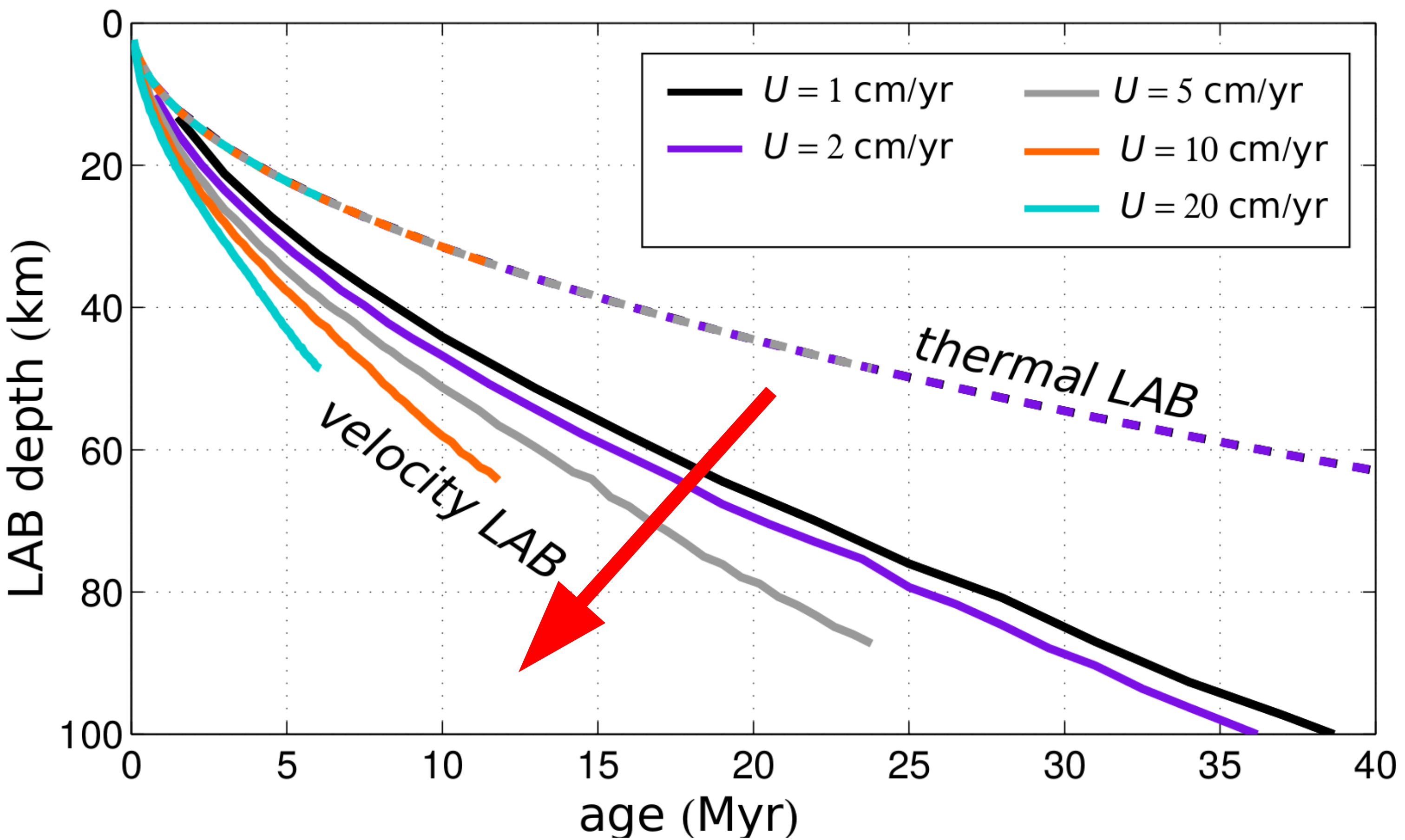
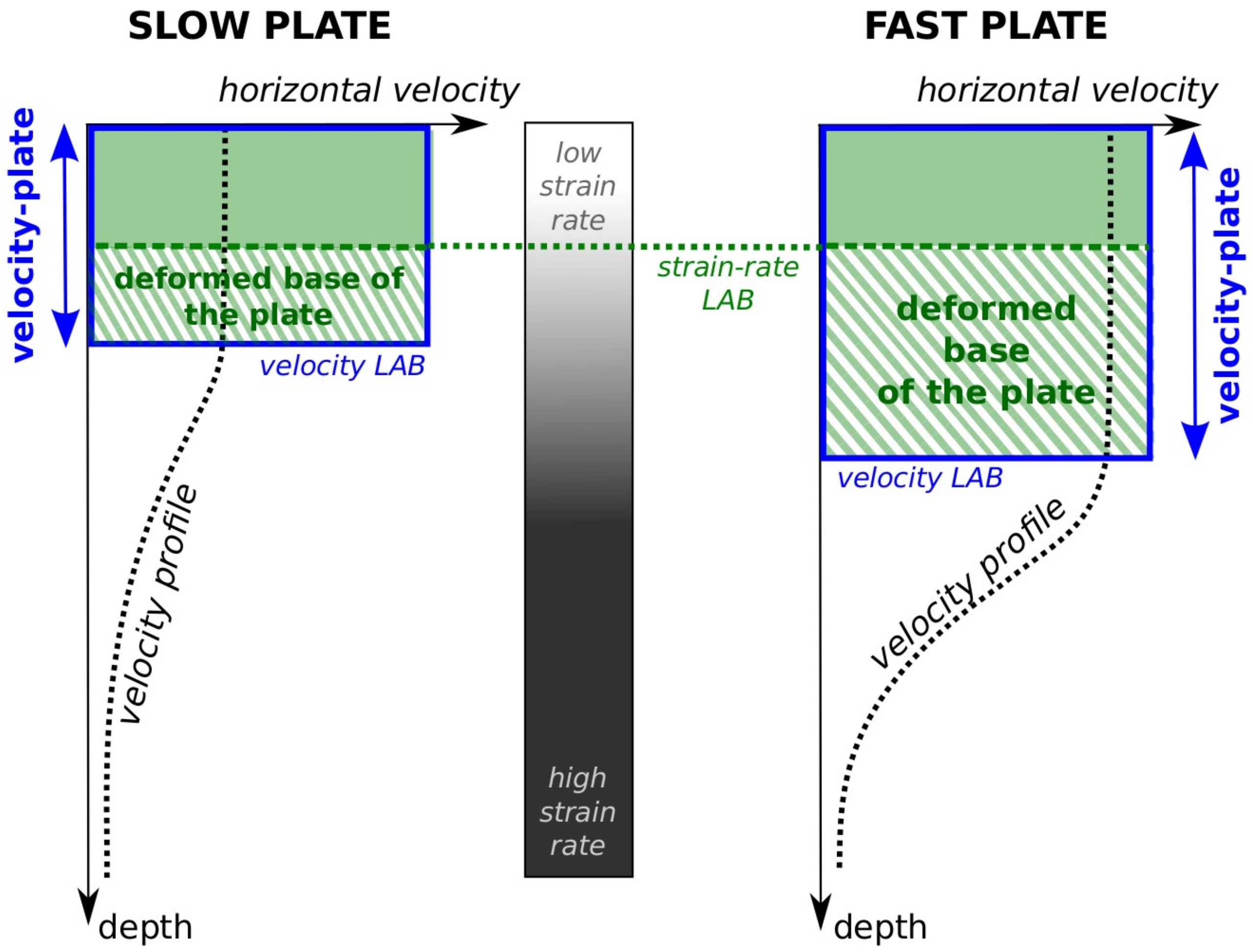


Garel & Thoraval, 2021

- 'constant-velocity' plate thickness is at first-order controlled by temperature

- **'constant-velocity' plate thickens as surface velocity increases**

Variation of LAB depth for steady-state plate-driven flow

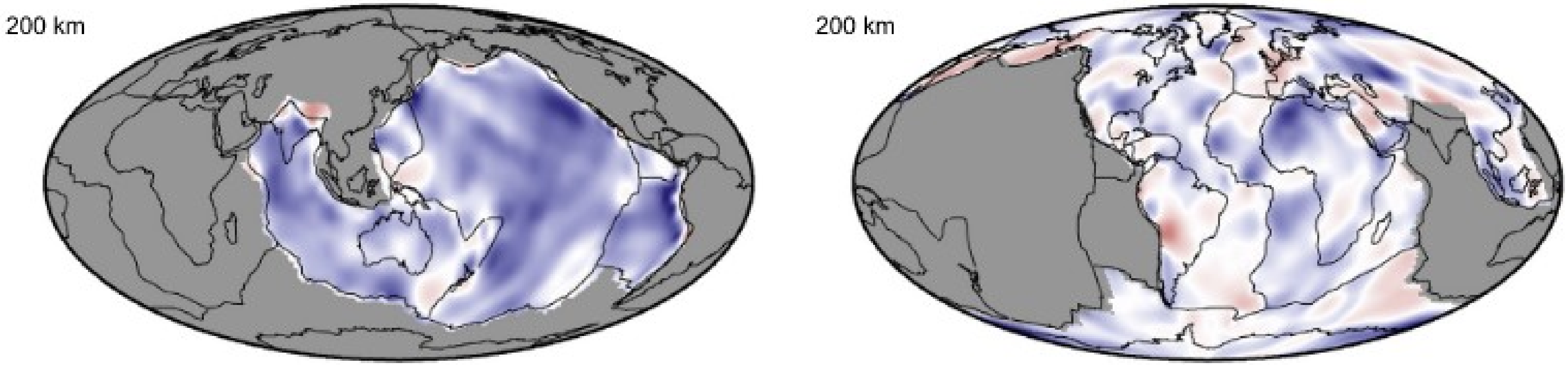


Garel & Thoraval, 2021

Agreement between fast direction of S_V waves and absolute plate motion (from NUVEL-1A)

Fast-moving plates

Slow-moving plates

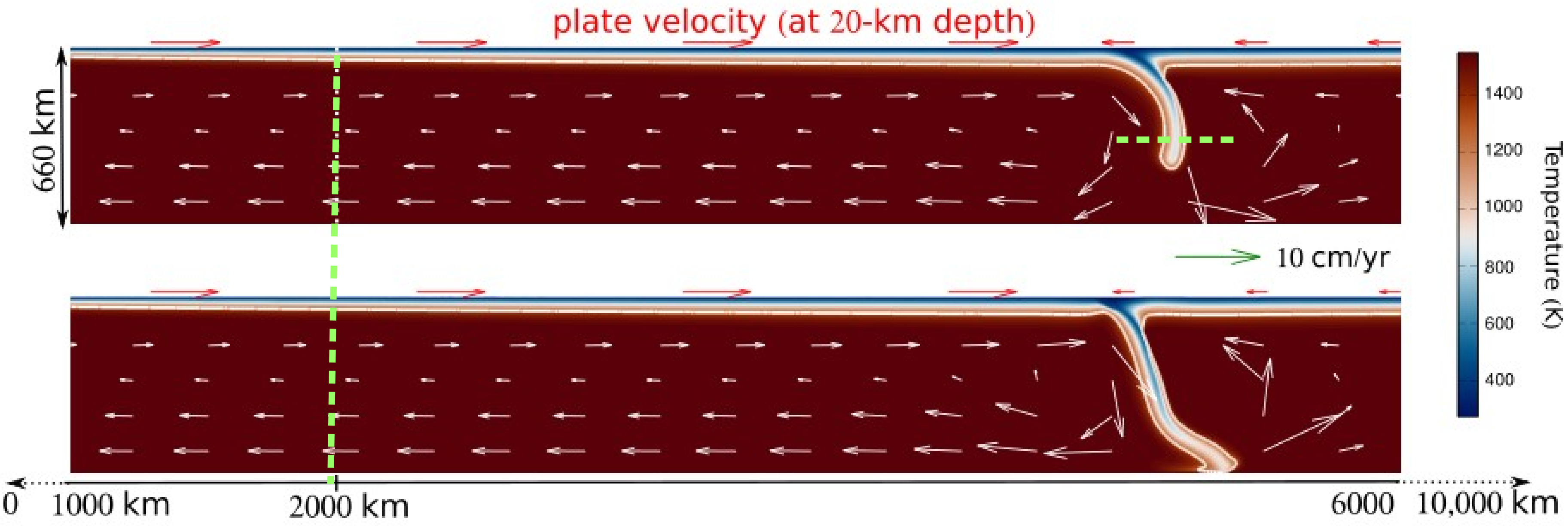


blue = parallelism

red = orthogonality

Debayle & Ricard, 2013

Transient asth. flow driven by subduction



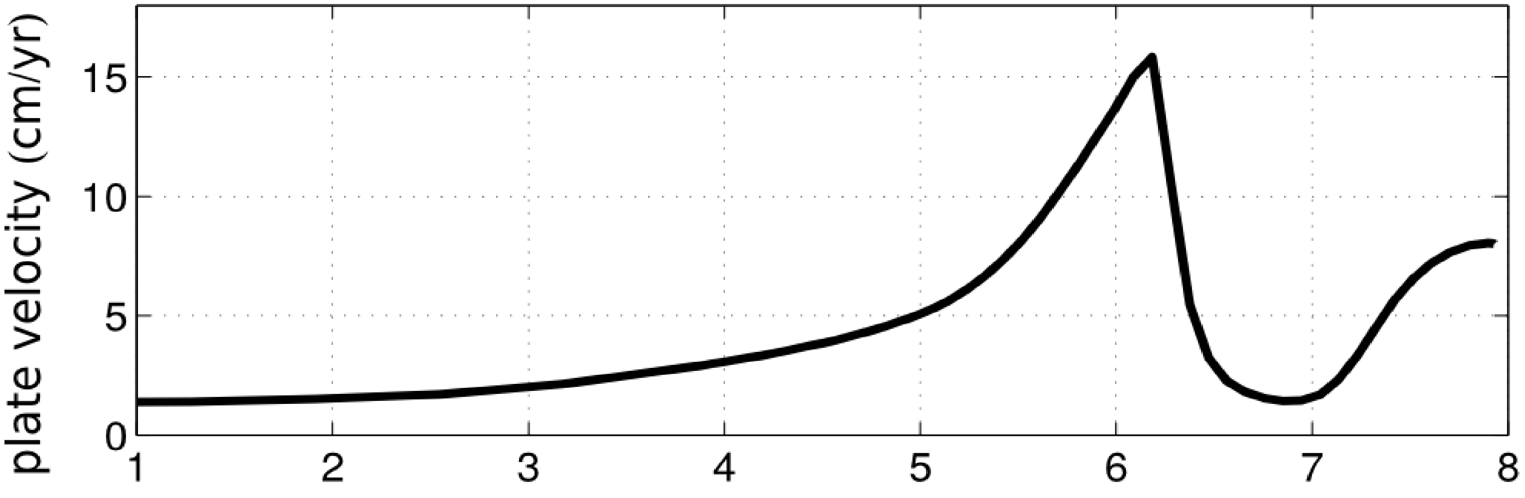


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8

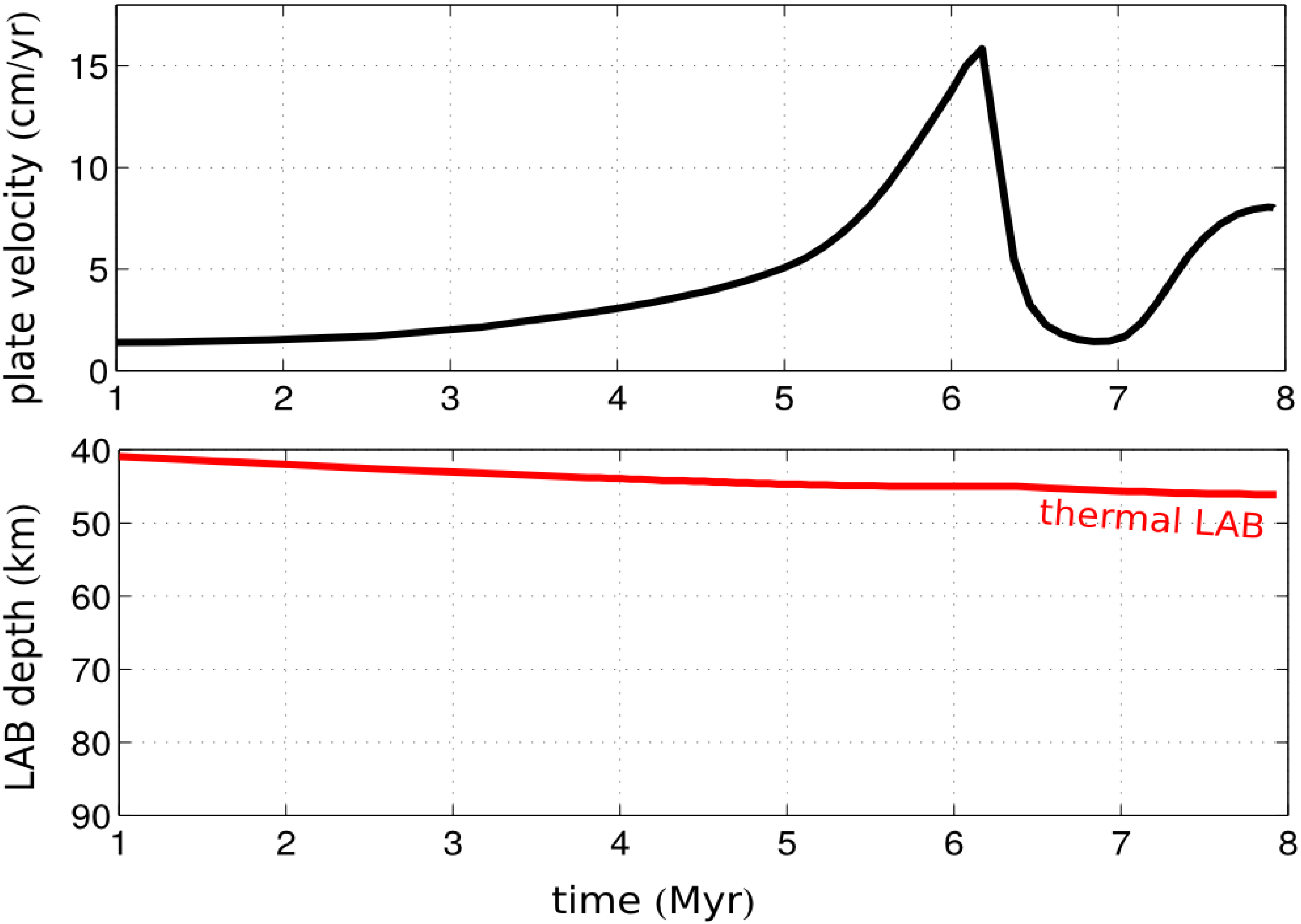
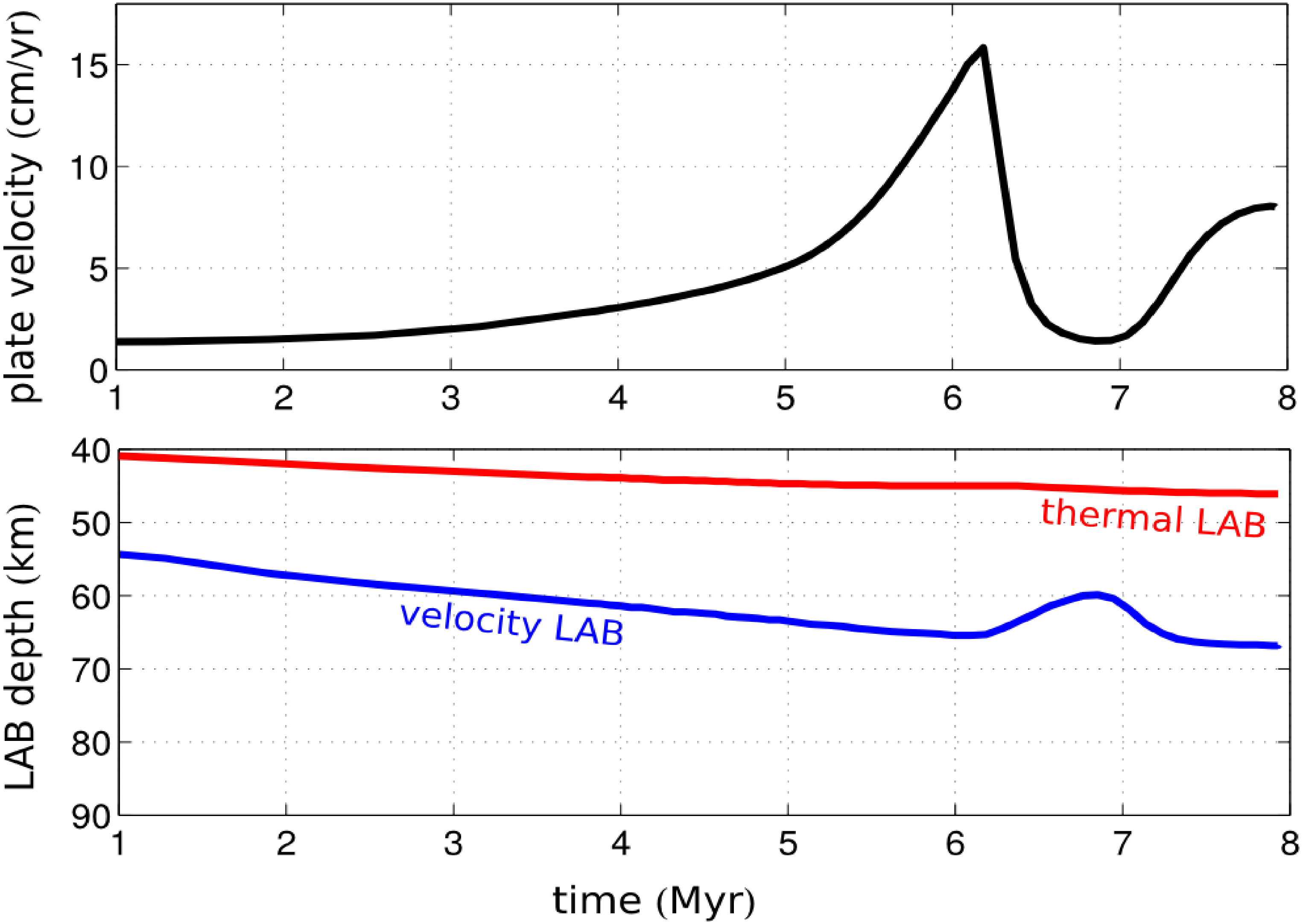


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8
LAB depth (km)
40
50
60
70
80
90
thermal LAB
1
2
3
4
5
6
7
8
time (Myr)



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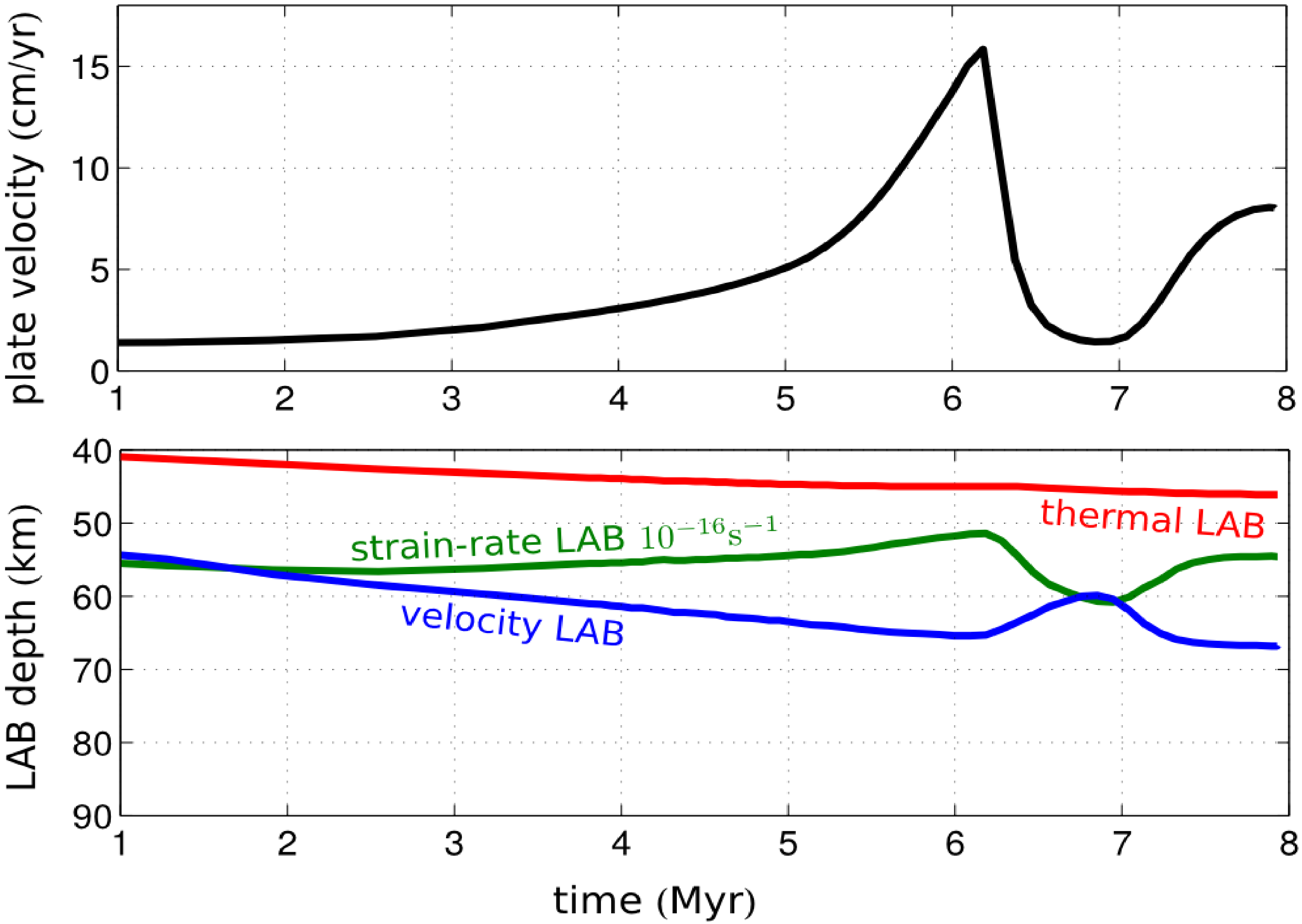
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thermal LAB
strain-rate LAB $10^{-16}s^{-1}$
velocity LAB
time (Myr)

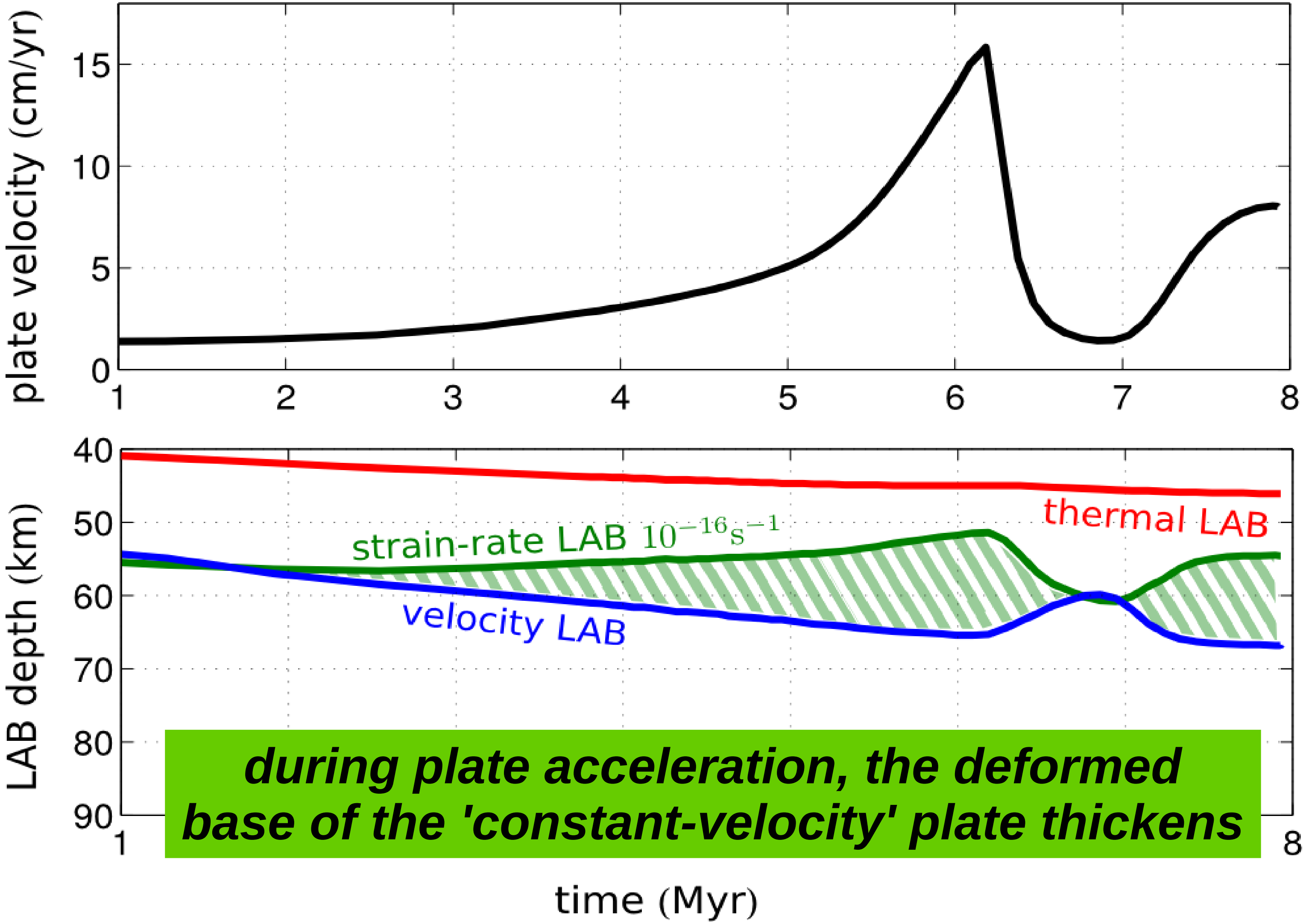
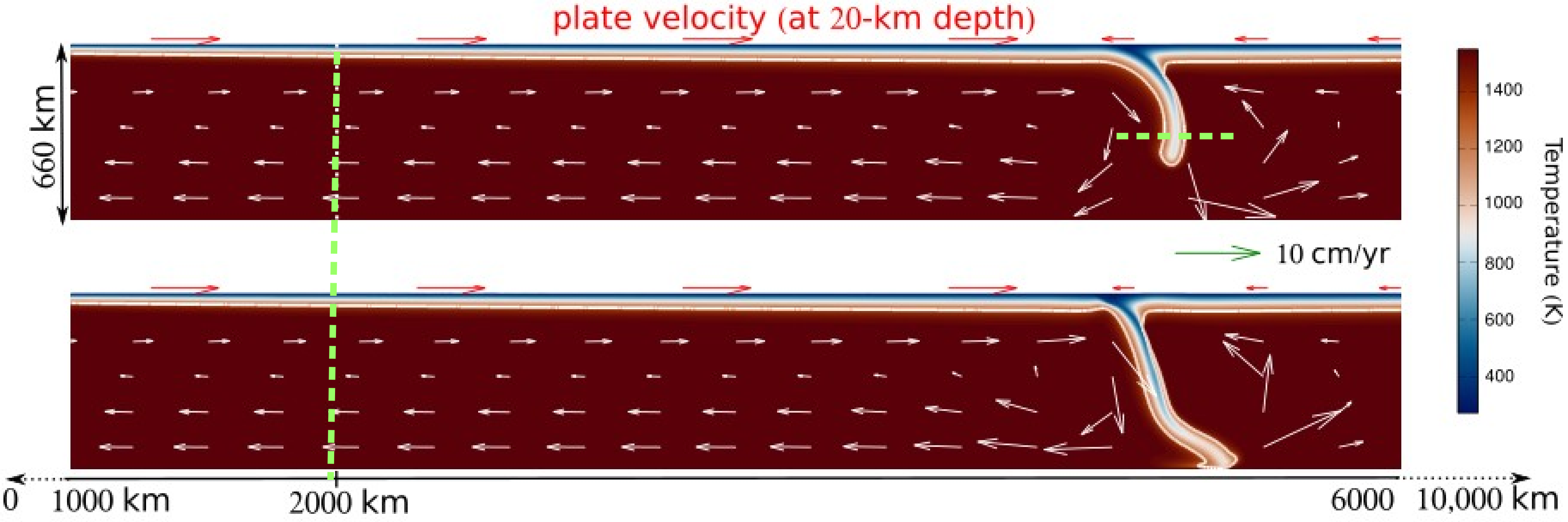


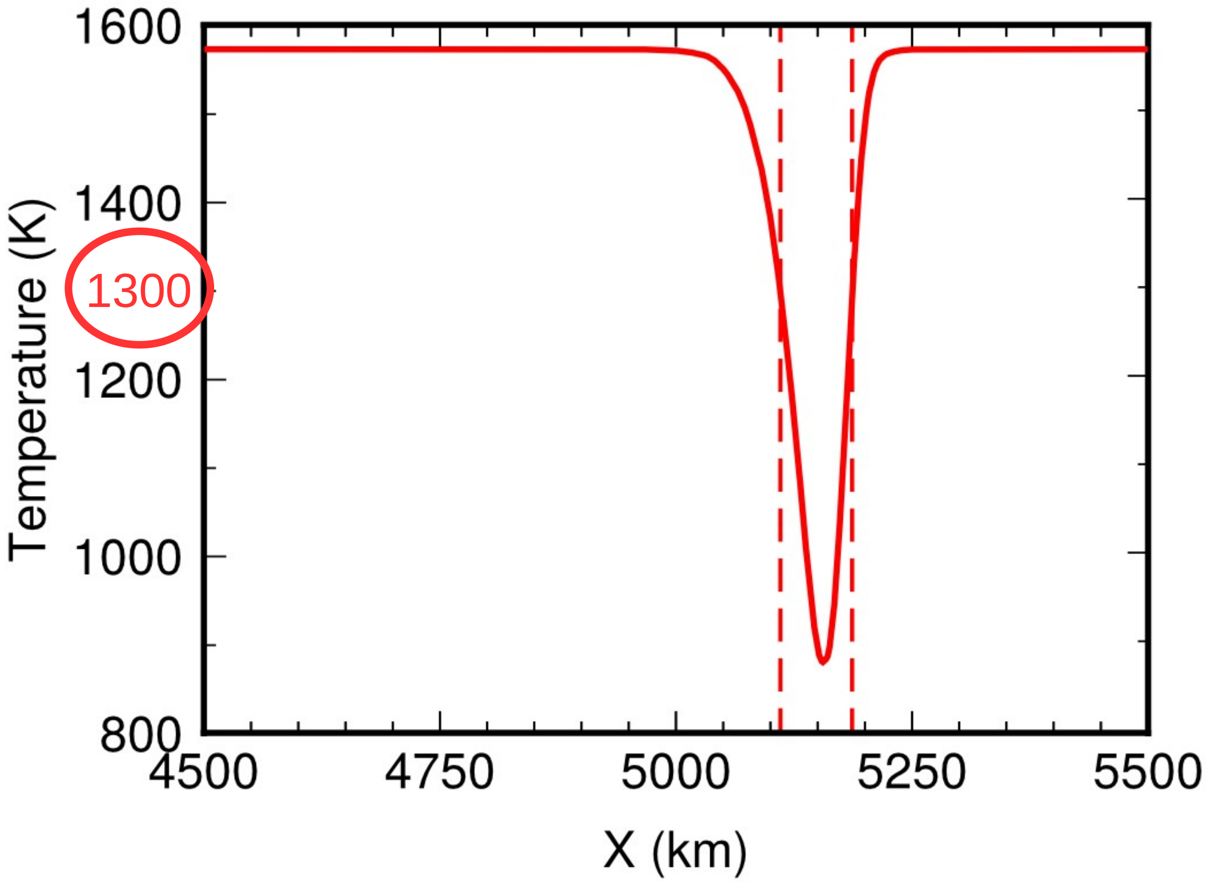
plate velocity (cm/yr)
15
10
5
0
1
2
3
4
5
6
7
8
LAB depth (km)
40
50
60
70
80
90
thermal LAB
strain-rate LAB $10^{-16}s^{-1}$
velocity LAB
during plate acceleration, the deformed base of the 'constant-velocity' plate thickens
time (Myr)

Transient asth. flow driven by subduction



Profile across the fast-sinking plate in the upper mantle

Transient asth. flow driven by subduction



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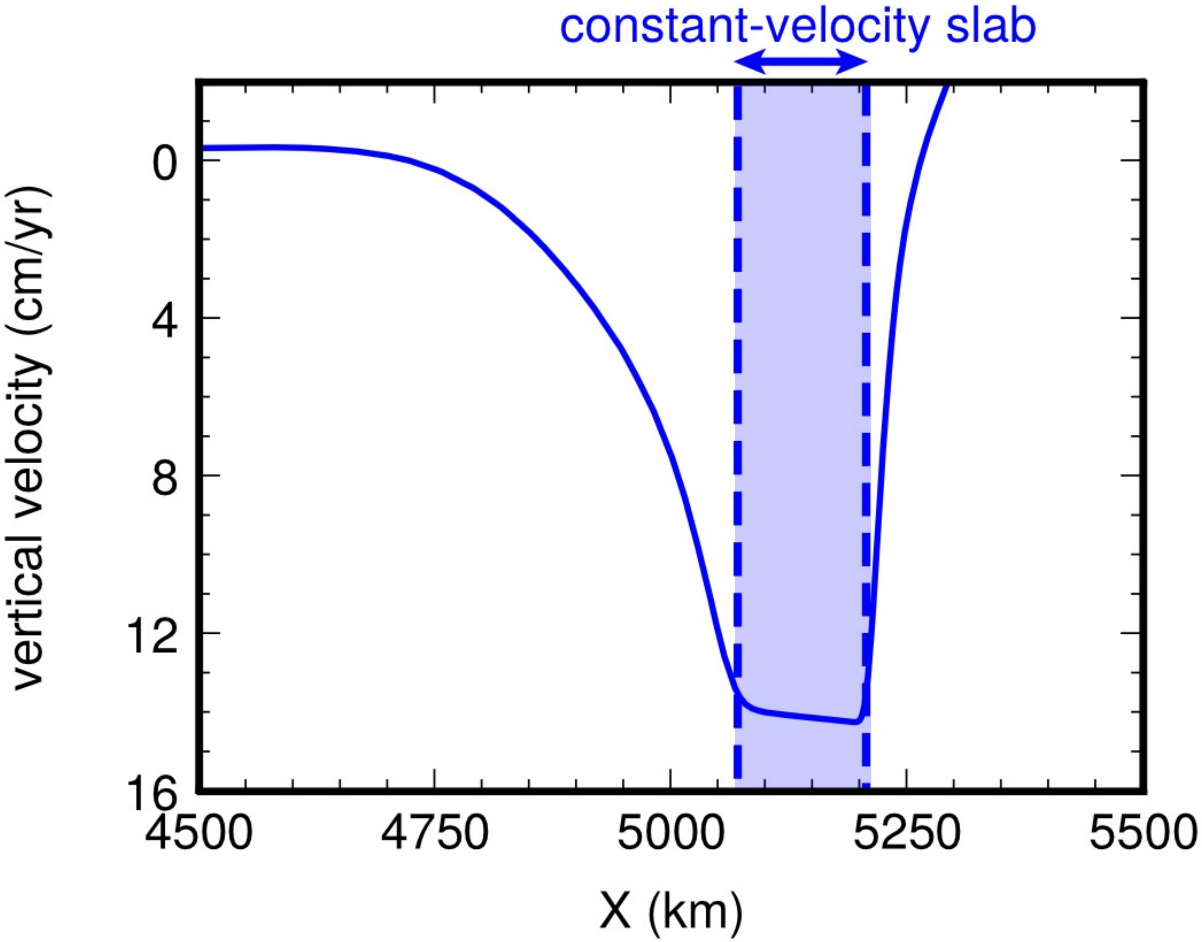

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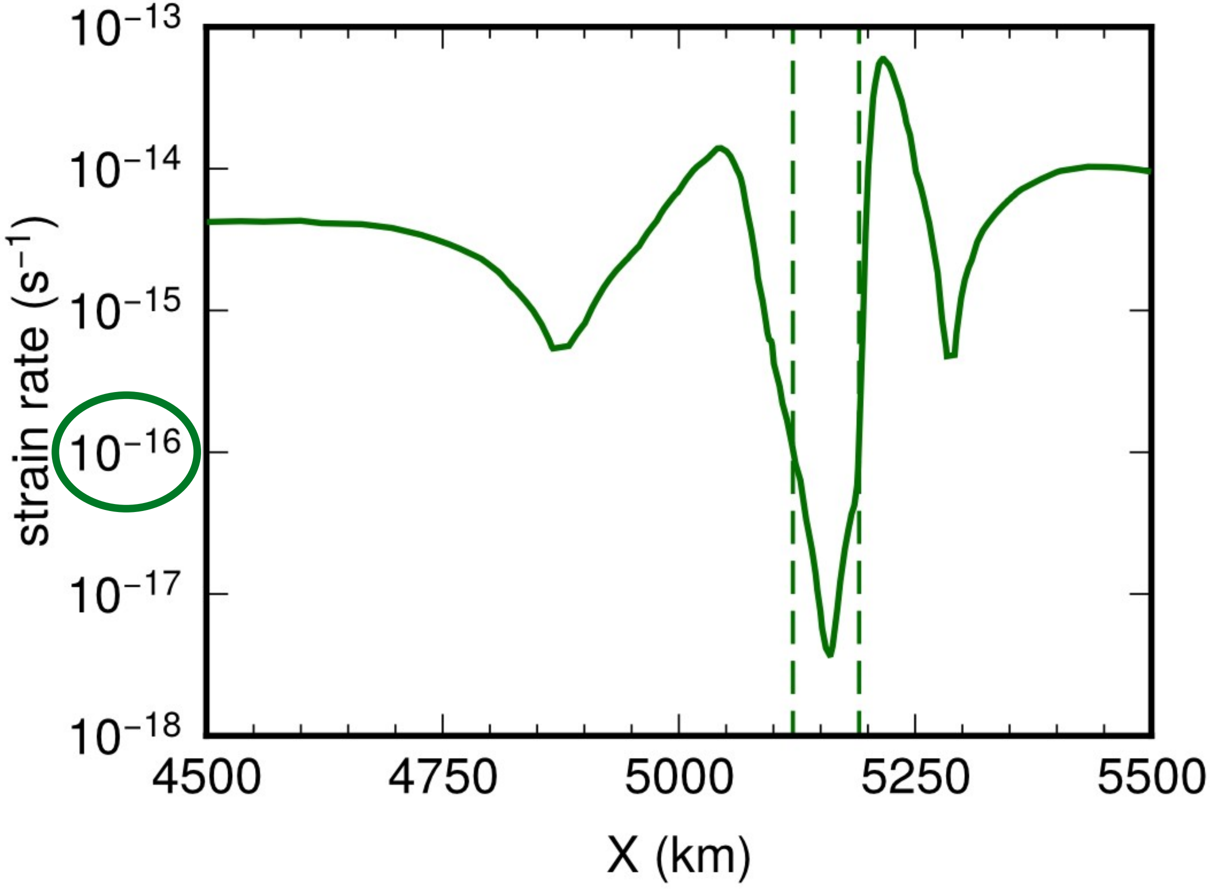

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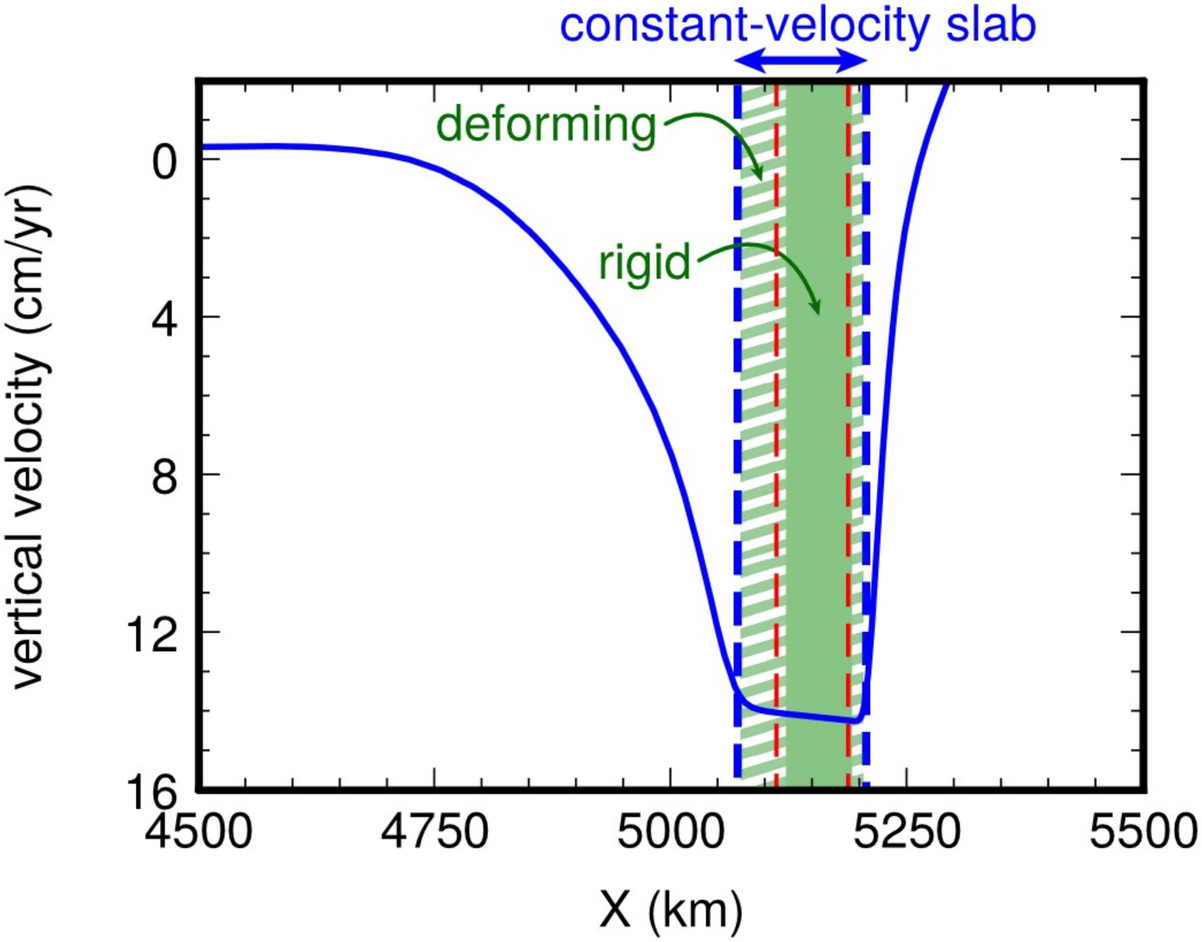

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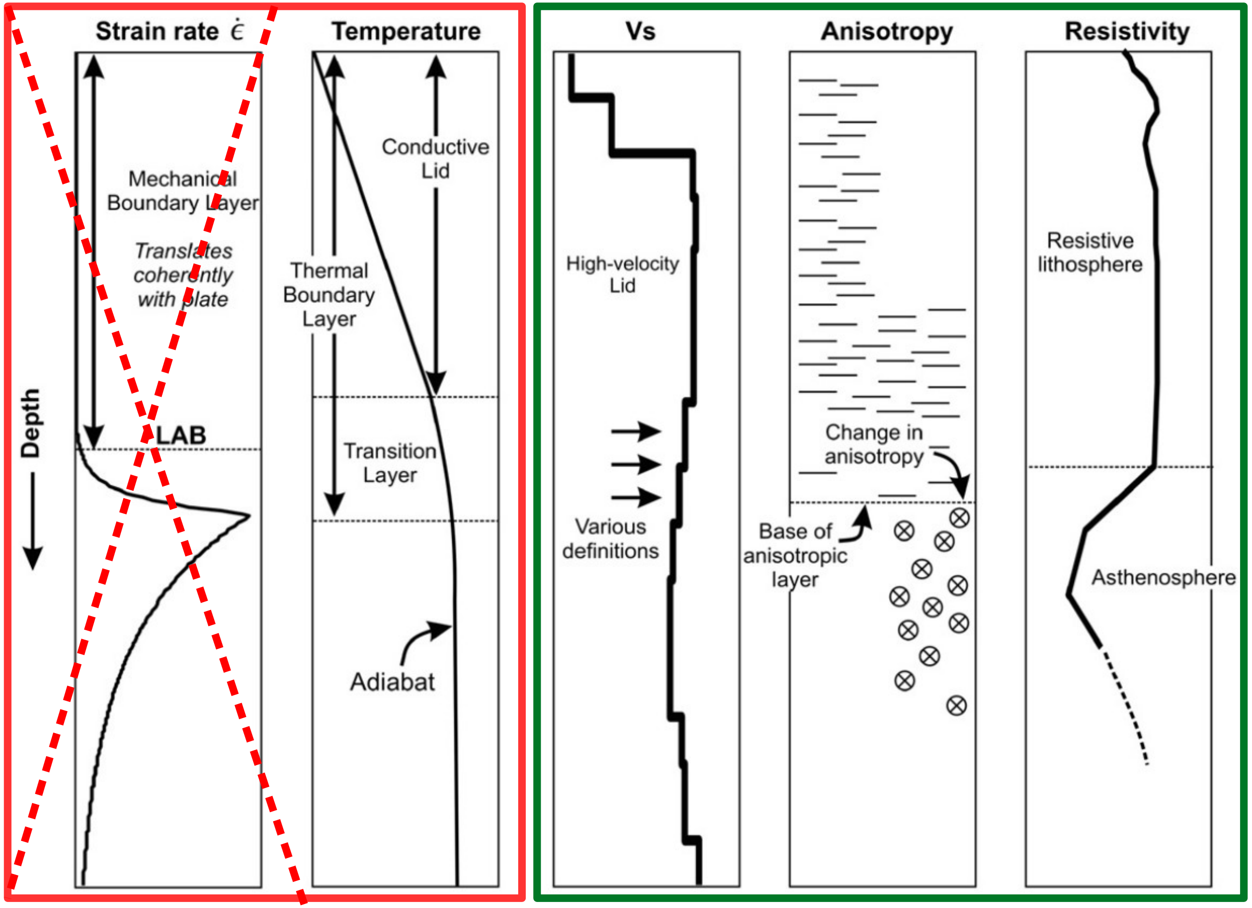
1. **Multiple definitions of lithospheric plates**

2. **Chasing a LAB in dynamical models**

3. **<u>Geophysical proxieS of an elusive LAB</u>**

Is the plate concept still relevant ?

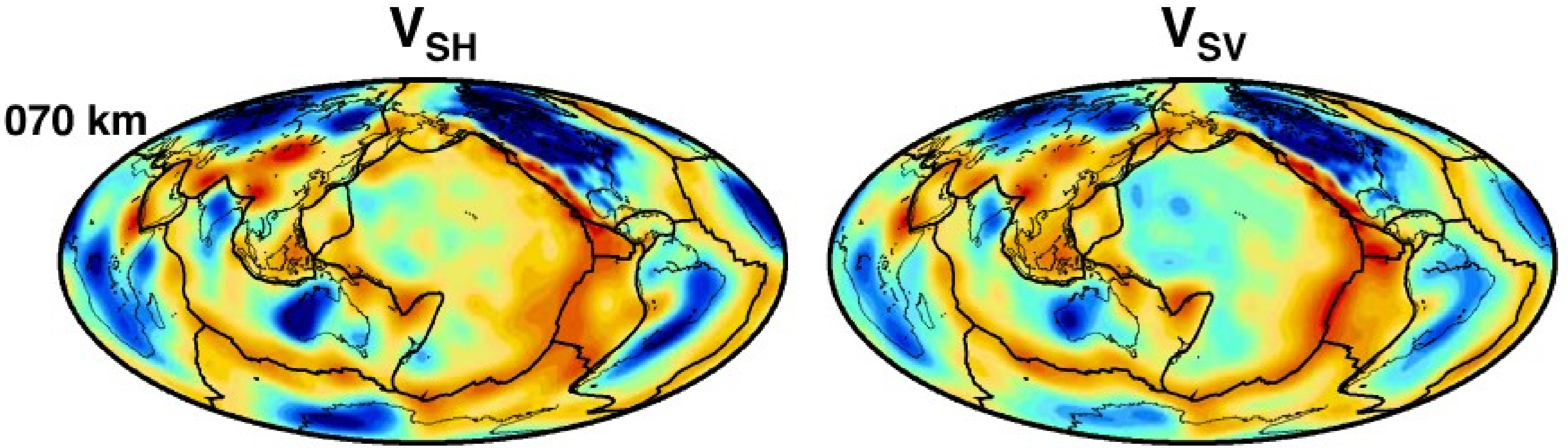
Geophysical proxies cannot directly provide thermo-mechanical profiles



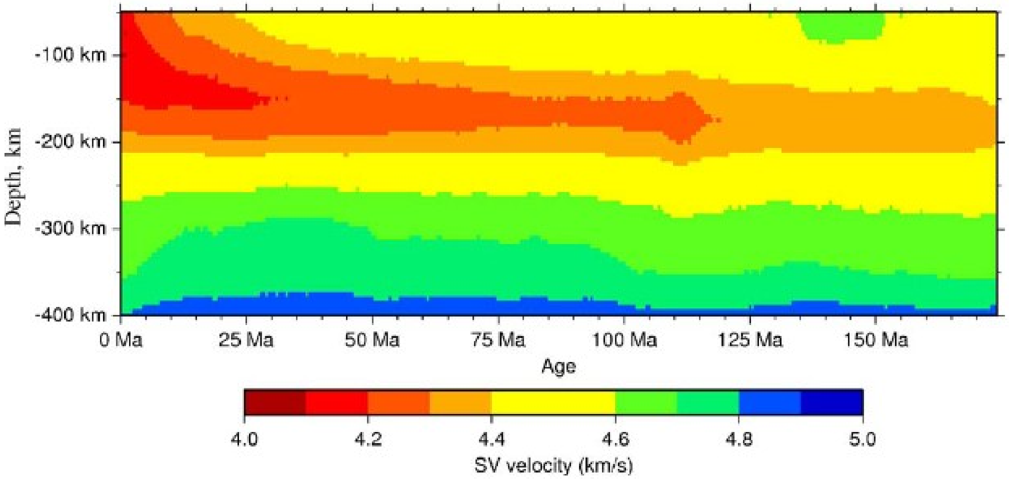
e.g. the seismic
Low Velocity Zone
is NOT necessarily
a "Low Viscosity Zone"
(not the same time-scale
of deformation)

Eaton et al., 2009

Shear-wave velocities, LVZ and thermal LAB

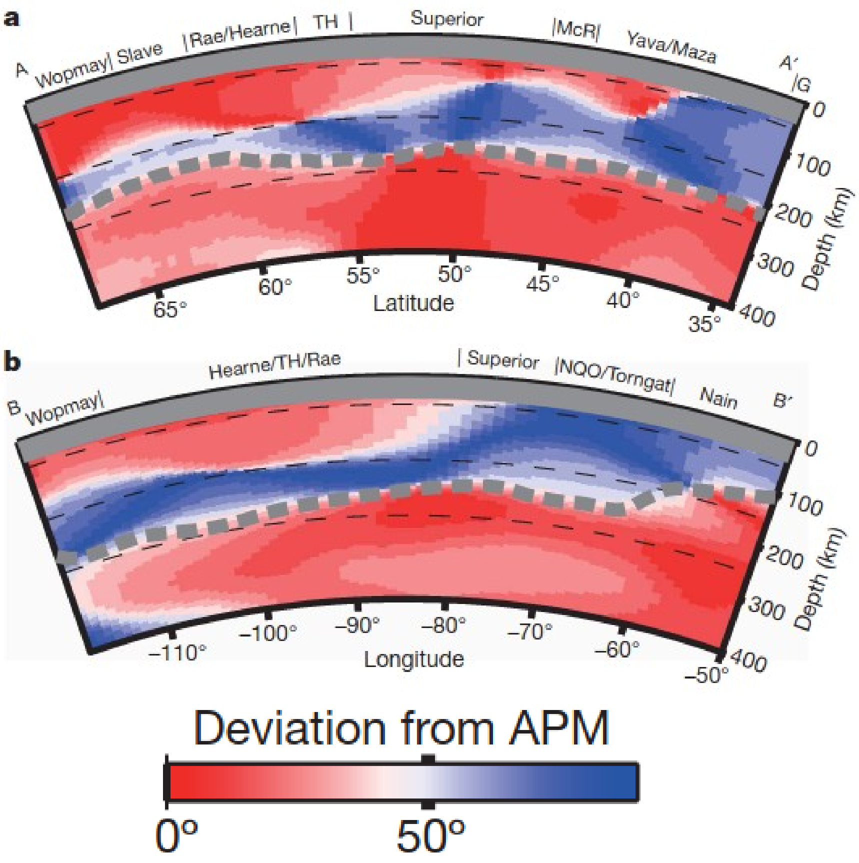


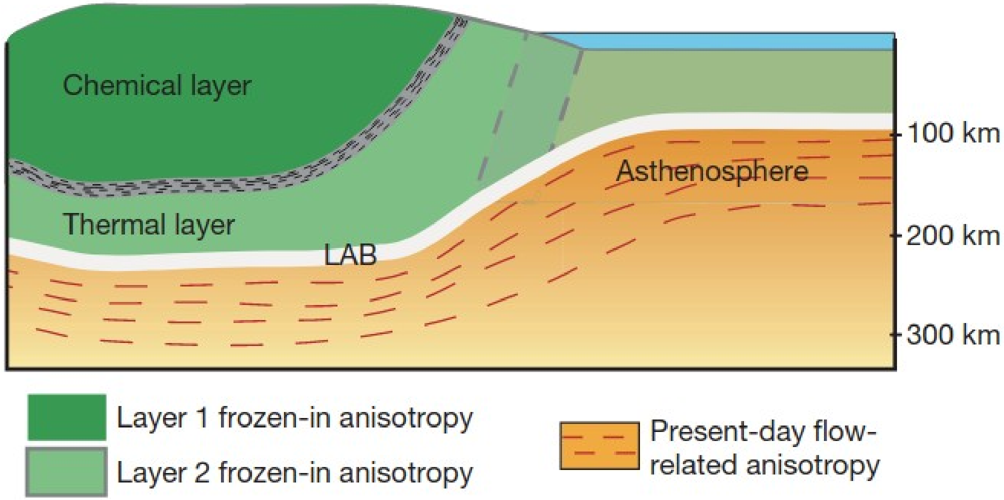
Nettles & Dziewonski, 2008



Priestely & McKenzie, 2006

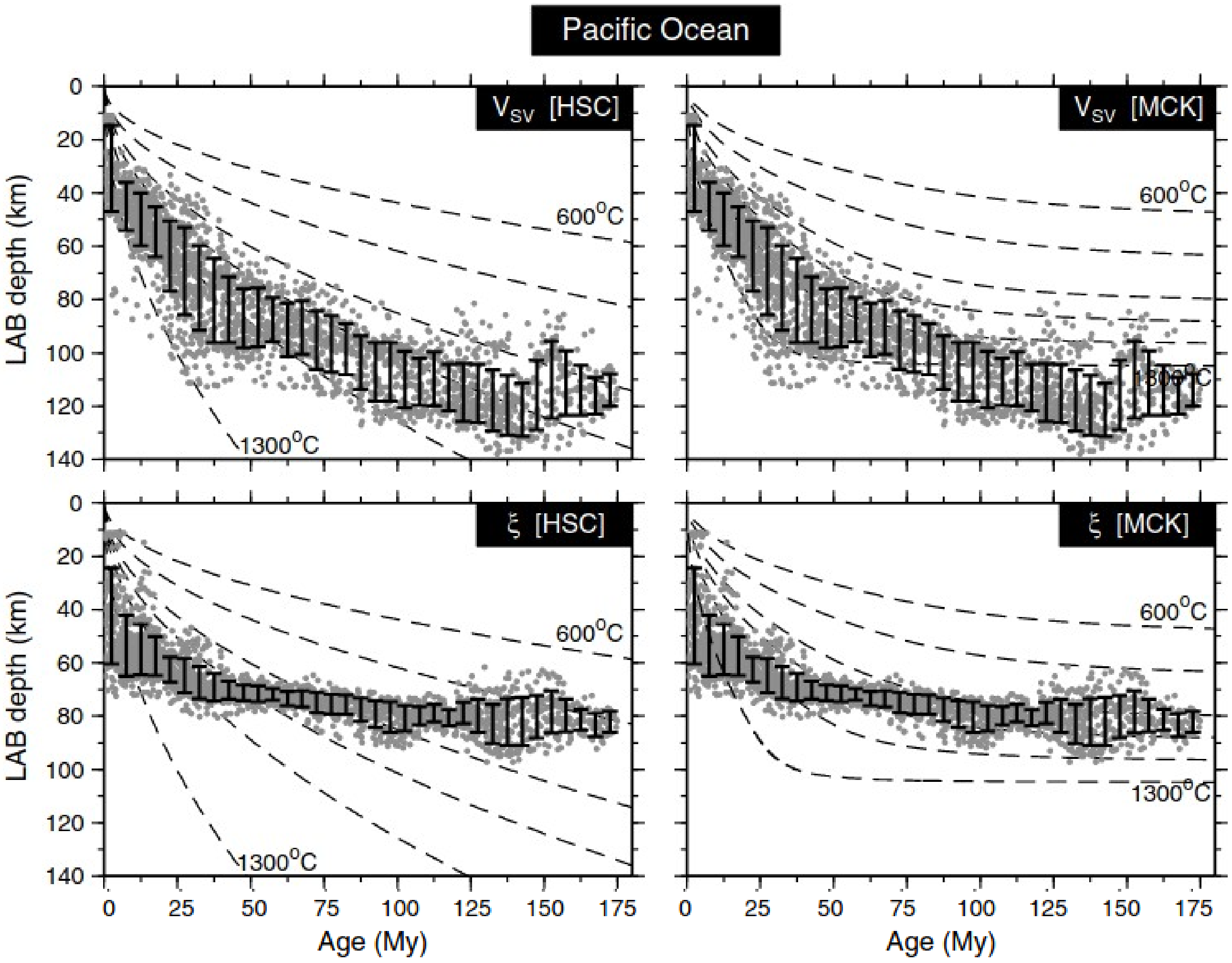
Mid-lithospheric discontinuity and asynchronous formation of anisotropy signal at different depths





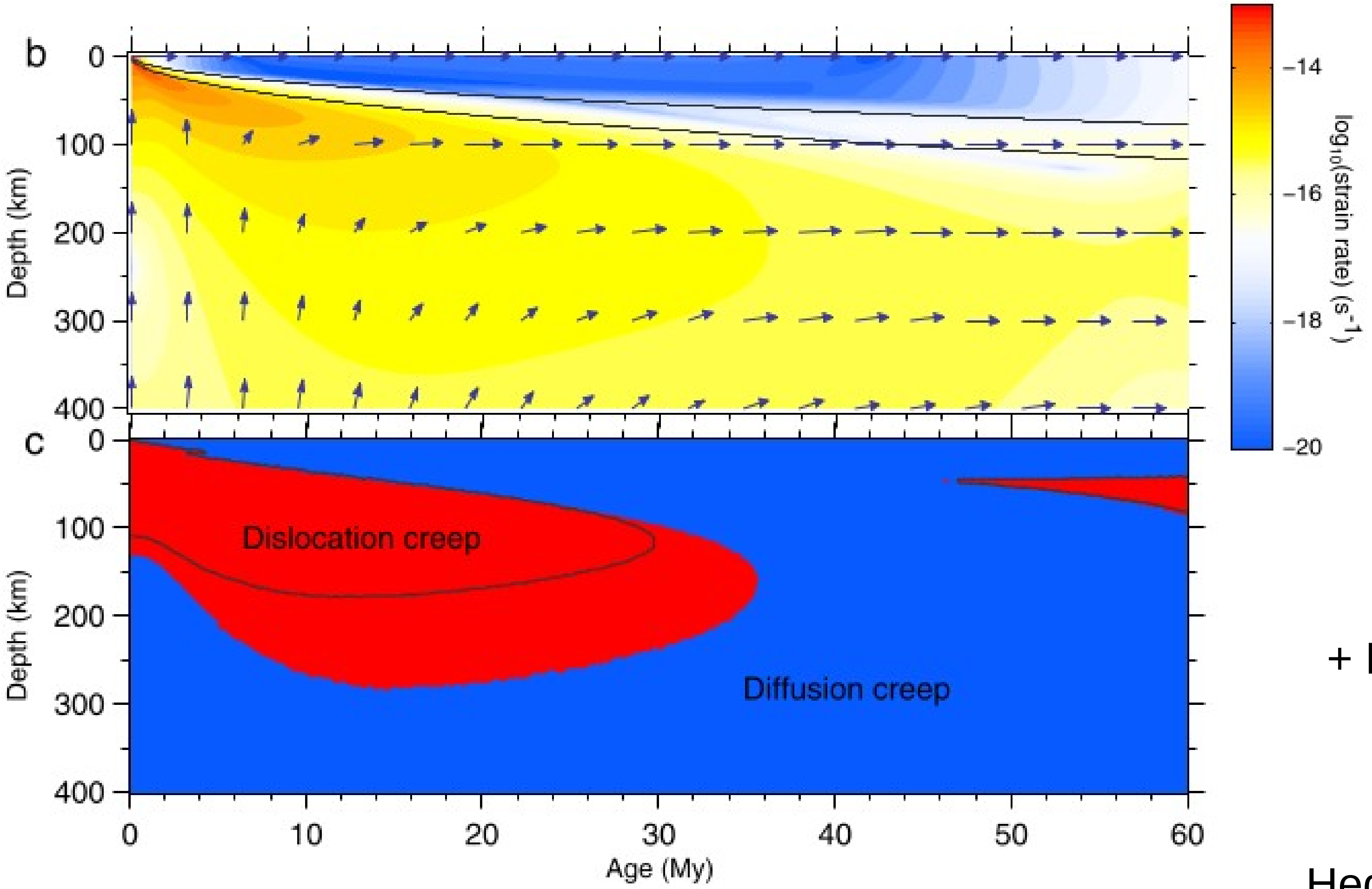
Yuan & Romanowicz, 2010

Age-independent radial seismic anisotropy



Burgos et al., 2014

Age-independent radial seismic anisotropy

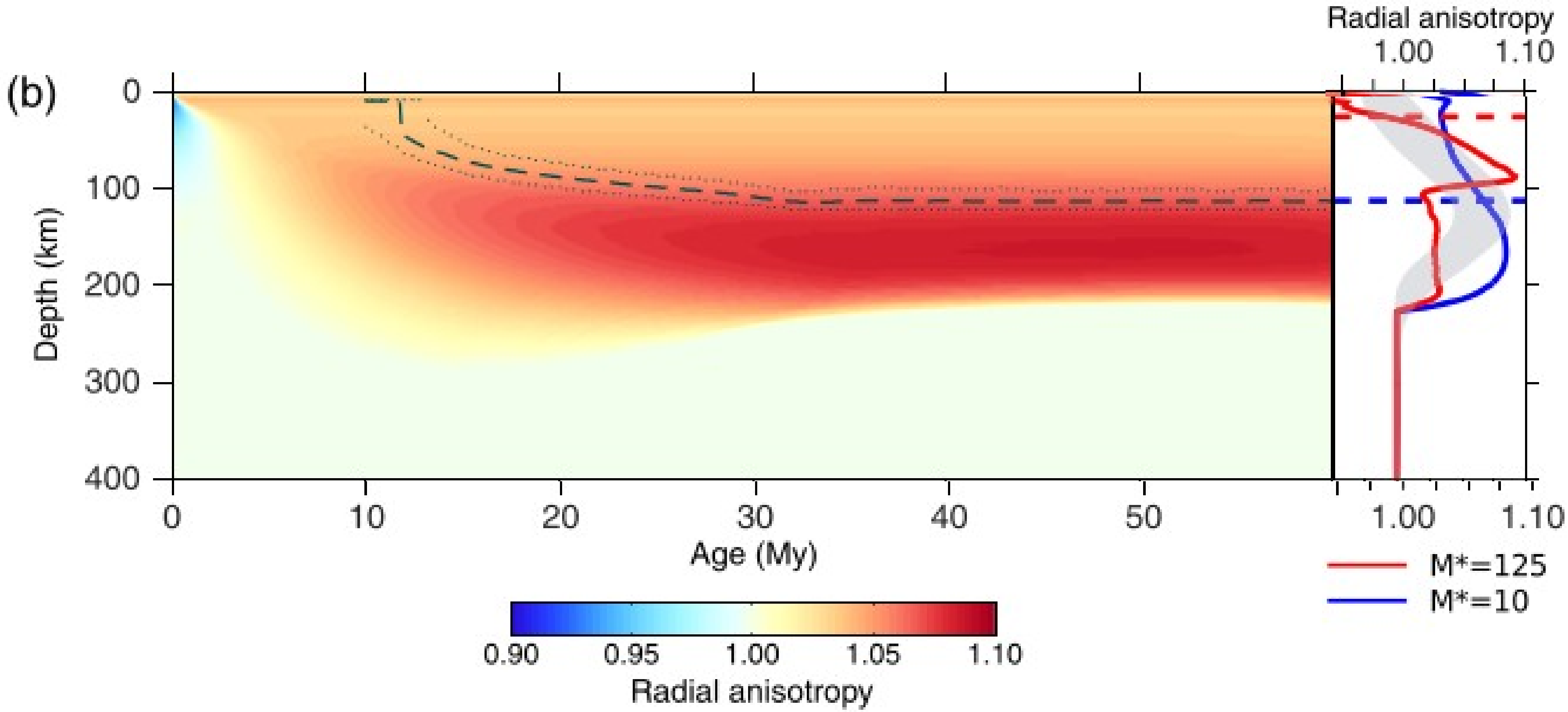


Flow model
below a plate

+ D-Rex calculation
of anisotropy

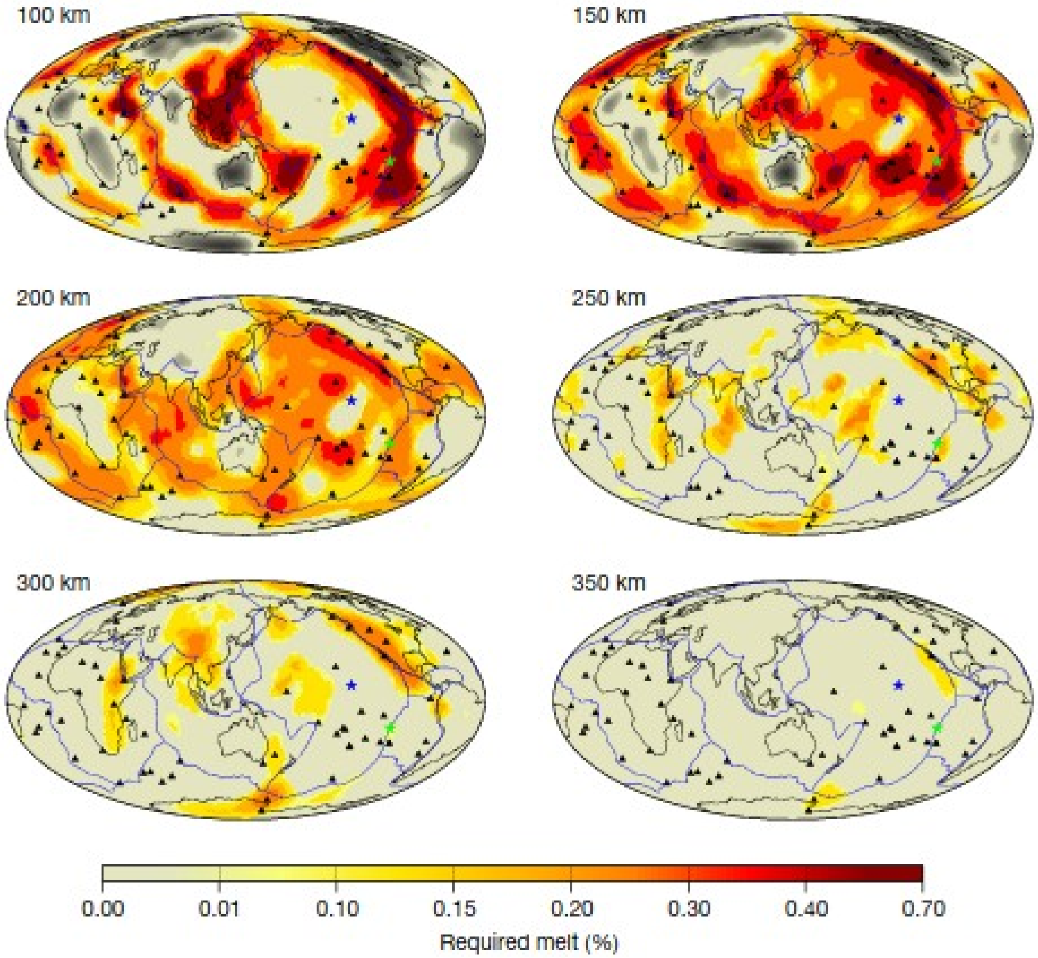
Hedjazian et al., 2017

Age-independent radial seismic anisotropy



Hedjazian et al., 2017

Partial-melt layer below oceanic plates ?

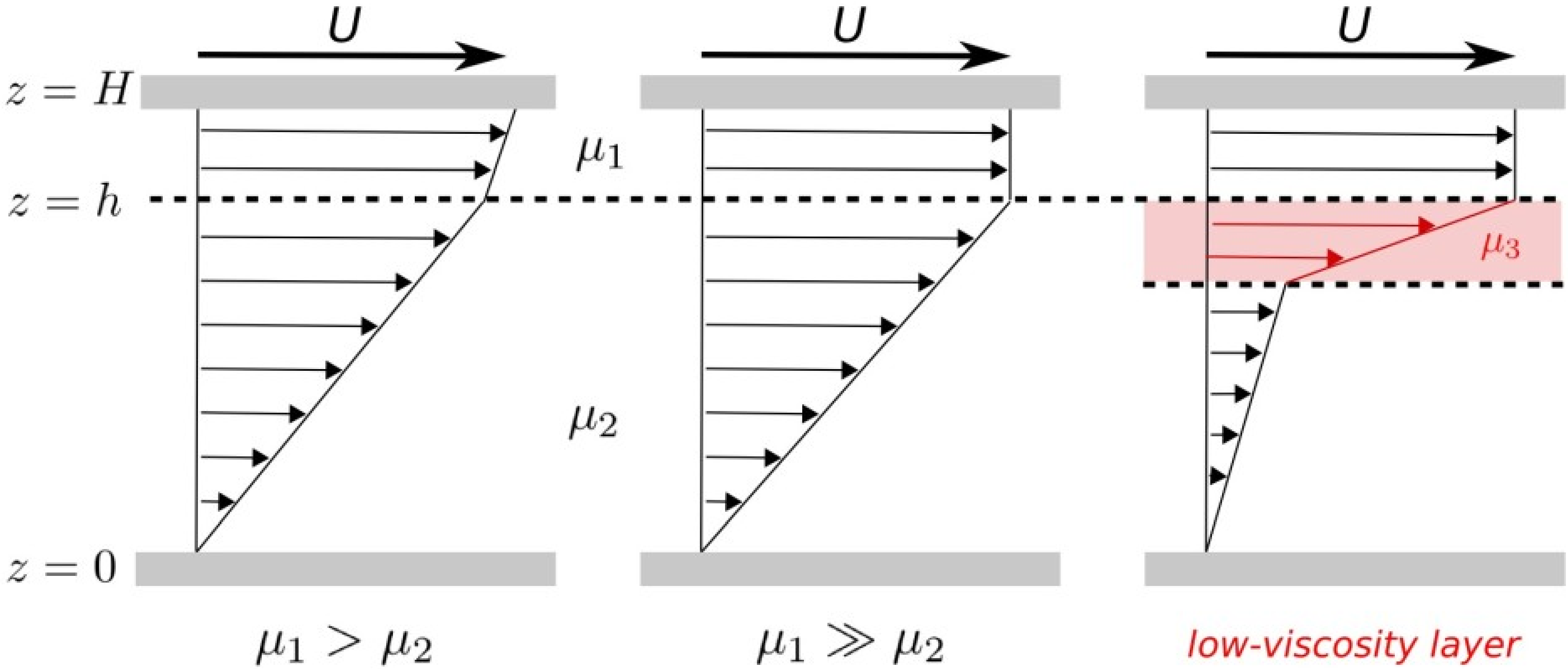


→ low-viscosity layer below the oceanic plates ?

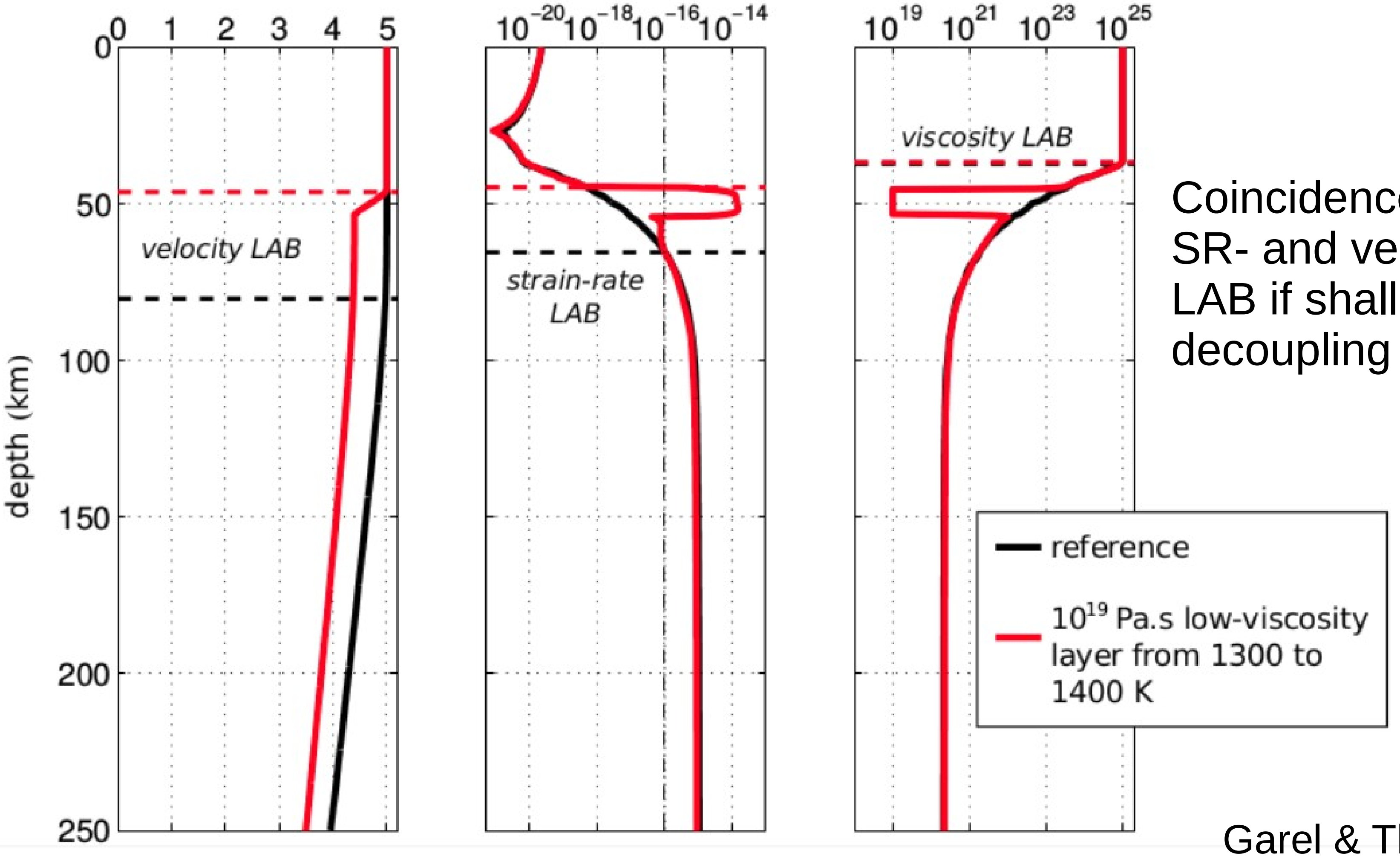
other origins for this weak layer : increase in temperature + pressure, grain size variation

Debayle et al., 2020

Partial decoupling with a low-viscosity layer



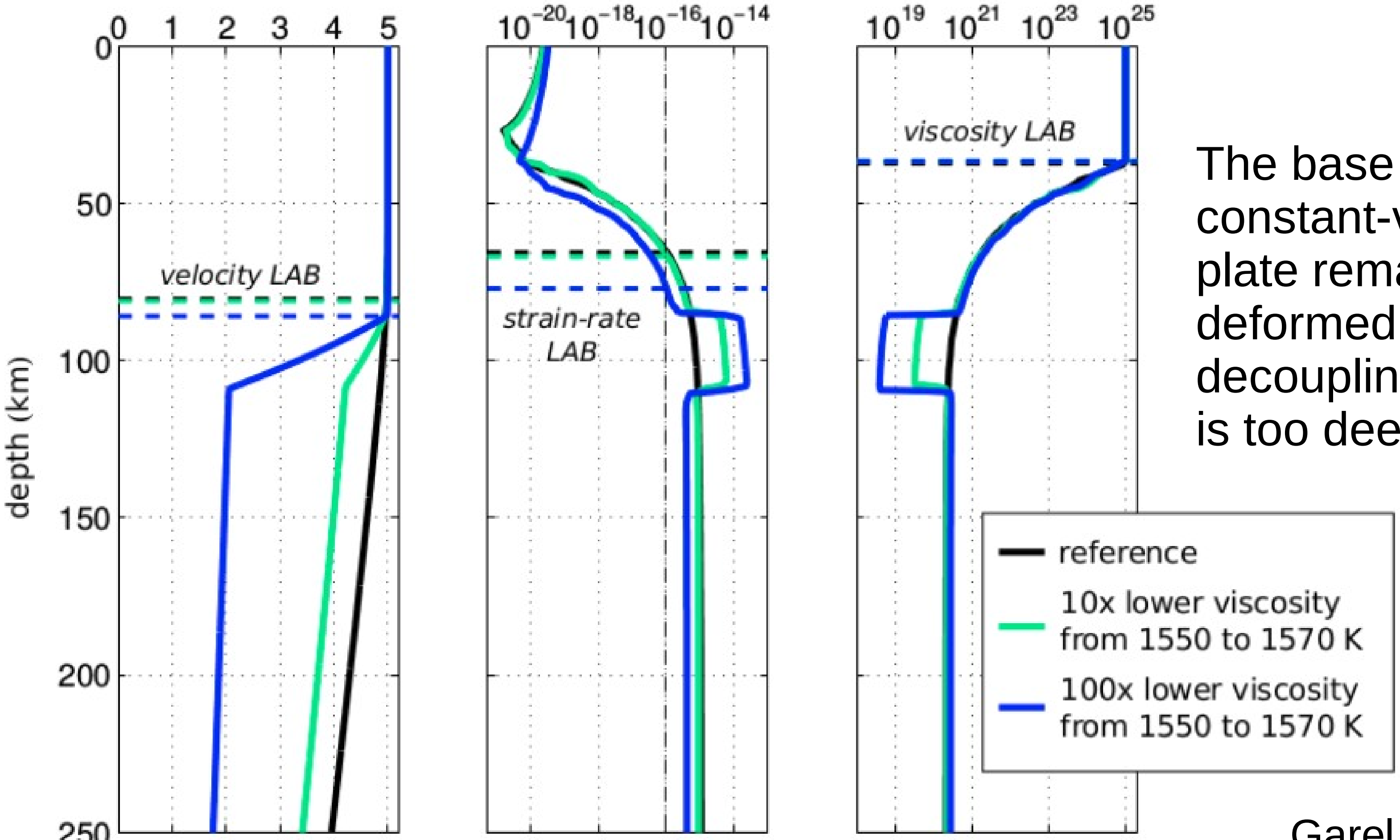
Partial decoupling with a low-viscosity layer



Coincidence of SR- and velocity-LAB if shallow decoupling

Garel & Thoraval, 2021

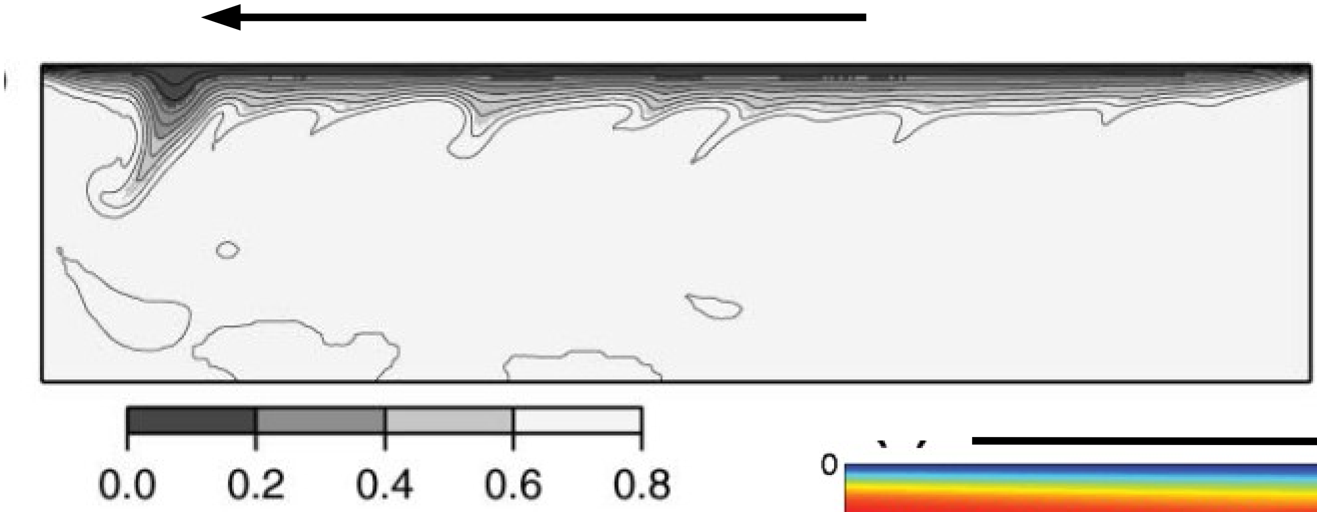
Partial decoupling with a low-viscosity layer



The base of the constant-velocity plate remains deformed if the decoupling layer is too deep

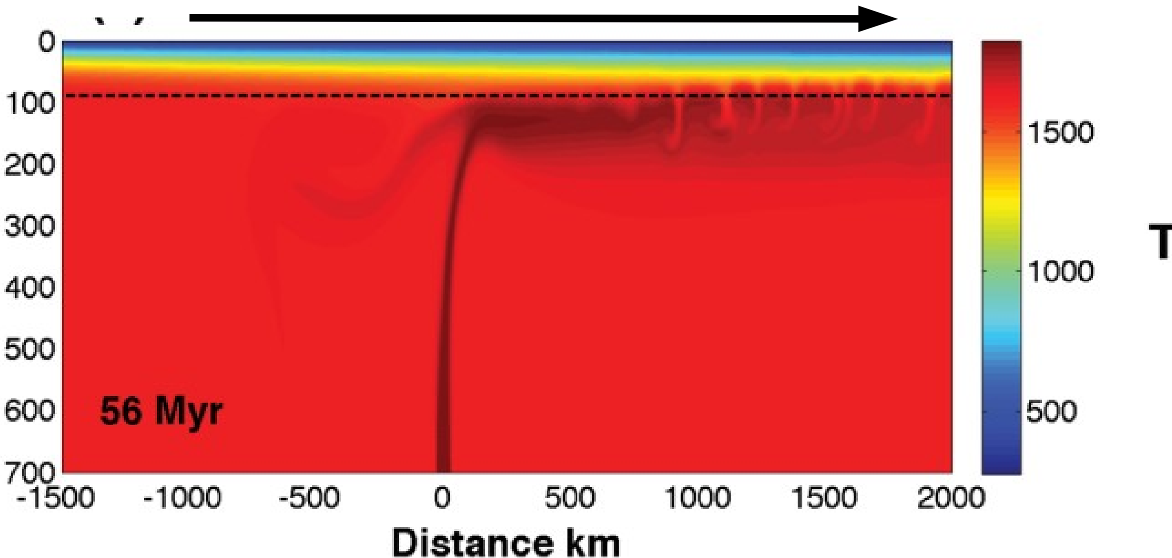
Garel & Thoraval, 2021

Coupling even in the case of small-scale convection ?



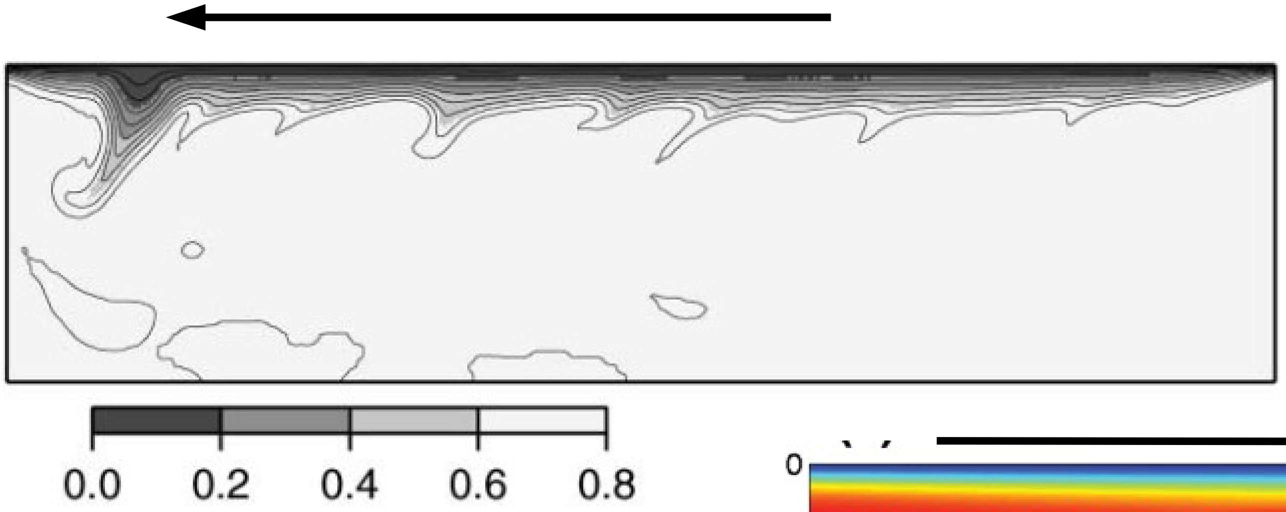
Dumoulin et al., 2001

Shallowing of both T-LAB and SR-LAB ?



Agrusta et al., 2013

Coupling even in the case of small-scale convection ?



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Shallowing of both T-LAB and SR-LAB ?

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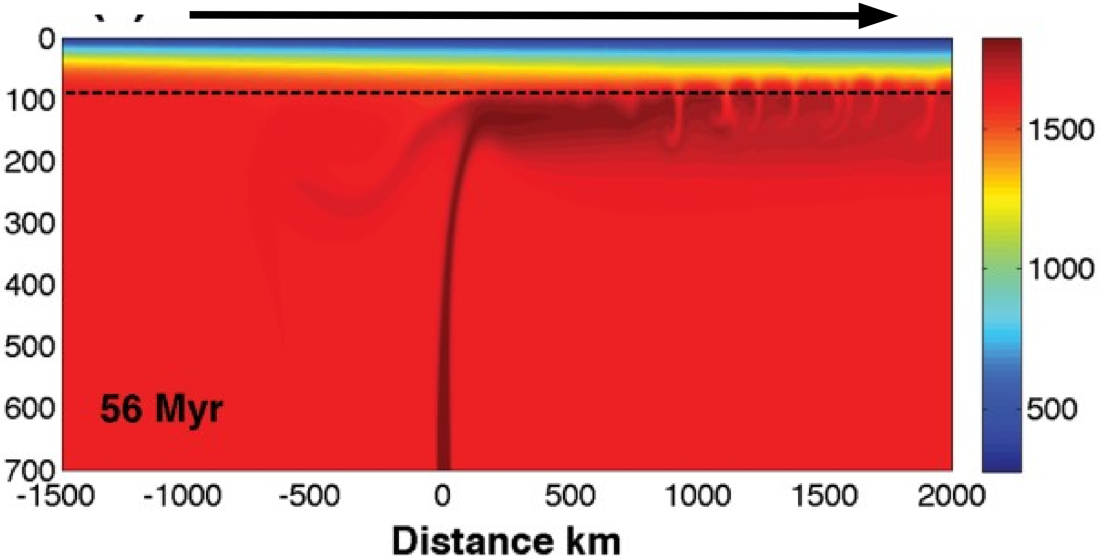


What is a plate ?

Plate tectonics vs. tectonic plate

1. Multiple definitions of lithospheric plates

2. Chasing a LAB in dynamical models

3. Geophysical proxieS of an elusive LAB

Is the plate concept still relevant ?

Conclusion

- From viscous dynamical models in temp- and SR-dep viscosity :

→ no sharp changes in thermo-mechanical fields

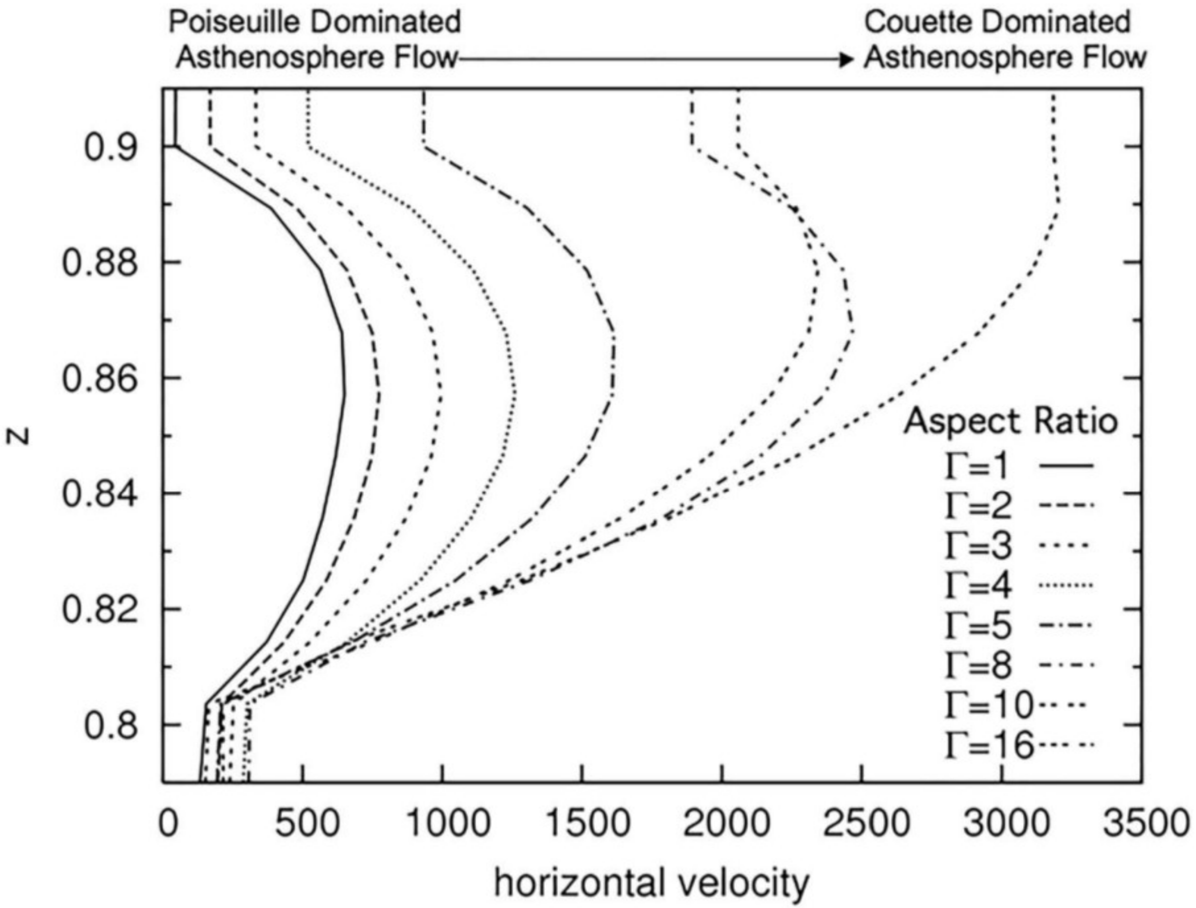
→ a layer moving coherently arises self-consistently = **'constant-velocity' plate**

- 1^{st} order :
cold > highly viscous > constant-velocity

BUT the constant-velocity plate
- is **not fully rigid** and deforms at its base
- is **transient** and adjusts to flow field evolution

Transition rather than shar boundary
between lithosphere and asthenosphere ?

Constant-velocity plate
also observed for 'active' asthenosphere flow



Hoink and Lenardic, 2010
Richards and Lenardic, 2018

No single thermo-mechanical definition of a plate
> is the concept still relevant ?

- thermal boundary layer leads to velocity transition
  depending on… rheology !

- rheological transition at the base of the plate
  > key to the formation of new plate boundary
  > key for coupling between deep and surface motions

- for mass transfers in the convective mantle
  > dragged mantle rather than the sole cold slab motion

- various proxies are not expected to locate the same transition
  (+ variation in space and time)