Chasing the lithosphere-asthenosphere transition in dynamical models of the Earth's mantle

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Workshop "**Global Scale Seismic Imaging and Dynamics of the Earth's Mantle**"
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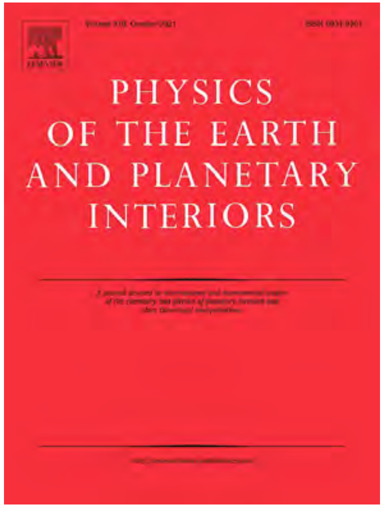


PEPI special issue 20-21

Physical properties and observations of the lithosphere-asthenosphere system

Editors : Rick Aster, Saskia Goes, Derek Schutt

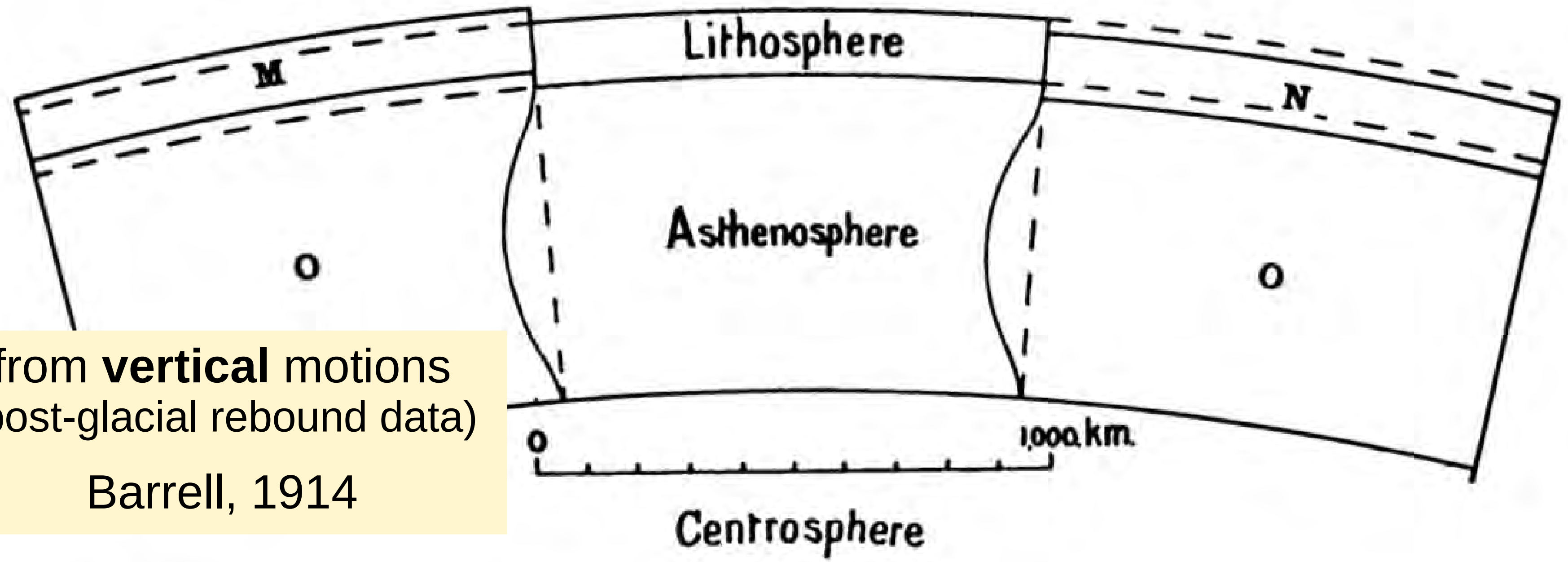
Strong “lithosphere” vs. soft “asthenosphere”

LITHOSPHERE

rigid layer
(crust + uppermost mantle)

ASTHENOSPHERE

relatively “softer” mantle layer

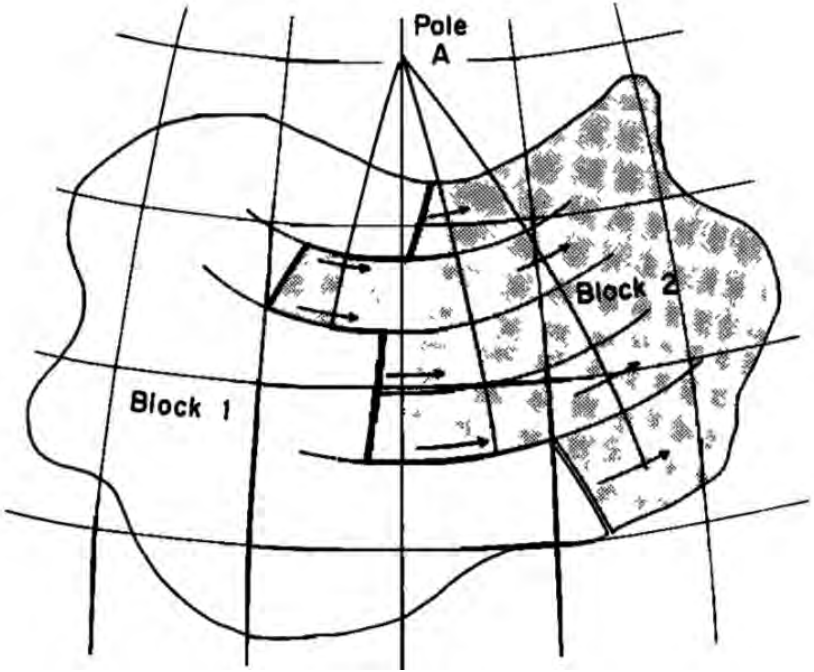


from **vertical** motions
(post-glacial rebound data)

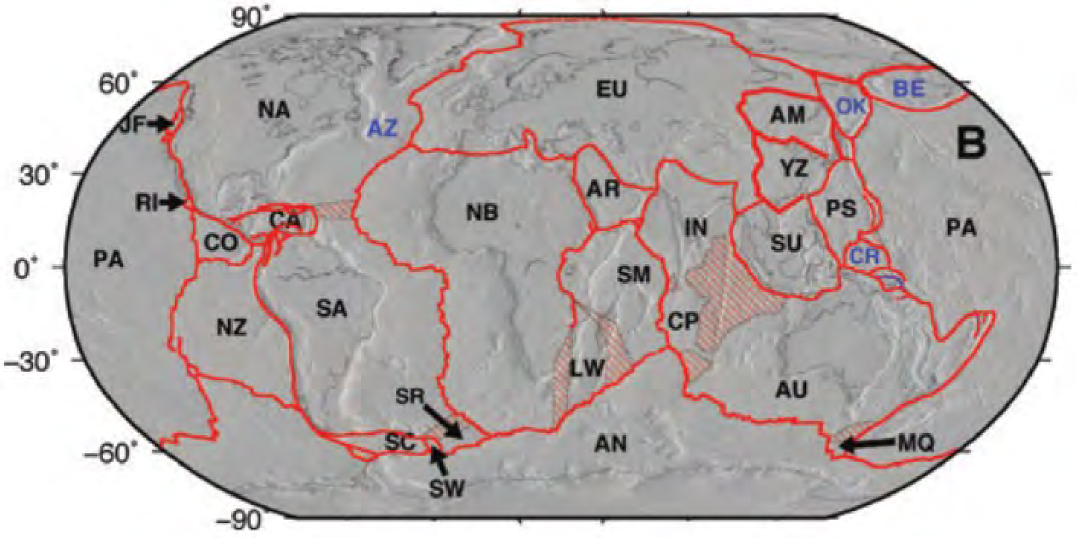
Barrell, 1914

Plate tectonics' theory : lithosphere ≡ dynamic plate

rigid blocks moving horizontally (2-D) at the surface of the Earth's sphere
(no reference to asthenosphere)



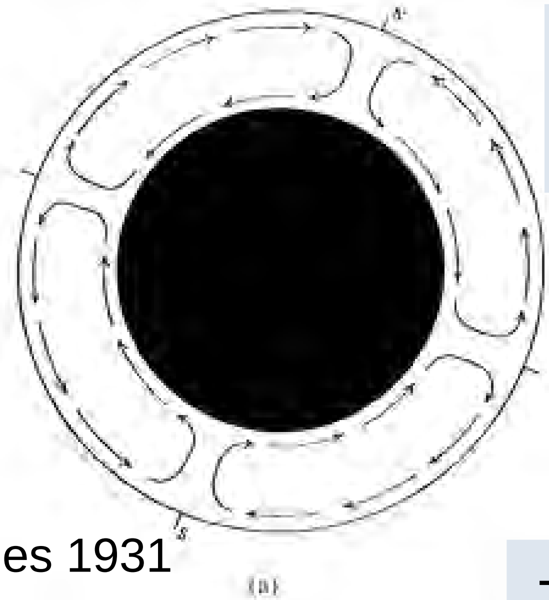
Morgan, 1968



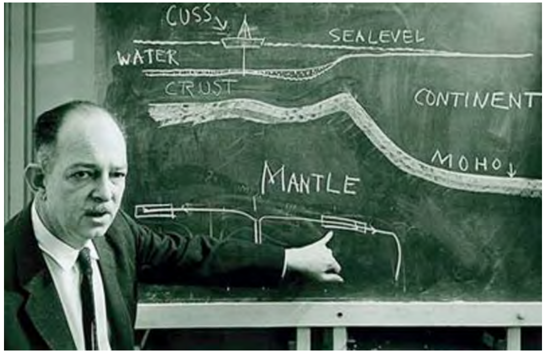
25 plates' model MORVEL (DeMets et al., 2010)

Cold lithosphere vs. hot asthenosphere

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

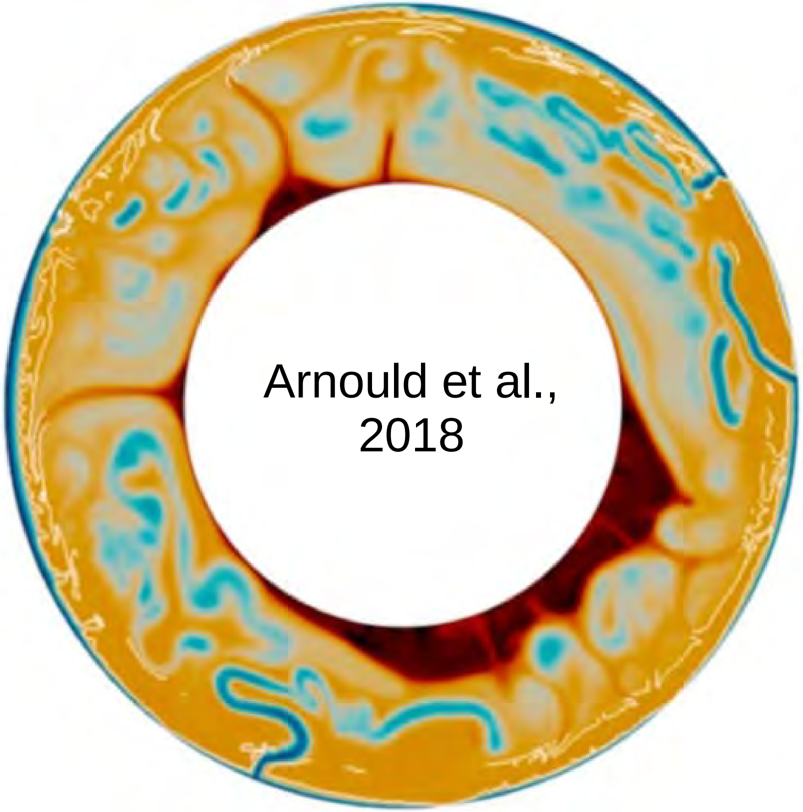


Holmes 1931



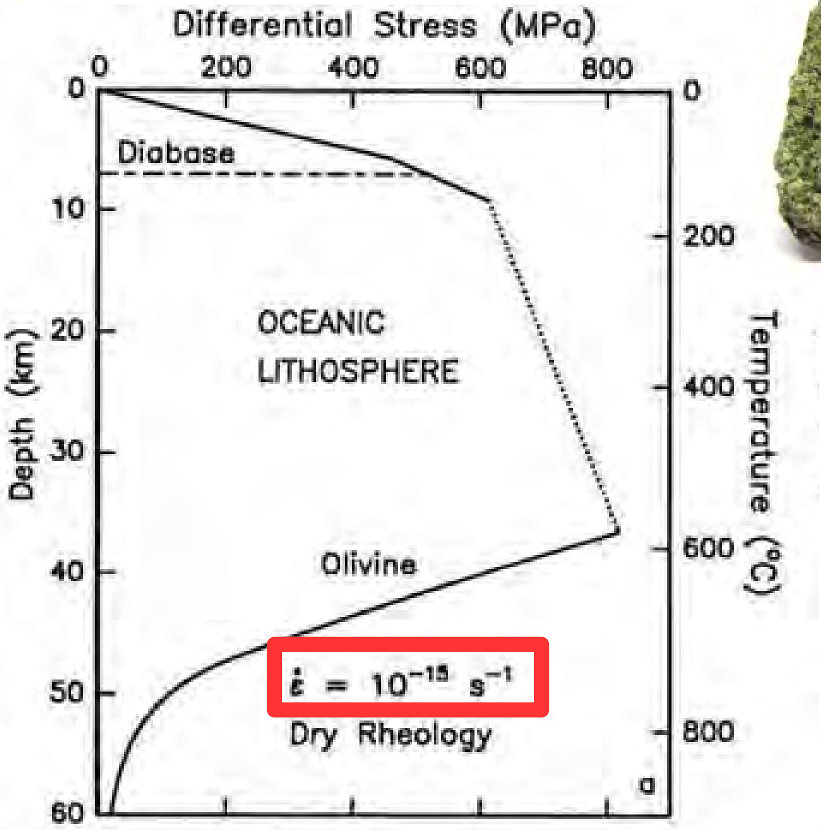
Hess, 1962

+ lithospheric plates sinking in the mantle

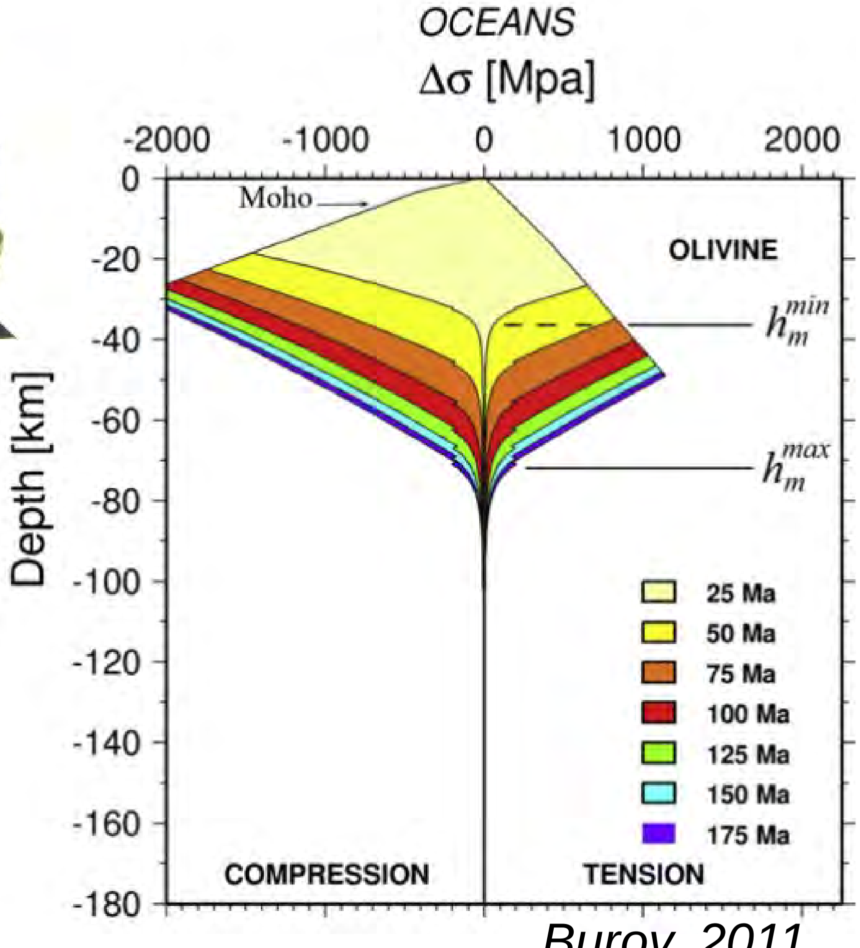


Arnould et al., 2018

Temperature-dependence of strength and viscosity : same peridotite either cold/strong or hot/weak ?



Kohlstedt et al., 1995



Burov, 2011

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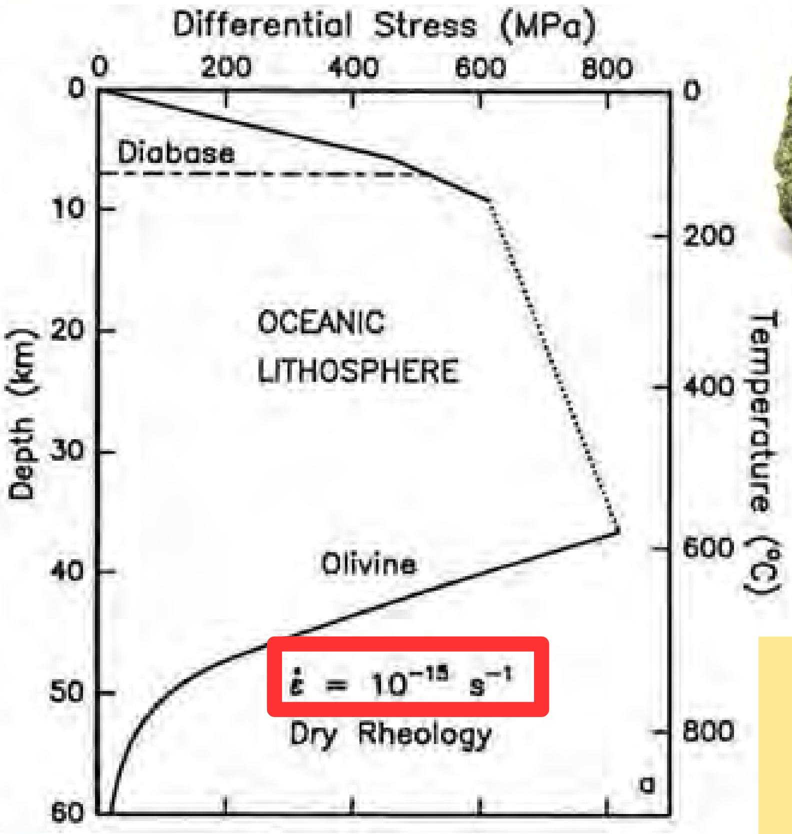
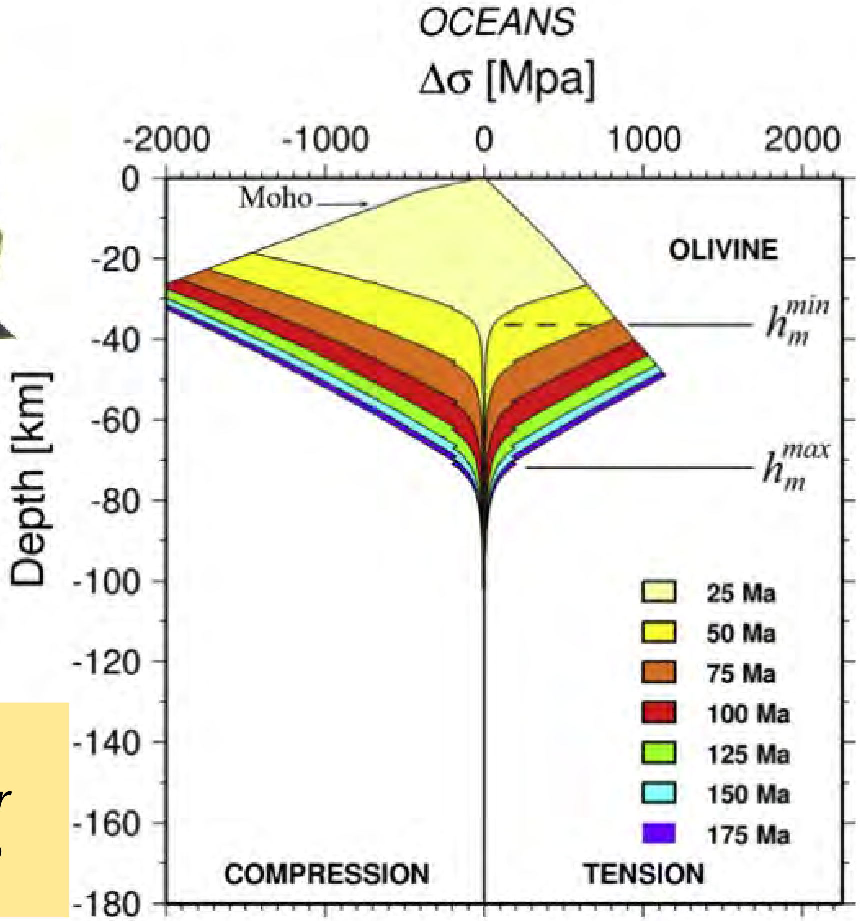


Kohlstedt et al., 1995

lith-asth ***transition*** *or* ***boundary*** *?*

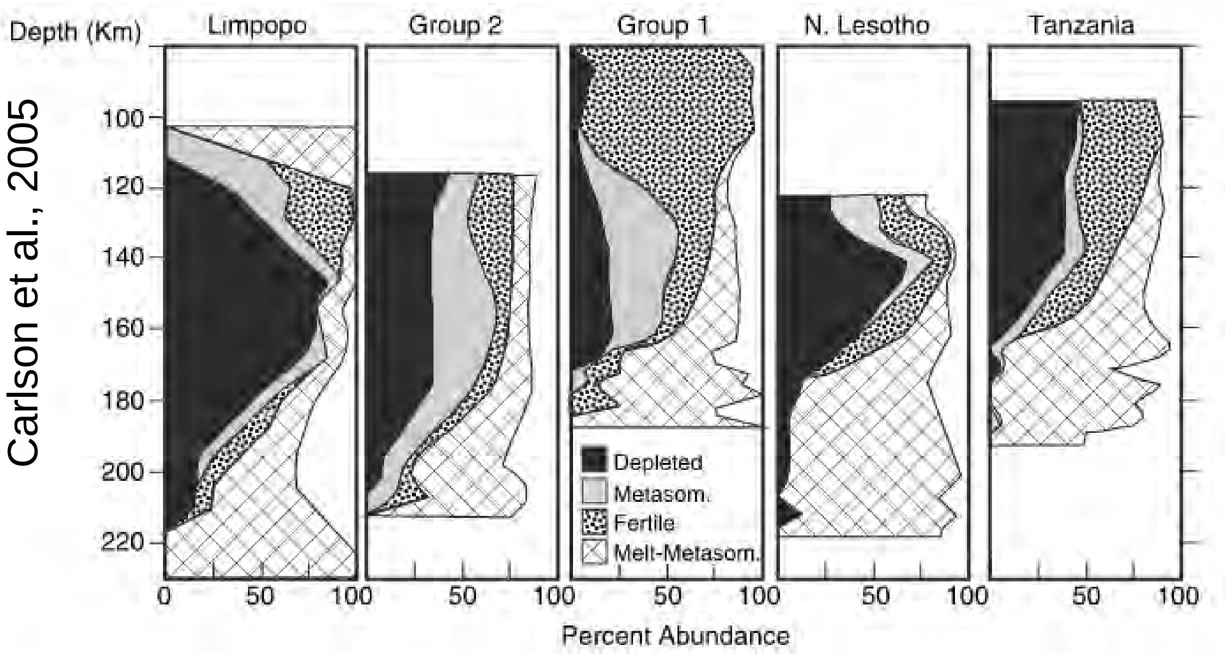


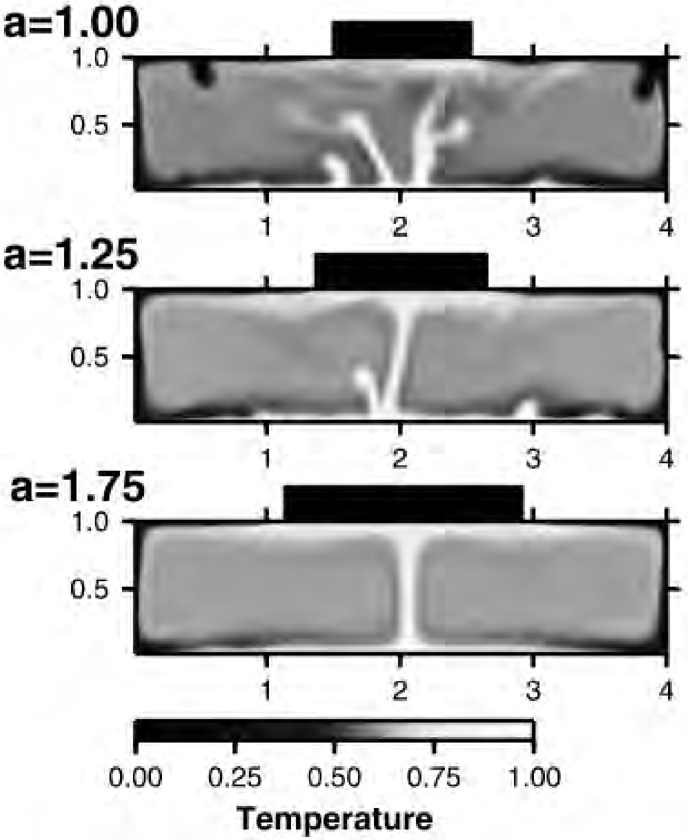
Burov, 2011

Lith.-asth. compositional boundary below continents ?

Continental lithosphere melt-depleted / dehydrated ?
→ effect on viscosity and conductivity ?
(implications for mantle flow and heat transfer)

Carlson et al., 2005

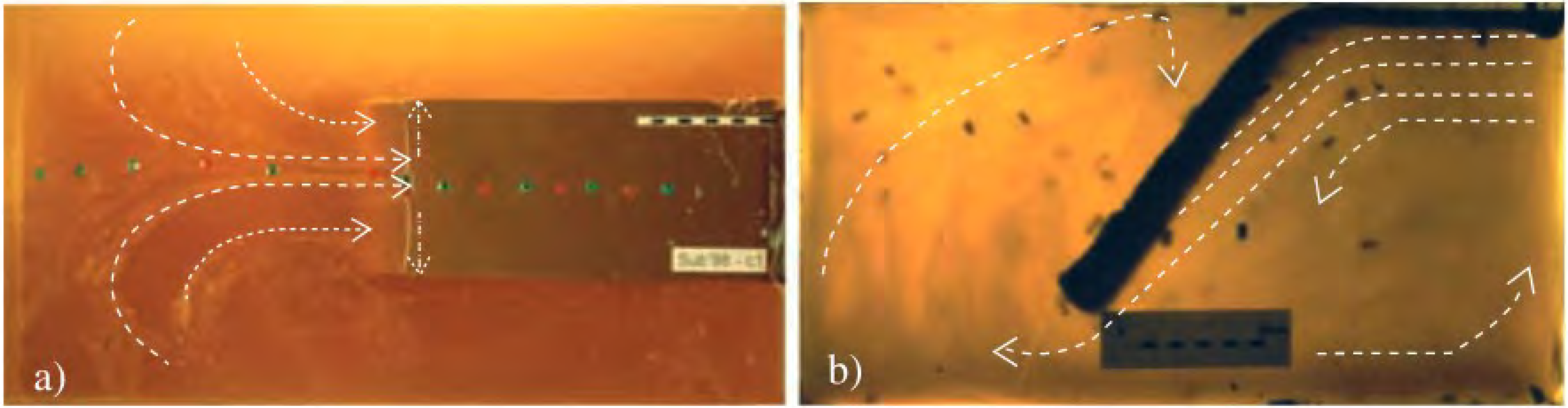




Mantle types in the African lithosphere interpreted from xenoliths

Grigné et al., 2007

Dynamic models with a lithosphere-asthenosphere **boundary**



Funiciello et al., 2003

Analogue experiments

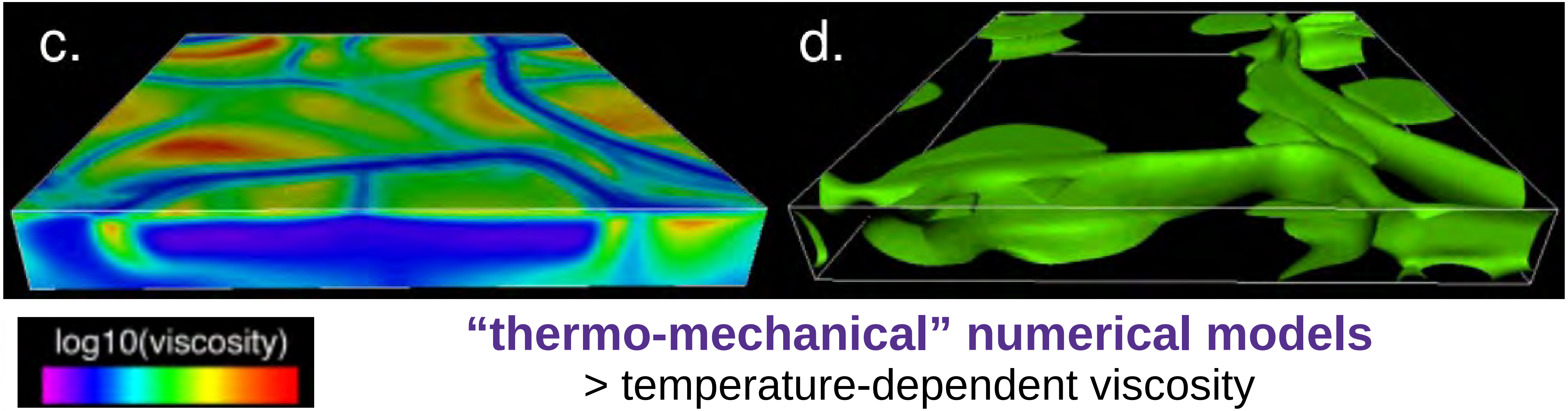
- lithosphere ≡ silicone putty
- asthenosphere = glucose syrup

> prescribed viscosity contrast (≥ 1000)

"Compositional" numerical models

Capitanio et al., 2010

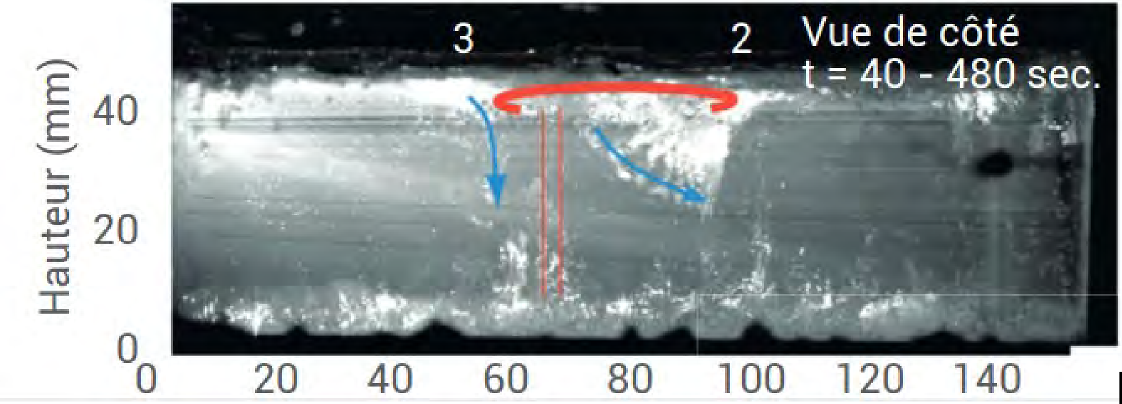
Dynamic models with a lithosphere-asthenosphere transition



Tackley, G3, 2000

"thermo-mechanical" numerical models

> temperature-dependent viscosity



Analogue experiments

Ludox (silica particle suspension)

> rheology = f(water content)

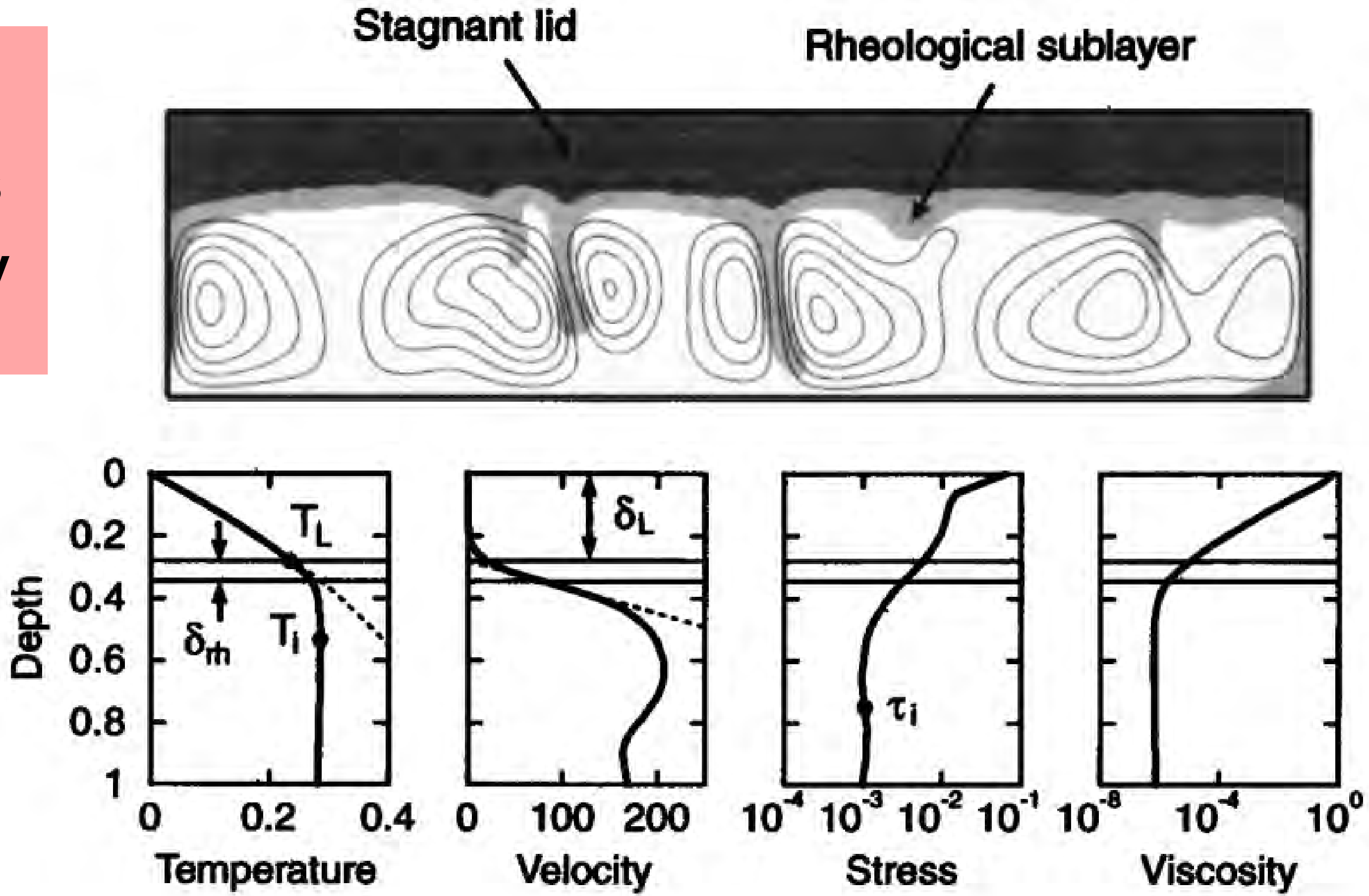
- dry "lithosphere"
- wet "asthenosphere"

Davaille et al., 2020

Thermal, mechanical, viscosity lith-asth transition…
but what about the velocity transition ?

Lithosphere superimposed to moving tectonic plates

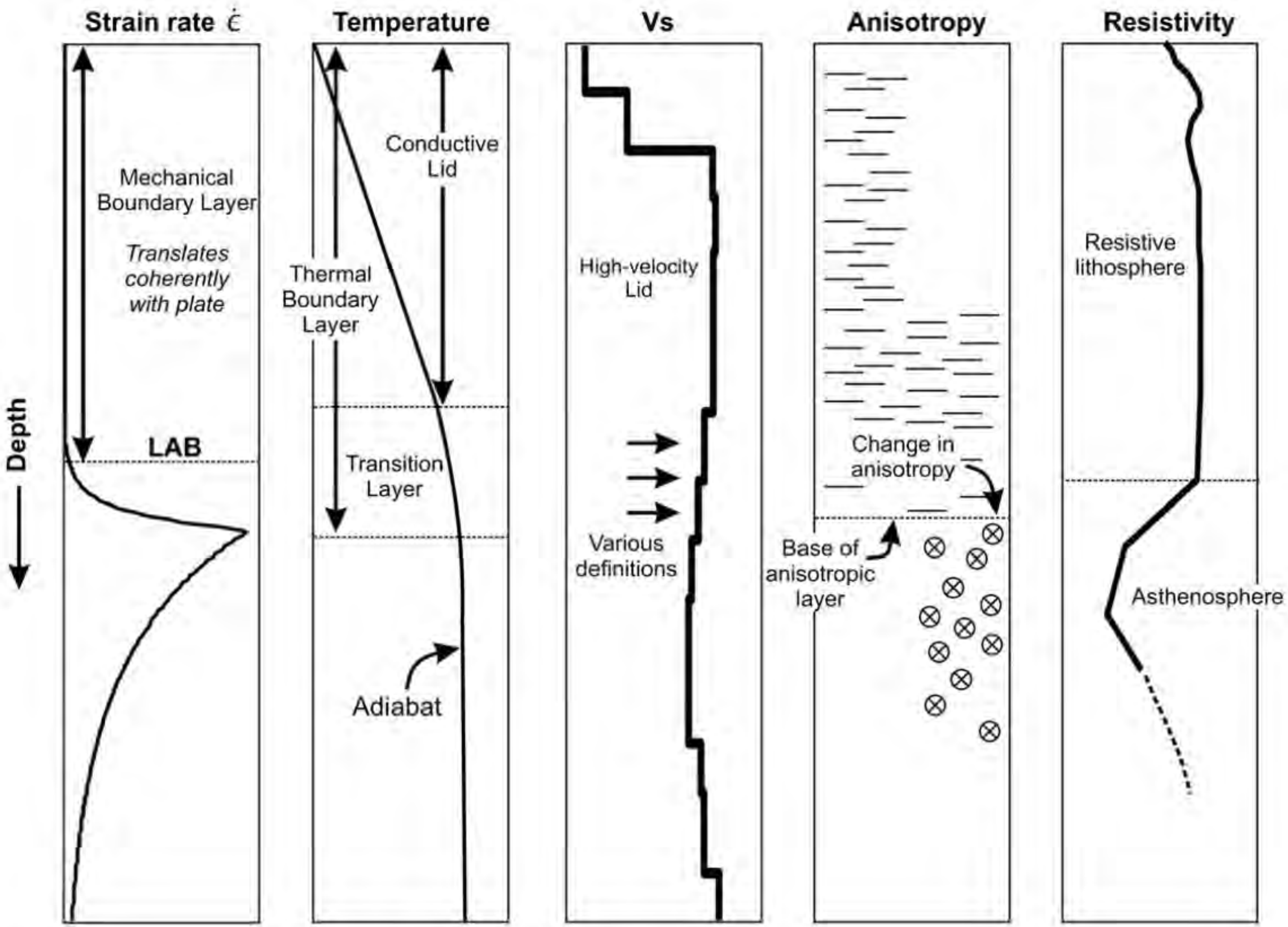
→ **how does velocity vary vertically ?**



Stagnant-lid simulation

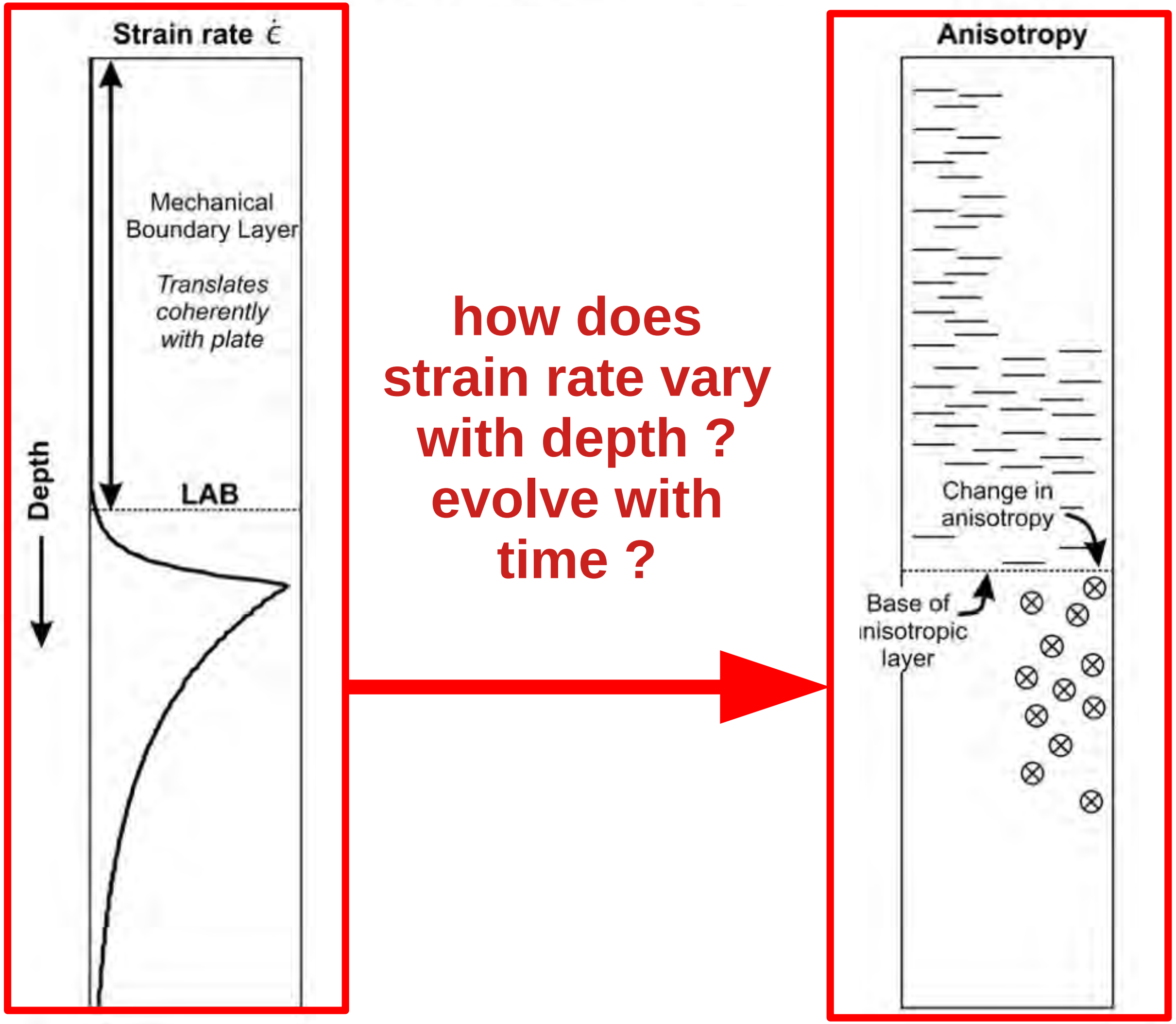
Solomatov & Moresi, 2000

Multiple definitions and proxies of the LAB



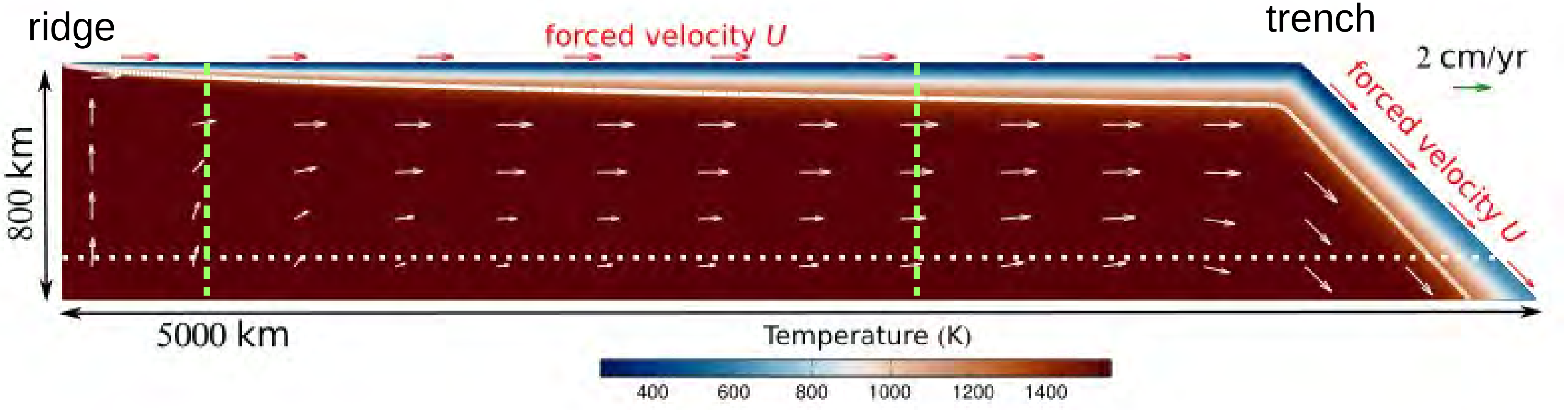
Eaton et al., 2009

Seismic anisotropy as a proxy for the lith-asth transition ?



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

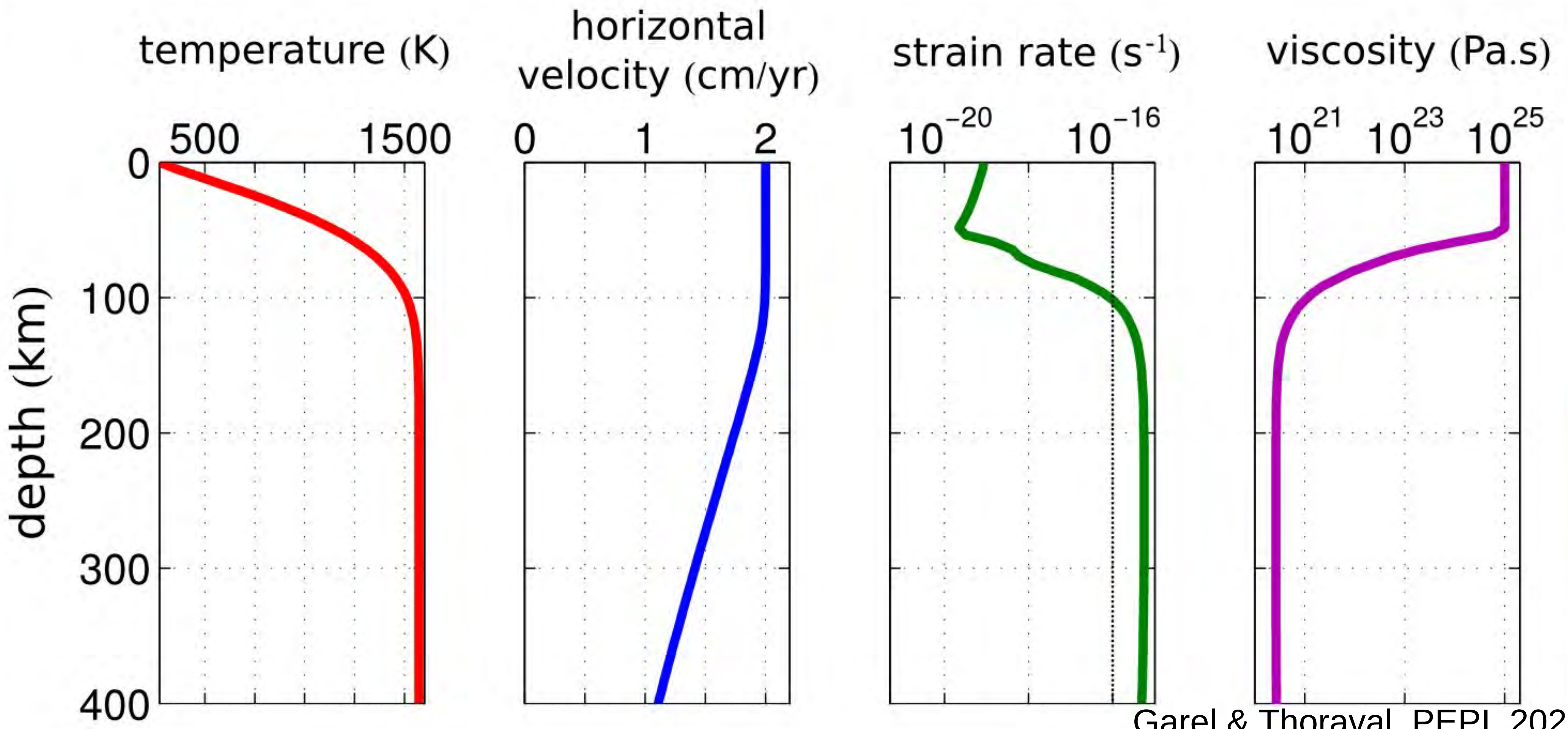
- one single material for both lithosphere and asthenophere

(no pre-imposed discontinuity)

- steady-state

Garel & Thoraval, PEPI, 2021

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



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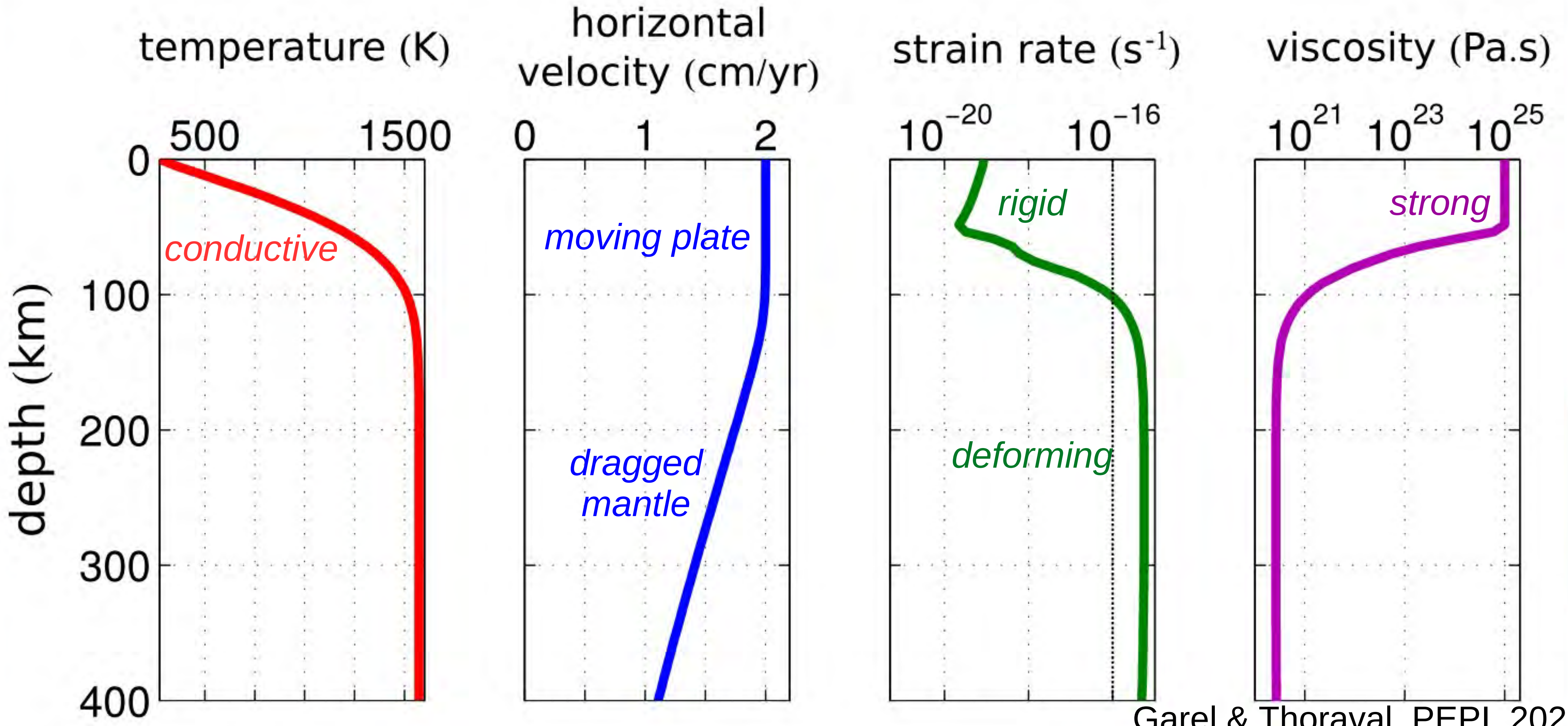

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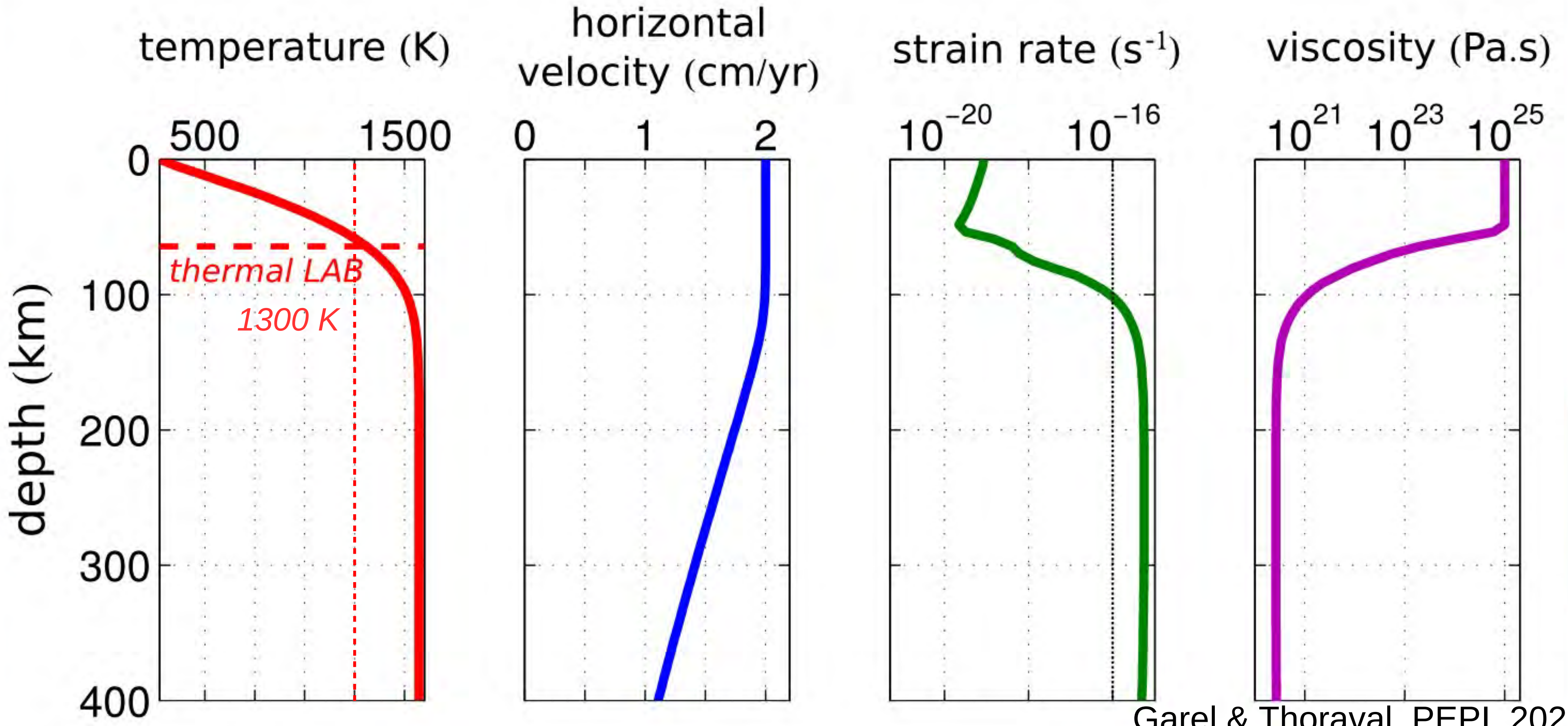

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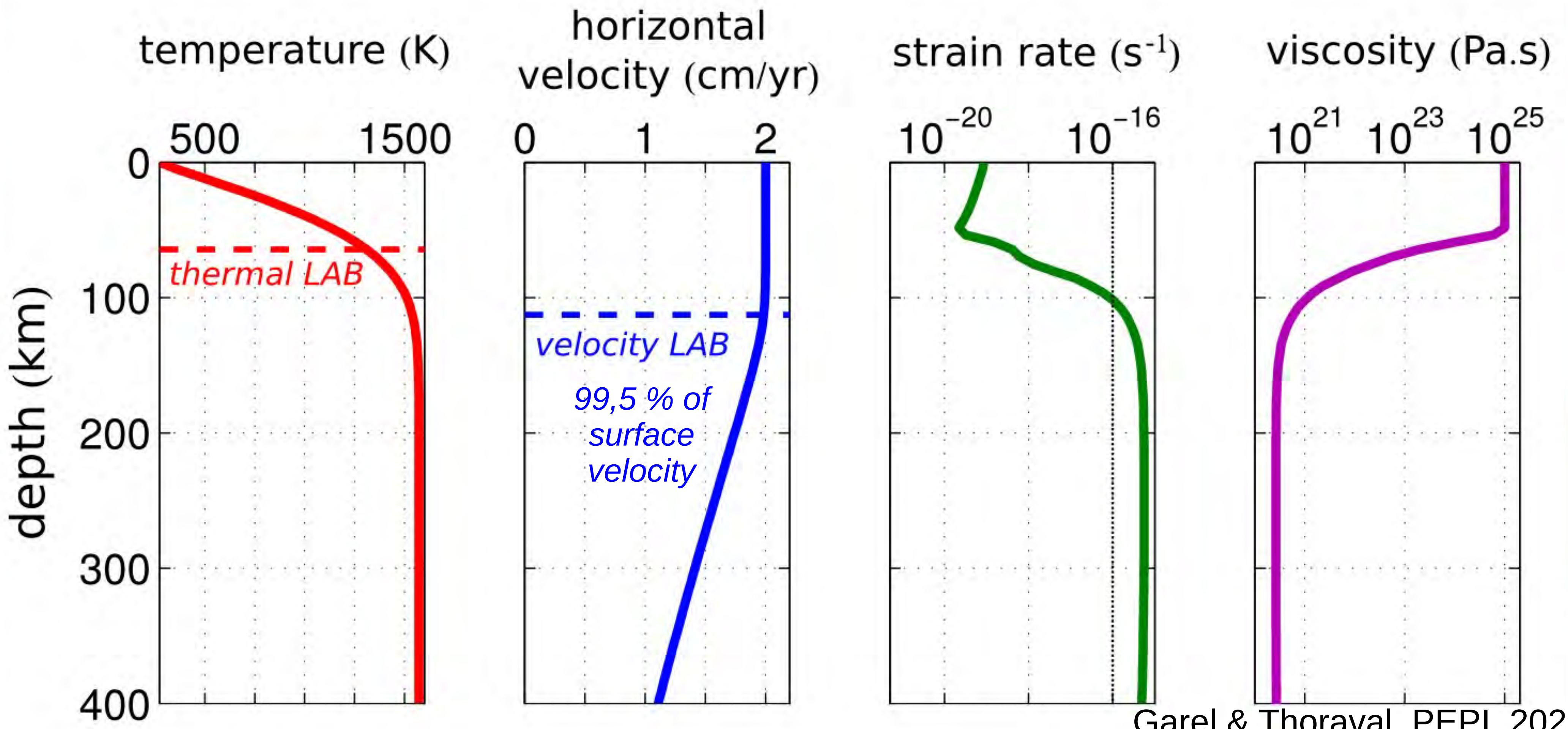

Garel & Thoraval, PEPI, 2021

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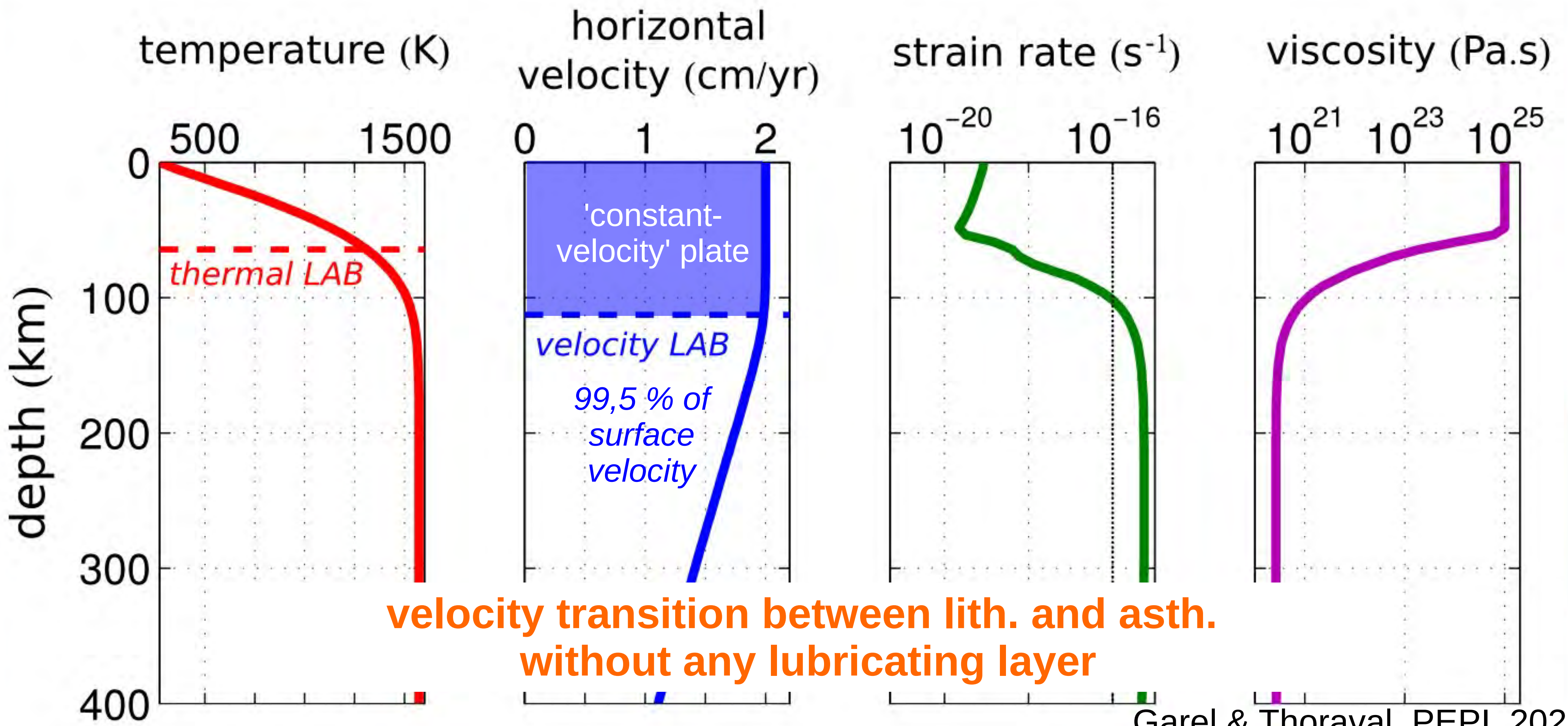

velocity transition between lith. and asth. without any lubricating layer

Garel & Thoraval, PEPI, 2021

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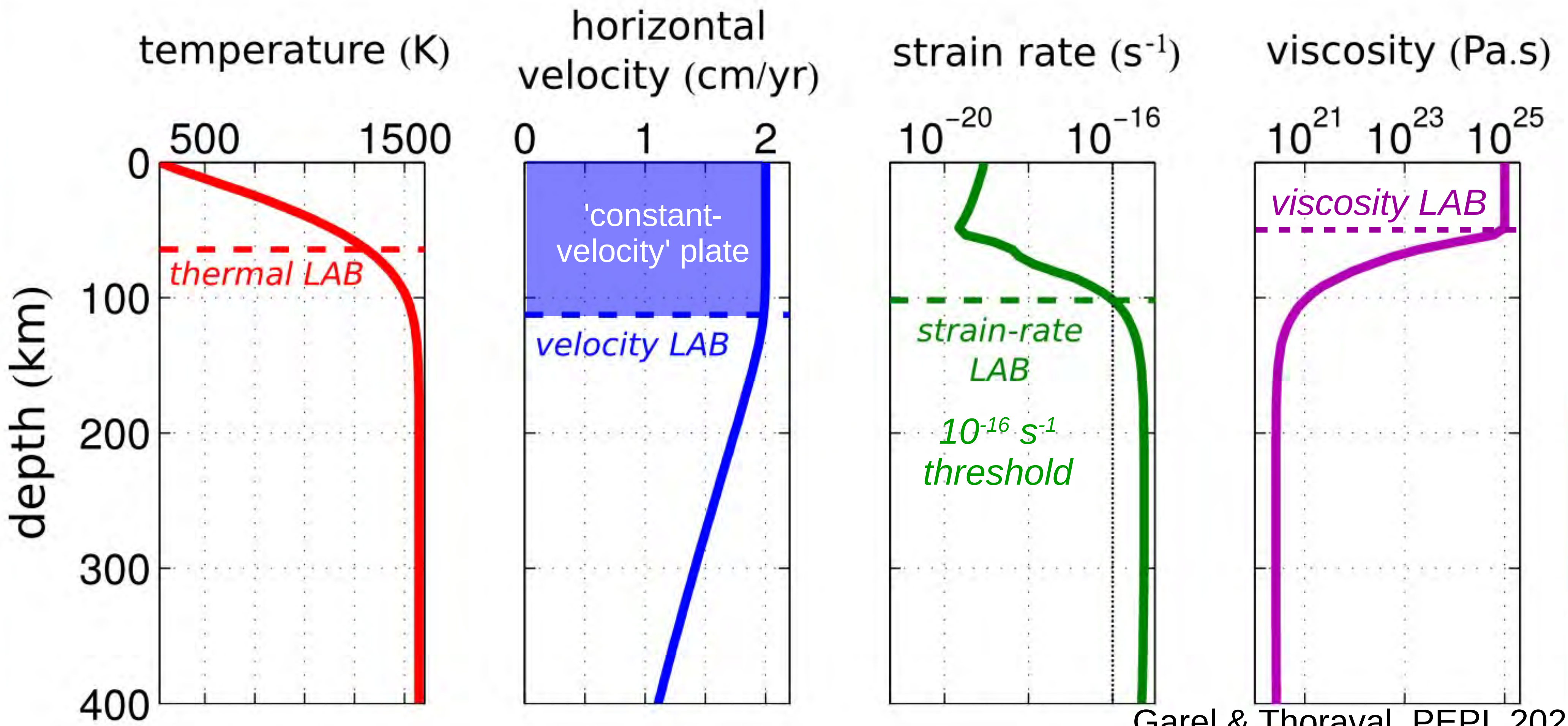

Garel & Thoraval, PEPI, 2021

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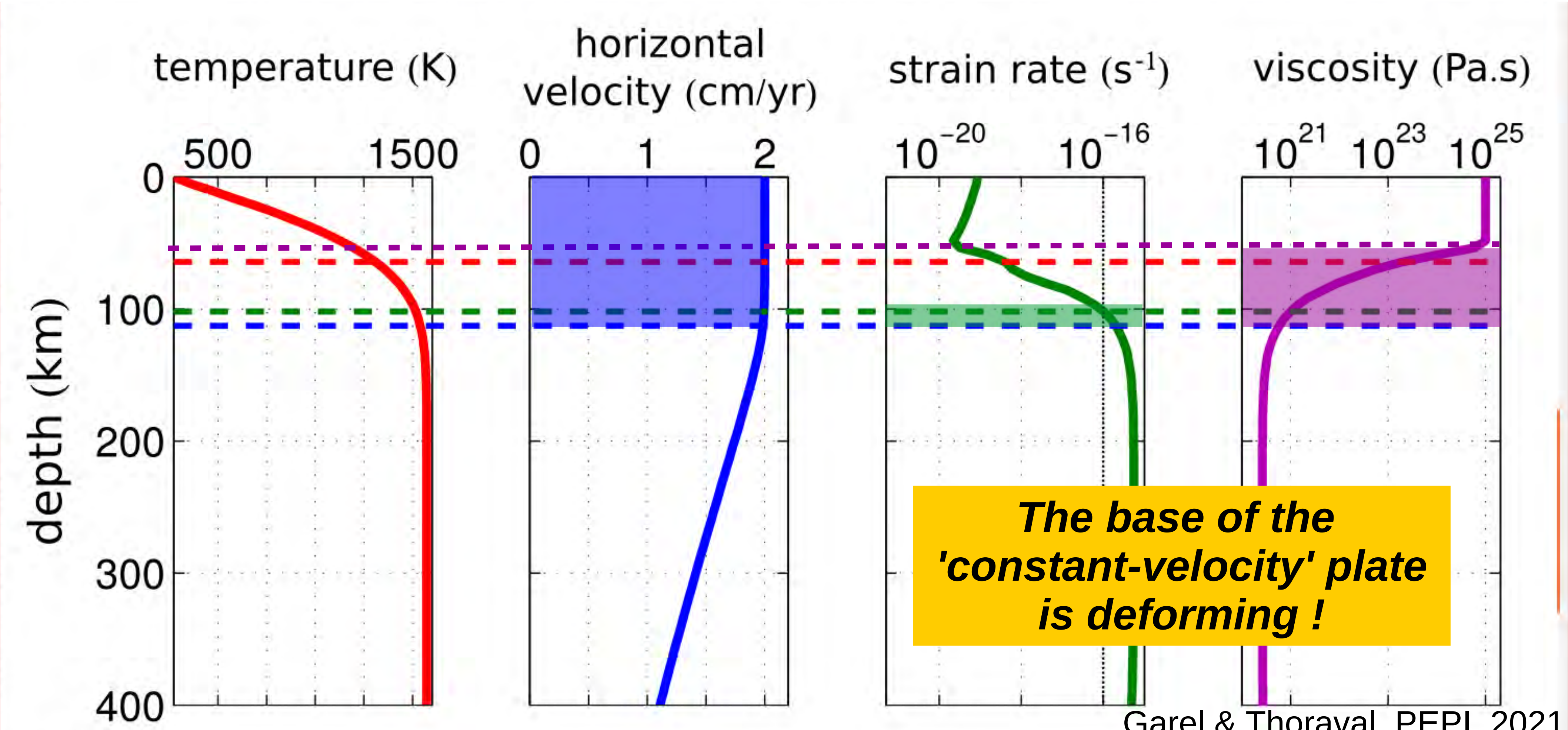
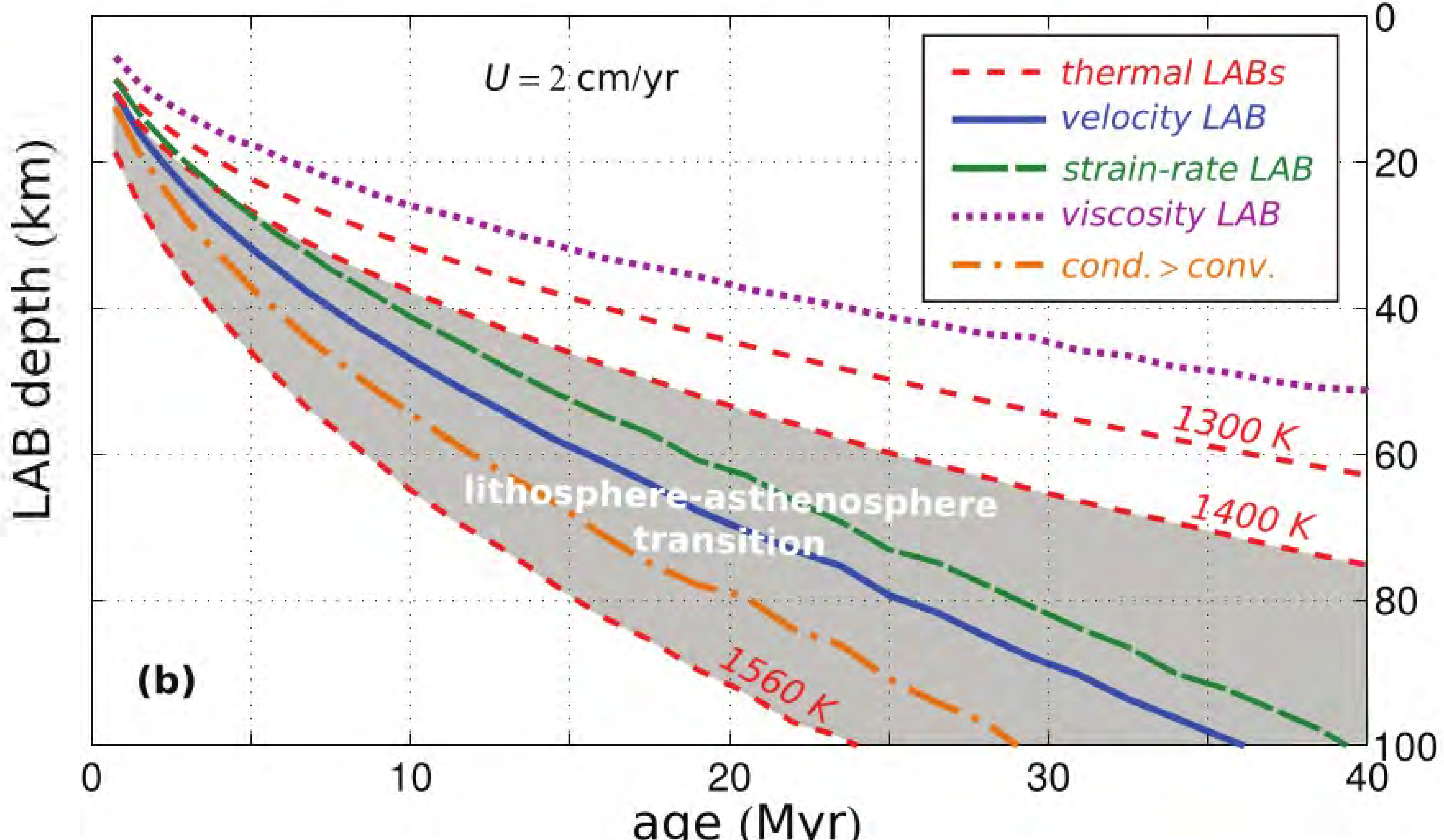


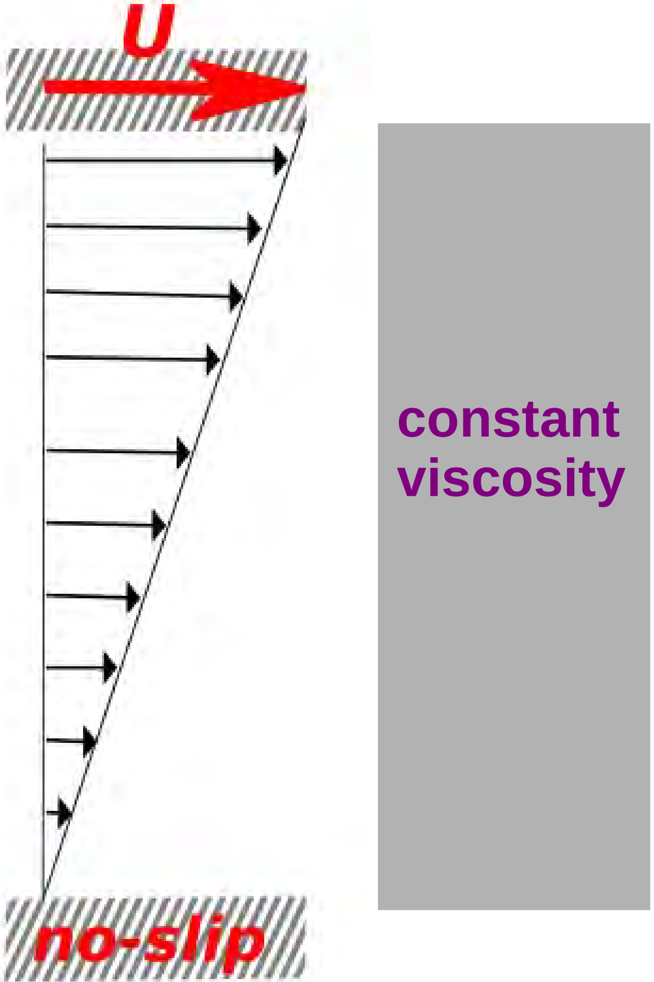
Garel & Thoraval, PEPI, 2021

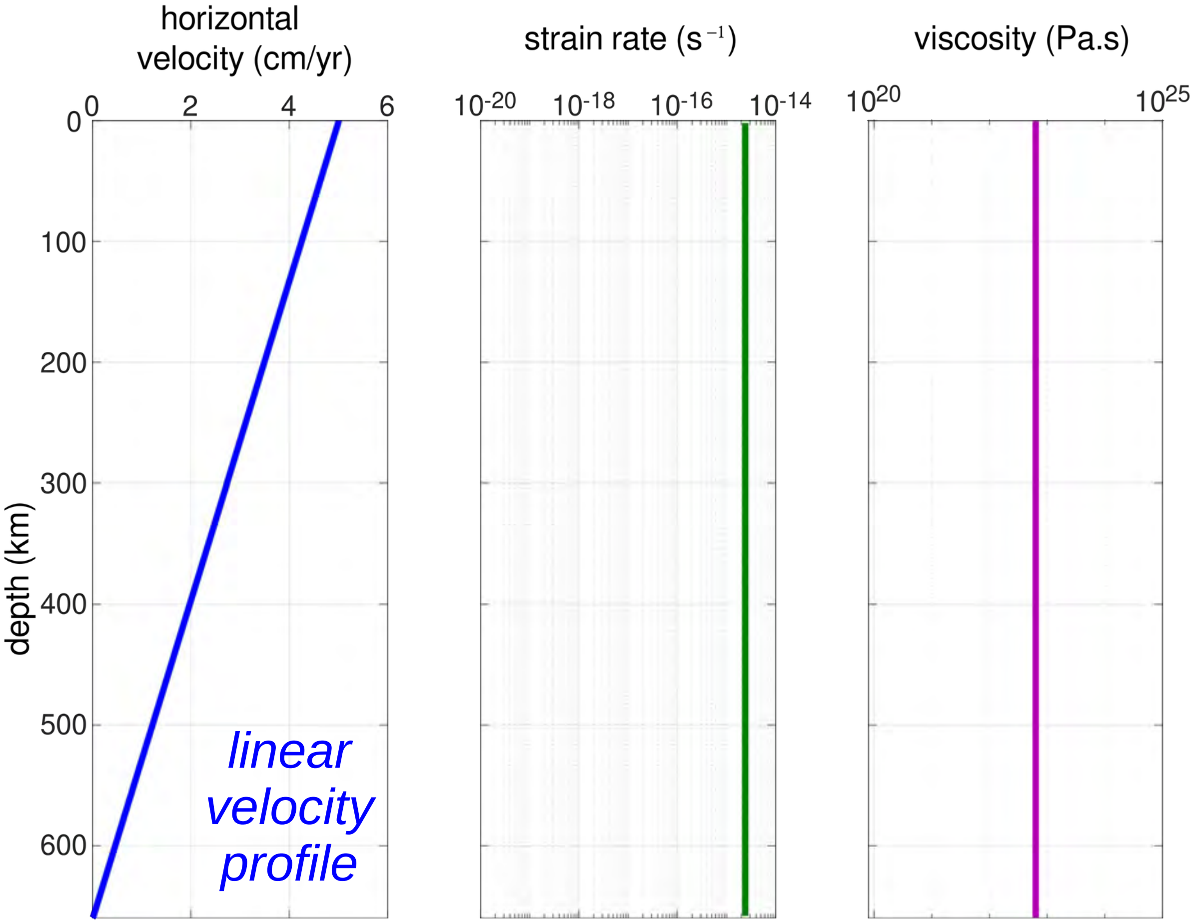
Progressive transition from lithosphere to asthenosphere for a homogeneous material with temperature-dependent viscosity



Garel & Thoraval, PEPI, 2021

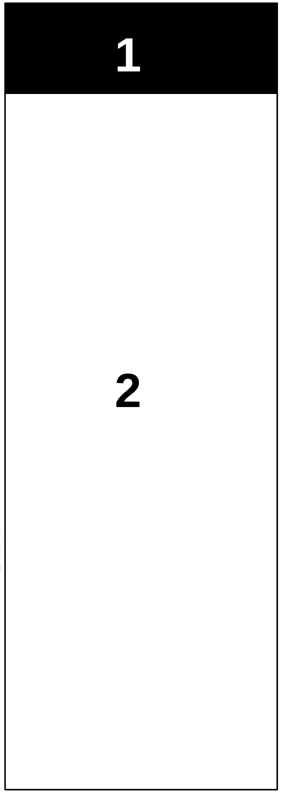
Explaining the ‘constant-velocity’ plate using a Couette flow in *n* layers with variable viscosity





Explaining the ‘constant-velocity’ plate using a Couette flow in *n* layers with variable viscosity

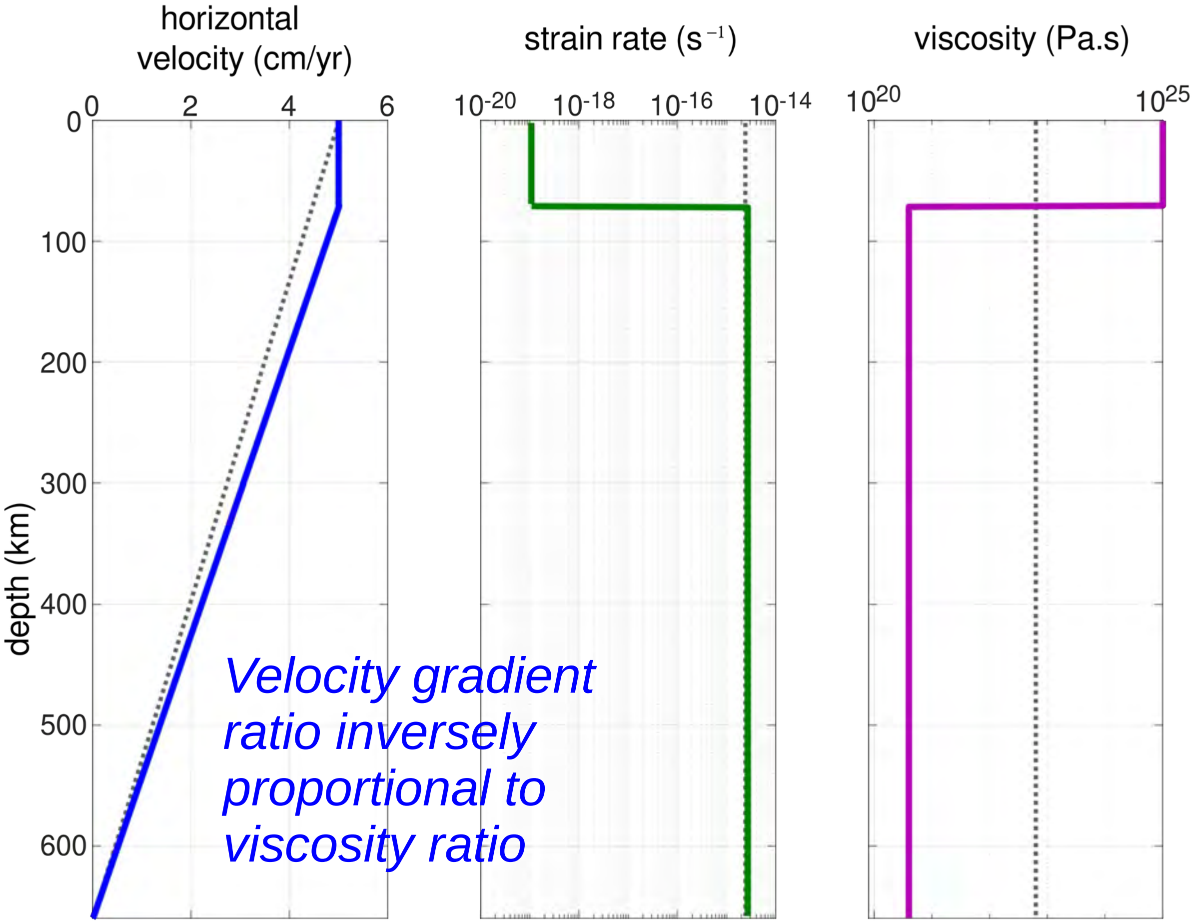
2 layers with different viscosities



- continuity of viscous shear stress at the interface :

$$\mu_1 \frac{\partial U_1}{\partial z}\Big|_{z=h} = \mu_2 \frac{\partial U_2}{\partial z}\Big|_{z=h}$$

- BCs at surface and bottom

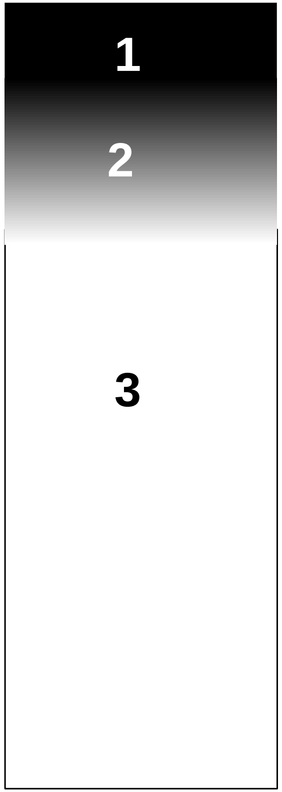


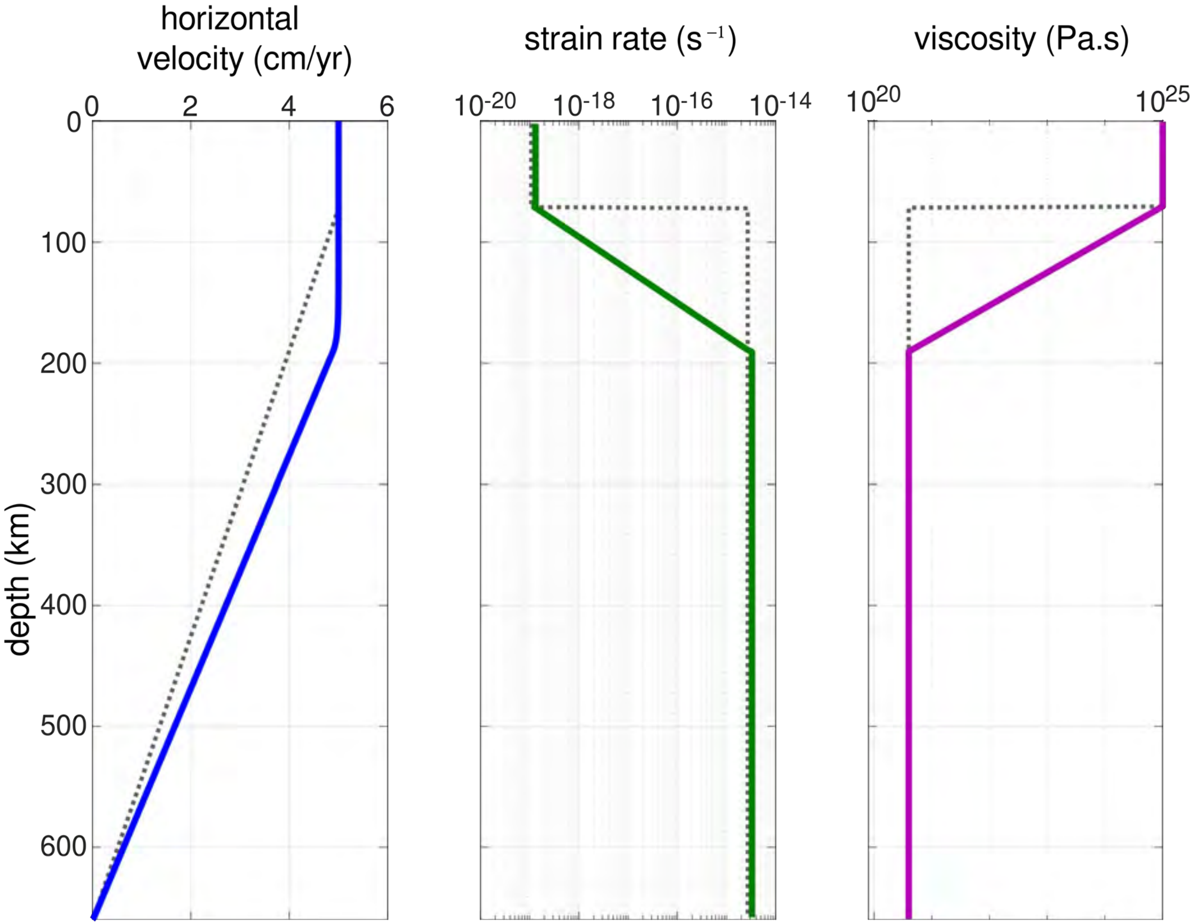
Explaining the ‘constant-velocity’ plate using a Couette flow in *n* layers with variable viscosity

Smooth viscosity-log transition between rigid surface and weak bottom layer

- continuity of viscous shear stress at layer interfaces

- BCs at surface and bottom





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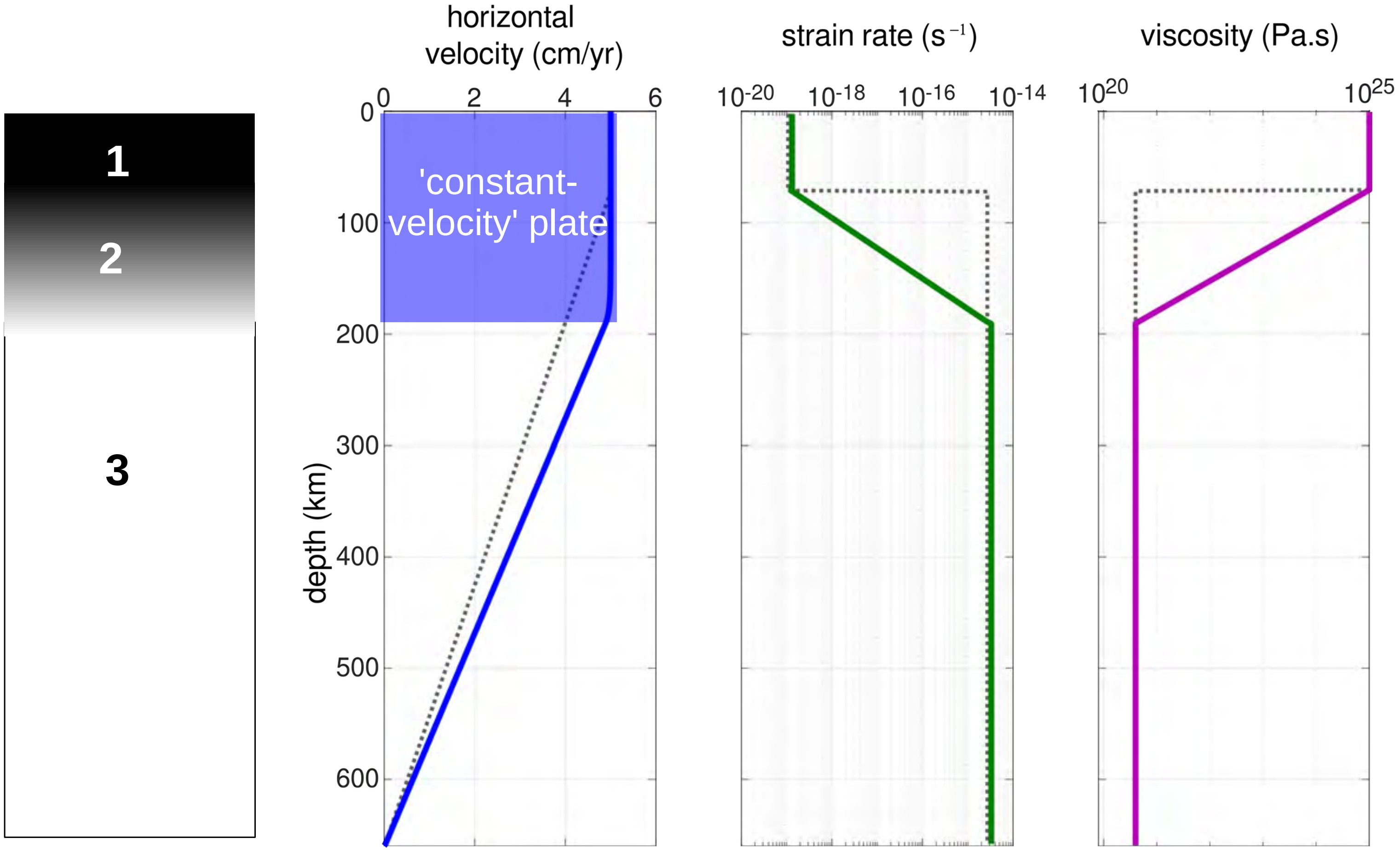
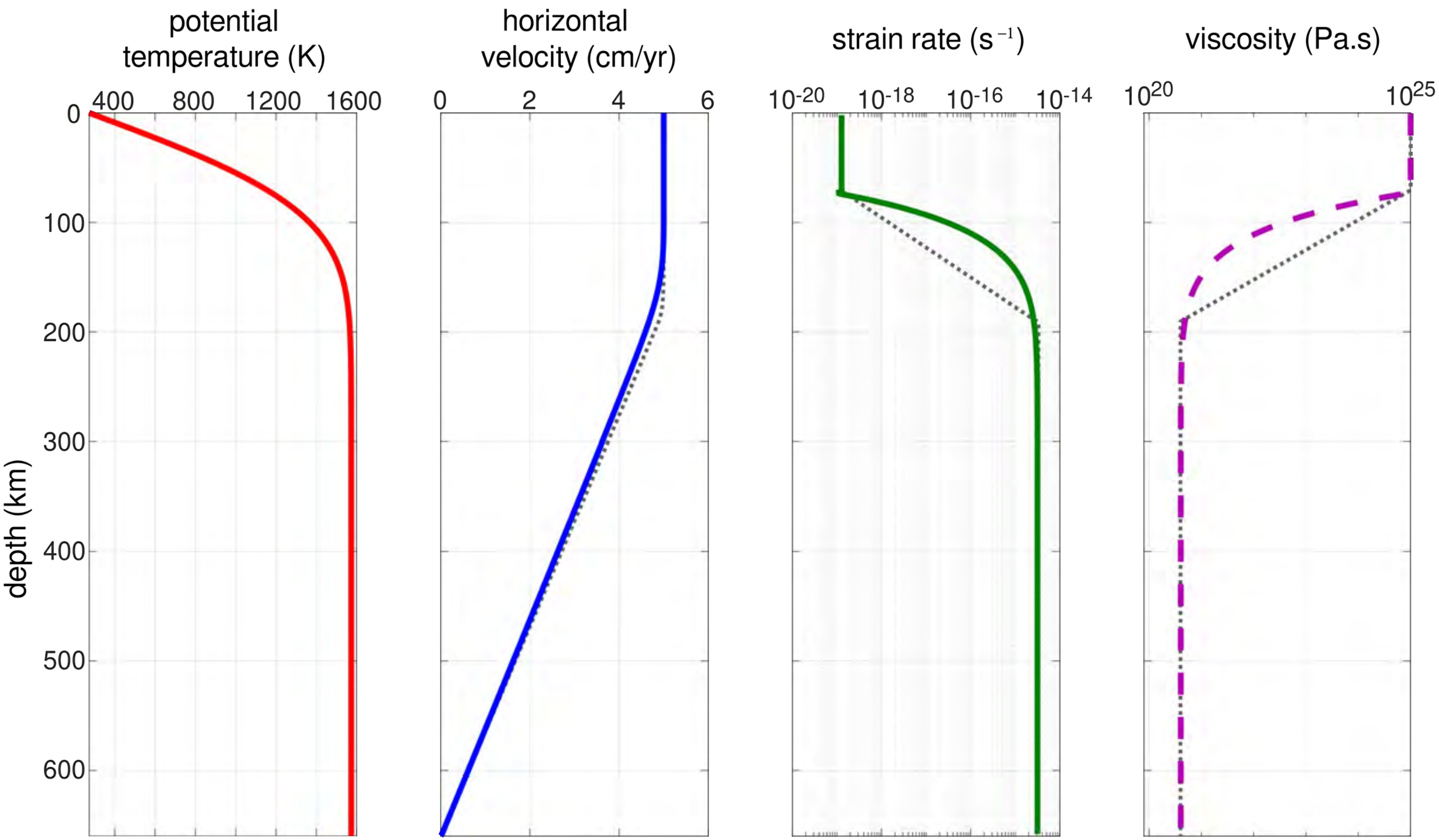


Explaining the 'constant-velocity' plate using a Couette flow in *n* layers with variable viscosity

Diffusion creep viscosity for a 80 Myr-old plate

- continuity of shear stress at layer interfaces

- BCs at surface and bottom



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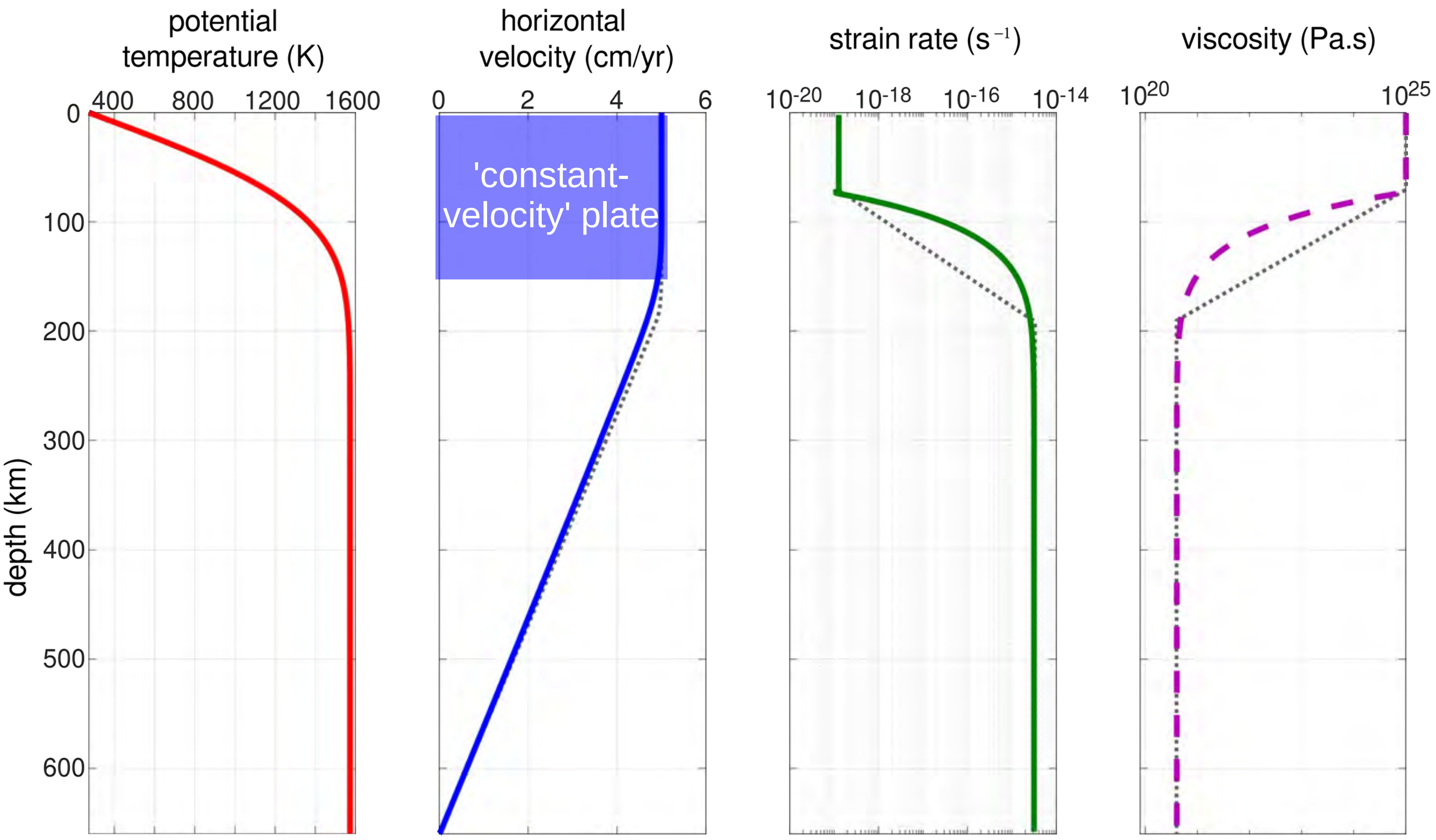

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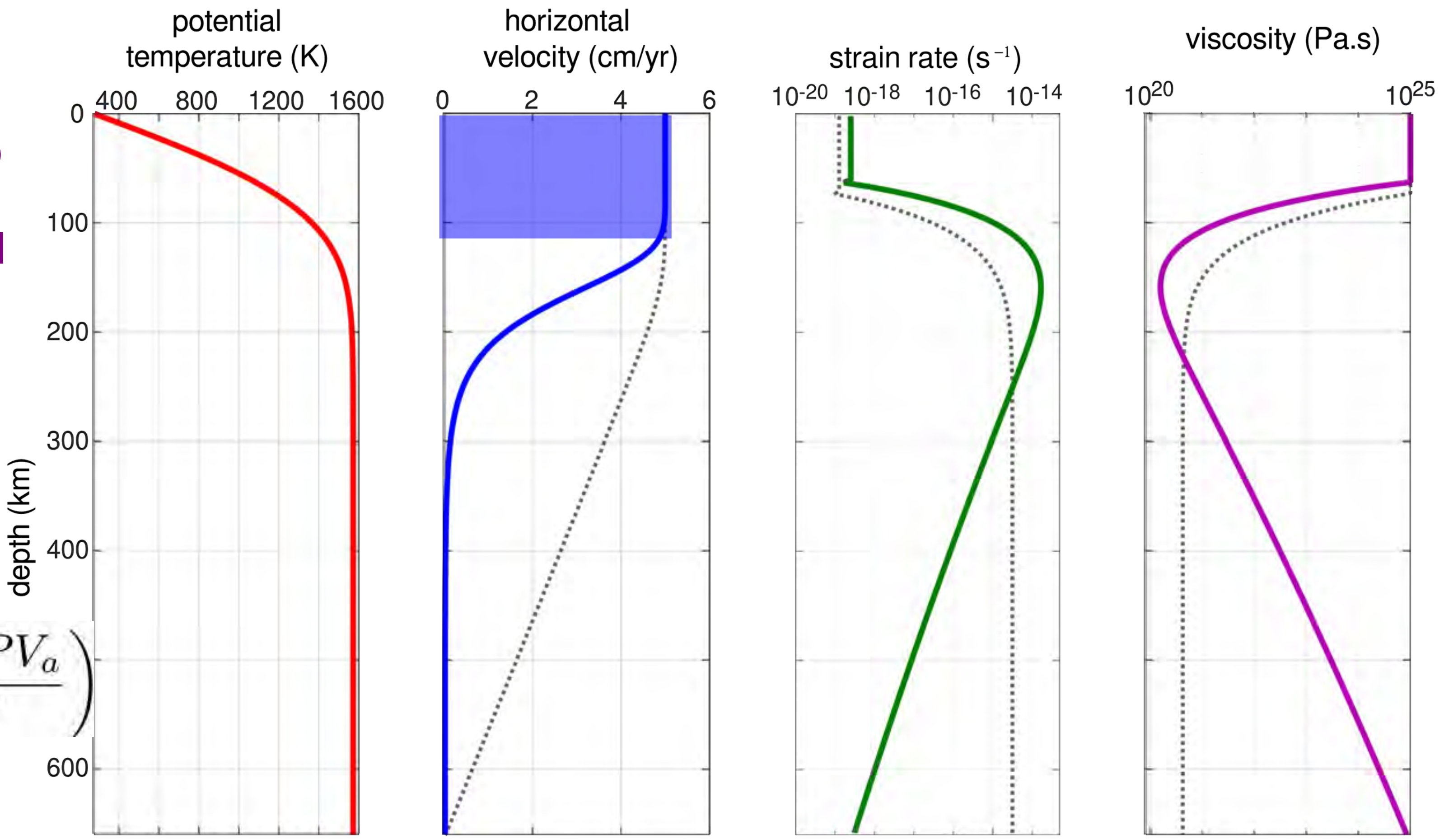
Diffusion creep viscosity for a 80 Myr-old plate

larger activation volume



$$\mu \propto \exp\left(\frac{E_a + PV_a}{RT}\right)$$

Explaining the ‘constant-velocity’ plate using a Couette flow in *n* layers with variable viscosity

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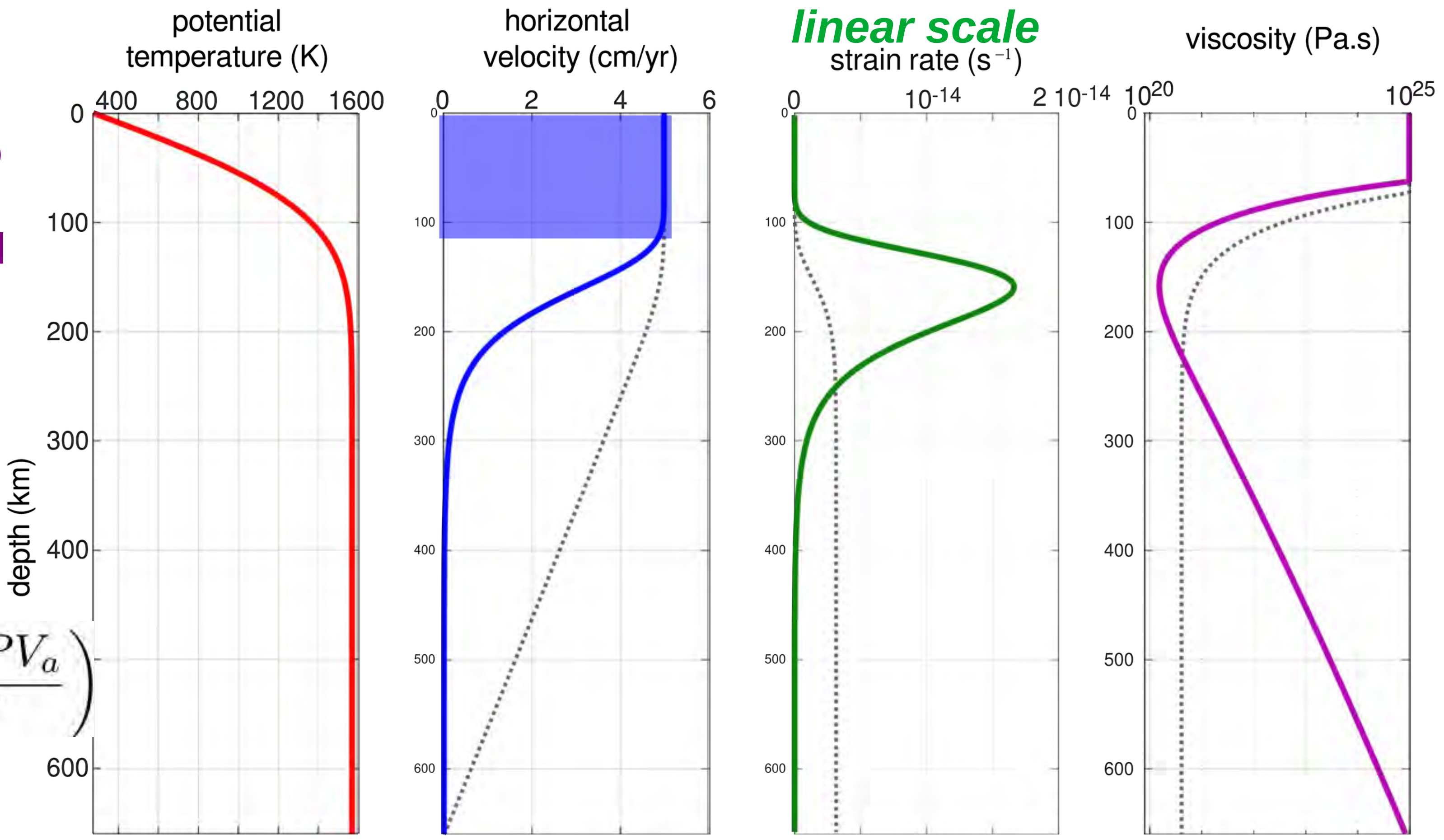
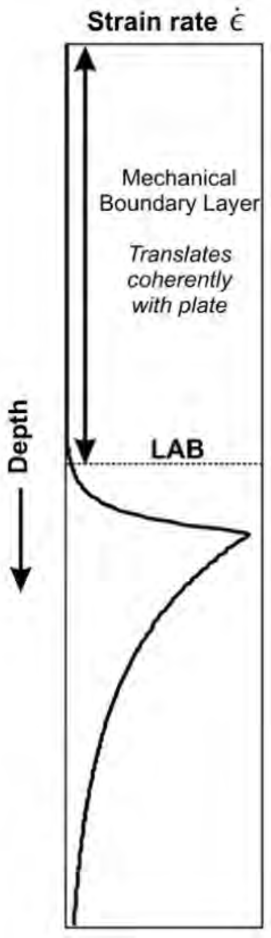
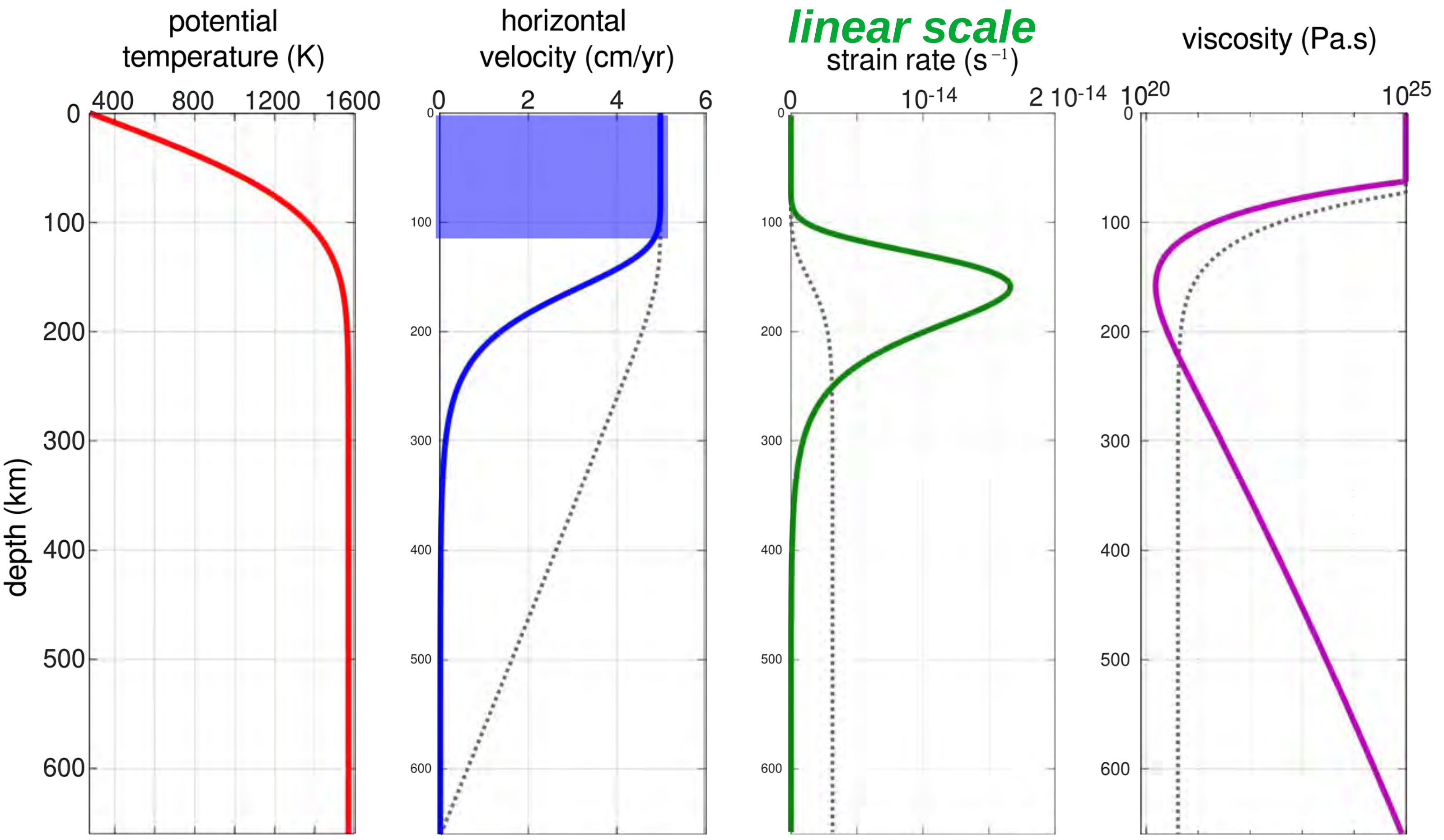


Explaining the ‘constant-velocity’ plate using a simple Couette flow in *n* layers



Eaton et al., 2009



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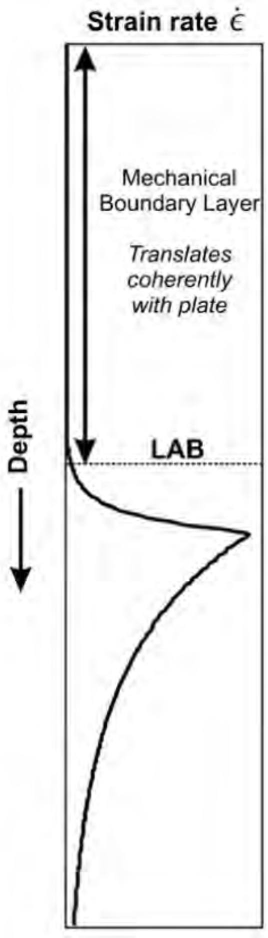
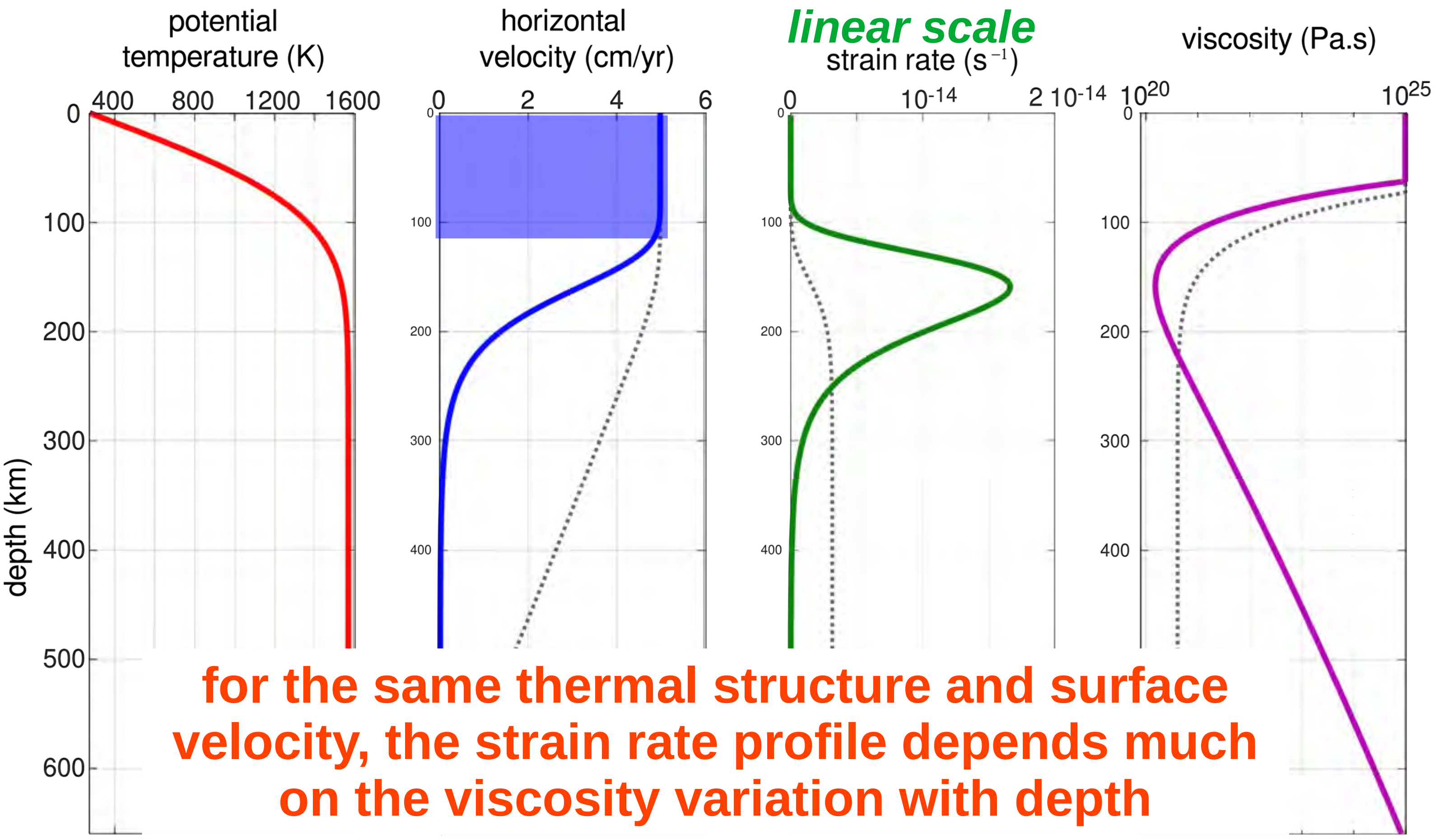
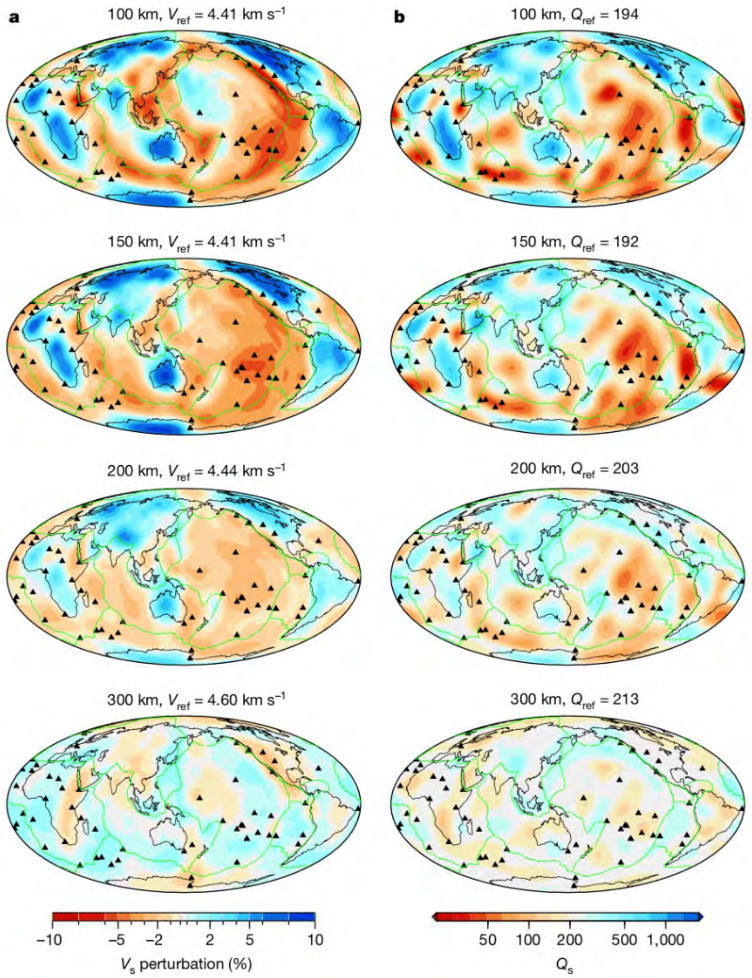




for the same thermal structure and surface velocity, the strain rate profile depends much on the viscosity variation with depth

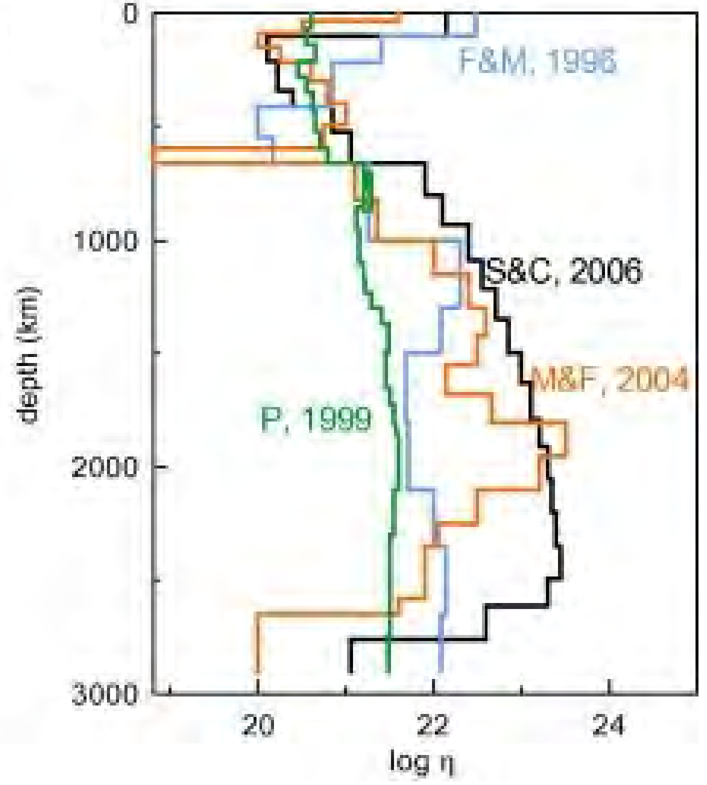
A low-viscosity layer below the plates ?

Shear velocity, attenuation



Debayle et al., Nature, 2020

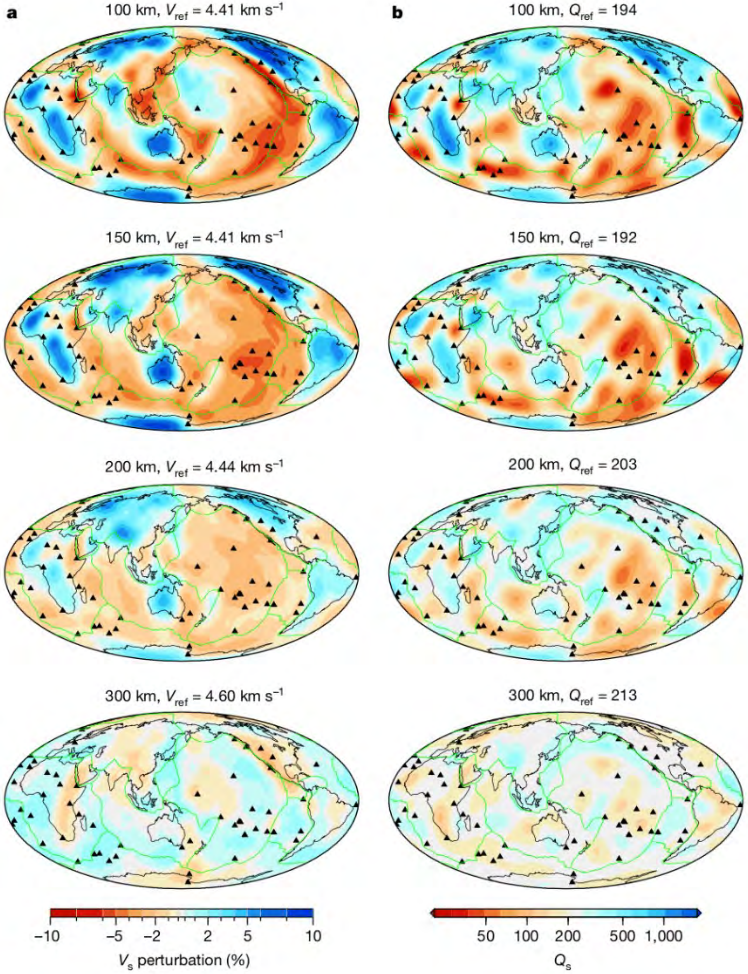
joint inversion of geoid and postglacial rebound data

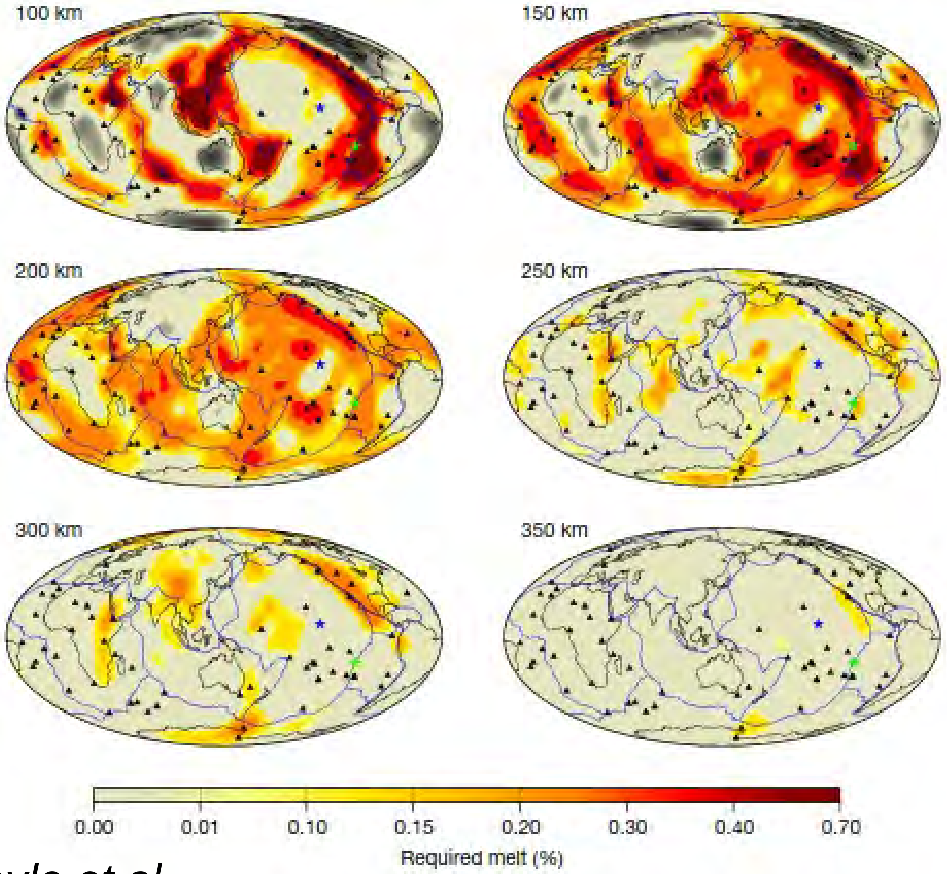


Compilation in Cizkova et al., PEPI, 2012

A low-viscosity layer below the plates ?

Shear velocity, attenuation ------------------► partial melt ?



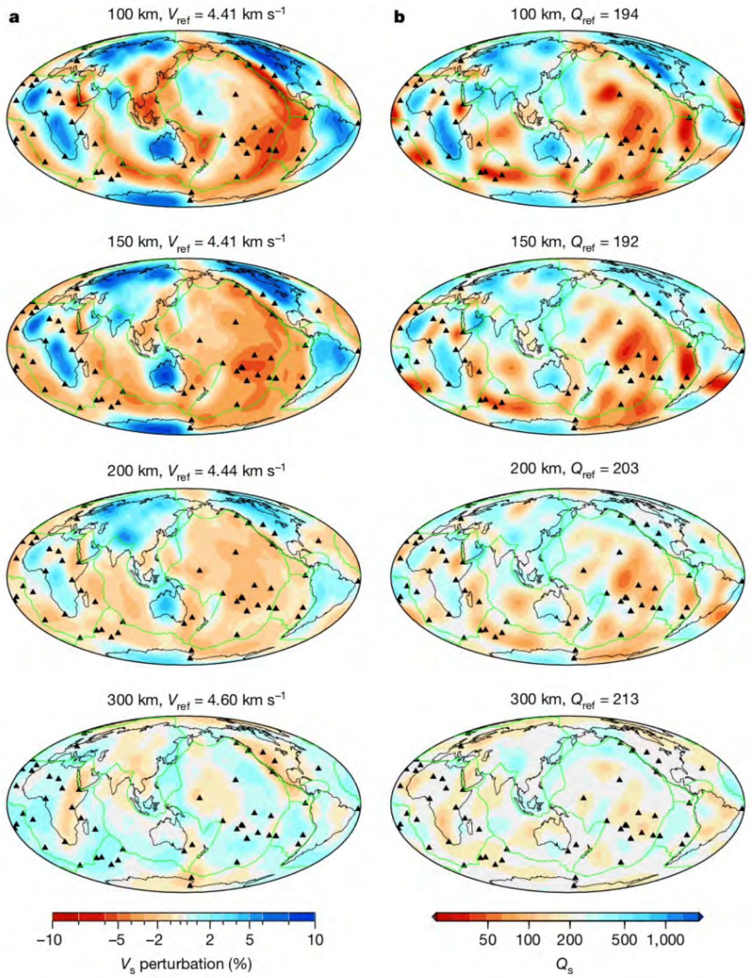


Debayle et al., Nature, 2020

A low-viscosity layer below the plates ?

Shear velocity, attenuation ------------------► partial melt ?

-----► grain size variations ?



creep laws → low-viscosity layer possible with certain rheological parameters

Debayle et al., Nature, 2020

A low-viscosity layer below the plates ?

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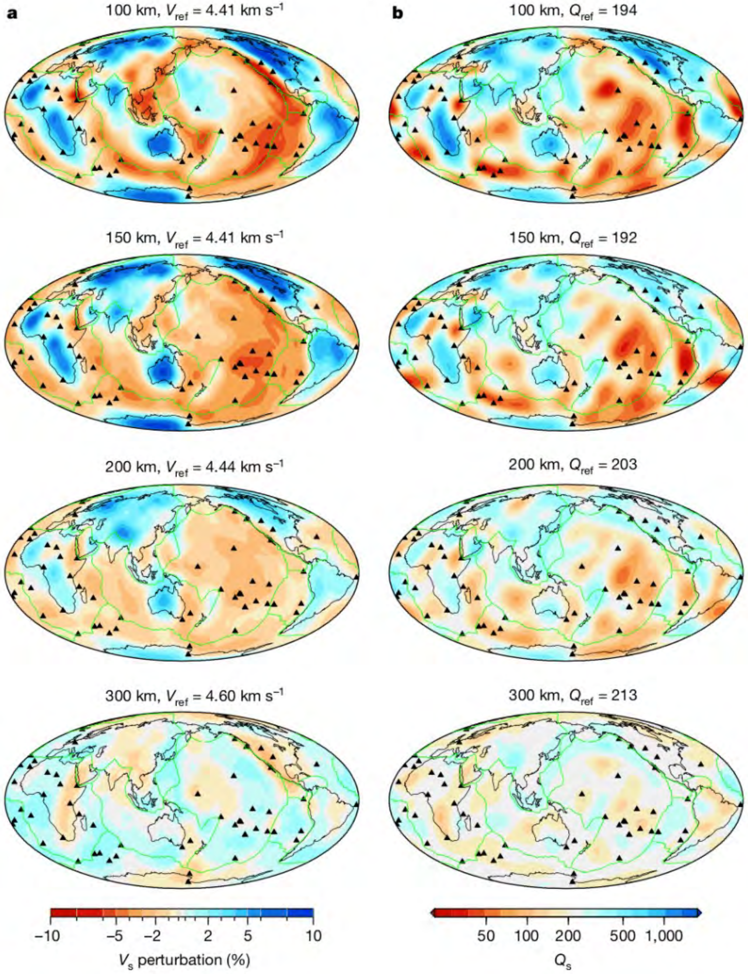


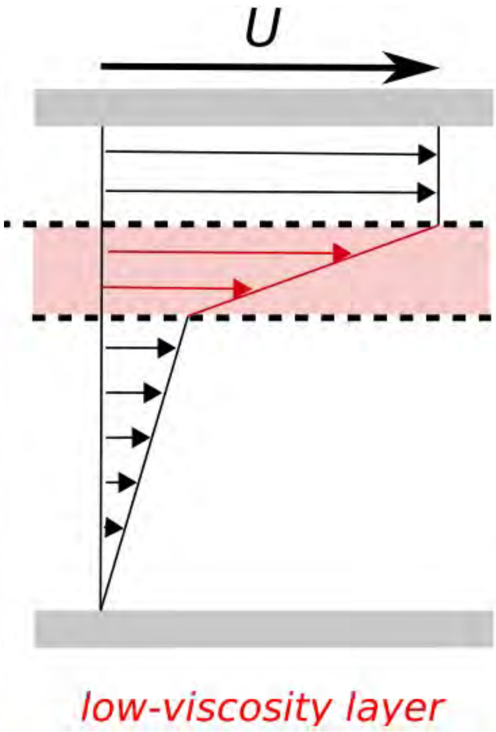
-----► grain size variations ?

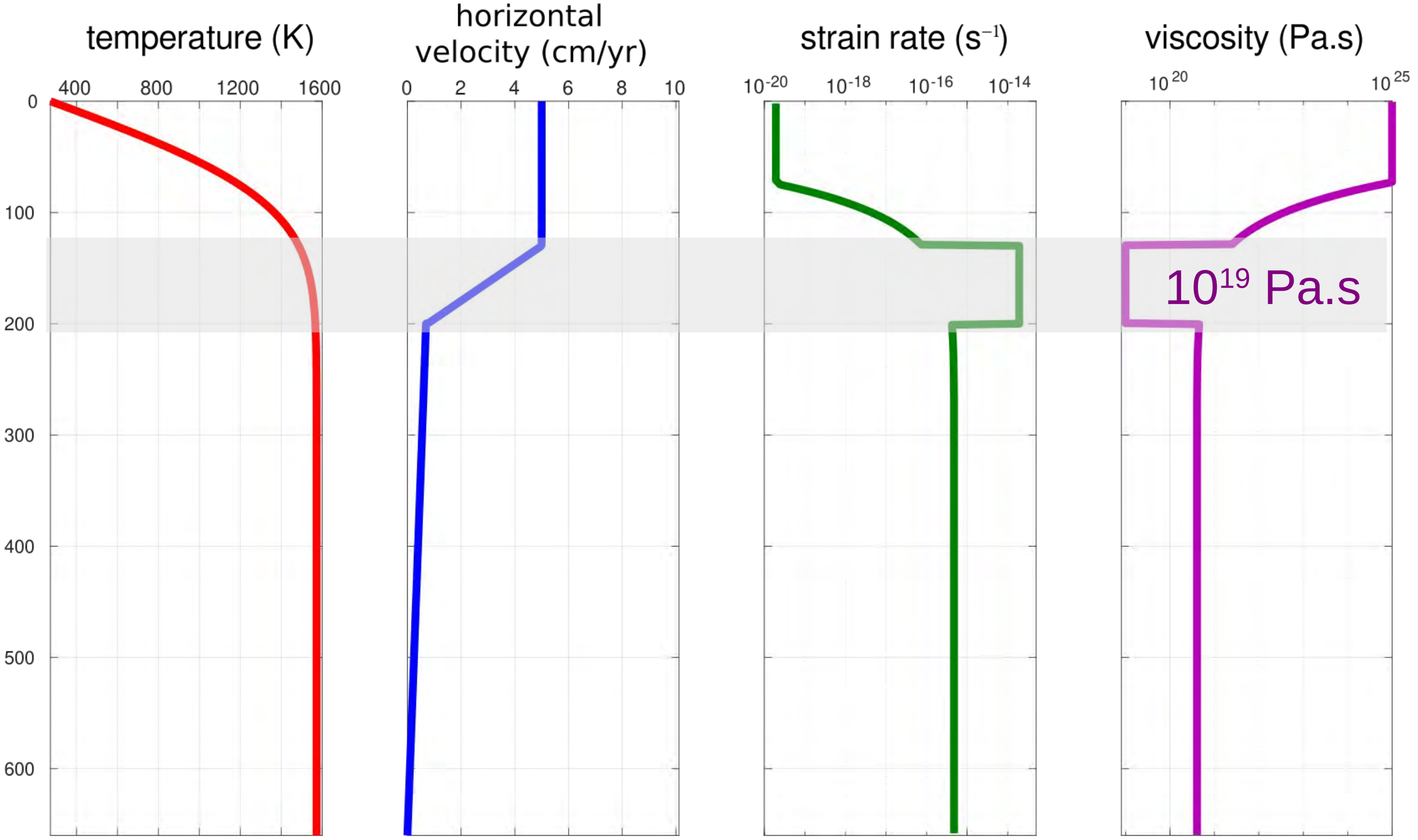
creep laws → low-viscosity layer possible
with certain rheological parameters

how weak?	*10^{19} Pa.s ?*
how much weaker?	*10-100 x ?*
how thick?	*< 250 km depth ?*

Debayle et al., Nature, 2020

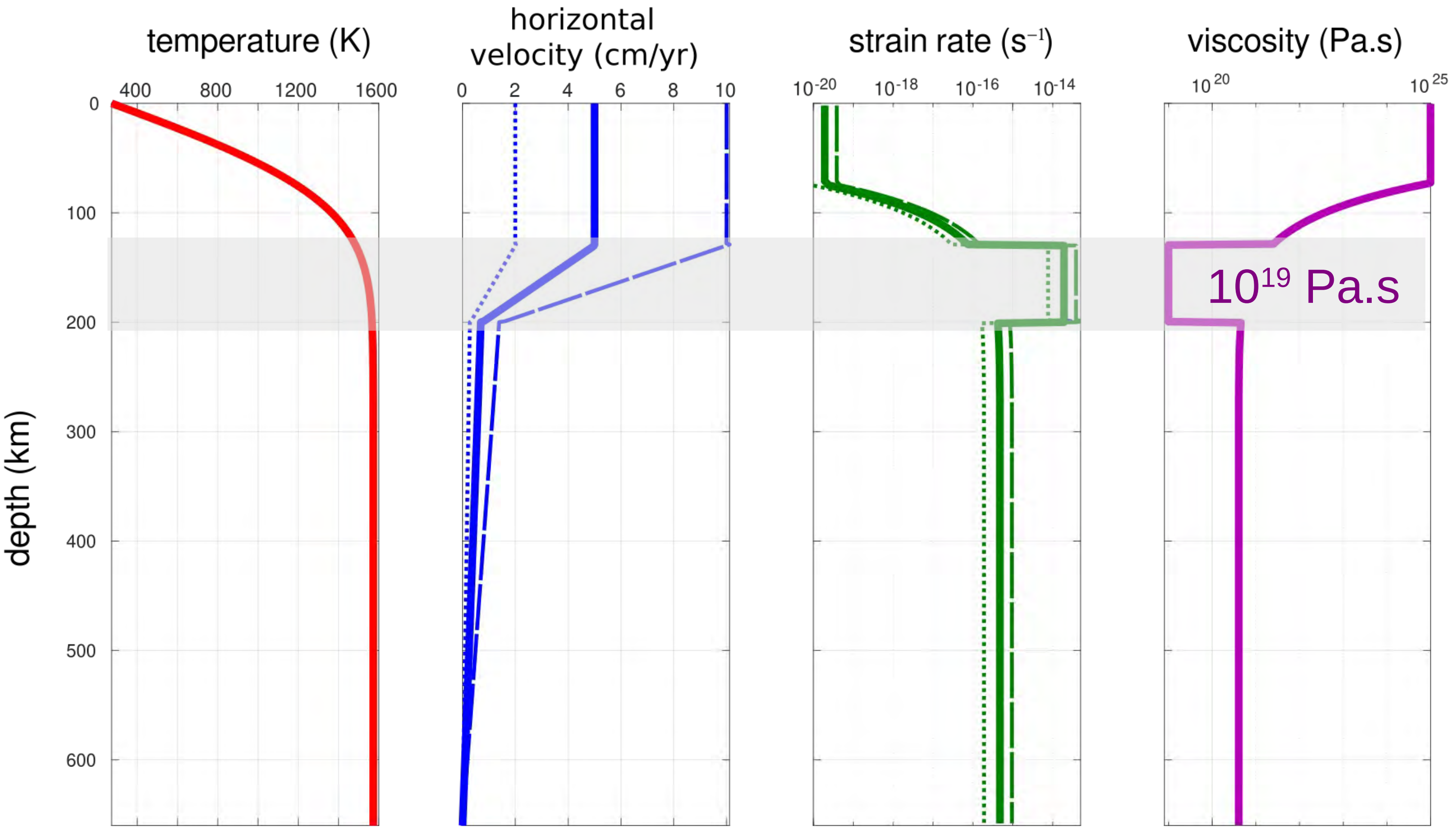
A decoupling low-viscosity layer ?





A decoupling low-viscosity layer ?

Various surface plate velocities : 2, 5, 10 cm/yr



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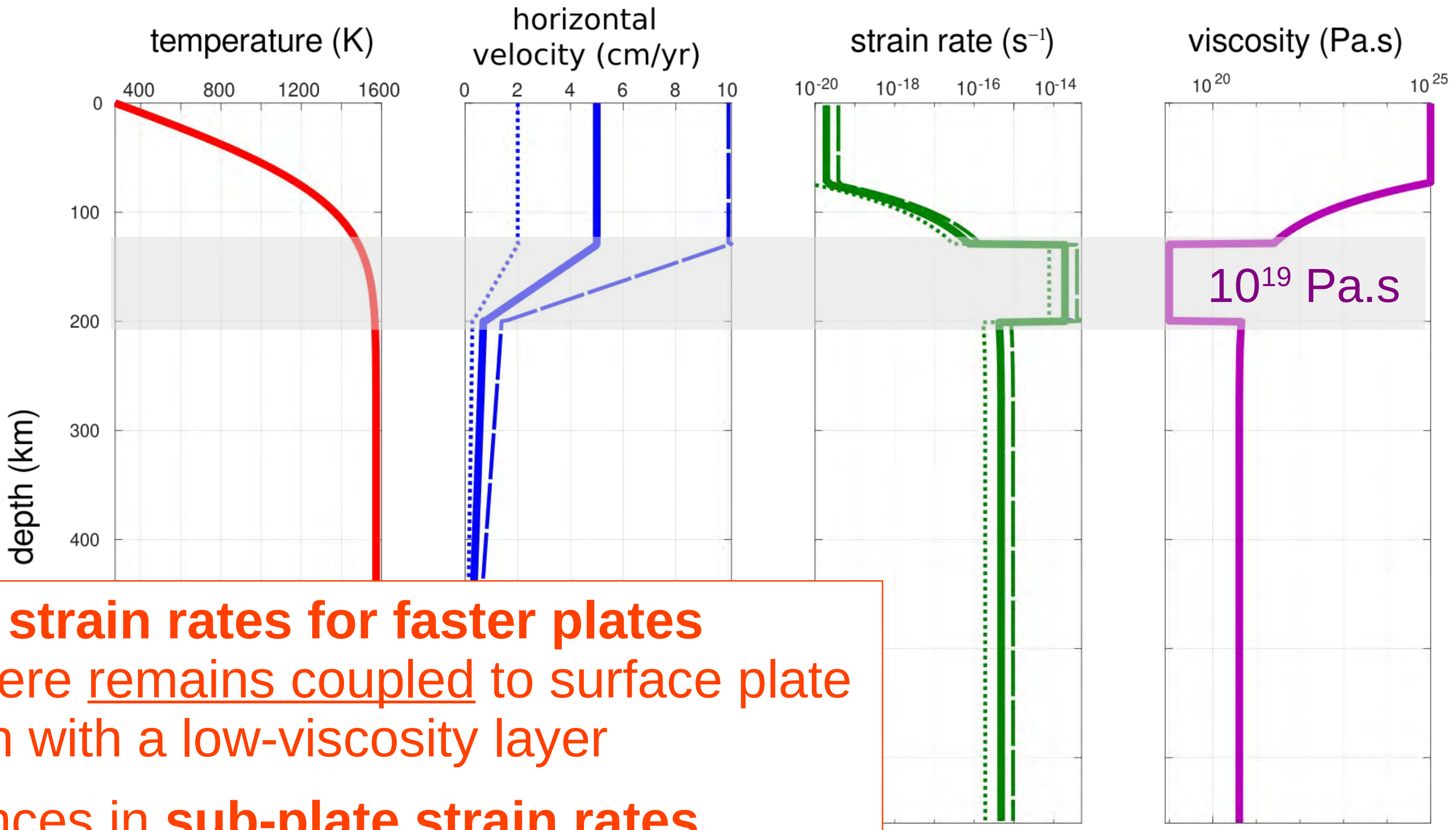


- **higher strain rates for faster plates**

→ asthenosphere <u>remains coupled</u> to surface plate even with a low-viscosity layer

- differences in **<u>sub-plate strain rates</u>** proportional to surface velocity ratio

Estimating the time required to develop crystal-preferred orientation under a constant velocity field

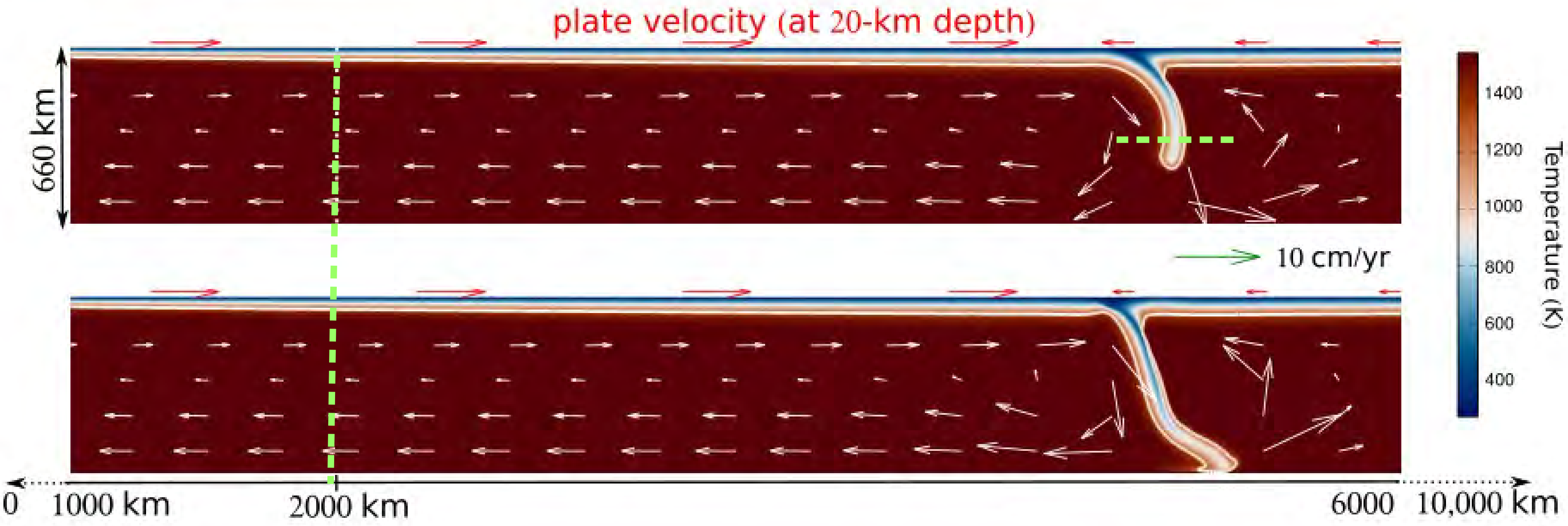
- hyp.: cumulative strain ε of 100 % needed to produce CPO retrievable from seismic anisotropy

- time = strain / strain rate = $\varepsilon / \dot{\varepsilon}$

10^{-14} s^{-1}	↔	3 Myr
10^{-15} s^{-1}	↔	30 Myr
10^{-16} s^{-1}	↔	300 Myr

But plate velocity magnitude and direction are not fixed...

Transient asth. flow driven by subduction



Garel & Thoraval, PEPI, 2021

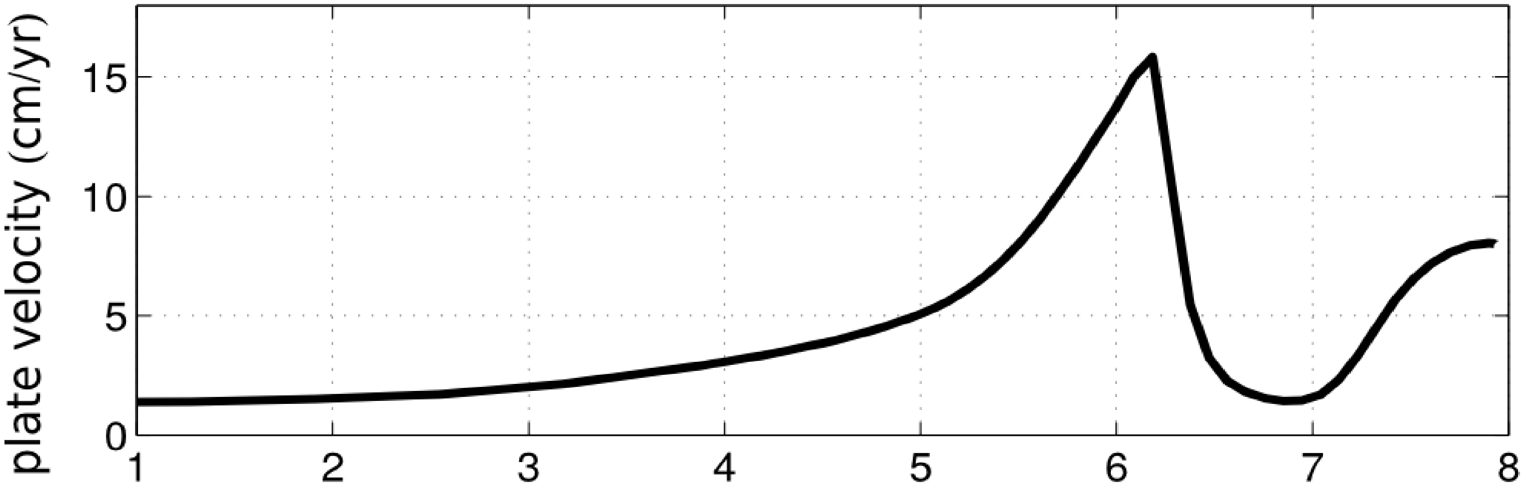


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8

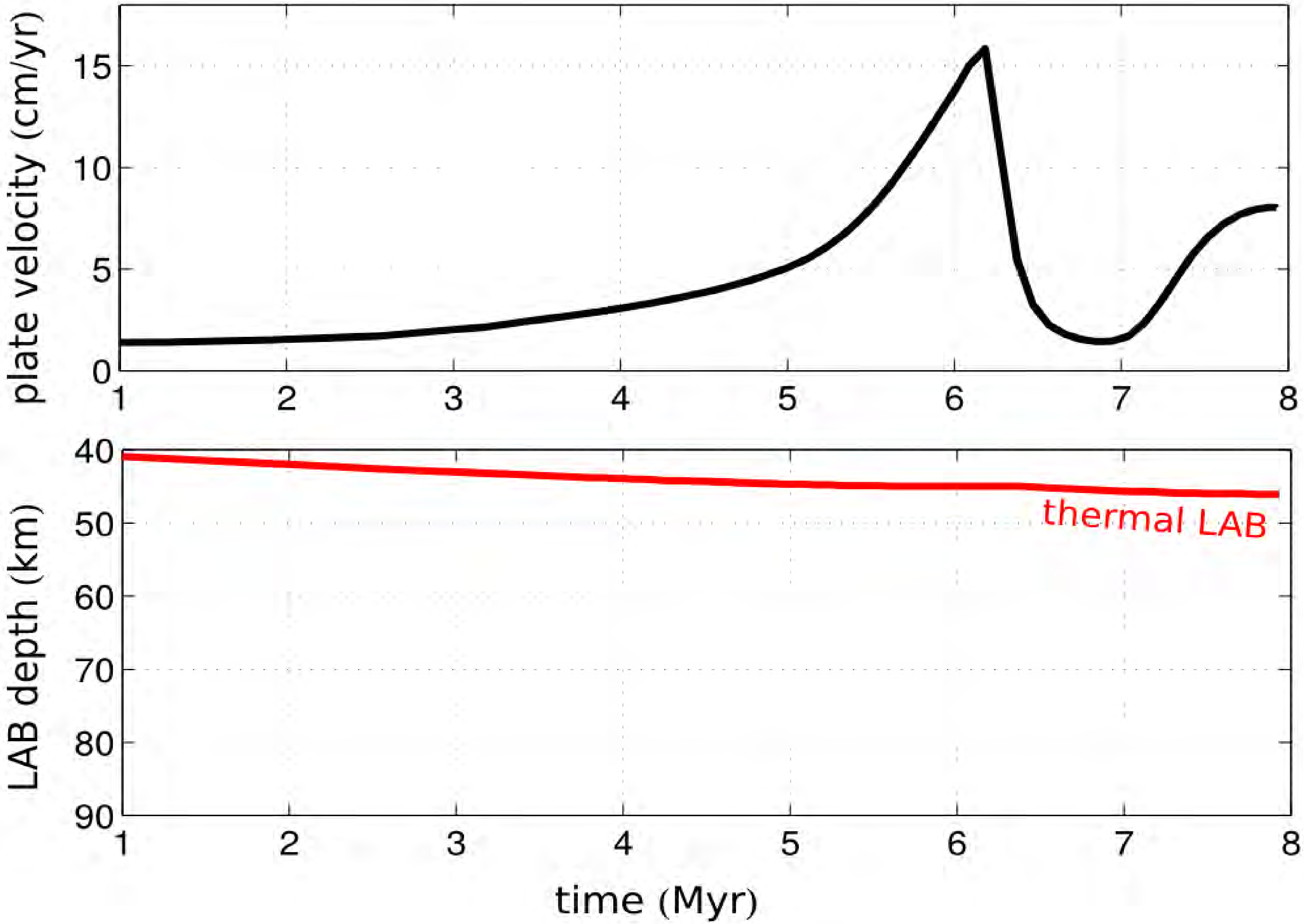


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8
LAB depth (km)
40
50
60
70
80
90
thermal LAB
time (Myr)

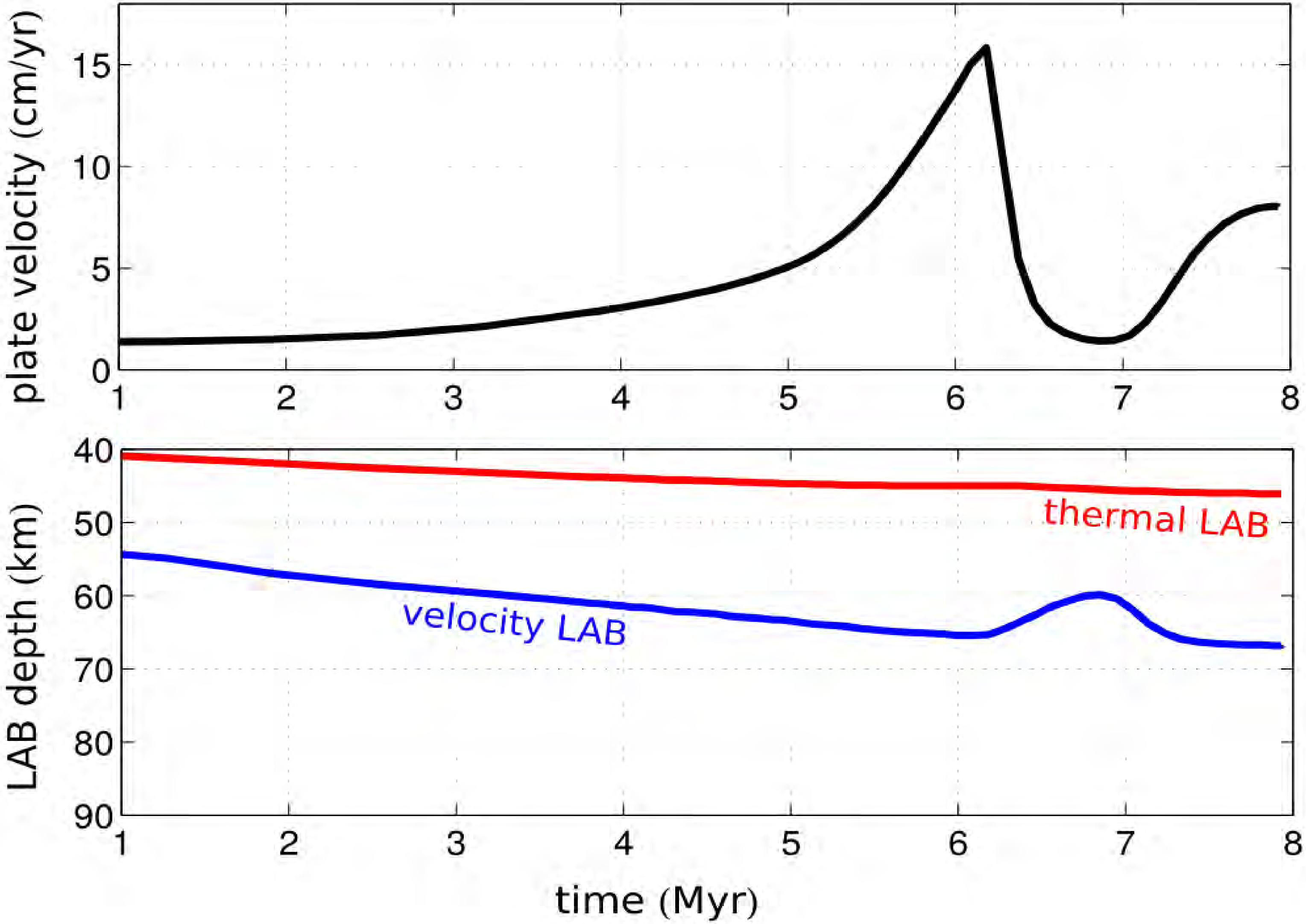


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8
LAB depth (km)
40
50
60
70
80
90
thermal LAB
velocity LAB
time (Myr)

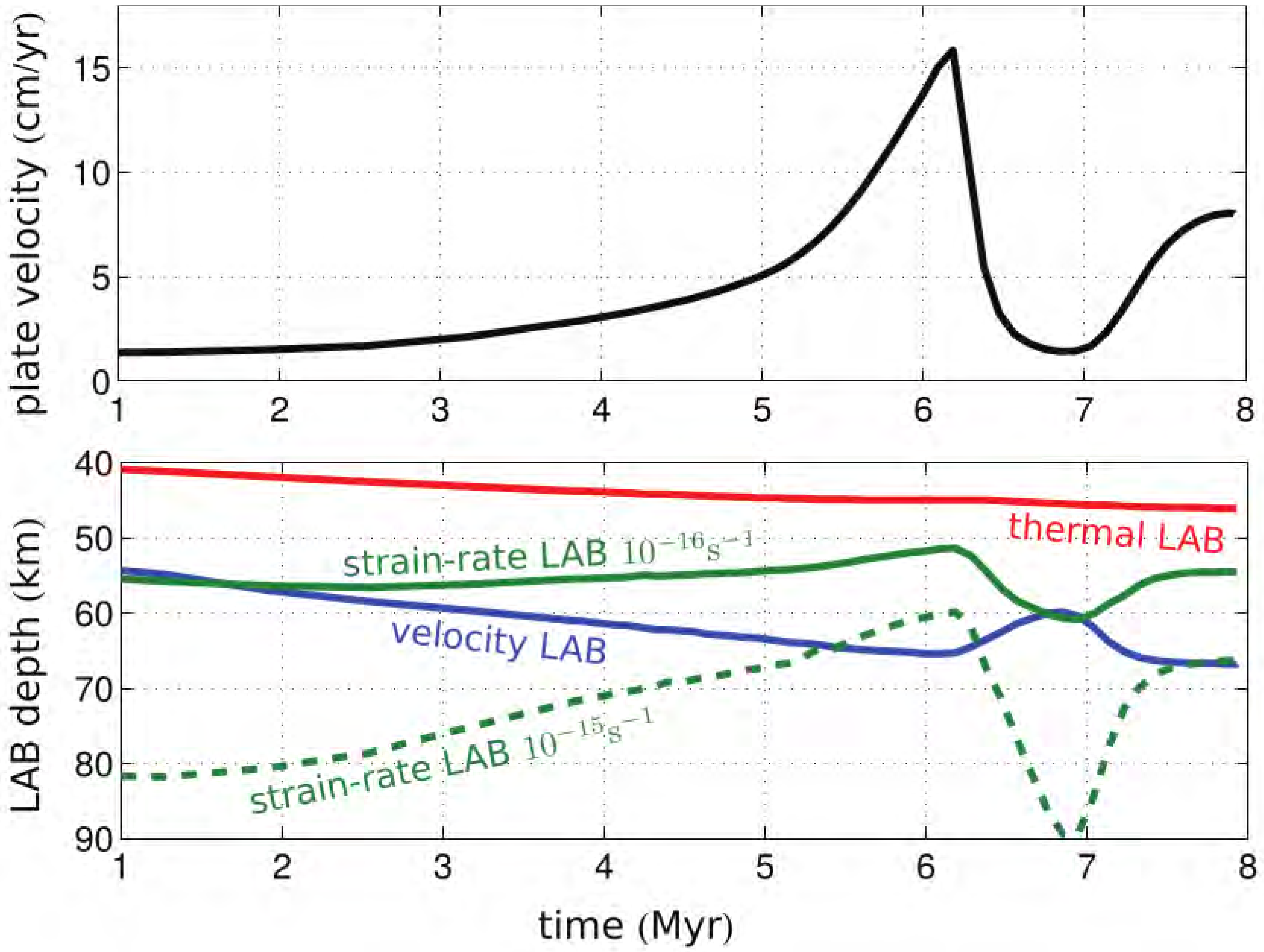
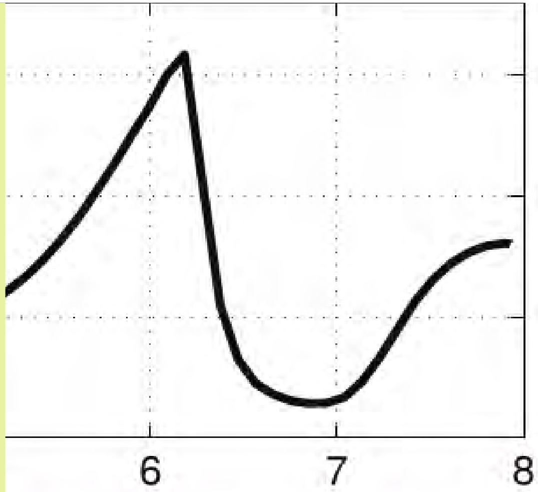
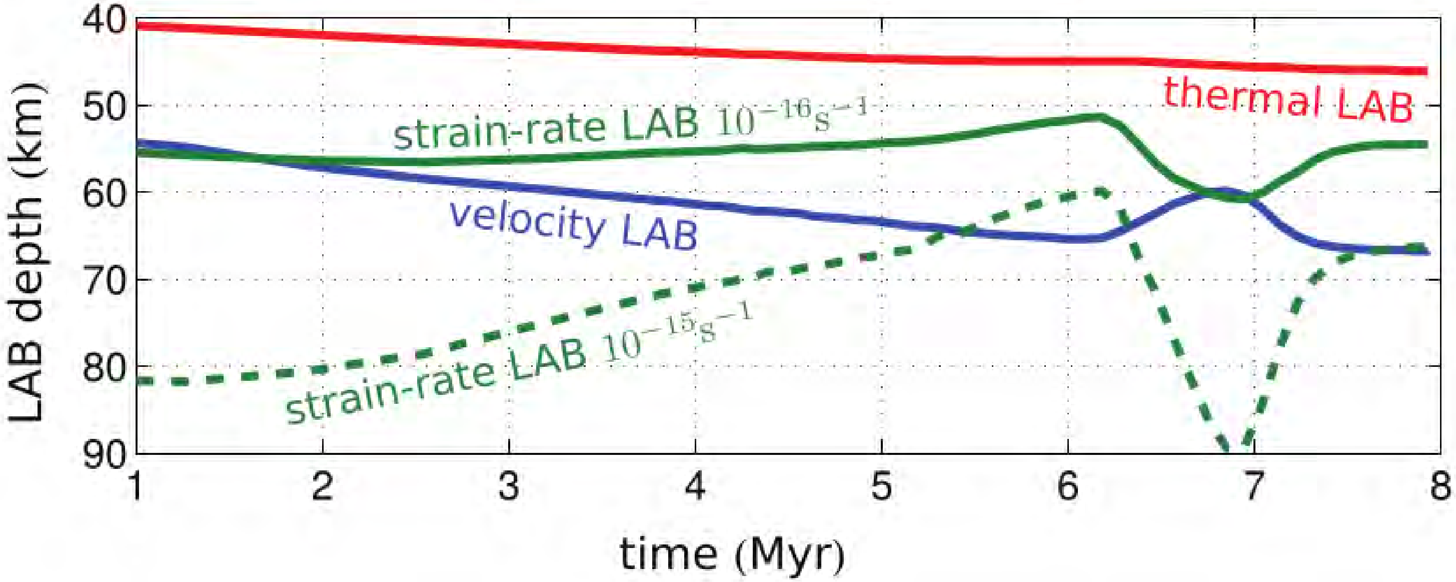


plate velocity (cm/yr)
0
5
10
15
1
2
3
4
5
6
7
8
LAB depth (km)
40
50
60
70
80
90
thermal LAB
strain-rate LAB $10^{-16}s^{-1}$
velocity LAB
strain-rate LAB $10^{-15}s^{-1}$
1
2
3
4
5
6
7
8
time (Myr)

lower strain rates reached at depth when plate decelerates (and vice-versa)

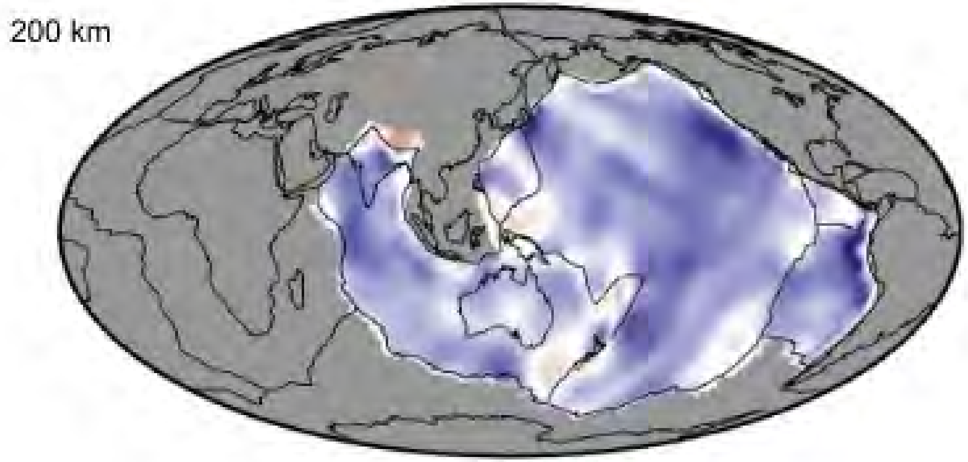
→ if a plate slows down, past CPO will persist longer for lower strain rate (slower plate)



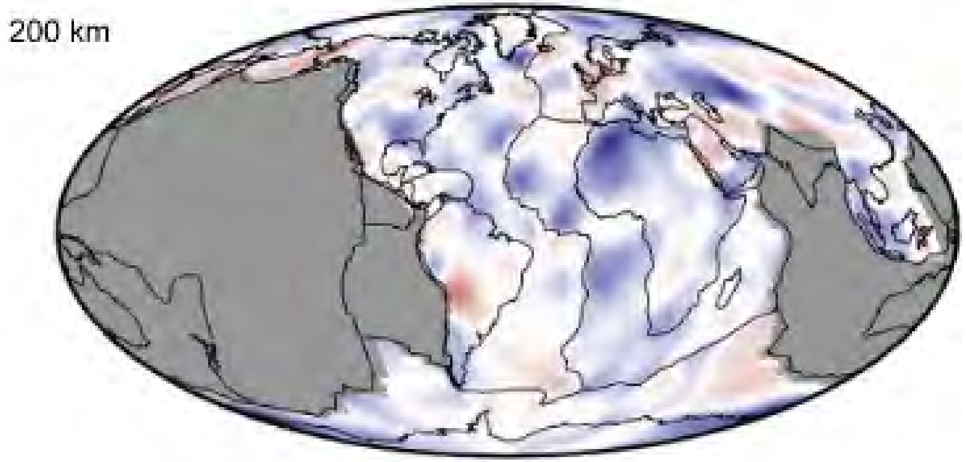


Agreement between fast direction of S_v waves and present-day absolute plate motion (from NUVEL-1A)

blue = parallelism **red = orthogonality**



Fast-moving plates

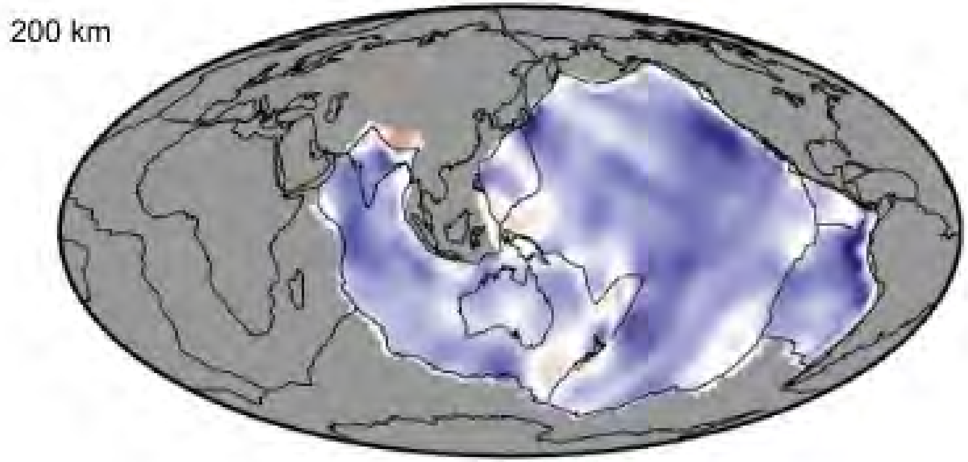


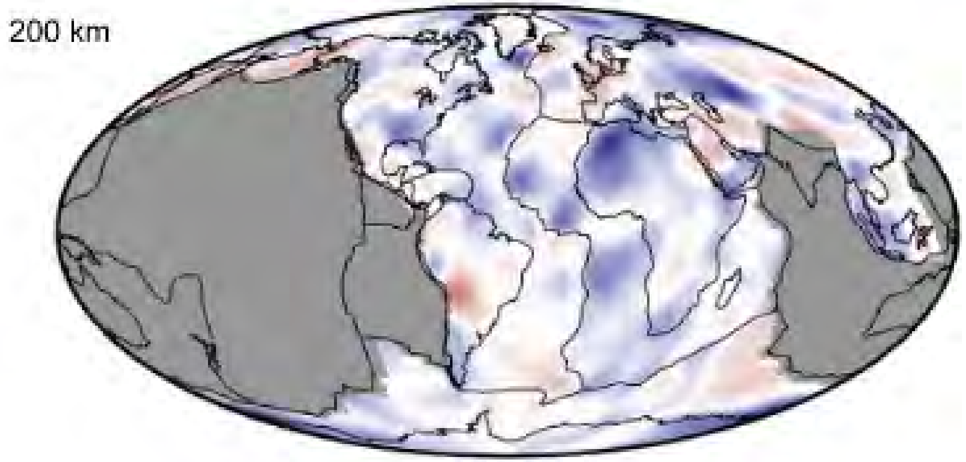
Slow-moving plates

Debayle & Ricard, 2013

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

blue = parallelism **red = orthogonality**





Fast-moving plates

Slow-moving plates

insufficient strain rates in the asthenosphere to generate CPO aligned with plate motion in less than 30 Myr

Debayle & Ricard, 2013

First conclusions

- From thermo-mechanical models :

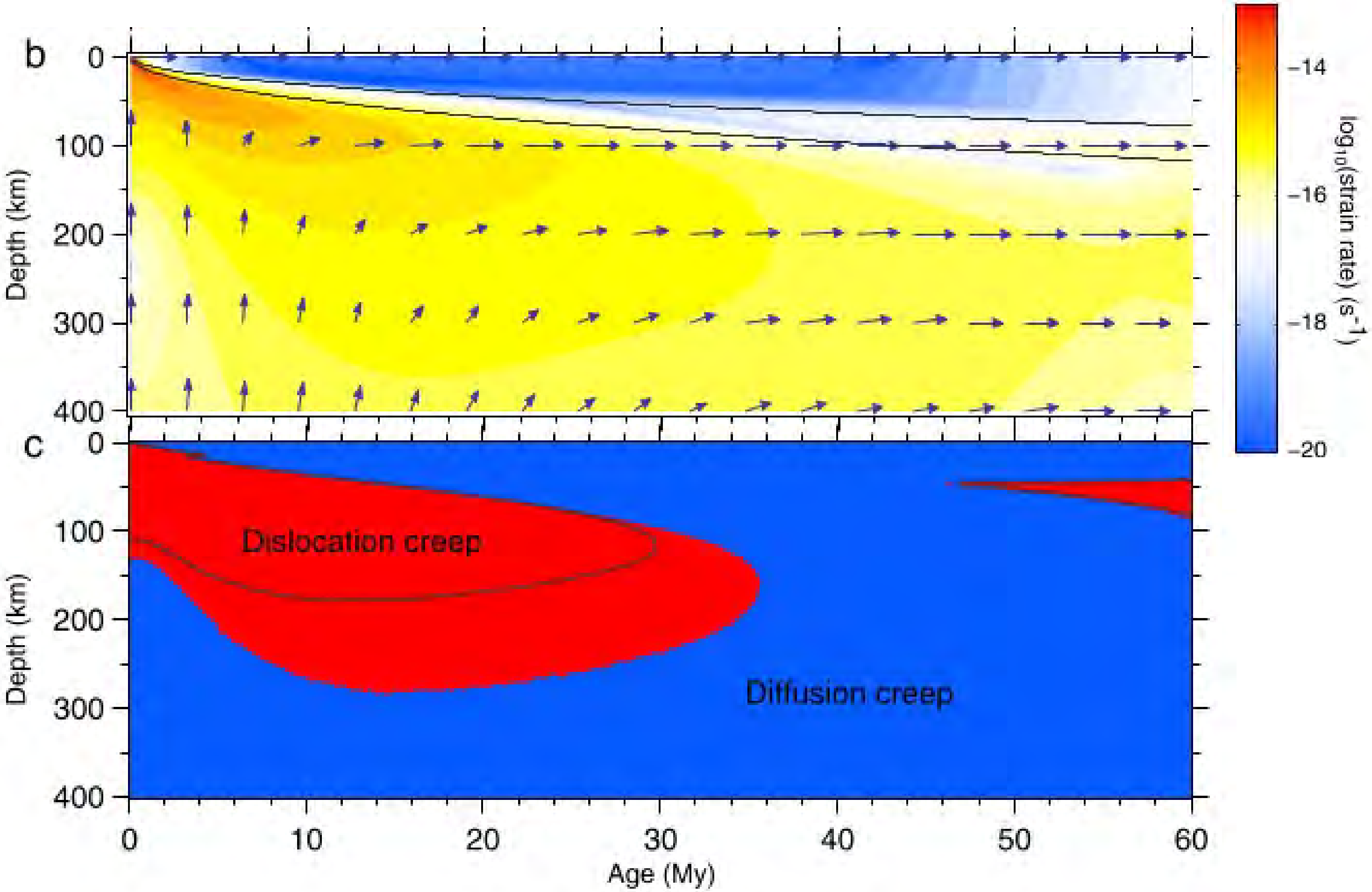
→ a dynamical transition from a **constant-velocity plate** to the underlying mantle appears self-consistently due to viscosity decrease with depth

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

- Even with a low-viscosity layer, asthenosphere flow and strain rates depend on surface plate velocities

- **Below slow plates anisotropy fast axis direction may align with past mantle flow** because of the long time-scales required to develop mantle CPO under small strain rates

Complexifing models towards the real Earth : dislocation vs. diffusion creep regimes



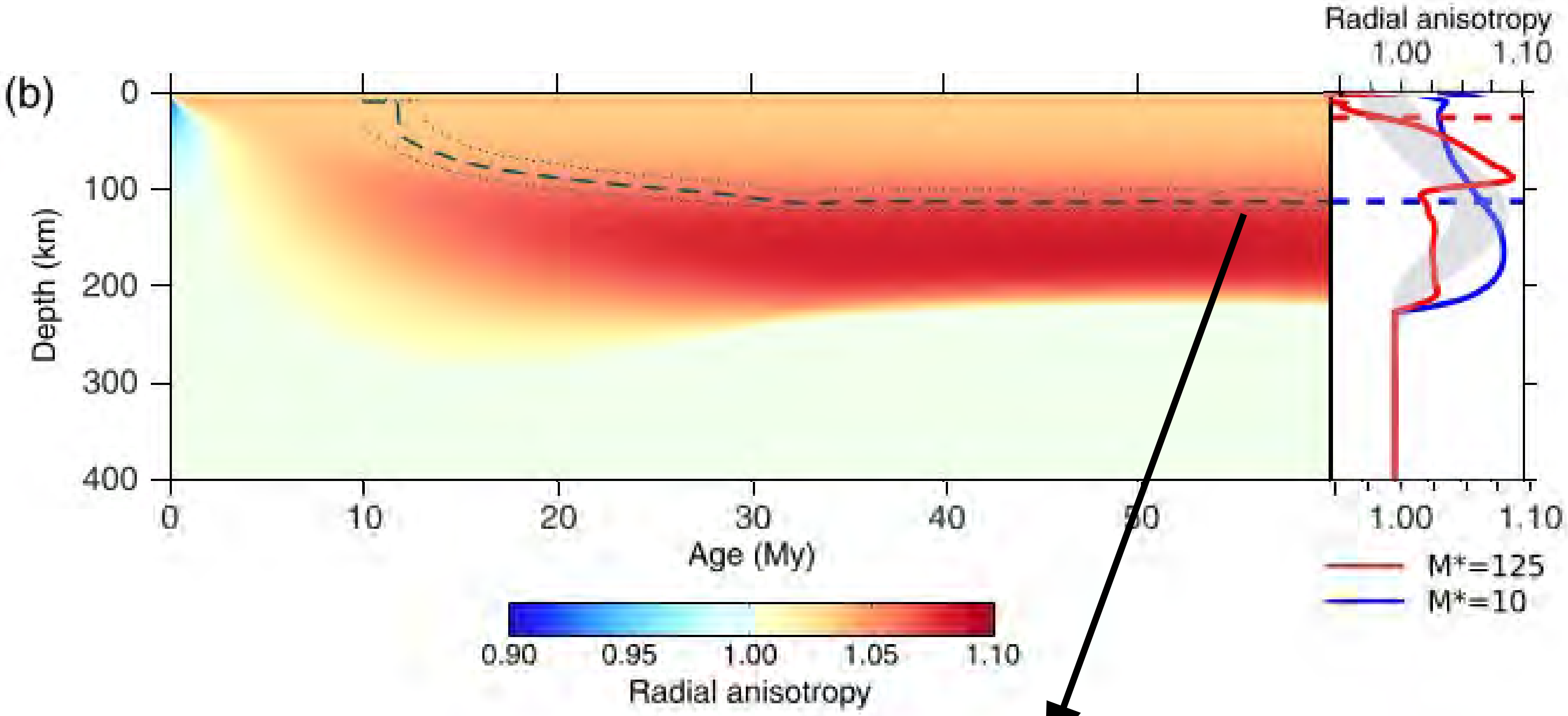
Steady-state flow model below a plate

+ composite rheology (diff + disl creep)

+ D-Rex calculation of anisotropy

Hedjazian et al., EPSL 2017

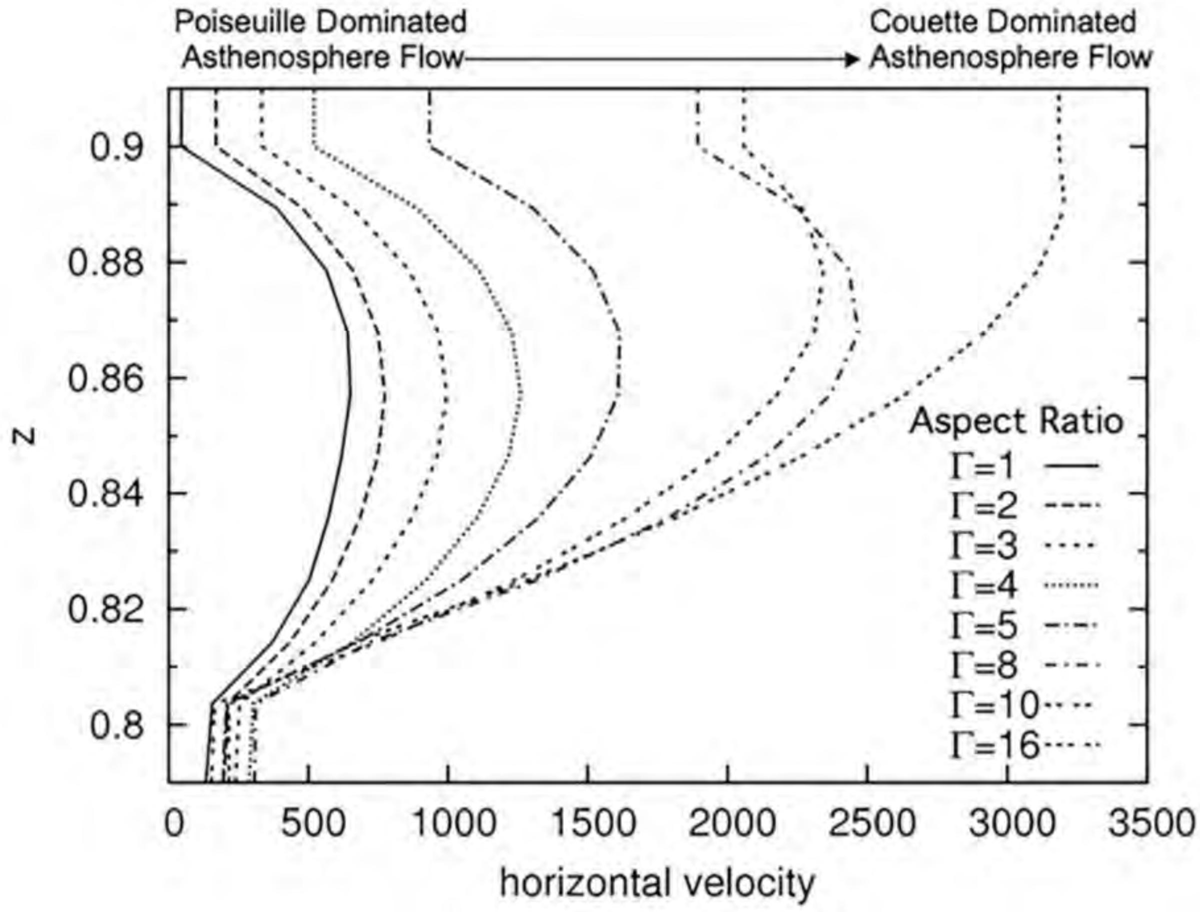
Complexifing models towards the real Earth : dislocation vs. diffusion creep regimes



age-independent radial seismic anisotropy !

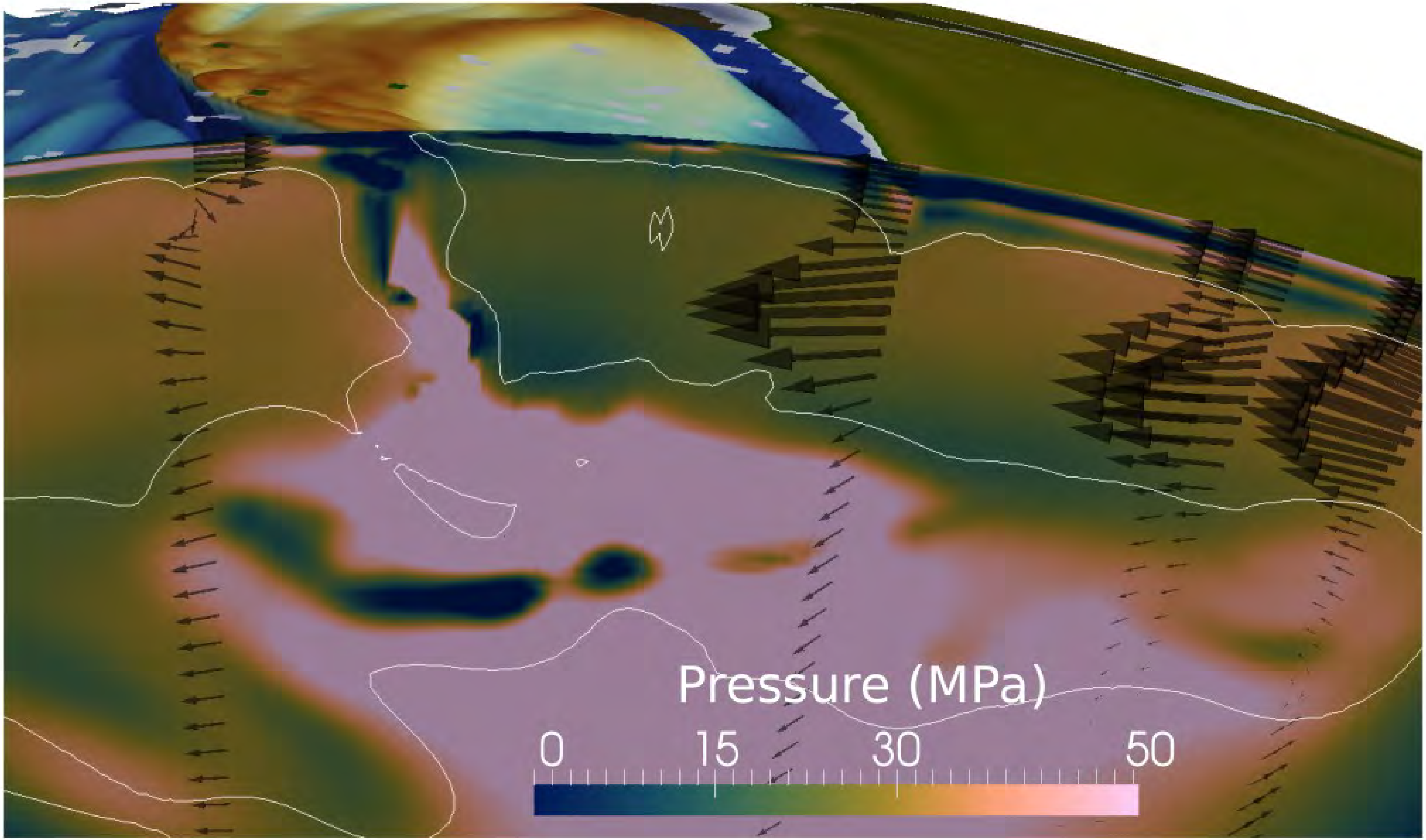
Hedjazian et al., EPSL 2017

Complexifing models towards the real Earth : Couette vs. Poiseuille flows



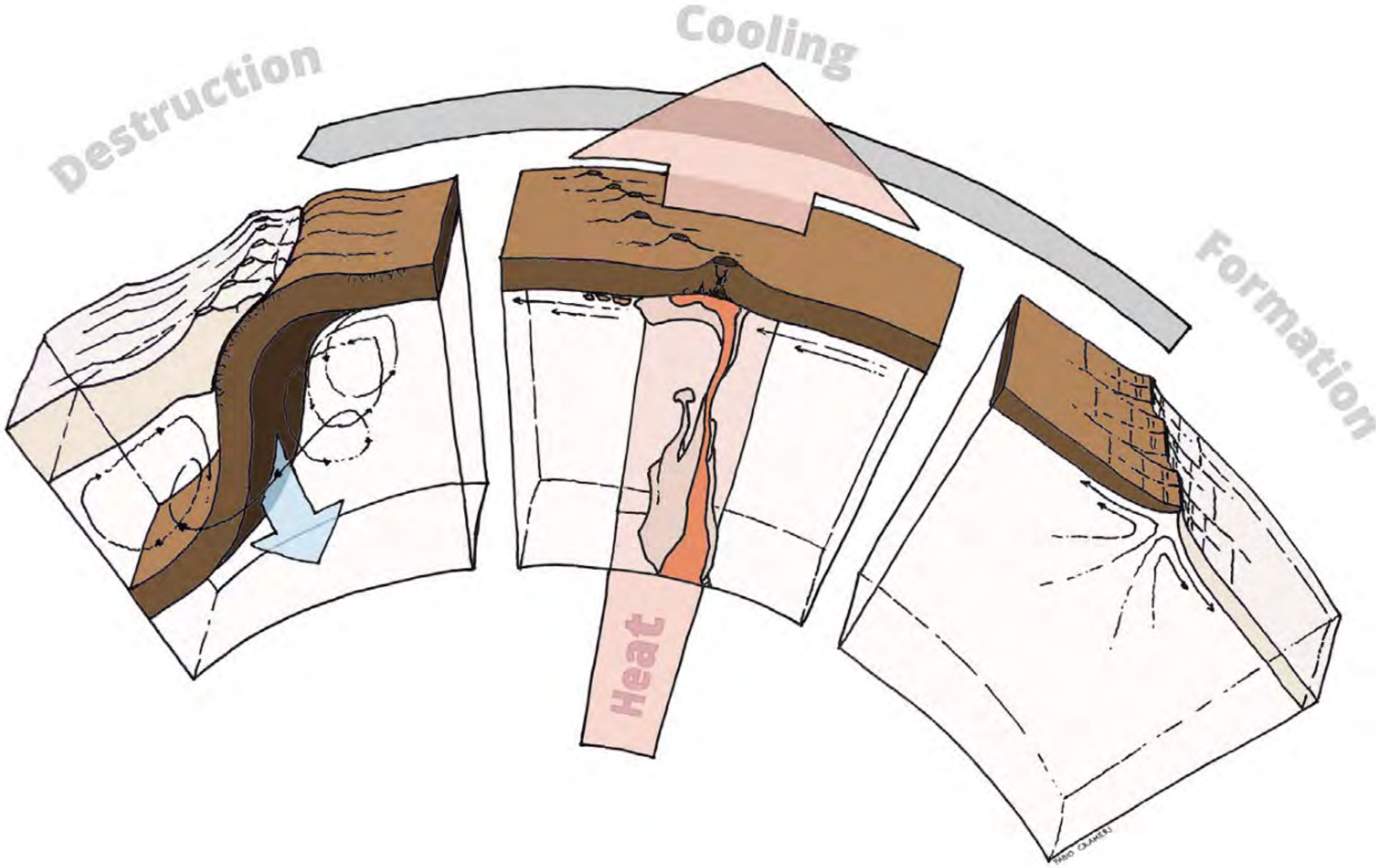
constant-velocity plate also observed for 'active' asthenosphere flow

Hoink and Lenardic, 2010
Richards and Lenardic, 2018



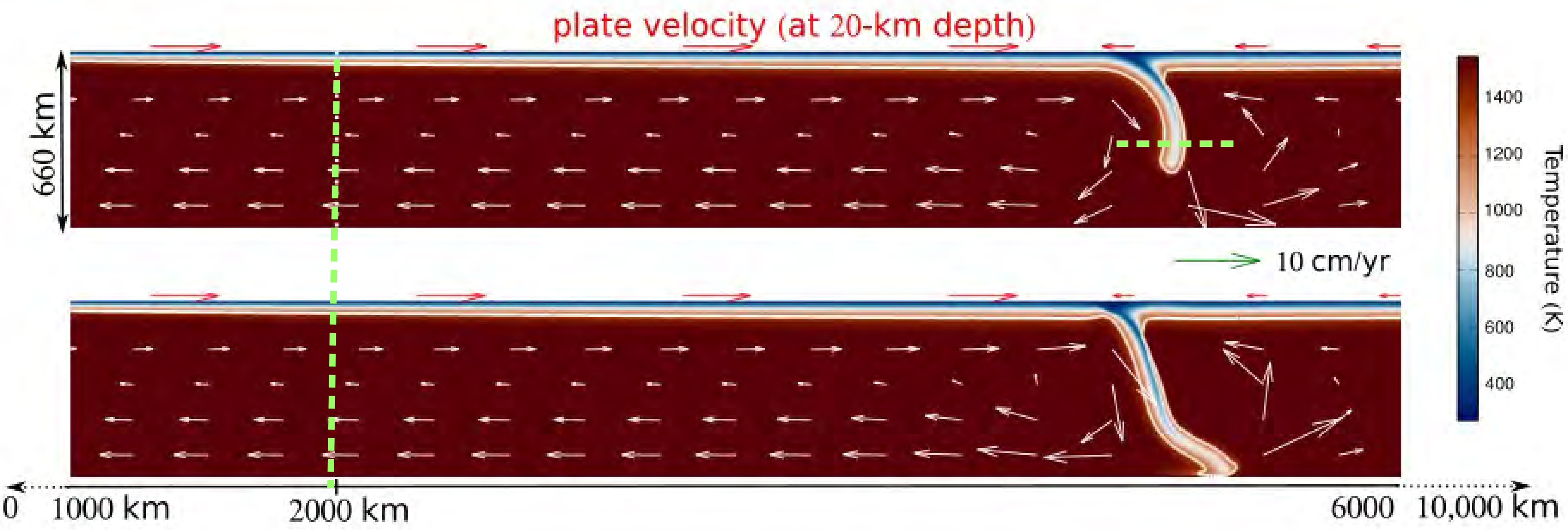
Coltice et al., Science Adv., 2019

Complexifing models towards the real Earth : LAB in sinking slabs



Crameri et al., Tectonophysics, 2019

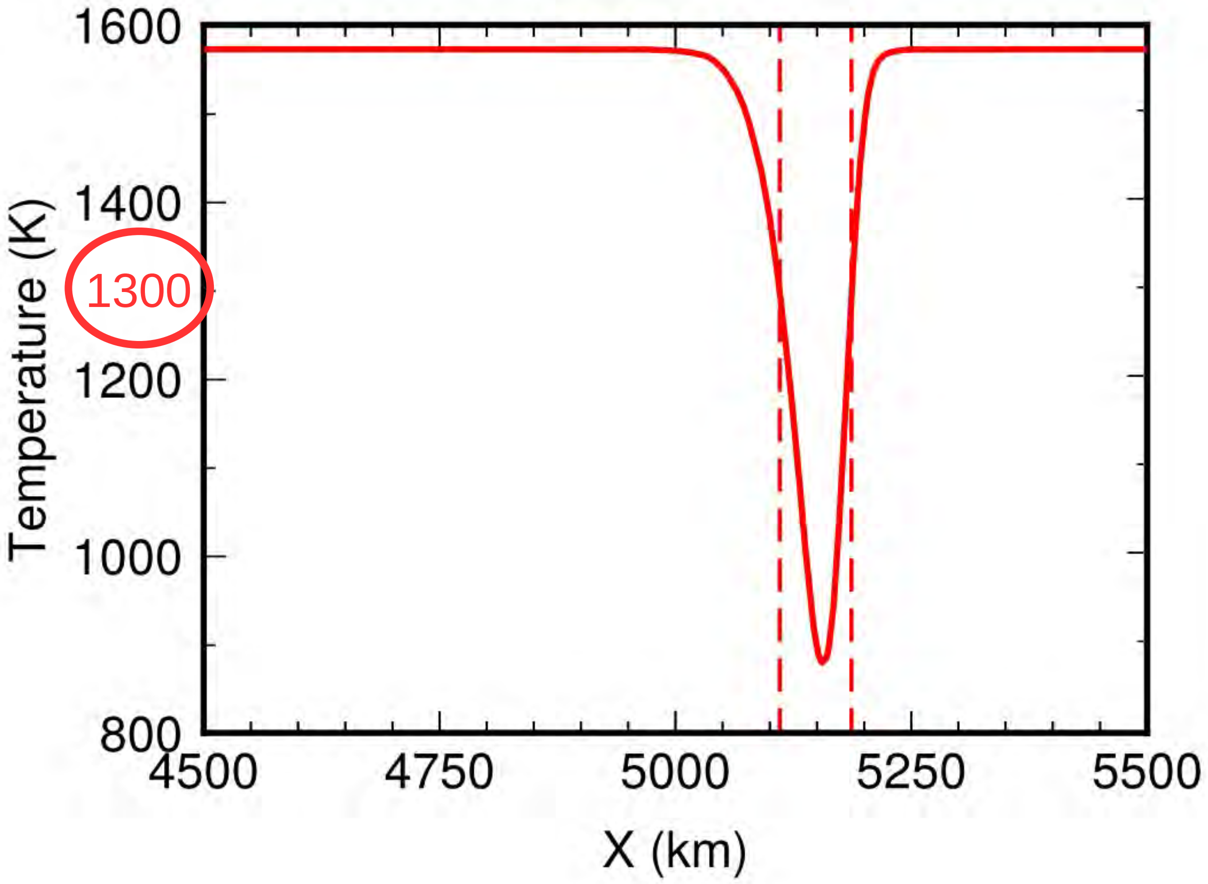
Transient asth. flow driven by subduction



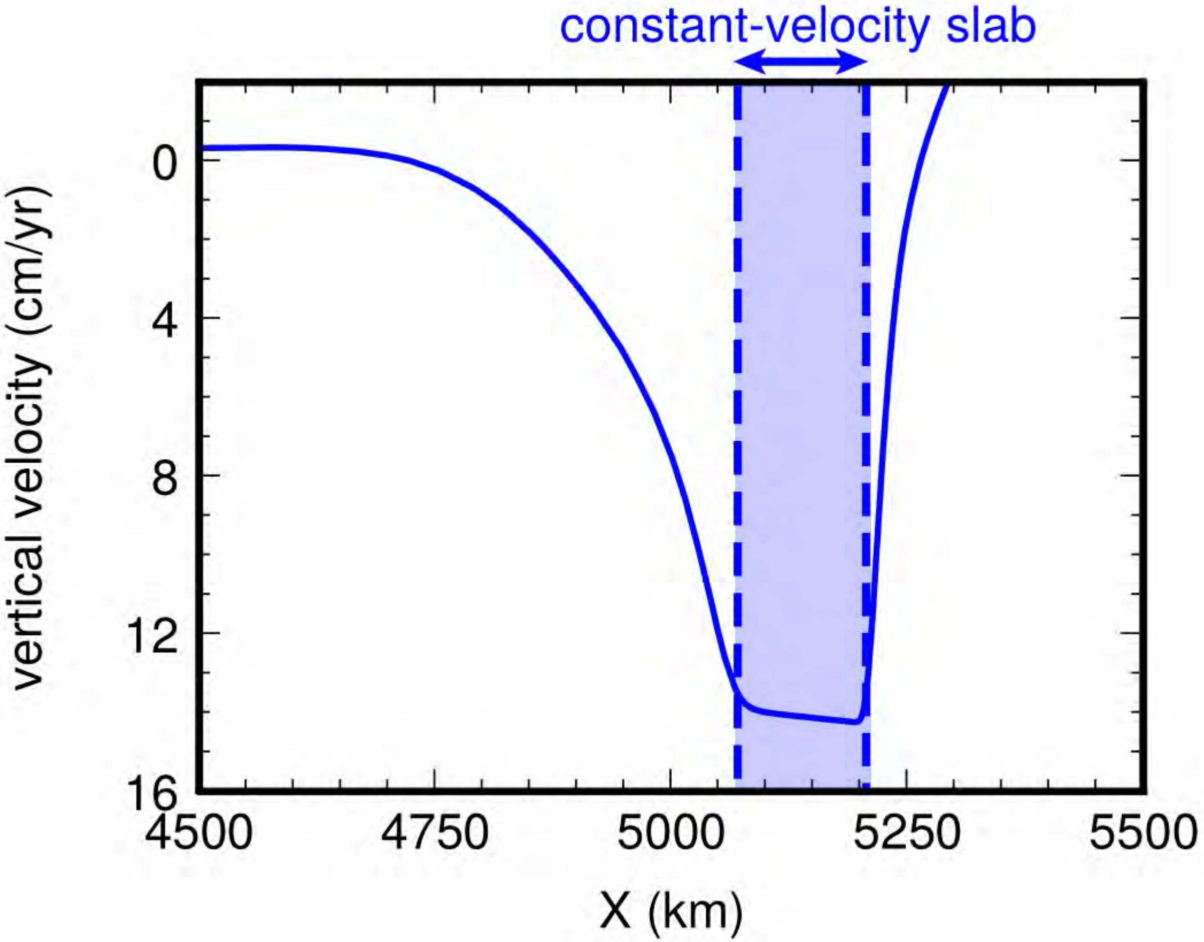
Profile across the fast-sinking plate in the upper mantle

Garel & Thoraval, PEPI, 2021

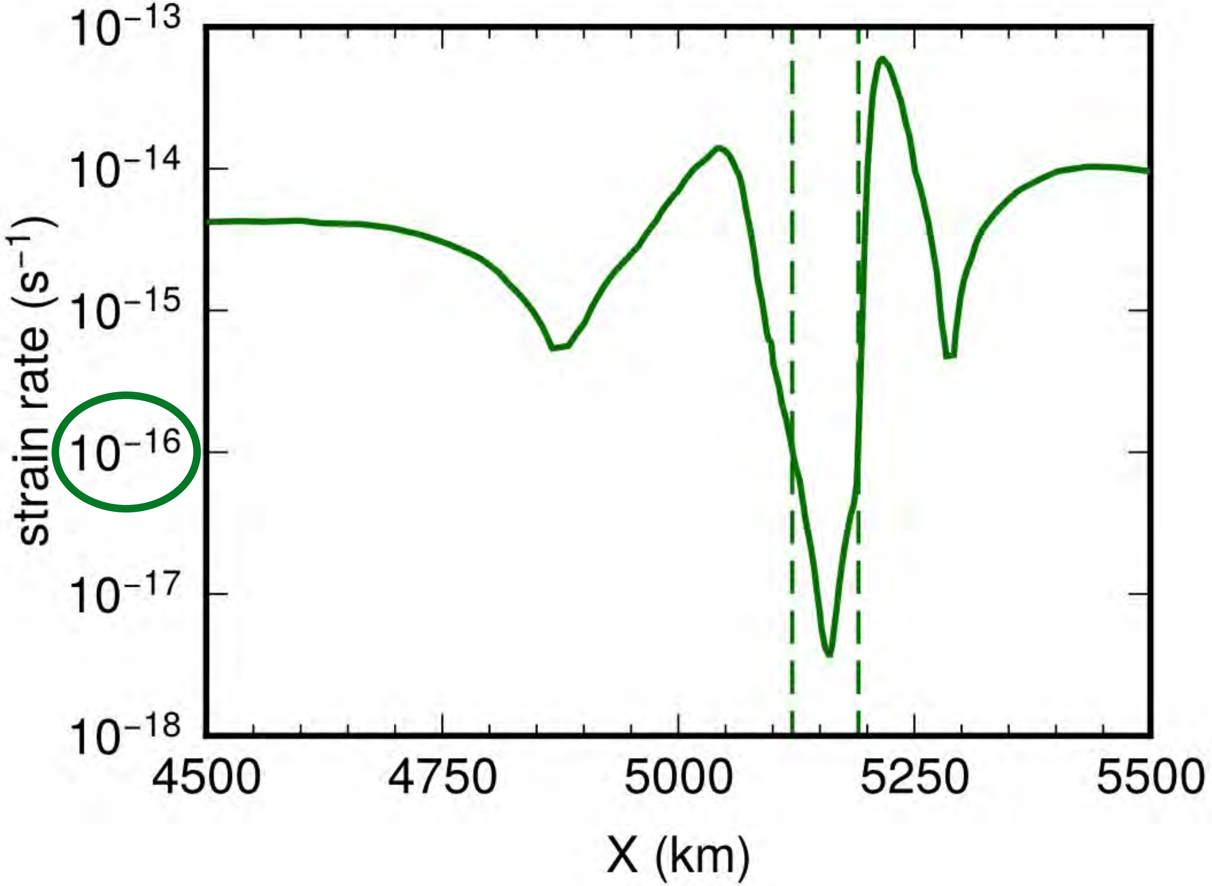
Transient asth. flow driven by subduction



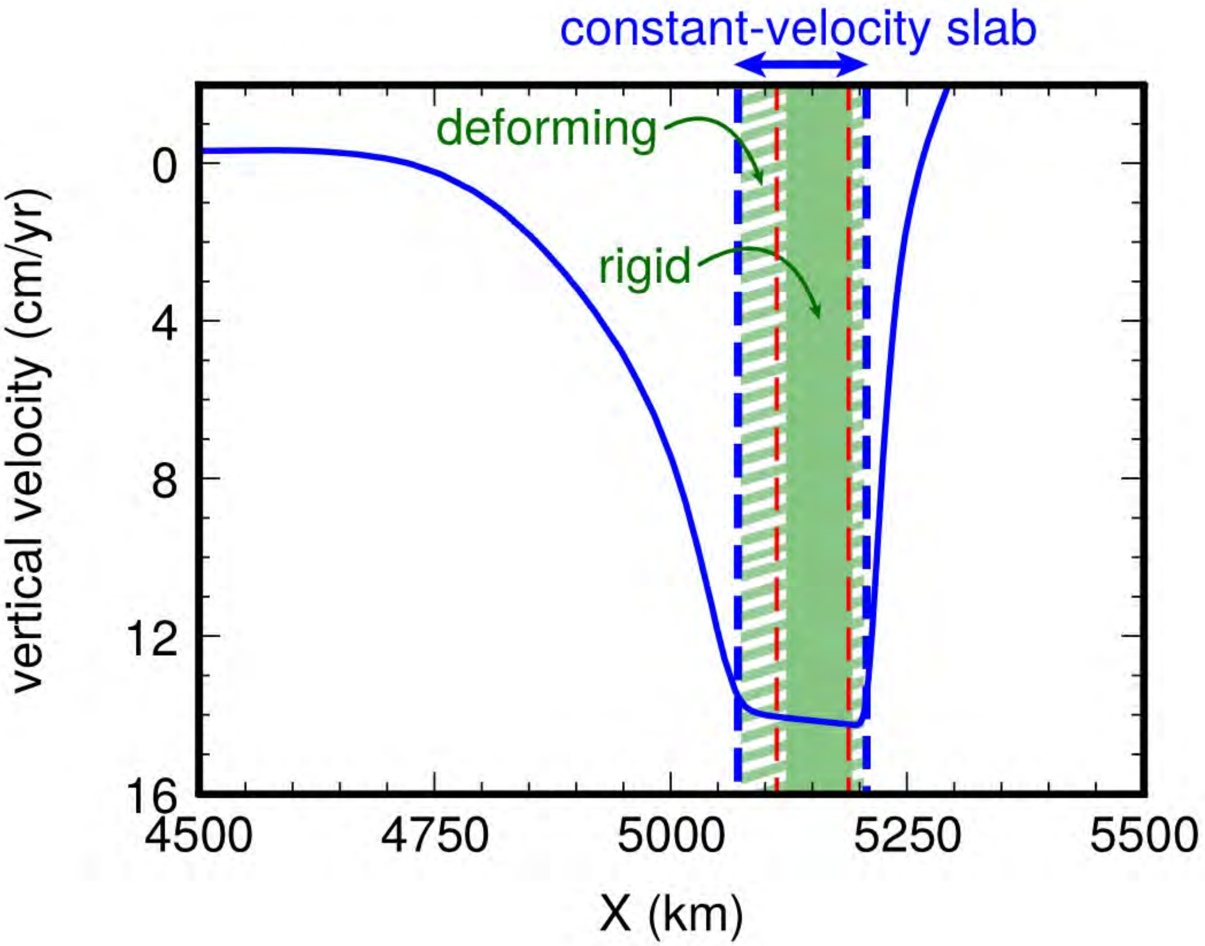
Transient asth. flow driven by subduction



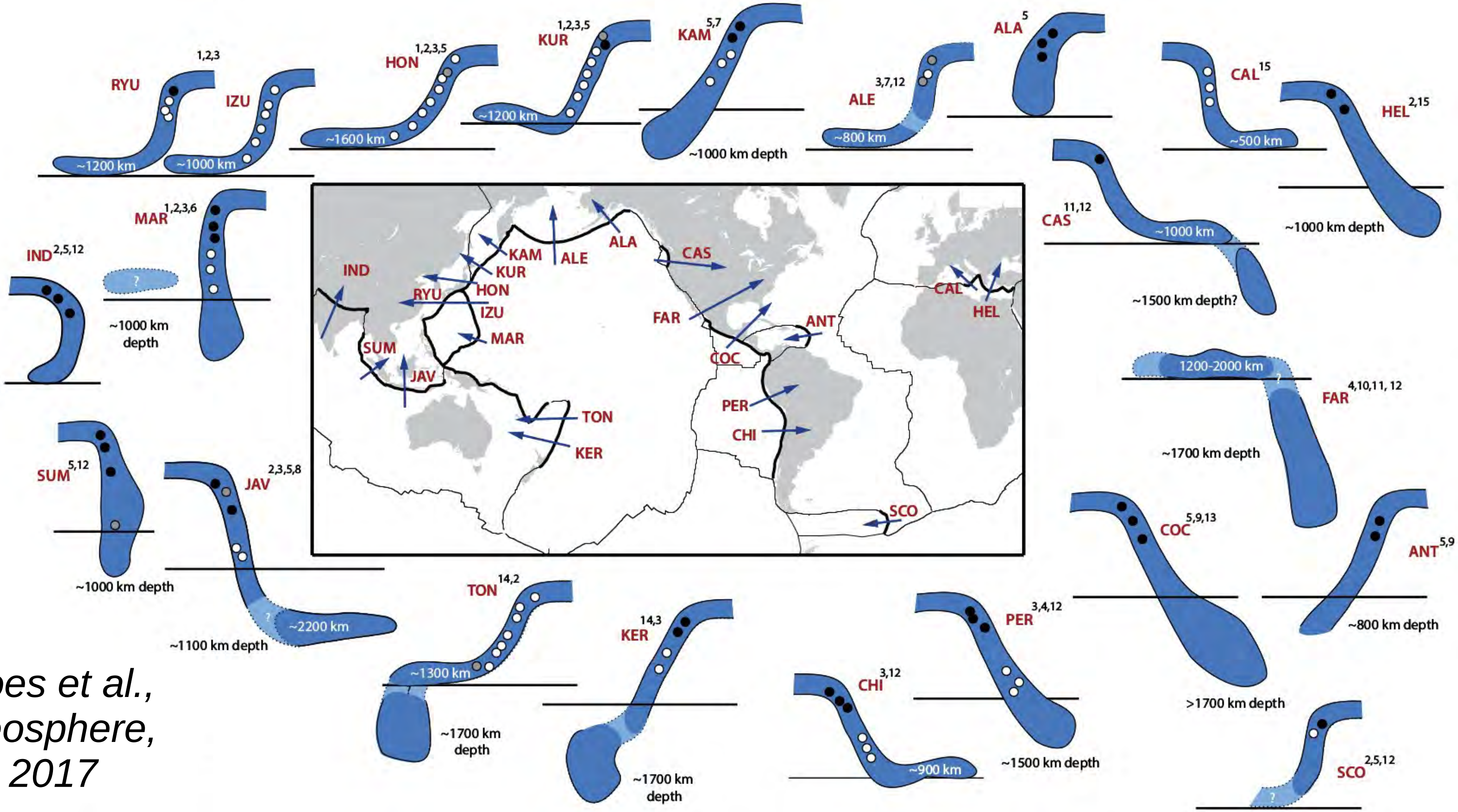
Transient asth. flow driven by subduction



Transient asth. flow driven by subduction



Mass transfers between upper and lower mantle through asthenosphere dragged by cold slabs ?



Goes et al., Geosphere, 2017