Lithospheric plates : a dynamical perspective

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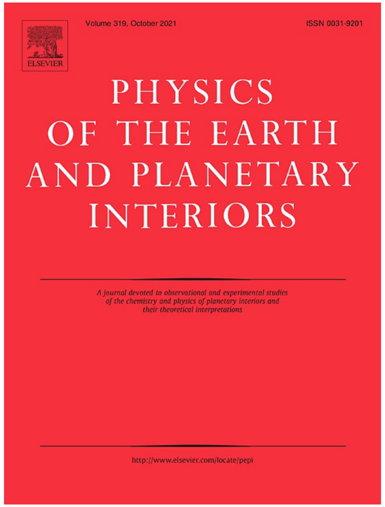
Deep Earth Doctoral School - Les Houches - Autumn 2022

ÉCOLE DE PHYSIQUE DES HOUCHES

Dynamical definition of surface plates and subducting slabs



PEPI special issue 20-21

Physical properties and observations of the lithosphere-asthenosphere system

Editors : Rick Aster, Saskia Goes, Derek Schutt

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

...

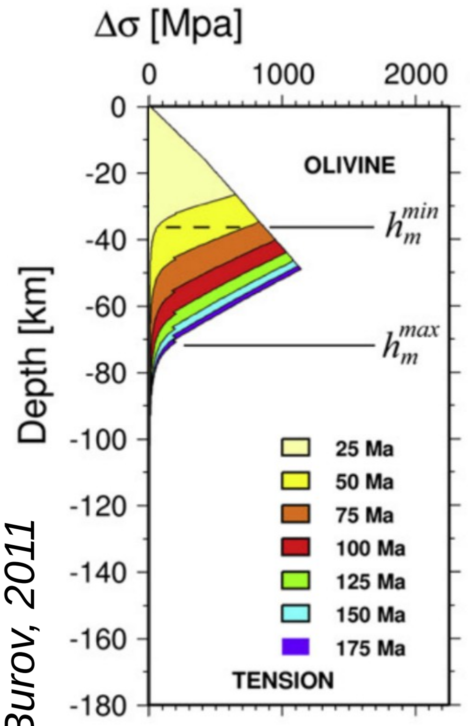
- **Thermal structures of slabs from gravimetry ?**
- **Breaking plates from below with dislocation creep ?**

anr RheoBreak

2022-2026

ANR-21-CE49-0009

Concepts and proxies of plates & LAB



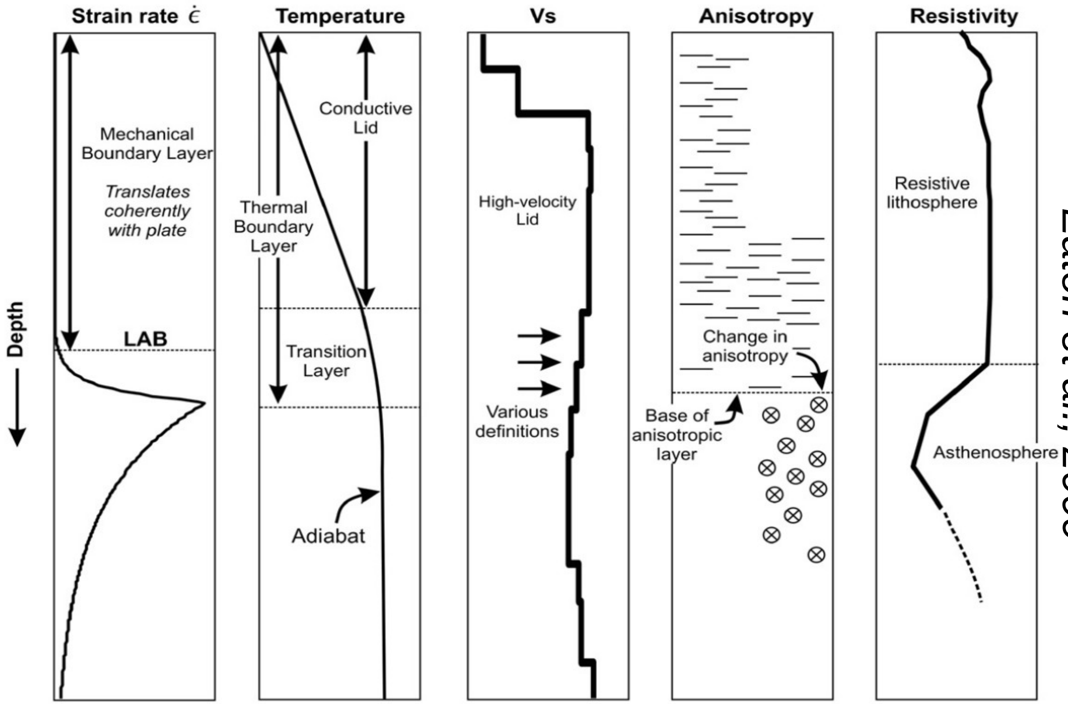
Burov, 2011

cold, strong, boundary-layer lithosphere

vs.

hot, soft, convective asthenosphere

bathymetry, heat flow, flexure, shear wave velocity, radial anisotropy...

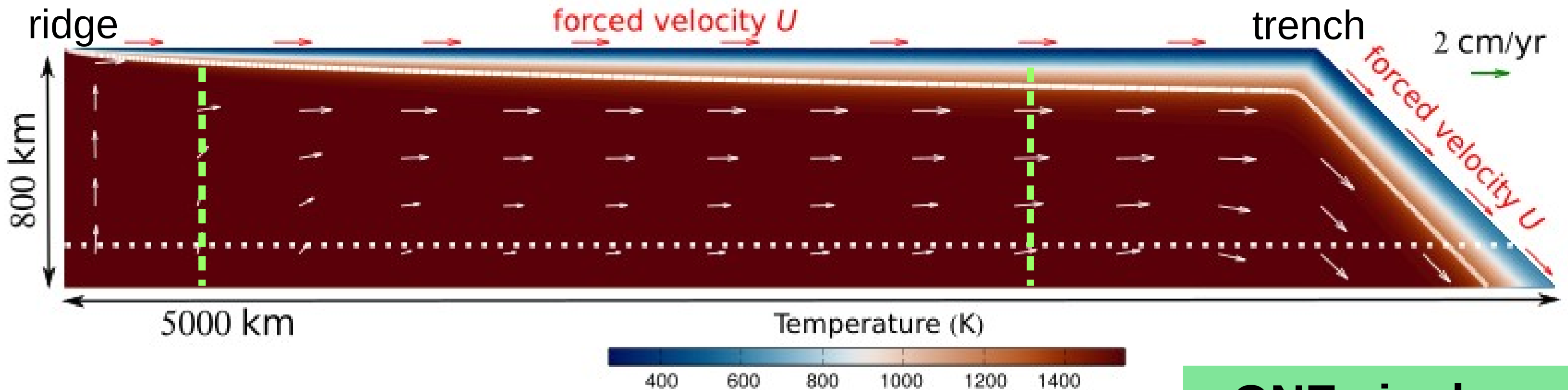


Eaton et al., 2009

→ velocity profile with depth ? evolution with time ?

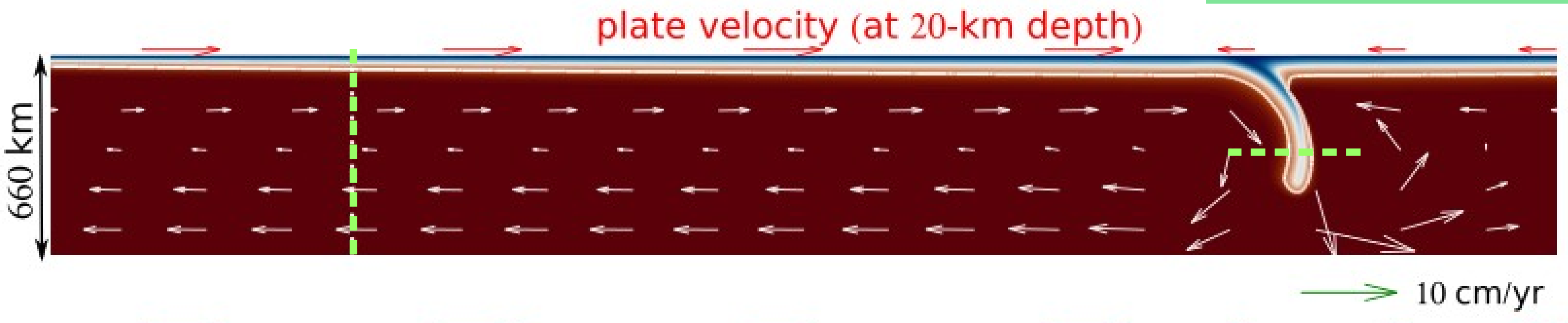
Finite-element thermo-mechanical models

> plate-driven set-up : steady-state



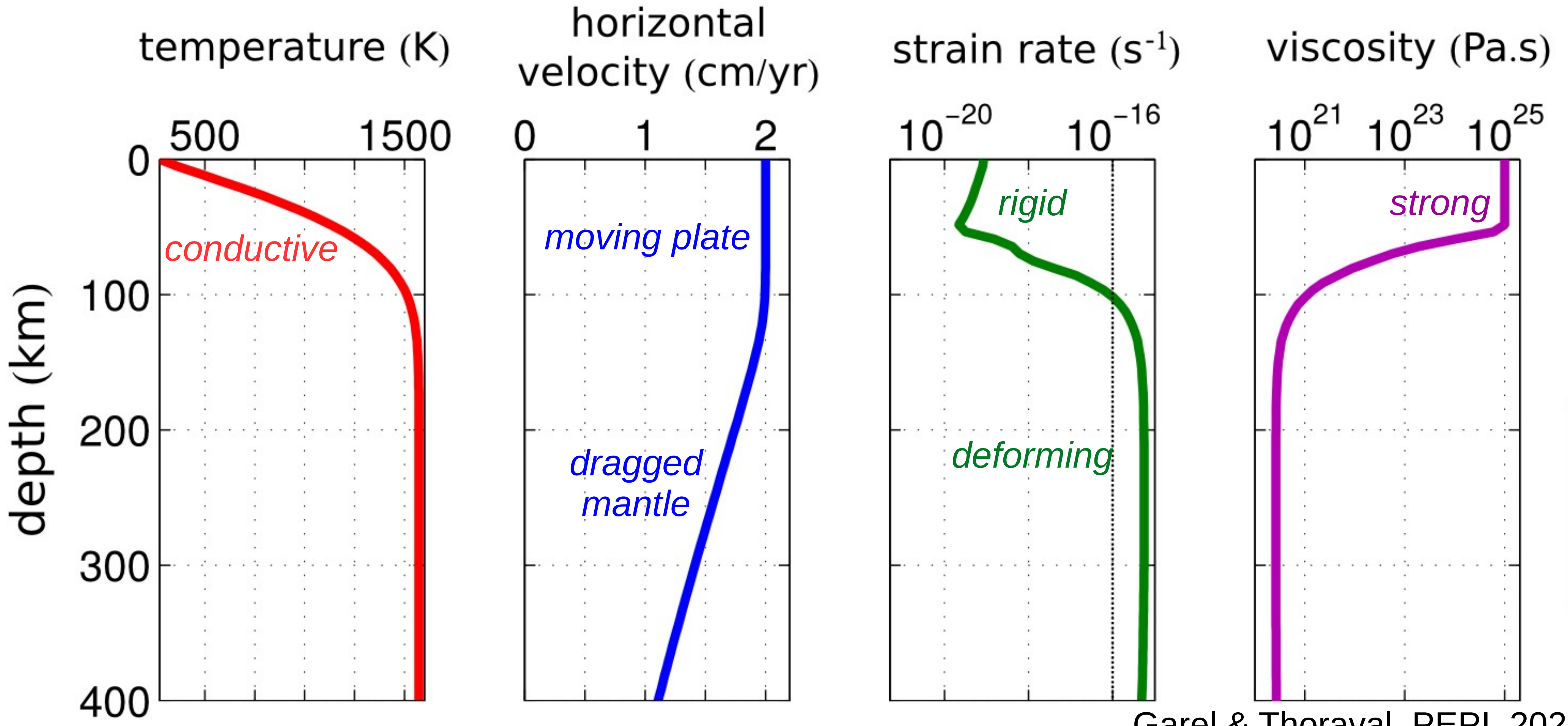
ONE single material for both lithosphere and asthenophere
(no pre-imposed discontinuity)

> free subduction set-up : time-evolving



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

PLATE-DRIVEN



Garel & Thoraval, PEPI, 2021

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

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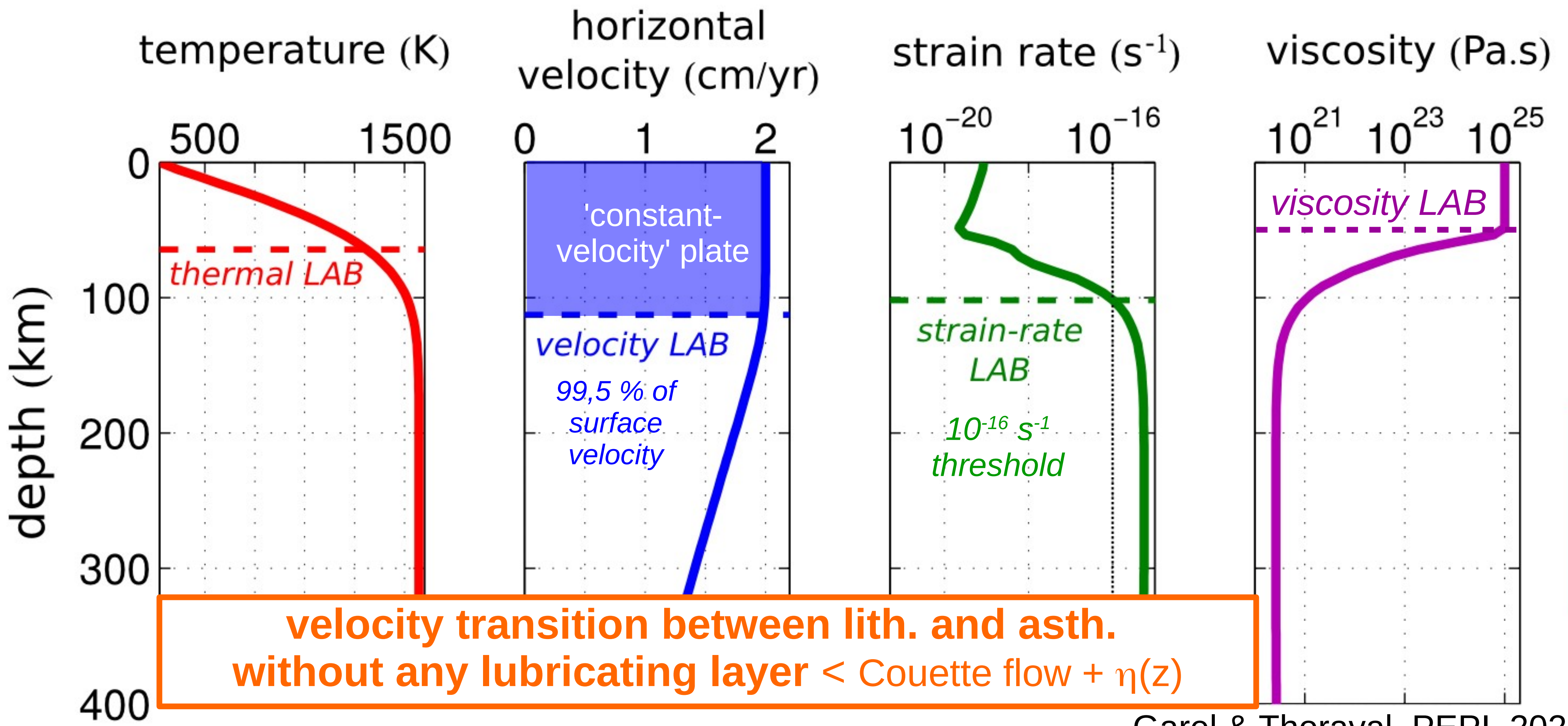
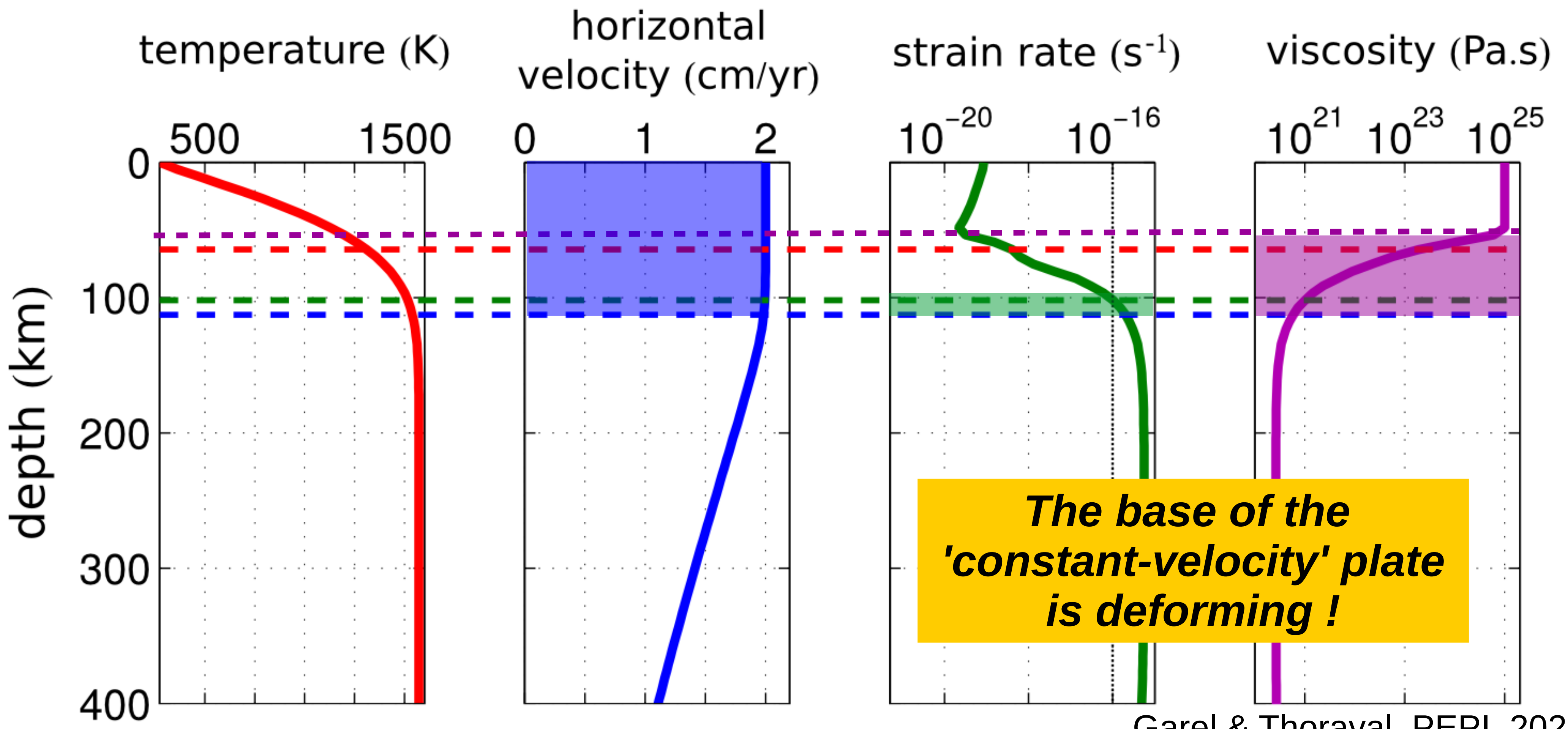


velocity transition between lith. and asth.
without any lubricating layer < Couette flow + η(z)

Garel & Thoraval, PEPI, 2021

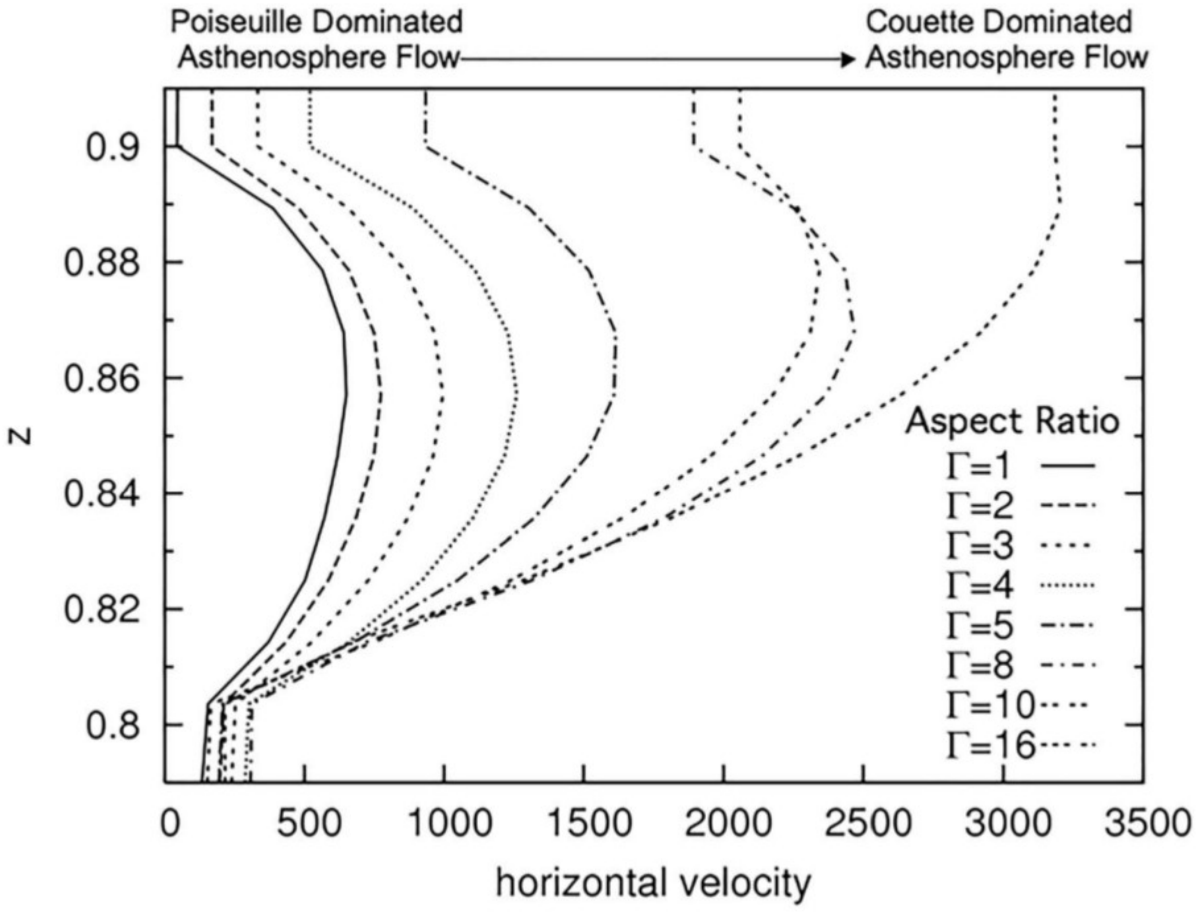
Vertical profiles below a moving plate (2 cm/yr)

PLATE-DRIVEN



Garel & Thoraval, PEPI, 2021

Dynamical plate in Couette or Poiseuille flows

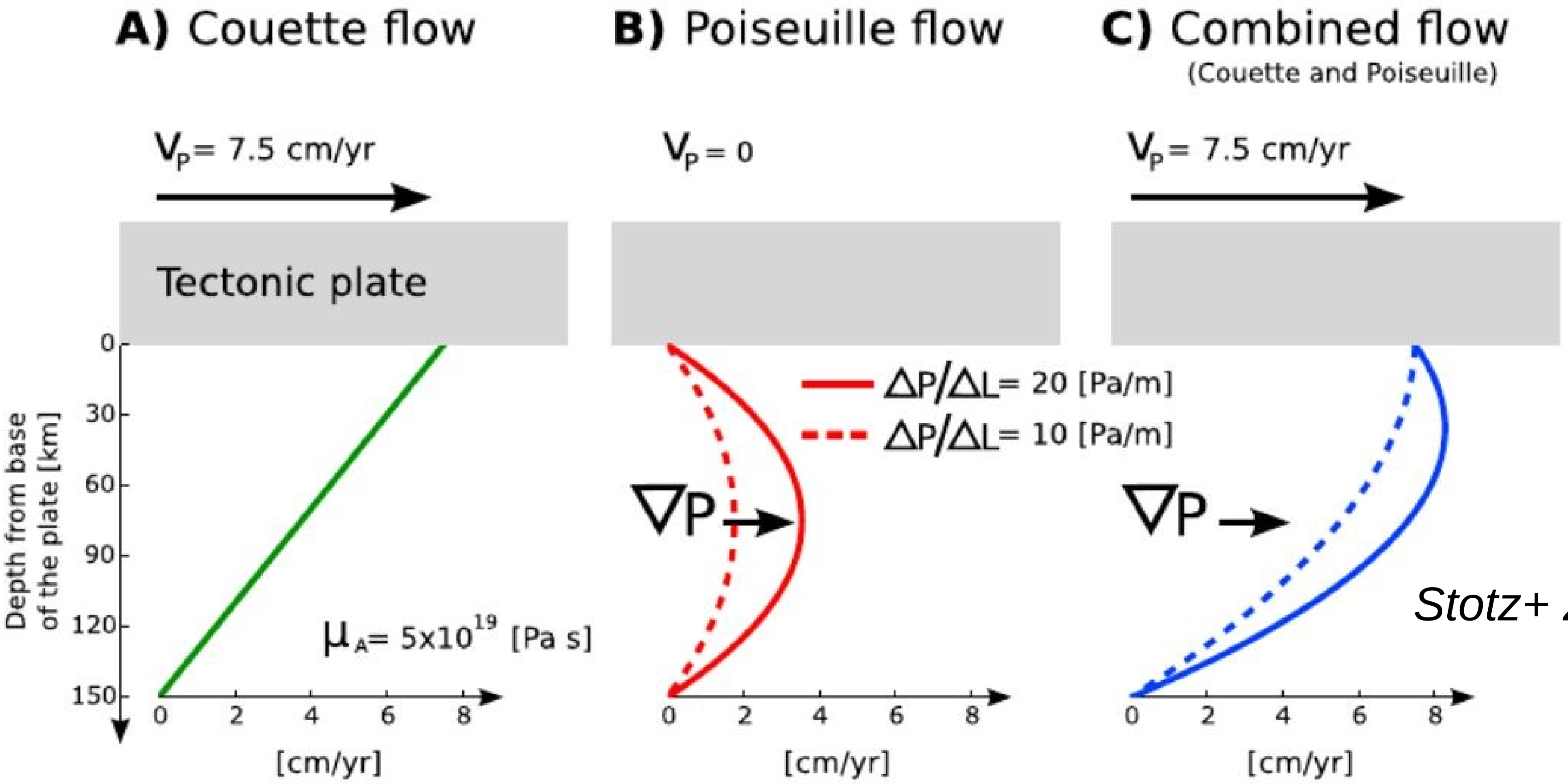


constant-velocity plate also observed for 'active' asthenosphere flow

Hoink and Lenardic, 2010
Richards and Lenardic, 2018

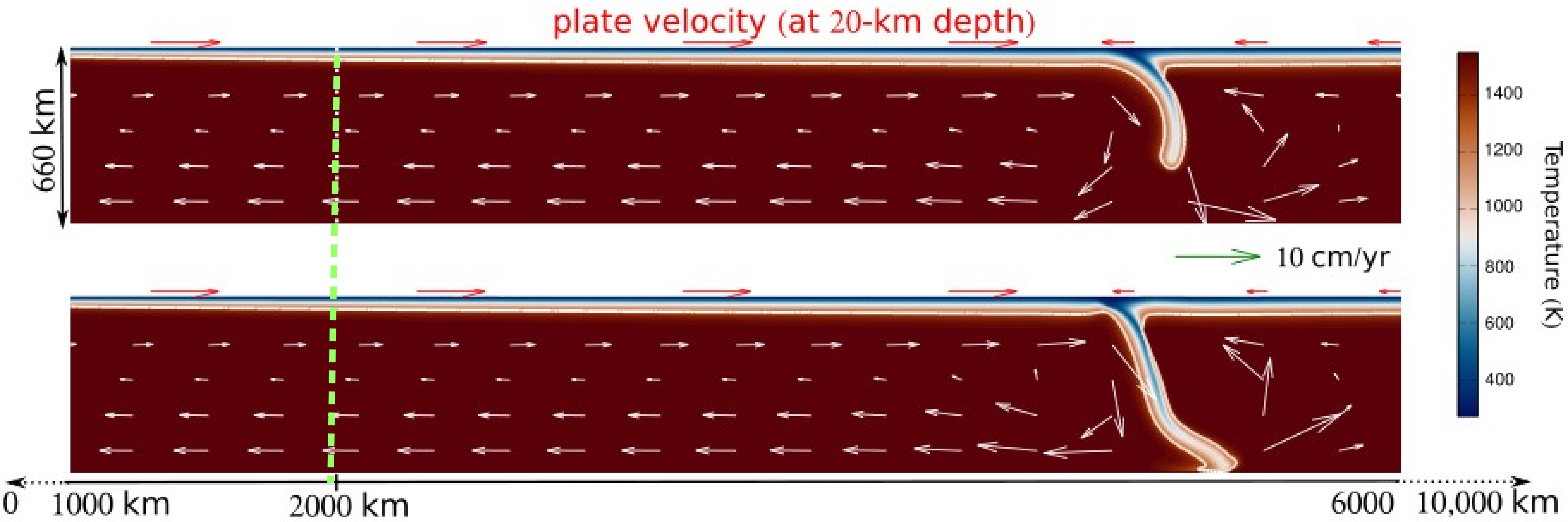
drag of asth.
by Pacific plate
(itself pulled by subduction)

asthenospheric "push" by Hawaiian plume



Stotz+ 2018

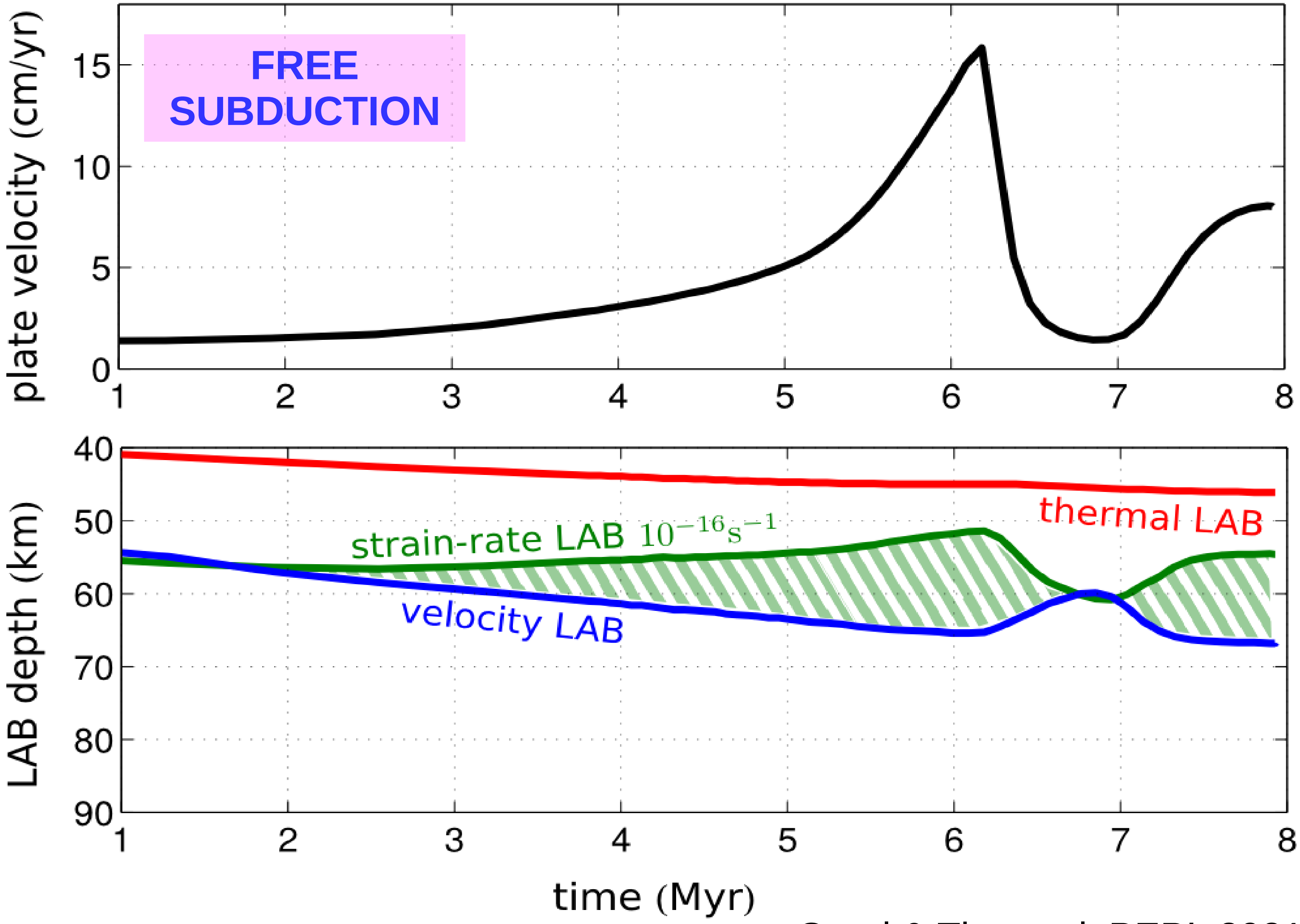
Transient asth. flow driven by subduction



Garel & Thoraval, PEPI, 2021

> during plate acceleration, the deformed base of the 'constant-velocity' plate thickens

> after plate deceleration, small sub-plate strain rate may not be enough to “erase” past CPO



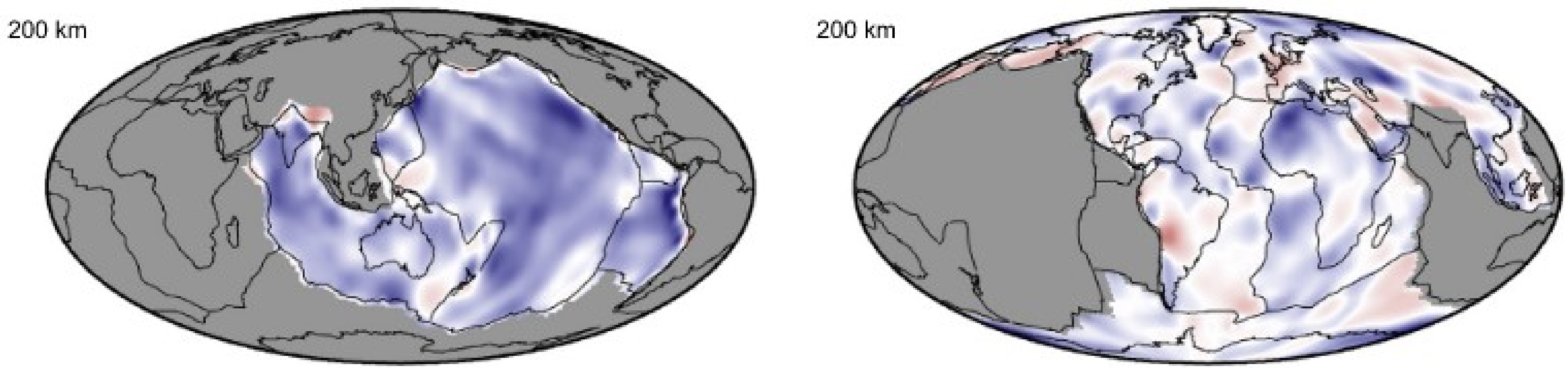
- agrees with anisotropy vs. current plate motions *(Debayle & Ricard, 2013)*

- it takes ~ 30 Myr to accumulate 100 % strain at a rate of 10^{-15} s^{-1}

Garel & Thoraval, PEPI, 2021

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

blue = parallelism **red = orthogonality**



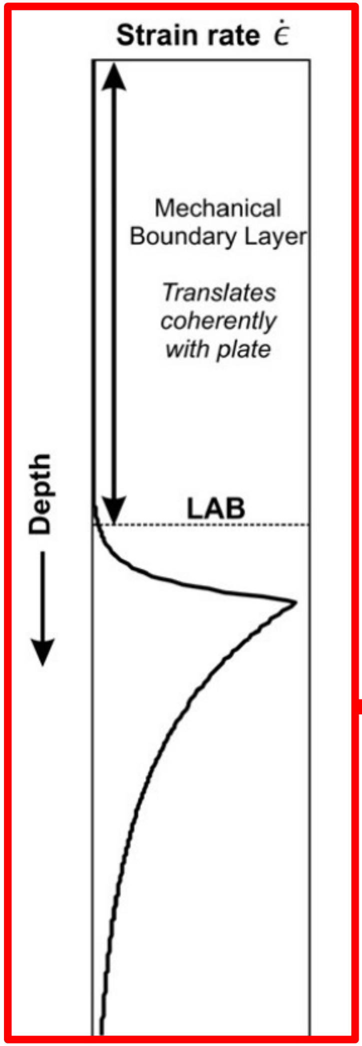
Fast-moving plates

Slow-moving plates

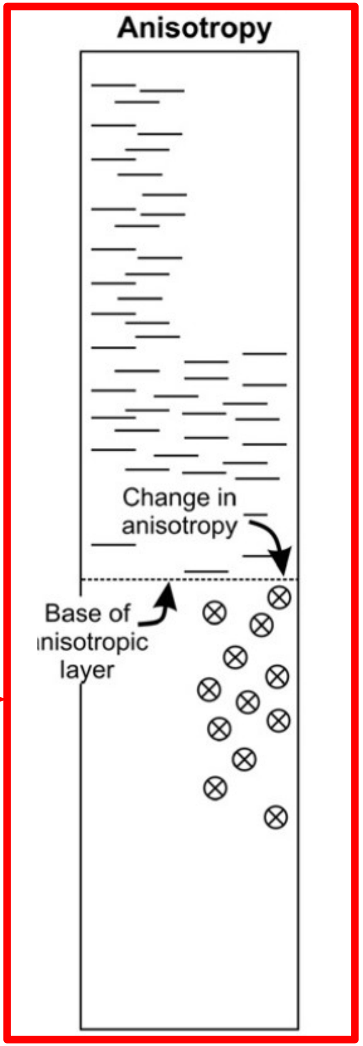
insufficient strain rates in the asthenosphere to generate CPO aligned with plate motion in less than 30 Myr

Debayle & Ricard, 2013

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

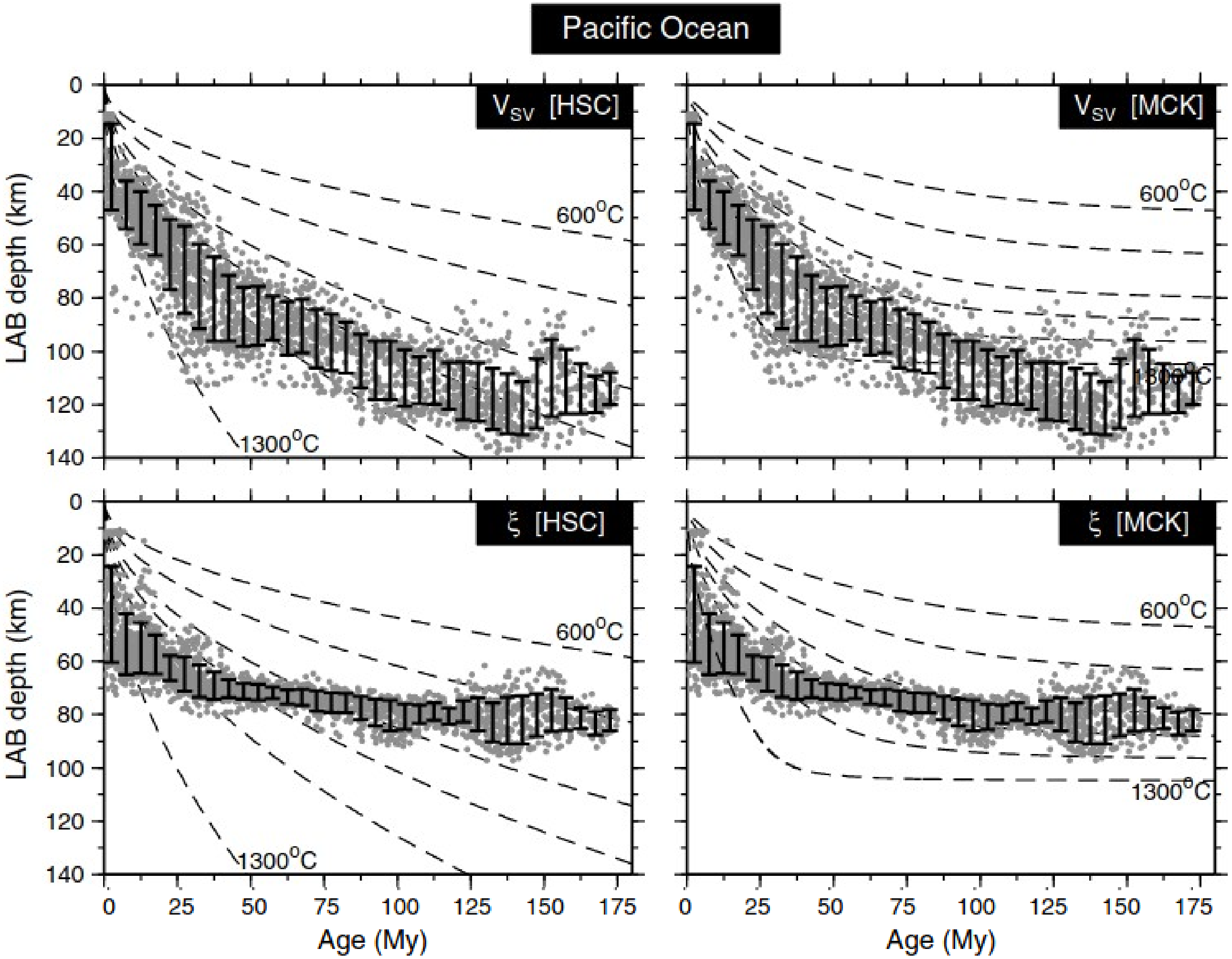


strain rate vertical variations & temporal evolution ?



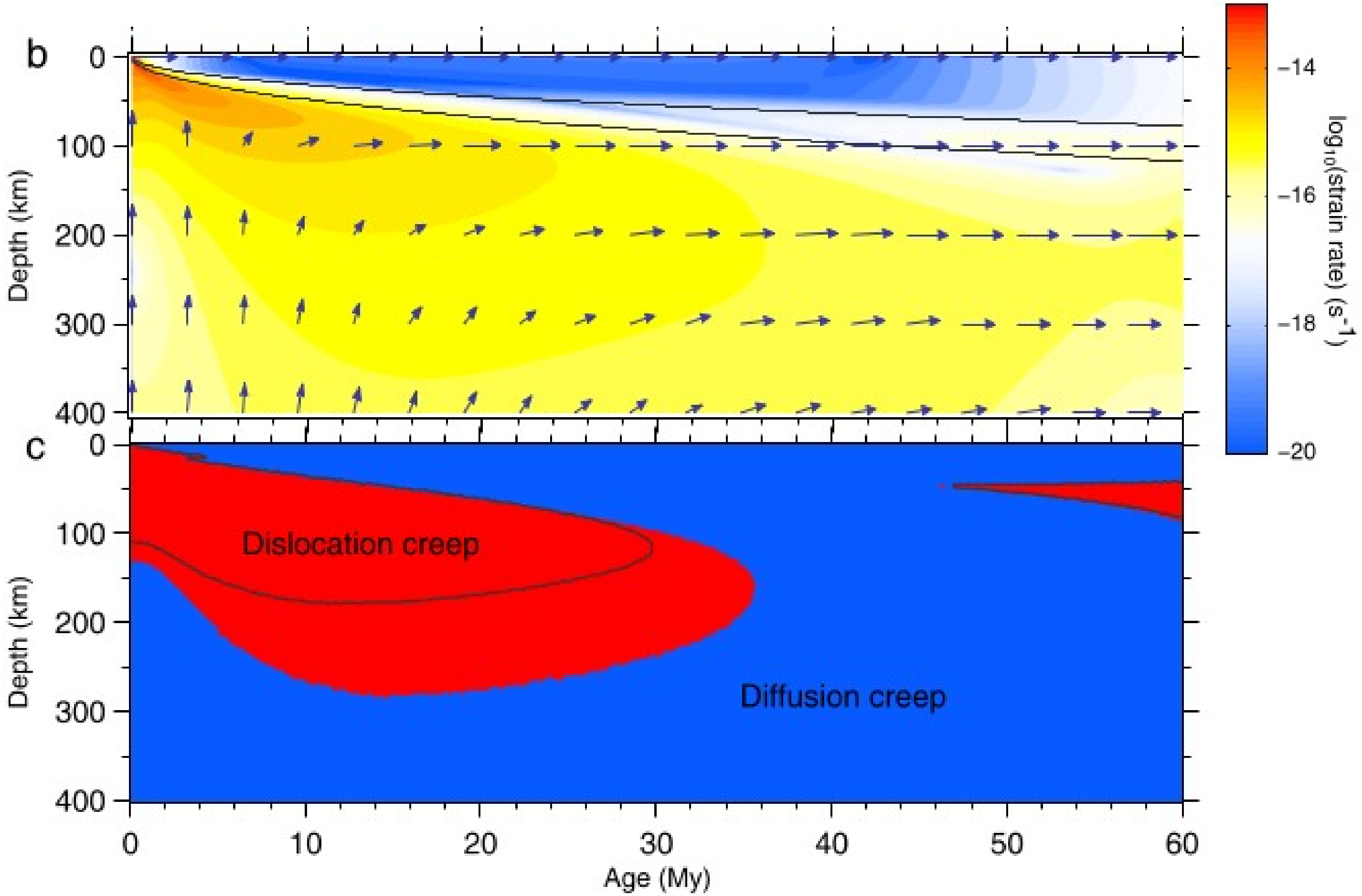
Eaton et al., 2009

Age-independent radial seismic anisotropy



Burgos et al., 2014

Dislocation & diffusion creep regimes below an oceanic plate



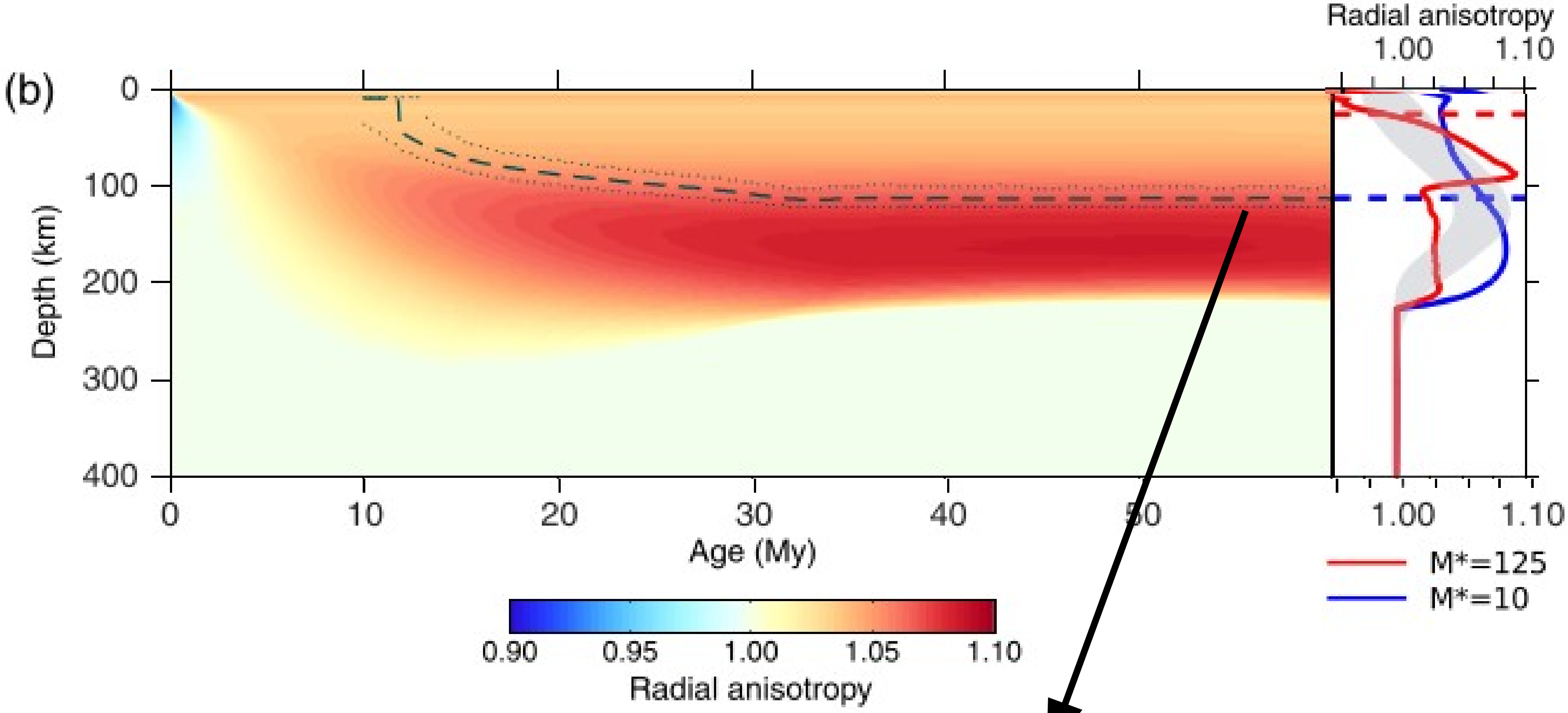
- steady-state **plate-driven flow** of upper mantle

- composite rheology *diffusion* + ***dislocation creep***

- D-Rex calculation of anisotropy

Hedjazian, Garel+. EPSL 2017

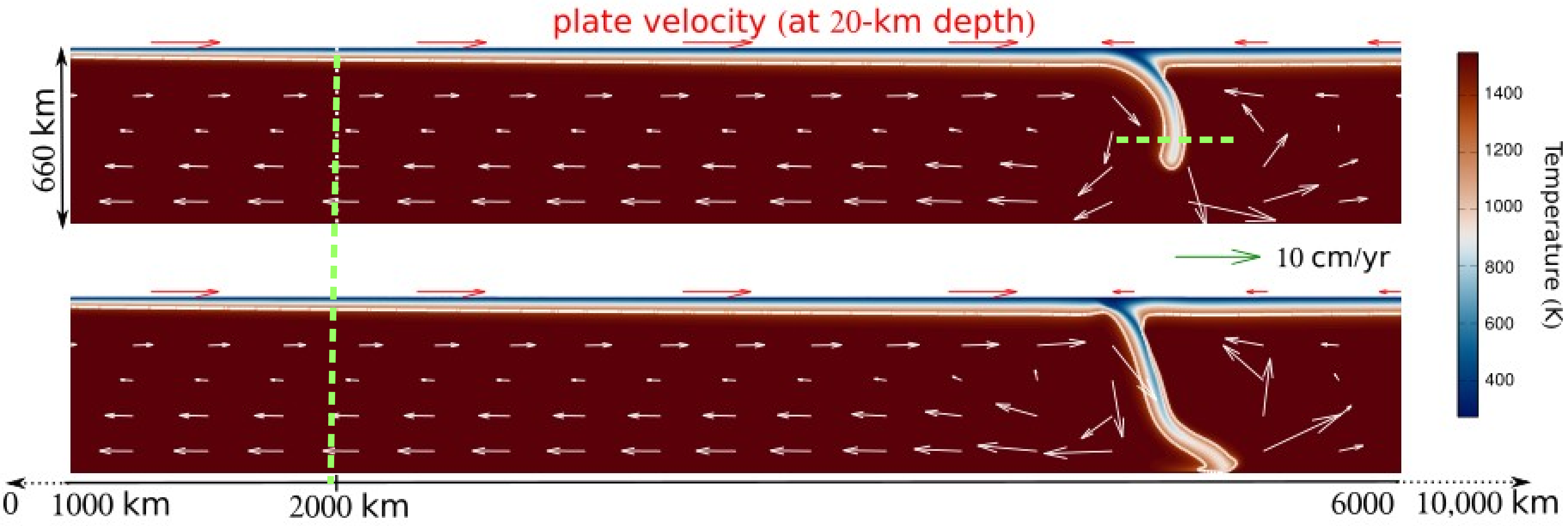
Dislocation & diffusion creep regimes below an oceanic plate



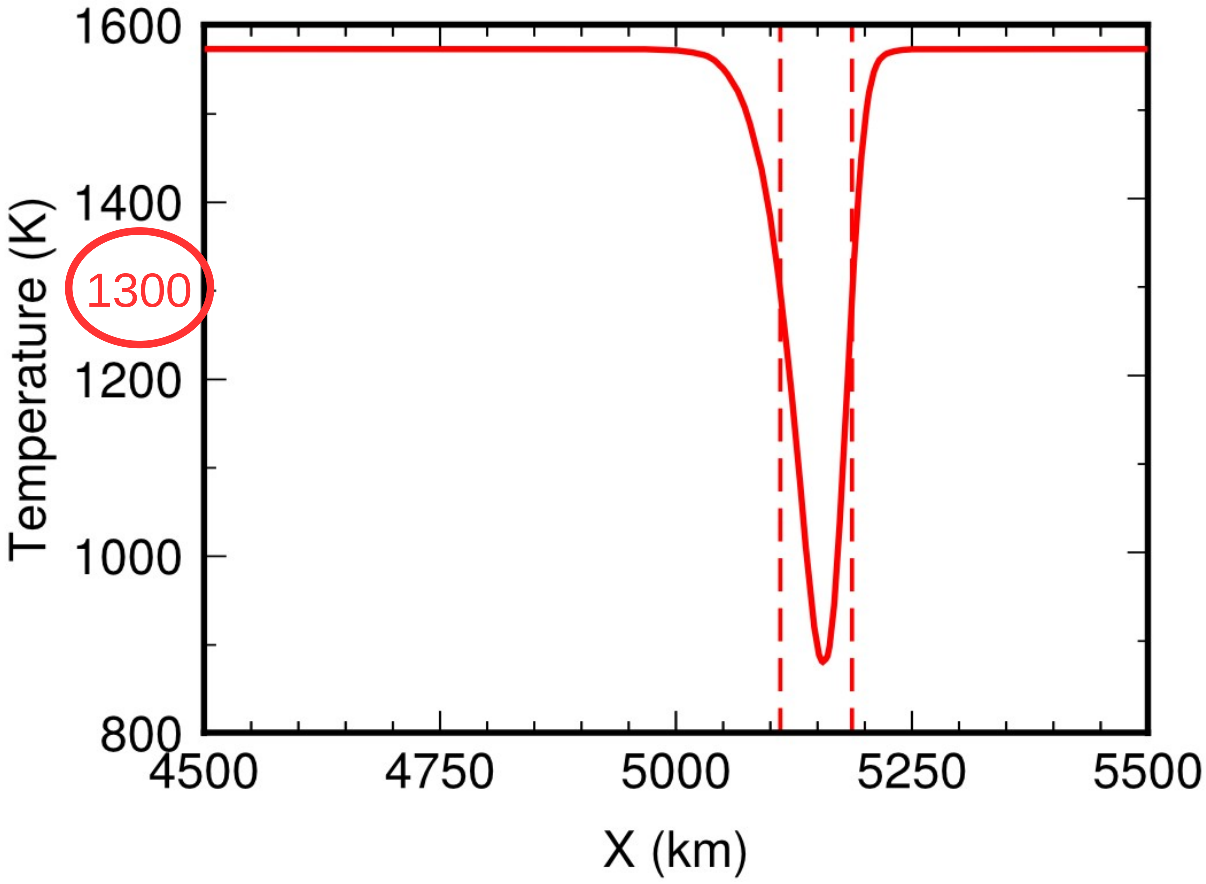
age-independent radial seismic anisotropy !

Hedjazian et al., EPSL 2017

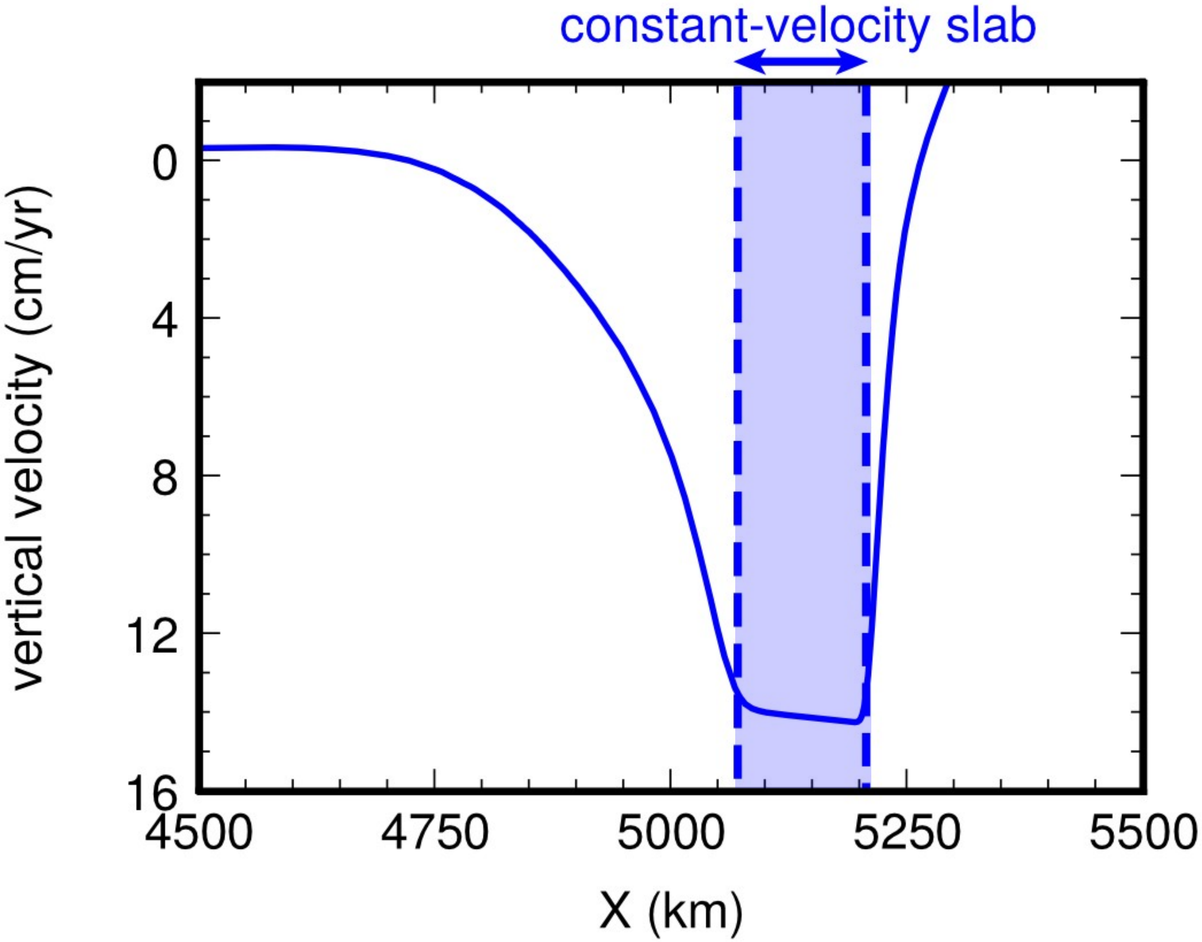
LAB in fast sinking slabs ? (upper mantle)



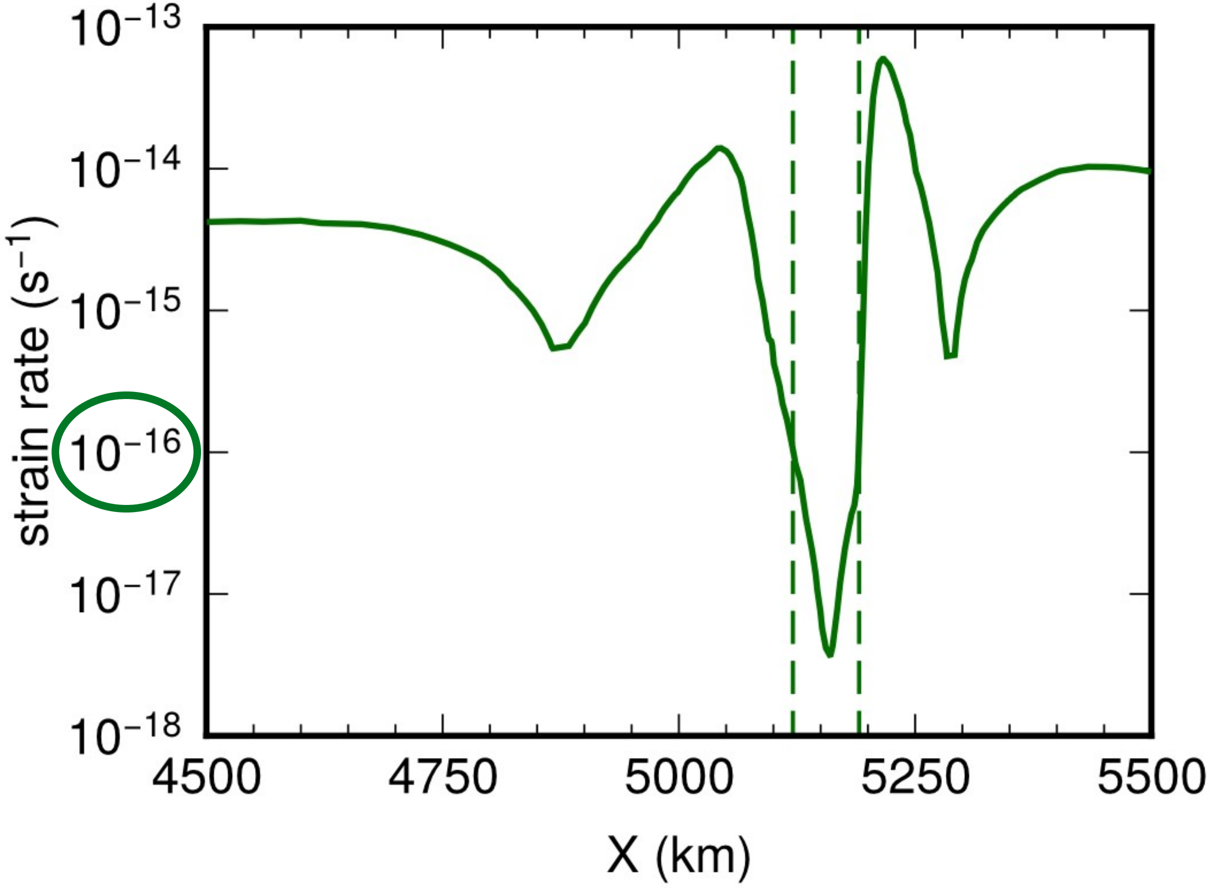
Garel & Thoraval, PEPI, 2021



Garel & Thoraval, PEPI, 2021

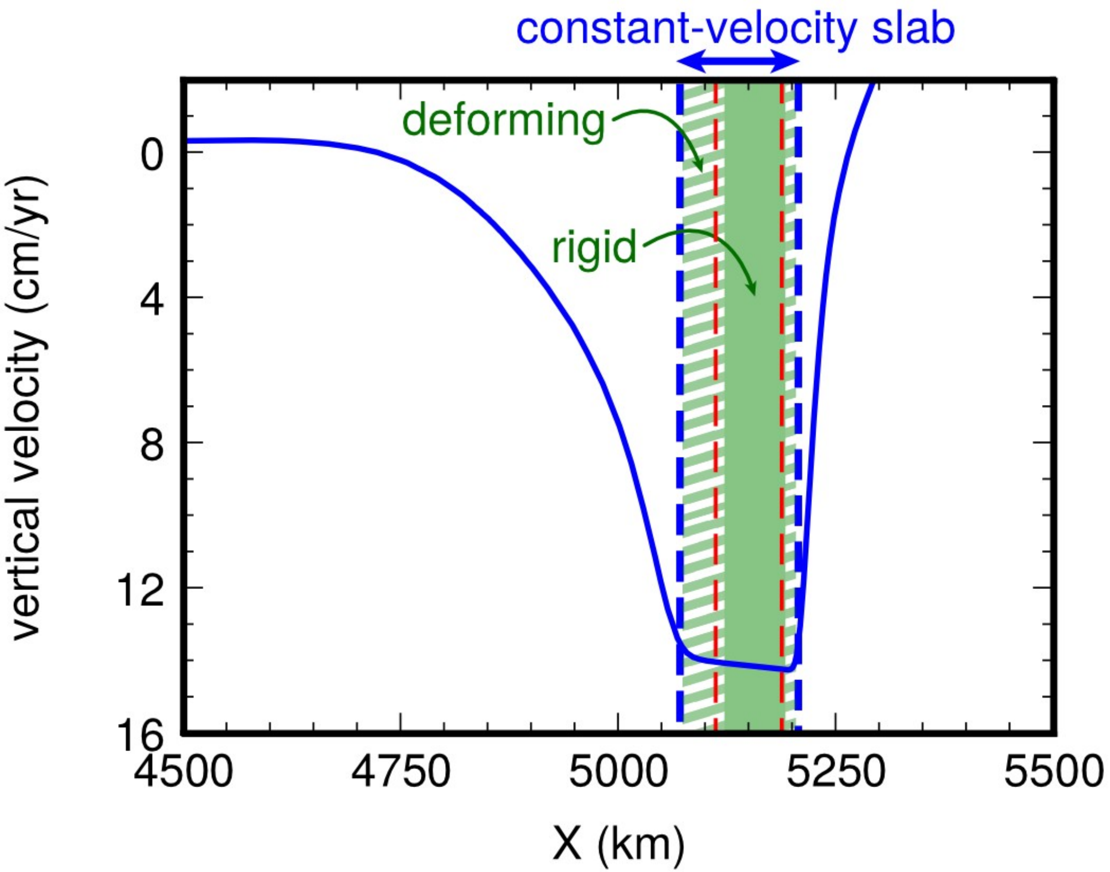


Garel & Thoraval, PEPI, 2021



Garel & Thoraval, PEPI, 2021

Horizontal profile across a fast-sinking slab

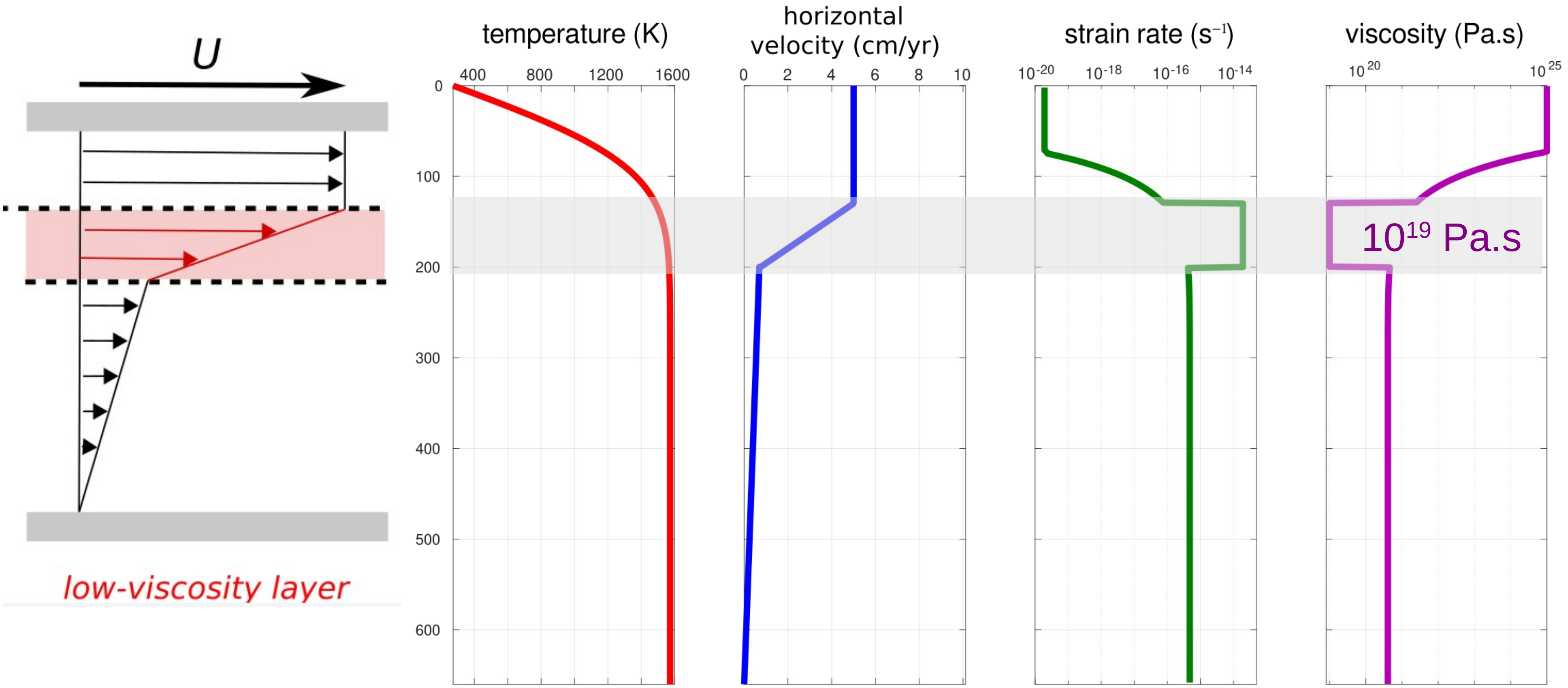


volume of downdip-dragged asthenosphere dependent on

- slab sinking velocity
- viscosity profile (dependent on rheological parameterizations)

Garel & Thoraval, PEPI, 2021

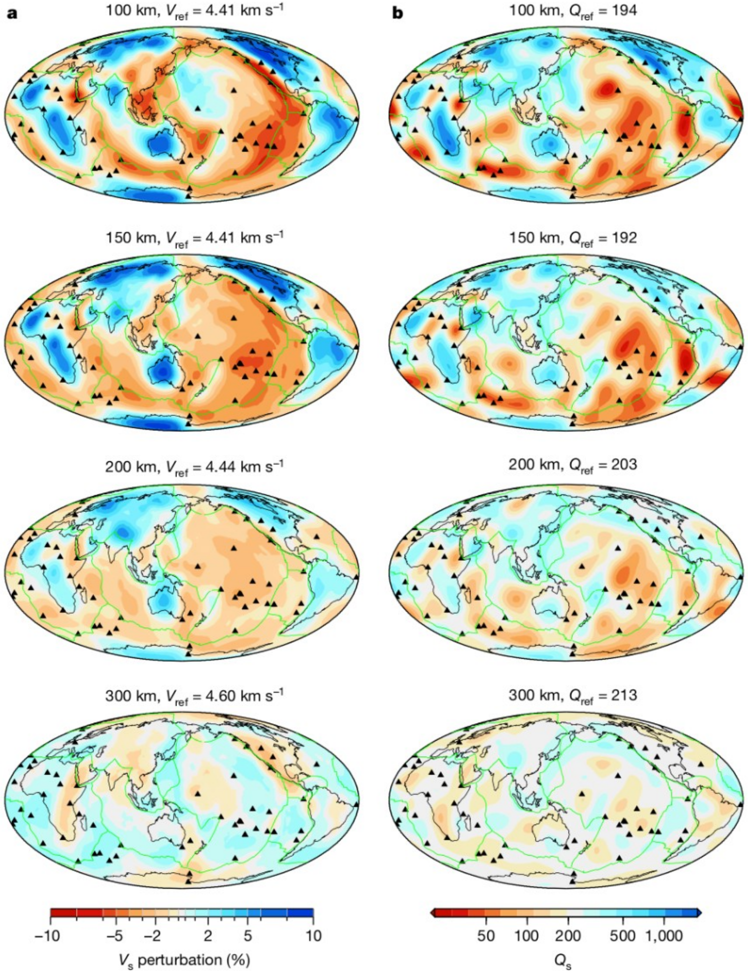
A decoupling low-viscosity layer ?



Garel & Thoraval, PEPI, 2021

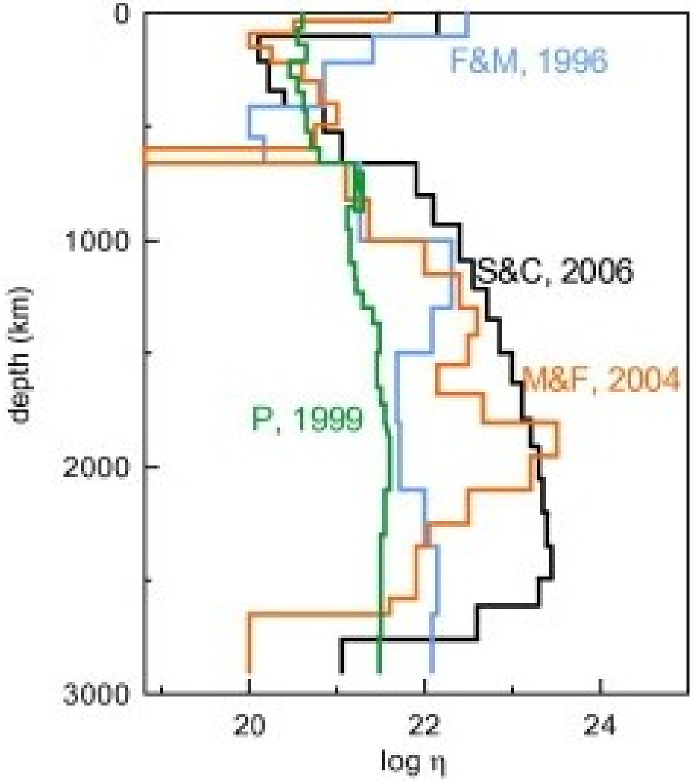
A low-viscosity layer below the plates ?

Shear velocity, attenuation



Debayle et al., Nature, 2020

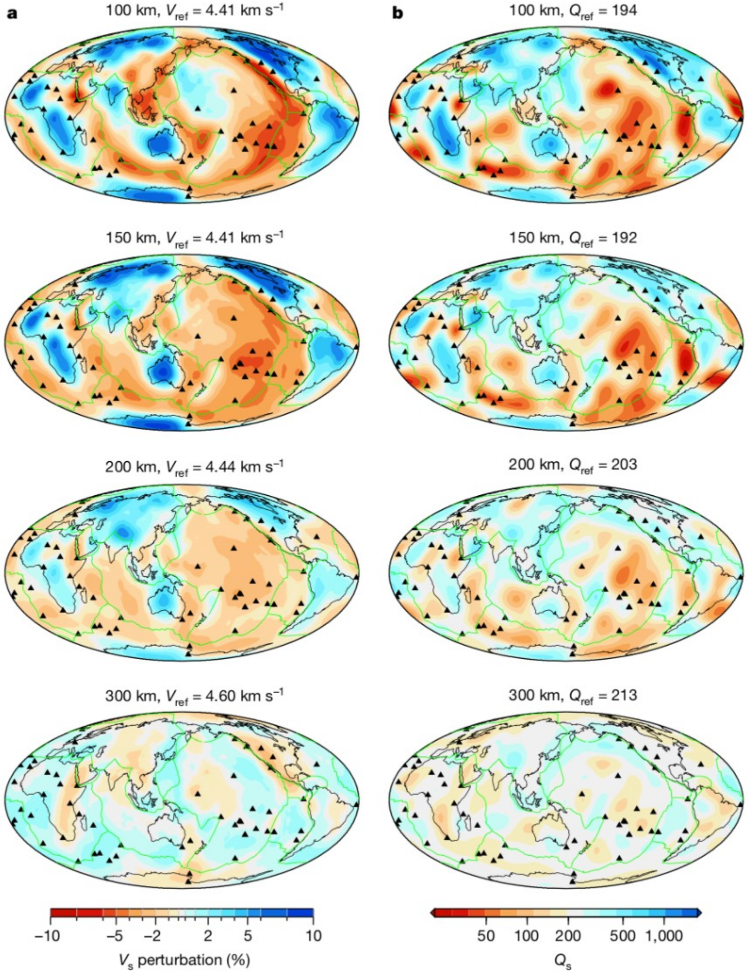
joint inversion of geoid and postglacial rebound data

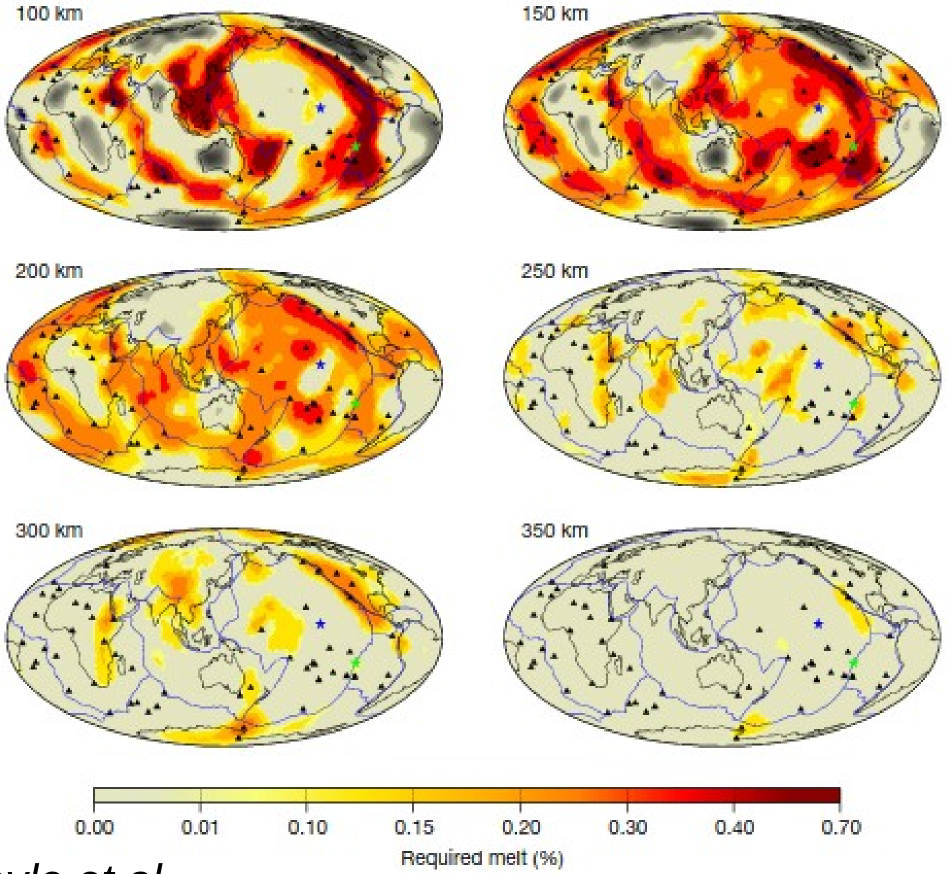


Compilation in Cizkova et al., PEPI, 2012

A low-viscosity layer below the plates ?

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





Debayle et al., Nature, 2020

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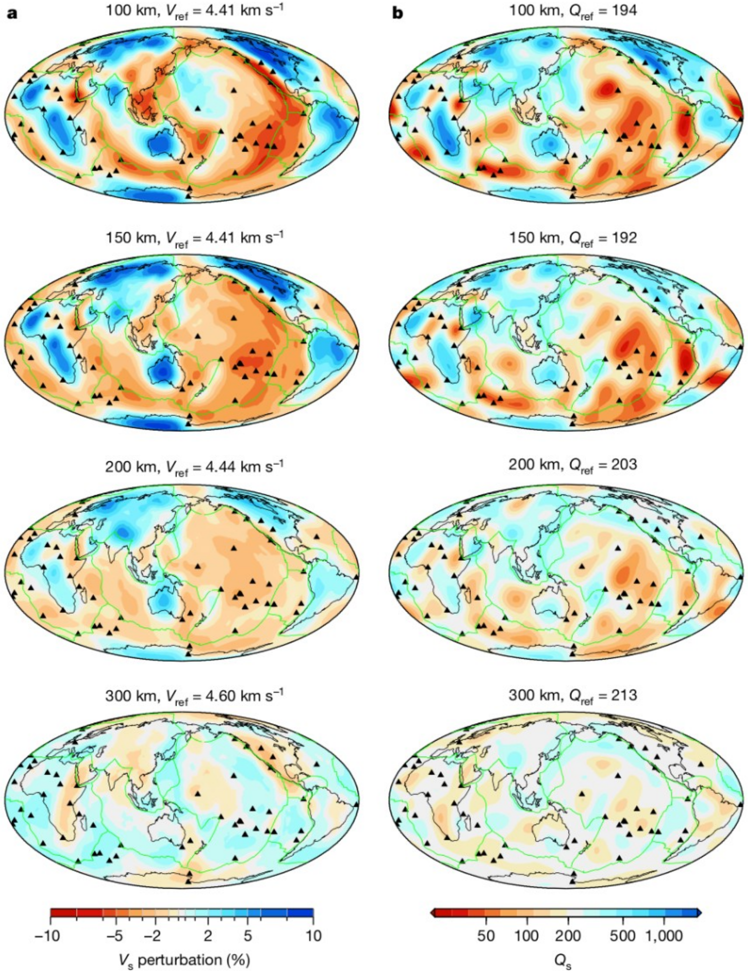


-----► grain size variations ?

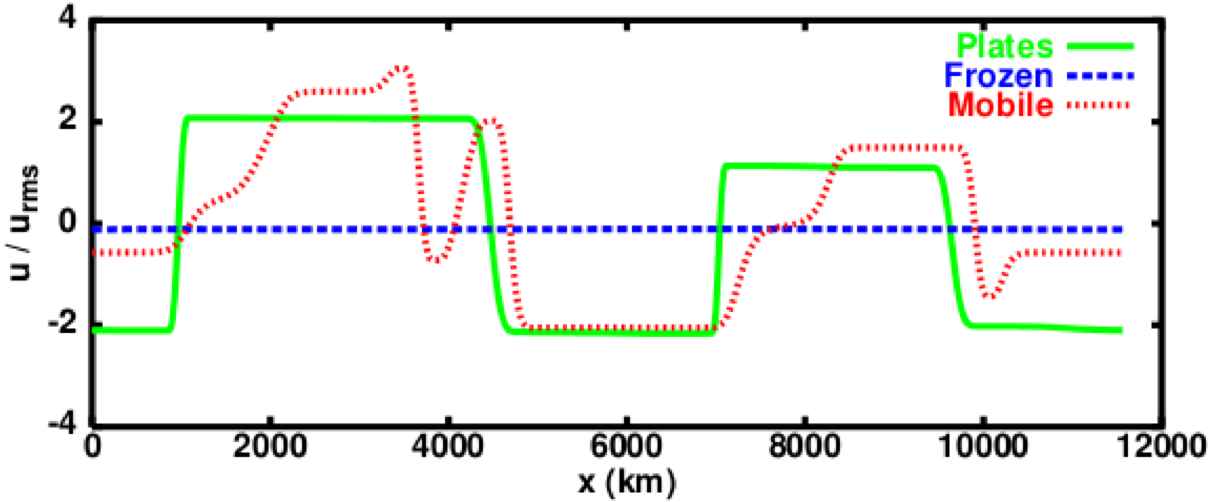
creep laws → low-viscosity layer possible with certain rheological parameters

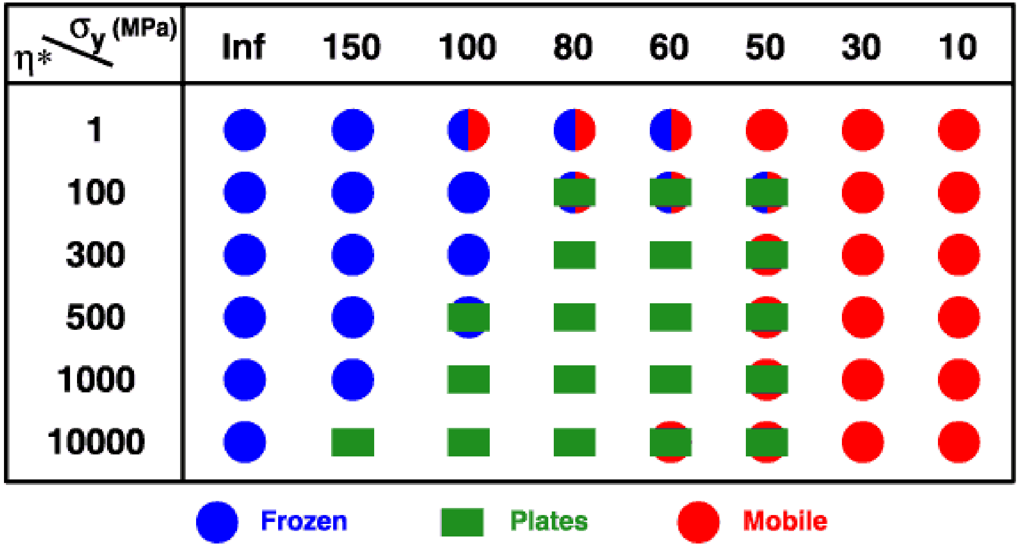
how weak?	*10^{19} Pa.s ?*
how much weaker?	*10-100 x ?*
how thick?	*< 250 km depth ?*

Debayle et al., Nature, 2020

A low-viscosity layer favoring plate tectonics regime

localizing deformation at plate boundary



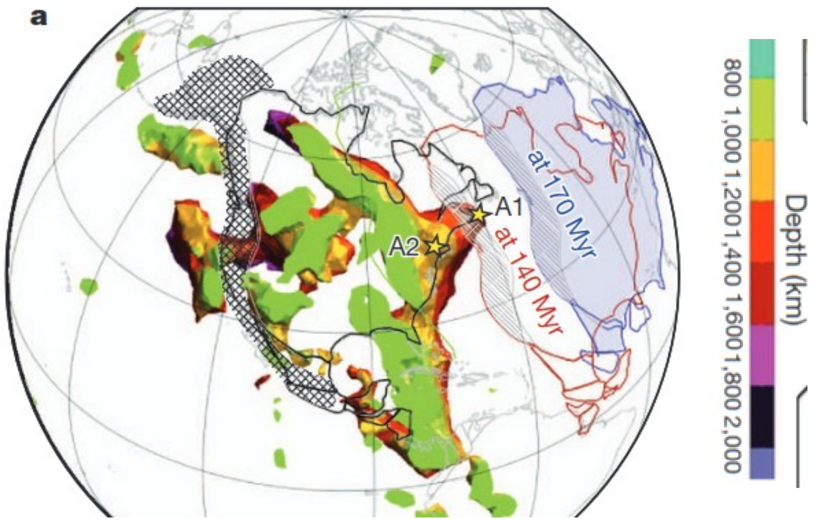


lithosphere mobility as a function of **yield stress** σ_y and viscosity contrast η^* for a **sub-plate low-viscosity layer**

Richards G³ 2001

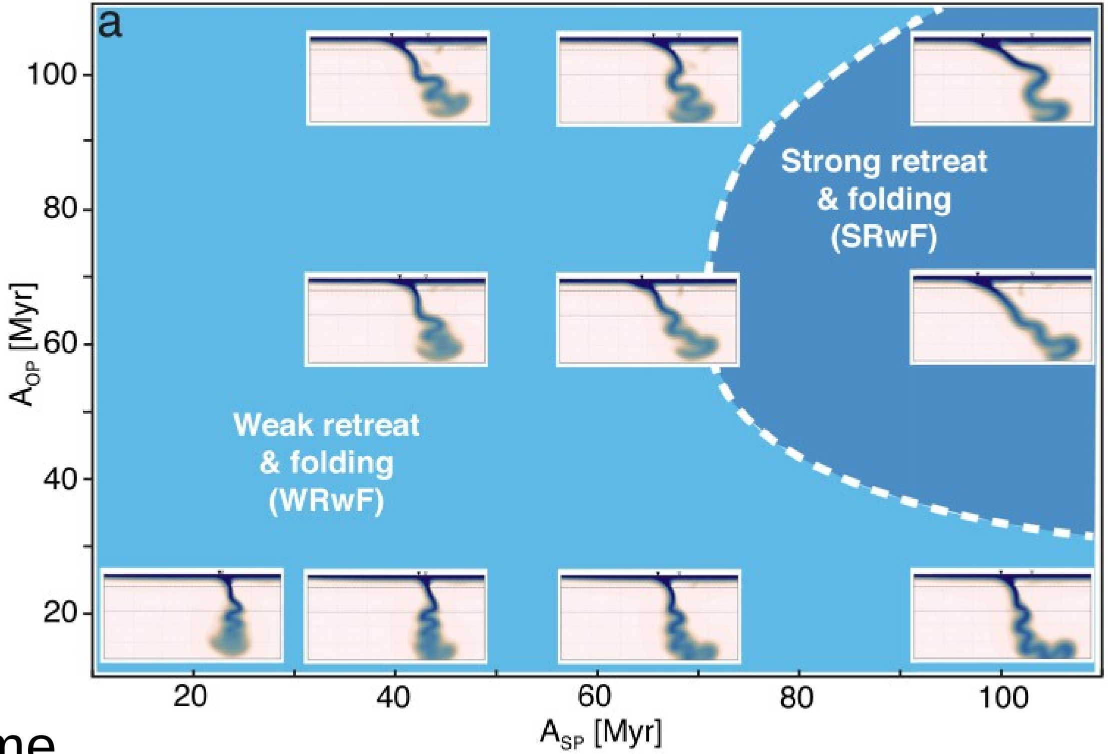
A low-viscosity layer reconciling plate vs. slab velocities

- **5 cmr/yr** surface plates **vs. 1 cm/yr** sinking slabs **> folding !?**
- imaged **slab "walls" = piled & folded ?**



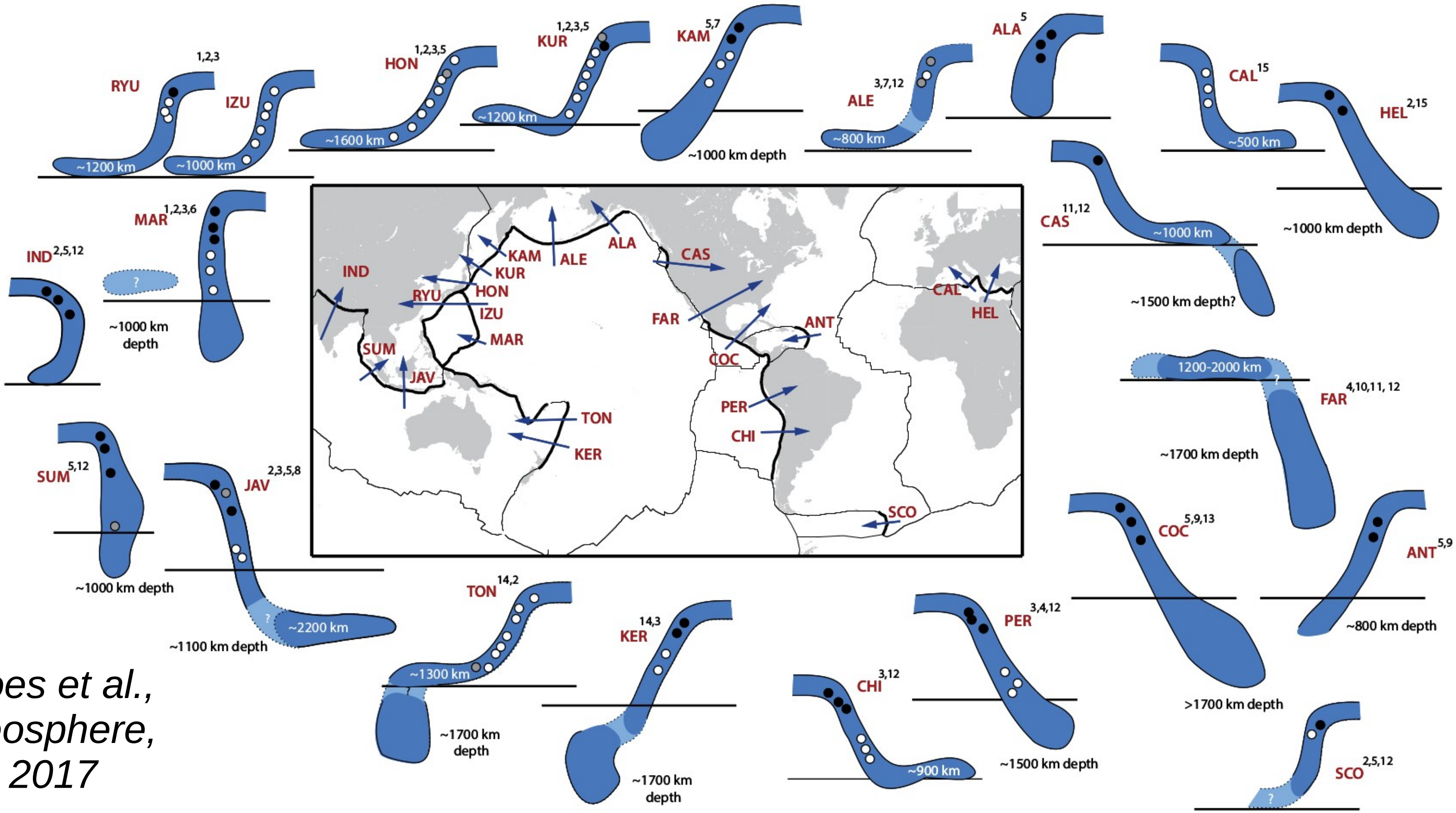
but most subduction models shows inclined/retreating slabs…

> dominance of vertical-folding regime
if addition of subplate 2-5x weak layer



Cerpa, Sigloch, Garel+ JGR 2022

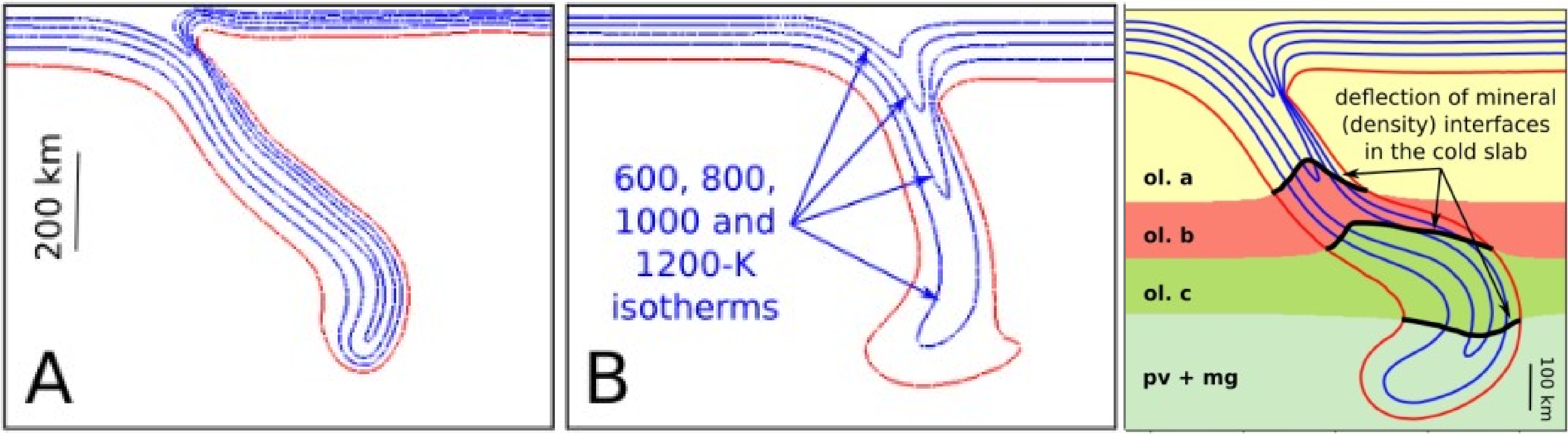
<u>Mass transfers</u> between upper & lower mantle : asthenosphere dragged and trapped by cold deforming slabs ?



Goes et al., Geosphere, 2017

Thermal structure of slabs imaged by spatial gravimetry & gradiometry to retrieve their history of sinking and deformation

starting PhD of **Xavier Vergeron**



CNES GraviSSym project
(PI Cécilia Cadio)

ANR-21-CE49-0009

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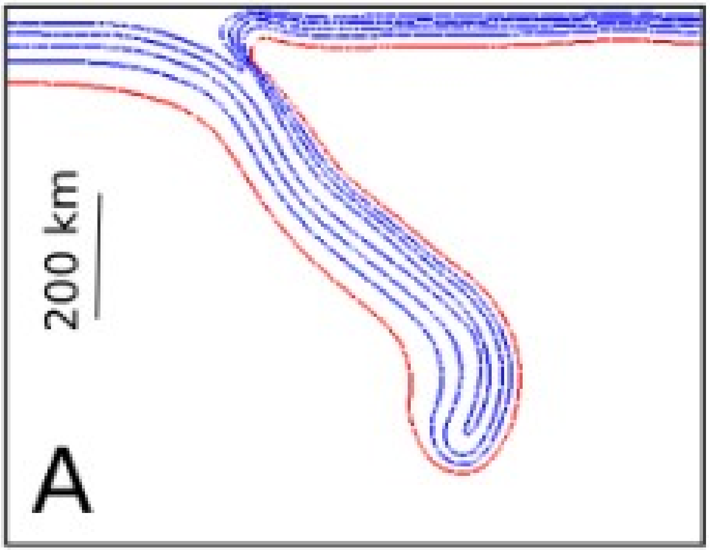

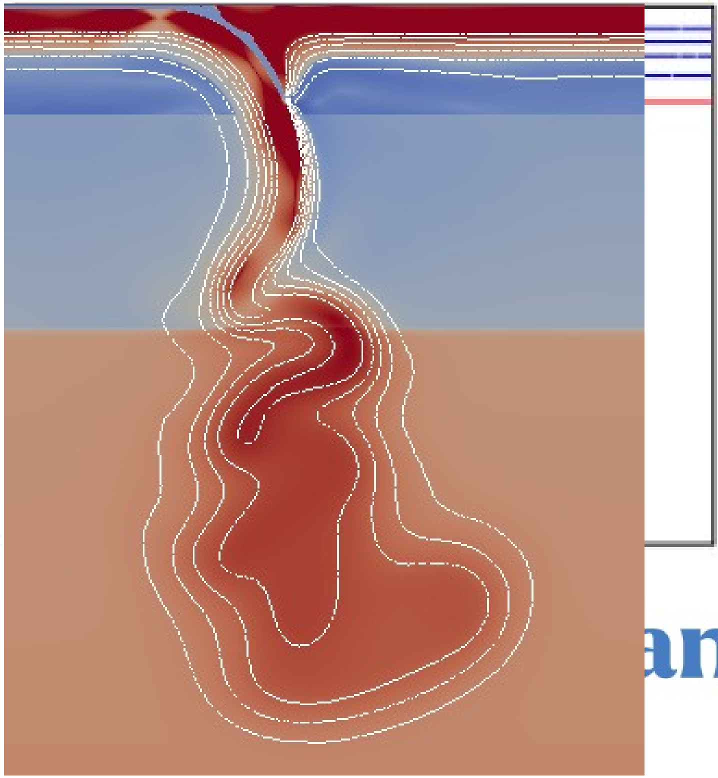

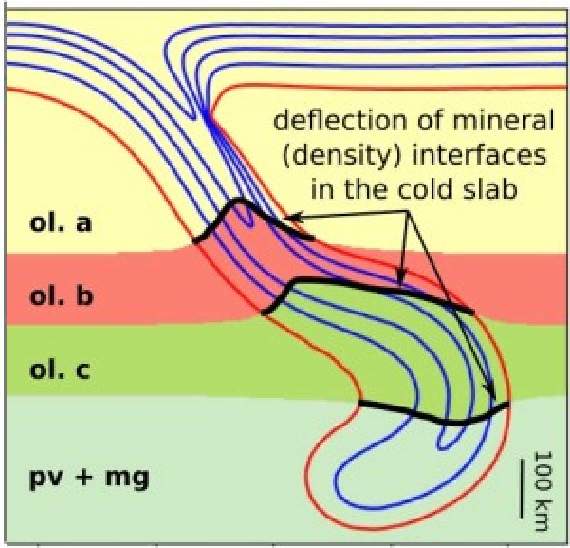

CNES GraviSSym project
(PI Cécilia Cadio)

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Breaking plates from below with dislocation creep ?

ANR-21-CE49-0009

“Memory” processes proposed for deformation localization feedbacks

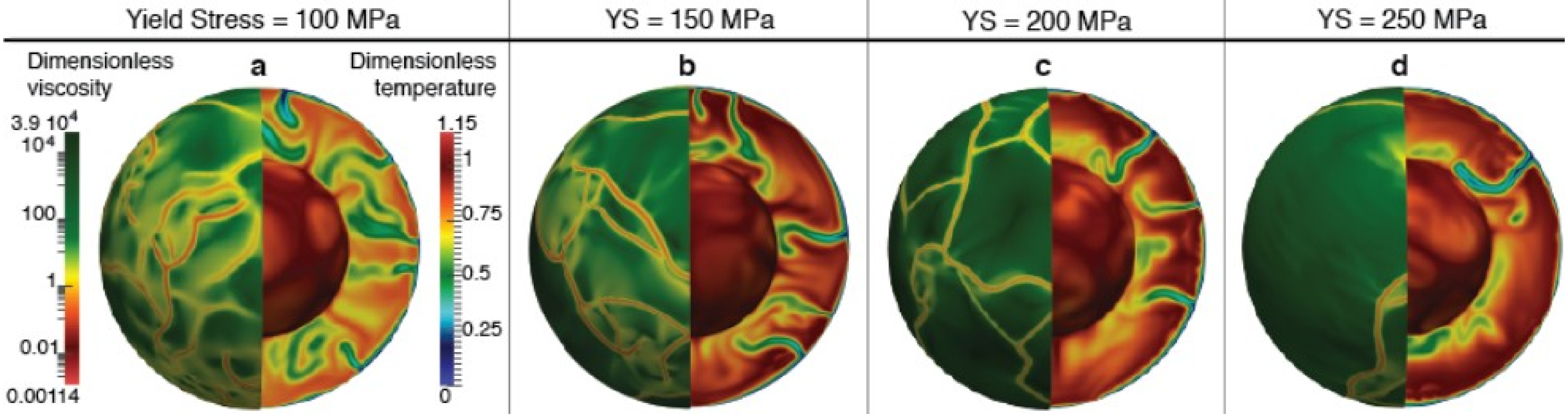
- grain size growth vs. recrystallization under stress

- strain weakening

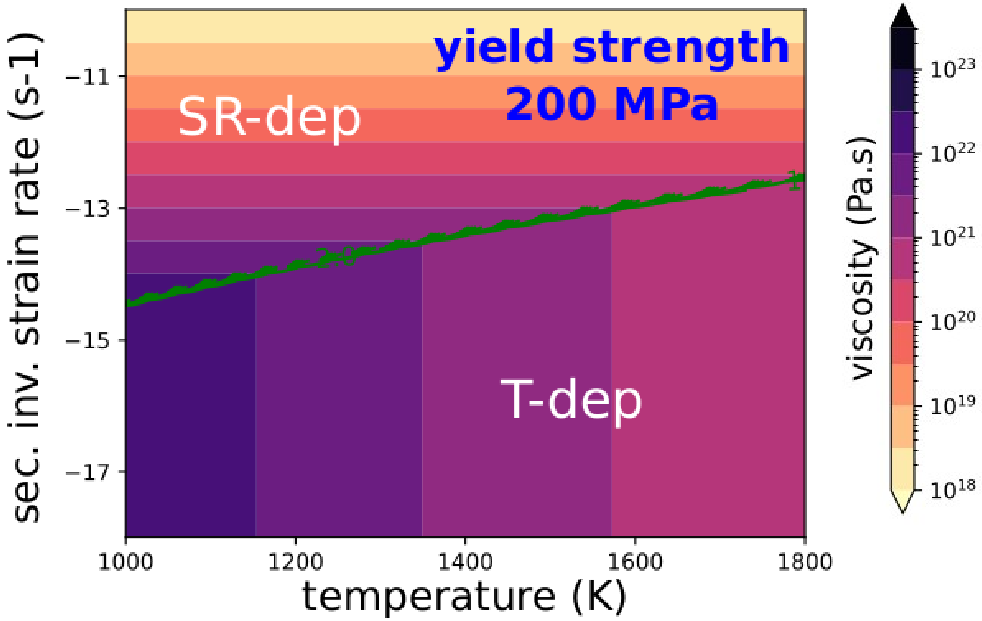
- shear heating

No memory effect :
shear thinning

strain-rate dependent viscosity
from dislocation creep (n>1)



Mallard, Coltice+ Science 2016



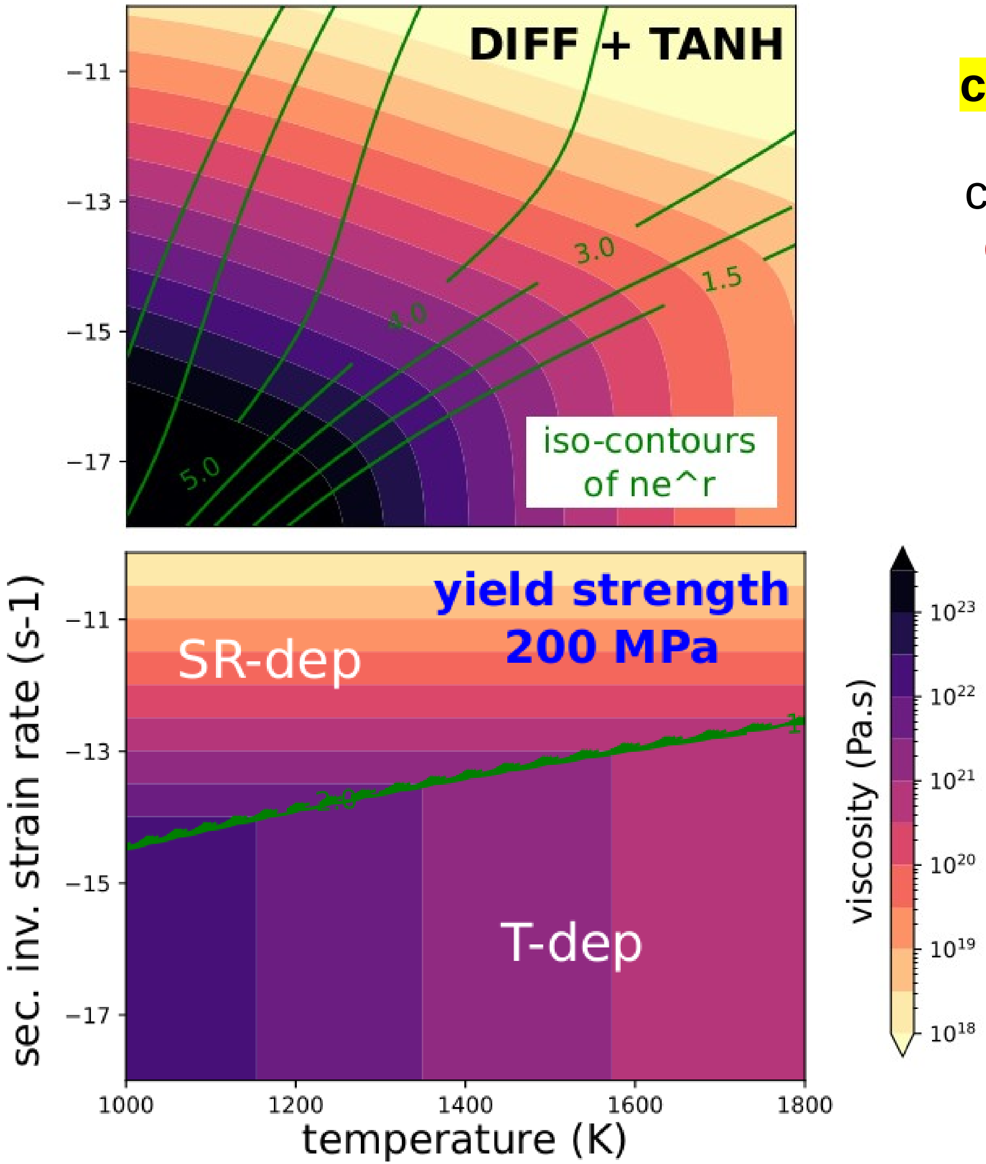
yield-stress rheology successful in localizing "viscous" plate boundaries

$$\eta_{\text{eff}} = \min\left[\eta\,(z, T), \frac{\sigma_y(z)}{2\dot{\varepsilon}}\right]$$

mantle + cold plates (**T-dep**)

weak plate boundaries (**SR-dep**)

Tackley 1998, 2000 ; Mallard+ 2016 ;
Coltice+, 2017, Arnould+ 2018....



composite dislocation + diffusion creep

compatible with deformation experiments :
effective viscosity dependent on both temperature and strain rate

Gouriet+ EPSL 2019
Garel+ EPSL 2020

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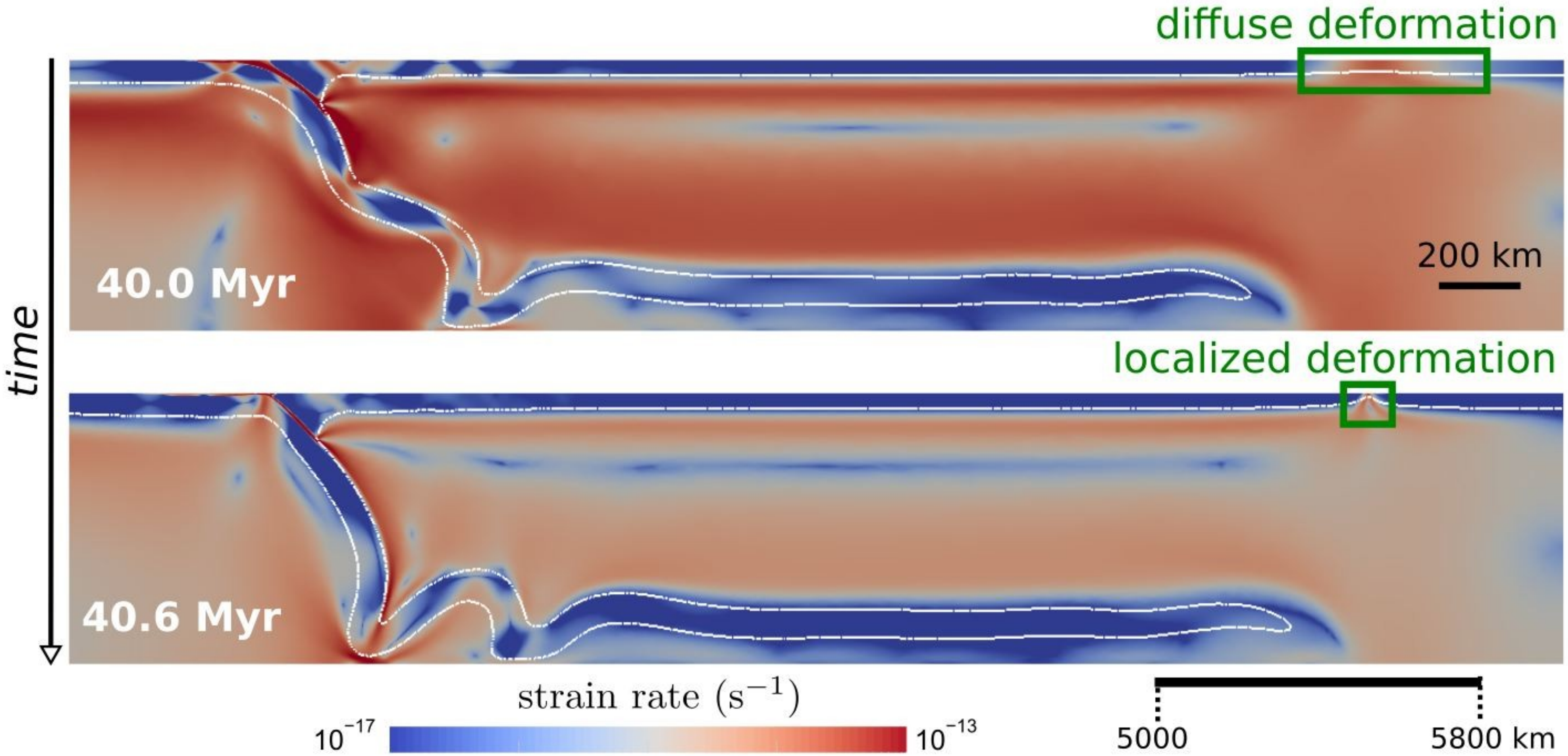
mantle + cold plates (**T-dep**)

weak plate boundaries (**SR-dep**)

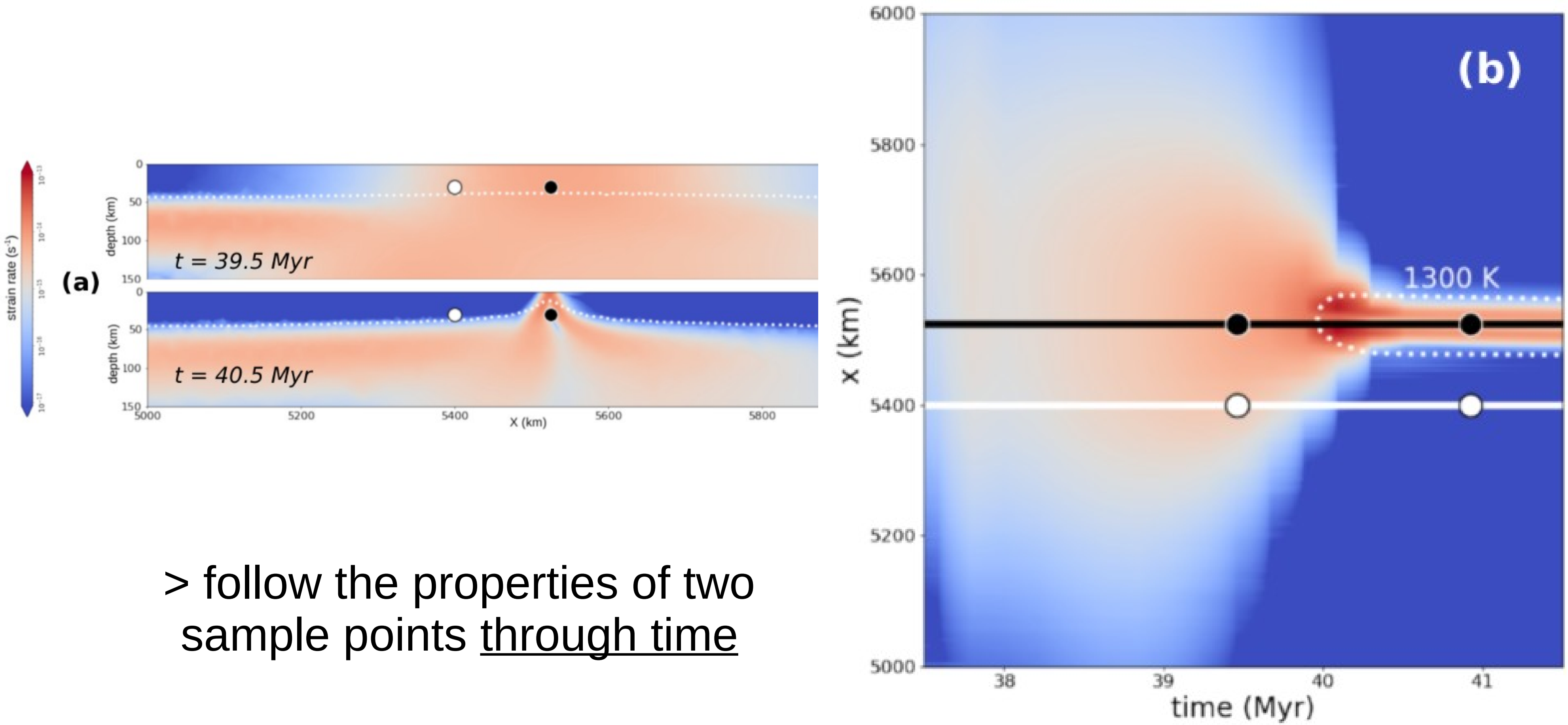
Tackley 1998, 2000 ; Mallard+ 2016 ;
Coltice+, 2017, Arnould+ 2018....

Model set-up enabling intraplate deformation localization

- accelerated subduction dynamics with a fixed upper plate - *Alsaif + EPSL 2020*
- olivine composite rheology *HT and LT **disl. creep*** + *diff. creep.* + *brittle*



Model set-up enabling intraplate deformation localization

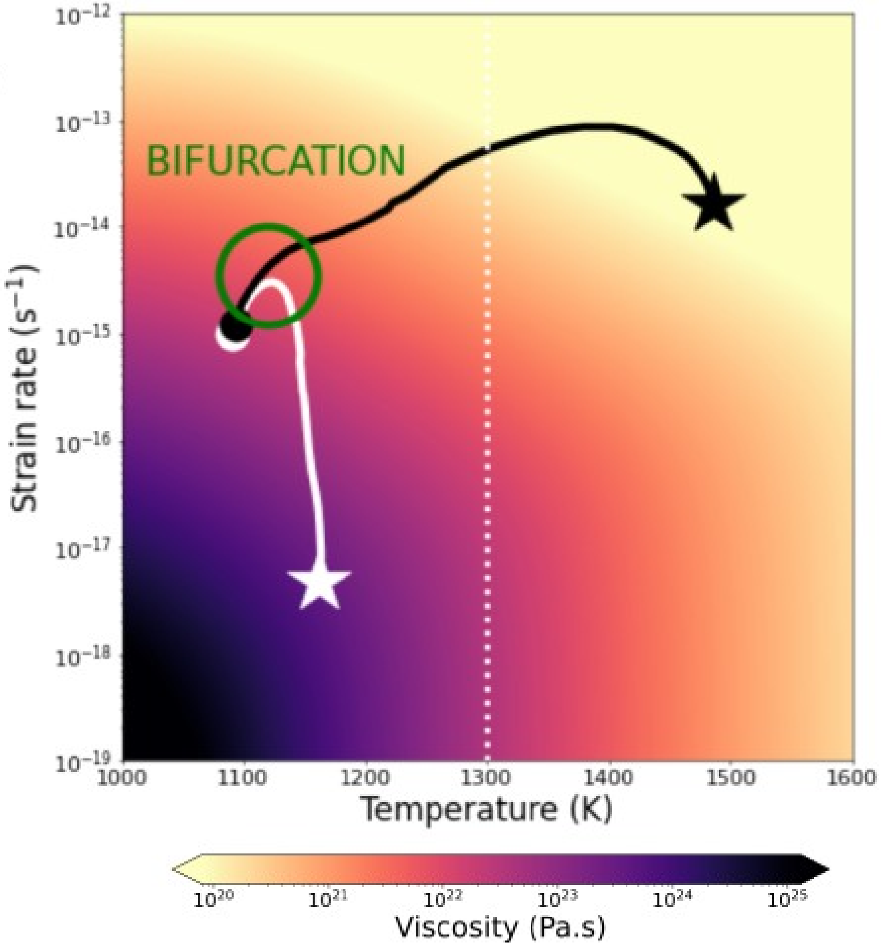


> follow the properties of two sample points through time

deformation-Temperature-time paths

(***def-T-t paths***)

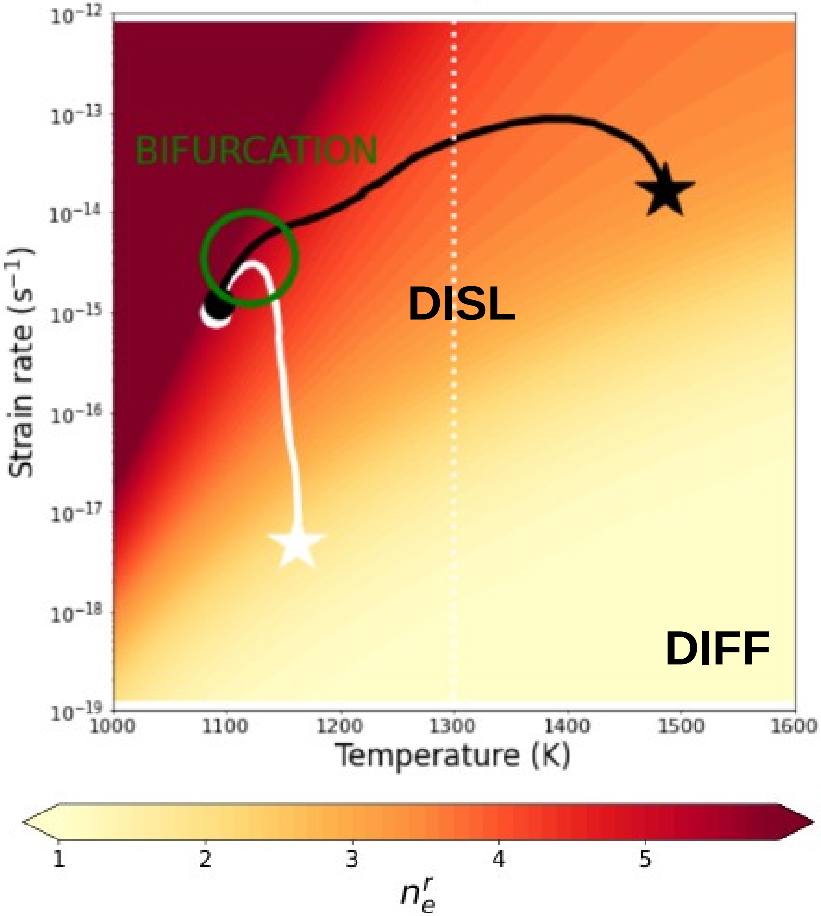
onto a background of viscosity



rheological effective stress exponent for a composite viscosity (diff + disl)

$$\dot{\varepsilon} \propto \sigma^n$$

$$n_e^r(T, \dot{\varepsilon}) = \frac{\partial \log(\dot{\varepsilon})}{\partial \log \sigma}$$



<u>time-dependent</u> "dynamic" effective stress exponent

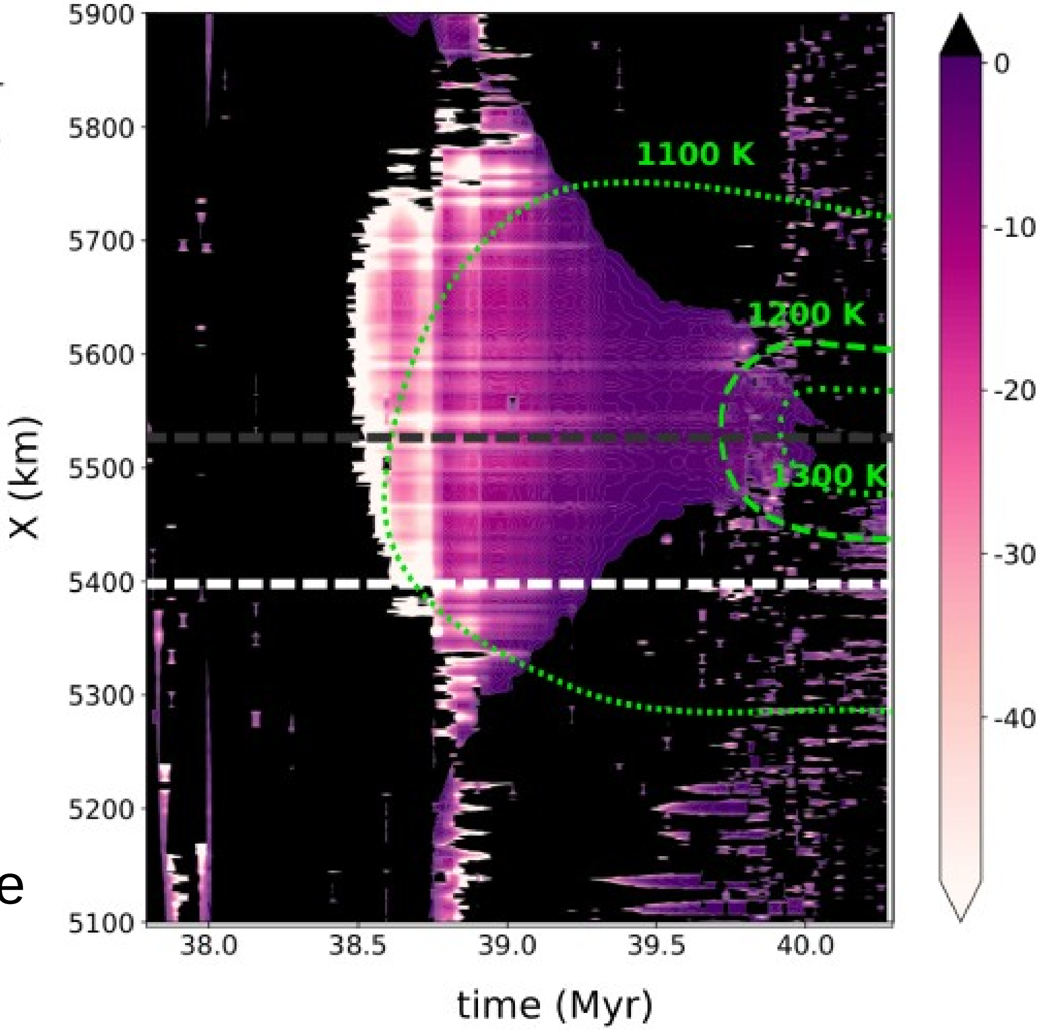
Montesi & Zuber, 2002

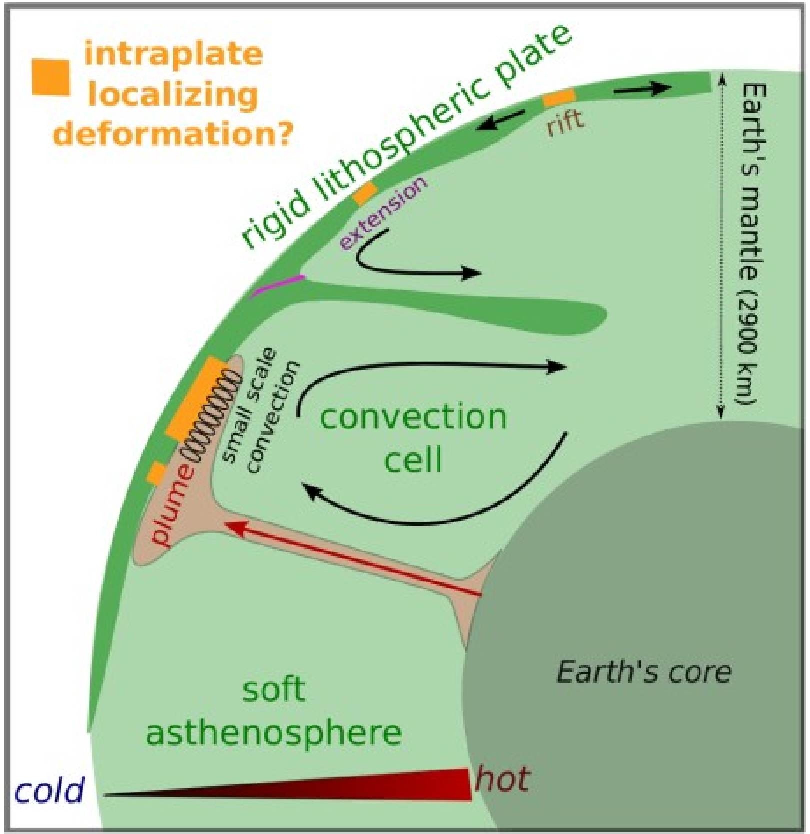
$$\frac{1}{n_e} \equiv \frac{\chi_0}{\sigma}\frac{d\sigma}{d\chi_0}$$

$$\frac{1}{n_e^d} = \frac{\mathrm{d}\log(\sigma)}{\mathrm{d}\log(\dot{\varepsilon}_{II})} = \frac{\mathrm{d}\log(\sigma)}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}\log(\dot{\varepsilon}_{II})}$$

dynamic localization occurs
for negative ne
and is strongest for more negative 1/ne

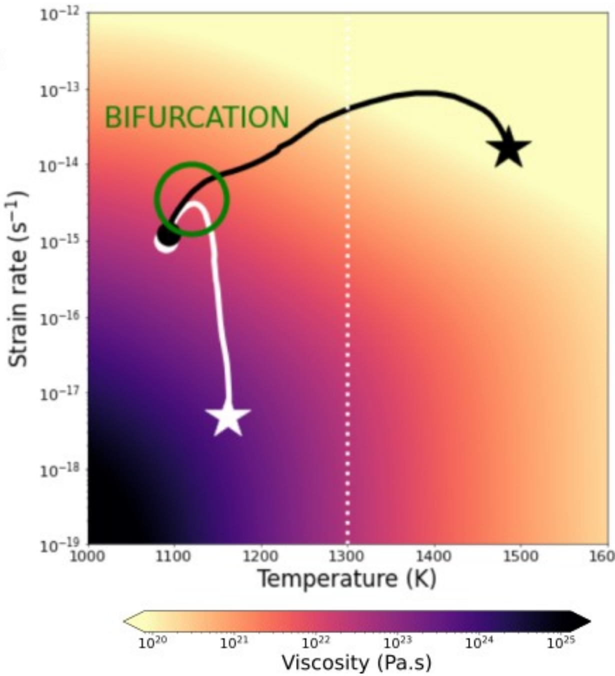
deformation localization
may be caused by a hot upwelling
but hot regions then return to
non-localizing, low-deformation state





- deformation-temperature-viscosity-time paths calculated in models of **various geodynamical contexts**

- rheological param. compatible with def. Exp. but with different gradients of viscosity / exponent n as a function of T and SR



> why some rheology localize deformation but others do NOT

> whole-mantle convection models → frequency of plate break-up ?

→ Early Earth ?