(upper) mantle rheology

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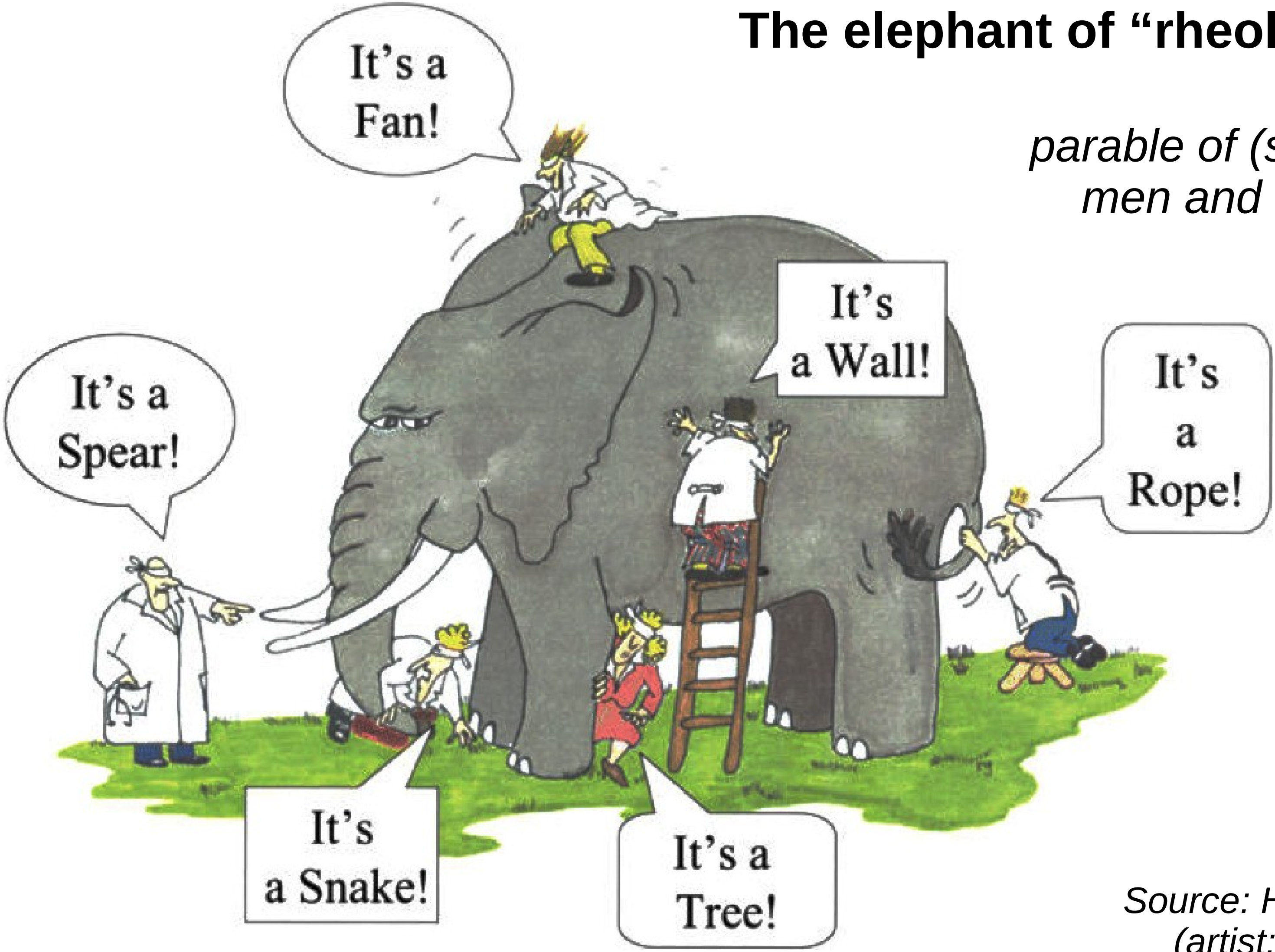
*with materials from lectures by Stéphane Labrosse, Maëlis Arnould,
Yanick Ricard, Maylis Landeau, Catherine Thoraval*

Deep Earth Doctoral School - Les Houches - Autumn 2022

The elephant of "rheology"

parable of (scientific) blind men and an elephant

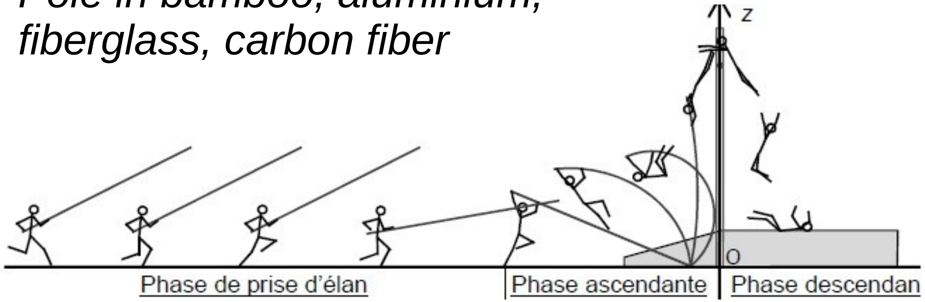


Source: Himmelfarb et al 2002
(artist: G. Renee Guzlas)

Various responses of solids to an applied force

Reversible deformation
> **elastic**

Pole in bamboo, aluminium, fiberglass, carbon fiber



Irreversible deformation
> **plastic**

mechanical rupture
> **brittle**

continuous deformation
> **ductile**

So let's get going…?

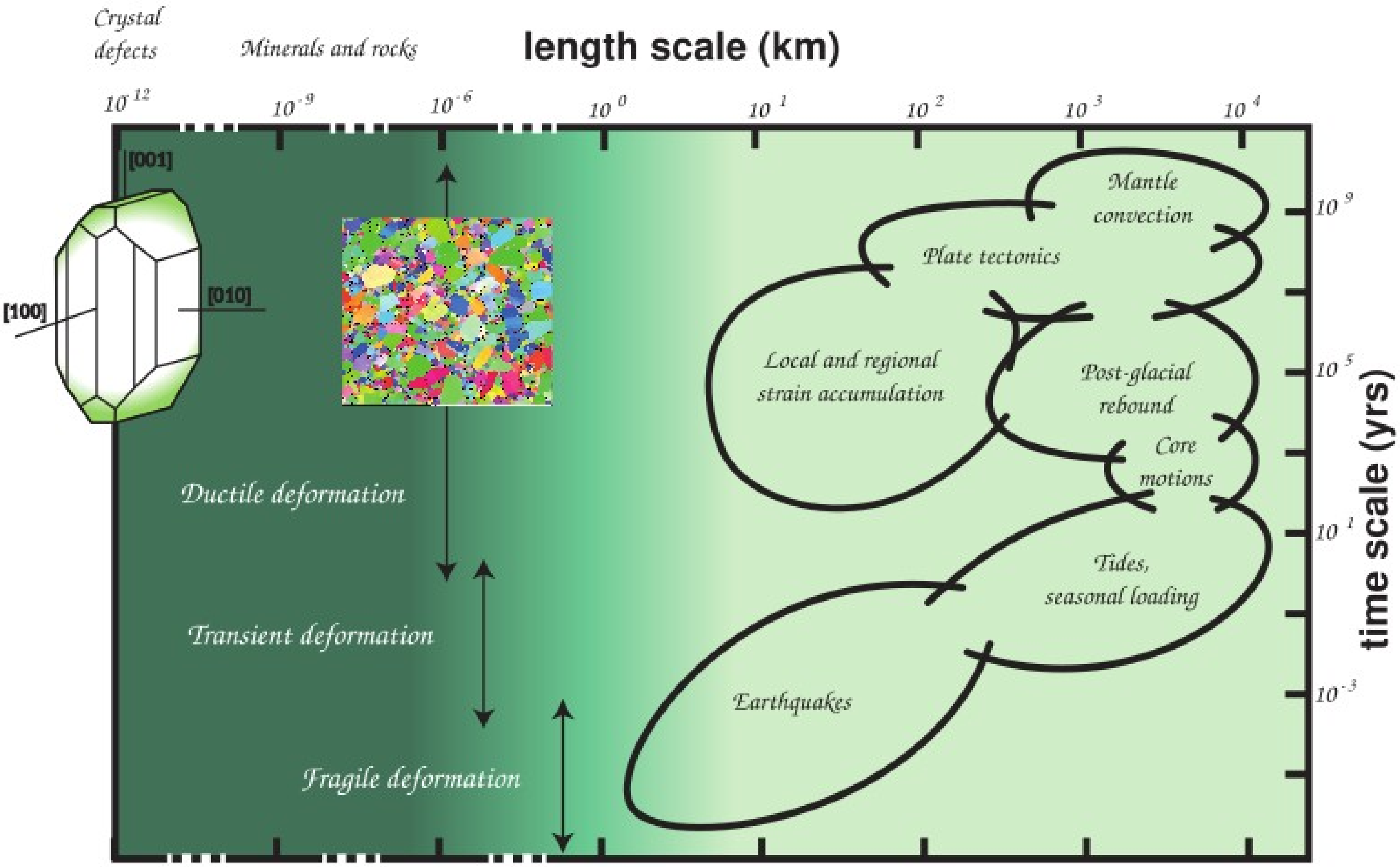
- identify & parameterize deformation processes

+ how do they coexist/interact?

- upscaling to nature

> from crystal to plate

> from lab rate to convection rate

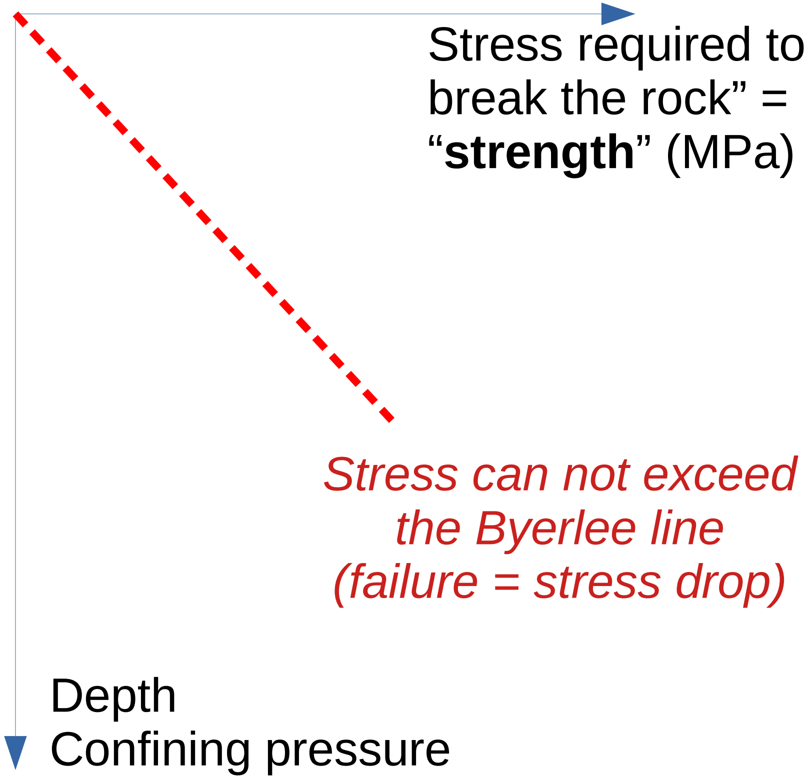


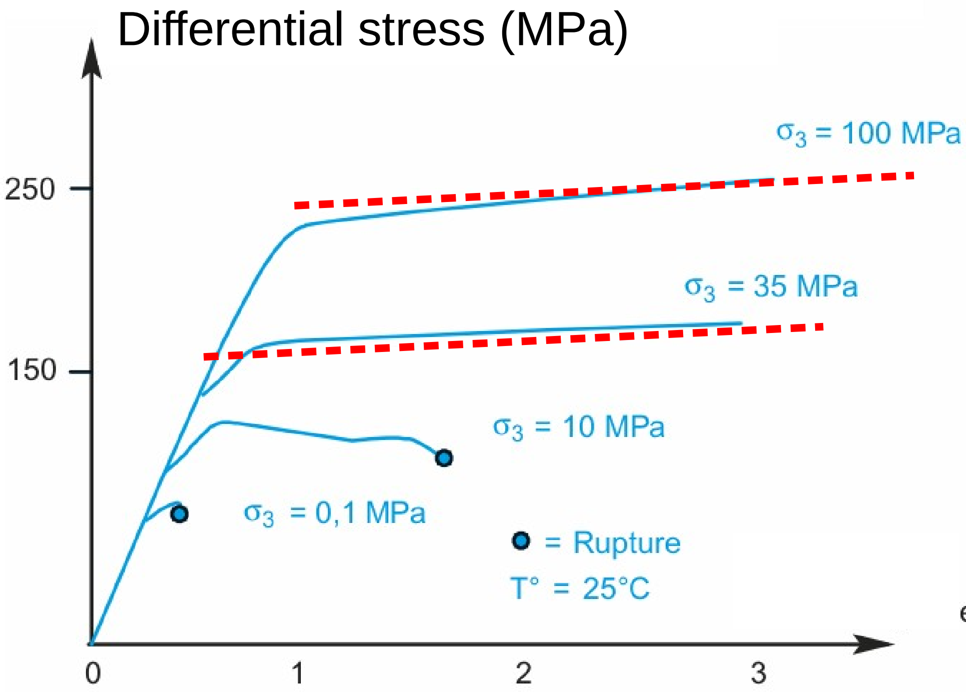
Modified from K. Lambeck (1988)

Rheology = deformation of material under a mechanical stress

→ *approached through laboratory experiments of crystal, aggregate or rock deformation*

- Byerlee's "law" of friction and strength profile
- Creep (++strain without additionnal stress) > **"yield stress"**





Géologie BCPST tout-en-un

For fluid and solid: viscous flow

Pitch drop exp. : *9 drops in 84 years !*

Credit : John Mainstone

→ if you wait long enough, everything flows !

dimensionless Debora number
"the mountains flowed before the Lord"

Viscosity = **measure** of material resistance to flow/deformation over time (> strain rate)

= resulting from "internal" friction

- *dynamic viscosity η or μ in Pa.s*

- *kinematic viscosity ν in m^2/s*
  "momentum diffusivity"

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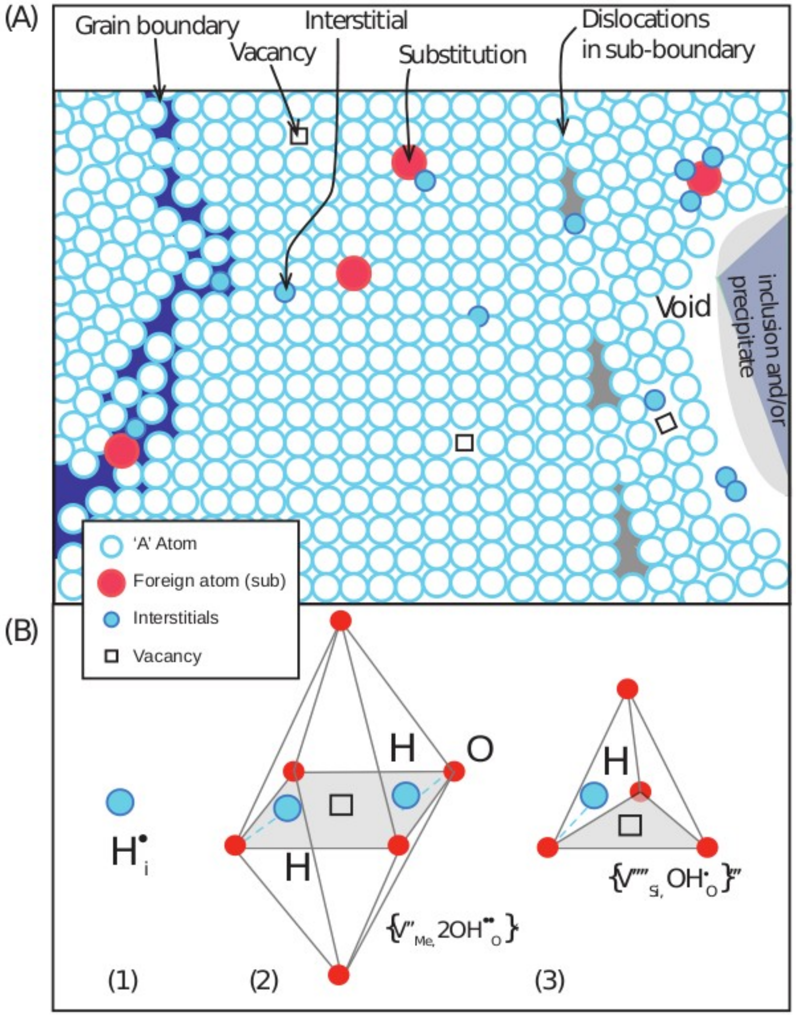
Viscosity – orders of magnitude

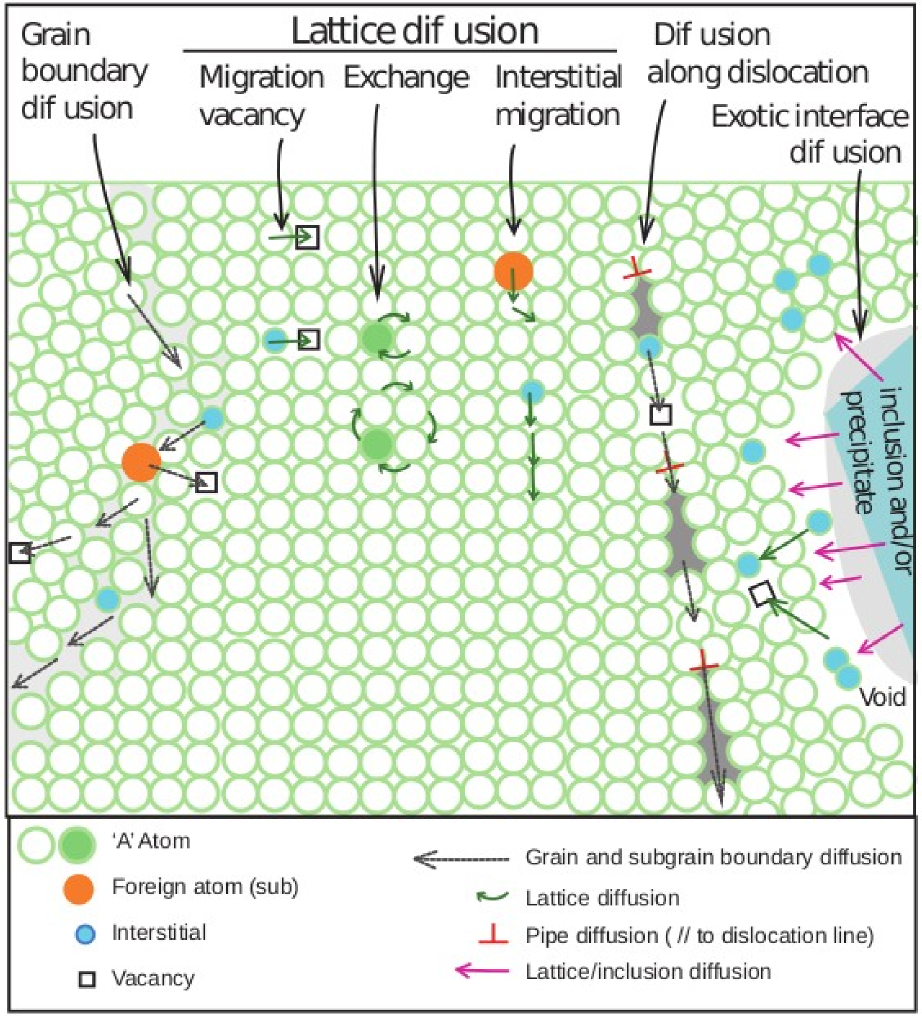
Water ~ 10^{-3} Pa.s,
Oil ~ 10^{-2} Pa.s

Maple syrup ~ 1 Pa.s
Peanut butter ~10^{2} Pa.s

Pea ~ 10^{11} Pa.s
Salt diapir ~ 10^{18} Pa.s
Rock ~ 10^{19-28} Pa.s

How do rocks flow ? > deformation by defects motion at micro-scale





Courtesy of S. Demouchy

Diffusion creep flow' law

Arrhenius-type law
(thermally-activated)

$$\dot{\varepsilon} = A_{\mathrm{diff}}\,\sigma_d \exp\left(-\frac{E_a + PV_a}{RT}\right)$$

activation energy

lithostatic pressure

activation volume

strain rate

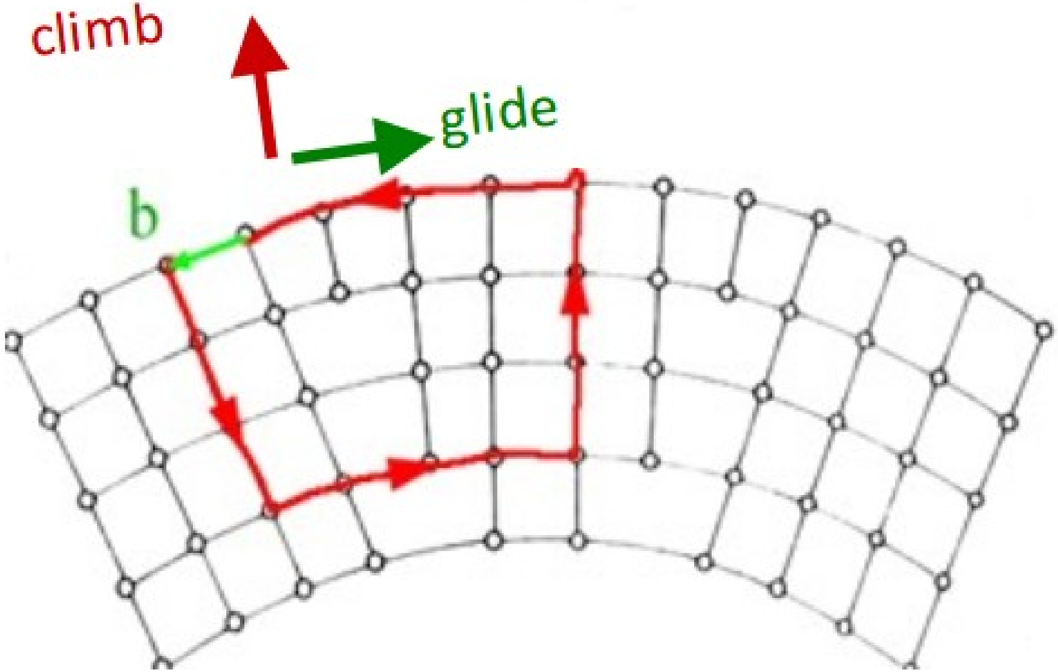
pre-factor

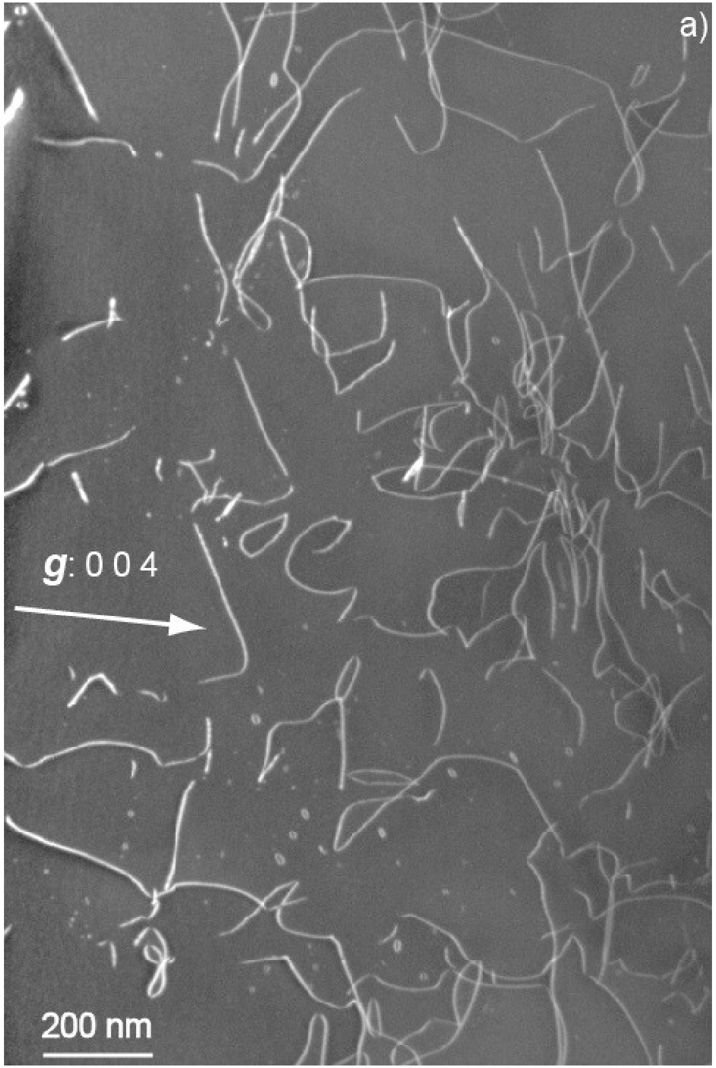
stress

temperature

Dependencies other than P and T : **grain size, mineralogy, chemistry/water**

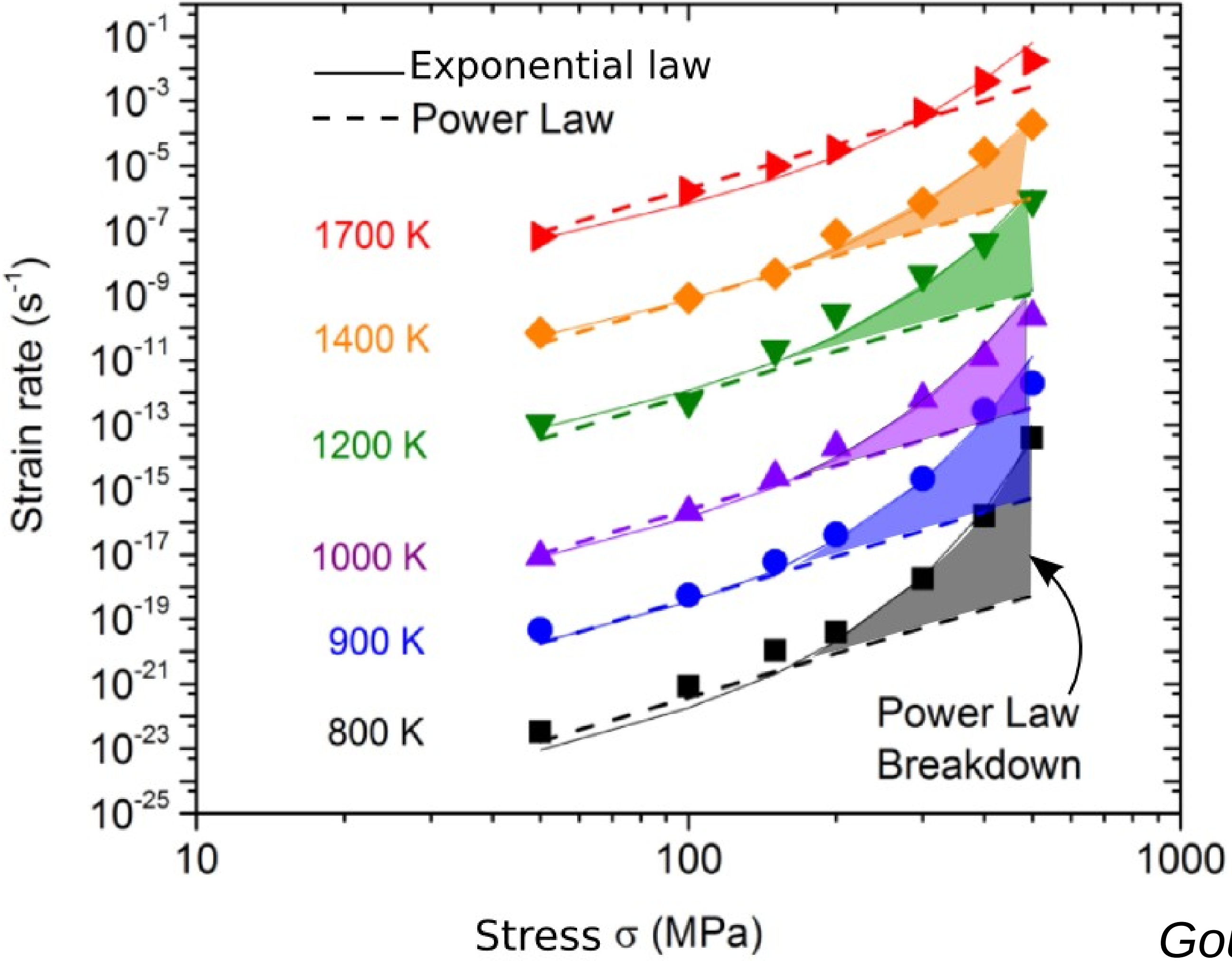
Deformation by defects motion at micro-scale





Dislocations
in olivine from TEM
(*Mussi et al., 2015*)

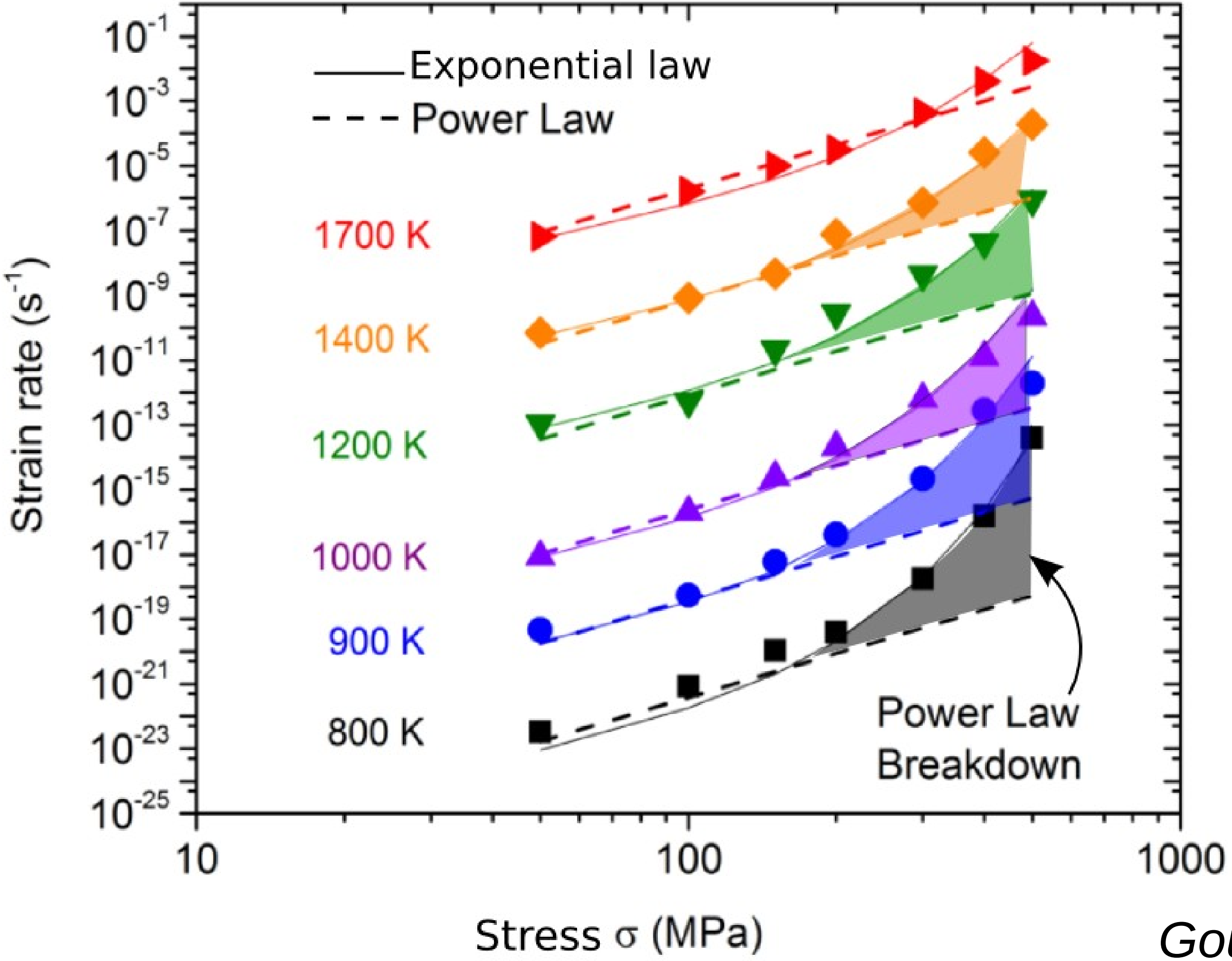
2.5-D dislocation dynamics (DD) *numerical experiments on olivine*



→ continuity of dislocation dynamics (glide + climb) from 800 to 1700 K and from low to high stresses

Gouriet et al., EPSL, 2019

2.5-D dislocation dynamics (DD) *numerical experiments on olivine*



- **Power-law** between strain rate and stress

valid at low stress and high T

- **power-law breakdown**

at low T, high stress (deforming plates and slabs)

Gouriet et al., EPSL, 2019

2.5-D dislocation dynamics (DD) *numerical experiments on olivine*

$$\dot{\varepsilon} = A_{\mathrm{disl}} \sigma_d^{\mathbf{n}} \exp\left(-\frac{E_a + PV_a}{RT}\right)$$

- **Power-law** between strain rate and stress

valid at low stress and high T

$$\dot{\varepsilon} = A\sigma^{\mathbf{n}} \exp\left[-\frac{E_a}{RT}\left(1-\left(\frac{\sigma}{\sigma_P}\right)^p\right)^q\right]$$

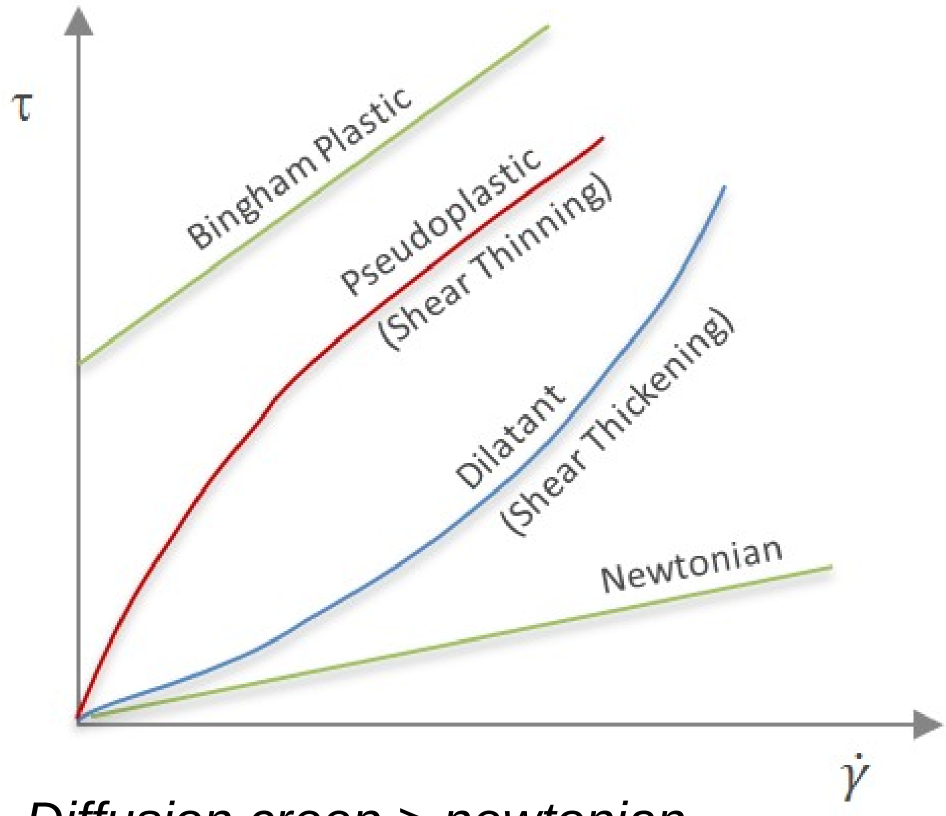
- **power-law breakdown**

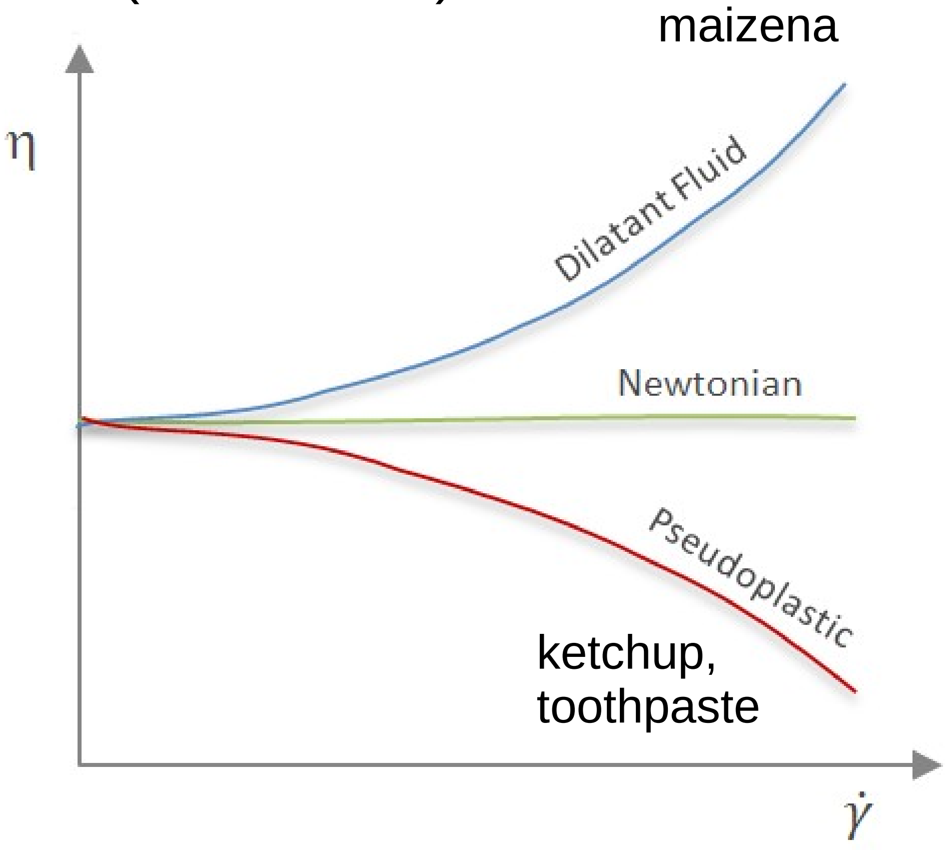
at low T, high stress (deforming plates and slabs)

Frost and Ashby, 1982

From flow “laws” to viscosity

At first order : viscosity = stress / (2 strain rate)

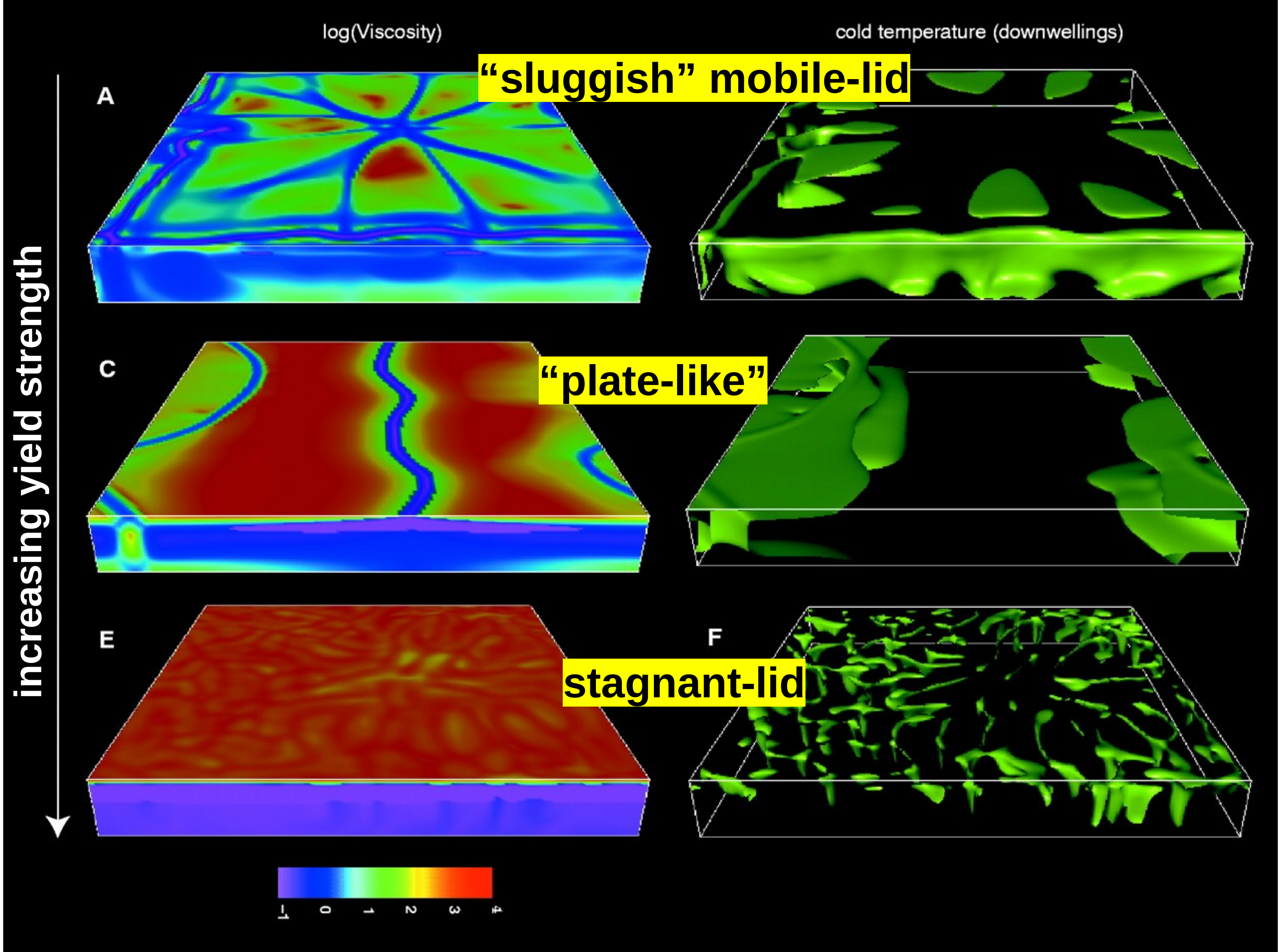




Diffusion creep > newtonian

Dislocation creep > non-newtonian

polymerdatabase.com

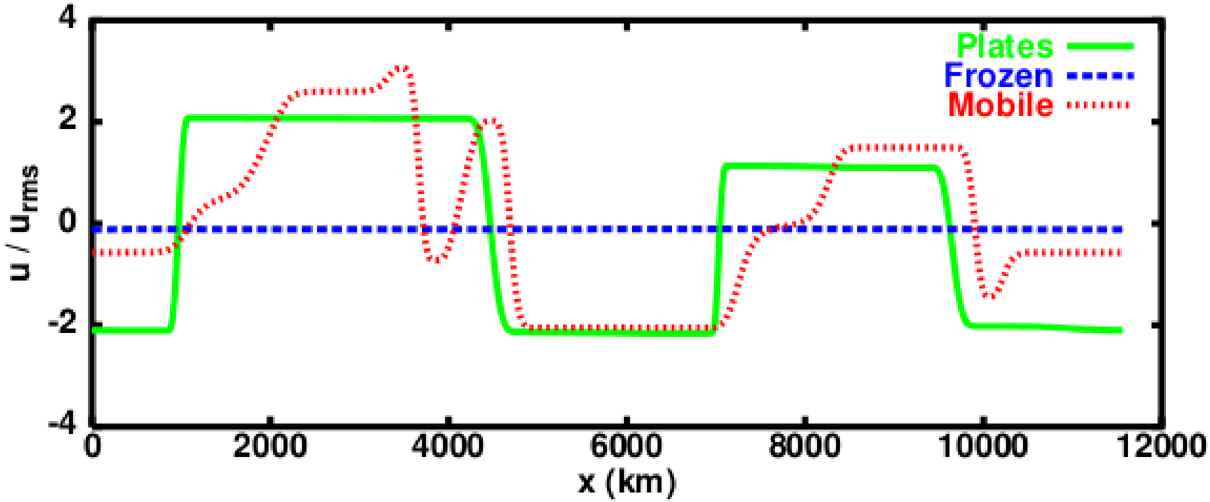


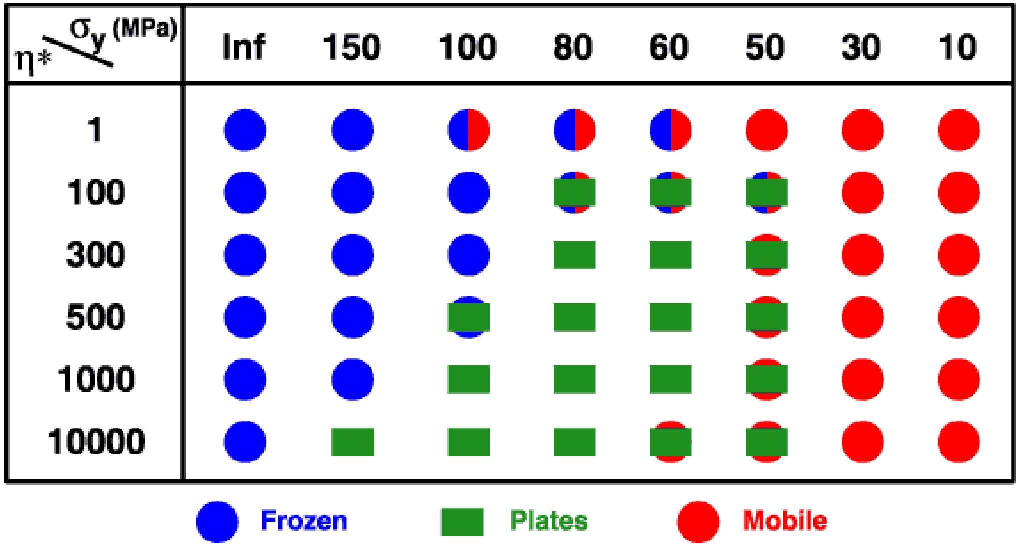
yield strength = mechanical resistance of the cold lithospheric boundary layer

Tackley Science 2000

Importance of viscosity parameterization

localizing deformation at plate boundary

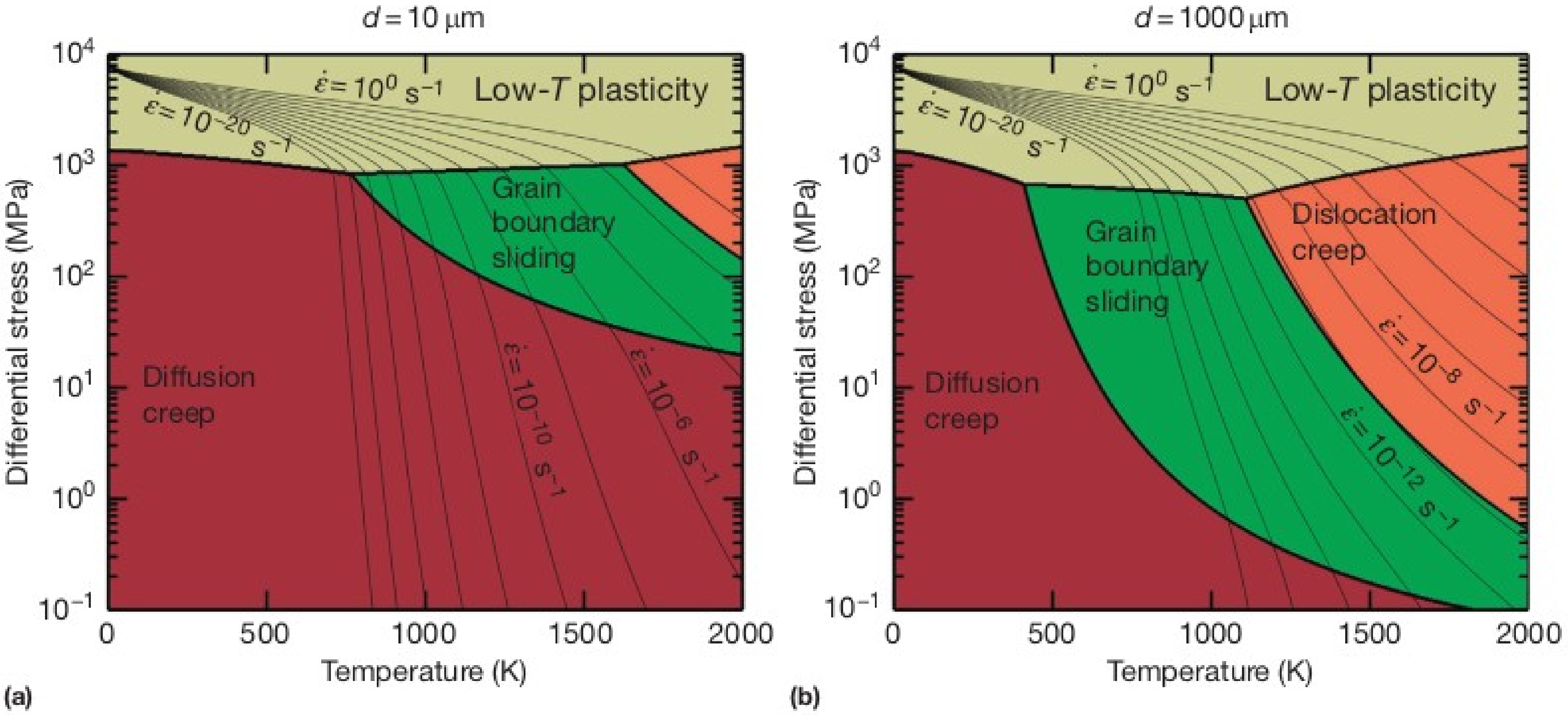




lithosphere mobility as a function of **yield stress** σ_y and viscosity contrast η^* for a **sub-plate low-viscosity layer**

Richards G³ 2001

Deformation partitioning (minimal viscosity)



… but probably <u>coexisting mechanisms</u> rather than bimodal partitioning

Kohlstedt & Hansen, Treatise on Geophysics, 2015

From flow "laws" to viscosity

Several coexisting deformation mechanisms → <u>addition of strain rates</u> ?

$$\begin{aligned} \dot{\varepsilon}_{\text{tot}} &= \dot{\varepsilon}_{\text{el}} + \dot{\varepsilon}_{\text{plastic}} \\ \dot{\varepsilon}_{\text{plastic}} &= \dot{\varepsilon}_{\text{brittle}} + \dot{\varepsilon}_{\text{ductile}} \\ \dot{\varepsilon}_{\text{ductile}} &= \dot{\varepsilon}_{\text{disl}} + \dot{\varepsilon}_{\text{diff}} \end{aligned}$$

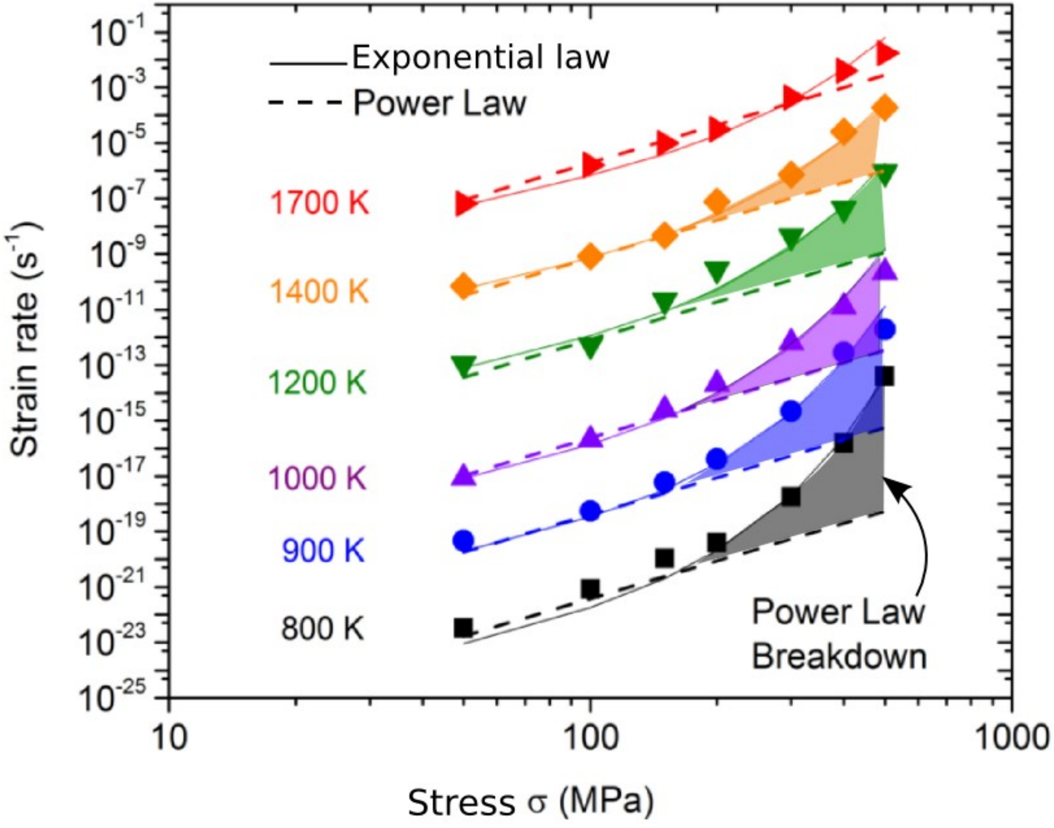
From flow “laws” to viscosity

Several coexisting deformation mechanisms → <u>addition of strain rates</u> ?

$$
\begin{aligned}
\mu_{\text{eff}} &= \frac{\tau_{II}}{2\dot{\varepsilon}_{II}} \\
\frac{1}{\mu_{\text{eff}}} &= \frac{2\dot{\varepsilon}_{II}}{\tau_{II}} \\
&= \frac{2\dot{\varepsilon}_{\text{disl}}}{\tau_{II}} + \frac{2\dot{\varepsilon}_{\text{diff}}}{\tau_{II}} \\
&= \frac{1}{\mu_{\text{disl}}} + \frac{1}{\mu_{\text{diff}}} \\
\mu_{\text{eff}} &= \left(\frac{1}{\mu_{\text{disl}}} + \frac{1}{\mu_{\text{diff}}}\right)^{-1}
\end{aligned}
$$

pseudo-harmonic mean for viscosity

Reconciling experimental micro-scale rheology and large-scale mantle viscosity
(through numerical modelling)



→ semi-empirical exponential fit

$$\dot{\varepsilon} = A\sigma^{\mathbf{n}} \exp\left[-\frac{E_a}{RT}\left(1-\left(\frac{\sigma}{\sigma_P}\right)^p\right)^q\right]$$

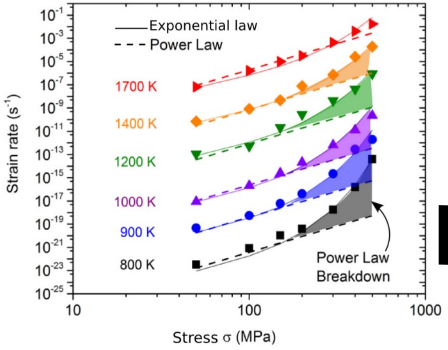
Frost and Ashby, 1982

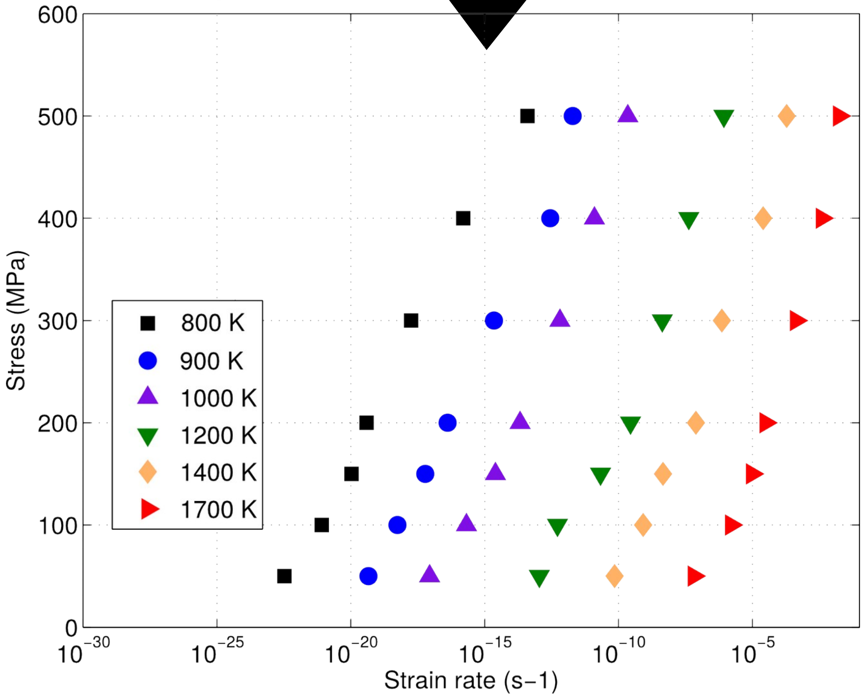
not modeler-friendly...

→ need to express stress as a function of strain rate for **viscosity calculation**

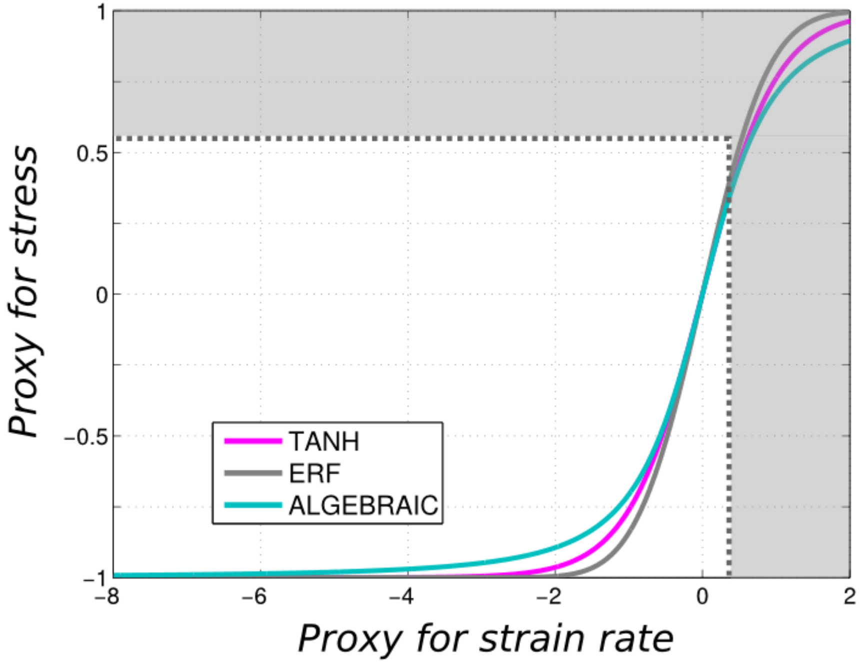
Gouriet et al., EPSL, 2019

Reconciling experimental micro-scale rheology and large-scale mantle viscosity
(through numerical modelling)

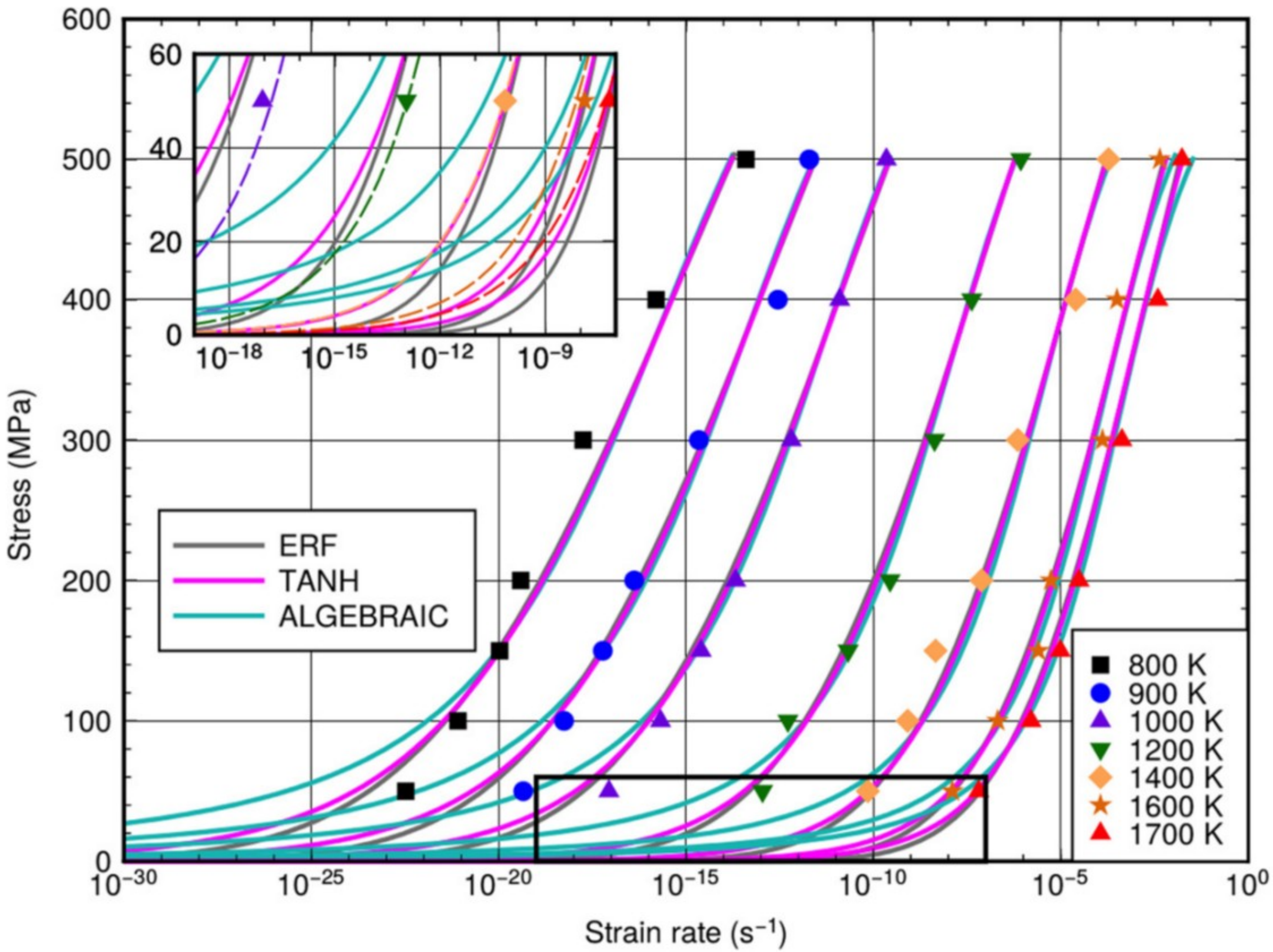




3 ≠ sigmoid functions to fit both high-T and low-T data



3 parameterizations for dislocation creep rheology...
fitting equally well the data !



Garel et al., EPSL, 2020

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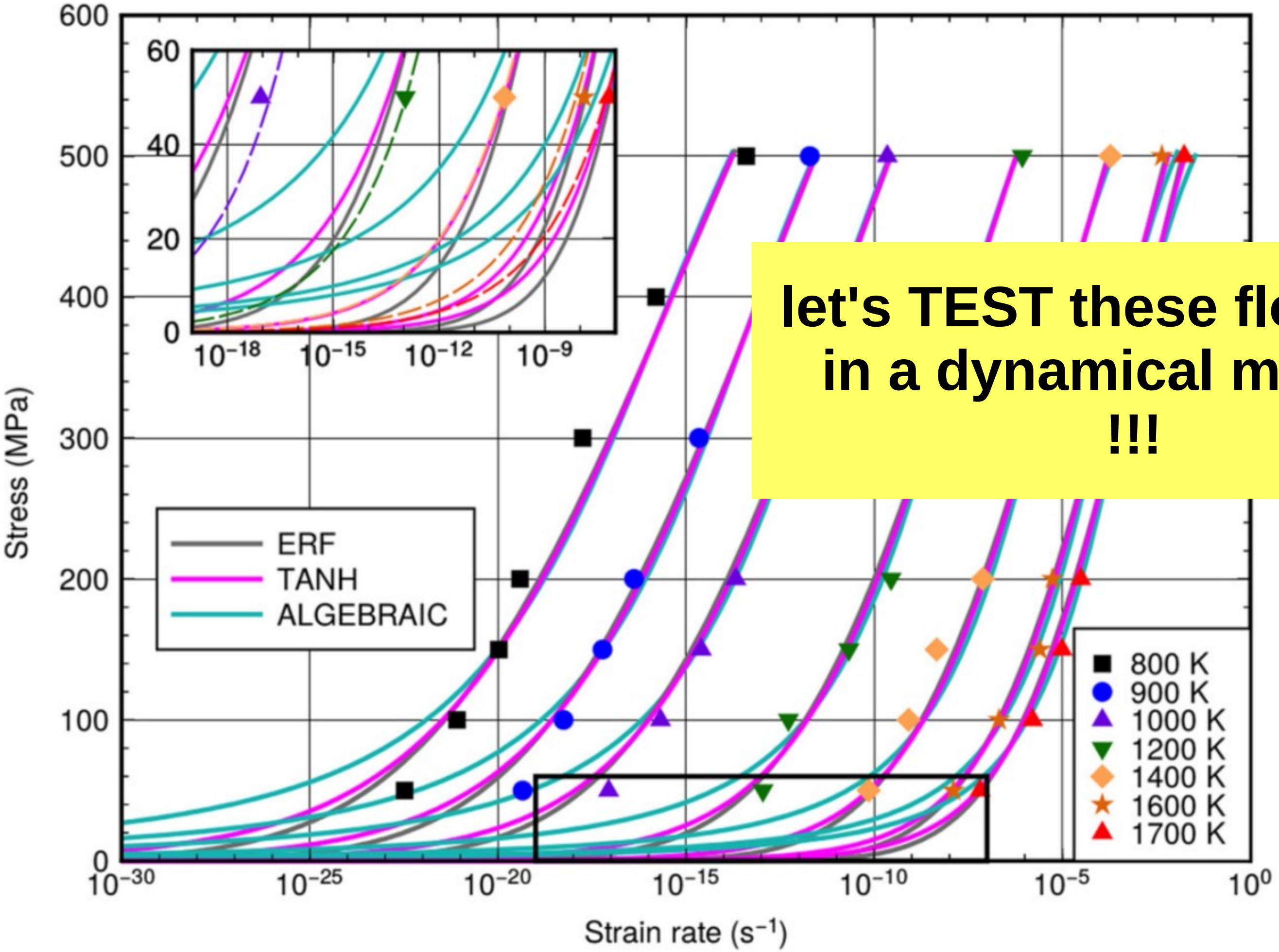
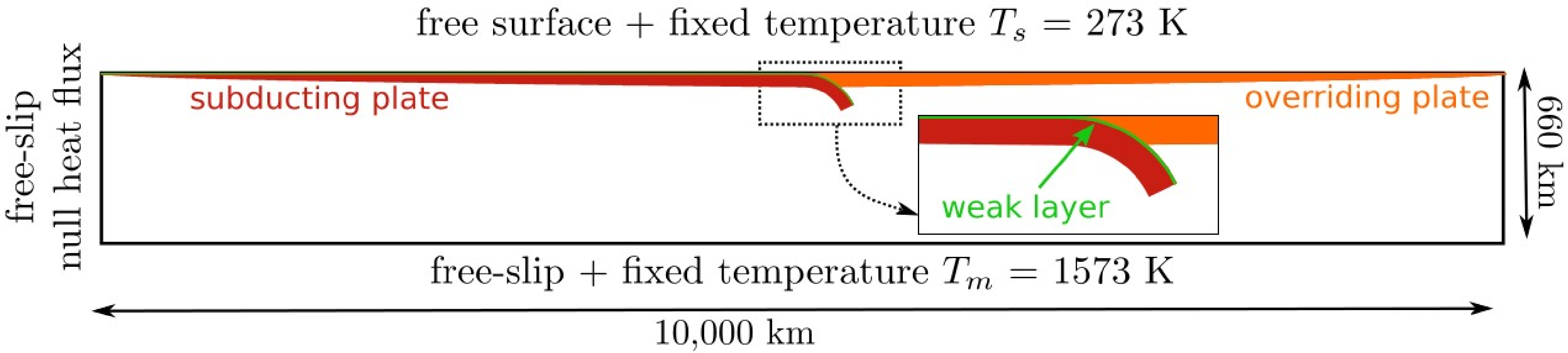


let's TEST these flow laws in a dynamical models !!!

Garel et al., EPSL, 2020

Free subduction model



Composite rheology (addition of strain rates)

$$\boxed{\frac{1}{\mu} = \frac{1}{\mu_{diff}} + \frac{1}{\mu_{disl}} + \frac{1}{\mu_{br}}}$$

- pseudo-brittle / yield stress
- diffusion creep
- **1 single parameterization for dislocation creep** (continuous from low to high temperature)

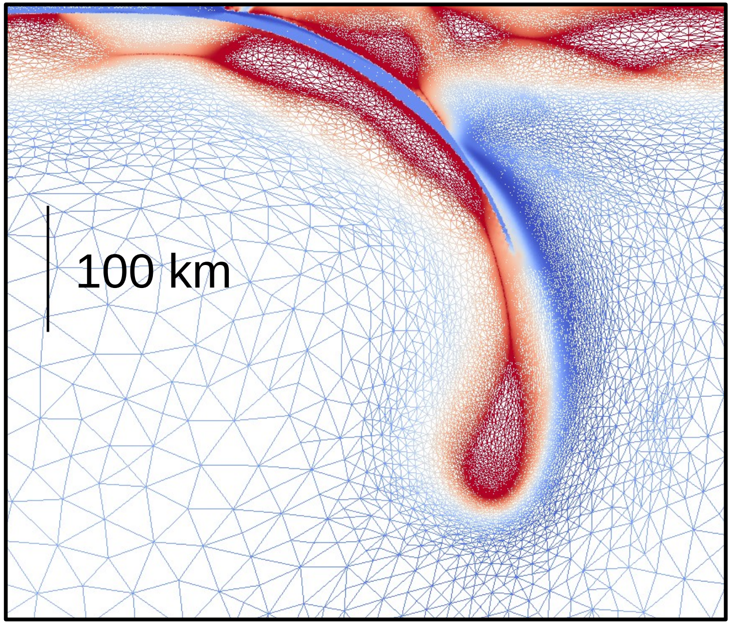
~~- BEFORE : 2 dislocation creeps (high-T and Peierls low-T)~~

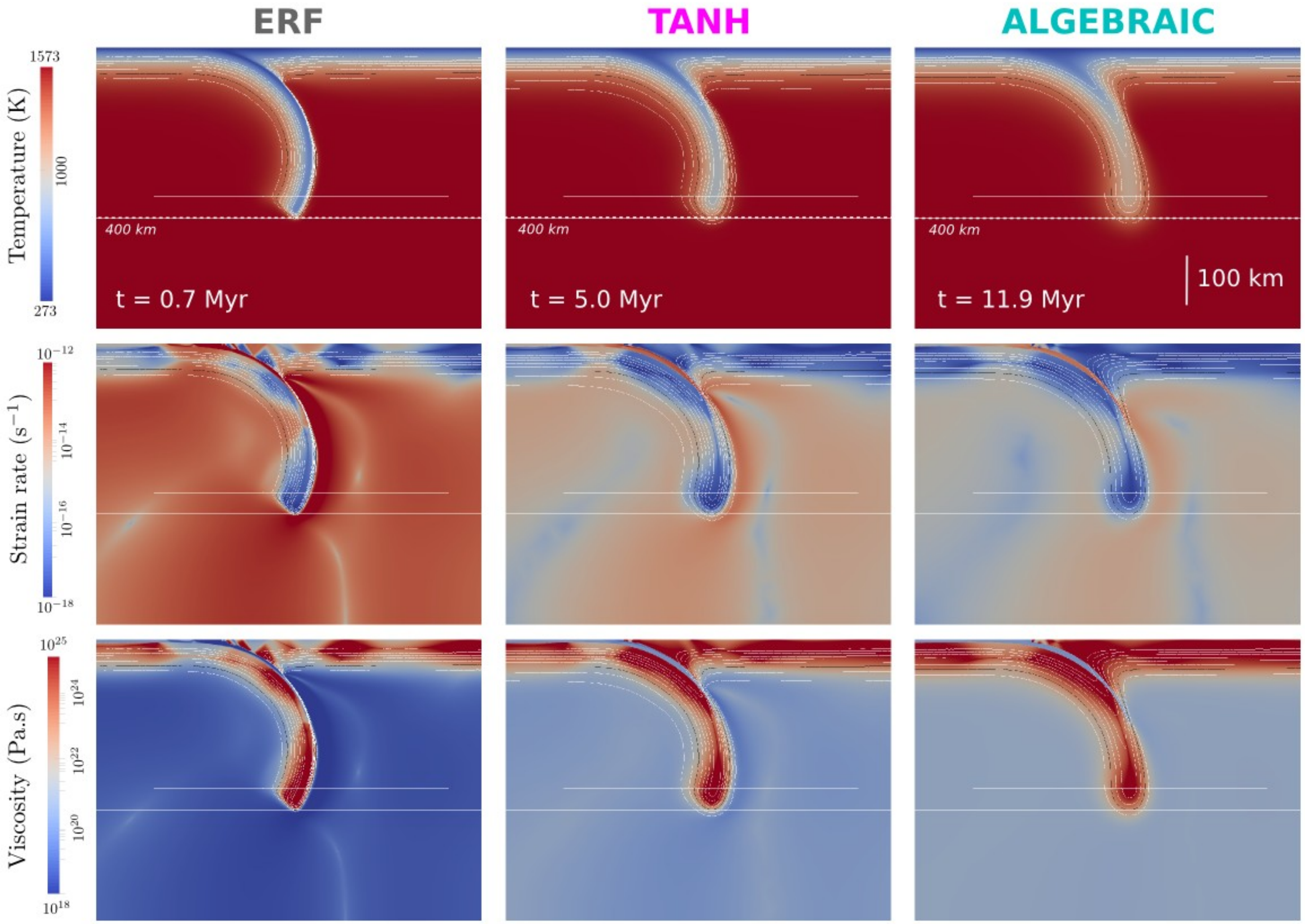
Garel et al., EPSL, 2020

Davies et al., G3, 2011
Kramer et al., PEPI, 2012

- **finite-element**, parallel-running code **solving conservation equations**
- developed by the AMCG group (Imperial College London)

- automatic adaptive meshing depending on spatial variations of temperature, velocity, viscosity...

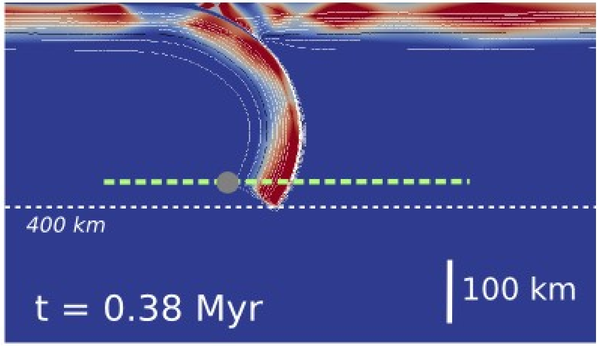




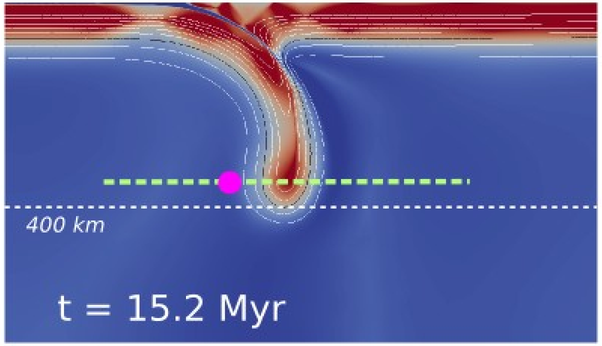
<u>VERY</u> contrasted subduction dynamics

Garel et al., EPSL, 2020

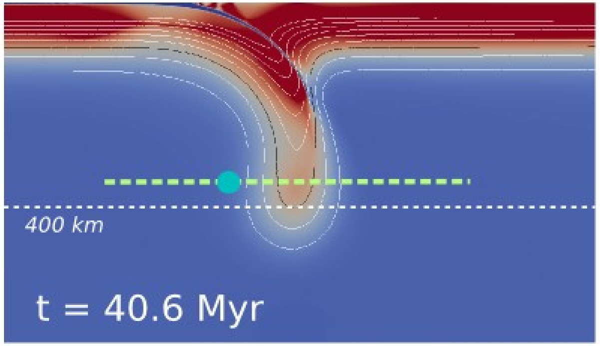
ERF



TANH



ALGEBRAIC

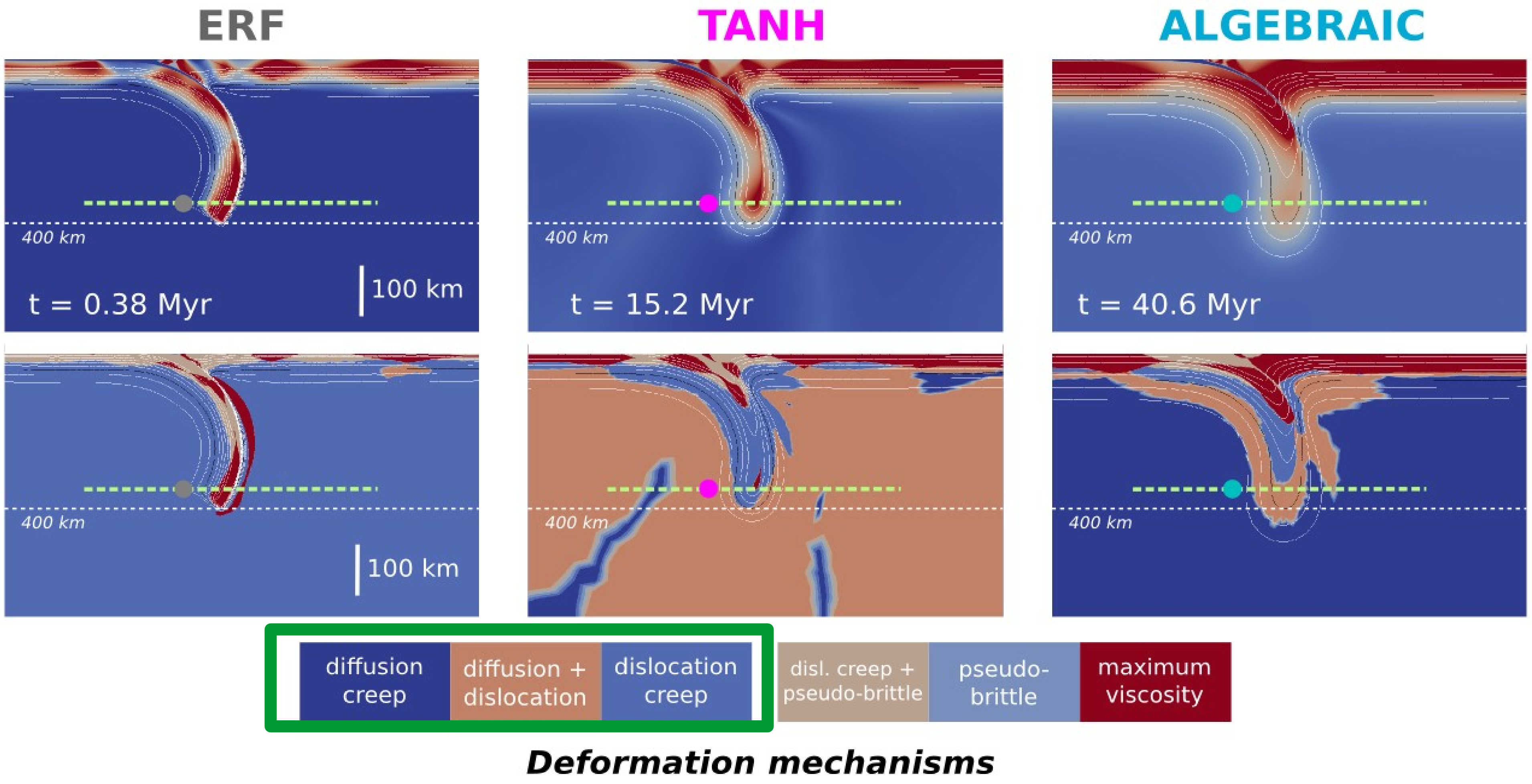


Sinking ++
- very weak asthenosphere
- high asth. strain rates
- very fast subduction
- cold, thin slab

Diffusive AND sinking

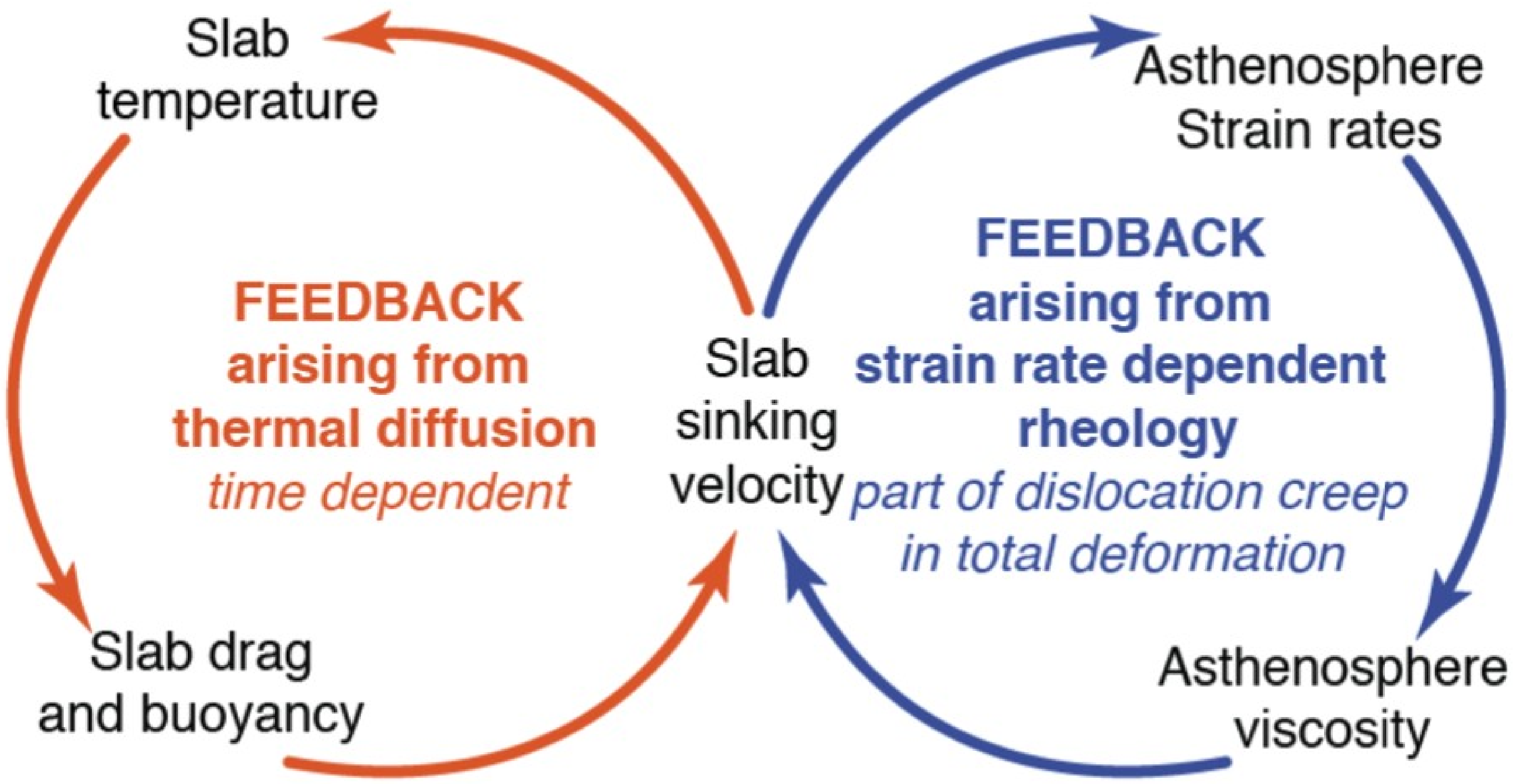
Thermal diffusion++
- high-viscosity asth.
- low asth. strain rates
- very slow subduction
- hot and wide slab

Garel et al., EPSL, 2020



partitioning btn viscosity depending on strain rate
(disl. creep, n> 1) **or not** (diff. creep, n=1)

Garel et al., EPSL, 2020

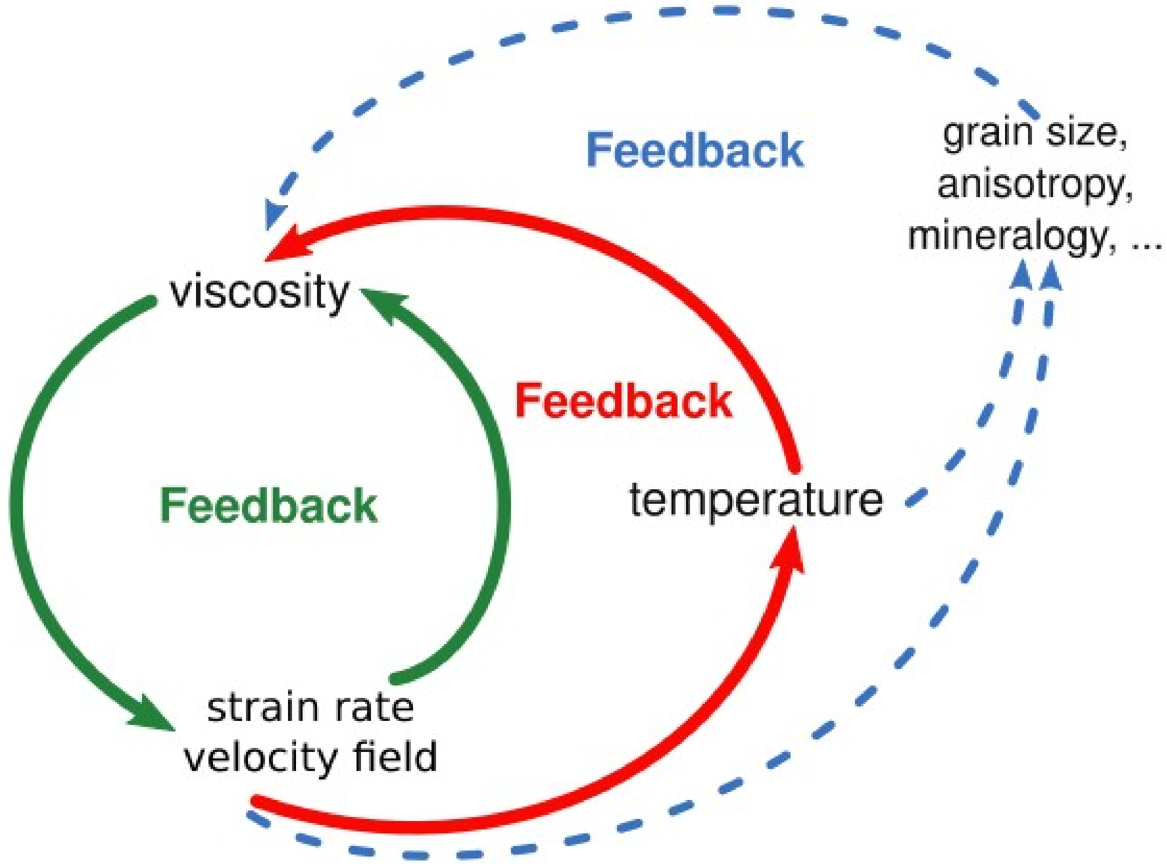


Garel et al., EPSL, 2020

Comparison with geological time-scales observables

Dislocation creep parameterization	ERF	TANH	ALGEBRAIC
Subduction dynamics	Thin, cold slab in free fall in low-viscosity upper mantle No time for thermal diffusion		Hot, diffusive slab in high-viscosity asthenosphere No strain-rate weakening
Time for the slab to reach 400-km	~0.5 Myr	~15 Myr	~40 Myr
Mean asthenosphere viscosity *post-glacial rebound and geoid modelling (~10^{20-21} Pa.s)*	10^{18-20} Pa.s	10^{20-21}Pa.s	10^{20-21}Pa.s
surface velocity of the subducting plate *Paleomagnetism and GPS data (1-10 cm/yr)*	~200 cm/yr	~1.5 cm/yr	~0.7 cm/yr
Slab morphology *tomographic imaging*			
Dislocation creep in the upper mantle *Seismic anisotropy*			

Feedbacks between deformation and dynamics

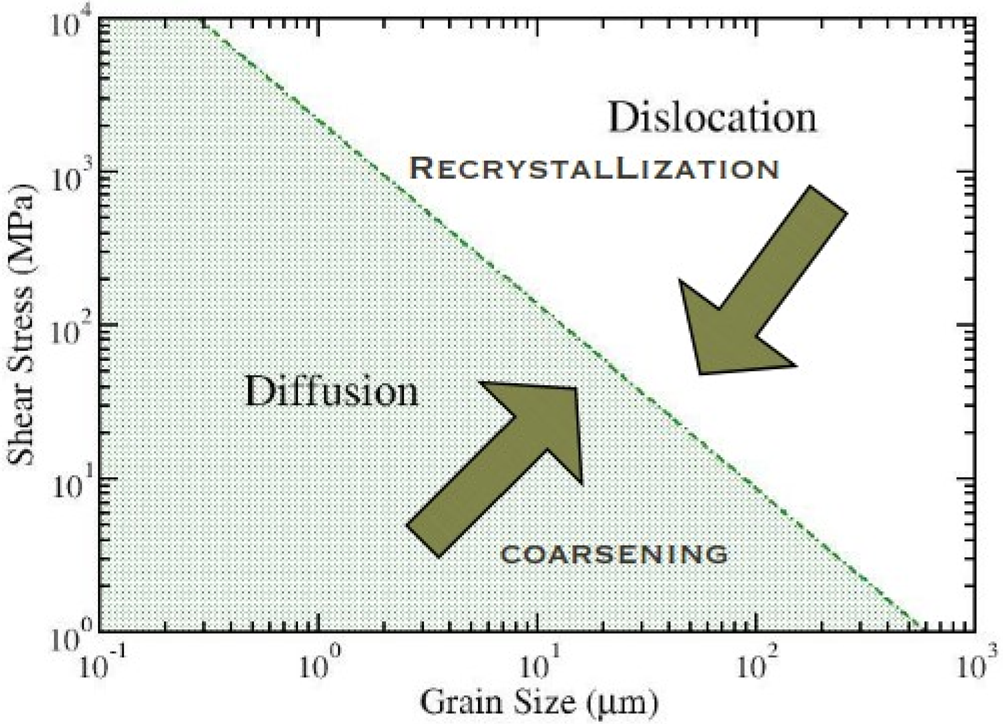


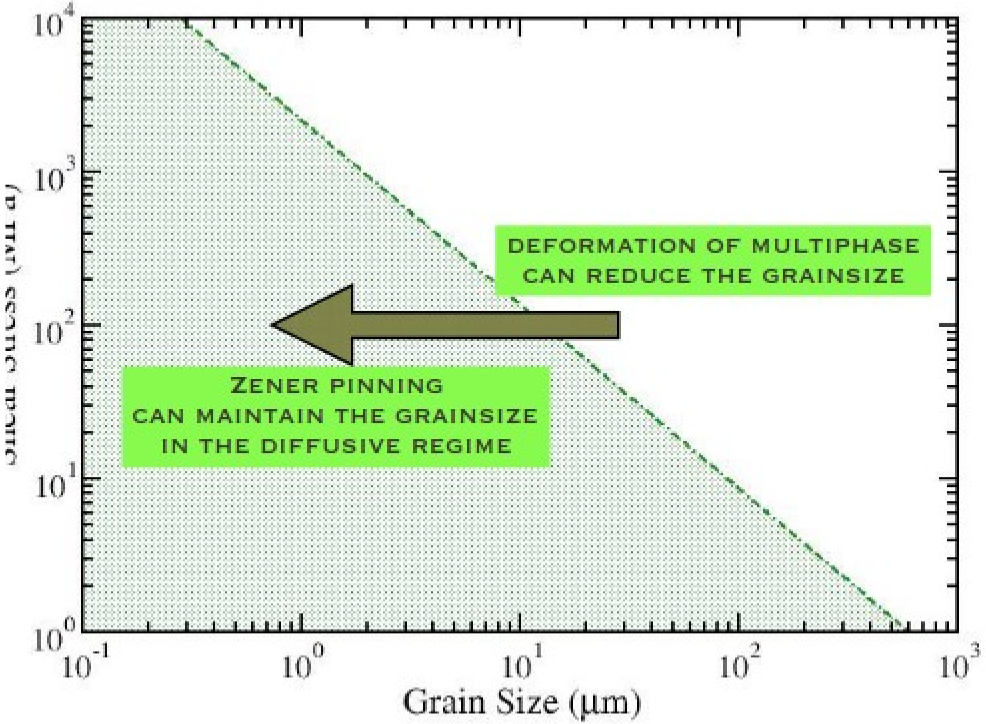
+ 2-phase viscosity (weak vs. strong phase, grain-boundary sliding...)

+ influence of shape of crystals ?

+ melt content...

Feedbacks between deformation and dynamics



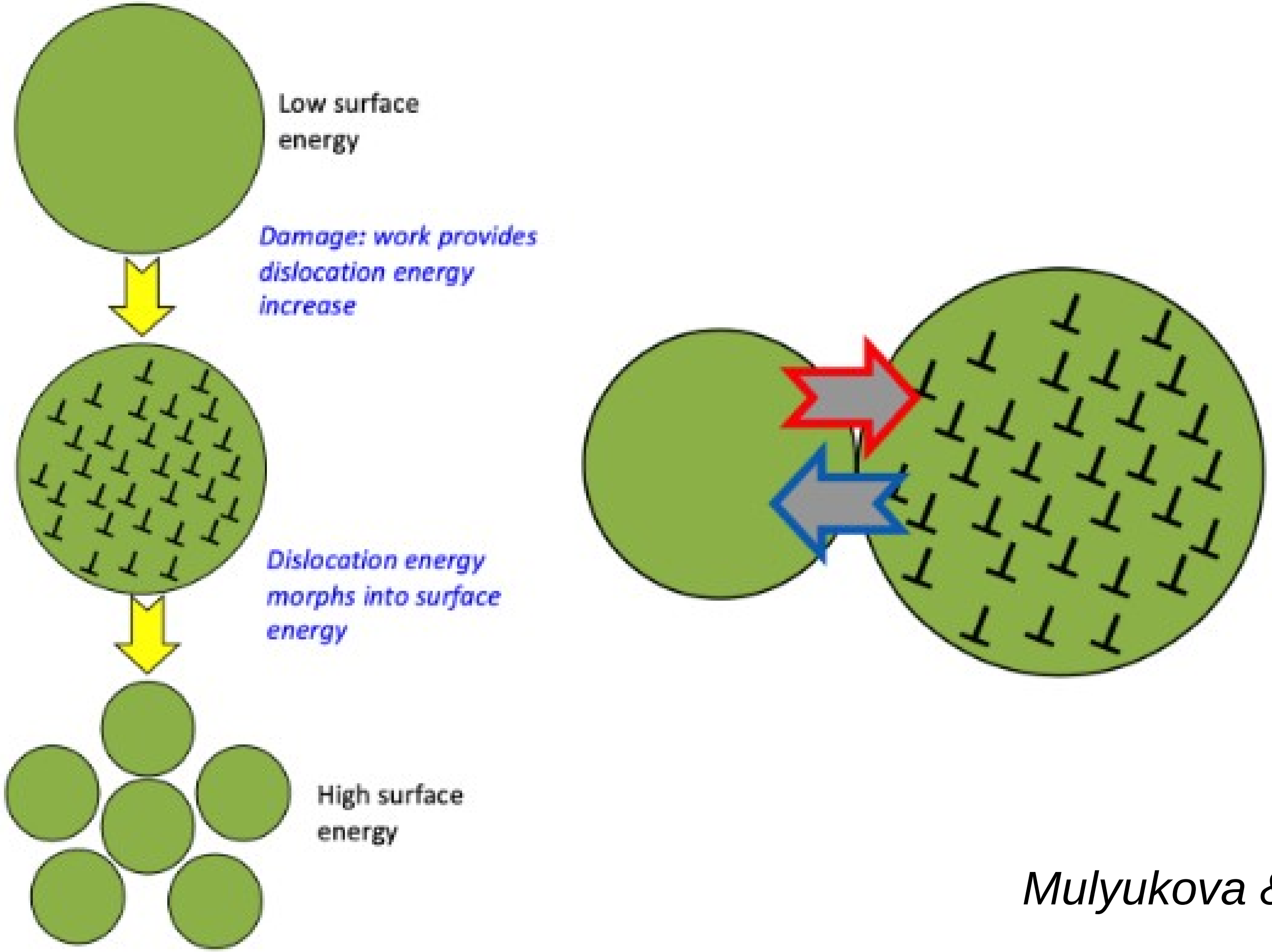


deformation-induced GS reduction + grain-size-dep viscosity (**diffusion creep**)

→ **deformation localization & plate tectonics**

Ricard +Bercovici
2012, 2013, 2014, 2016

Feedbacks between deformation and dynamics



Mulyukova & Bercovici, 2019

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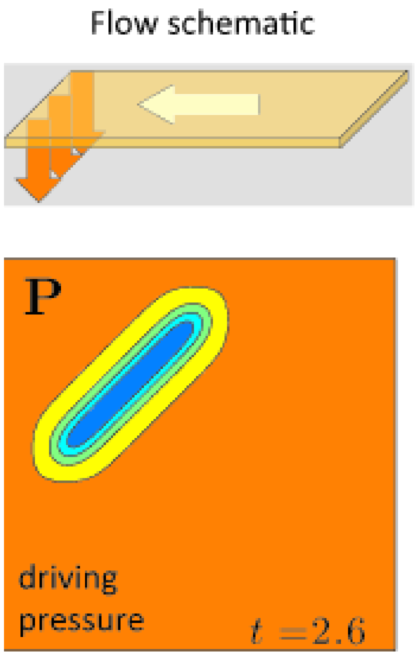

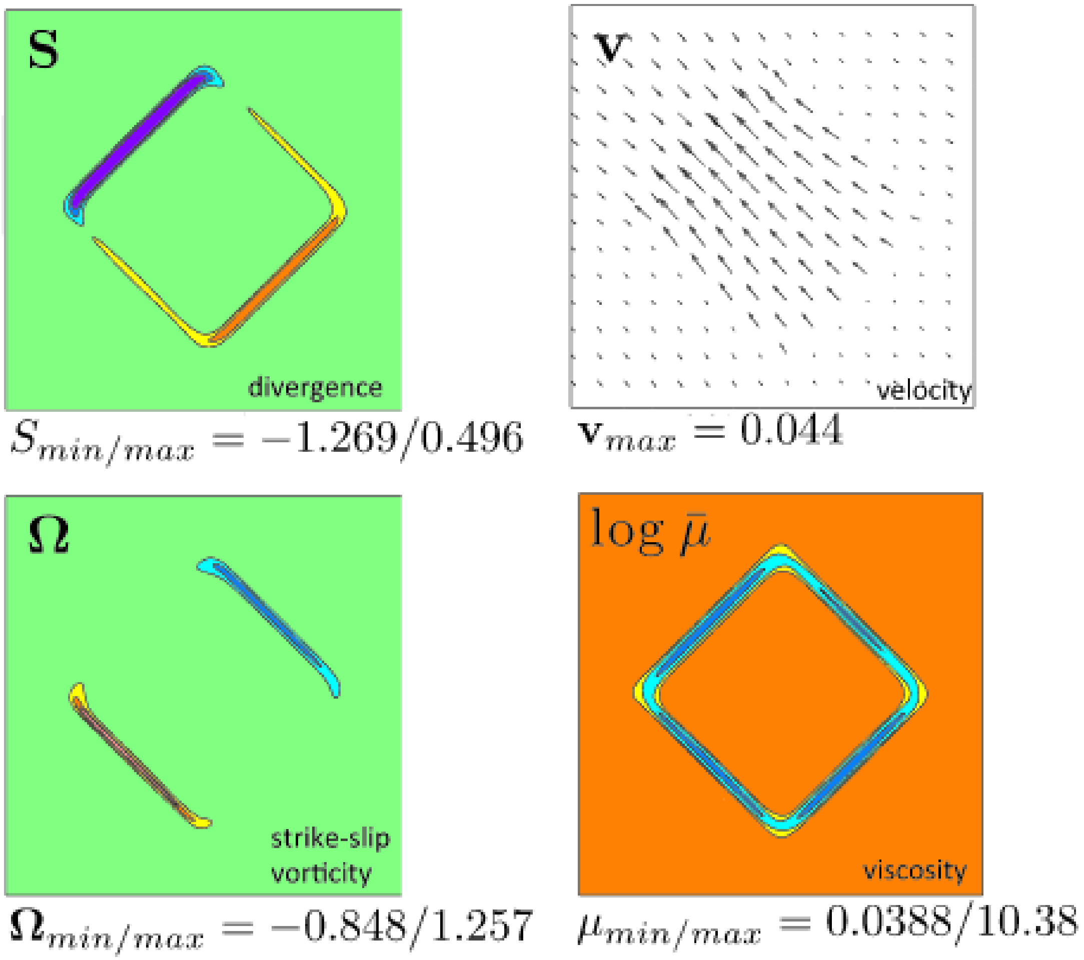

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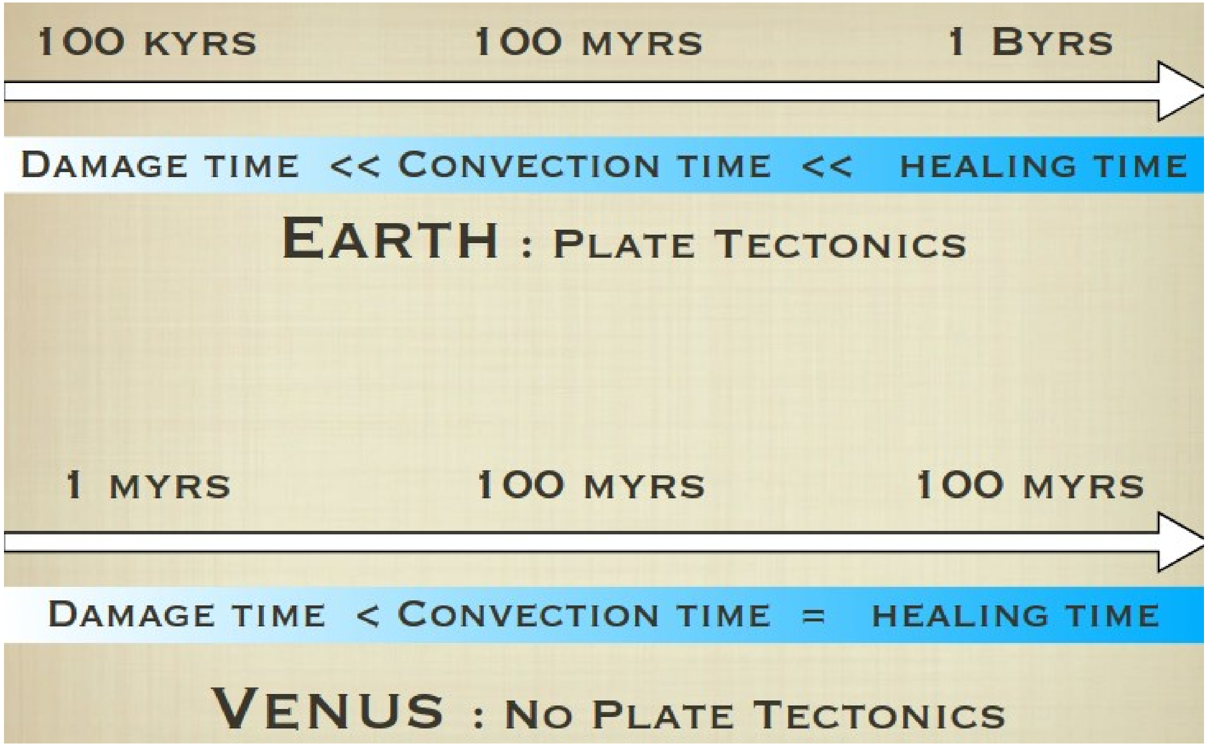

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