Heidelberg University

Mechanically-controlled rock-microstructures: Witnesses of the long-term stress-state in the continental lithosphere

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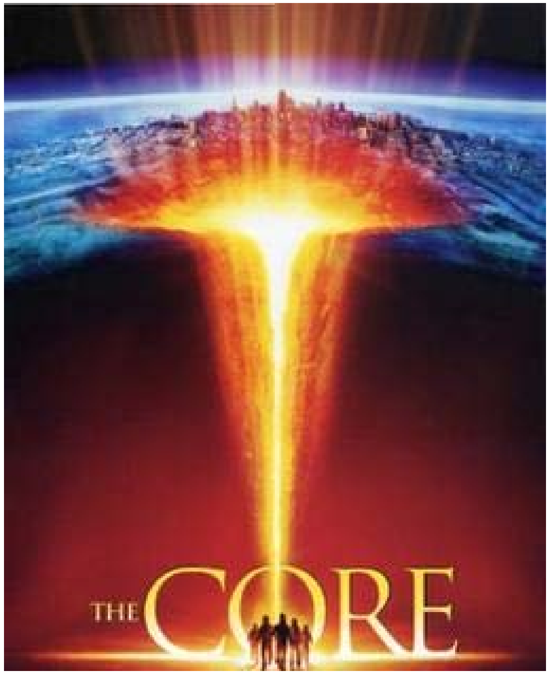
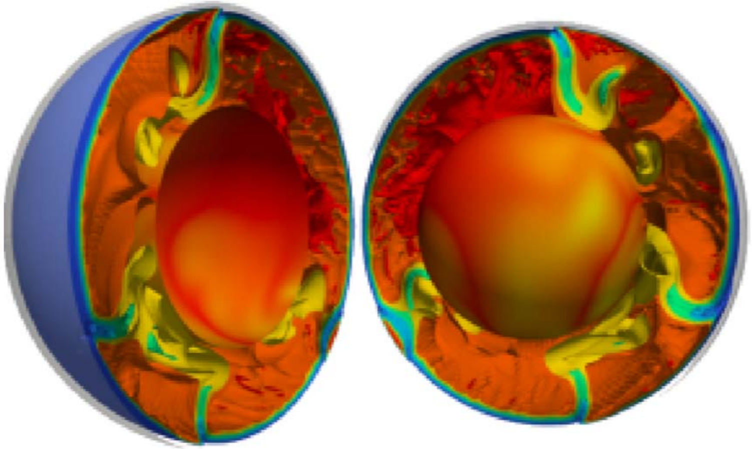


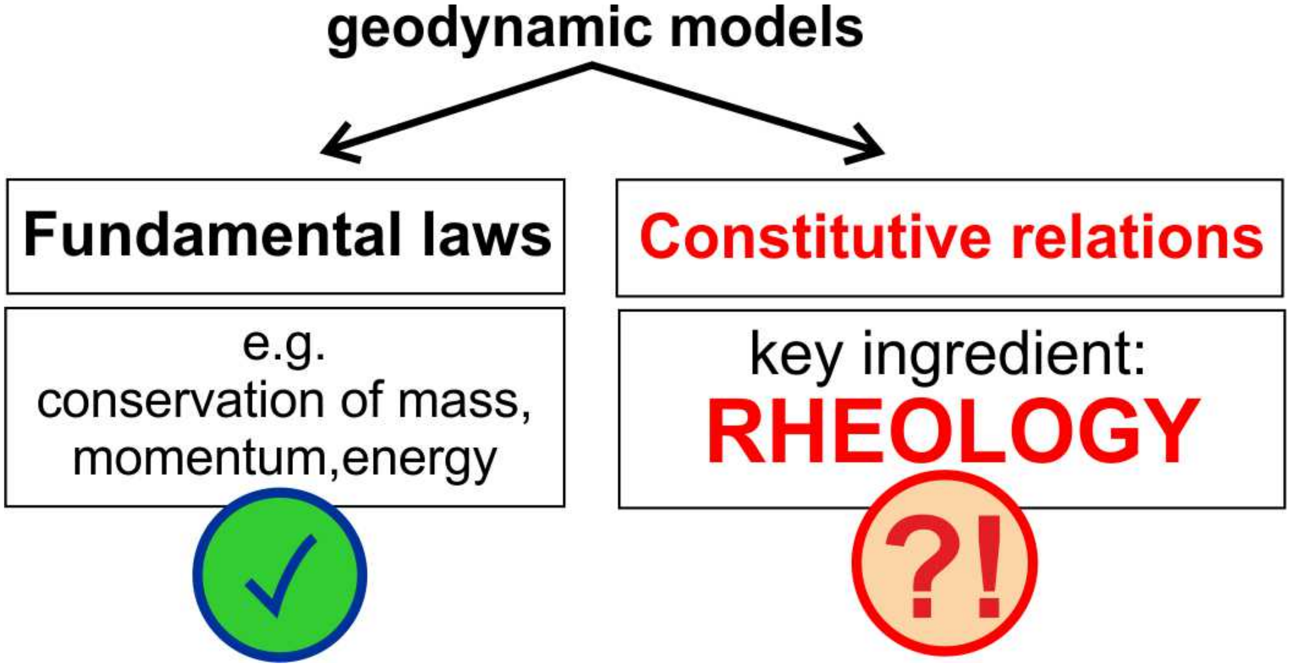
Motivation: Modelling of geodynamic processes

CURRENT AIMS:

- Understanding processes in the Earth interior
- Mitigation measures, e.g. earthquakes



May et.al., 2013 & Crameri et al., 2012



geodynamic models

Fundamental laws

e.g.
conservation of mass,
momentum,energy

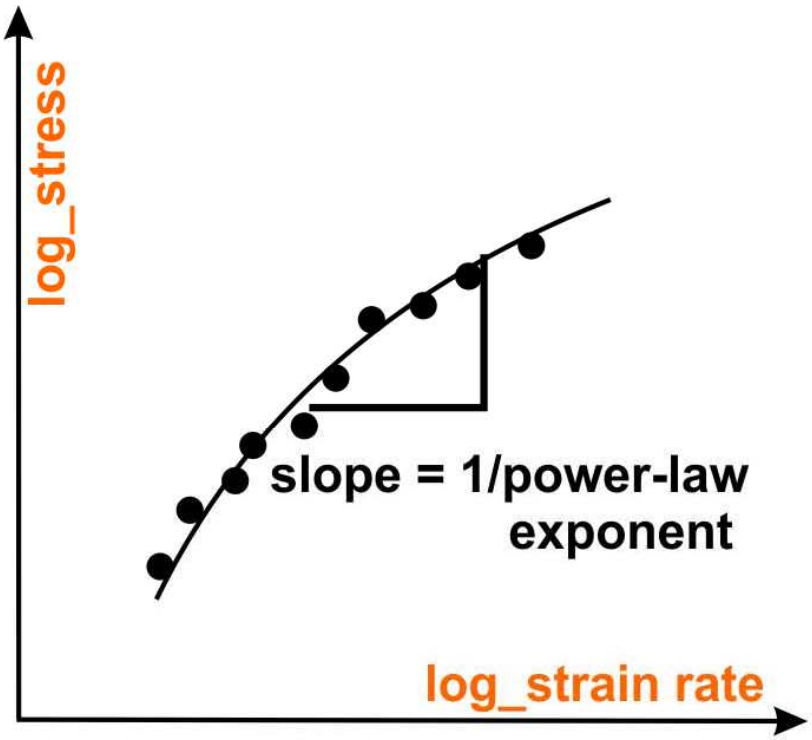
✓

Constitutive relations

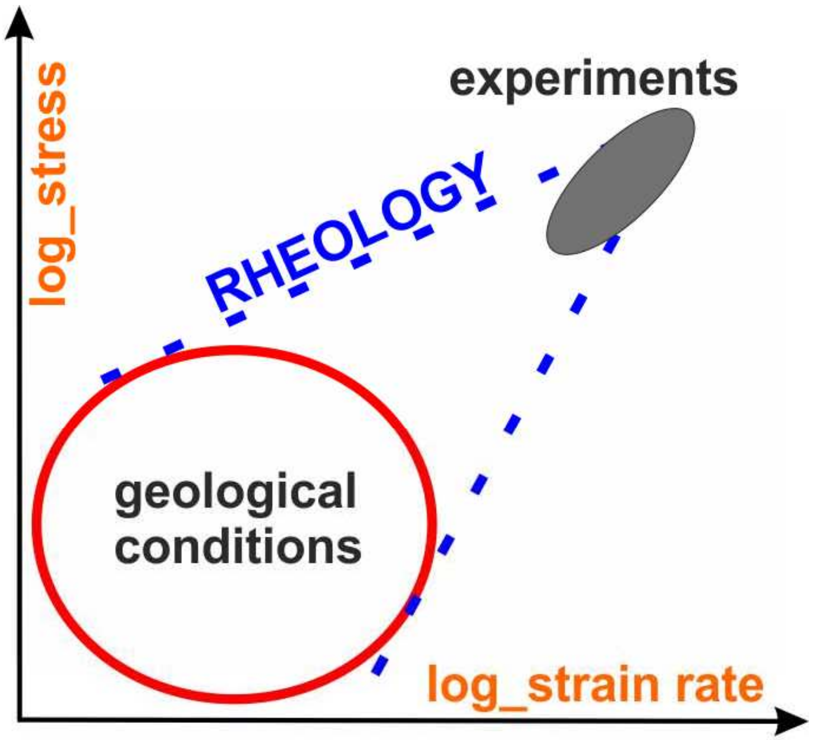
key ingredient:
RHEOLOGY

?!

Rheology: an extrapolation problem



Log-Log stress-strain rate diagram to determine the stress exponent n



Extrapolation to geological conditions

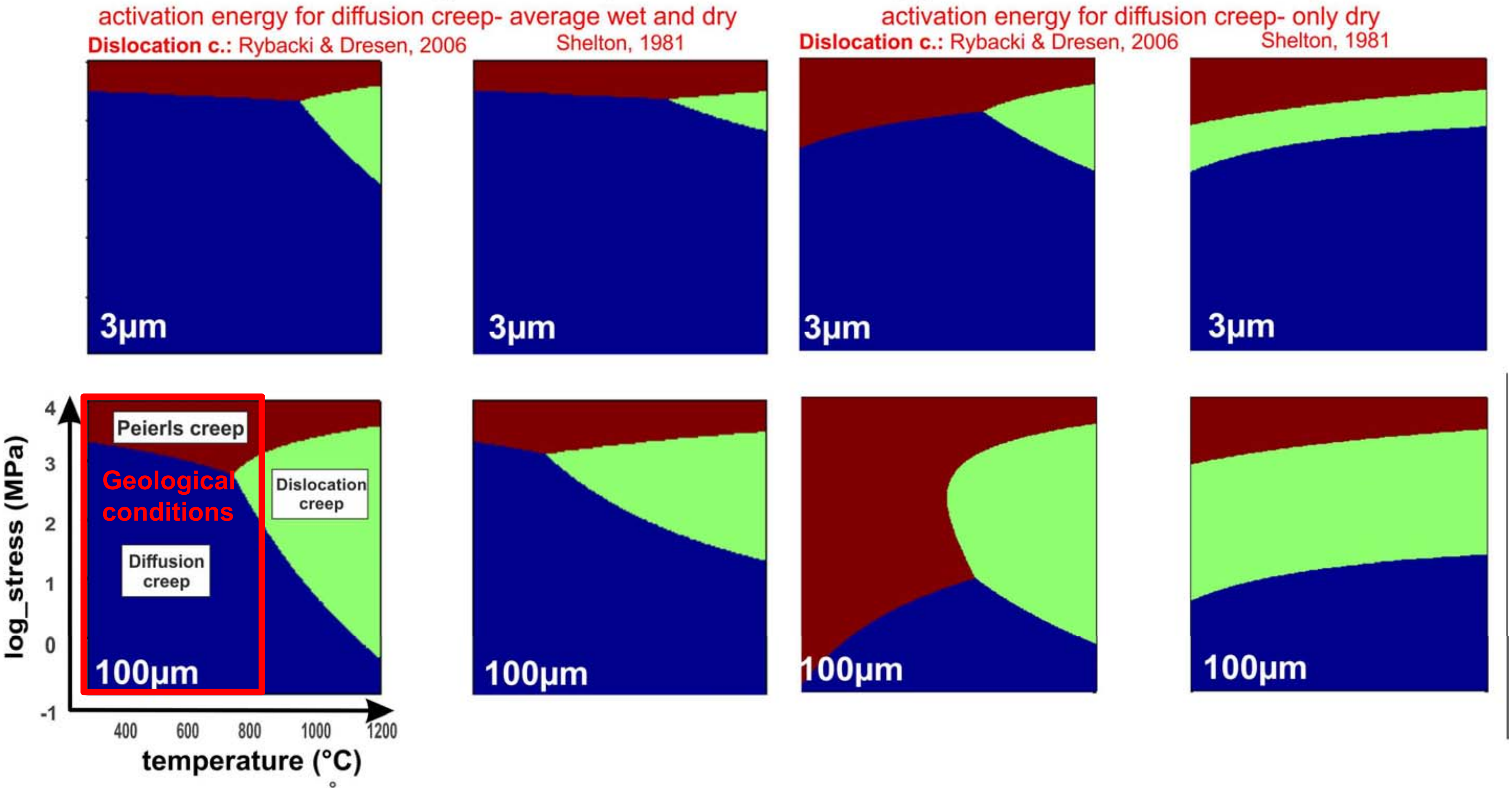
CURRENT UNCERTAINTY:

- ***Rheology*** *extrapolated from lab over* ***10 orders of magnitude***

Rheology: an extrapolation problem

PLAGIOCLASE – the most abundant mineral in the Earth's crust

Differences in grain size, activation energy and dislocation creep data

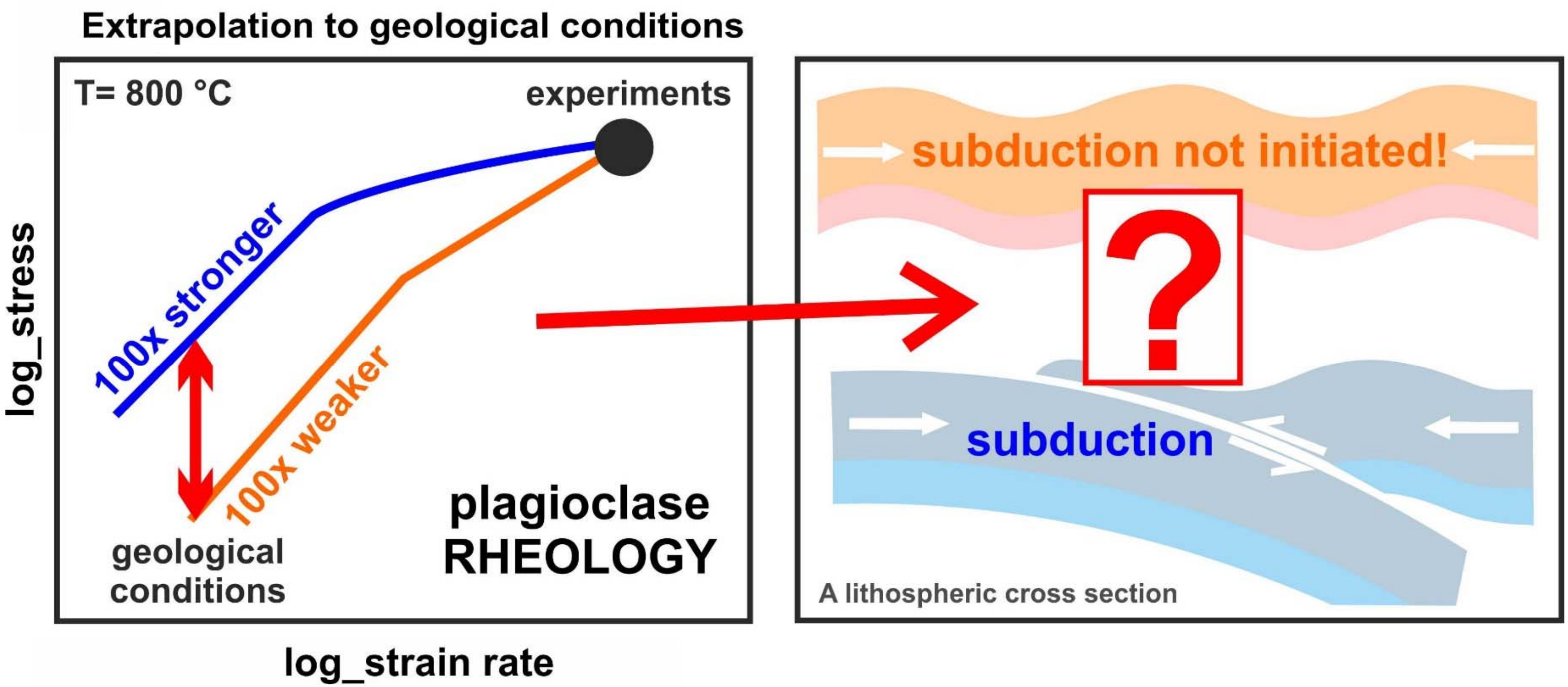


No predictive power for geo-material towards high stresses.

Constraint under geological conditions is missing.

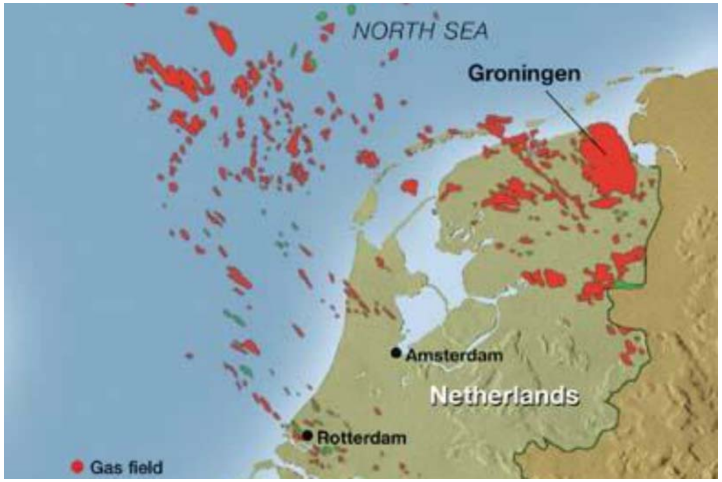
Rheology: an extrapolation problem

PLAGIOCLASE – the most abundant mineral in the Earth’s crust



=> This questions our understanding of geodynamic processes!

Groningen gas field (Netherlands)



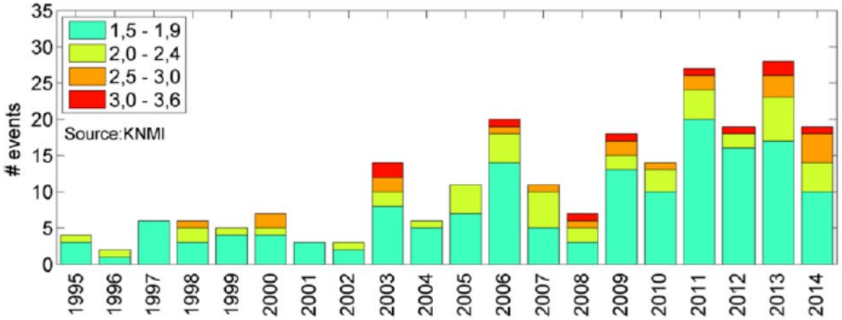
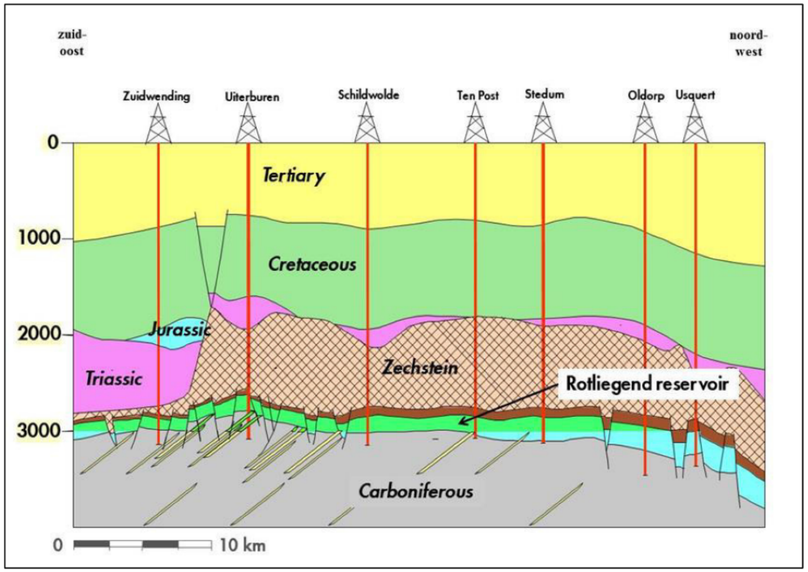


Figure 1. Groningen seismicity ($M > 1.5$) vs. time.



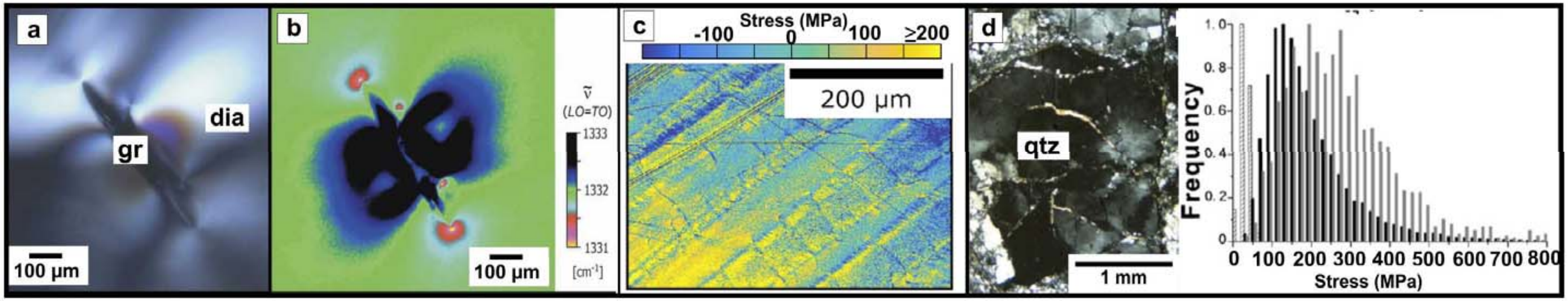
- Only **1-2 orders of magnitude** difference in extrapolation, i.e. years vs. months
- **Close to the surface**
- Elastic vs. **creeping** behavior problem

=> How confident are we for conditions in the lower crust?

Any hope for a constraint at geologically relevant conditions?

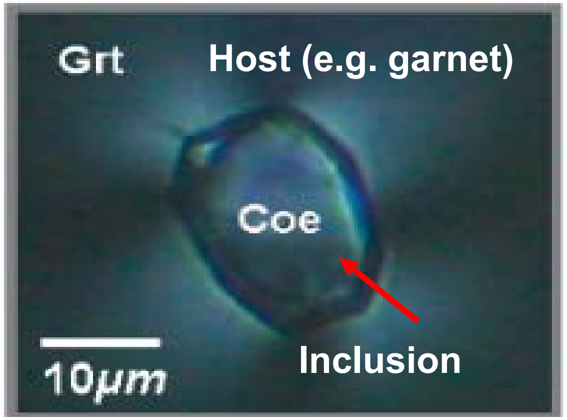
Any hope???

Mechanically-controlled microstructures

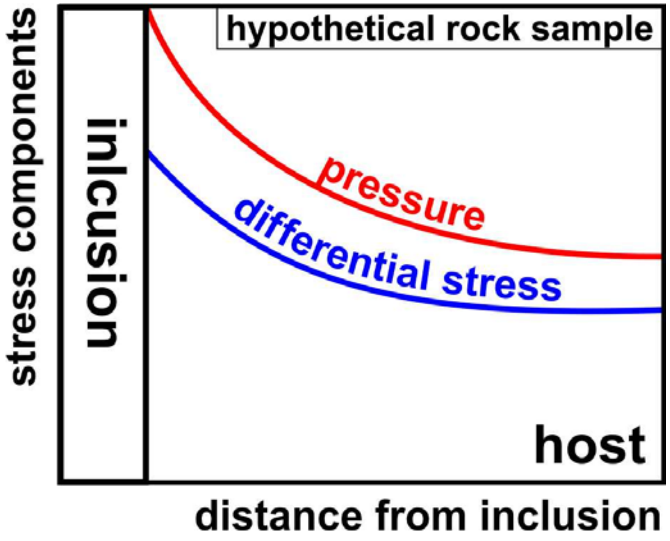


Pressure and stress **directly measured** by state-of-the-art analytical methods.

Witnesses of the long-term stress state in the lithosphere!



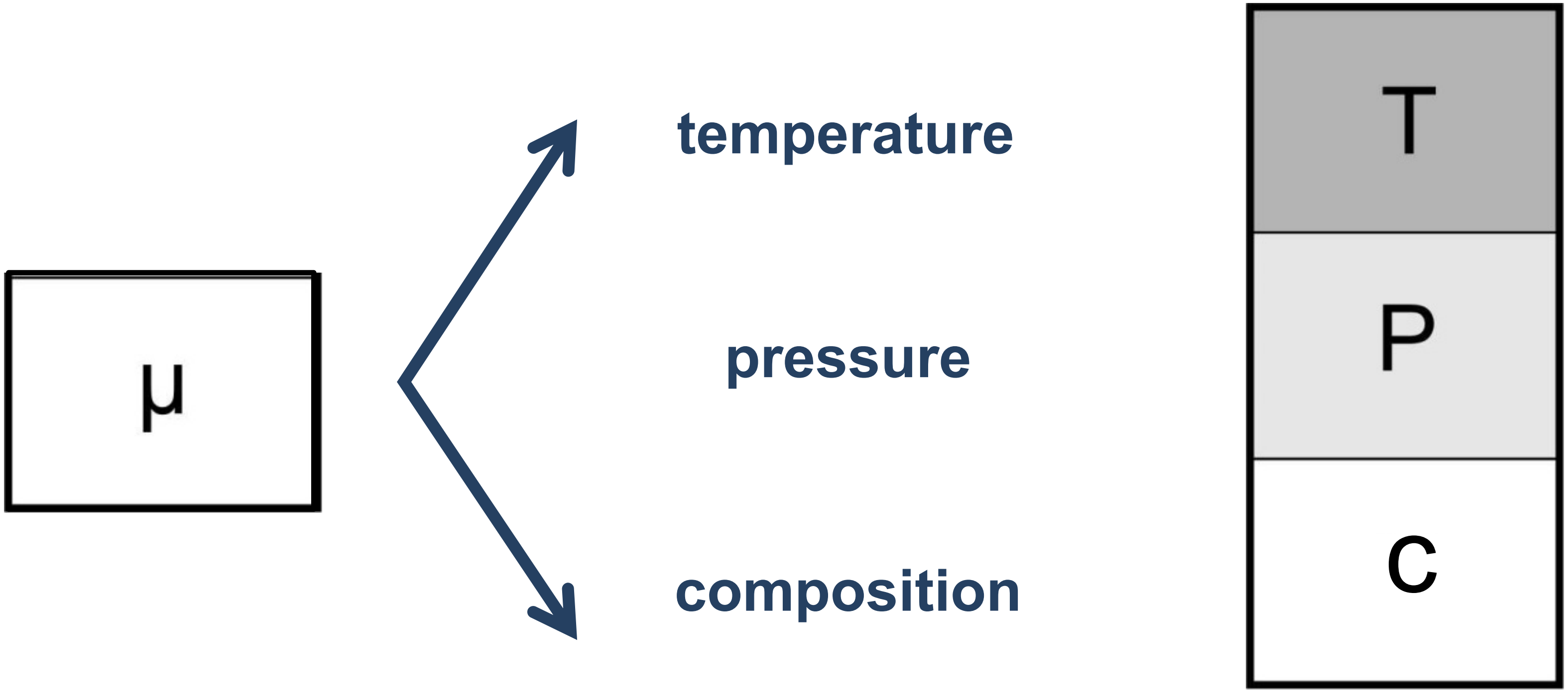
Inclusion-host environment



Unconventional Rheometry:

Little bit of background first

Chemical potential and equilibrium



μ

temperature

pressure

composition

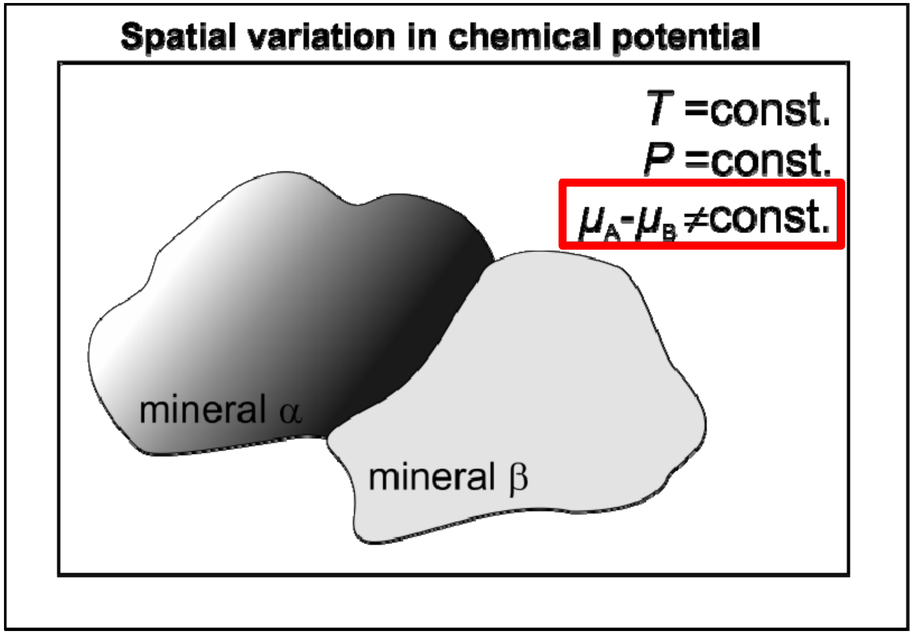
T

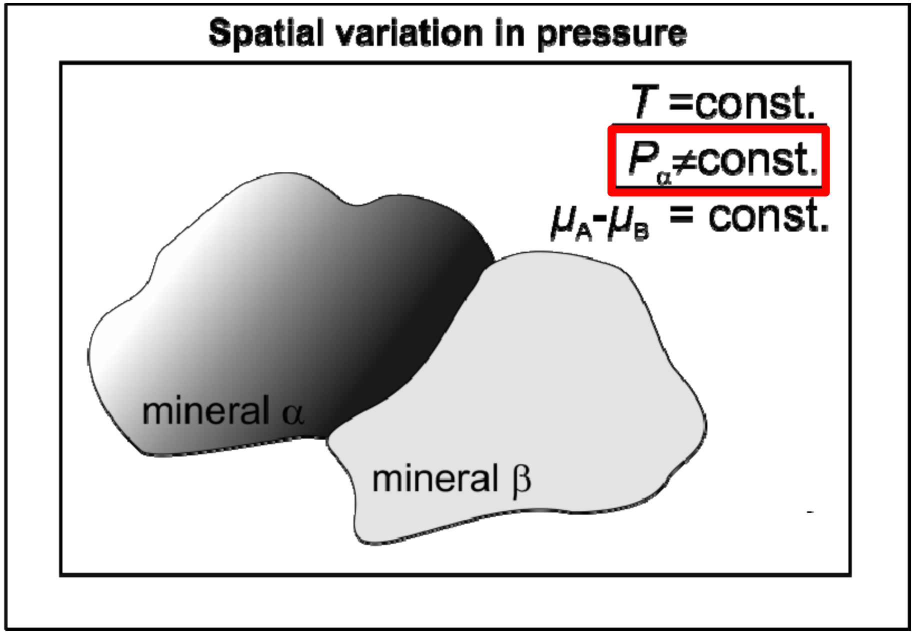
P

C

$$\mu_i = \mu_0(\boxed{P,T}) + RT\,\boxed{\ln a}$$

Compositional vs. pressure variations





Chemically- controlled

fast viscous relaxation and slow chemical diffusion

Mechanically- controlled

slow viscous relaxation and fast chemical diffusion

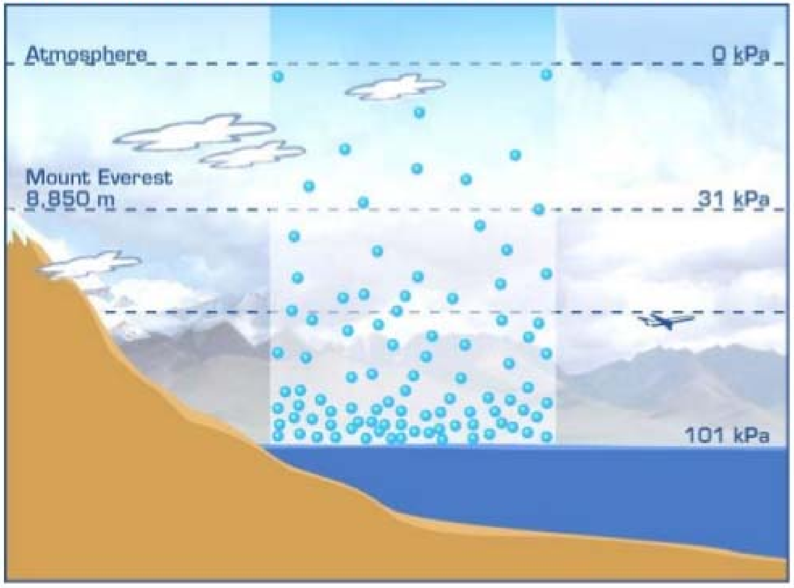
The effect of pressure variation on chemical redistribution

Equilibrium under external force: pressure variations

Gases

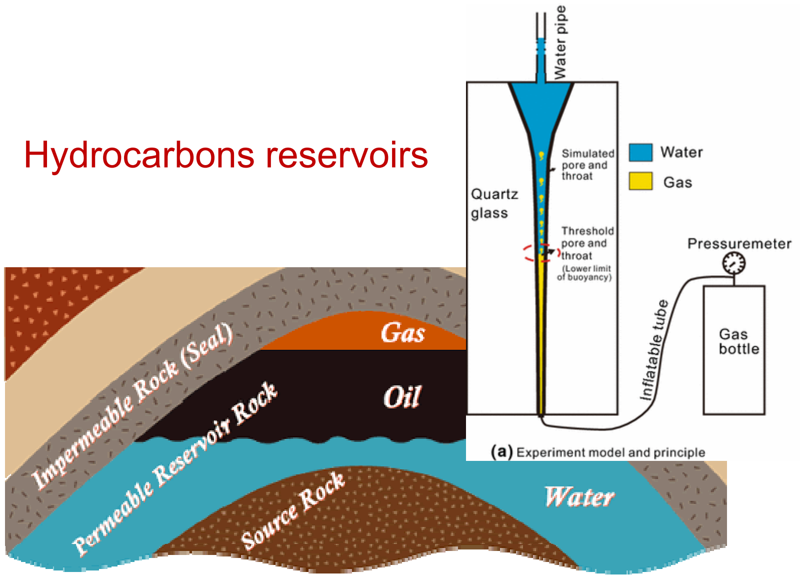
Liquids

Atmospheric pressure decreases with altitude



PRESSURE

Hydrocarbons reservoirs

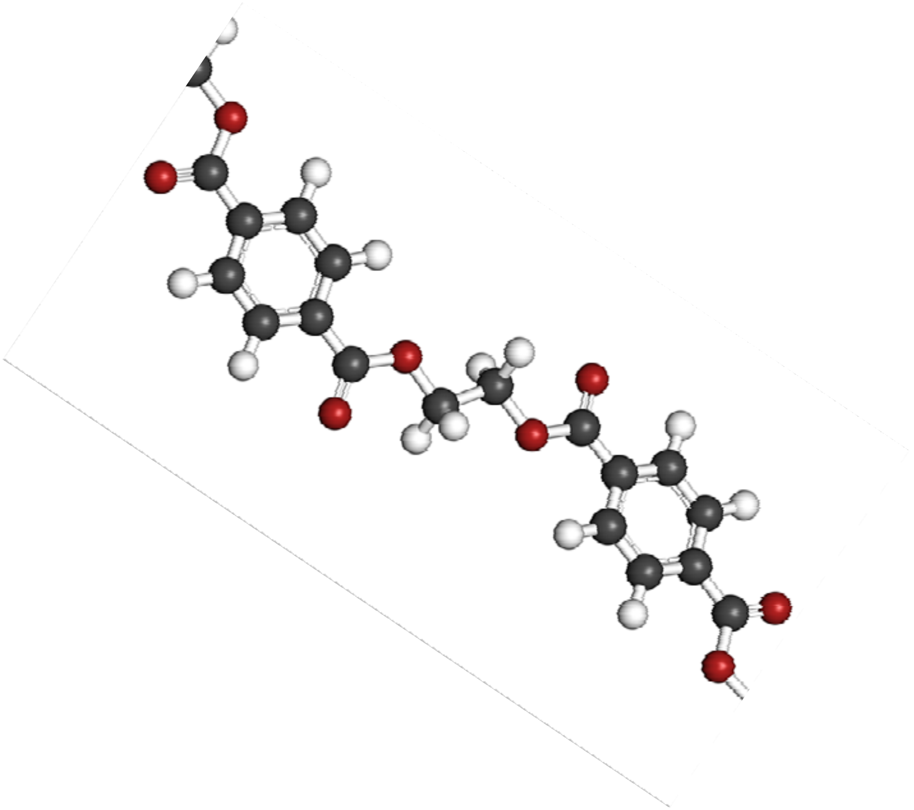


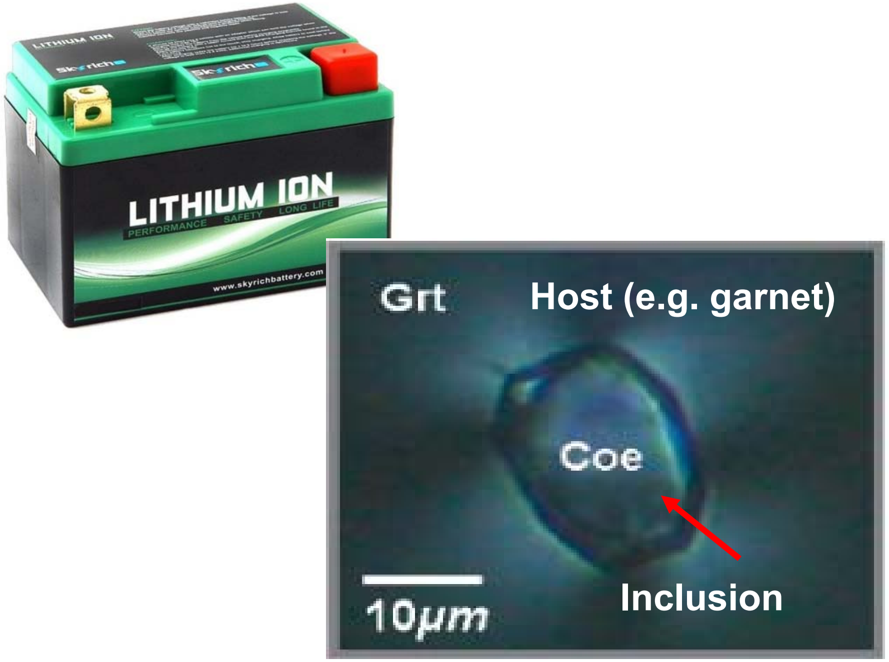
The effect of pressure variation on chemical redistribution

Equilibrium under external force: pressure variations

Polymers

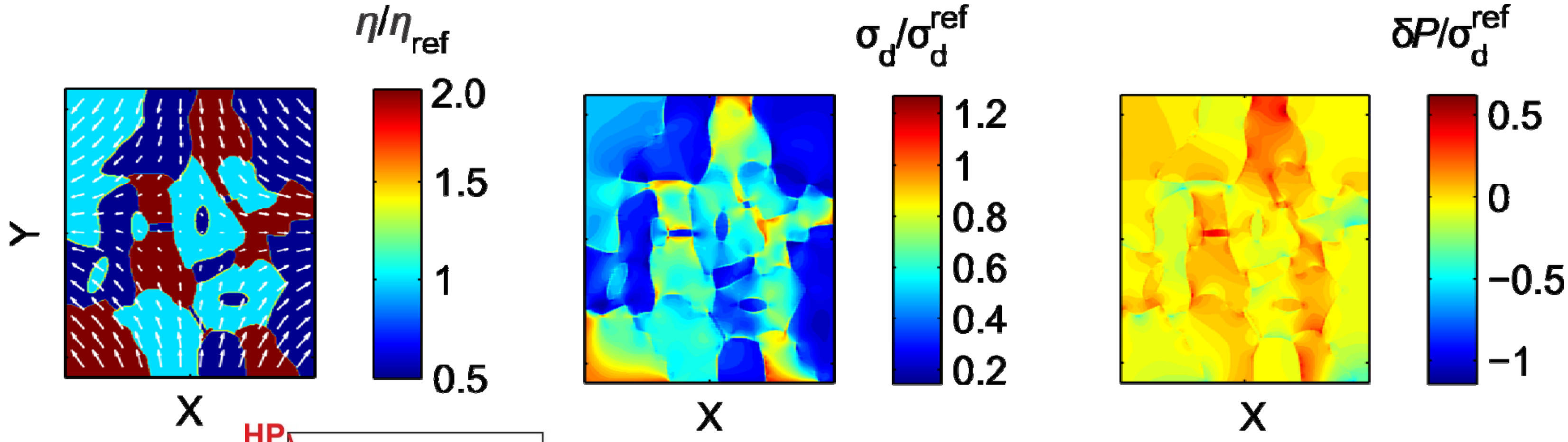
Solids???

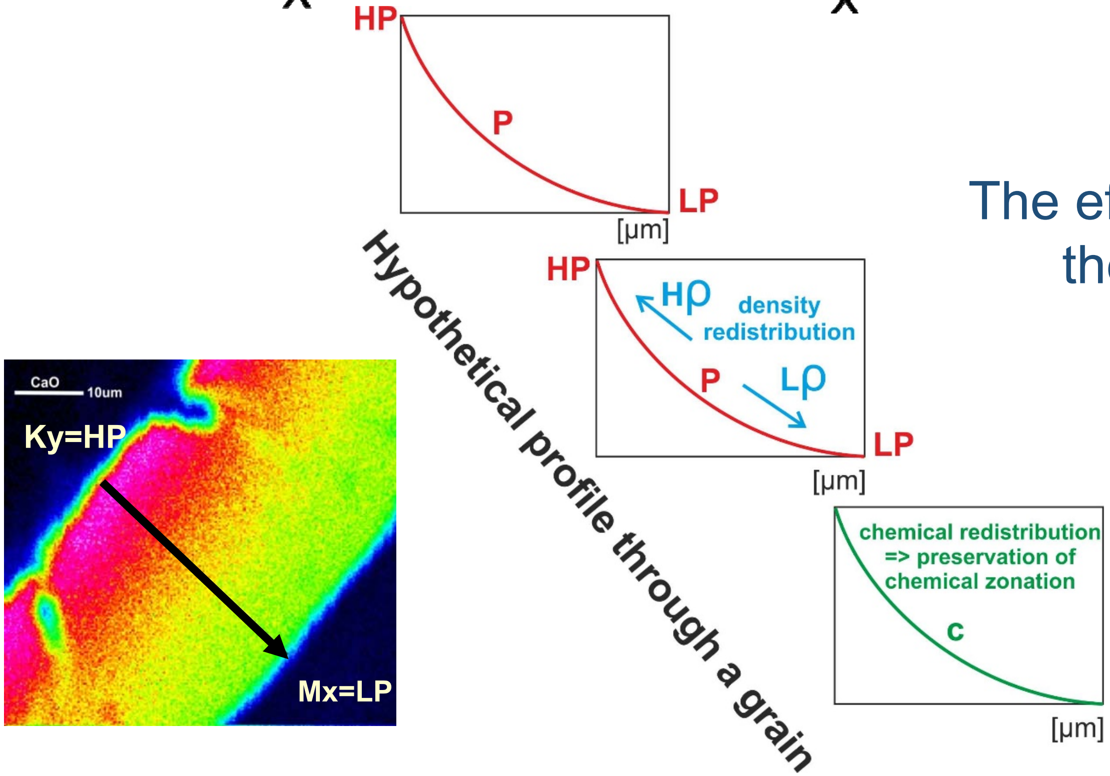




Currently and active research

Equilibrium under pressure gradients: Unconventional barometry





The effect of pressure variation on the chemical redistribution

$$\mu_i = \mu_0(\boxed{P,}T) + RT\ln a$$

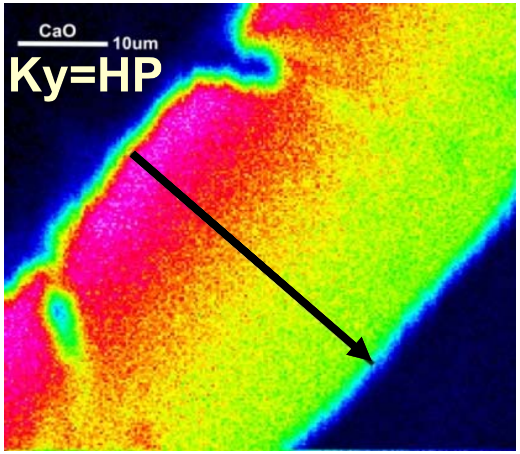
Unconventional Rheometry:

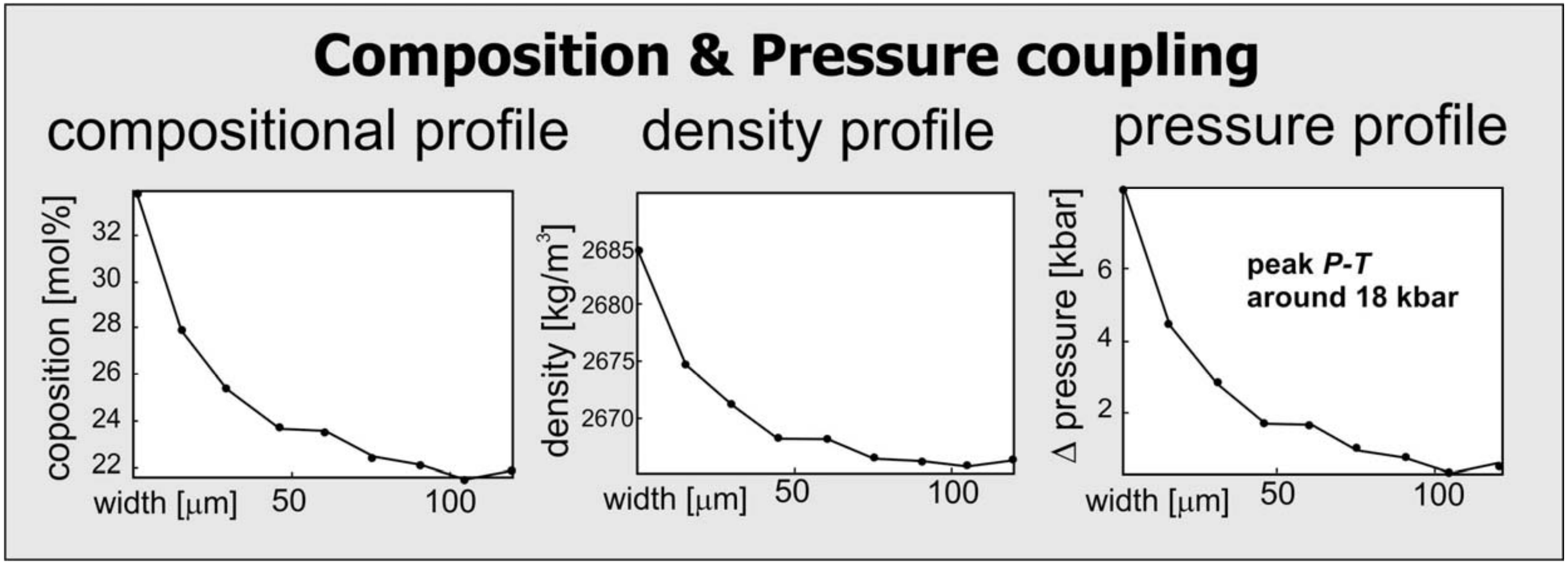
Key steps of the alternative approach

Unconventional Rheometry:

Key steps of the alternative approach

1/ Chemically zoned mechanically-controlled microstructure, e.g. inclusion-host environment



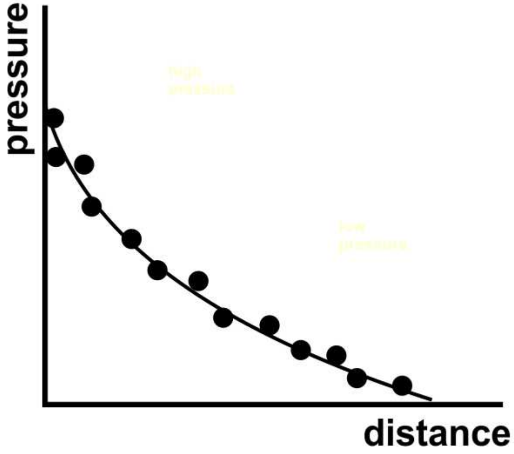

Composition & Pressure coupling

compositional profile density profile pressure profile

Unconventional Rheometry:

2/ Classical mechanics: From pressure to stress decay

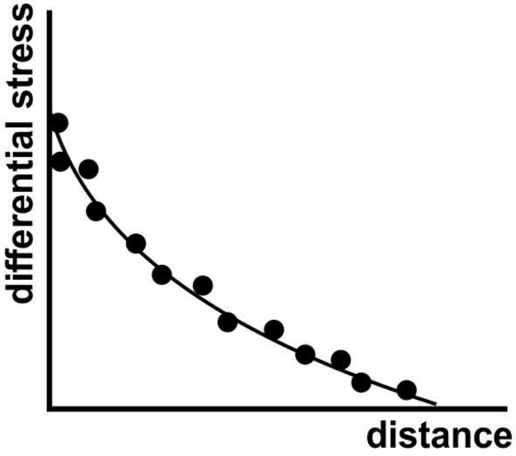
Thermodynamic method to derive
pressure from direct observations



$$\xrightarrow[\textbf{balance}]{\textbf{force}}$$

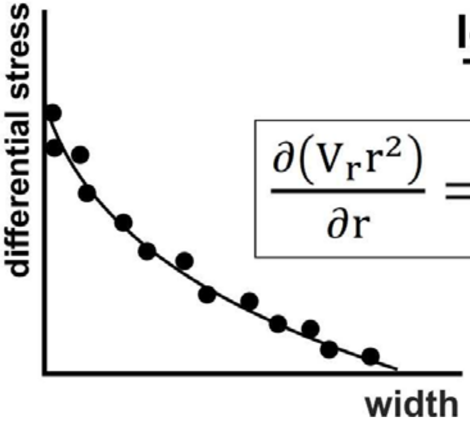
$$-\frac{\partial P}{\partial r} = \frac{2}{3}\frac{\partial \sigma}{\partial r} + 2\frac{\sigma}{r}$$

Differential stress estimates



3/ Classical mechanics: from stress decay to effective stress exponent (n)

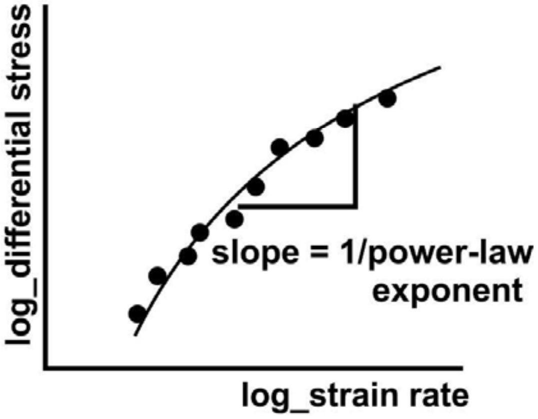
Differential stress estimates



$$\xrightarrow[\textbf{balance}]{\textbf{local mass}}$$

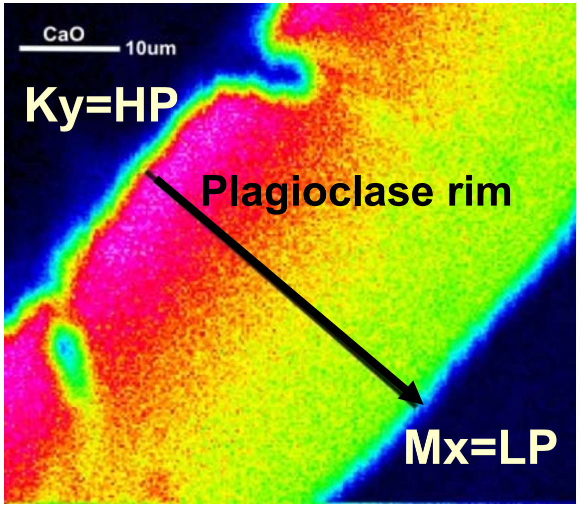
$$\boxed{\frac{\partial\left(V_r r^2\right)}{\partial r} = 0 \ \&\ \dot{\varepsilon}_{rr} = \frac{\partial V_r}{\partial r}}$$

Differential stress and strain rate
relation from direct observation



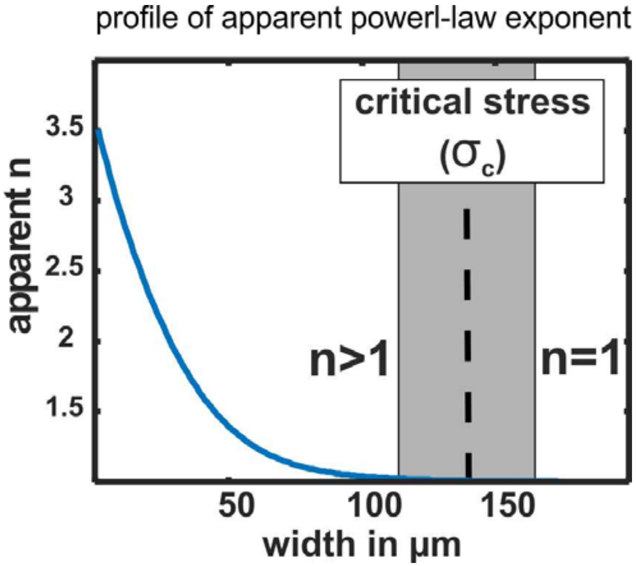
Unconventional Rheometry:

4/ Results: From composition to apparent stress exponent and critical stress



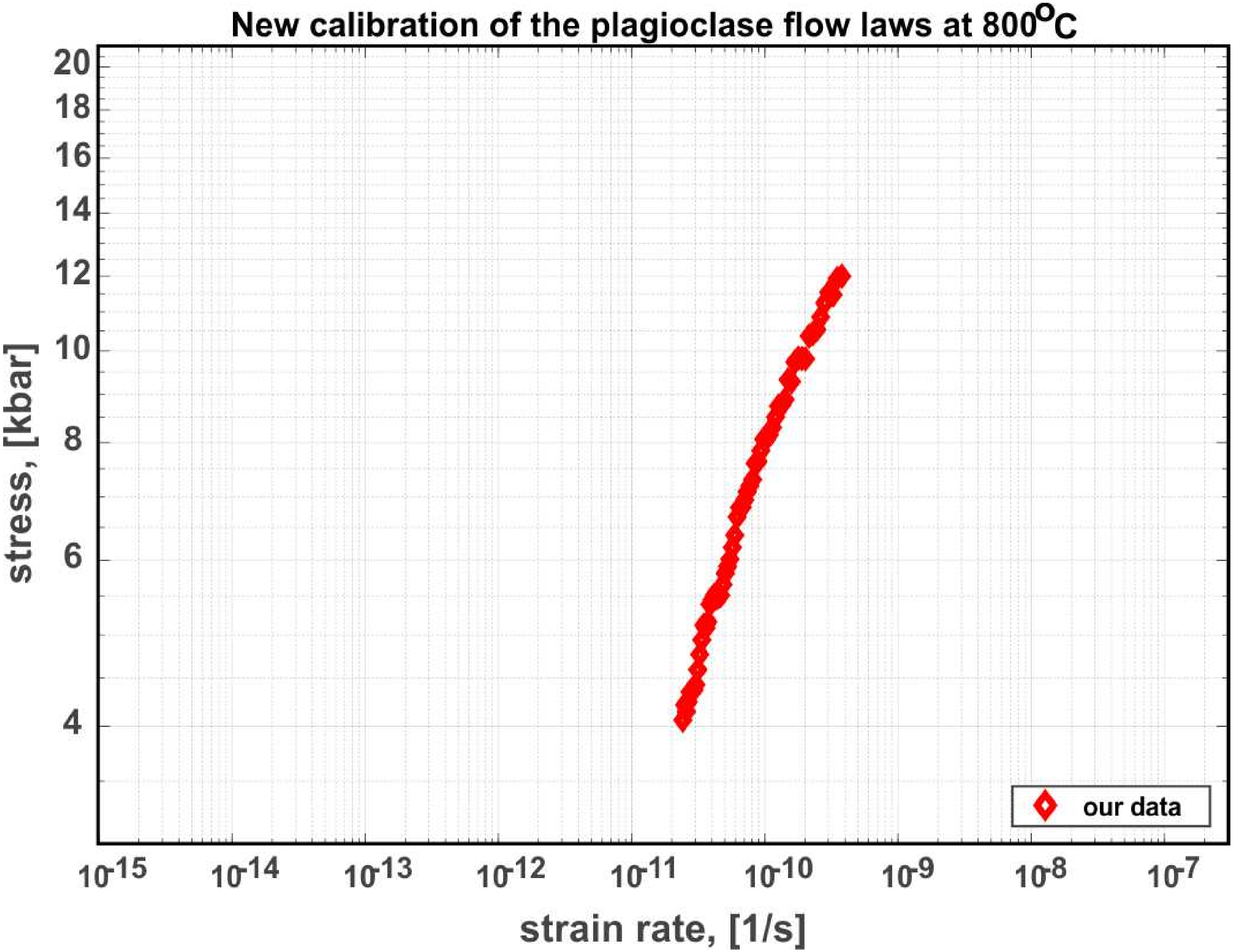
$$\boxed{n_{app} = \frac{\partial(\log \dot{\varepsilon}_{rr})}{\partial(\log \sigma)}}$$

$$\boxed{\sigma_c = \frac{\partial(\sigma)}{\partial(\log \dot{\varepsilon}_{rr})}}$$

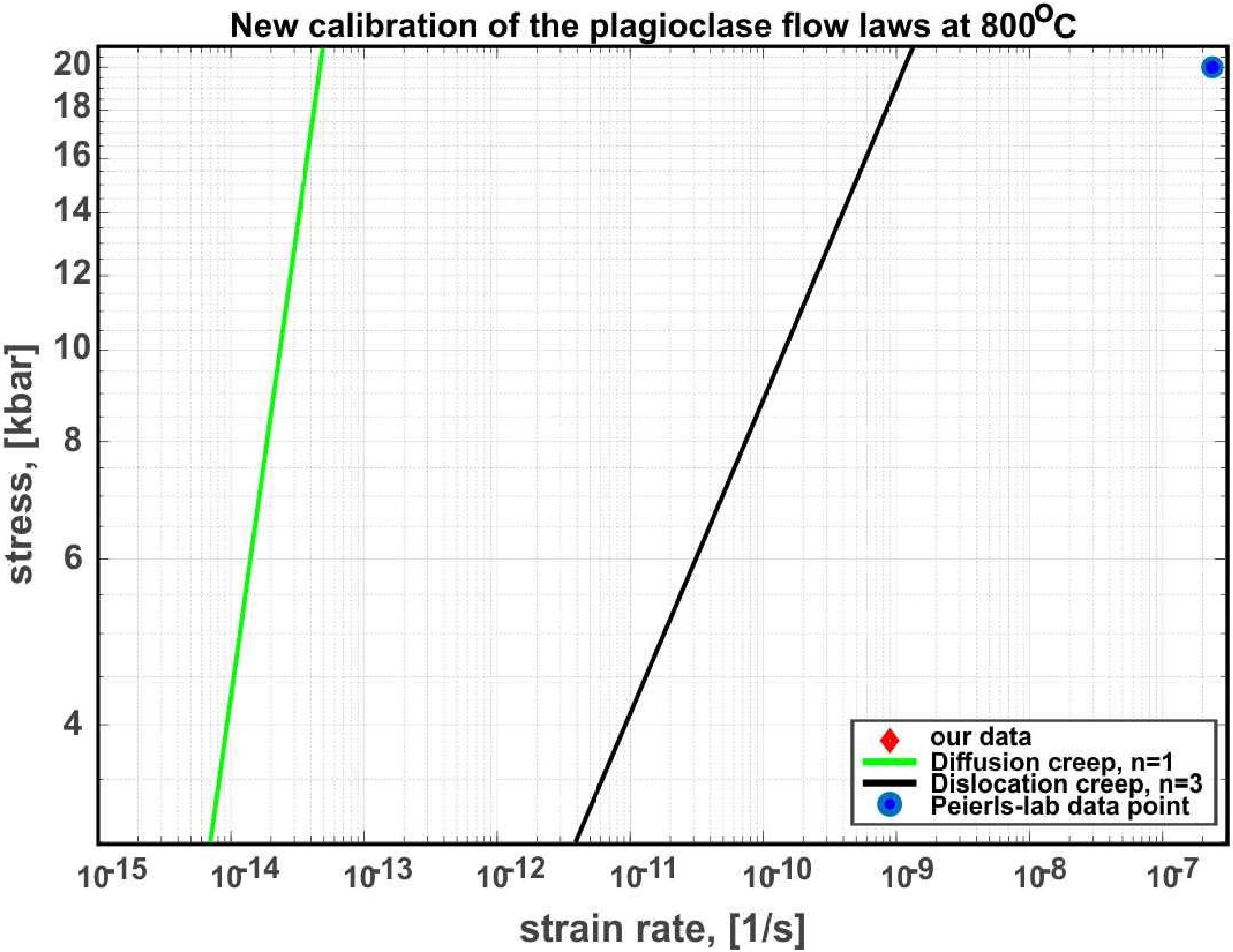

profile of apparent powerl-law exponent

non-constant power-law exponent

Results & Comparison



Results & Comparison



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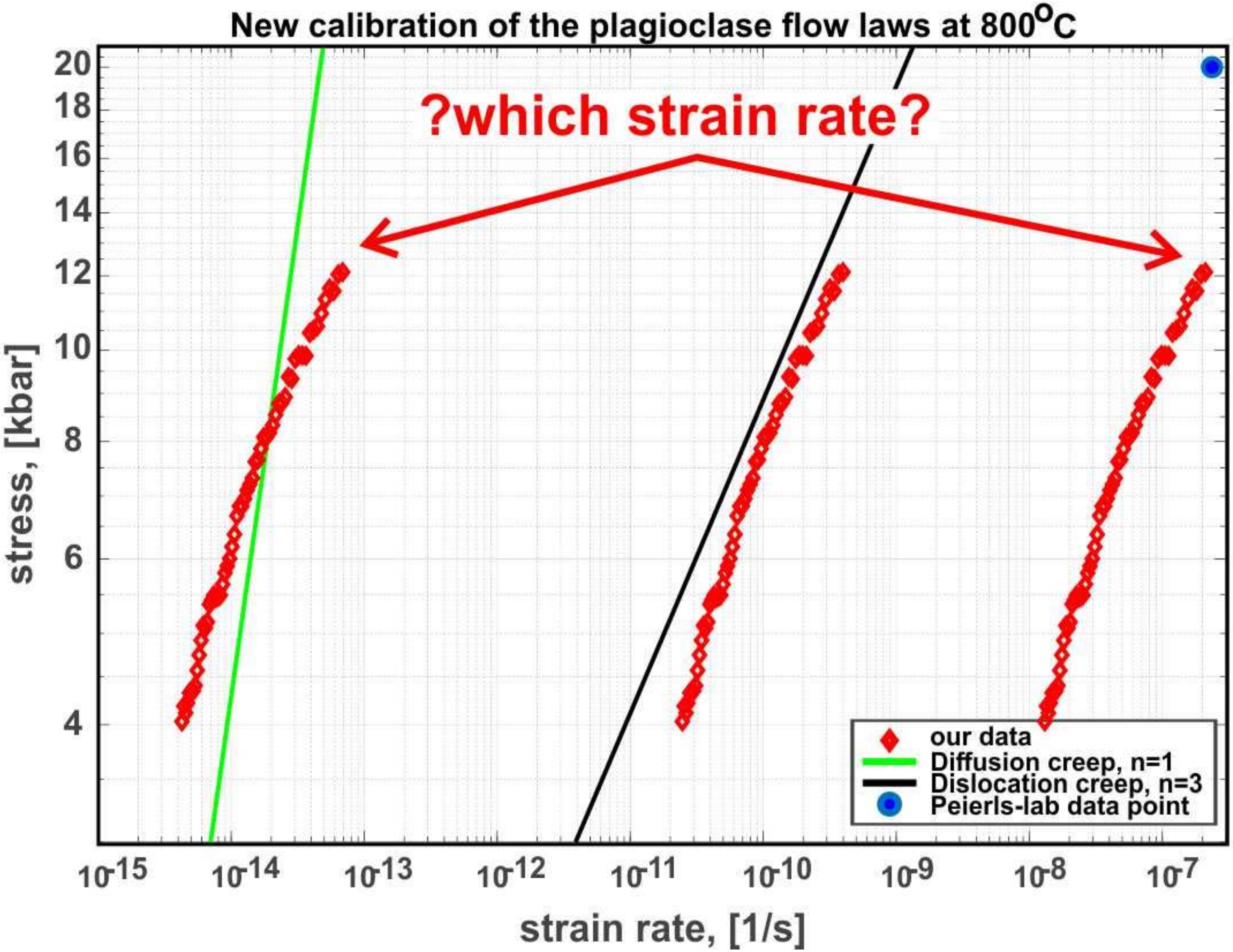
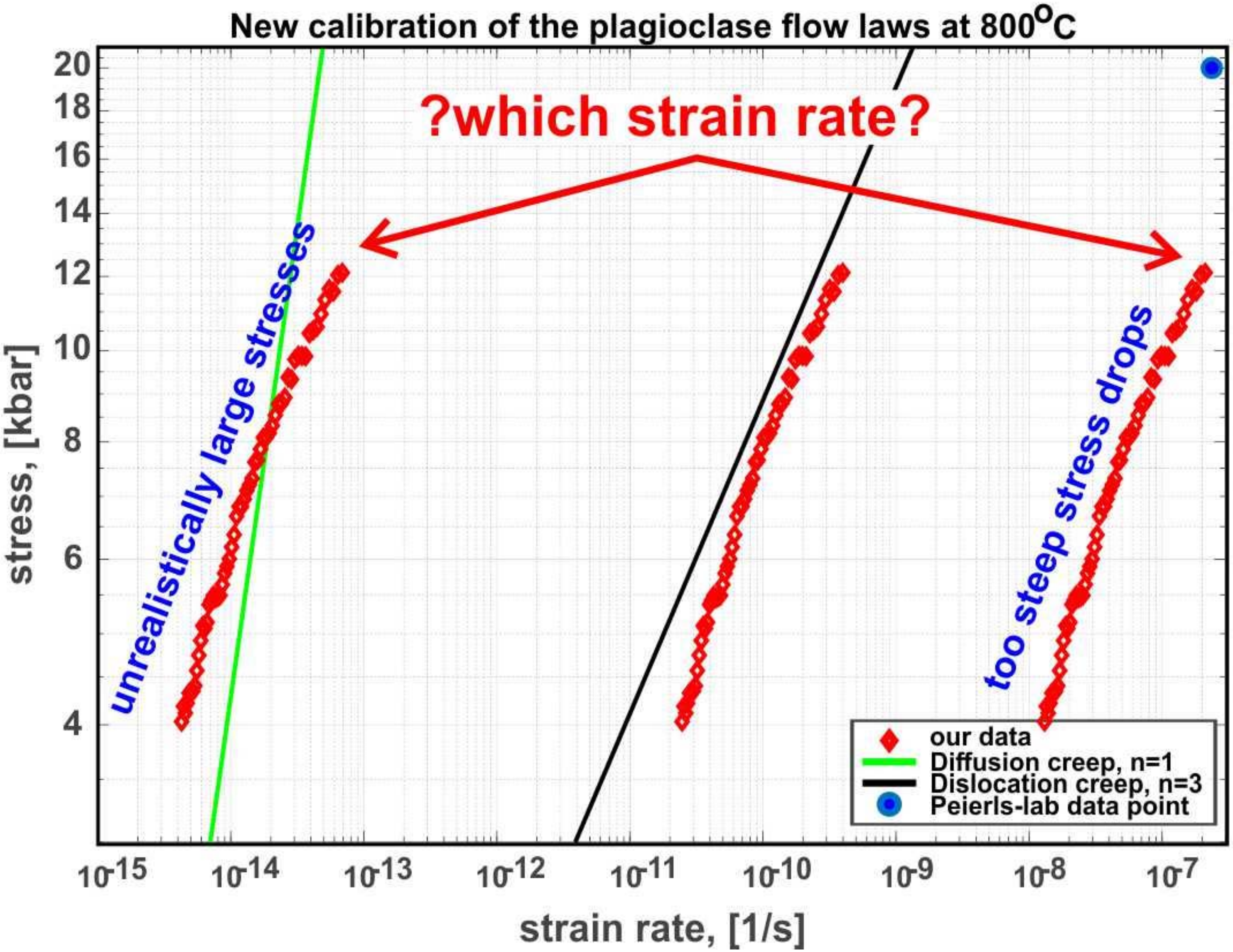


Results & Comparison



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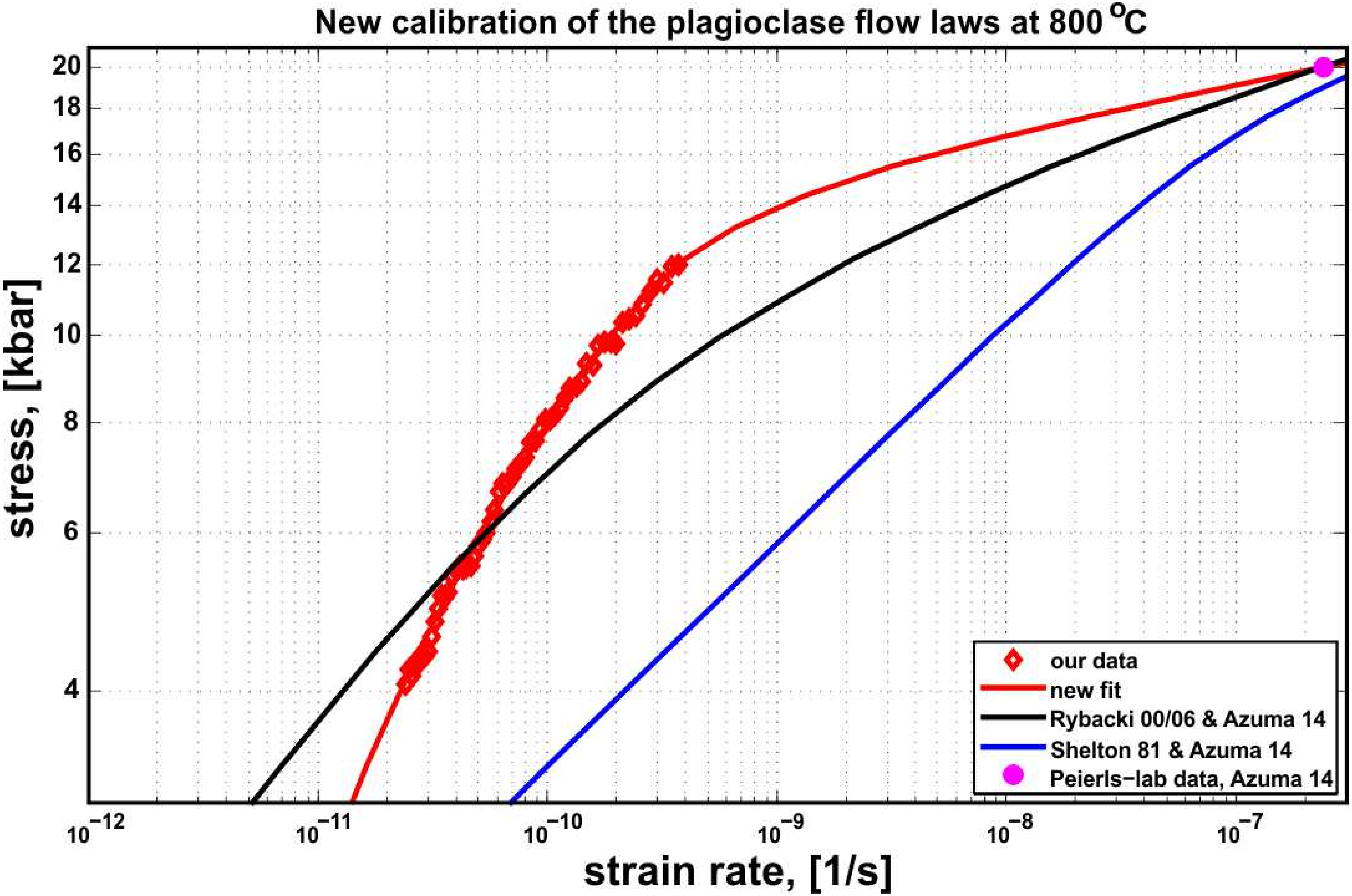

Concluding remarks:

- Mechanically-controlled microstructures provide information on the long-term stress state in the lithosphere
- New approach to infer rheology directly from natural samples, for naturally relevant T, grain size and time scale.
- Independent of conventional constitutive laws: based on equilibrium thermodynamics and classical mechanics
- Constraint for the extrapolation – an inspiration also for olivine and pyroxene