Effects of strain weakening in mantle convection models with plate-like behavior and continental drift

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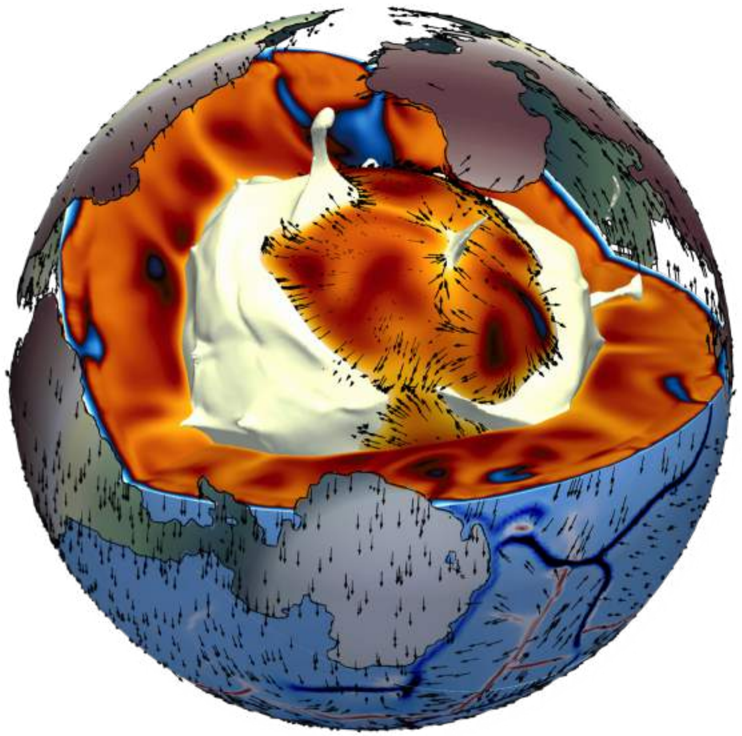
State-of-the-art global mantle flow models

... have advanced a lot in the past decades.

Key Ingredients: Viscoplastic rheology (strong temperature-dependence of viscosity + plastic failure at yield stress)

→ **Plate-like behaviour** ✓ **Supercontinent cycles** ✓ **Earth-like topography** ✓

e.g. Mallard et al. (2017), Rolf et al. (2018), Crameri et al. (2012)



Example of a „no memory/damage"-mantle flow with plate-like behaviour [e.g., Rolf et al., 2018].

But rheology as no memory on previous damage!
→ Previously formed weak zones vanish instantaneously.

This is unlike on Earth! e.g. Tommasi et al. (2009)

! Effects of memory on the evolution of plate tectonics and mantle flow are only poorly understood!

Rheological memory via Strain weakening

Prefactors for depth- and composition-dependence
→ continents Rolf & Tackley (2011)

„Standard" viscoplastic rheology:
(e.g. Tackley, 2000)

$$\eta_1 = f_d\, f_C \exp\left(\frac{E_A}{T+1} - \frac{E_A}{1.5}\right) \;;\; \eta_2 = \frac{YS}{\dot{\varepsilon}_{II}} \longrightarrow \eta = \frac{1}{1/\eta_1 + 1/\eta_2}$$

Arrhenius (E_A activation energy)

effective viscosity

Strain weakening
(Fuchs & Becker, GJI, 2019):

$$YS = \boldsymbol{YS_U}\left(1 - \boldsymbol{\lambda}\frac{\gamma}{\boldsymbol{\Gamma}}\right)$$

$YS_U = f(d)$ *Drucker-Prager criterion*

Strain evolution

$$\frac{d\gamma}{dt} = \dot{\varepsilon}_{II} - \gamma H$$

Healing

$$H = \boldsymbol{B} \exp\left(-\frac{1}{2}\left(\frac{E_A}{T+1} - \frac{E_A}{1.5}\right)\right)$$

Governing plastic parameters:

- $\boldsymbol{YS_U}$ Undamaged yield Stress
- $\boldsymbol{B}$ Healing rate constant
- $\boldsymbol{\lambda}$ Weakening rate
- $\boldsymbol{\Gamma}$ Critical strain

Here we analyse (1) how strain gamma accumulates in the mantle,
(2) whether continents experience strain,
(3) how strain weakening affects model plate-like behaviour.

Accumulation of strain

Reference model (code StagYY, Tackley, 2000)

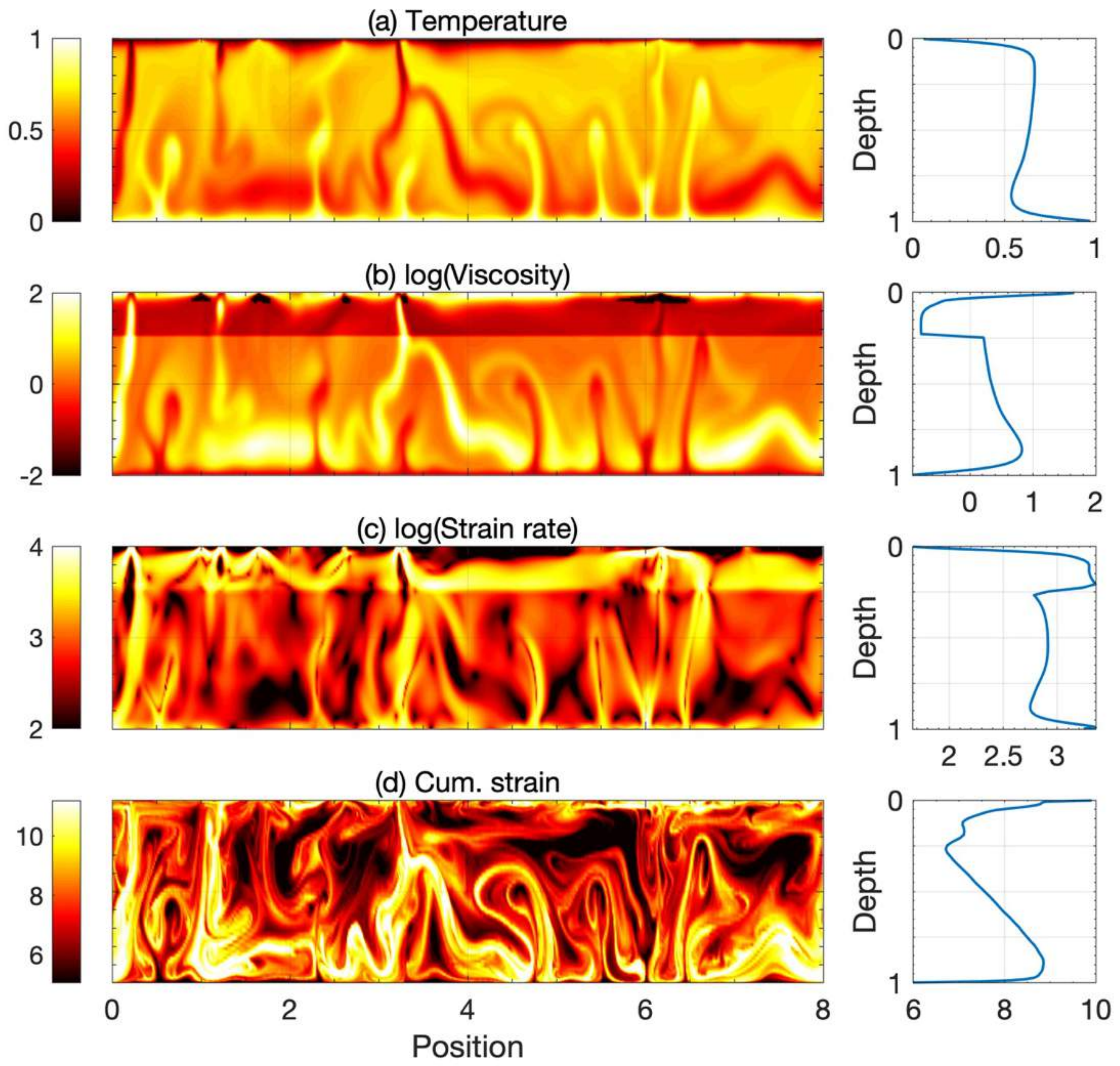
Domain: 8x1 box with resolution 512x64
Rayleigh number: 10^6
Internal heating rate: 10 (~50% internal, ~50% core heating)
Top / bottom isothermal: T=0 / 1
Strain tracked by markers (30/cell)
Thermal viscosity contrast 10^6
Viscosity jump (10x) at 660 km and where $T>T_{solidus}$ (0.1x)
Undamaged yield stress: $YS_U = 4x10^3 + 0.05d$

No weakening $\lambda = 0$
Healing constant $B = 92$

Results:

(1) Max. strain at the surface and in lithosphere
(2) Little strain in upper mantle (hot → faster healing)
(3) More strain in lower mantle (cold slab graveyard)

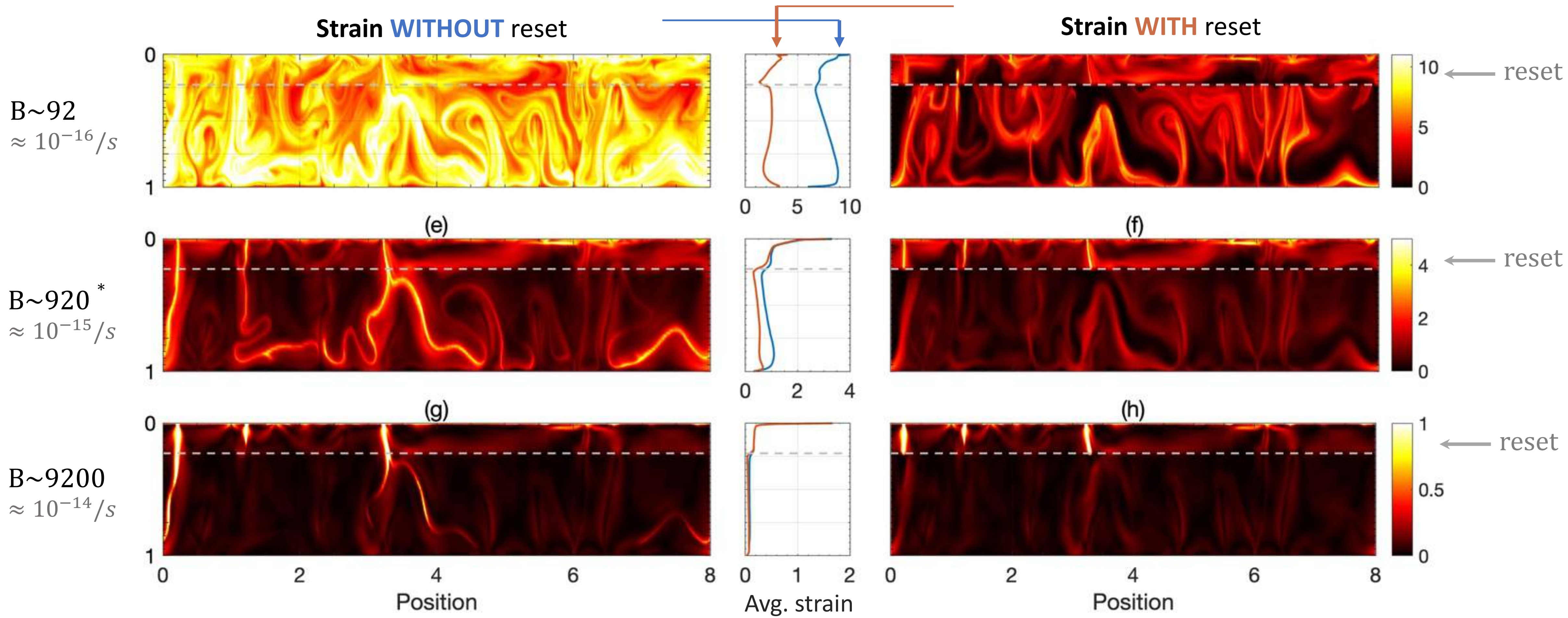
Snapshot from equilibrium state **Profile (avg)**



Reset at 660? $(\lambda = 0)$

* NB: Conversion from non-dim to dimensional via transit time:
$B[1/s] = B\ \tau^{Model} / \tau^{Earth} = B\ v_{char}^{Earth} / v_{char}^{Model} D_{mantle}$

The phase transformations within the Earth's transition zone may erase all previously accumulated strain.



Strain levels are lower with reset at 660 km) and high lower mantle strain disappears with sufficiently large healing rate

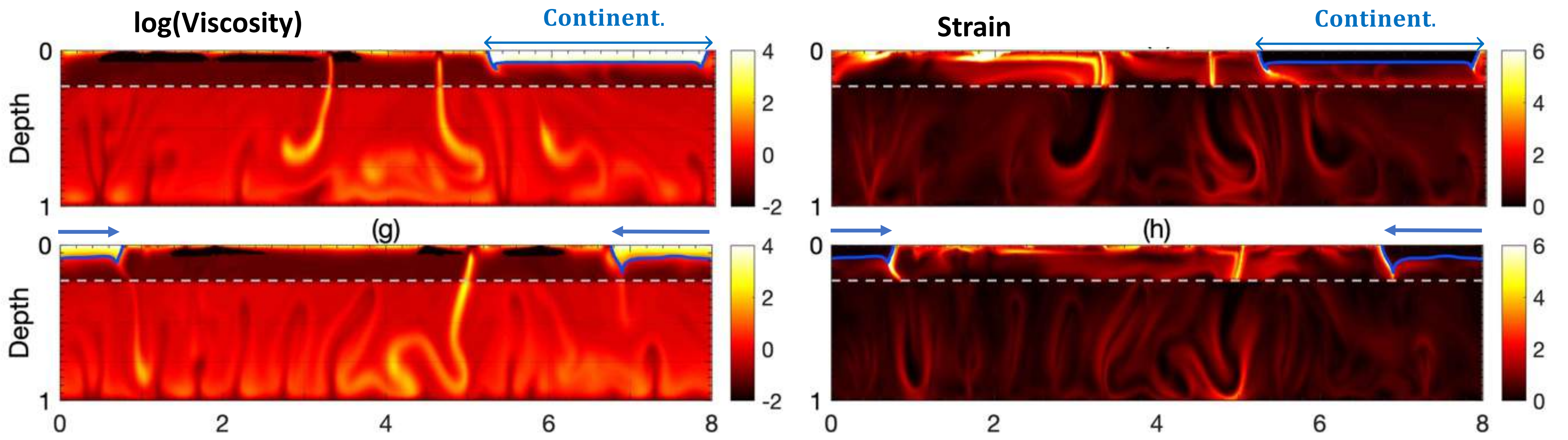
→ Using a constant critical strain Γ in weakening formalism is feasible with large healing rate B

Continents ($\lambda = 0$)

$\Delta\eta_C =$ compositional viscosity contrast between continent and ocean, Rolf & Tackley (2011)

$\Delta\eta_C = 100$
Strong root

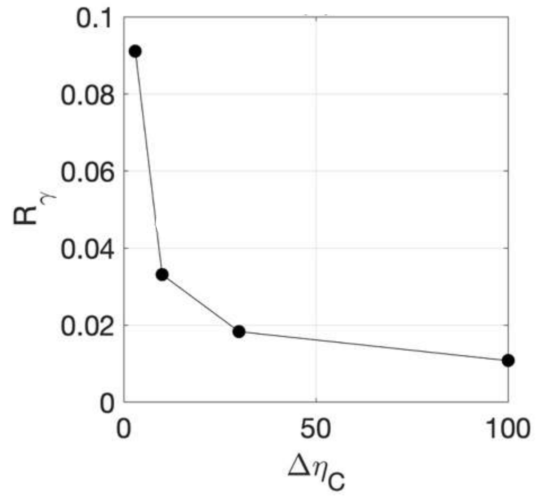
$\Delta\eta_C = 3$
Weak root

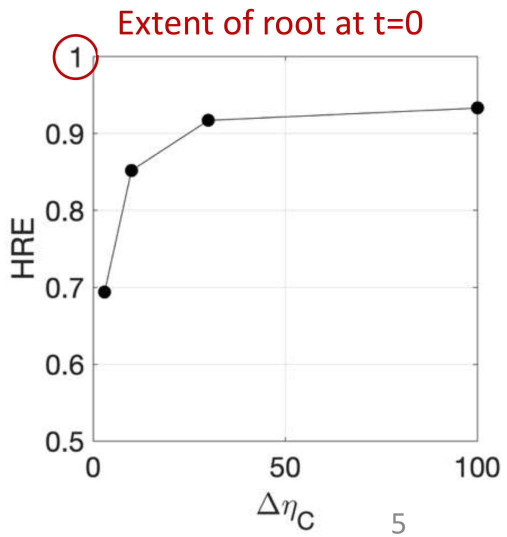


→ **Little strain in continents**: $R_\gamma \stackrel{\text{def}}{=} \langle \gamma_{cont}^{surf} \rangle / \langle \gamma_{ocean}^{surf} \rangle \ll 1$

→ Depends on the viscosity contrast of continents $\Delta\eta_C$

→ More strain with low $\Delta\eta_C$, but also **reduced resistance** of continent against convective erosion: the norm. horizontal extent of the root (*HRE*) decreases sharply for $\Delta\eta_C \to 1$



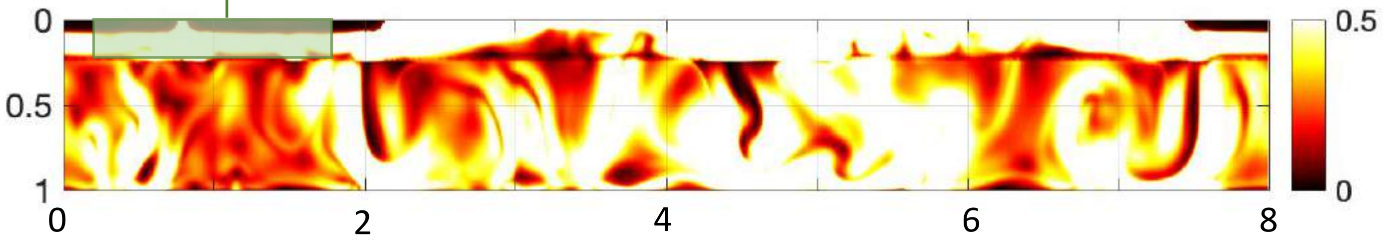


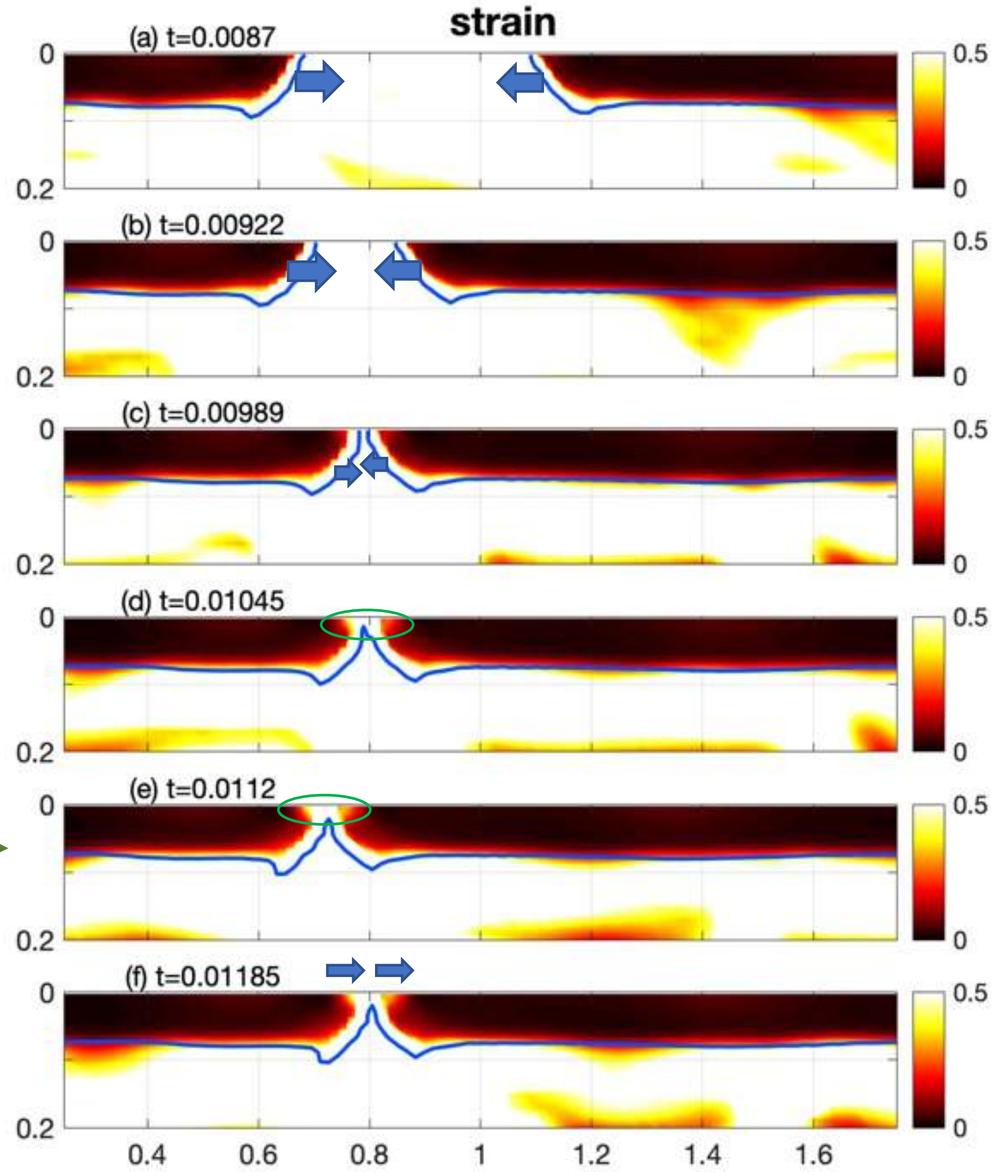
Continent collisions ($\lambda = 0$)

Sometimes continents collide. Then, strain increases in the colliding tips of continents, but only by a bit. $R_\gamma \ll 1$ holds.

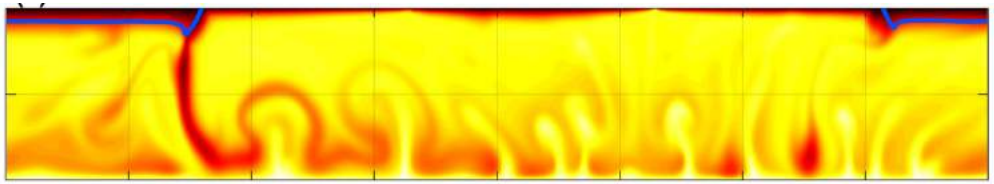
→ **With constant critical strain Γ and healing rate B* in oceanic and continental lithosphere, it is tricky to accumulate enough strain to cause persisting weak zones in continents which may be activated later on during rifting.**

*Imposing reduced B inside continents helps, but not enough.

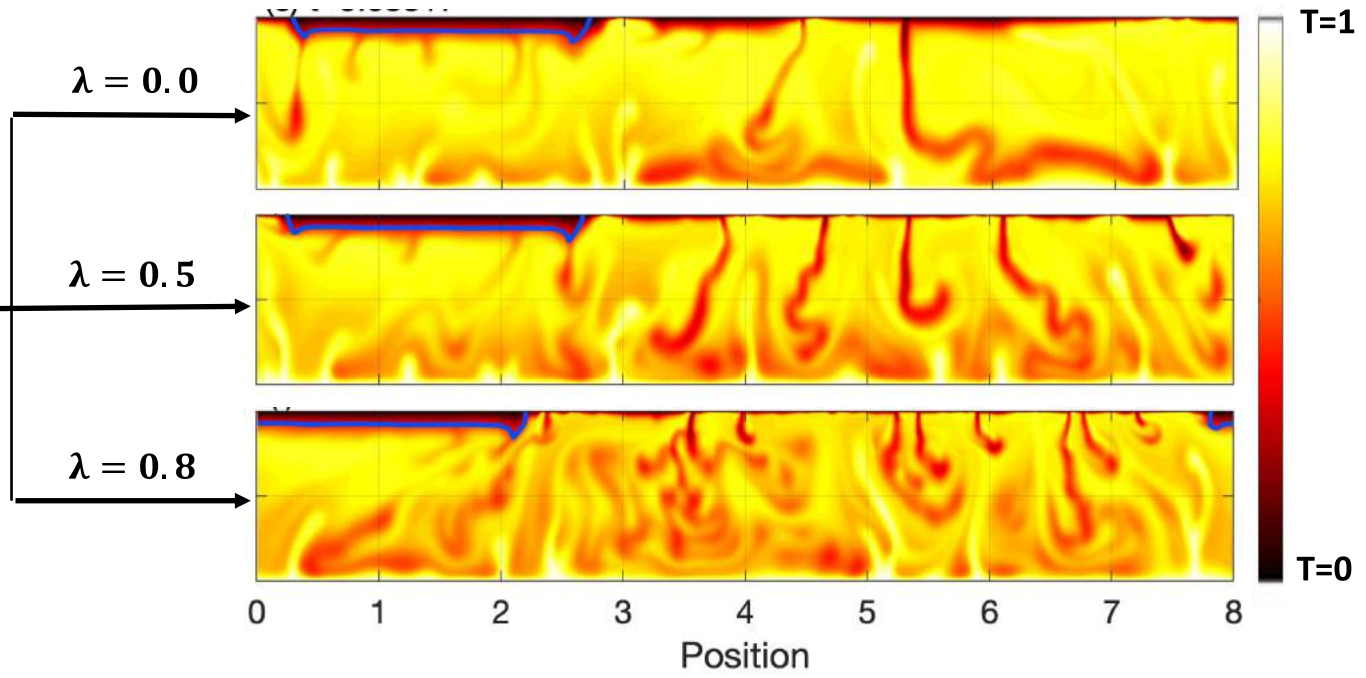




Strain Weakening ($\lambda = 0$)



Initial temperature field (blue outline = continent)

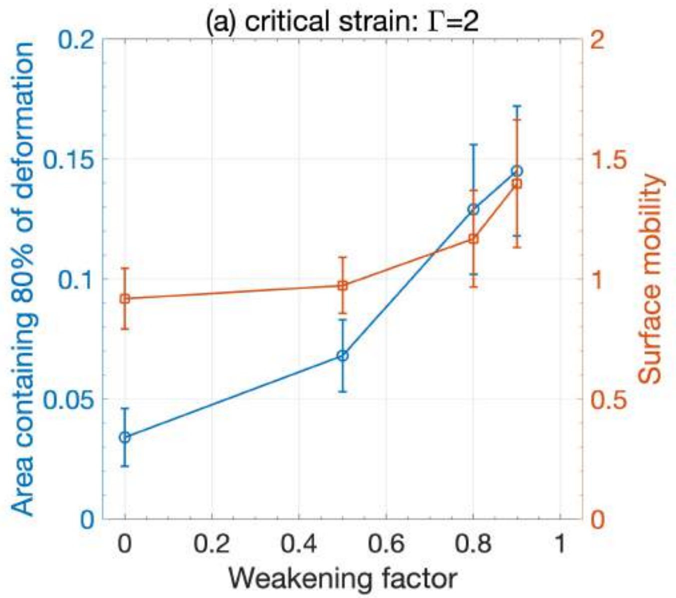


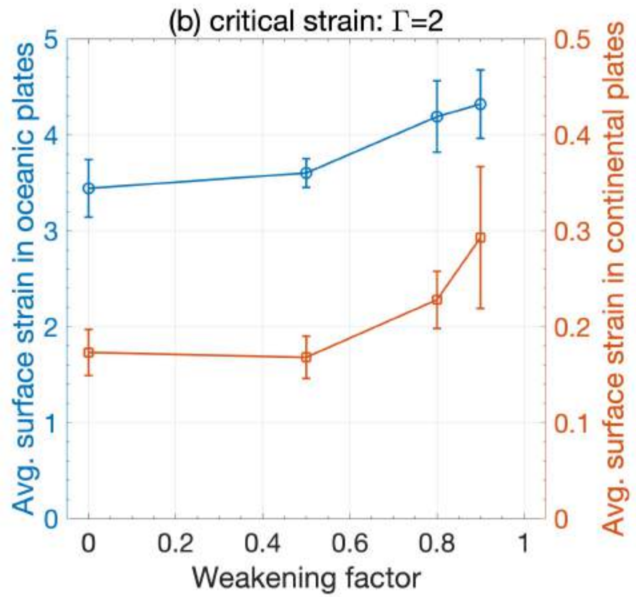
With weakening ($\lambda > 0$)

→ Enhanced strain in plates, easier to reach yield stress: more, but smaller plates **(wavelength)**

→ Surface mobility increases, but localisation of deformation degrades as deformation spreads over larger area: **degraded plate-like behaviour**

Note: Depends on critical strain (Γ), which is rather low here:
→ Further exploration needs to be done ...





Conclusions (so far)

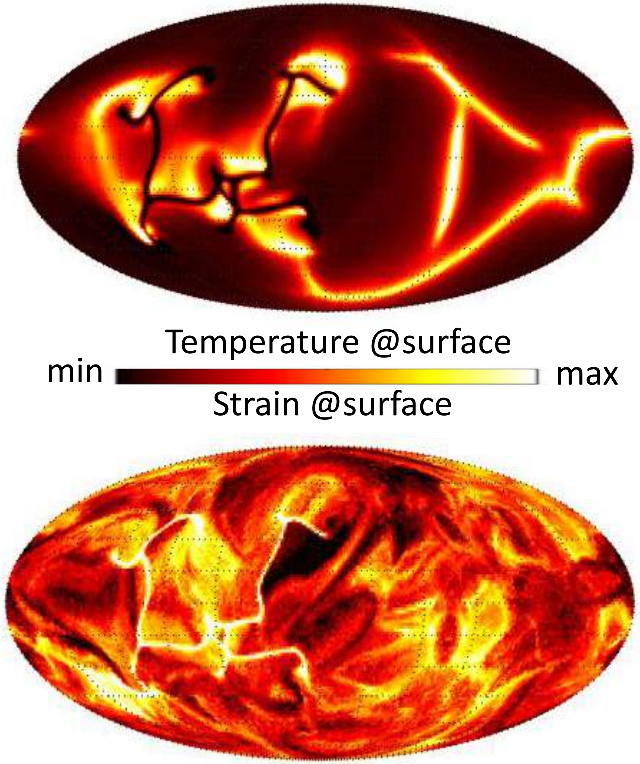
→ Strain weakening may strongly affect plate-like behaviour (and with that mantle evolution), like how well deformation islocalised and how large the resulting plates are.

→ It seems very difficult to accumulate substantial strain within strong continents (like shields and cratons). On the other hand, weak continents do not sufficiently resist recycling by tectonic processes.

→ For now, the influence of strain weakening on the potential break-up of continents is not prominent in our models *(in contrast to break-up on Earth?!)*

Perspectives

→ Further investigation of the parameter space for the weakening parameters
→ Improved setup of continents (e.g. add crust and/or pre-existing weak zones)
→ Go to 3D



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