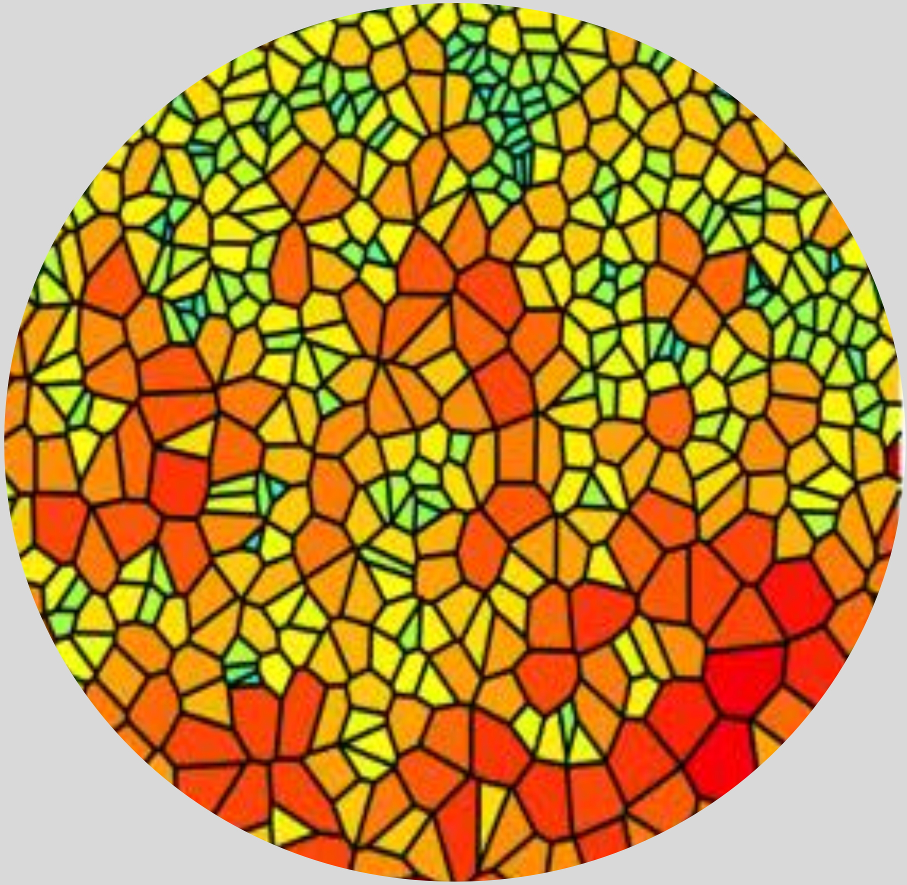
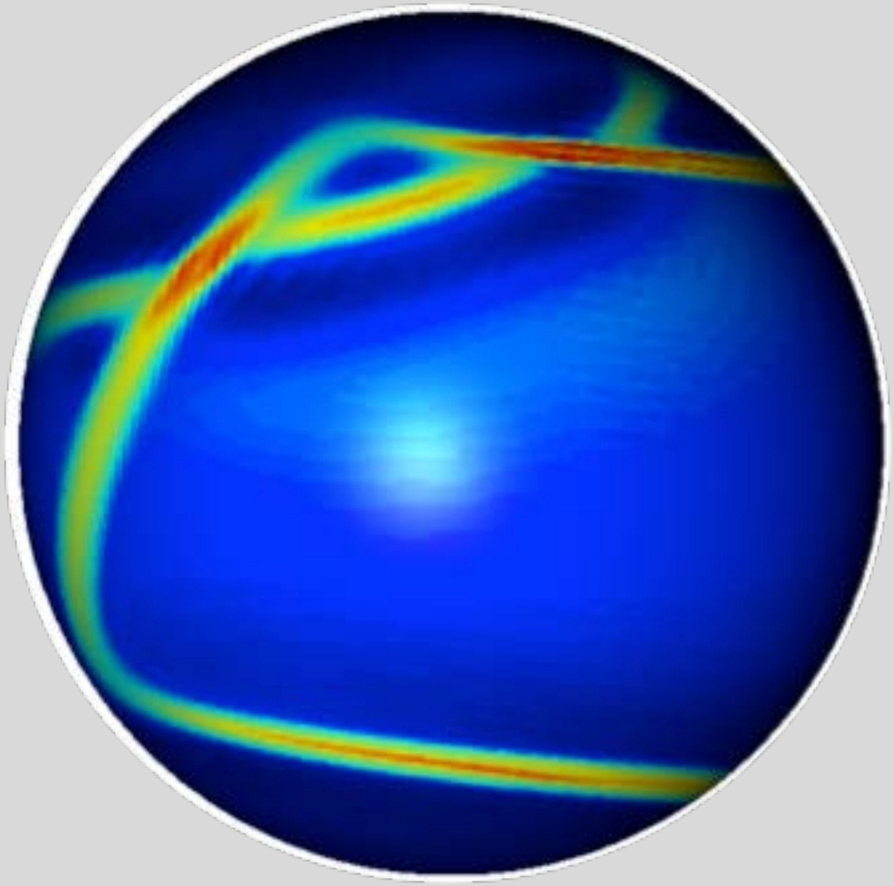
Generation of plate tectonics from grain to global scale





David Bercovici
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50 Years of Plate Tectconics, College de France

June 26 2018

Collaborators

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Wash. Univ. St. Louis

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1963 (maybe)

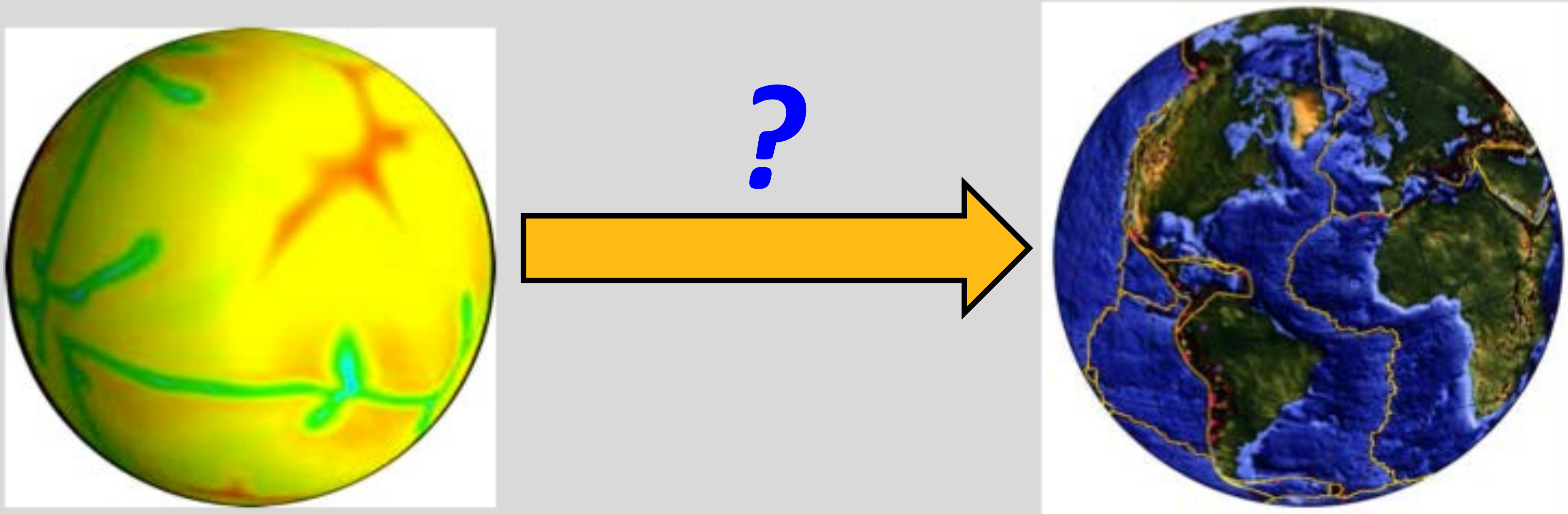
1968

Unique Earth?

Why is Earth the only terrestrial planet in our solar system with plate tectonics, liquid water, temperate climate, and life

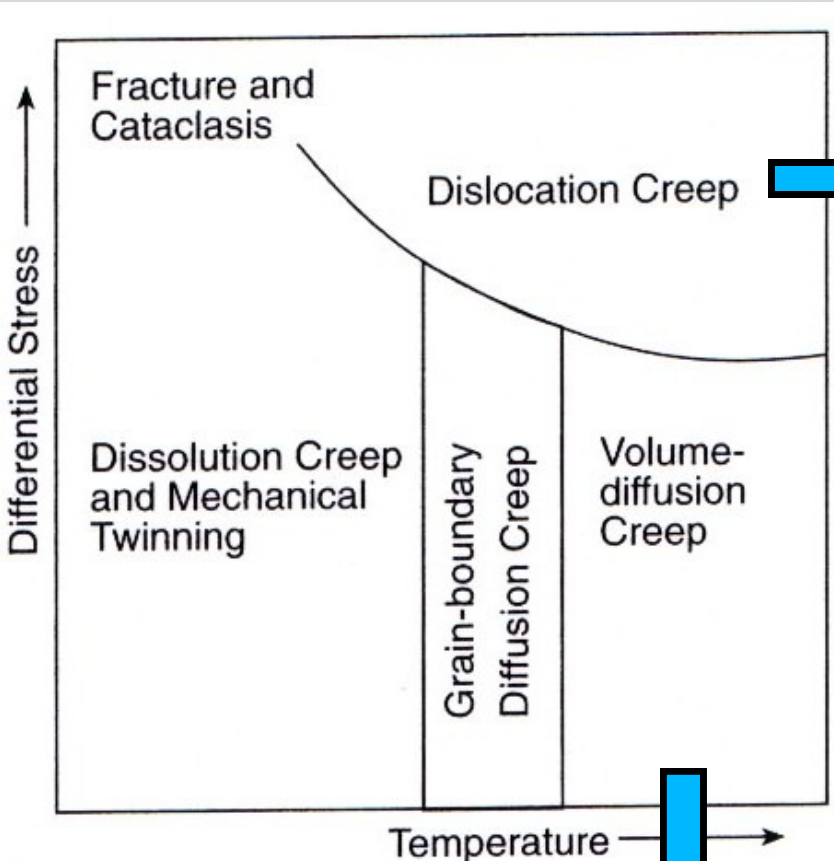
- ***Plate tectonics likely governs planetary evolution from core to atmosphere***
  - Plate tectonics as a carbon scrubber (Walker et al 1981; Berner et al 1983)
- ***Desire a predictive theory about conditions for plate tectonics to occur***

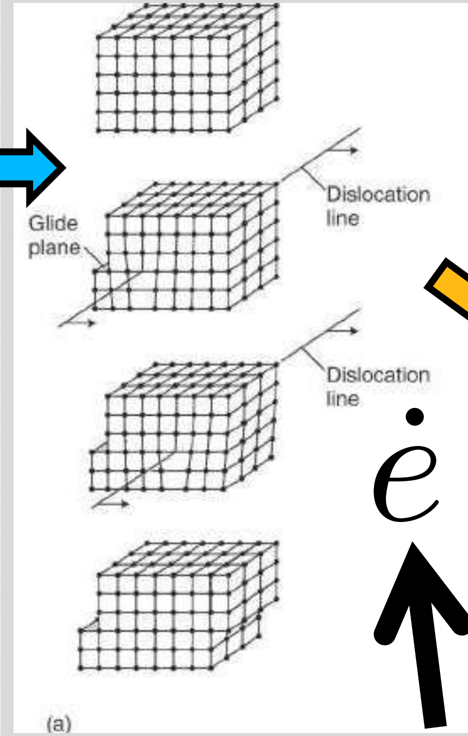
The "Plate Generation" questions



How does plate tectonics arise from a convecting mantle?
Why Earth, not Venus (or Mars)?
What governs whether we expect to find plate tectonics in other solar systems?
When and how did plate tectonics emerge?
How do plates evolve and reorganize?

Mantle rock "creep" rheology





$$\dot{e} = A(T)\sigma^n$$

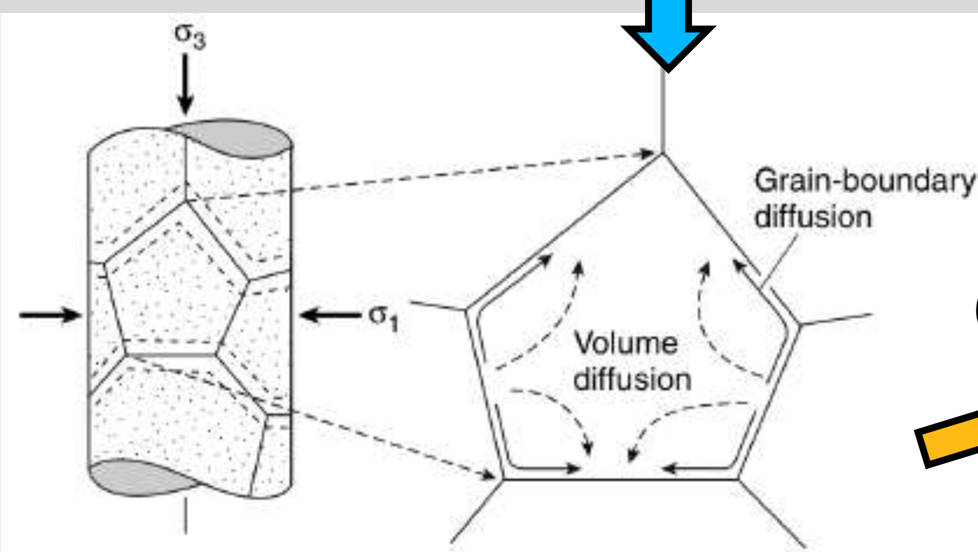
strain-rate

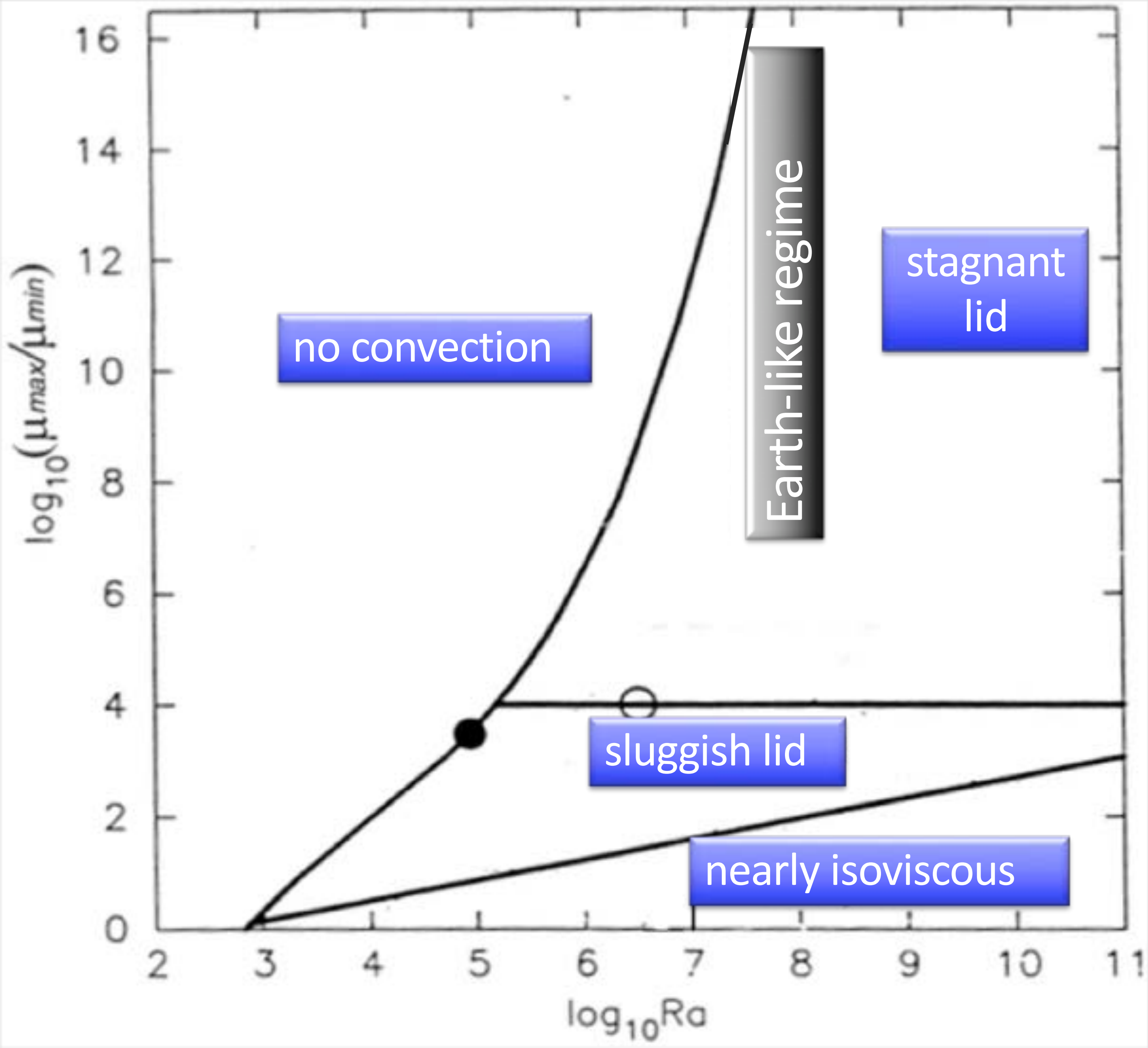
temperature

stress

grain-size

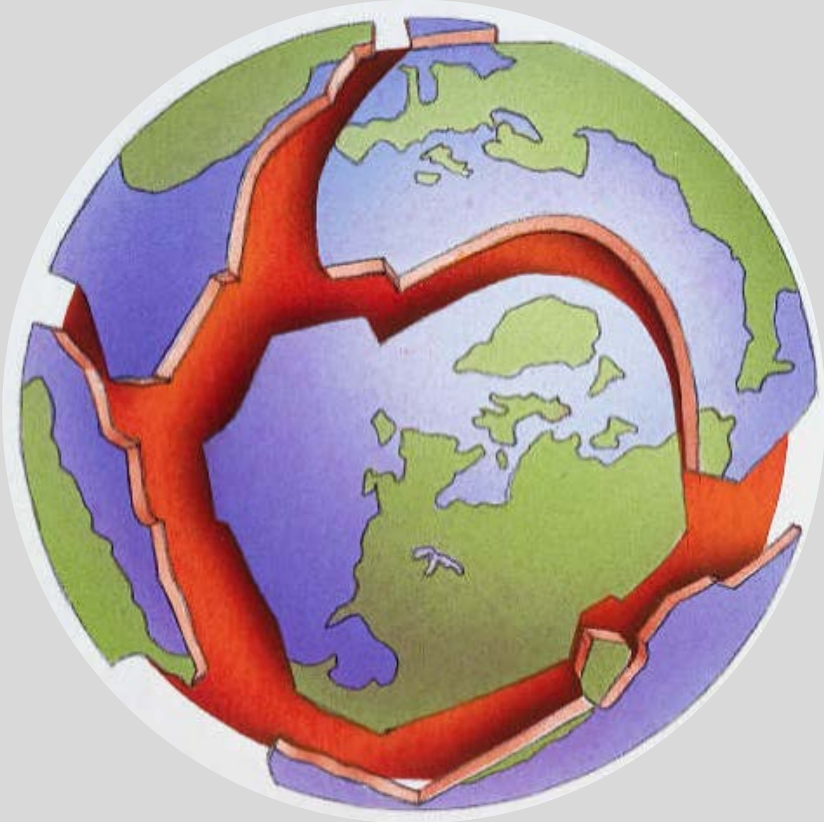
$$\dot{e} = B(T)\sigma/\mathcal{R}^m$$





V. Solomatov (1995)

Plate Generation Mechanisms



Most terrestrial mantles undergo *stagnant lid* convection

Earth has self-softening feedbacks

- deformation softens material
- weak zones focus deformation
- causes more softening, more focusing: shear-localization

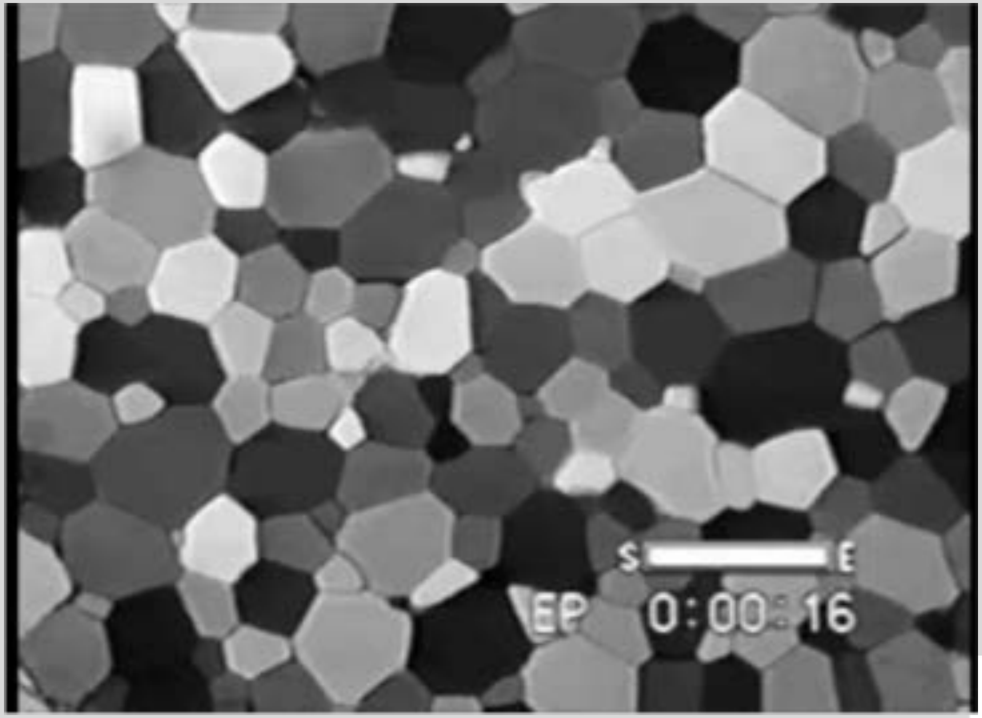
Allows convecting mantle to generate

- strong broad plates,
- narrow, weak **long-lasting boundaries**
- **localized strike-slip shear**

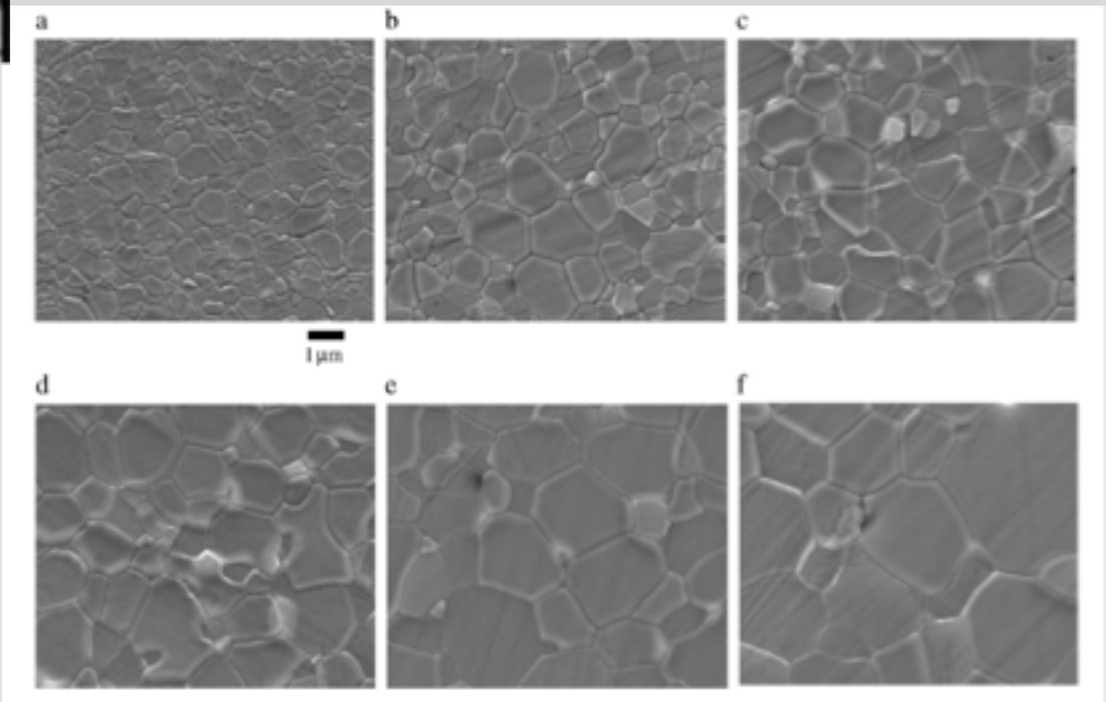
Peridotite mylonite (Lars Hansen)

Grain-scale Processes

- Mineral grains grow if "static"



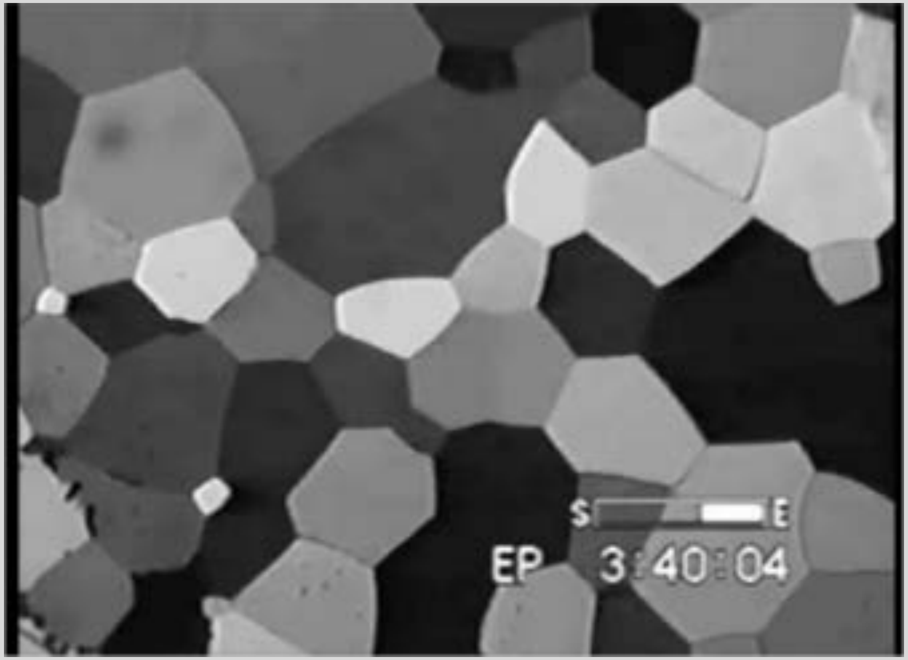
Octochlorpropane (Park et al 1997)



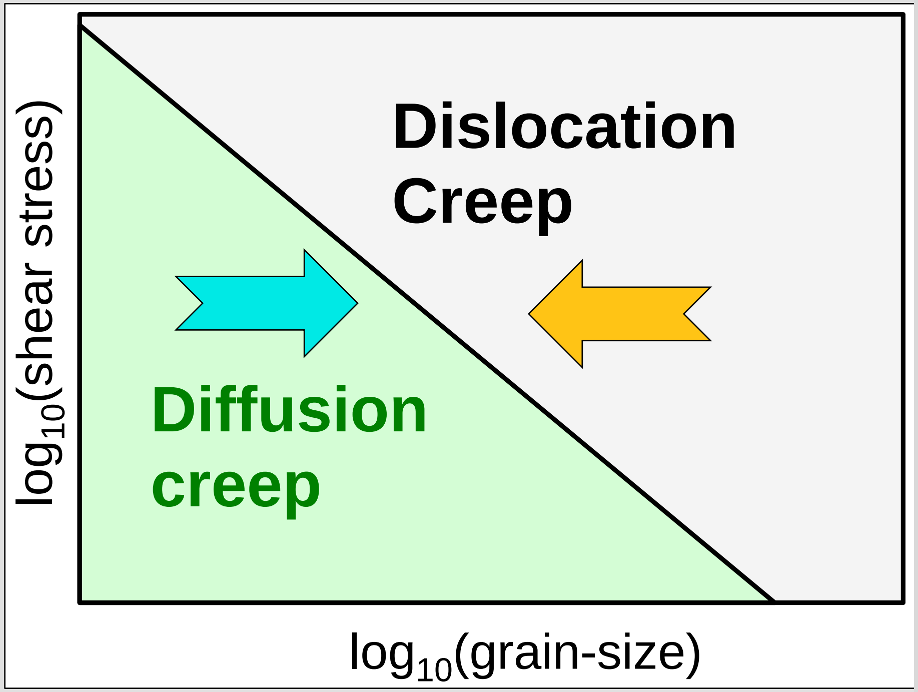
Hiraga et al 2010

Grain-scale Processes

- Mineral grain-size reduction?



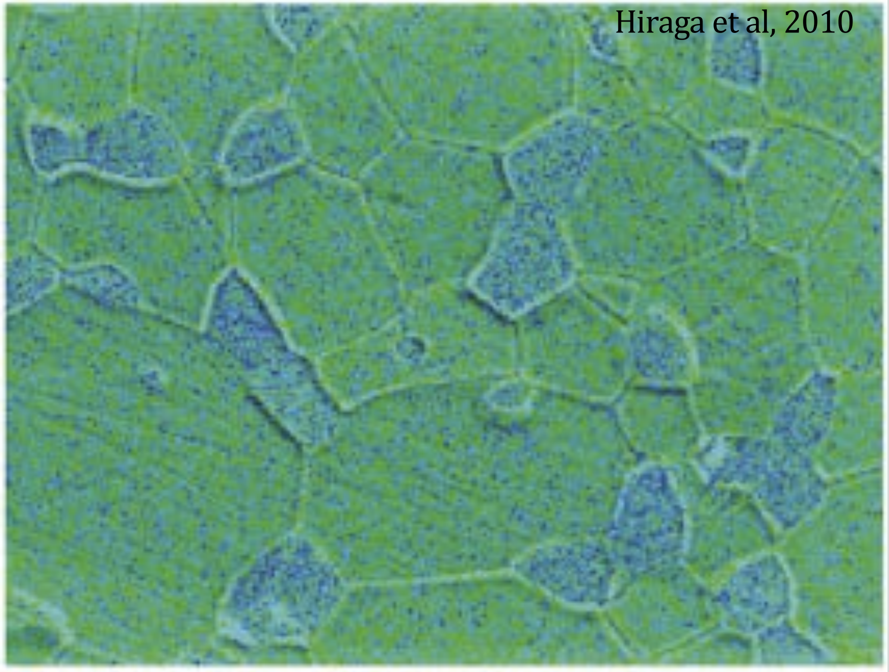
- With deformation and *damage* (dislocations), grain-size reduces
- Rocks apparently soften as grains "shrink" ➔ **positive feedback**
- **"Deep" lithospheric mechanism**
  - **cold ductile region**
- **Evident in mylonites**



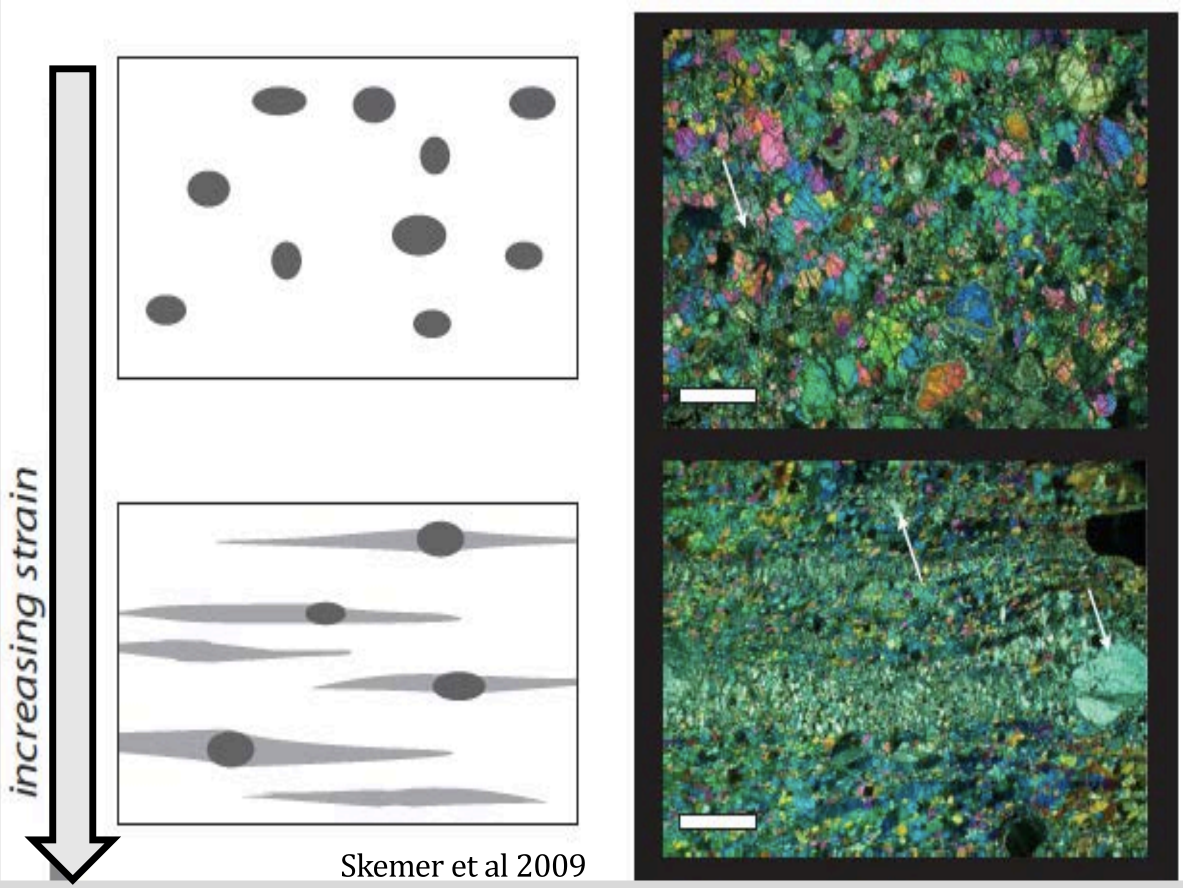
But in single-phase rocks…

- Grain reduction only in dislocation creep (*dynamic recrystallization):* independent of grain-size
- Grain-size weakening only in diffusion creep when grains only grow
- **Shoudn't be any self-softening feedback**
  - de Bresser et al (2001)

*Grain-damage & pinning in rock mixtures**



- Mantle rocks (peridotite) are mixture of olivine and pyroxene
- Grain growth blocked (*pinned*) by interface between components
- Damage acts to "sharpen" interface
- Sharpening of interface and *pinning* drives grains to smaller sizes and material softens
- **Damage and softening coexist**
- **Pinning retards healing**

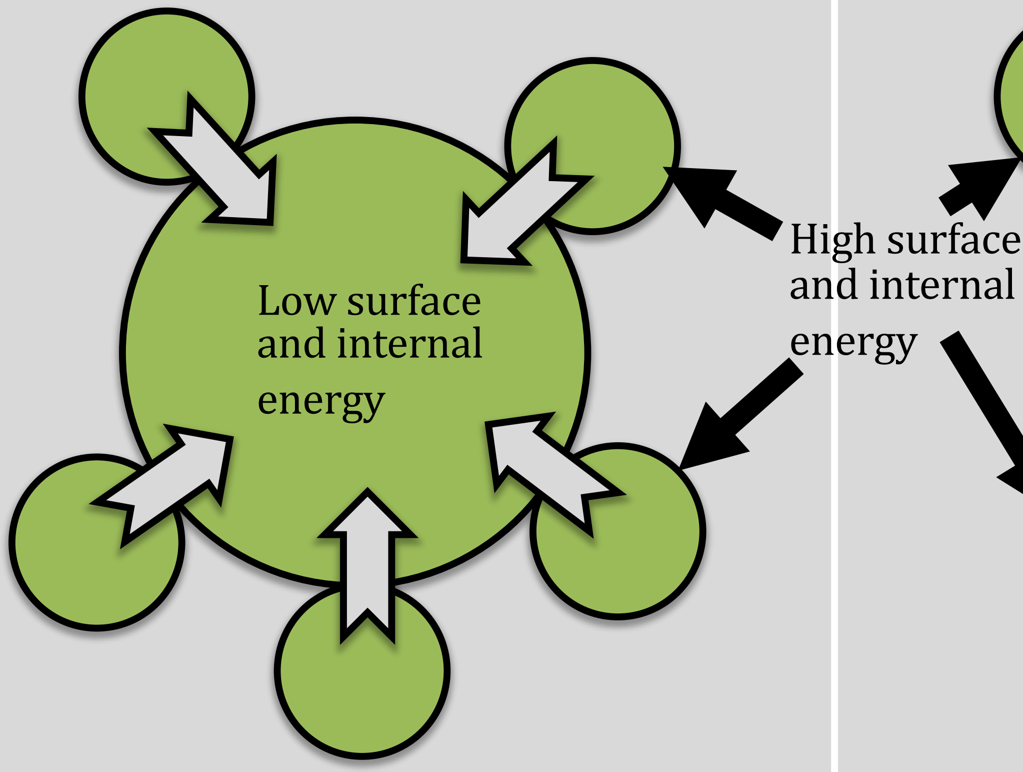


Skemer et al 2009

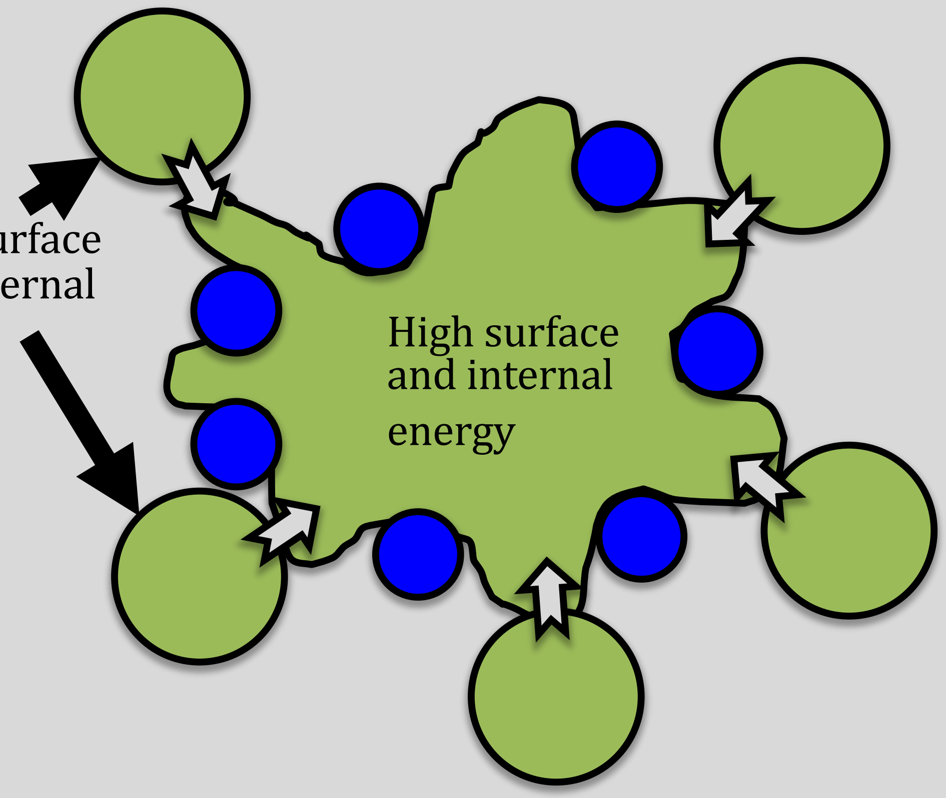
*Bercovici & Ricard 2012, 2013

Pinning slows grain-growth

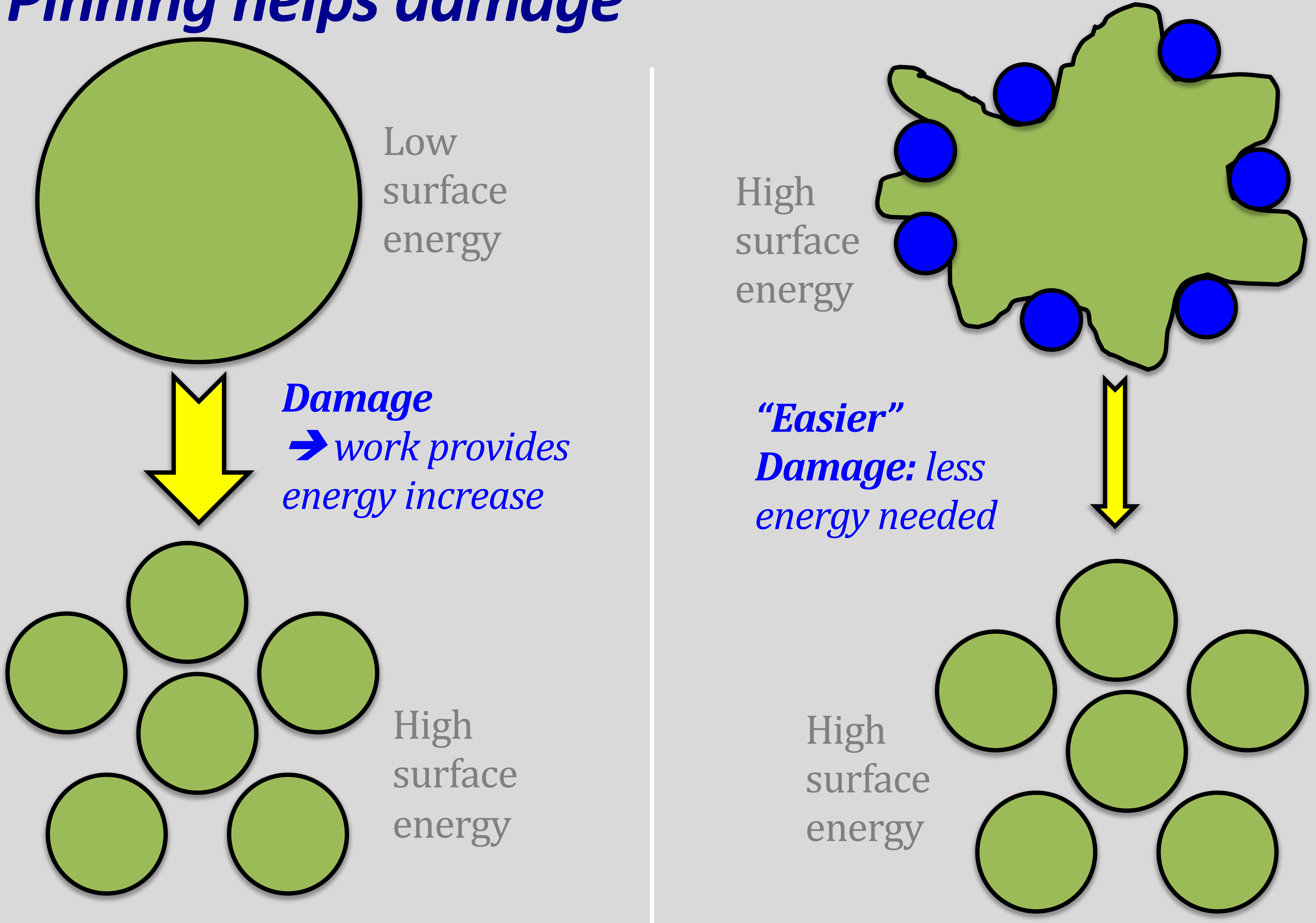
Single-phase coarsening



In two-phases with pinning, coarsening is impeded



Pinning helps damage



Coupled "interface" and "grain-size" evolution laws

coarsening
healing

damage

Interface "roughness" or radius of curvature *r*

$$\frac{Dr^q}{Dt} = \mathcal{C}_I - q\mathcal{D}r^{q+1}\bar{\Psi}$$

Grain-size $\mathcal{R}_i$ in each phase

$$\frac{D\mathcal{R}_i^p}{Dt} = \mathcal{C}_i\mathcal{Z}_i - p\mathcal{D}\mathcal{R}_i^{p+1}\frac{a_i\tau_i^{n+1}}{\mathcal{Z}_i}$$

Zener pinning factor

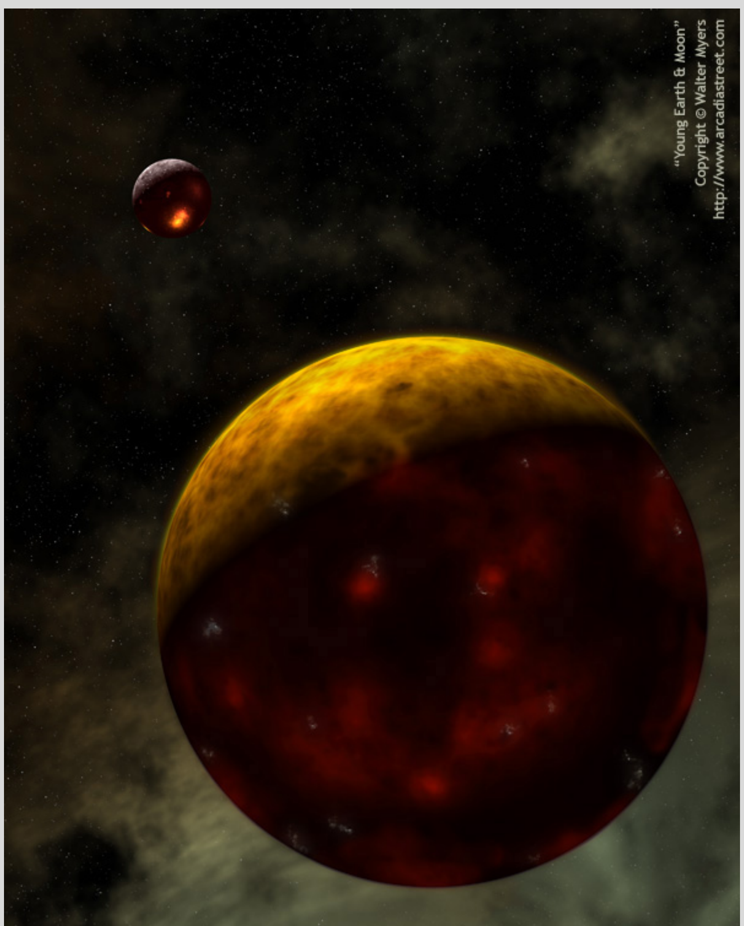
$$\mathcal{Z}_i = 1 - \mathfrak{c}(1-\phi_i)\frac{\mathcal{R}_i^2}{r^2}$$

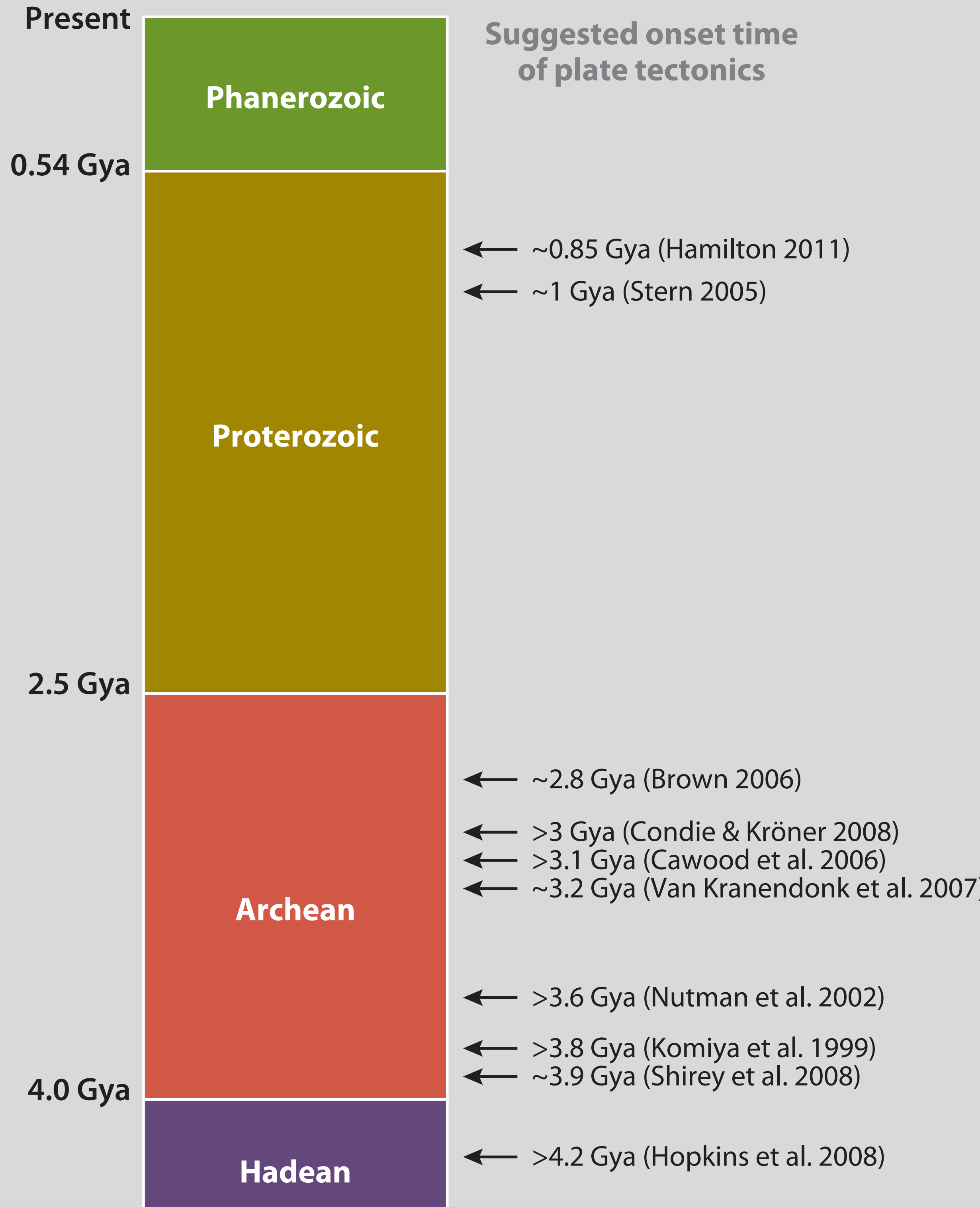
Composite dislocation + diffusion creep rheology

$$\dot{\underline{\mathrm{e}}} = \left(a_i\tau_i^{n-1} + b_i\mathcal{R}_i^{-m}\right)\underline{\tau}_i$$

Coefficients based on comparison to lab experiments

Emergence of plate tectonics: When and how did plate tectonics begin?

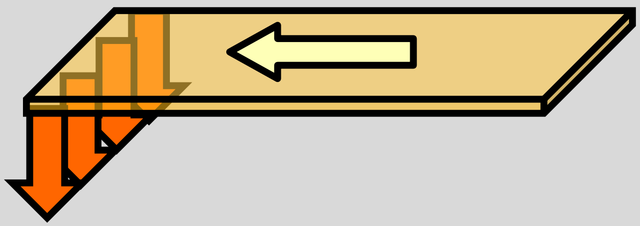


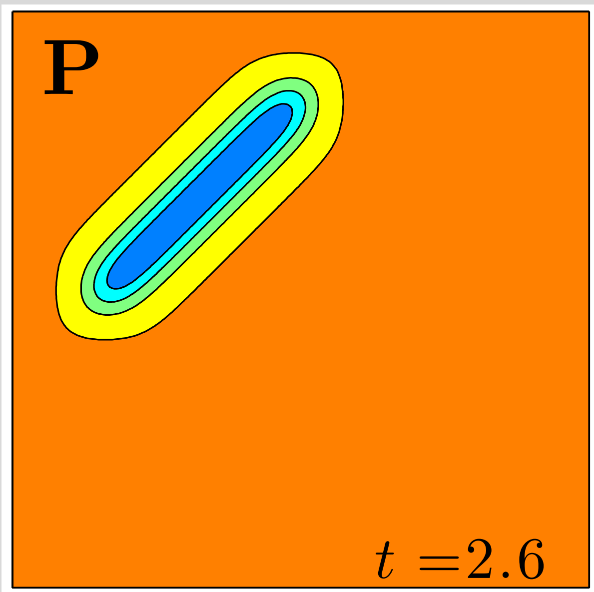


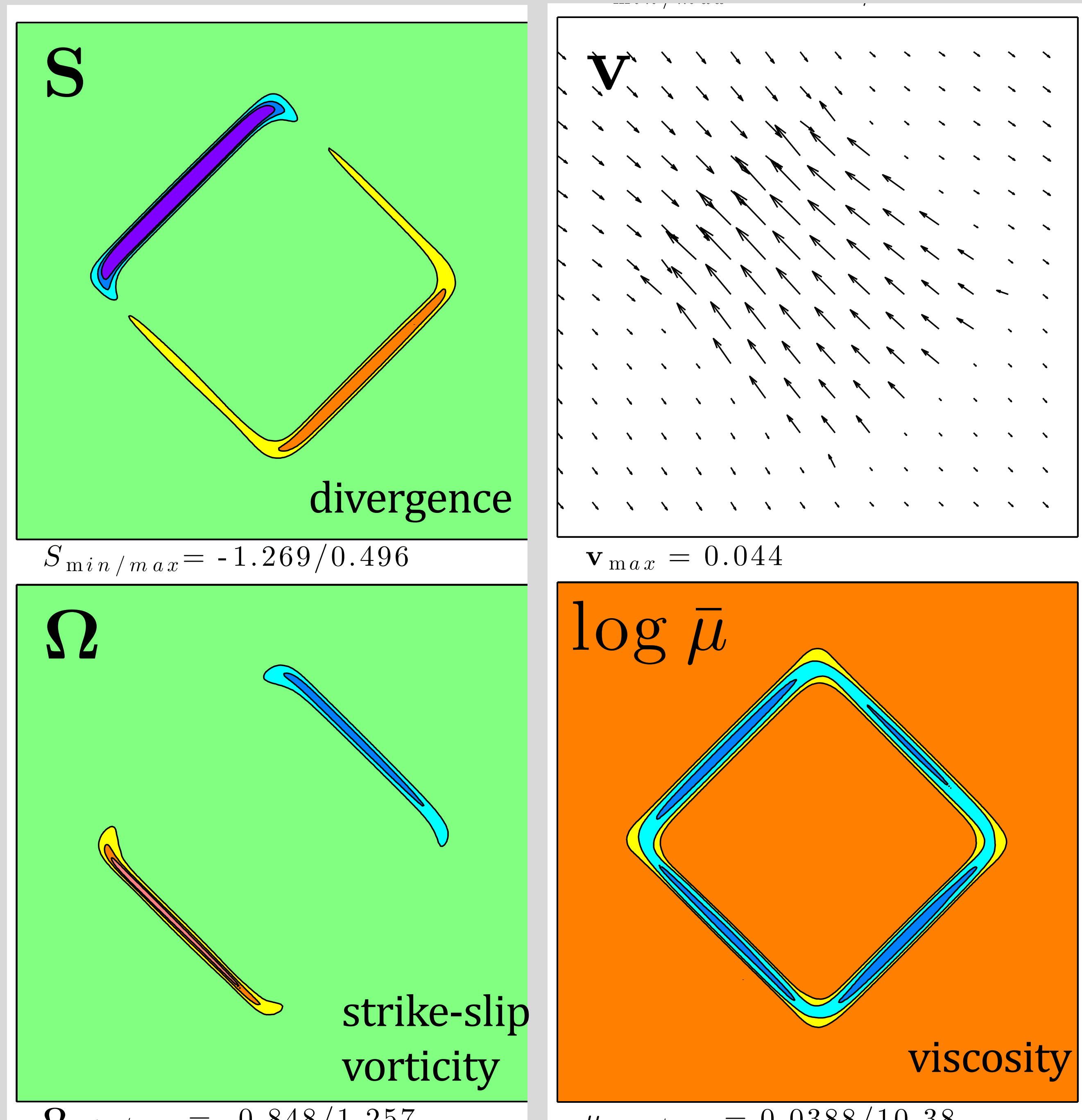
Korenaga Ann.Revs EPS 2013

Intermittent subduction and inherited damage

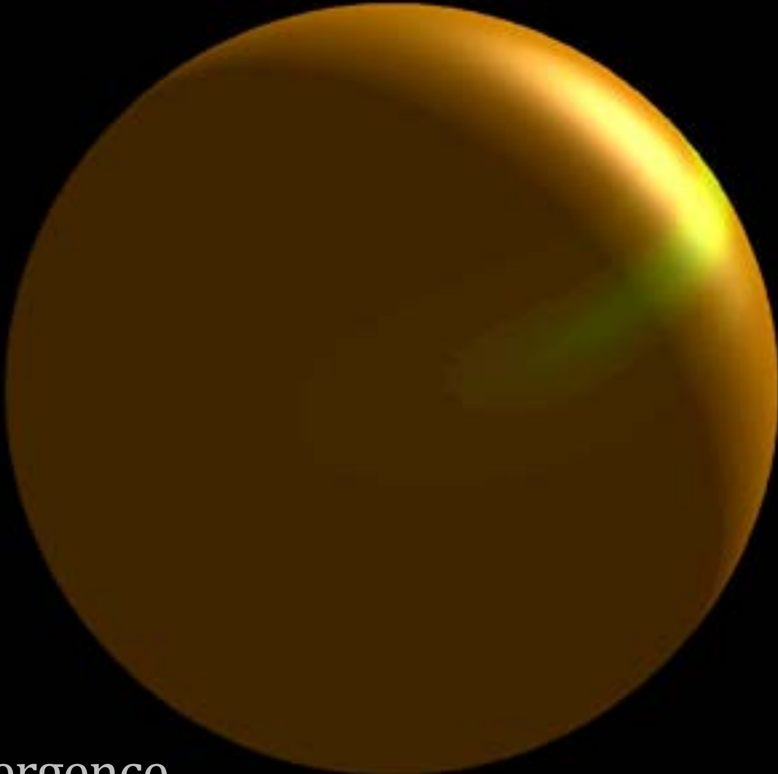
Bercovici & Ricard (2014)



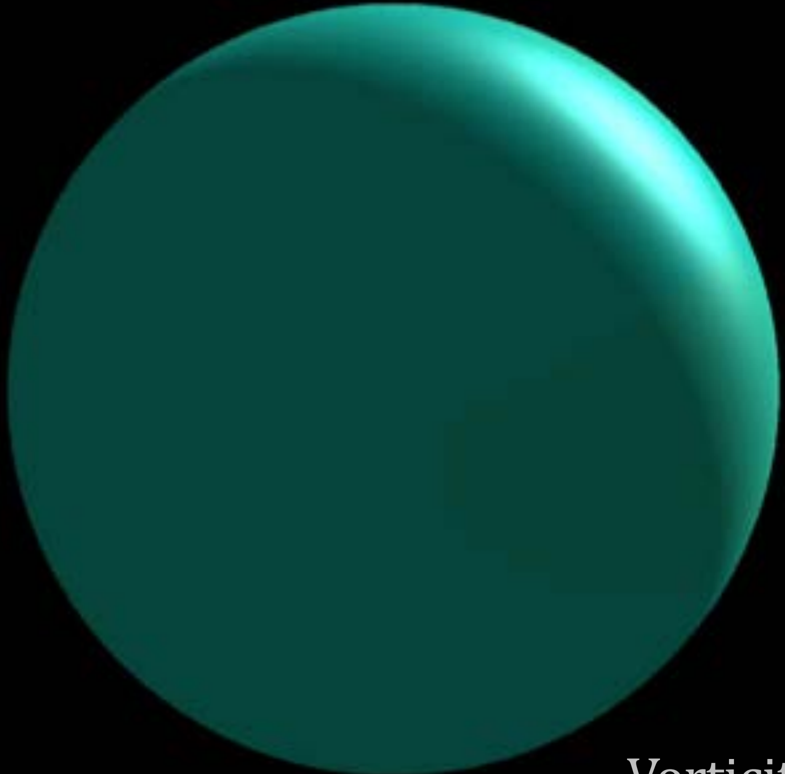




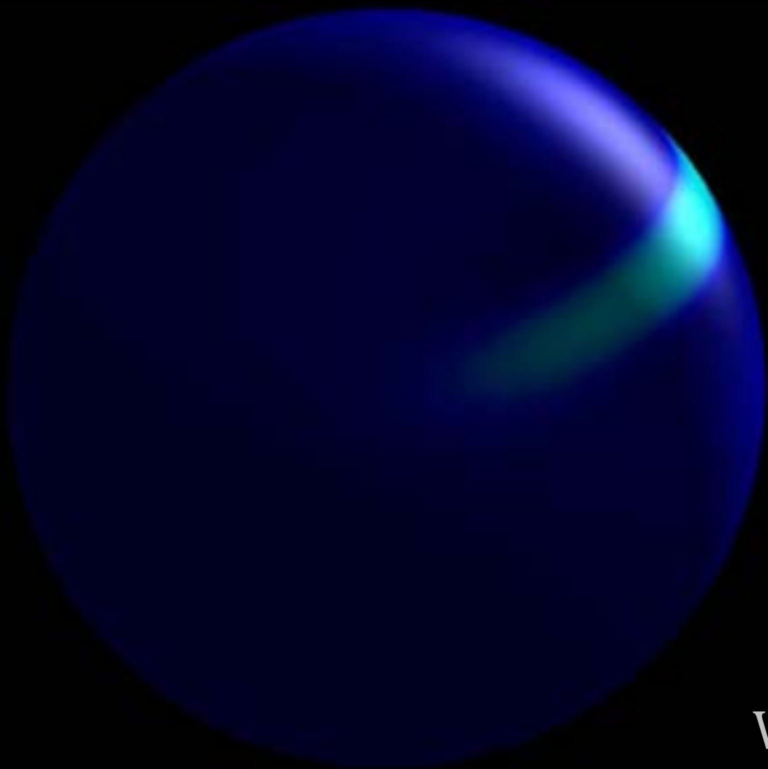
- **Migrating subduction low P zone**
- **Inherited weak zones**
- **Accumulate plate boundaries in ~ 1Gyr**



Divergence



Vorticity



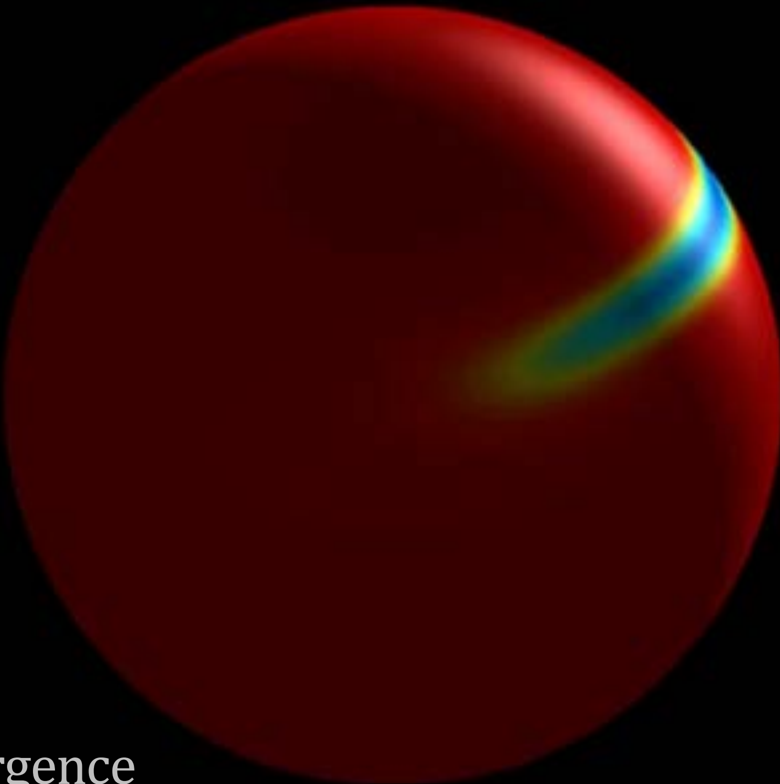
Viscosity

Earth-like case

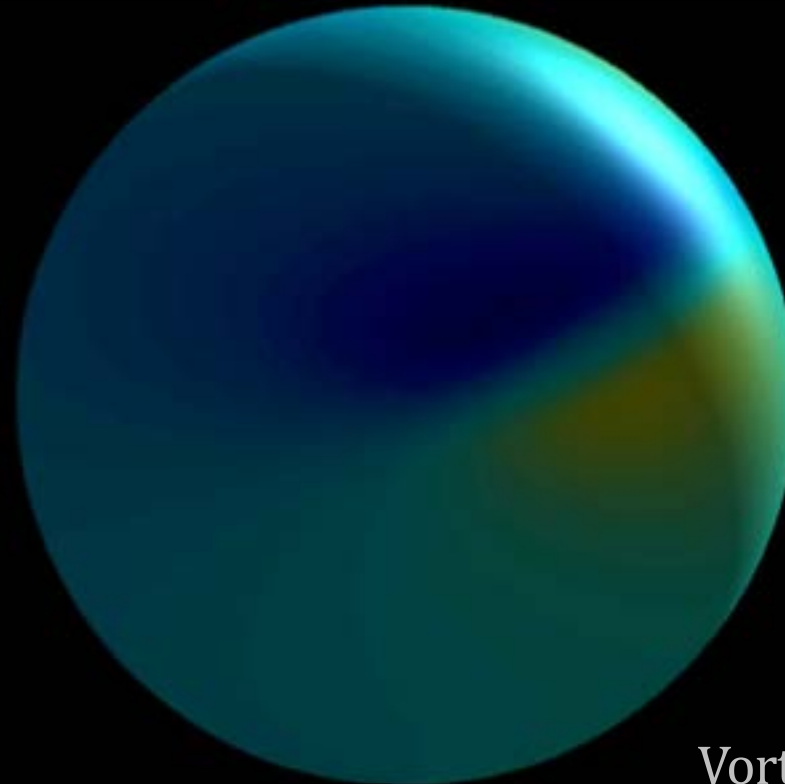
Cool surface:

Low healing

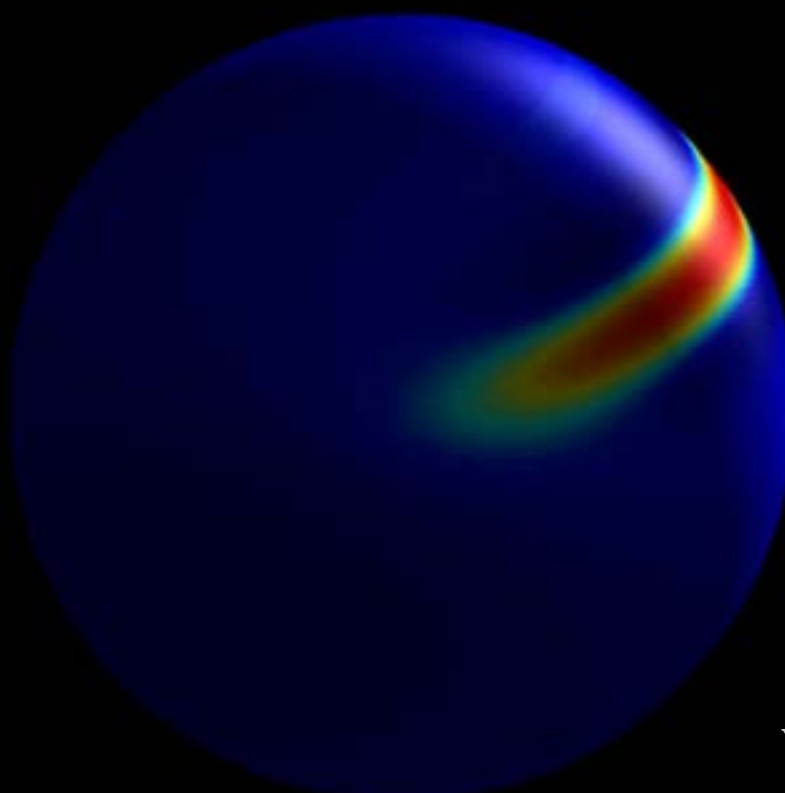
High damage



Divergence



Vorticity



Viscosity

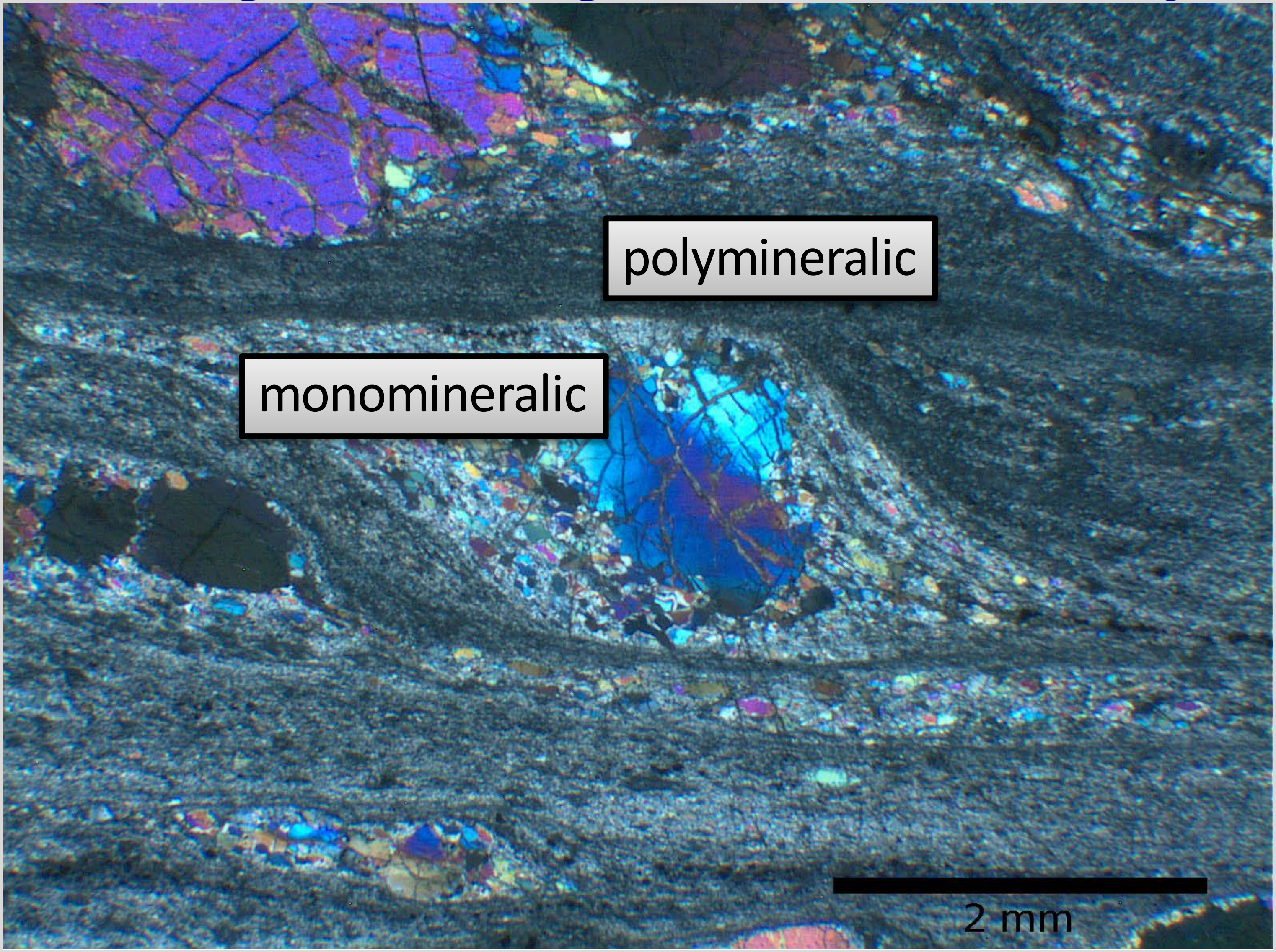
Venus-like case

Hot surface:

High healing

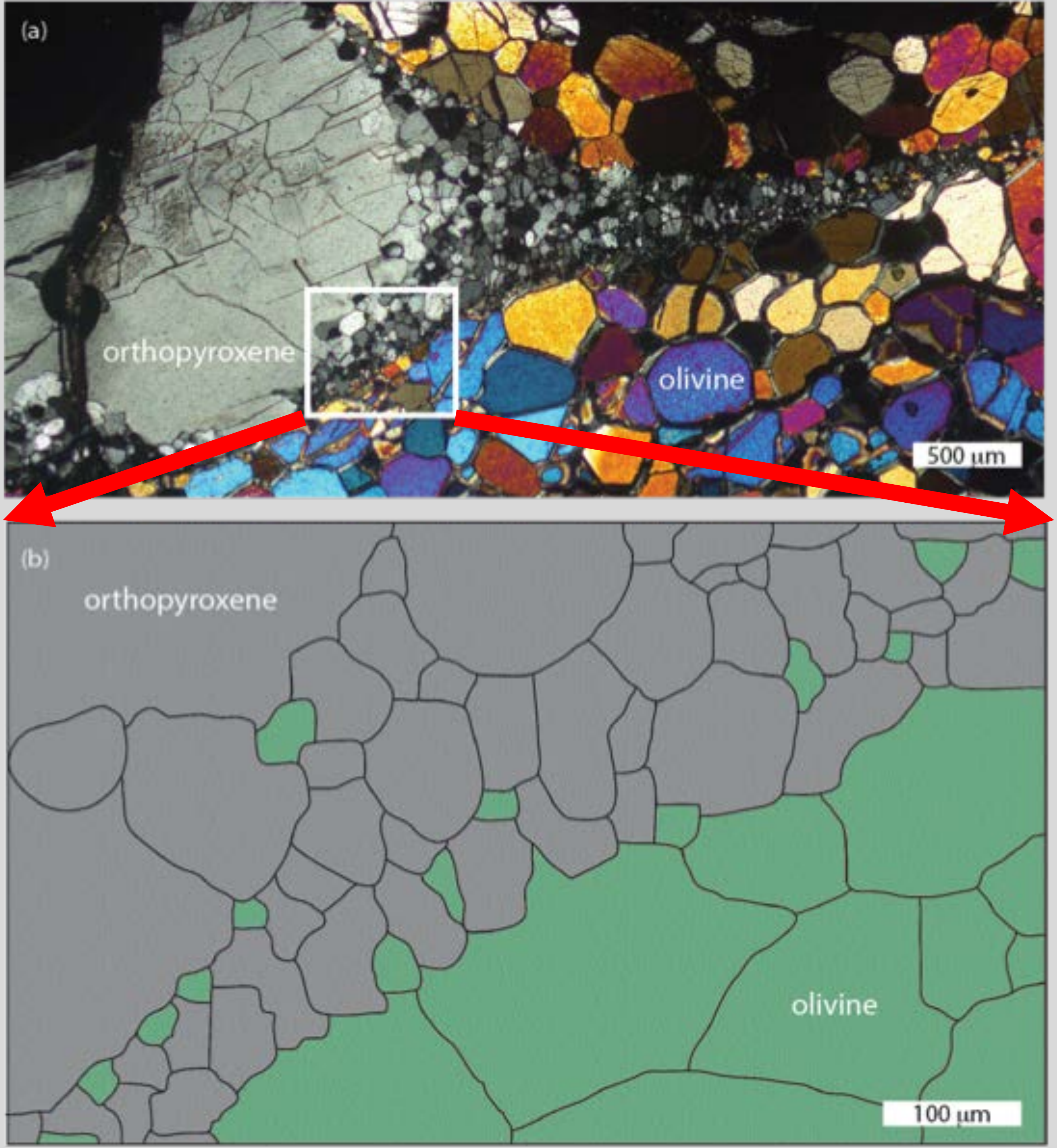
Low damage

Grain damage, mixing and tectonic hysteresis



- Mylonites and ultramylonites often form bands of mixed grains (esp. in peridotites)
- Polyminerallic damage+pinning enhanced by inter-grain mixing

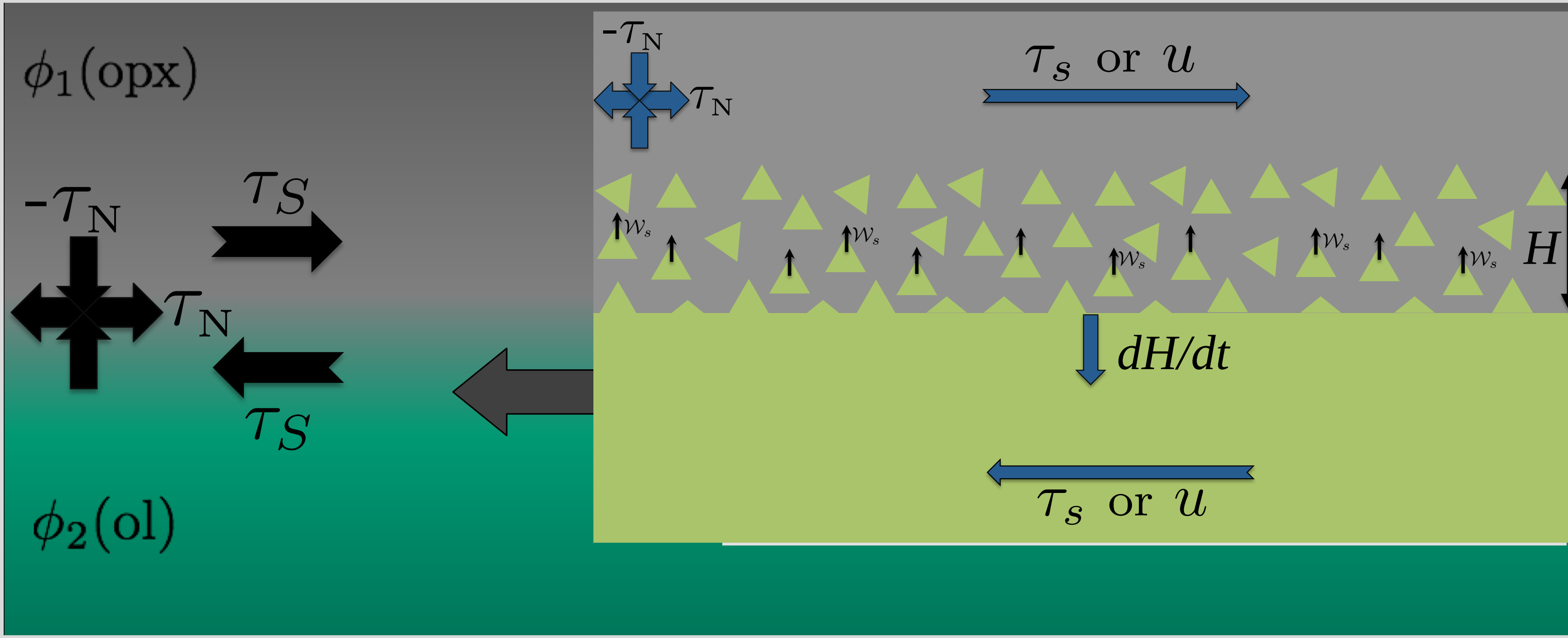
Grain mixing



Sheared (lherzolite) peridotite (Skemer & Karato 2008)

Drawing after EBSD image (Bruijn & Skemer 2014)

Diffusive grain mixing model



$$\frac{\partial \phi_i}{\partial t} + \boldsymbol{\nabla} \cdot (\phi_i \mathbf{v}_i) = 0$$ mass conservation

$$\mathbf{v}_i = \mathbf{v} + \mathbf{u}_i \quad \mathbf{v} = \sum_i \phi_i \mathbf{v}_i \quad \sum_i \phi_i \mathbf{u}_i = 0$$ mean and grain-diffusive velocity

$$\mathbf{u}_i = -\phi_j \underline{\boldsymbol{K}} \cdot \boldsymbol{\nabla} \phi_i \quad \text{where} \quad j \neq i$$ diffusive velocity ~ vol. fraction gradient

$$\underline{\boldsymbol{K}} = \chi(\phi, R_i, r)\underline{\boldsymbol{\tau}}$$ anisotropic diffusivity ~ stress tensor

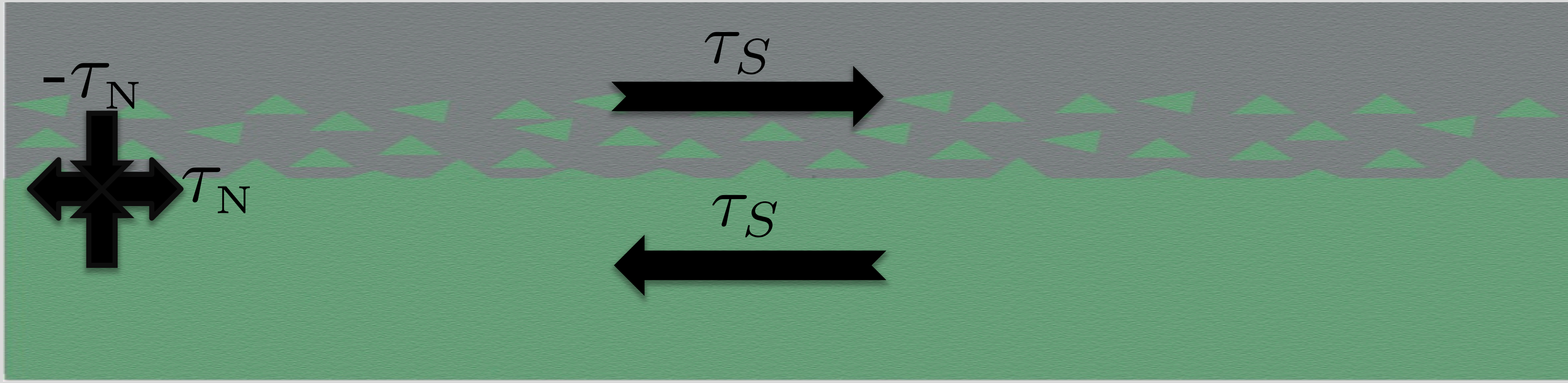
$$\frac{D\phi_i}{Dt} = \boldsymbol{\nabla} \cdot \left(\phi_i \phi_j \chi \underline{\boldsymbol{\tau}} \cdot \boldsymbol{\nabla} \phi_i\right)$$ Mass advection-diffusion eqn

Bercovici & Skemer (2017)
Bercovici & Mulyukova (2018)

Diffusive grain mixing + damage: 1D example

$$\underline{\boldsymbol{\tau}} = \begin{bmatrix} \tau_{\rm N} & \tau_{\rm S} \\ \tau_{\rm S} & -\tau_{\rm N} \end{bmatrix} \equiv \tau_{\rm N}(\hat{\mathbf{x}}\hat{\mathbf{x}} - \hat{\mathbf{z}}\hat{\mathbf{z}}) + \tau_{\rm S}(\hat{\mathbf{x}}\hat{\mathbf{z}} + \hat{\mathbf{z}}\hat{\mathbf{x}})$$

$$v_x = \dot{e}_N x + U(z)\ , \quad v_z = \dot{e}_N z \qquad \tau_N = 2\mu\dot{e}_N \qquad \tau_S = \mu\frac{\partial U}{\partial z}$$



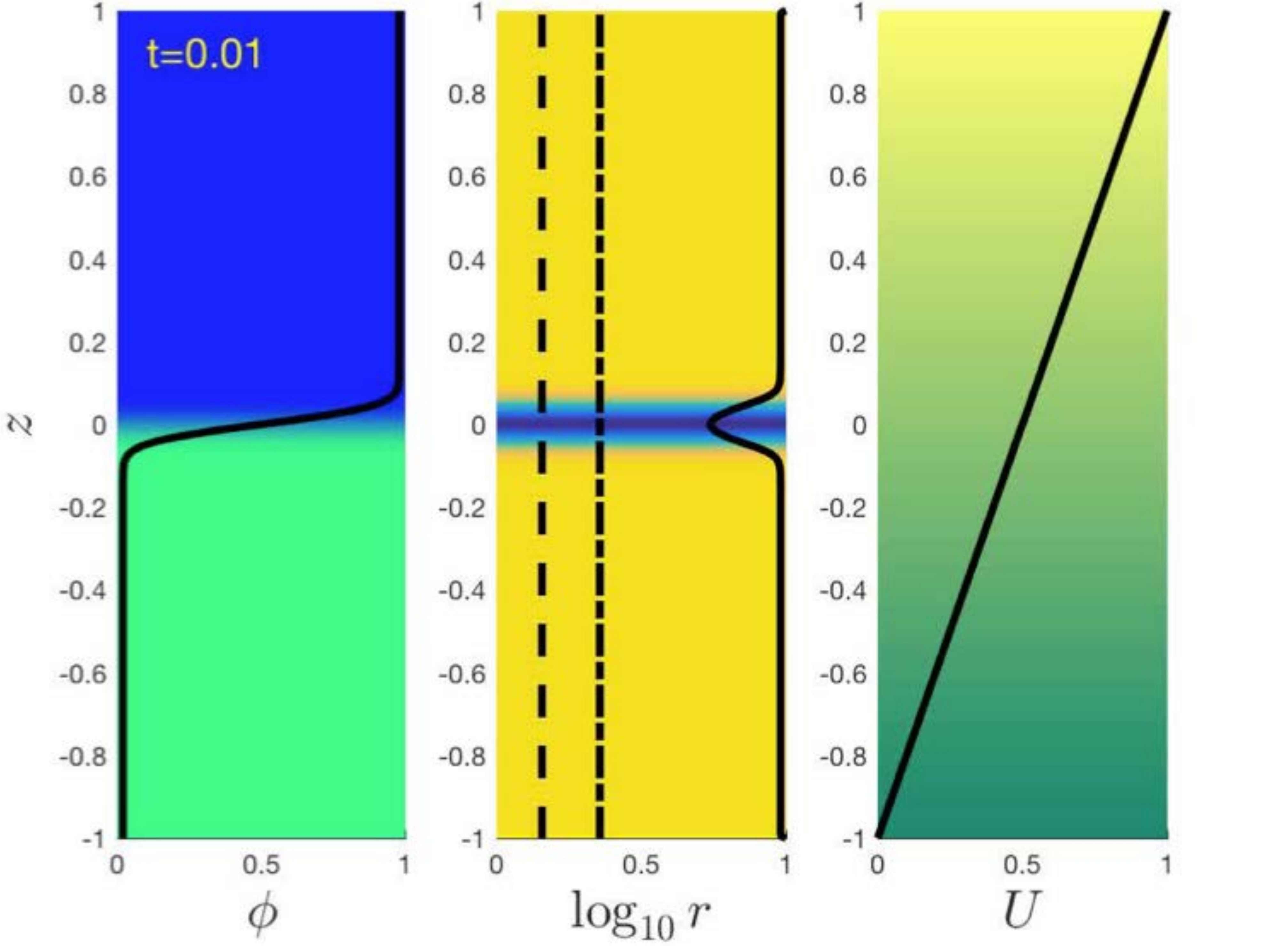
Mass advection-diffusion eqn

$$\frac{\partial \phi}{\partial t} - \dot{e}_N z\frac{\partial \phi}{\partial z} = \tau_N\frac{\partial}{\partial z}\left(\mathcal{K}(\phi, r)\frac{\partial \phi}{\partial z}\right)$$

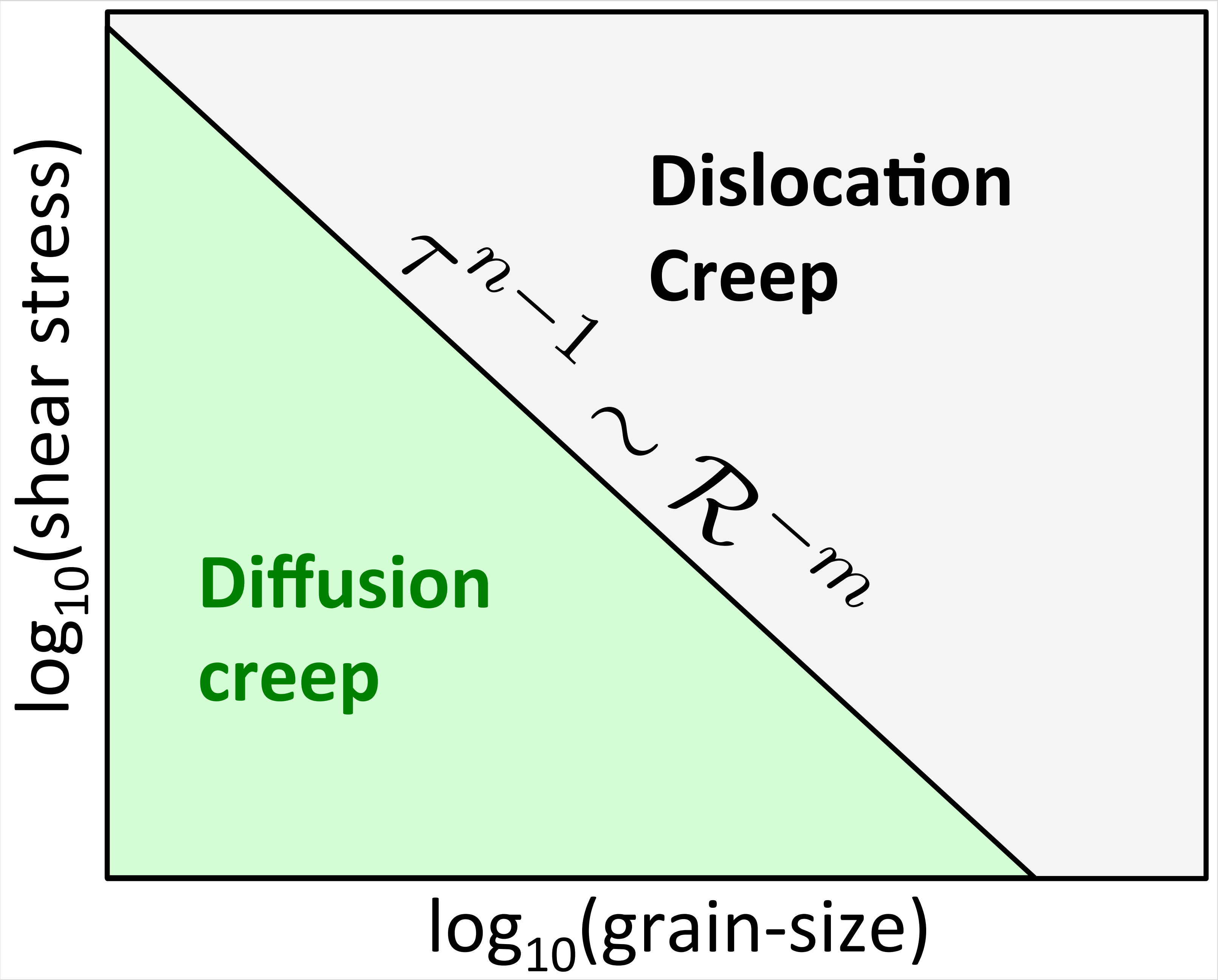
Grain damage (simplified)

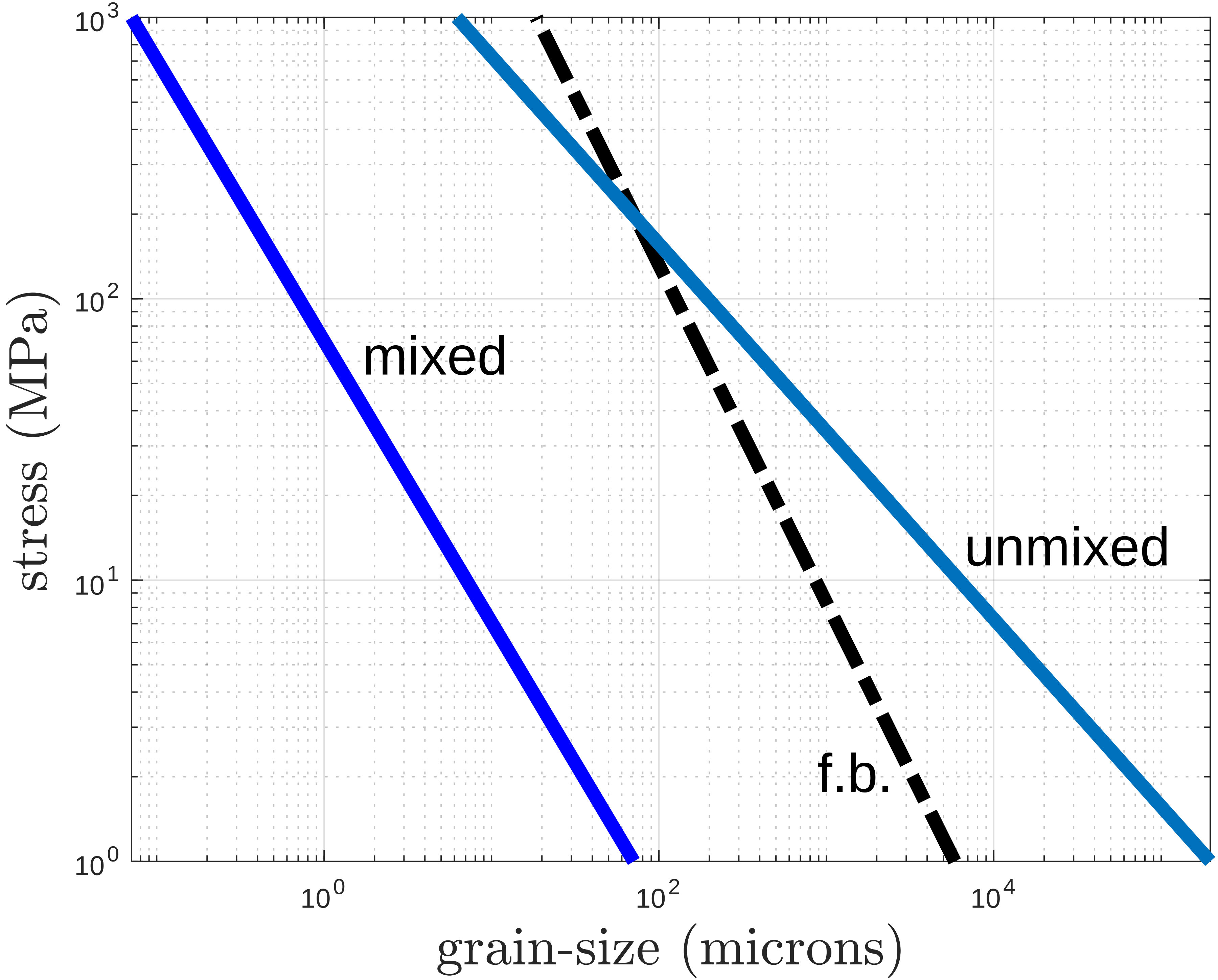
$$\frac{\partial r}{\partial t} - \dot{e}_N z\frac{\partial r}{\partial z} = \frac{\mathcal{C}}{qr^{q-1}} - \mathcal{D}r^2\left(A\tau^{n+1} + B(\phi)\tau^2 r^{-m} + \tau^2\mathcal{K}\left(\frac{\partial \phi}{\partial z}\right)^2\right)$$

Zoomed out ("wide" domain)



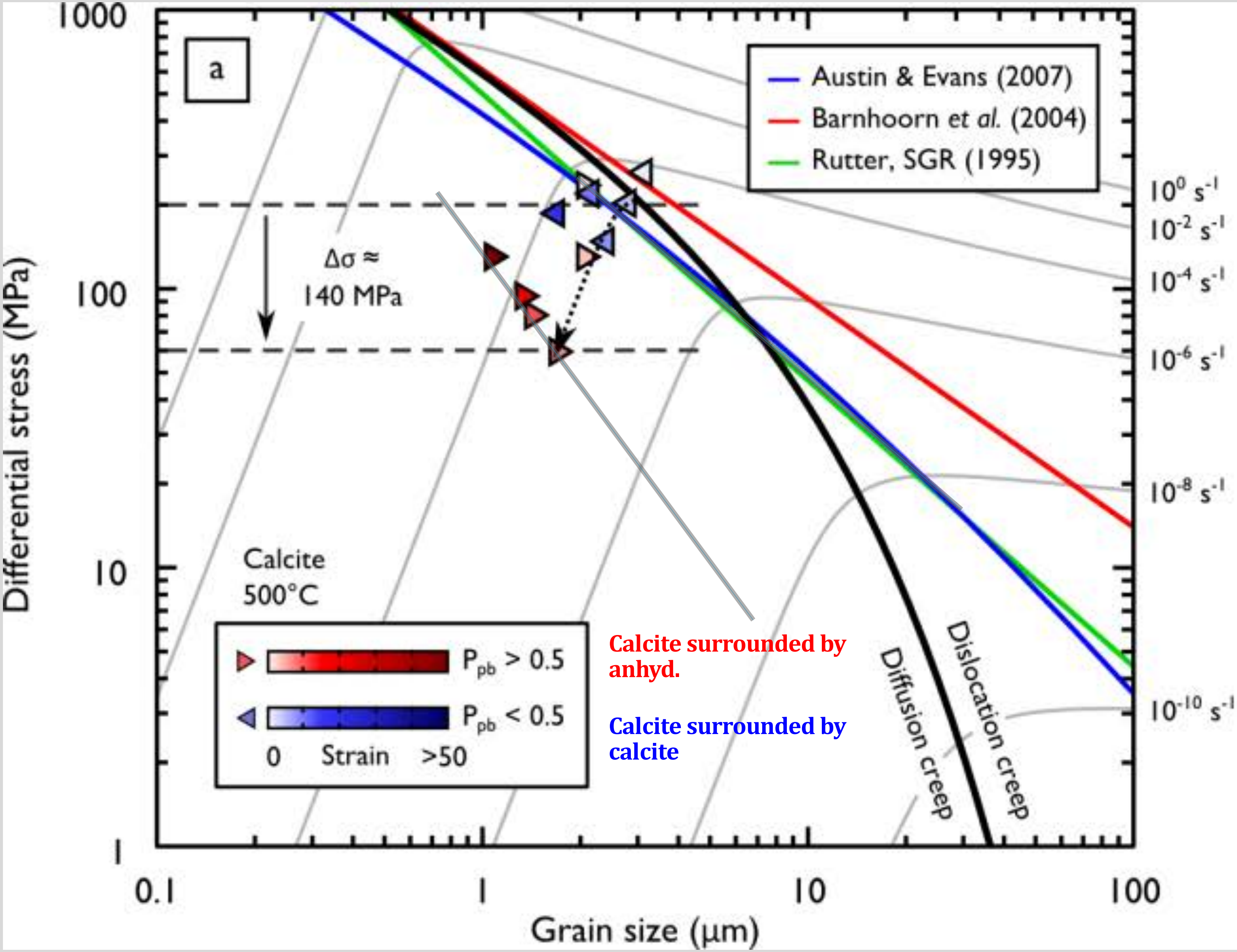
Deformation maps and observations (field and lab)

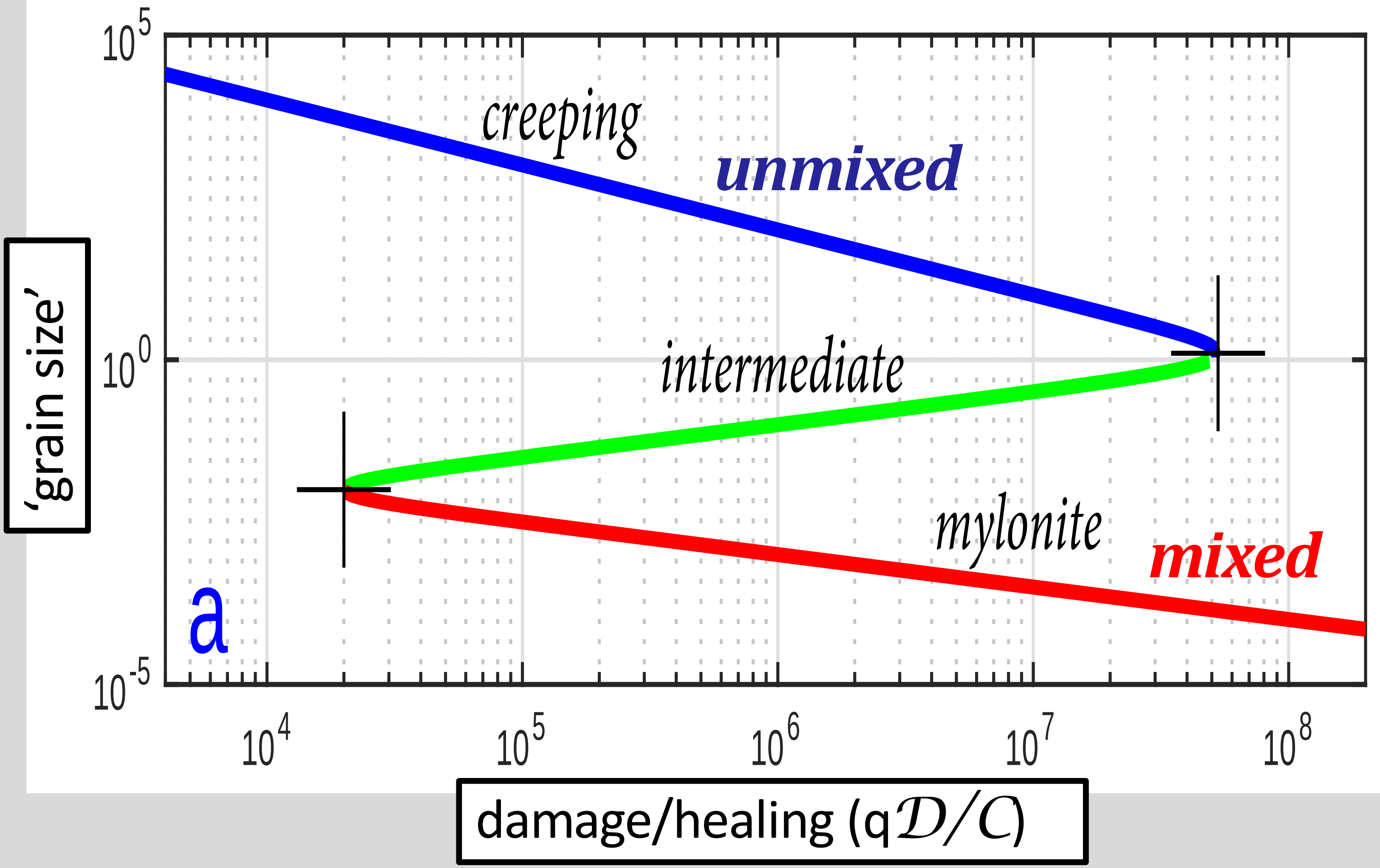




10^3
10^2
10^1
10^0
stress (MPa)
mixed
unmixed
f.b.
10^0
10^2
10^4
grain-size (microns)

Cross & Skemer 2017
calcite/anhydrite experiments





Two-phase grain damage with mixing transition

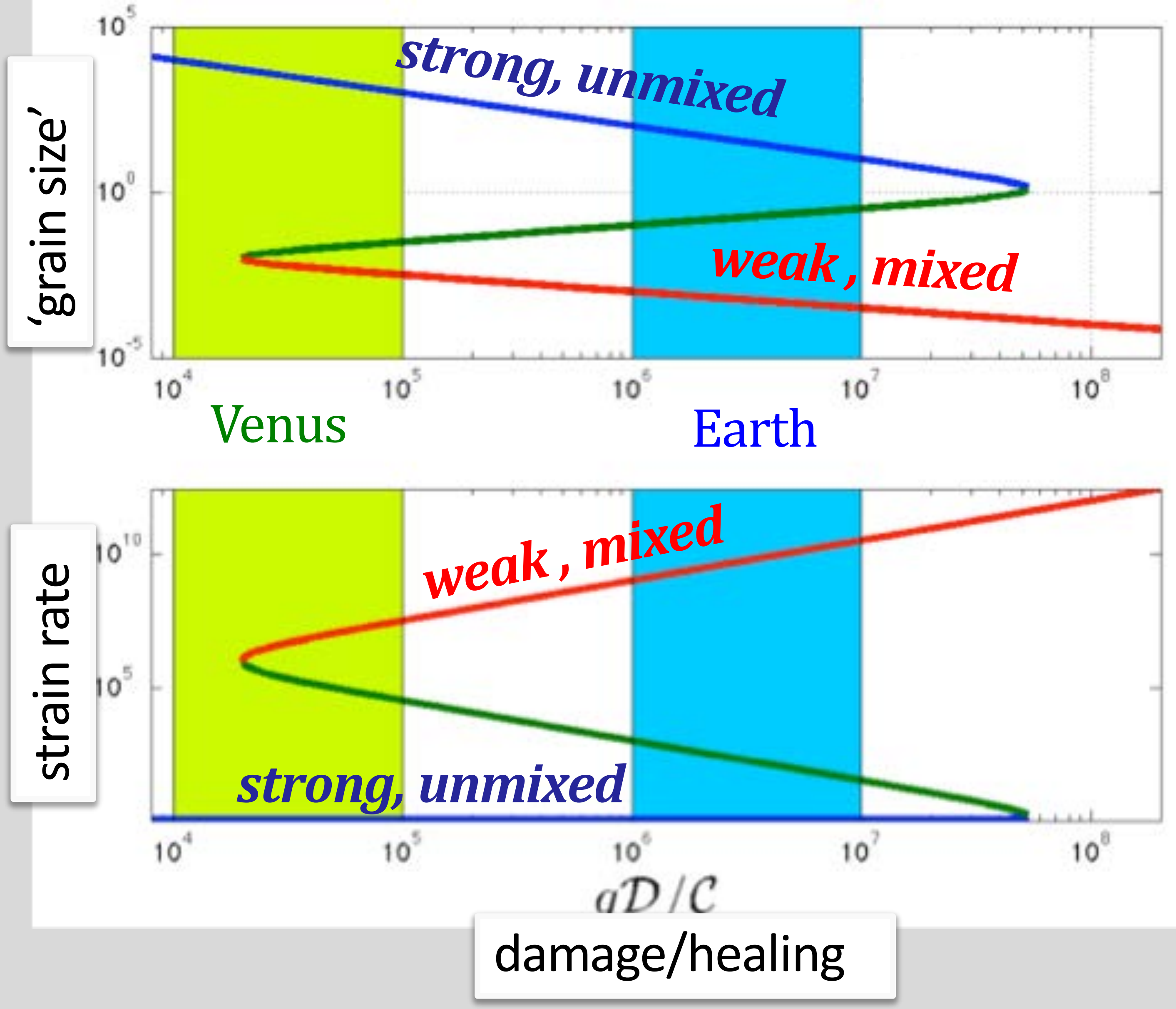
- Three equilibrium branches
  1. Unmixed, large grain, strong "creeping" branch
  2. Mixed, small grain, weak "mylonite" branch
  3. Intermediate grain unstable branch

Bercovici & Ricard (2016)

Planetary states

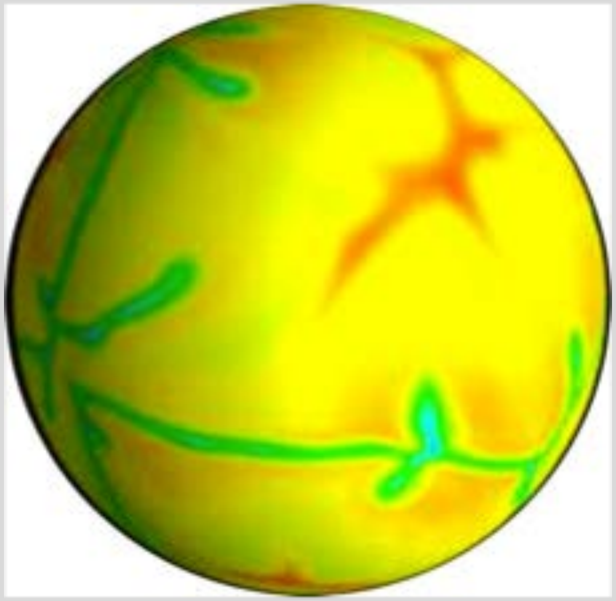
Grain-damage hysteresis

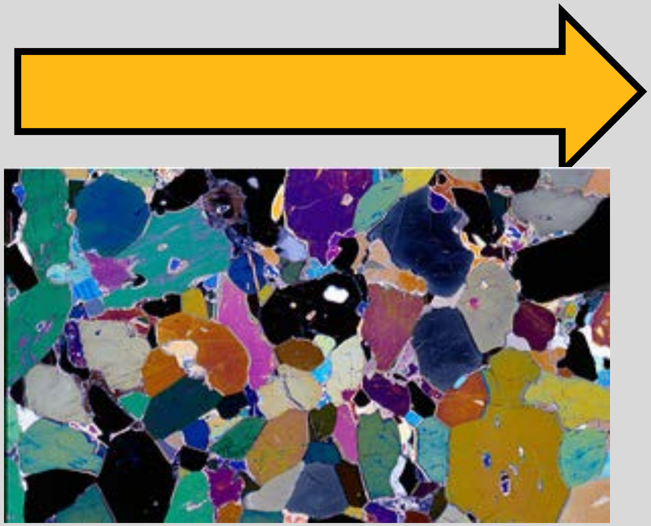
- implies a plate-tectonic state allows for co-existence of strong and very weak states
- representing plates and plate boundaries



- Co-existence largely depends on damage:healing $q\mathcal{D}/C$
- Earth has large $q\mathcal{D}/C$ and Venus much smaller

Summary





- Grain-damage mechanism, built from basic physics, consistent with lab and field observations, allows generation of plate tectonics with Earth conditions
- Emergence of global plate tectonics takes 1Gyr as damage zones accumulate and are inherited to yield fully formed plates driven by subduction only
  - On, Venus damaged weak zones heal and don't accumulate
- Grain-damage, mixing and (effective) hysteresis implies two deformation states: plates and plate boundaries