What rheology for plate tectonics ?

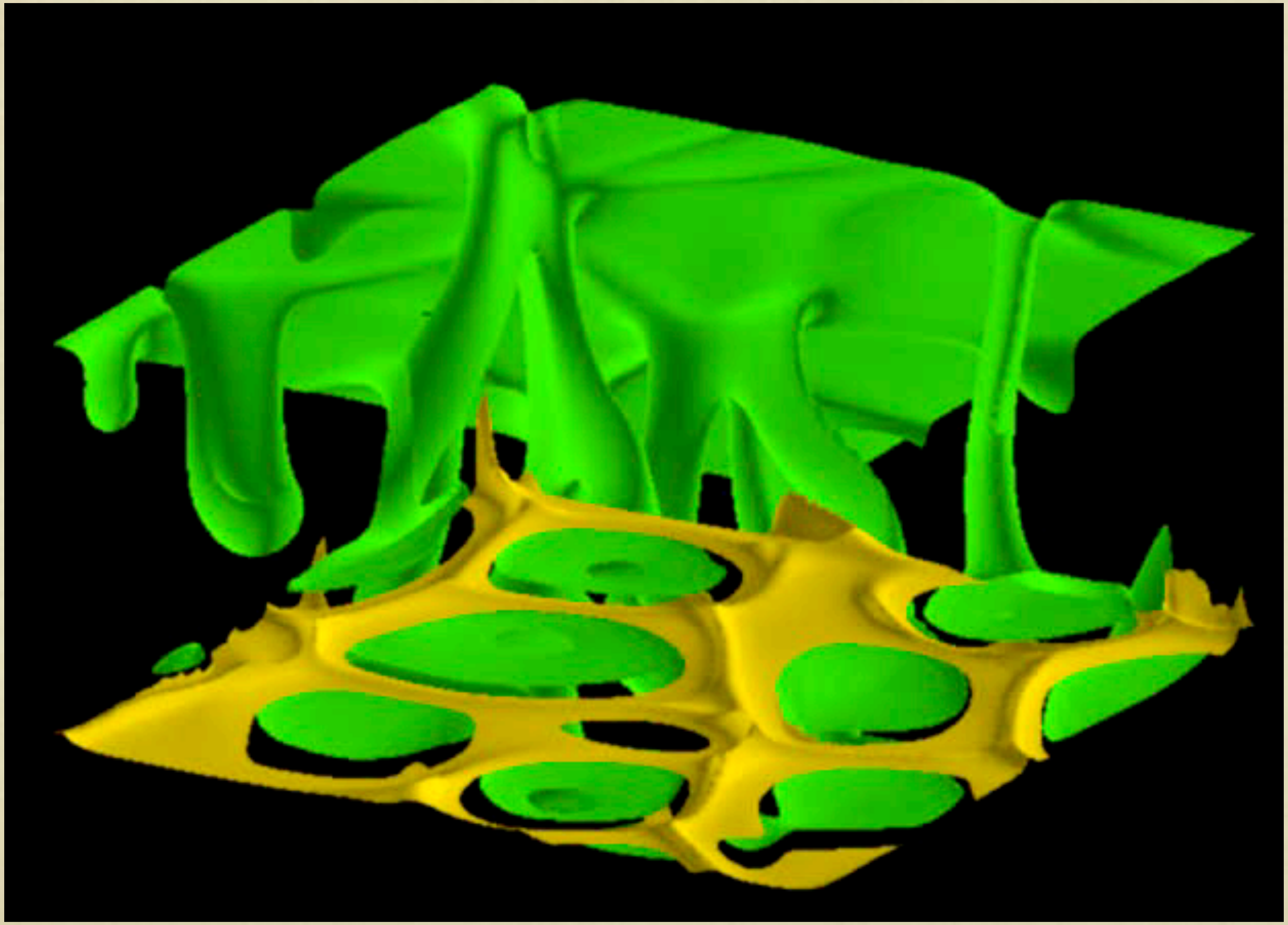
Yanick Ricard

Laboratoire de Géologie de Lyon
Terre Planètes Environnement

Université Claude Bernard Lyon 1

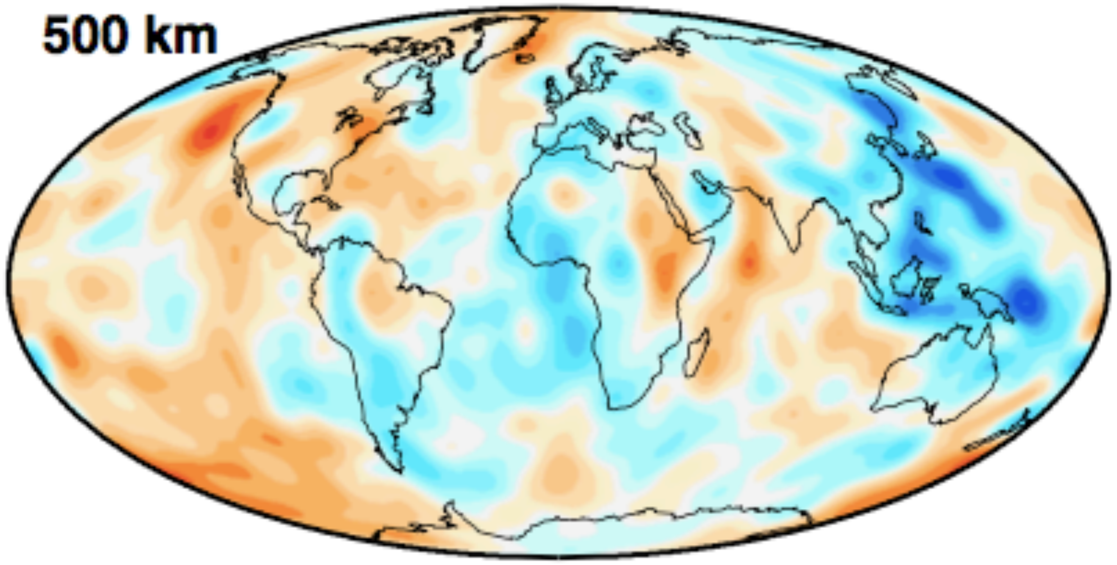
ENS DE LYON

What convection heated from within looks like

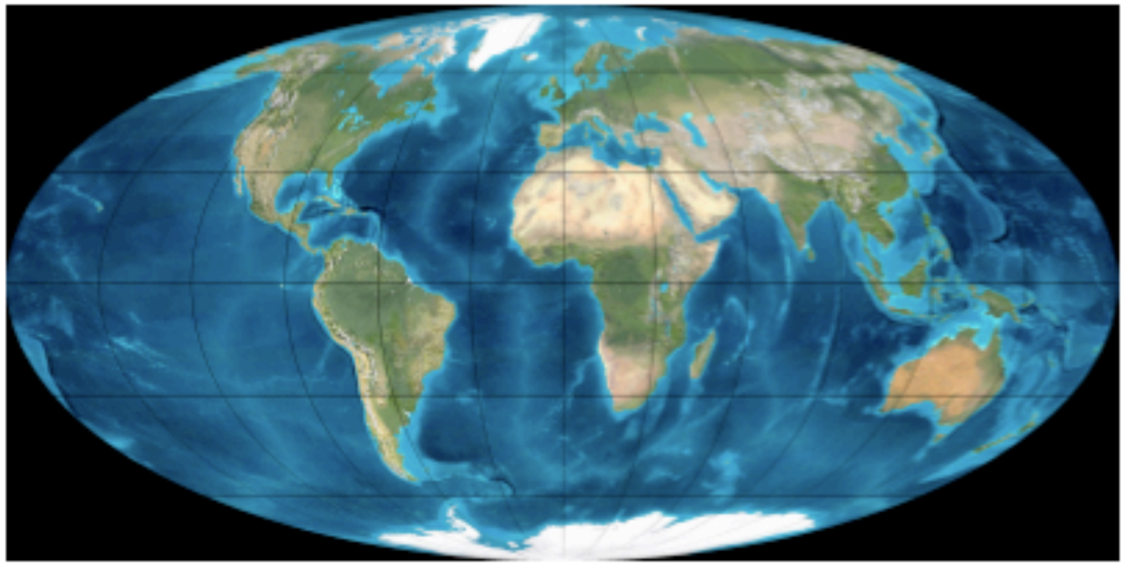


Sotin and Labrosse 1999

500 km

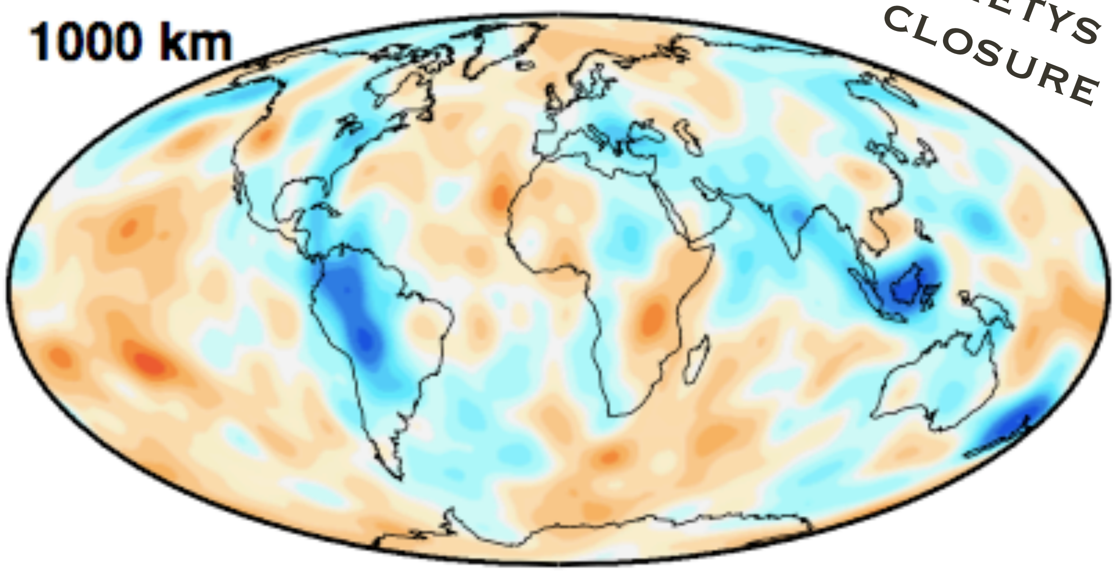


Present

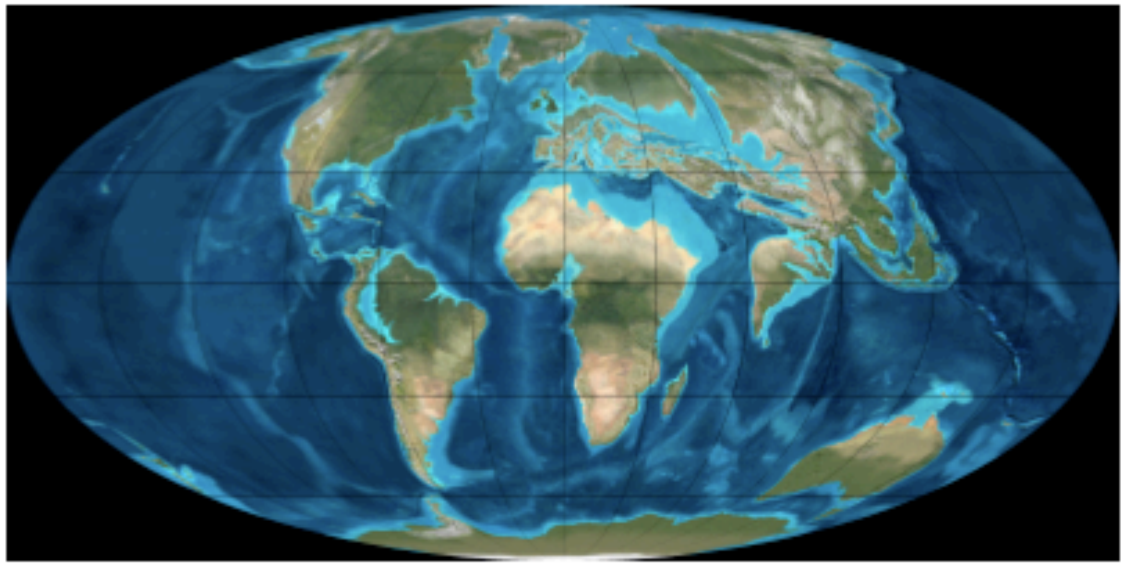


Thetys closure

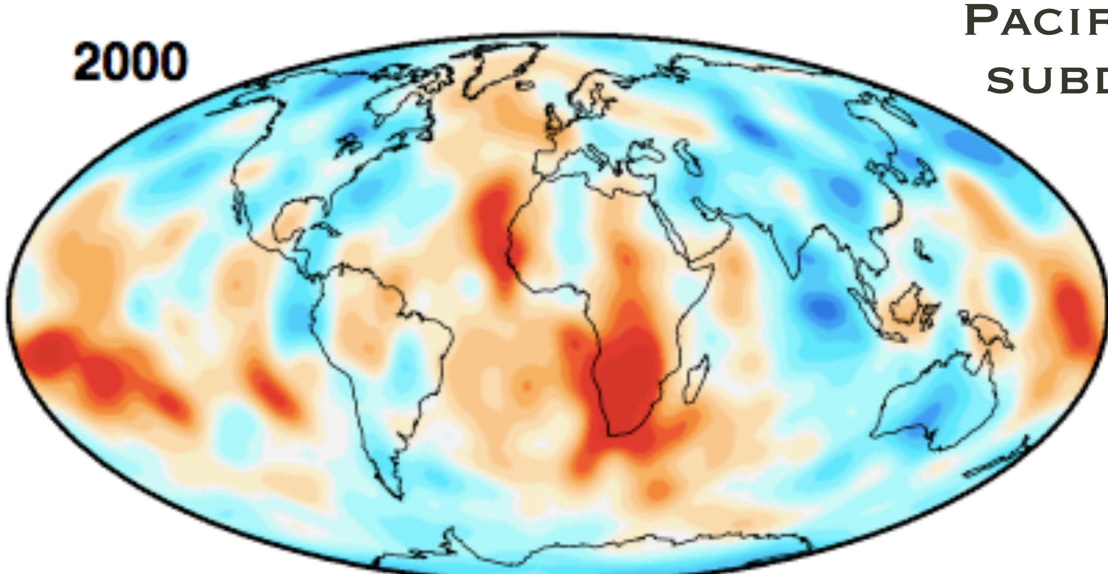
1000 km



Eocene 50 Ma

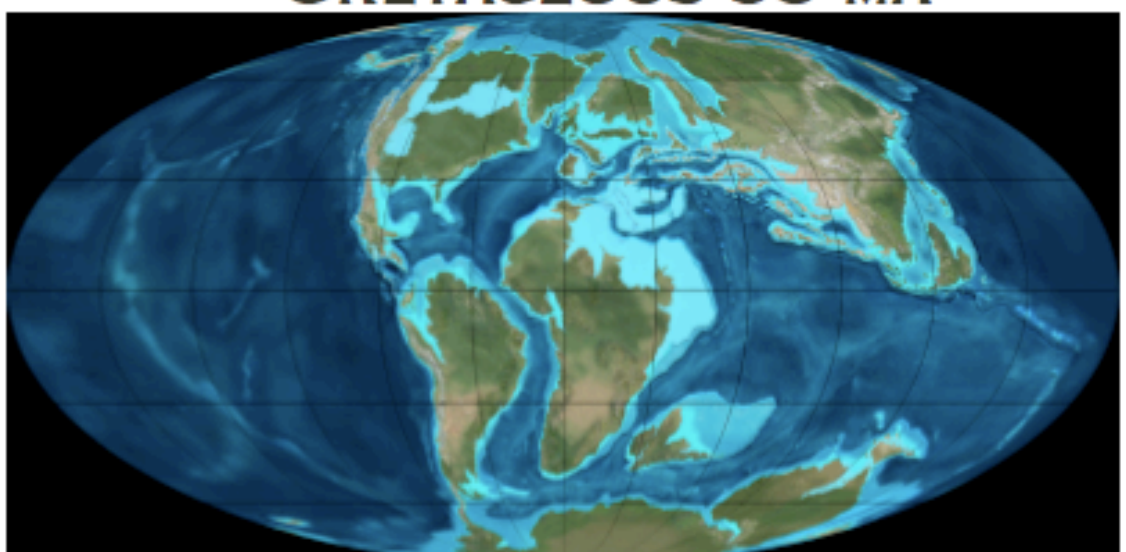


2000



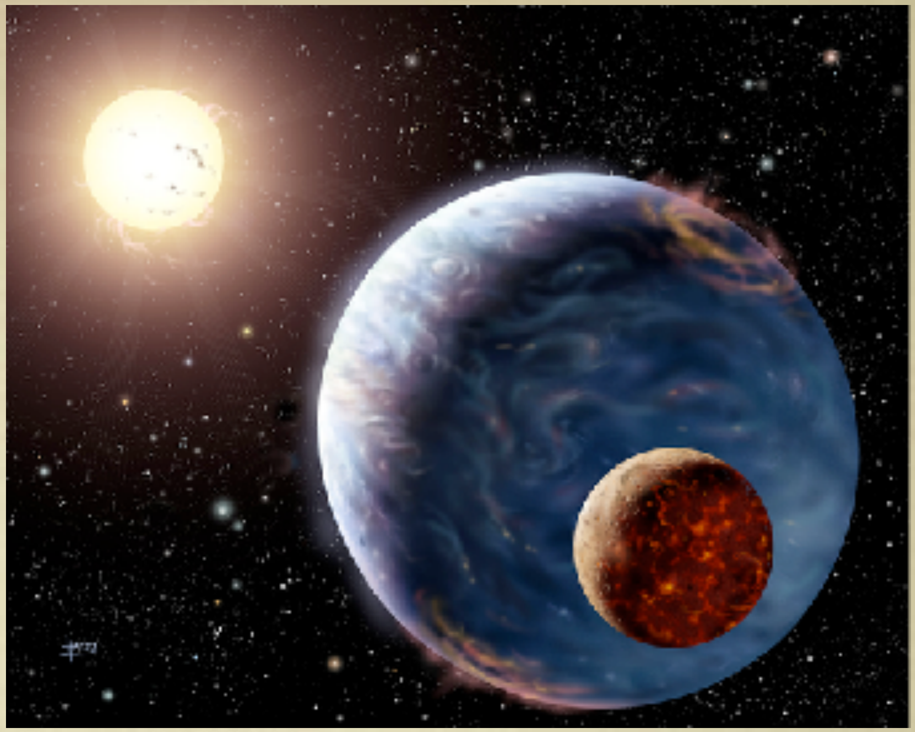
Pacific subd.

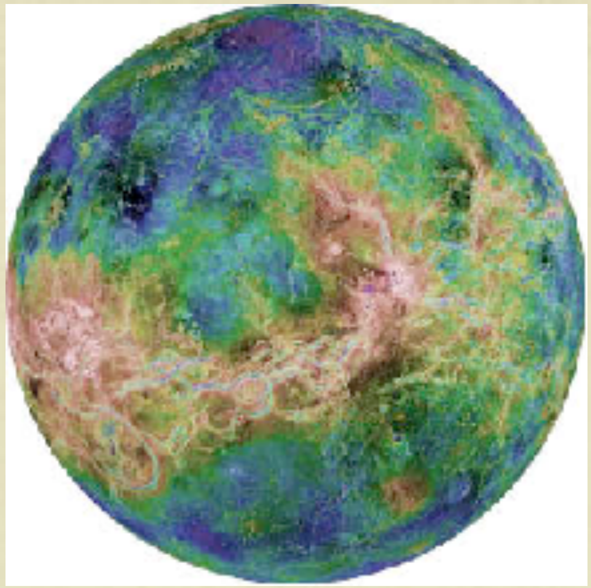
Cretaceous 95 Ma



Blakey 2011

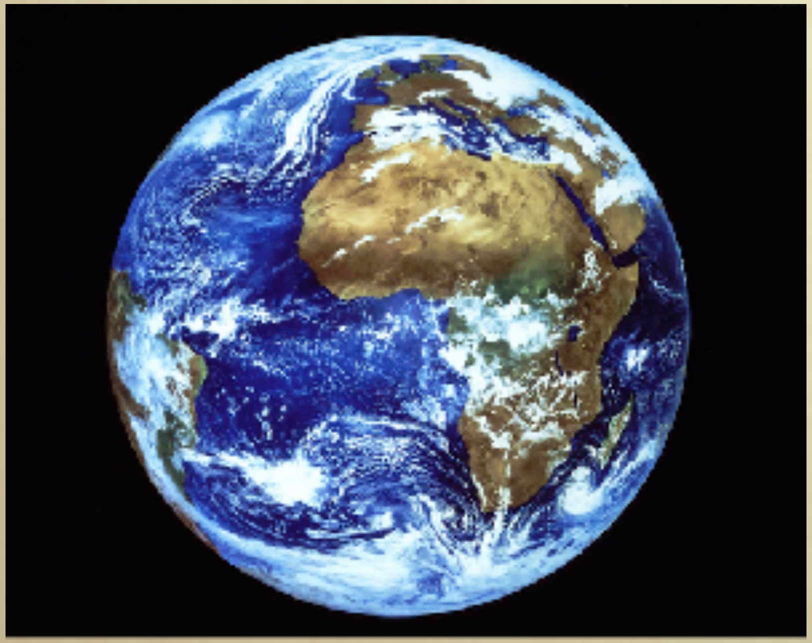
Do we have plate tectonics on other planets



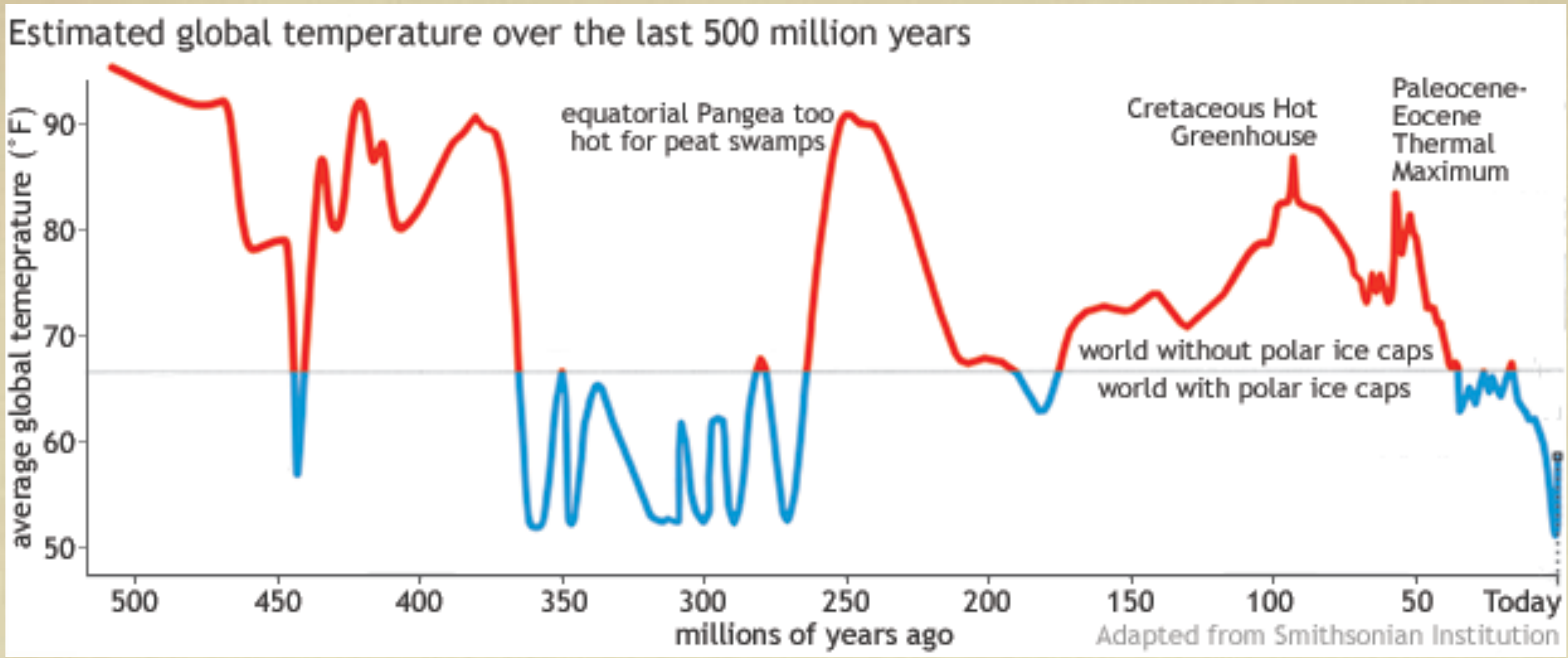


Venus

Sister Planets

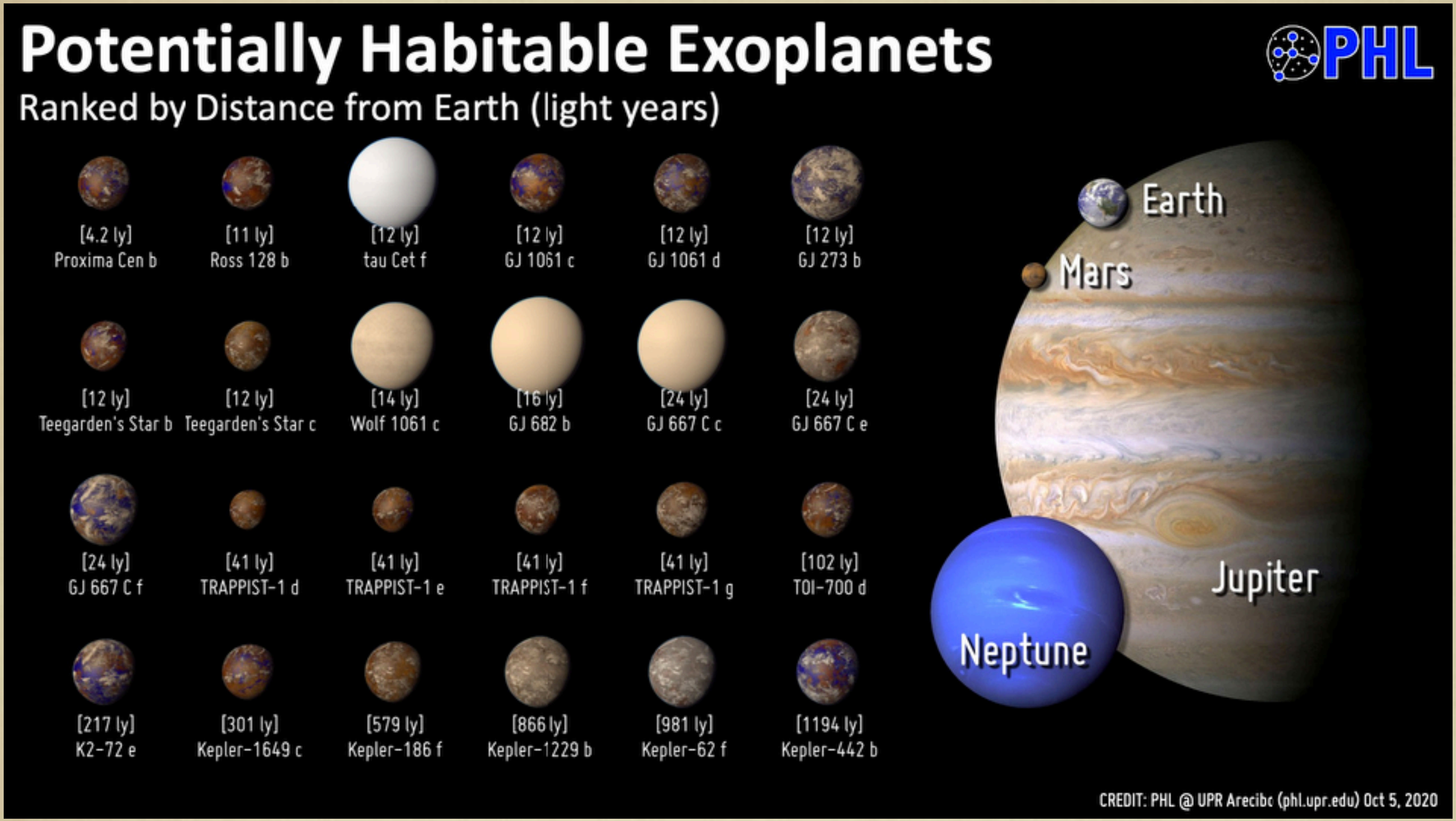


Earth



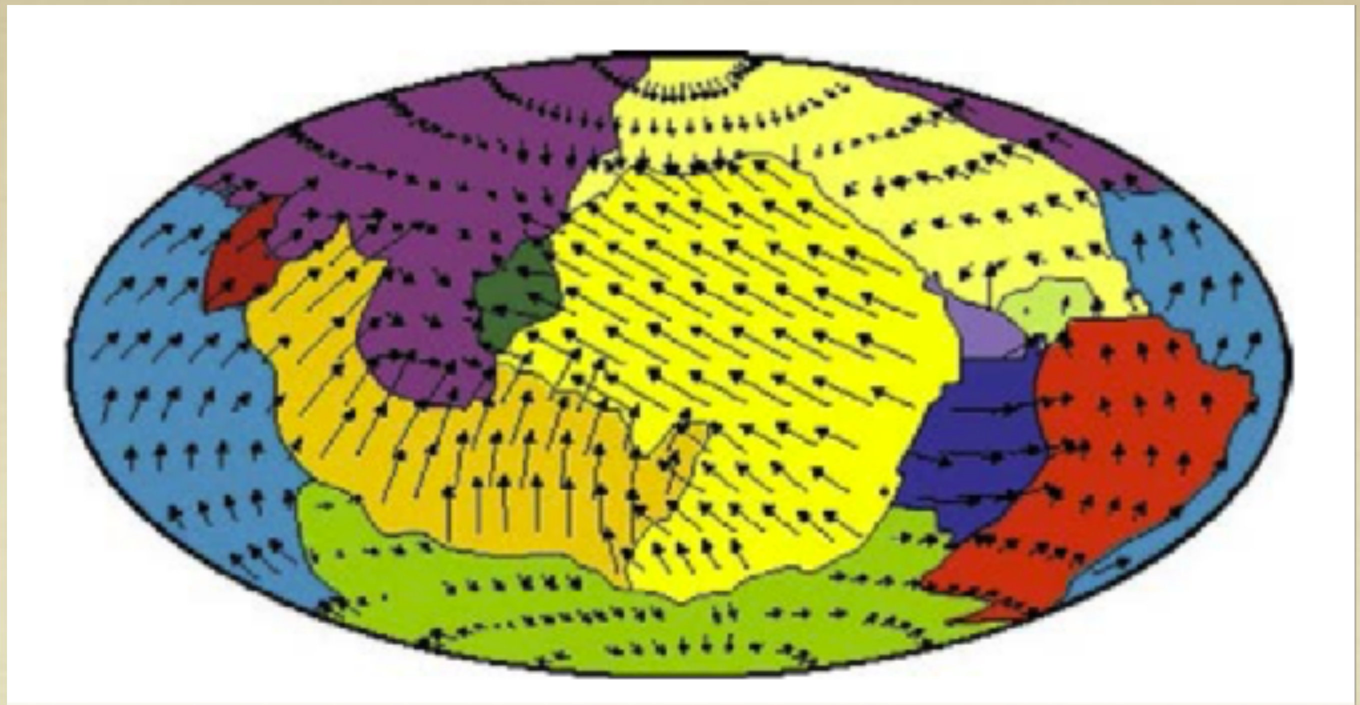
A chaotic behavior ?
A stable situation ?

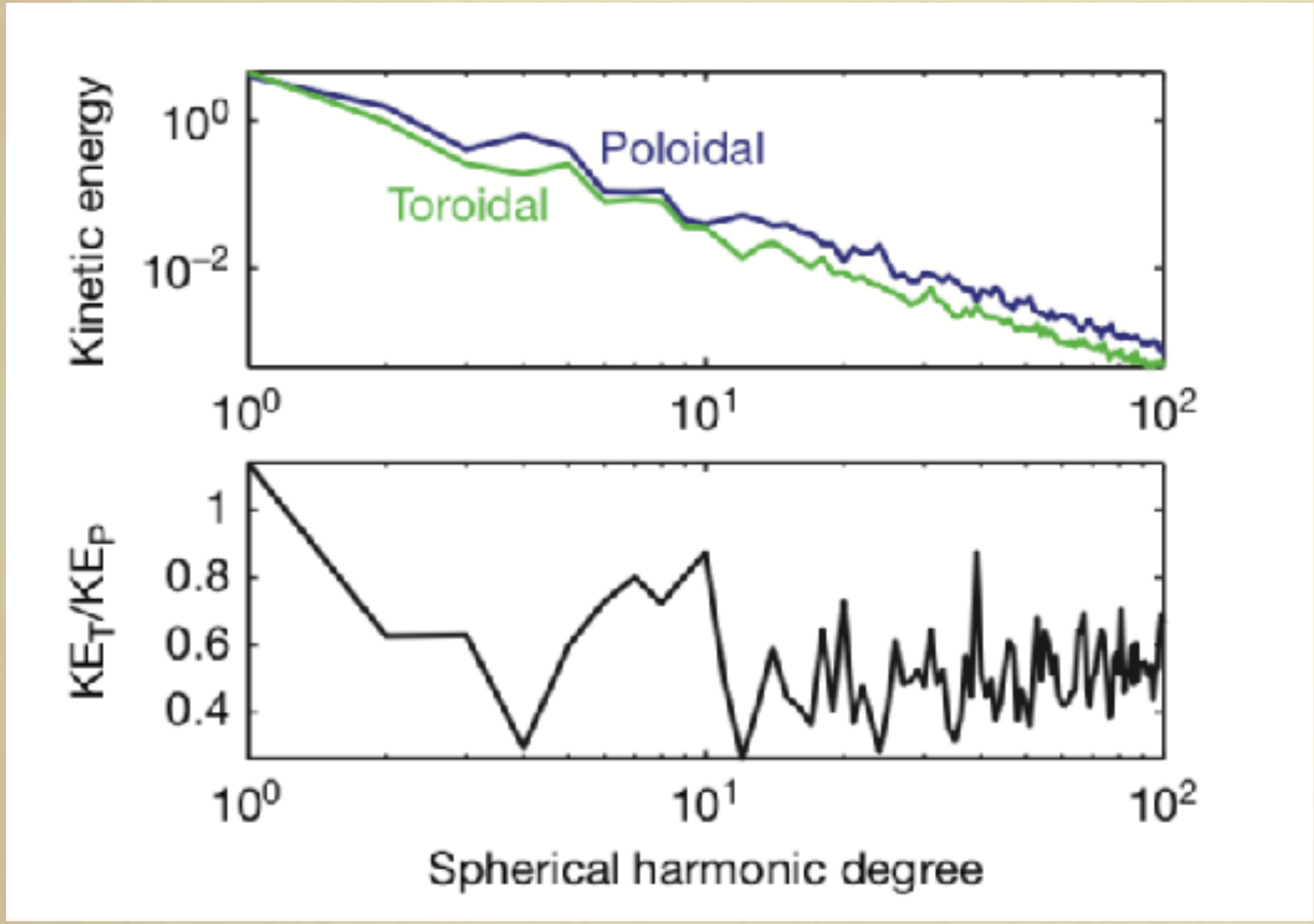
late tectonics is presumed to be a necessary condition for a temperate climate, by the carbon buffer and negative feedbacks associated with resurfacing and mineral exposure, erosion, weathering, and volcanism

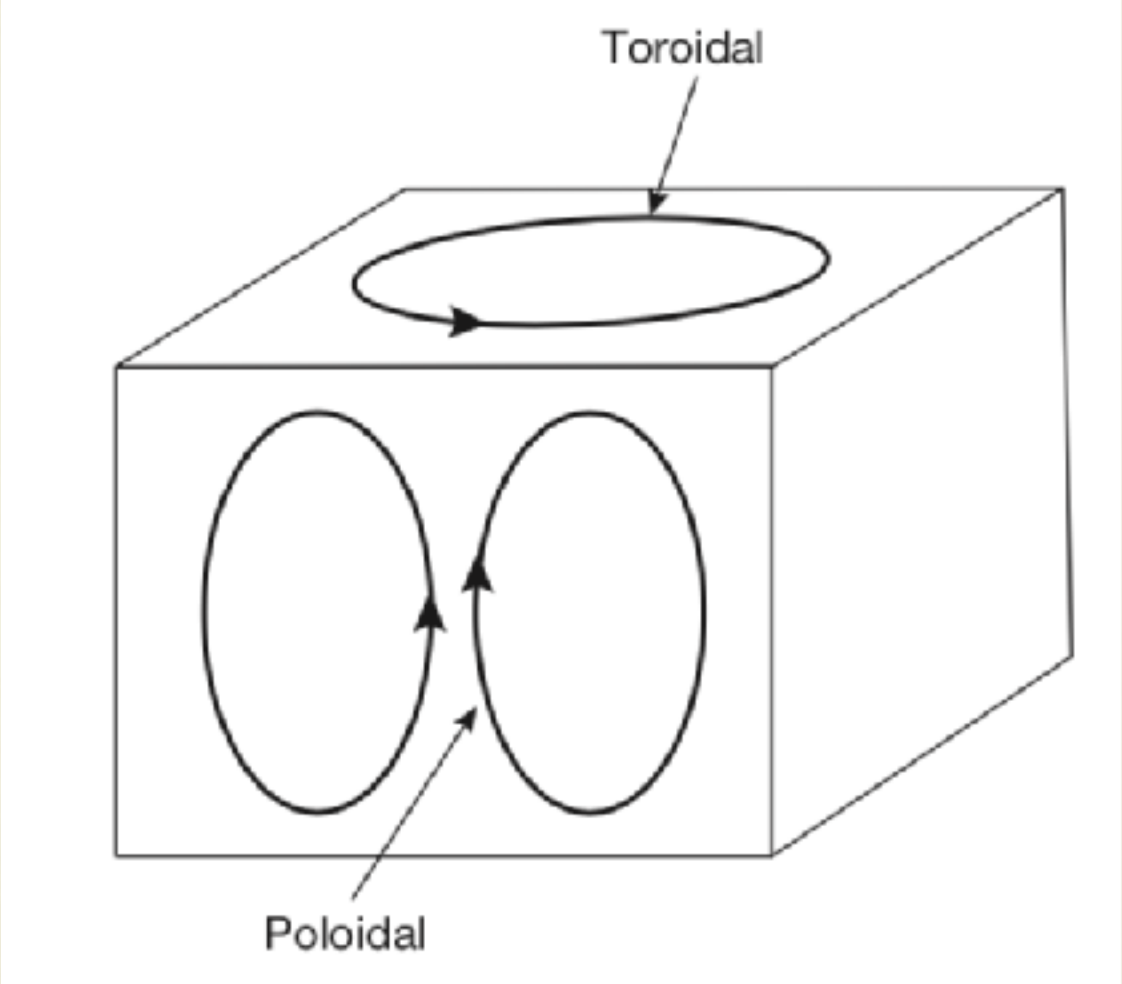


This is a list of the exoplanets that are more likely to have a rocky composition and maintain surface liquid water (*i.e.* 0.5 < Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth masses).

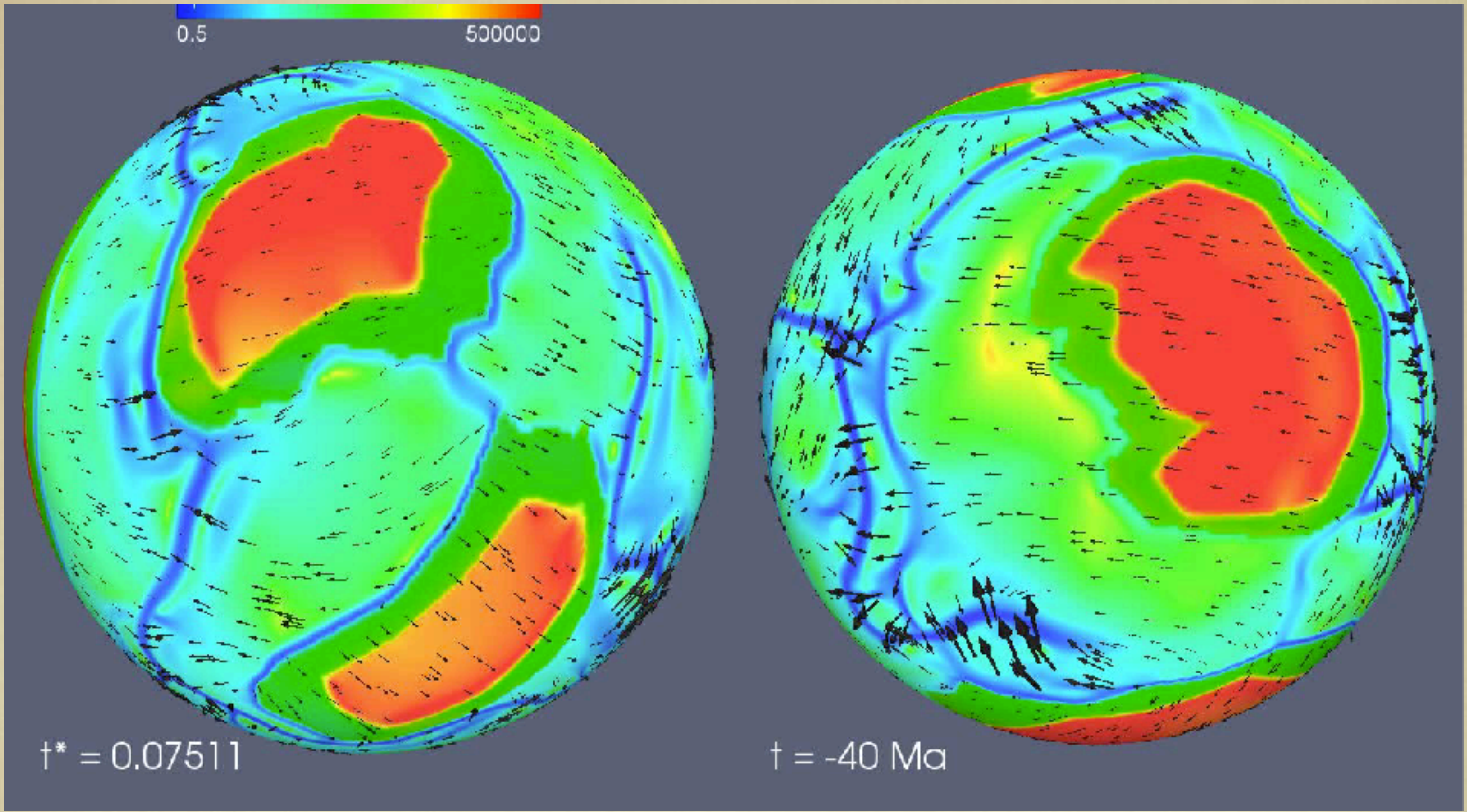
SOLEIL : 1.6×10^{-5} AL




Kinetic energy
Poloidal
Toroidal
KE_T/KE_P
Spherical harmonic degree


Toroidal
Poloidal

Coltice, Rolf et al. 2012

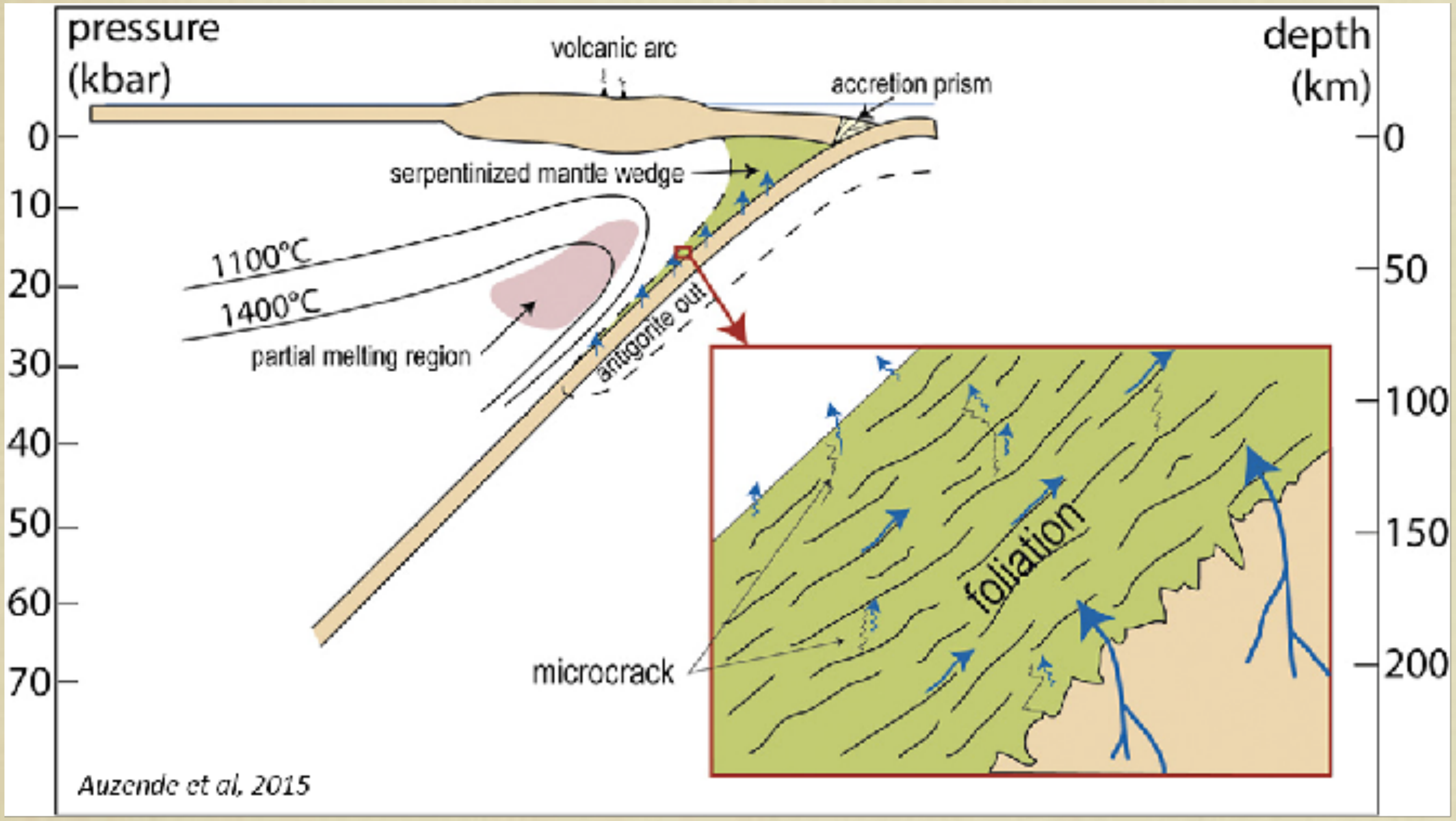


Geophysicists are able to generate plates in numerical models.

Tackley; 1998, 2000; Stein et al., 2004...

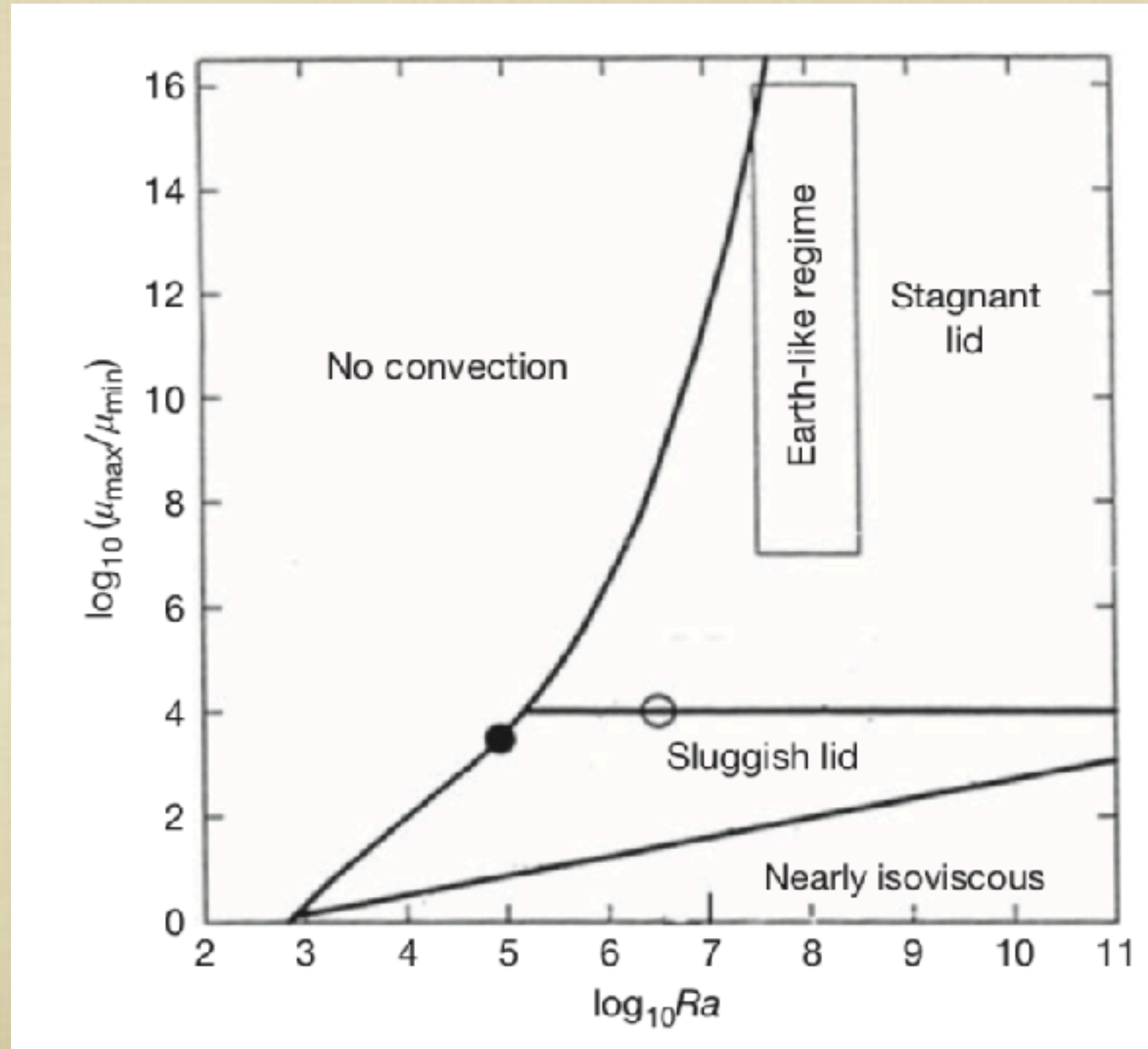
Why do we have plates ?

Because of the special properties of rocks...



...that exist because of plate tectonics

Because of temperature properties of the the rheology ?

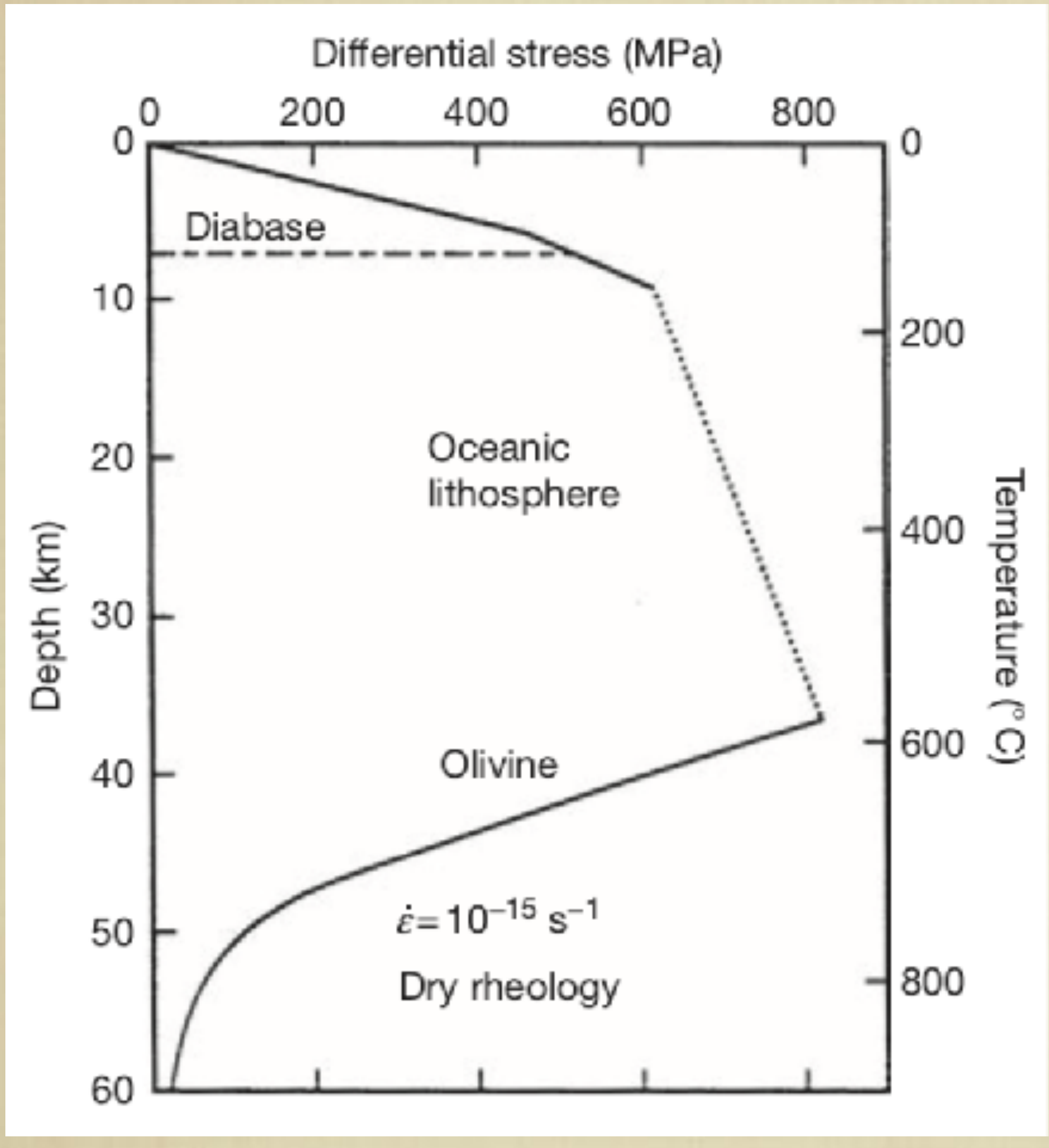


$\eta(T)$

What amplitude of viscosity variations are needed to explain plate boundaries ?

At least 3 orders of magnitude in viscosity variations are needed to localise plate deformation

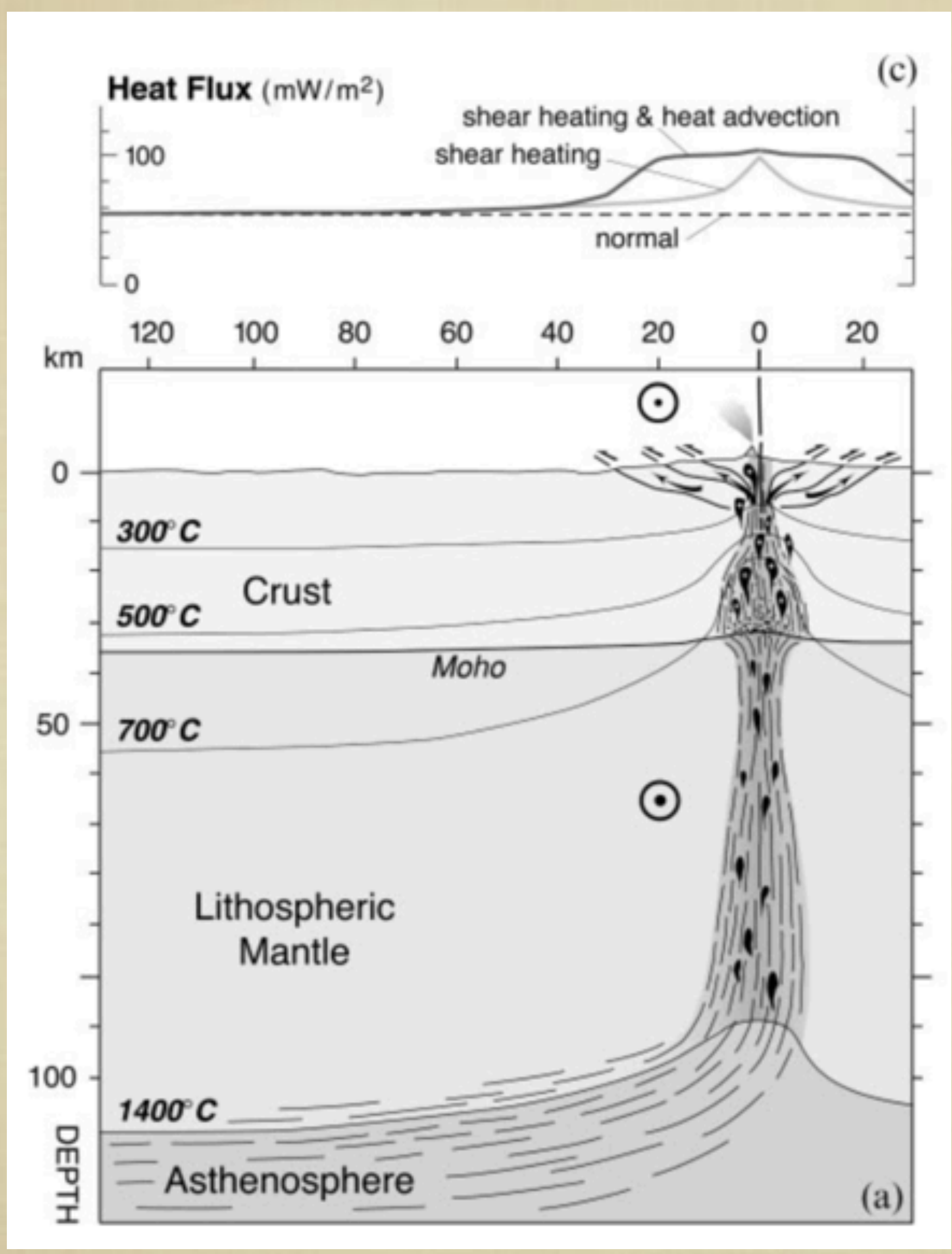
The lithosphere controls plate tectonics



Possible effects leading to localisation

- Temperature
- Surface temperature
- Non linear rheology
- Composition
- Water
- Anisotropy
- Grain-size

Localisation by shear dissipation



Old idea

heat production
due to dissipation

$$\psi = \underline{\tau} : \underline{\dot{\epsilon}}$$

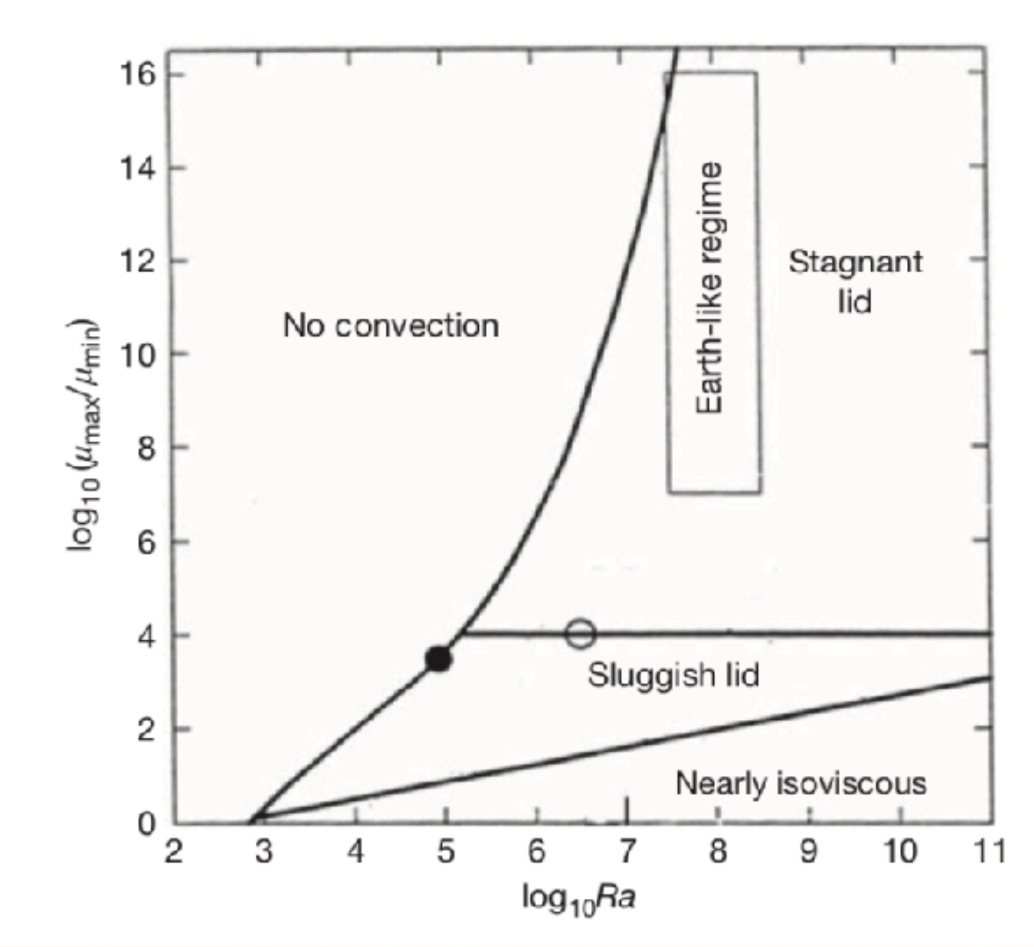
increases T and localises
because

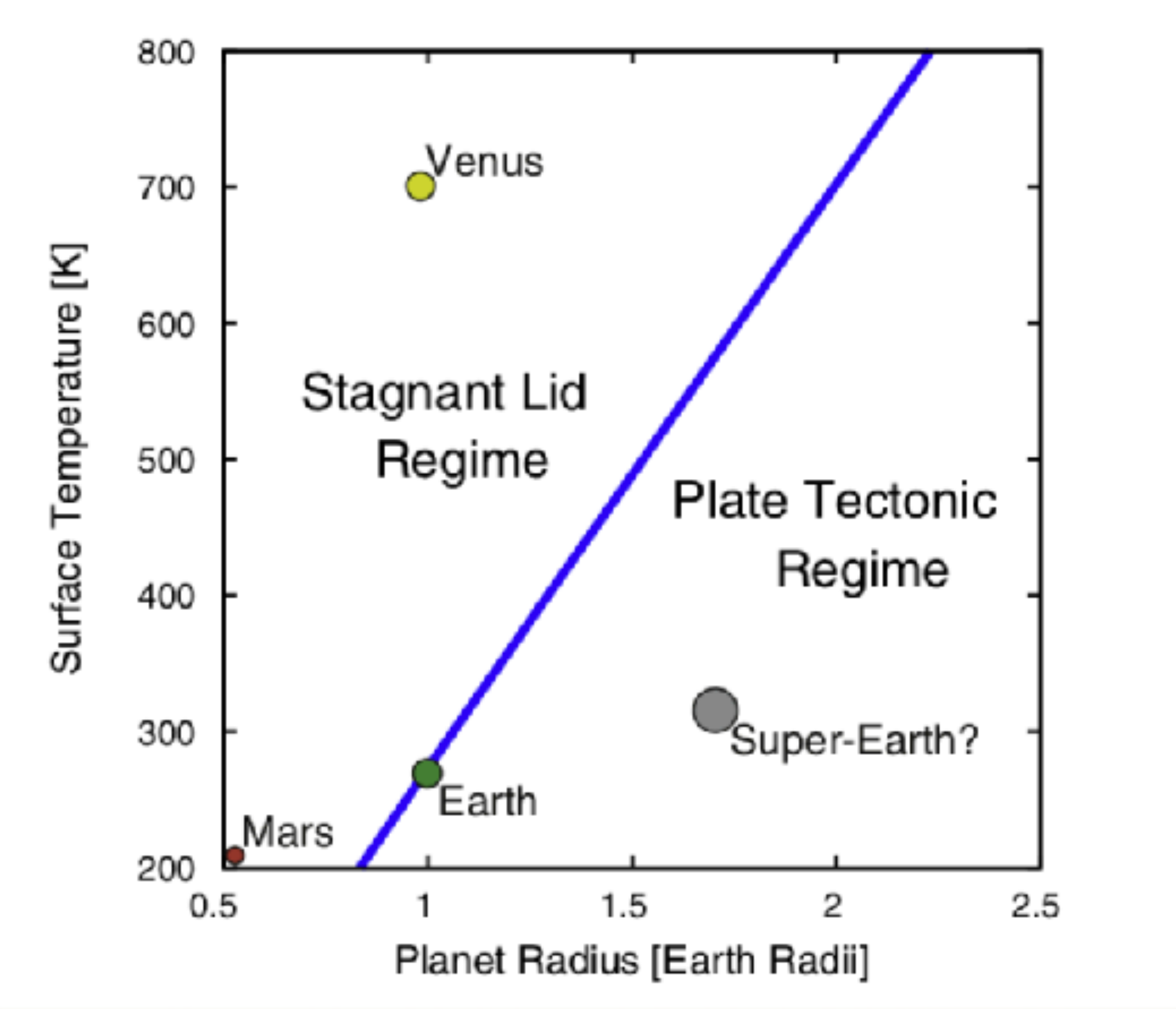
$$\eta(T)$$

Unfortunately...

$$\psi = 2\eta\underline{\dot{\epsilon}} : \underline{\dot{\epsilon}}$$

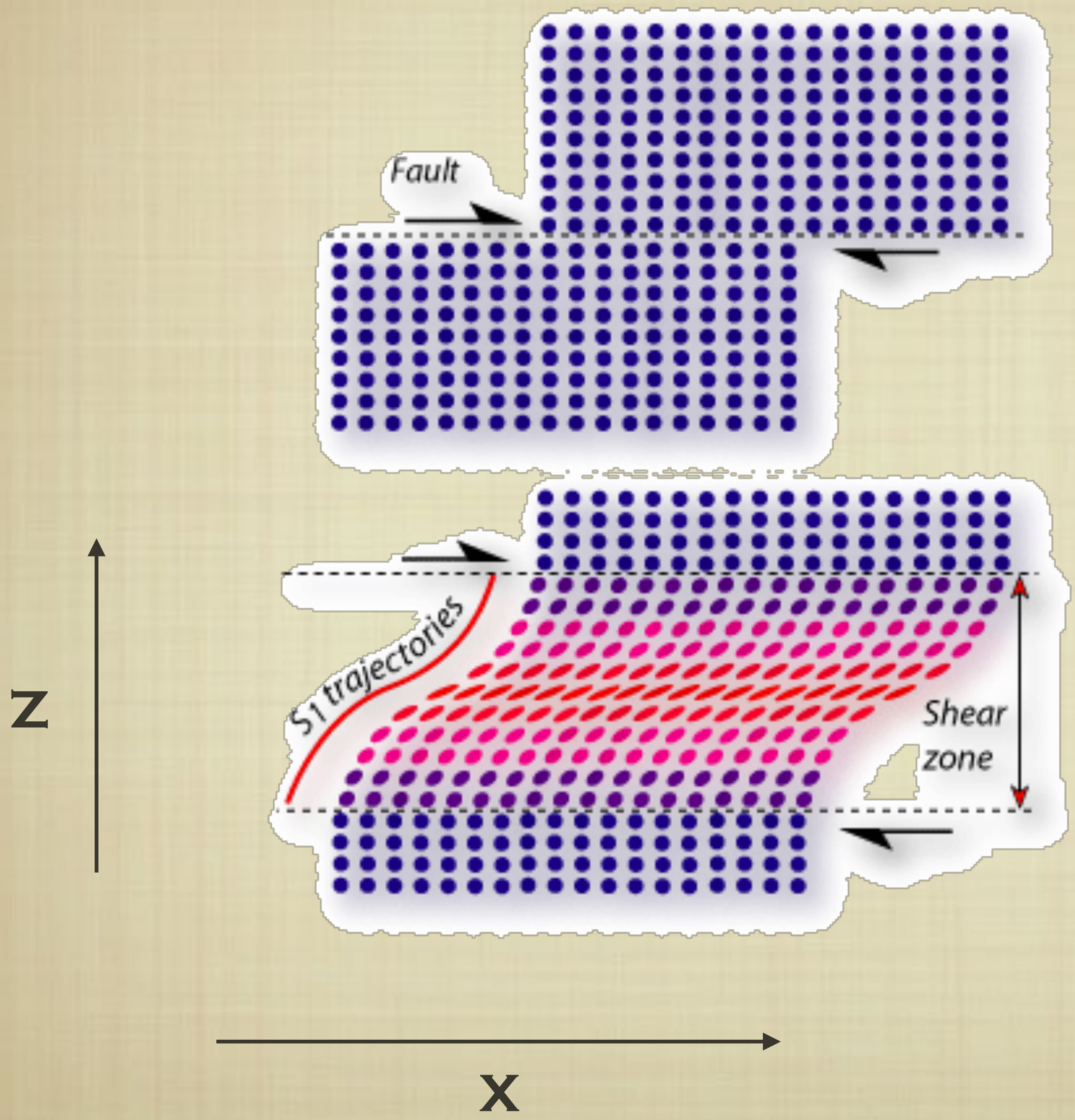
Localisation: controlled by surface temperature





Foley et al.

Localisation controlled by non linear rheology



$$\nabla . \underline{\tau} = 0$$

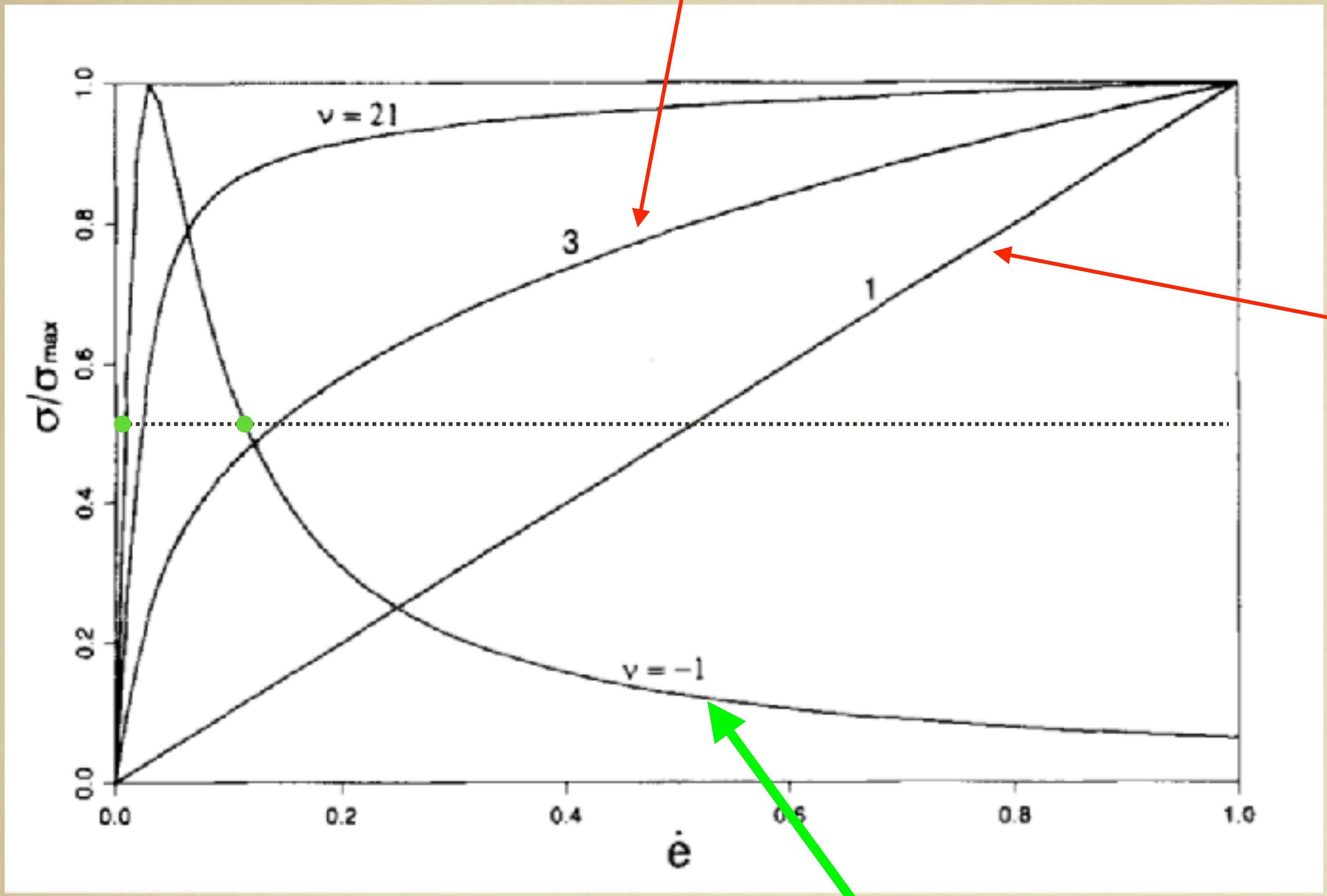
$$\tau_{xz} = Cte$$

$$\text{if} \qquad \dot{\epsilon} = f(\tau)$$

$$\dot{\epsilon}_{xz} = Cte \quad !!!$$

Dislocation

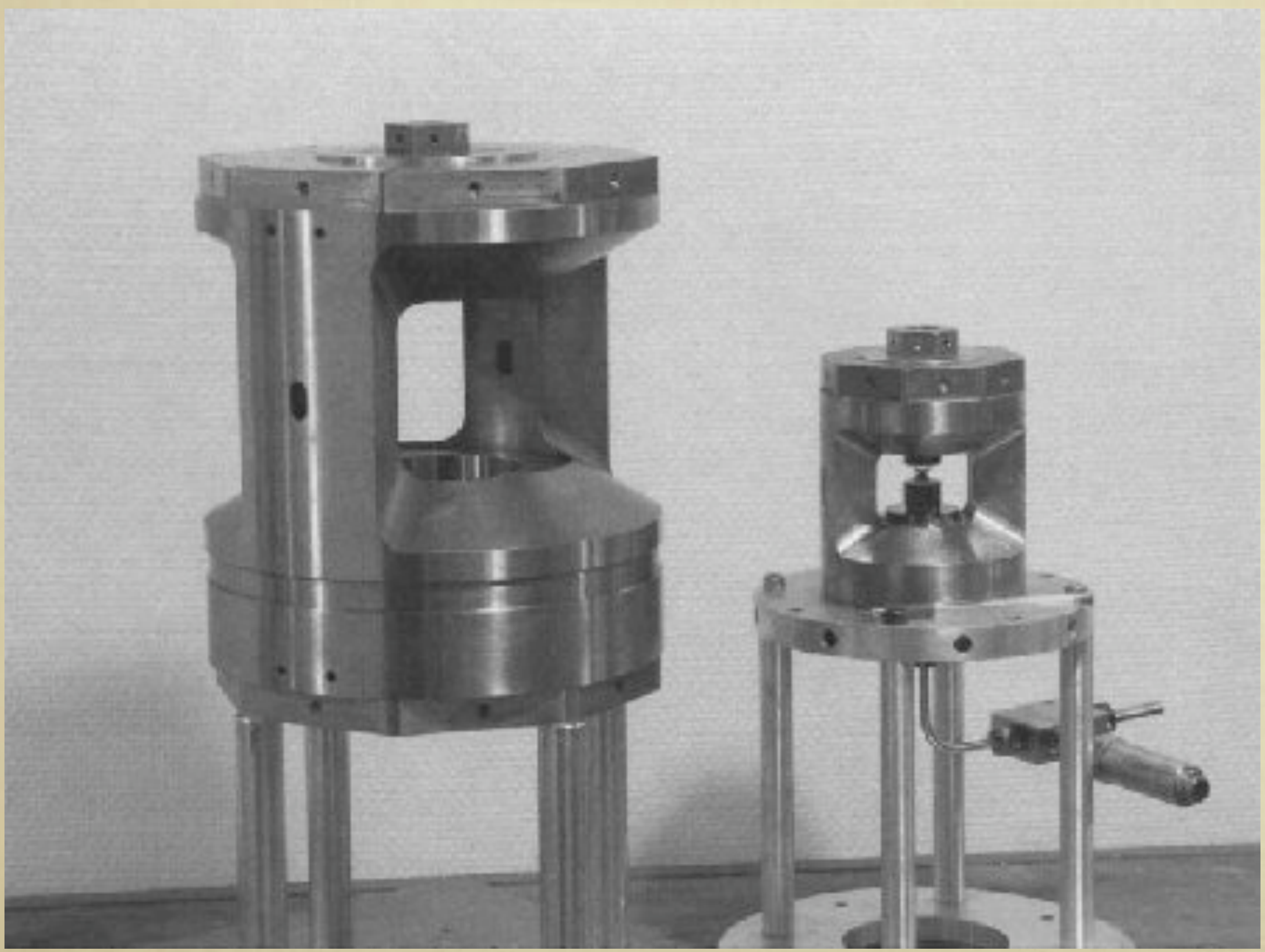
Laboratory observations



Diffusion

What makes plates

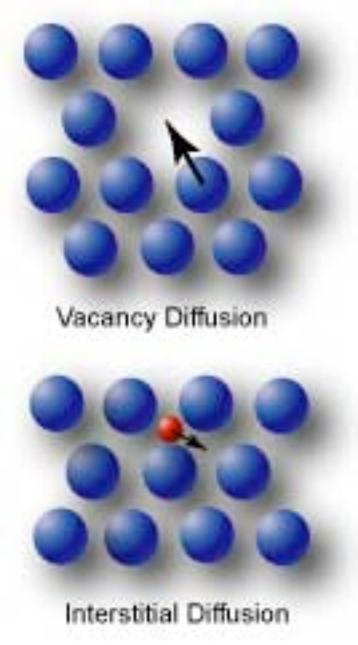
The rheology used in numerical codes and that observed at laboratory scale are incompatible.
What happens on a hotter/colder/wetter/dryer planet?



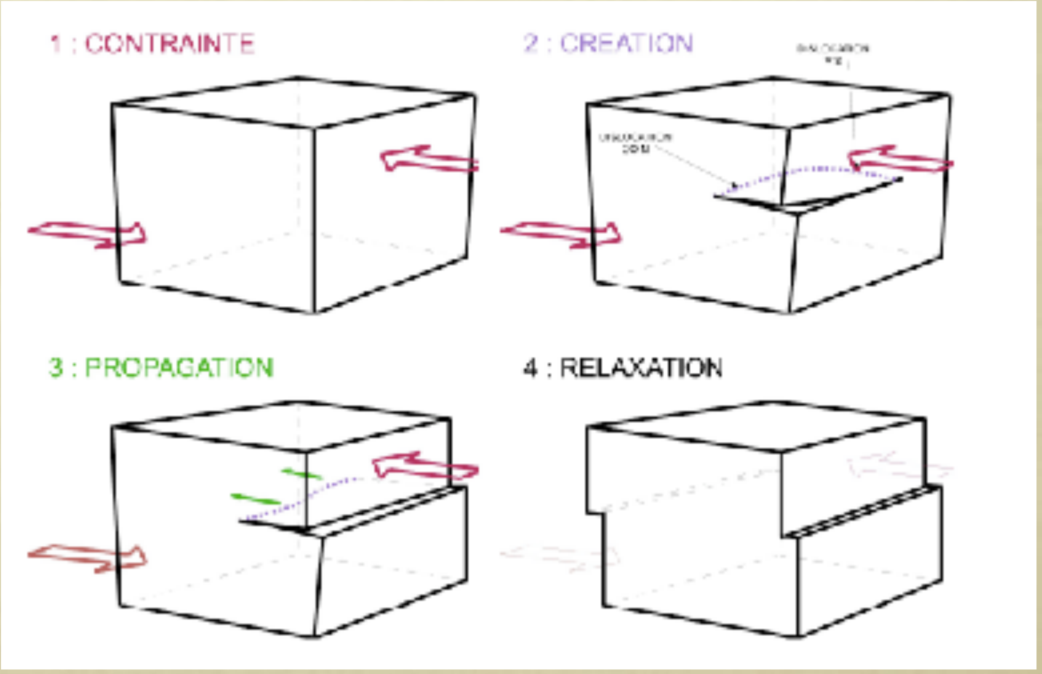
What rheology for the mantle?

Mostly diffusion vs. dislocation

diffusion =
individual motion



dislocation =
collective motion



Dislo. Creep $$\underline{\dot{\epsilon}} = B I_\sigma^{n-1} \underline{\sigma}$$

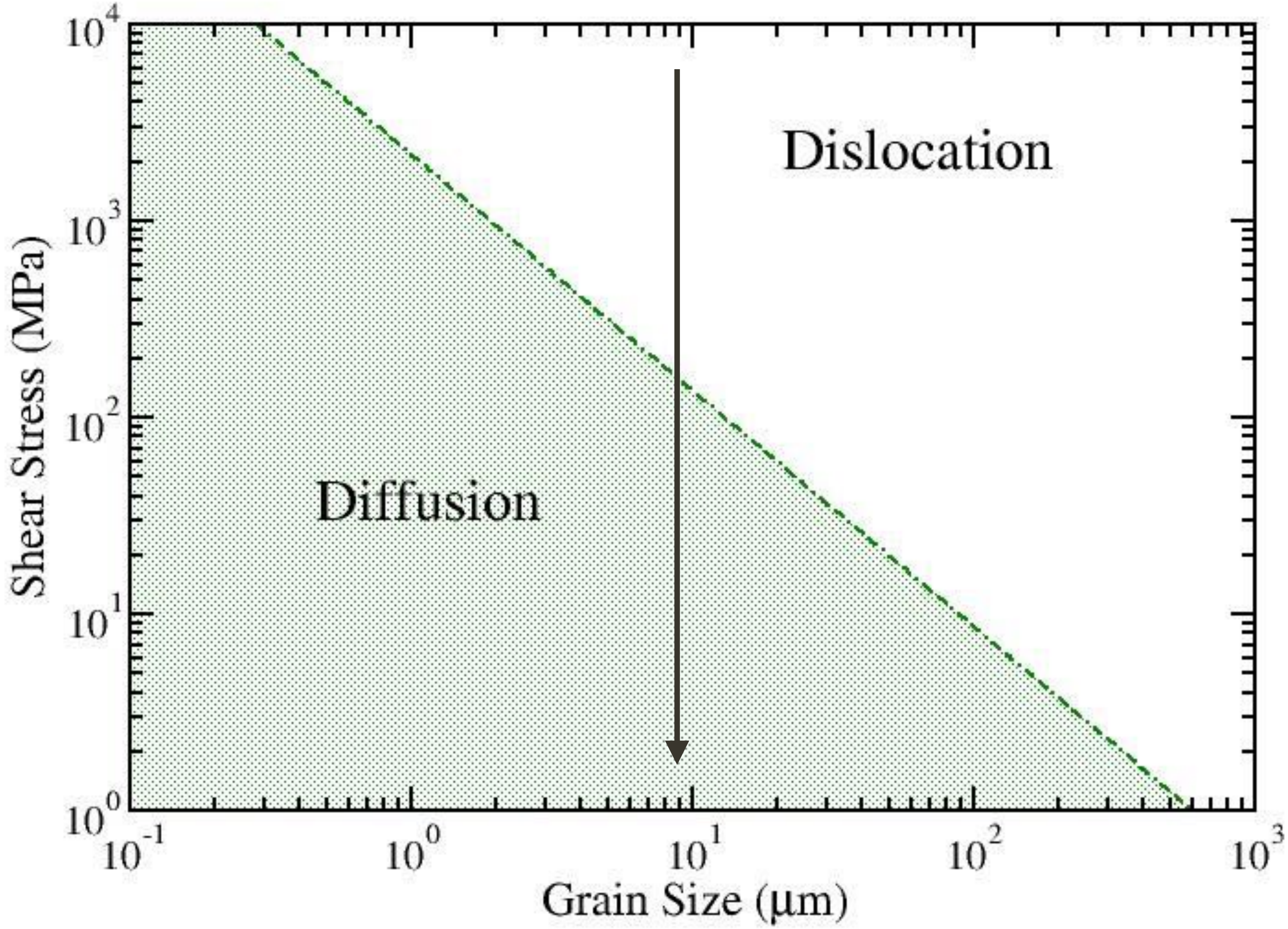
Diff. Creep $$\underline{\dot{\epsilon}} = A R^{-m} \underline{\sigma}$$

Mixt. Creep $$\underline{\dot{\epsilon}} = (A R^{-m} + B I_\sigma^{n-1}) \underline{\sigma}$$

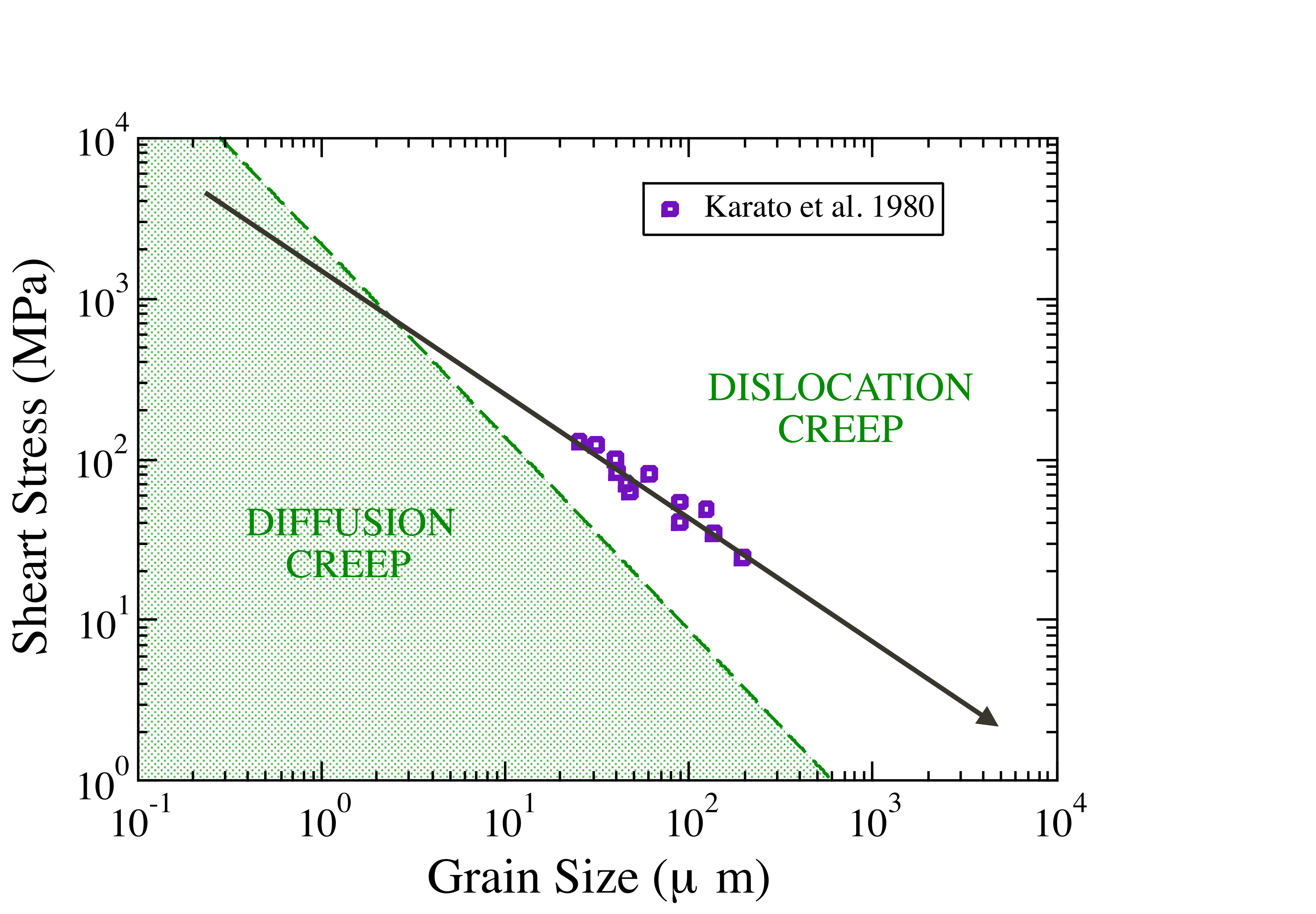
GBS. Creep $$\underline{\dot{\epsilon}} = C R^{-m} I_\sigma^{n-1} \underline{\sigma}$$

Without knowing the average grain size, we do not know much…

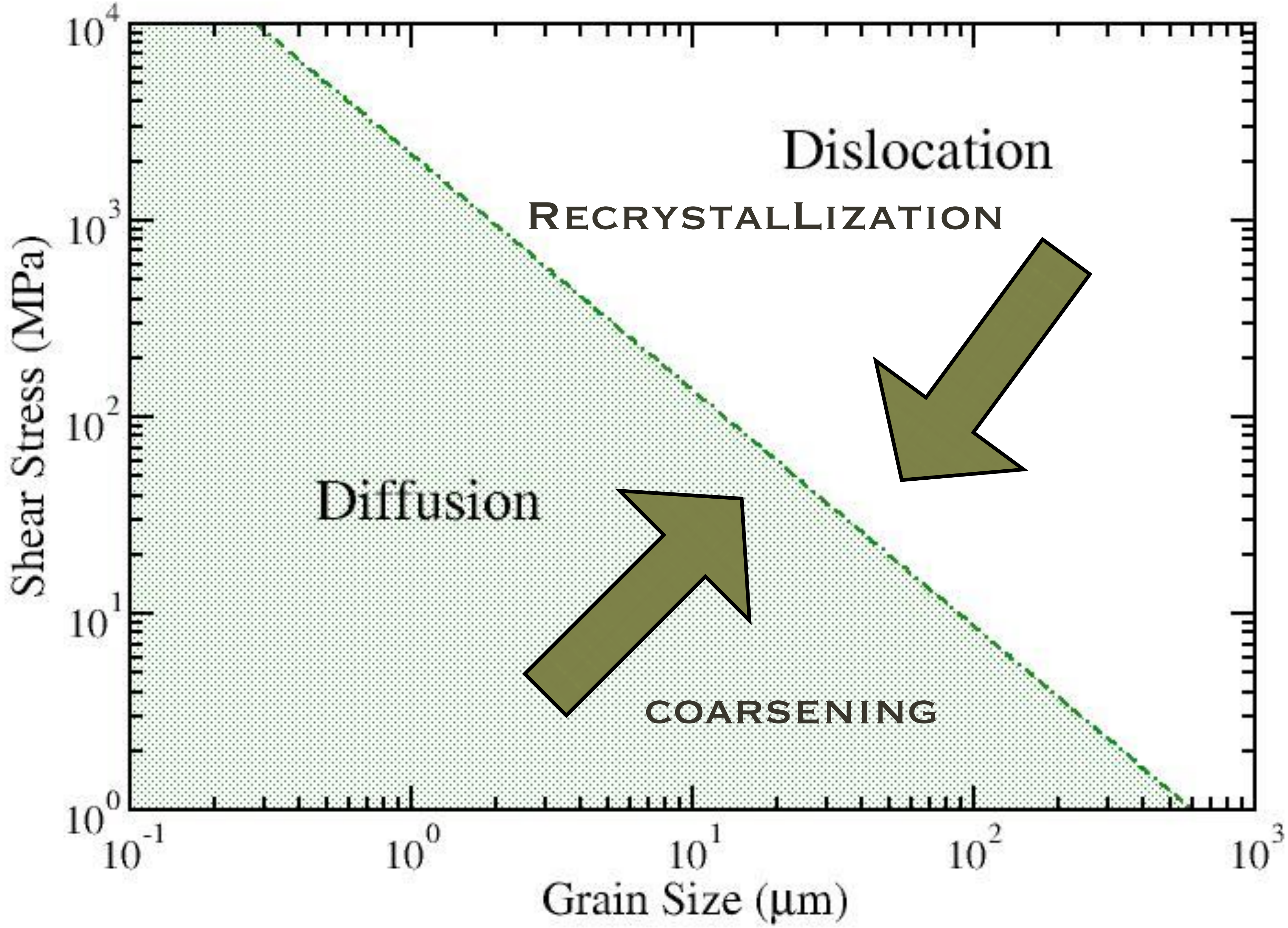
For a fixed grainsize, none of these expressions leads to plate tectonics…



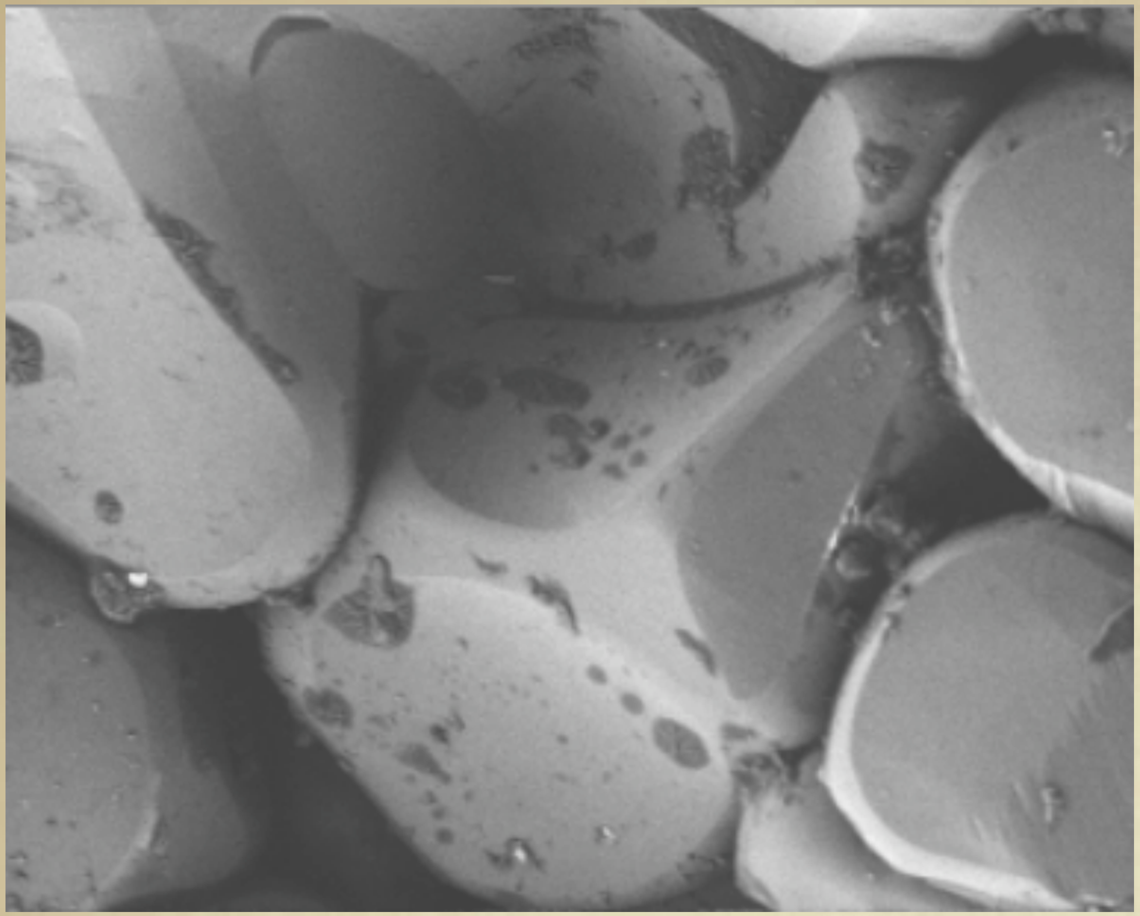
Dislocation
Diffusion
Shear Stress (MPa)
Grain Size (μm)
10^4
10^3
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3



Grainsize = piezometer



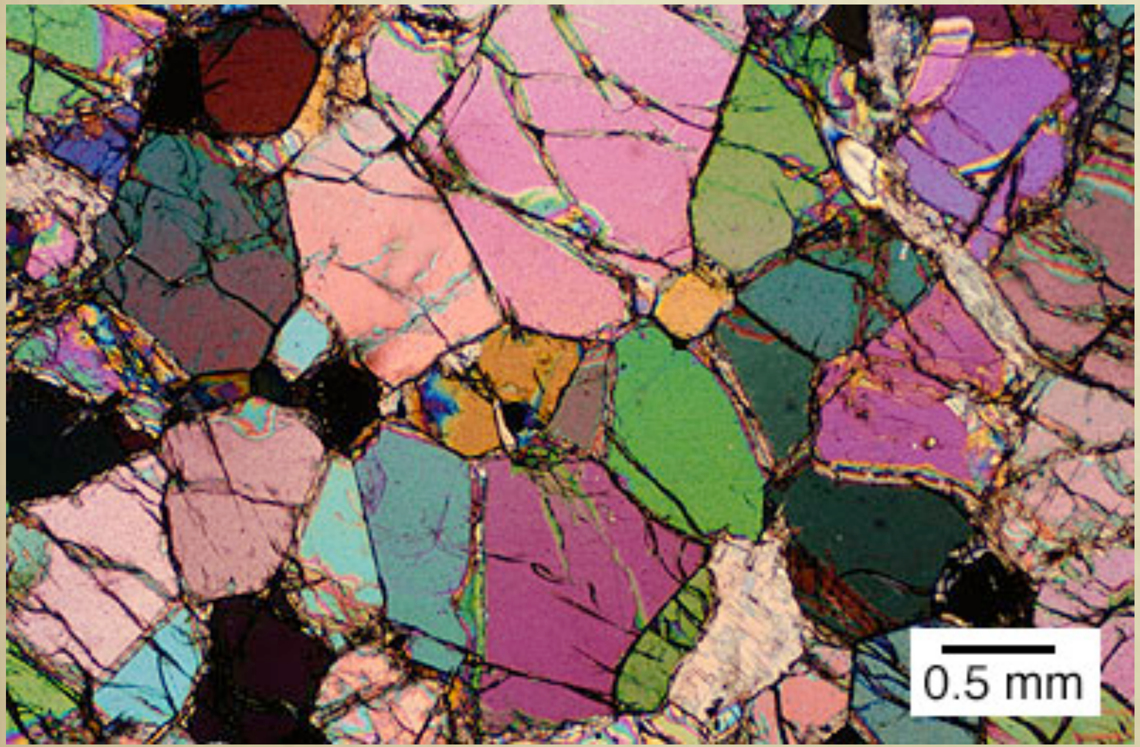
Dislocation
RecrystalLization
Diffusion
coarsening
Shear Stress (MPa)
Grain Size (μm)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3



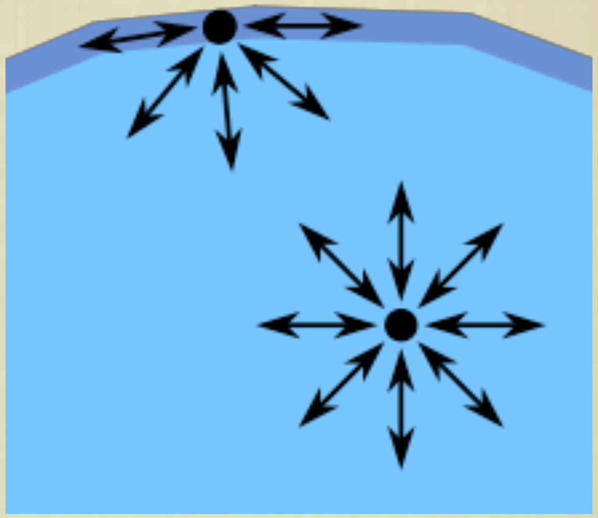
A very weird fluid!

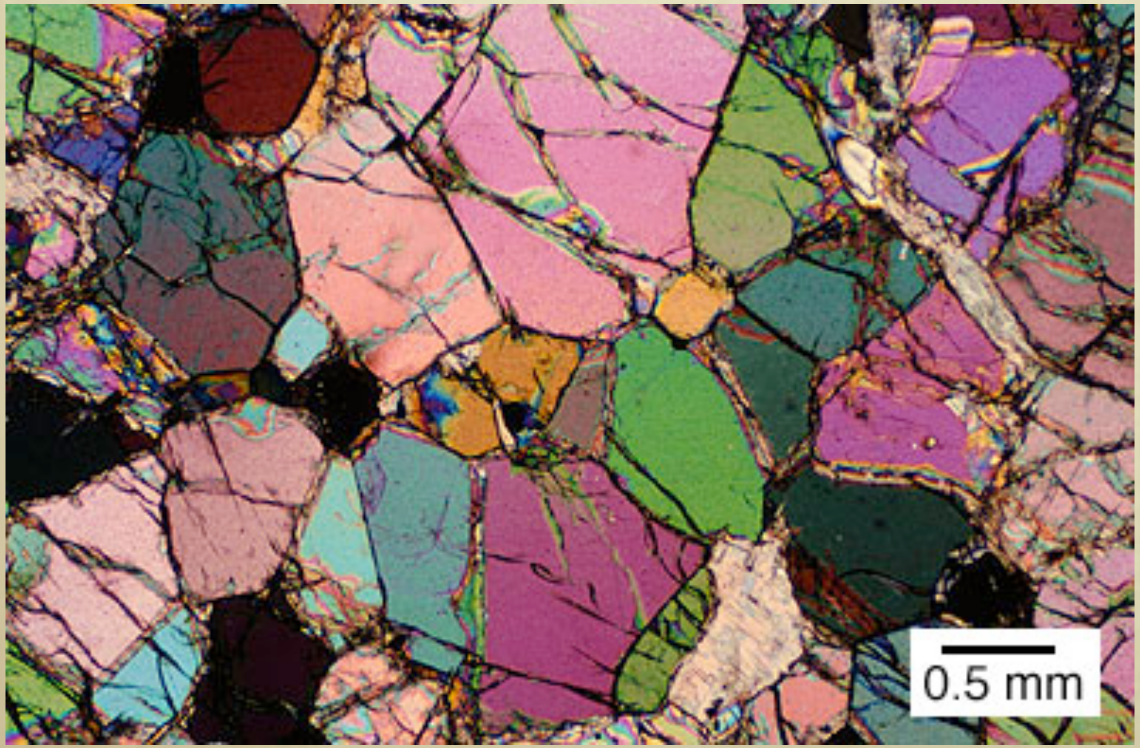
Minerals are made of grains

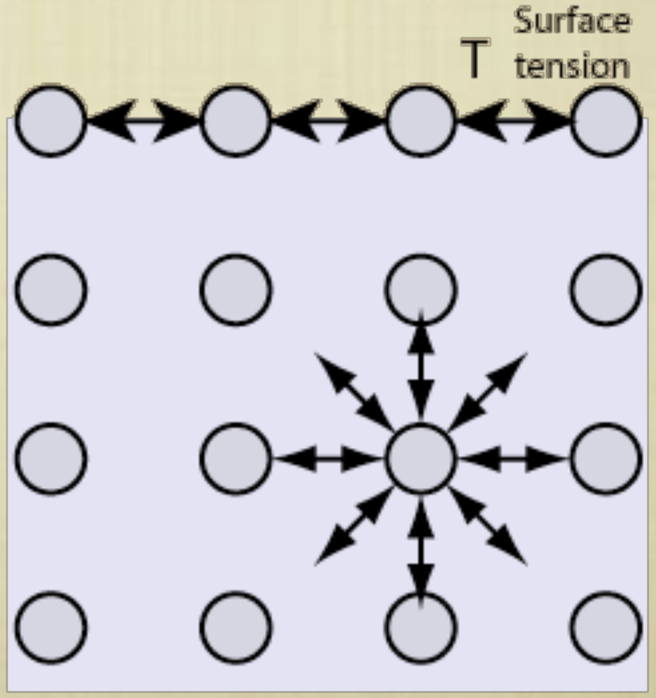
Foam is made with bubbles



Bubbles... grains... both involve surface energy/tension







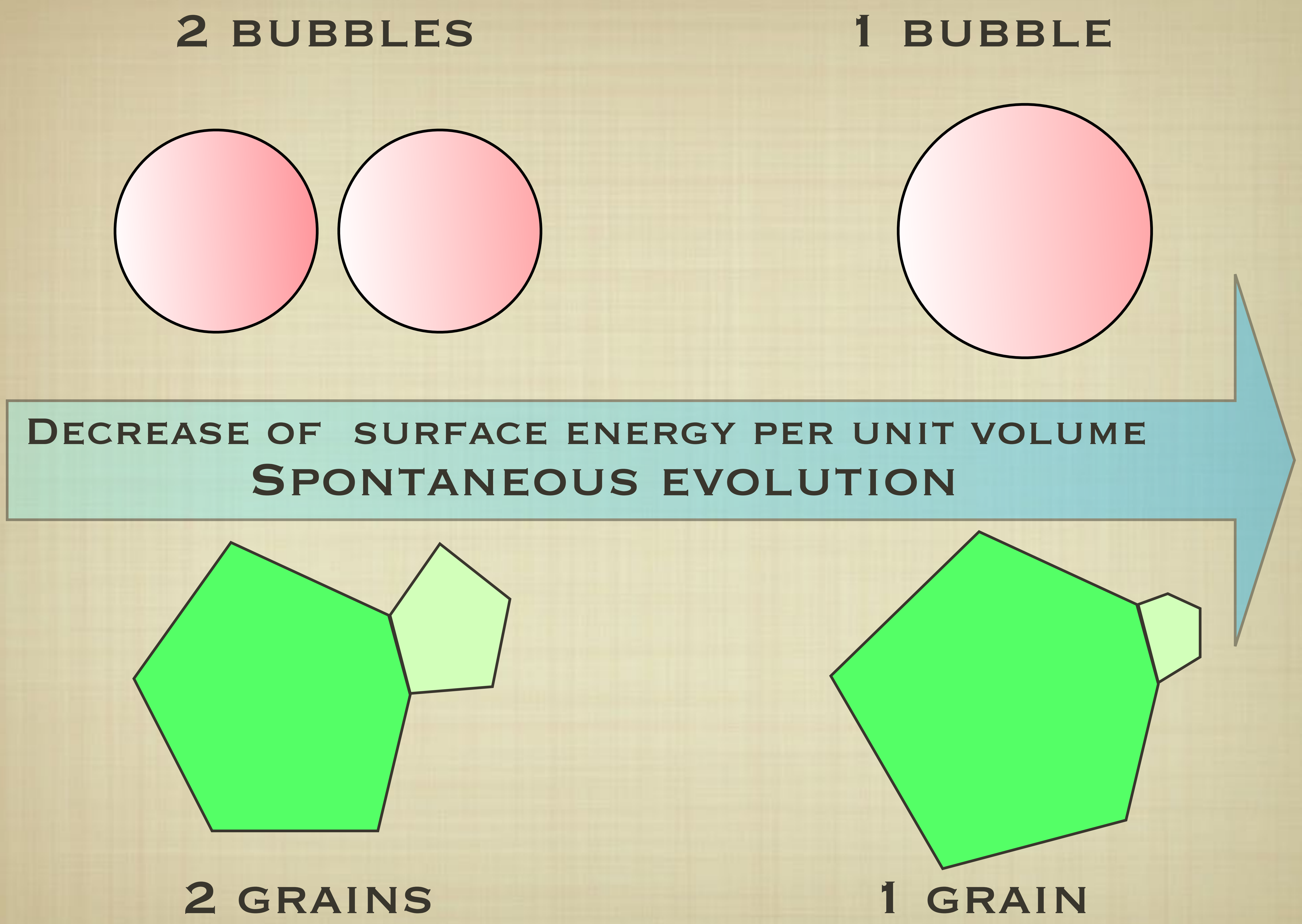
Evolution of an ensemble of grains with surface energy

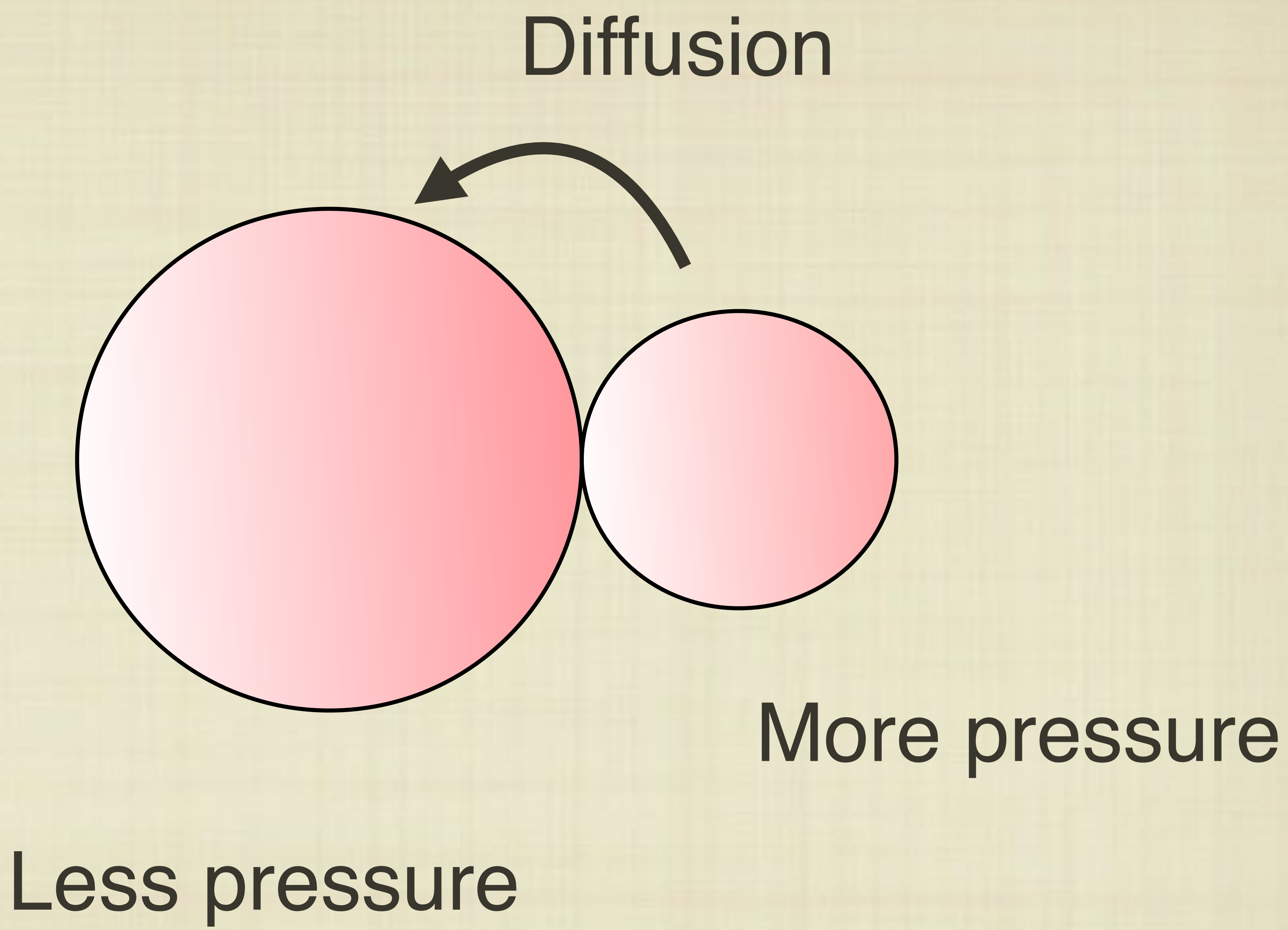
Surface of grains per unit volume

$$T\frac{DS}{Dt} = \underline{\tau} : \underline{\dot{\epsilon}} - \gamma\frac{D\alpha}{Dt} \geq 0$$

Surface tension

Without deformation, the surface of grains per unit volume must decreases (which increases the temperature)


2 bubbles
1 bubble
Decrease of surface energy per unit volume
Spontaneous evolution
2 grains
1 grain

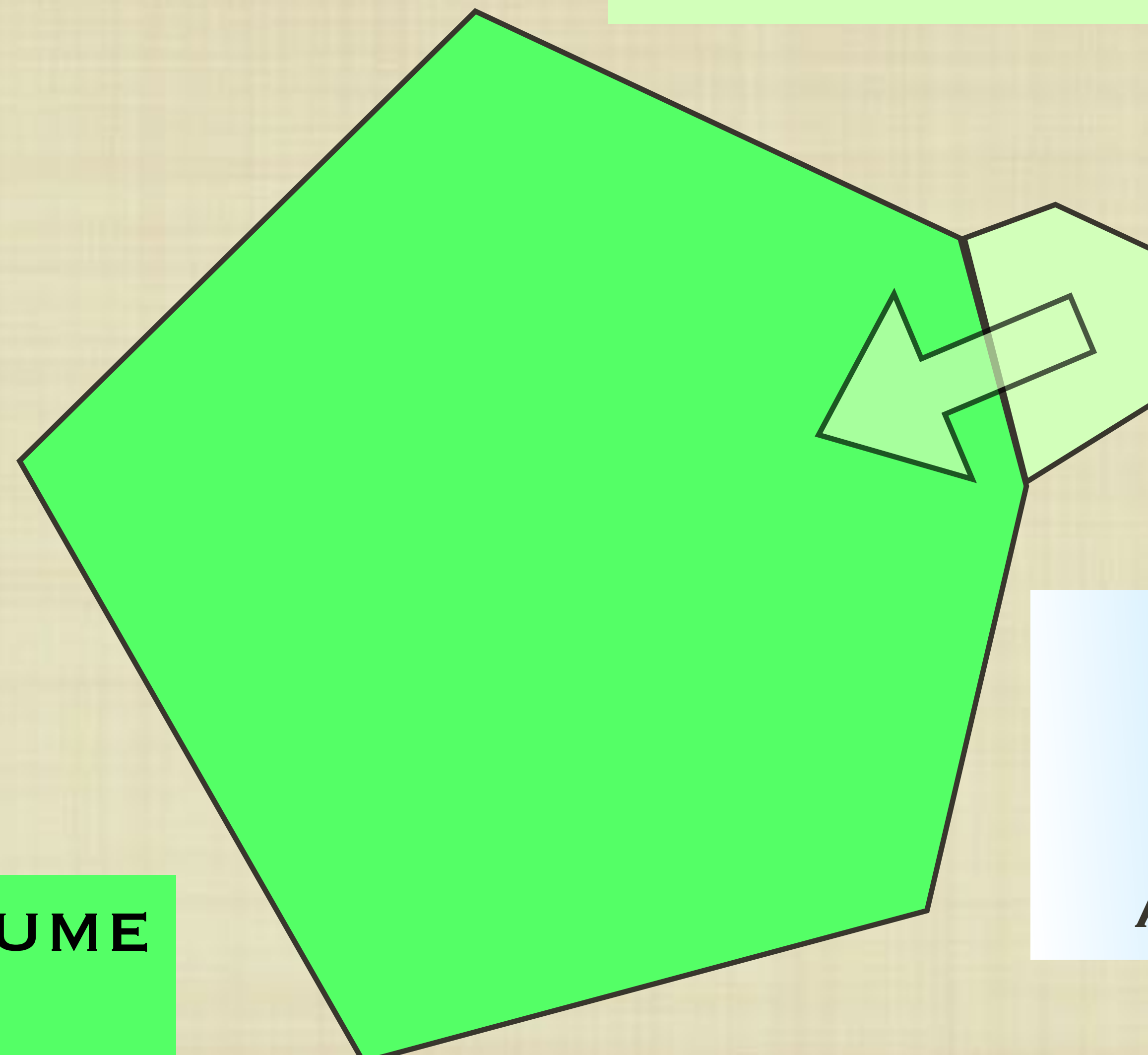


$$P_1 - P_2 = 2\gamma \left(\frac{1}{R_1} - \frac{1}{R_2} \right)$$

Laplace

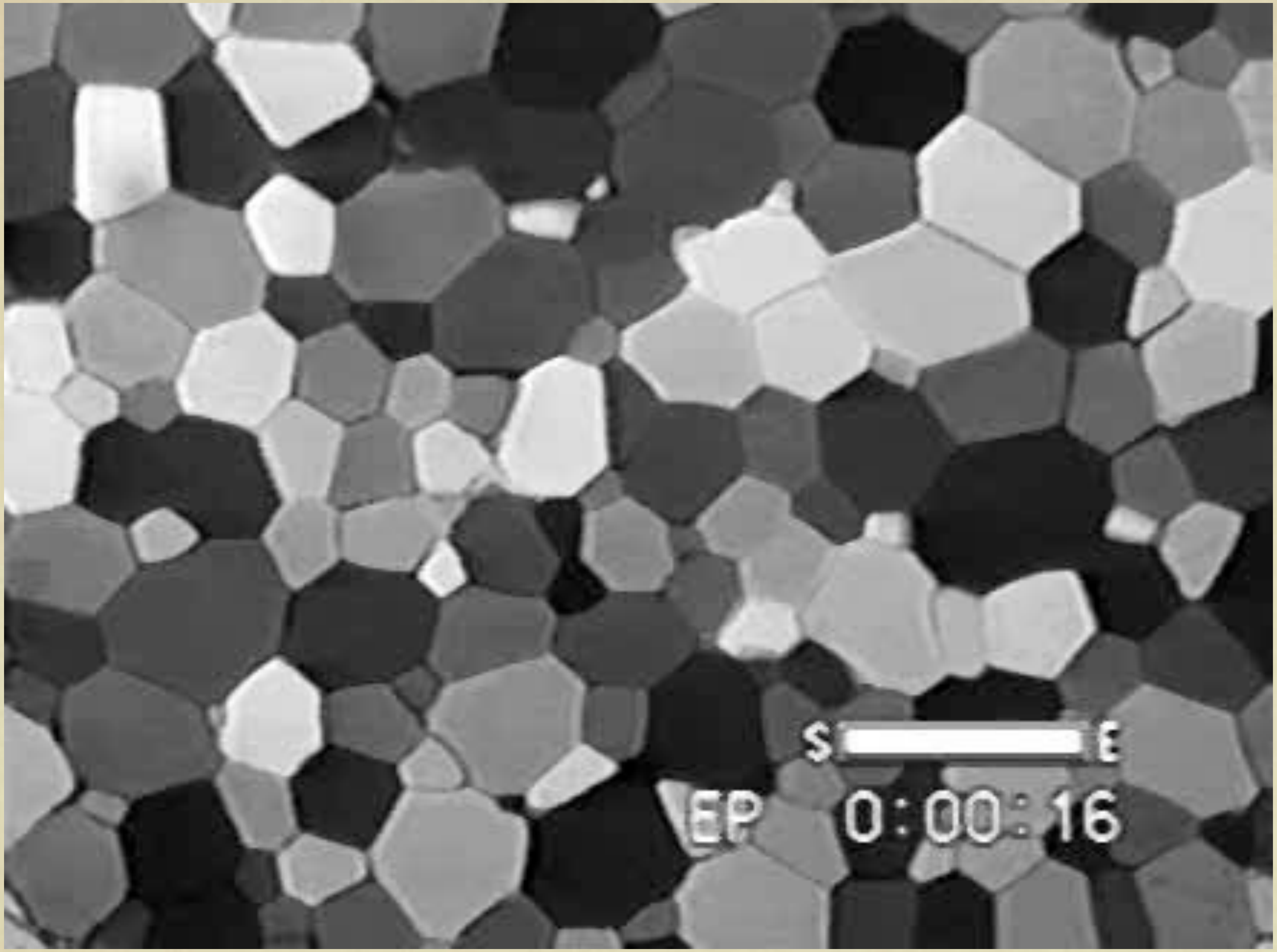
Energy γ, Pressure $\frac{2\gamma}{<R>}$

MORE SURFACE/VOLUME
=
MORE CURVATURE
=
MORE PRESSURE

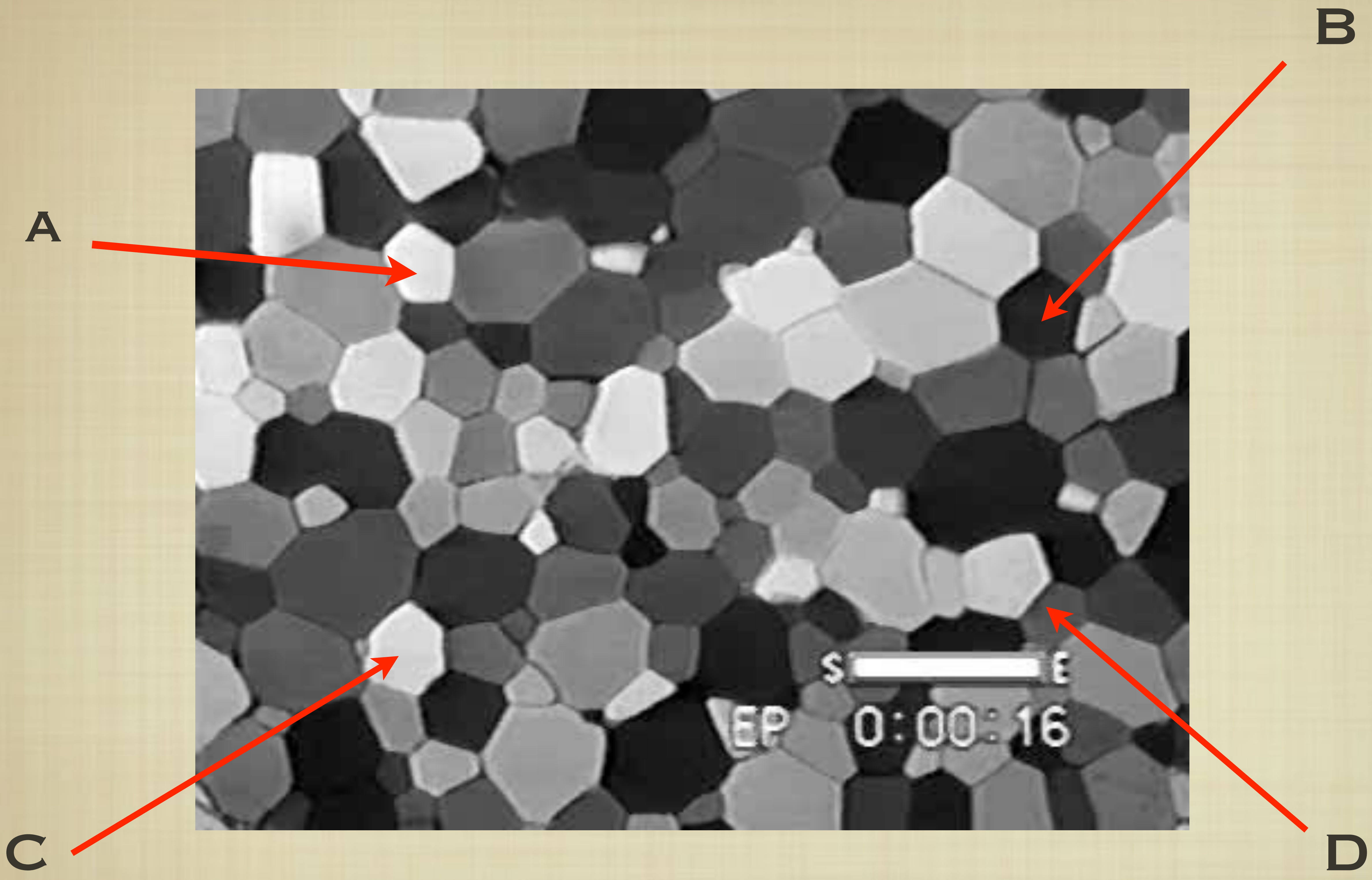


PRESSURE
DIFFERENCE
=
ATOM DIFFUSION

LESS SURFACE/VOLUME
=
LESS CURVATURE
=
LESS PRESSURE

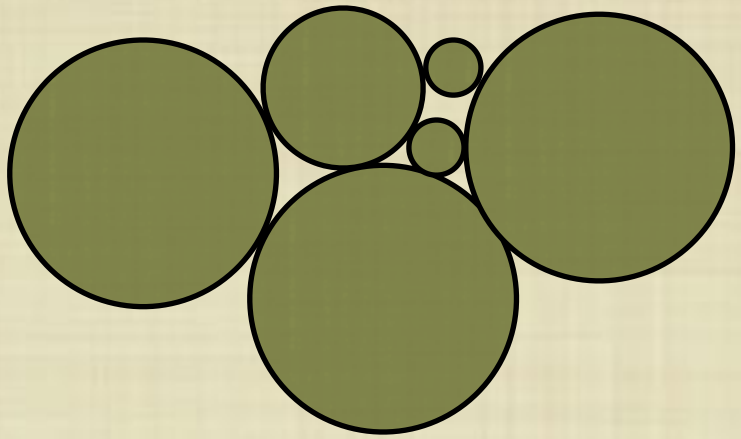


Y Park (octochloropropane)

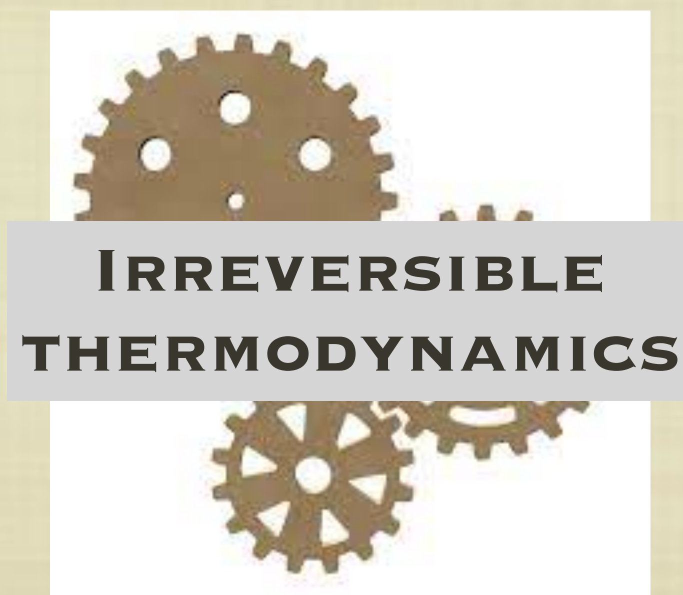


Y Park (octochloropropane)

If all grains are spheres (?)



$$-\gamma \frac{D\alpha}{Dt} \geq 0$$



$$\frac{dR}{dt} = G(R, \overline{R})\gamma \left(\frac{1}{\overline{R}} - \frac{1}{R} \right)$$

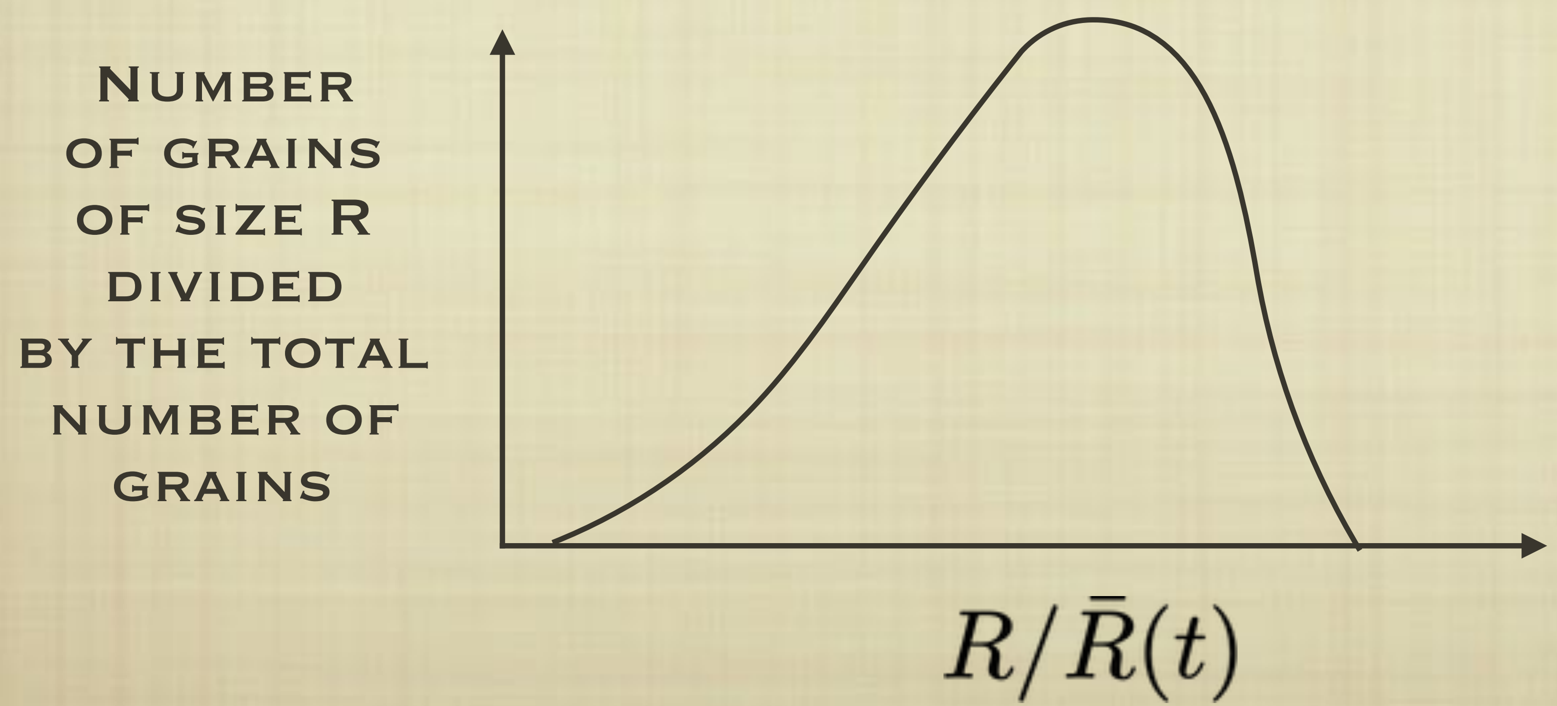
$$\frac{dR}{dt} = M\left(\frac{1}{\bar{\bar{R}}} - \frac{1}{R}\right)$$

M=mobility

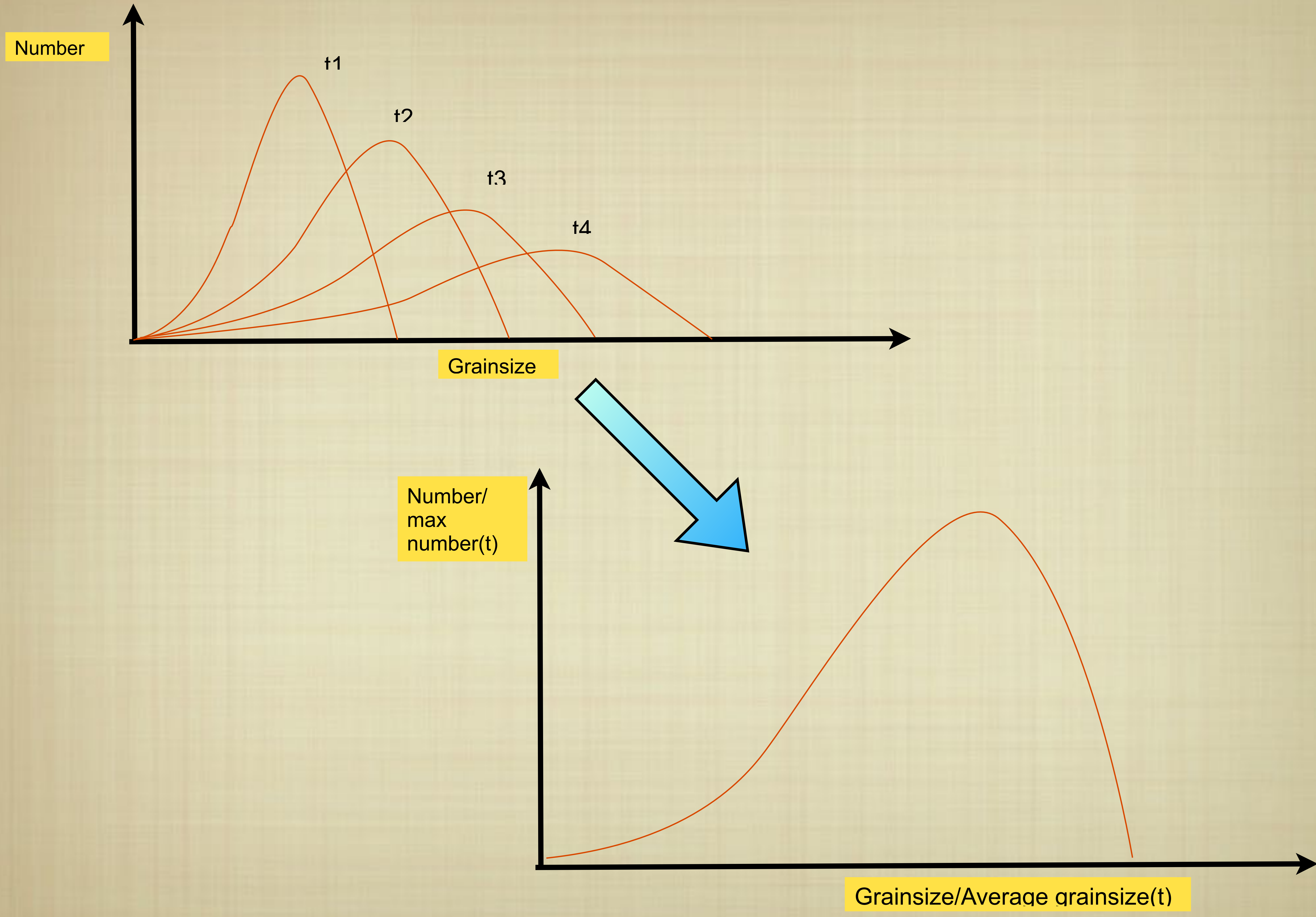
Big grains grow, small grains shrink

From this we can deduce $$\frac{d\overline{R}}{dt} = \frac{G}{p\overline{R}^{p-1}}$$

and the grain size distribution is « self similar »



Slyzov-Lifshitz
Hillert


Number
t1
t2
t3
t4
Grainsize
Number/
max
number(t)
Grainsize/Average grainsize(t)

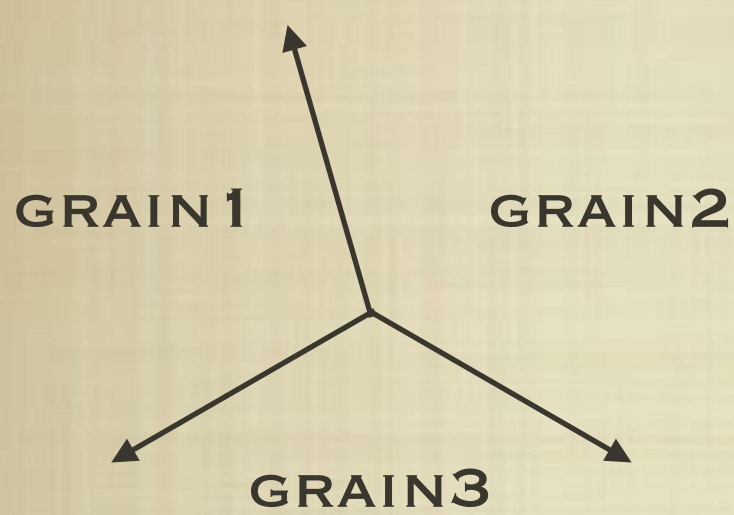
Most of the grains shrink (so that some can grow)

A grain smaller than average shrinks,
a large one grows...
but this changes the average curvature... until only one grain remains

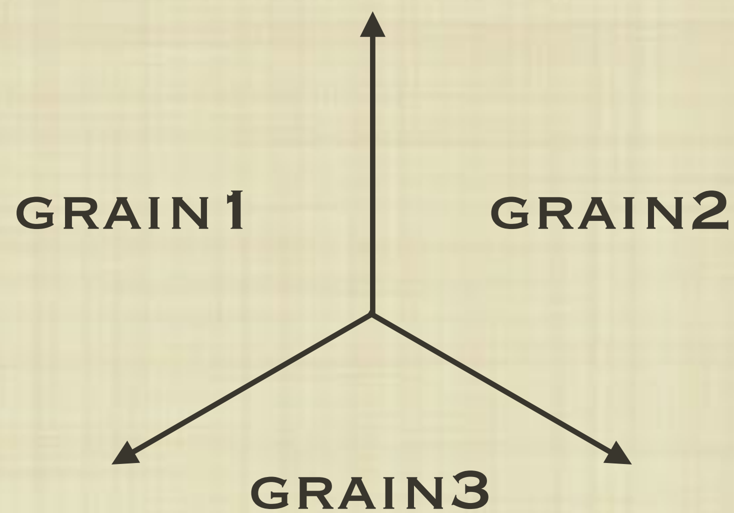
«Un propriétaire peut augmenter le loyer de son locataire si ce loyer est au dessous de la moyenne des prix pratiqués»

But grains are not spheres

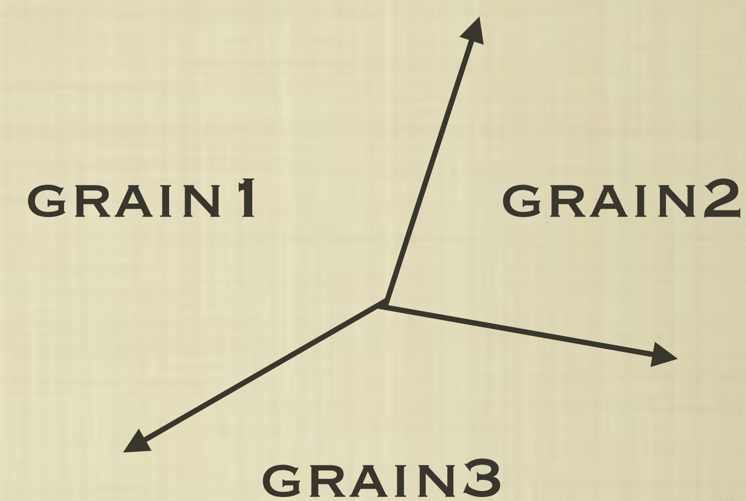
assuming they are 2D polygons



grain2 coarsens



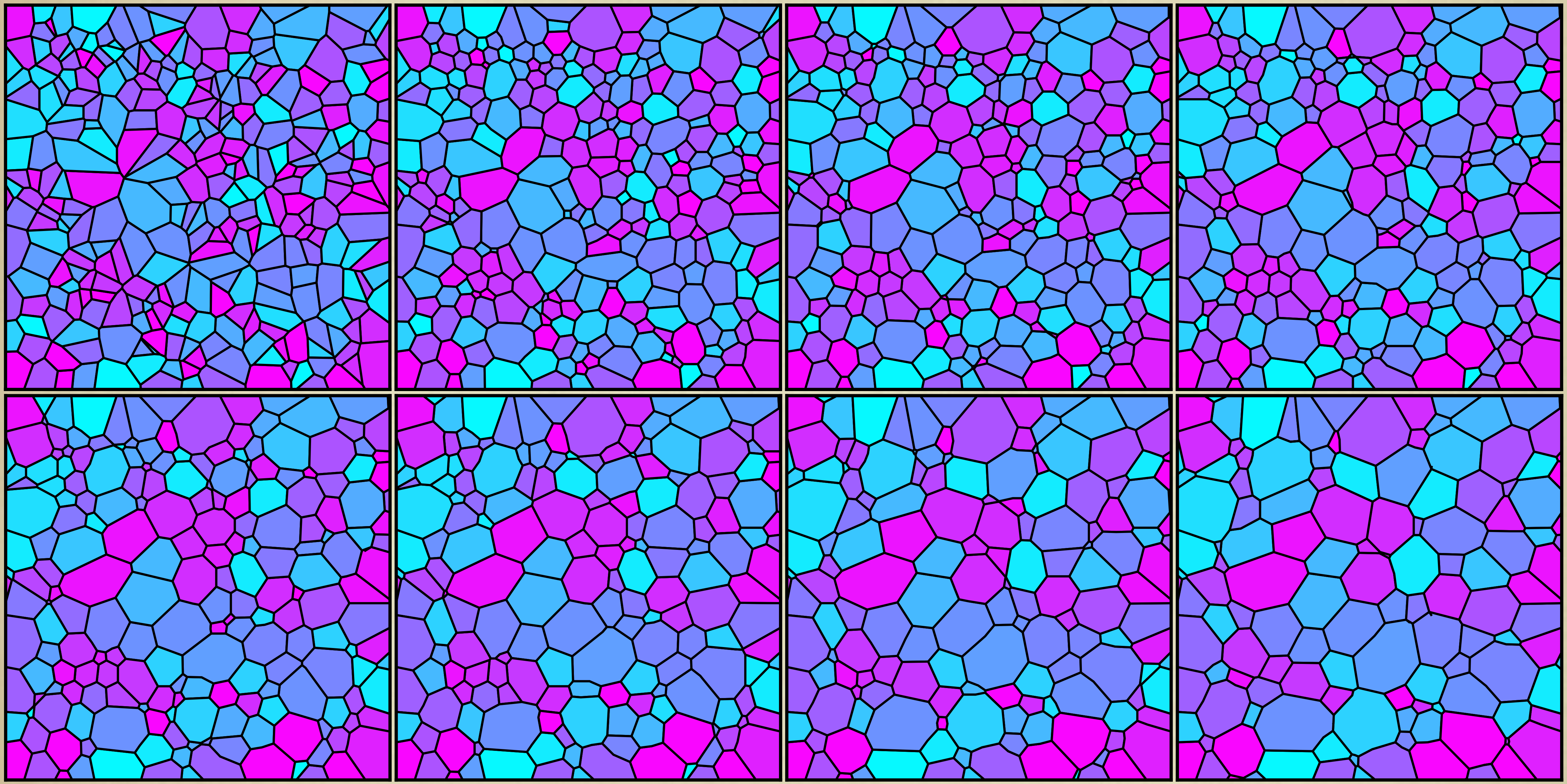
stable



grain2 shrinks

It's like forces moving the vertices

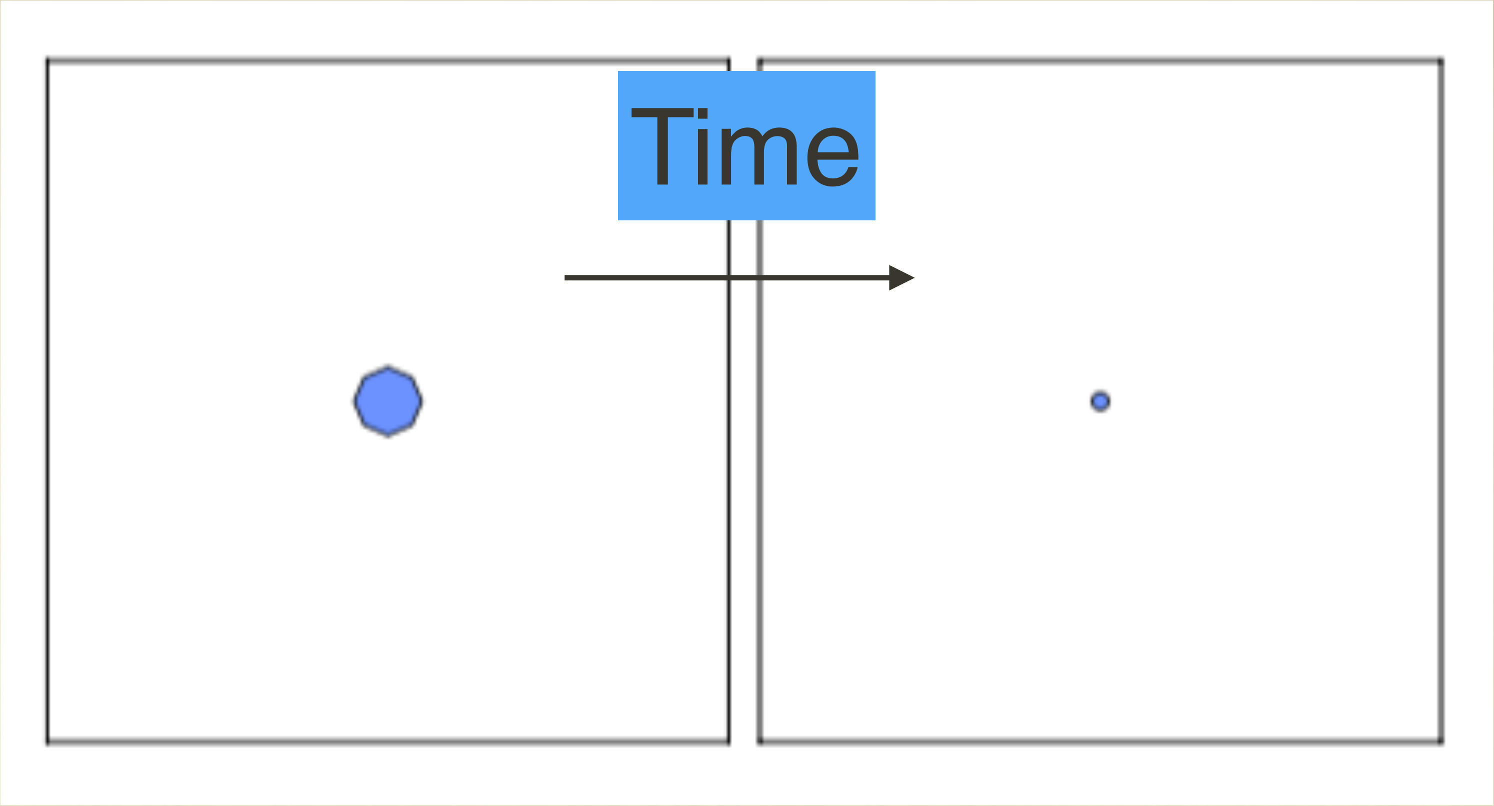
(ARBITRARY COLORS)



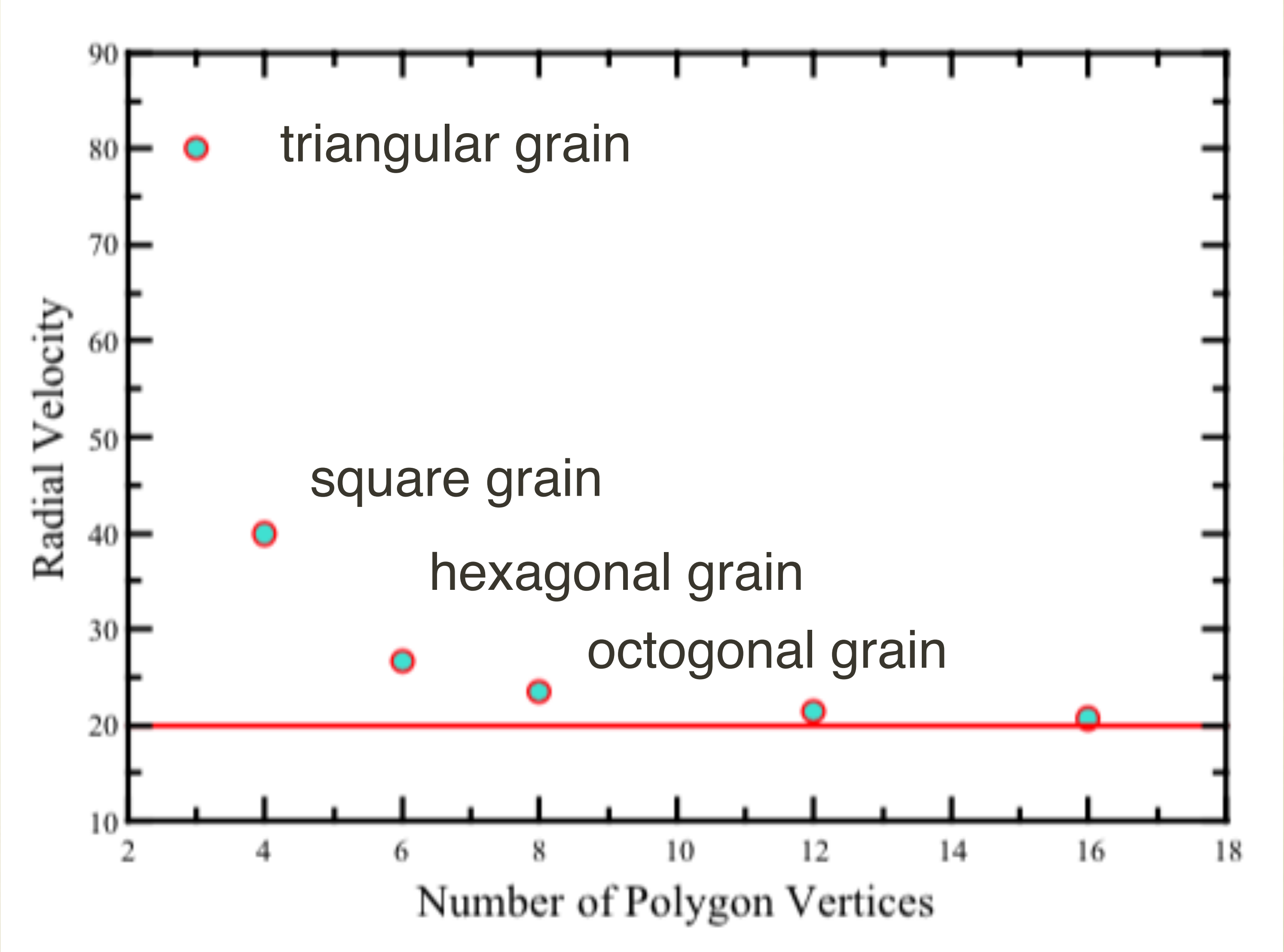
First test :

one octogonal grain embedded in a large garin

It shrinks

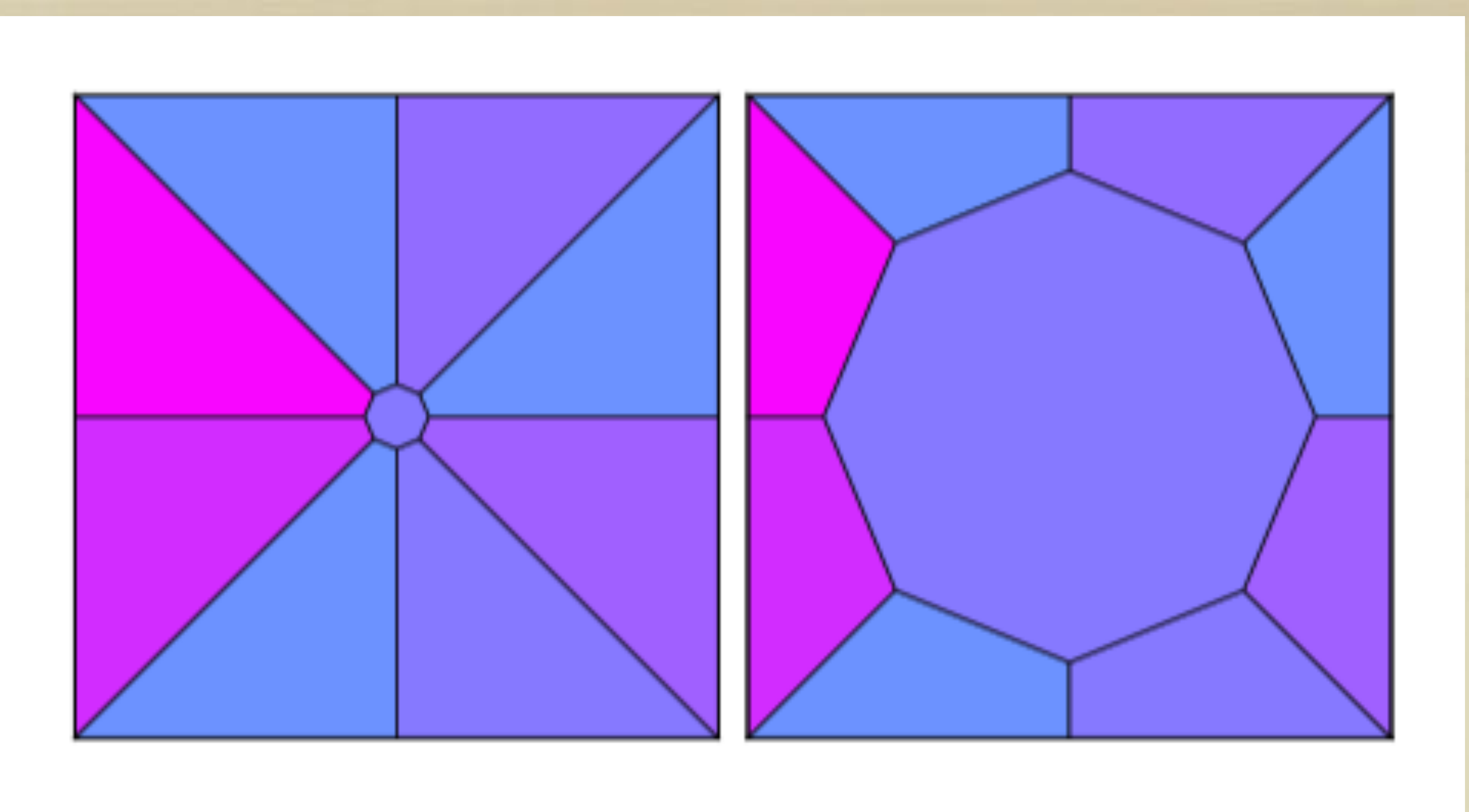


the radial velocity when R=0.05 is 1/R=20



Second test

one
octogonal
grain+8 big grains



It coarsens

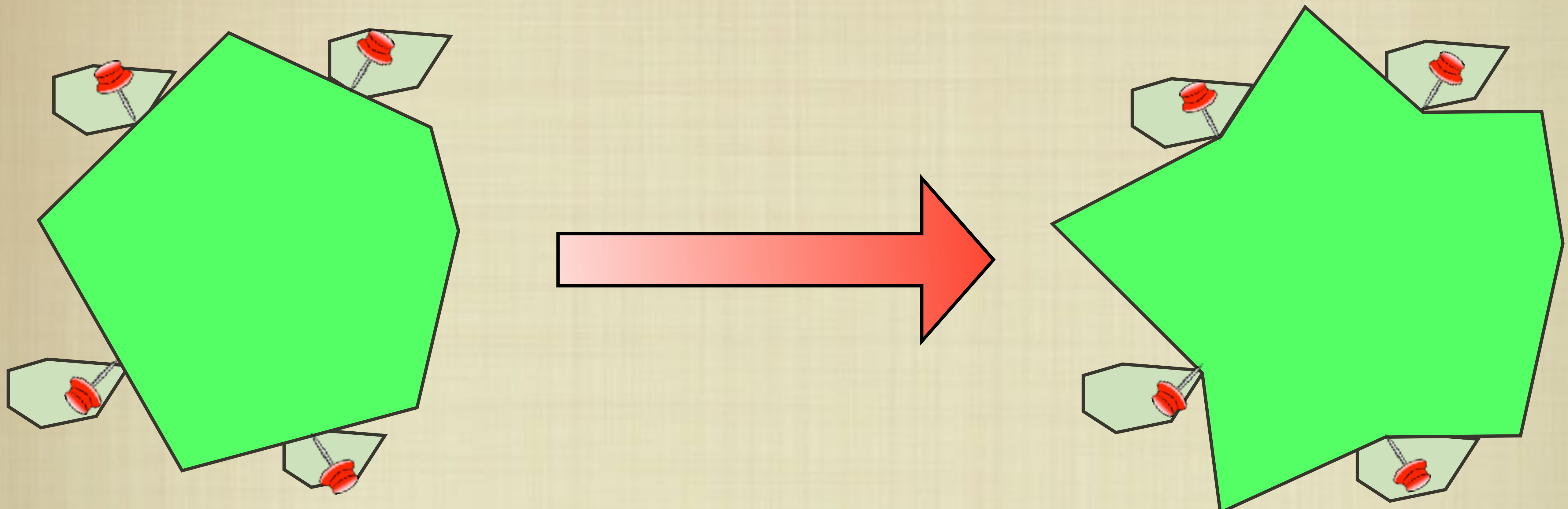
…and the surface energy is continuously decreasing

…faceted grains do not behave like bubbles…

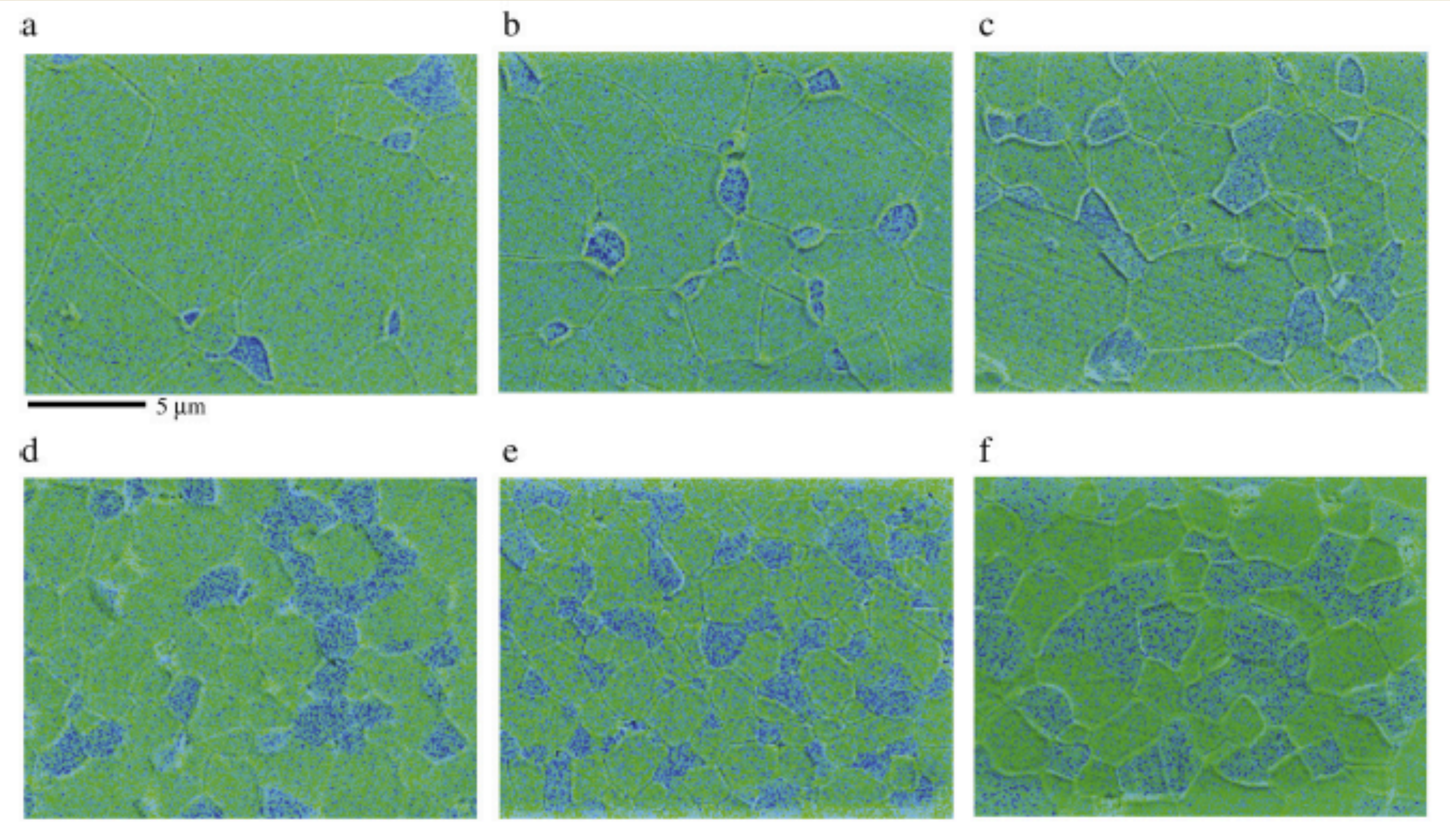
But from olivine experiments (eg Karato) the grain growth seems much too fast for geological times

The mantle is not made of a single phase !
The Zener pinning !

Corsening more difficult



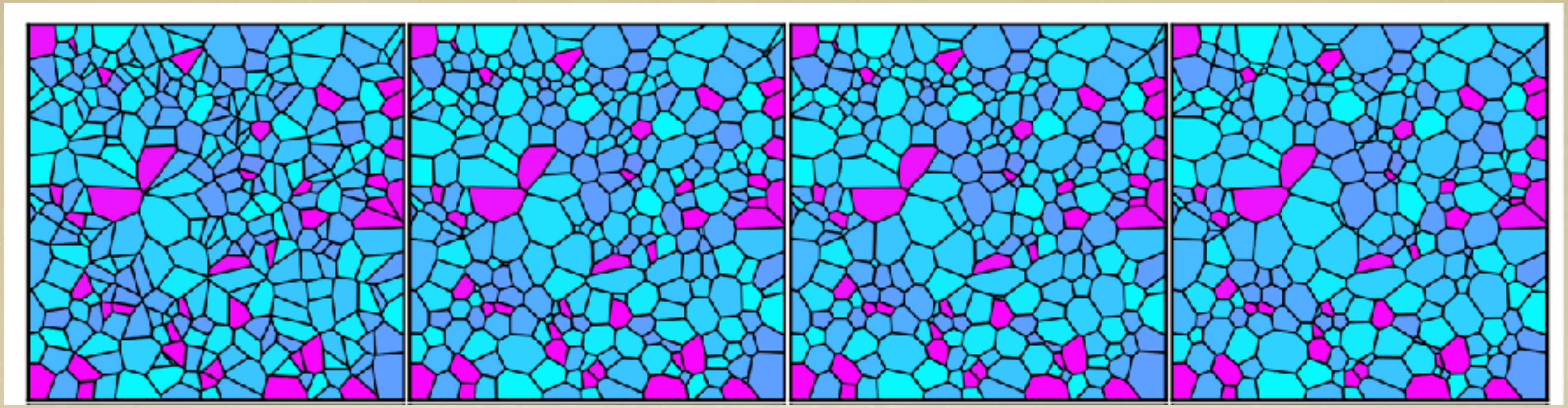
Increasing the surface of the green grain would increase and not decrease its surface/volume ratio

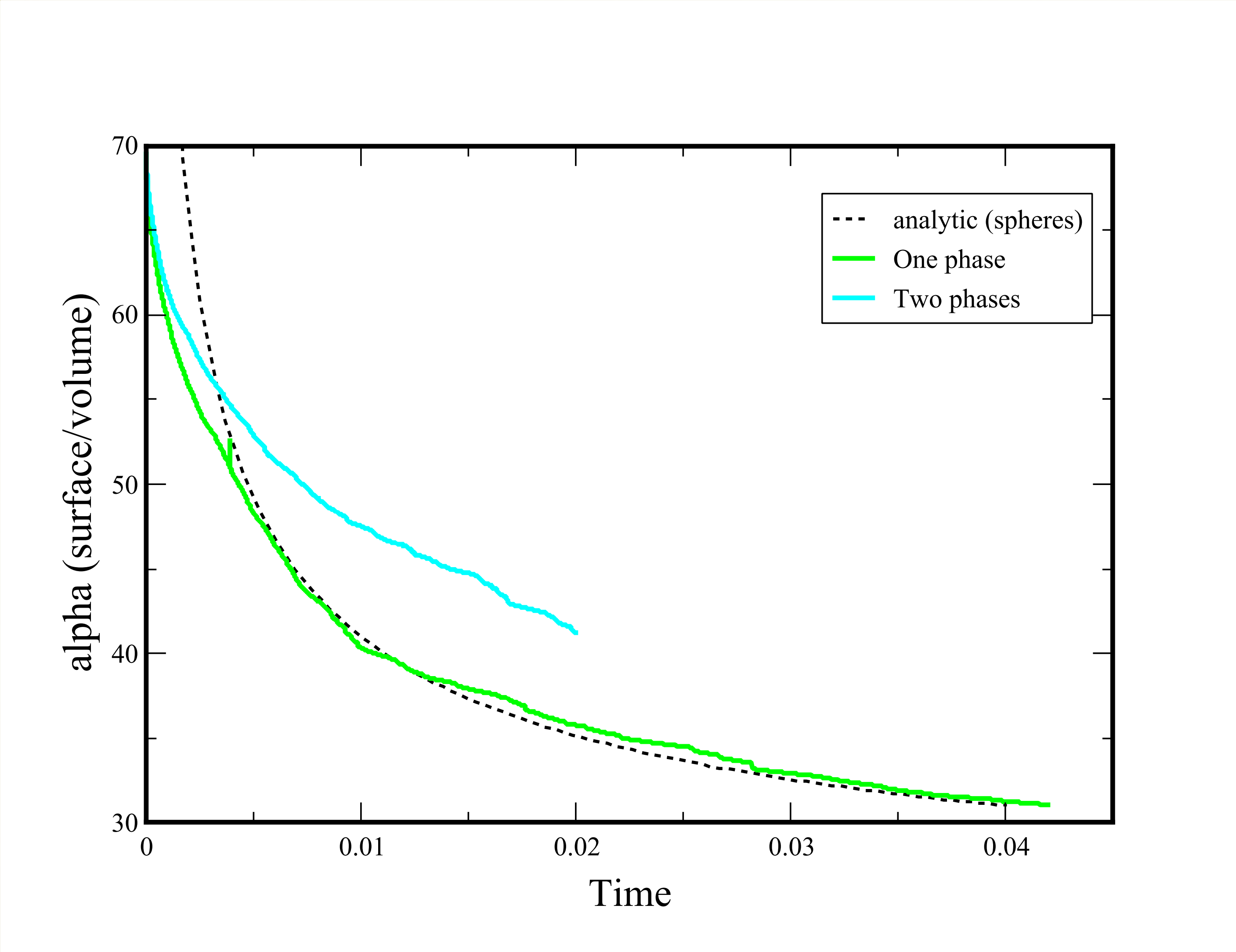


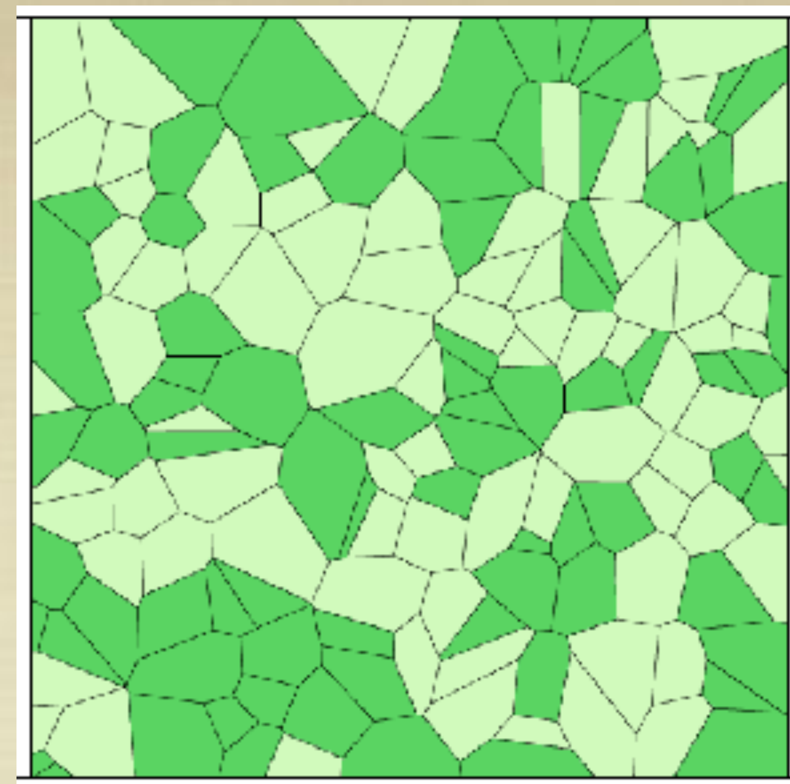
The effect of a second phase is know in metallurgy as Zener pinning

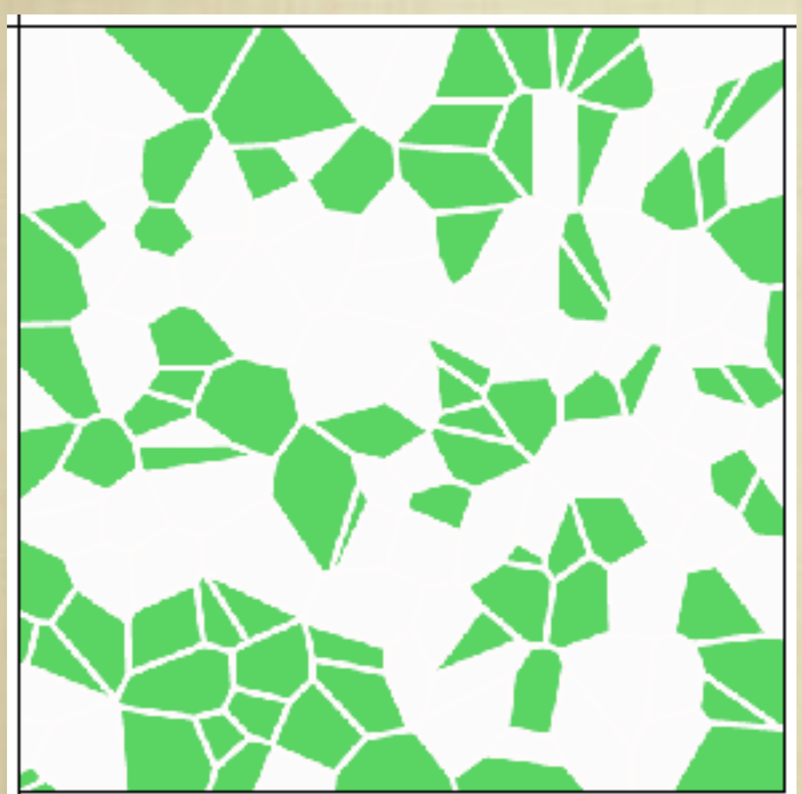
Hiraga et al., 2010

Meaningfull colors







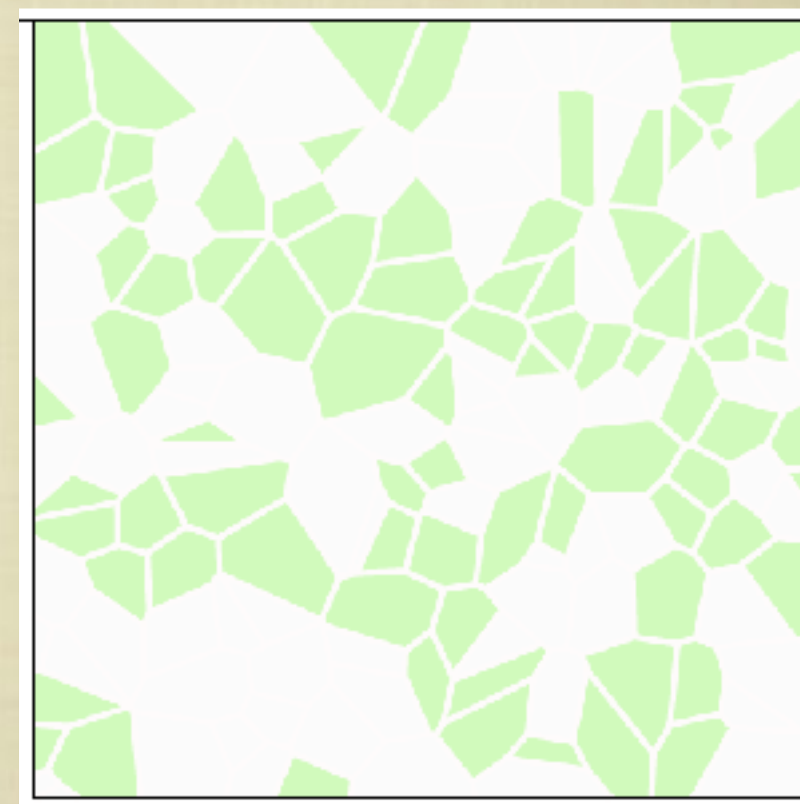


$< \mathcal{R}_1 >$

THE AVERAGE GRAIN SIZE

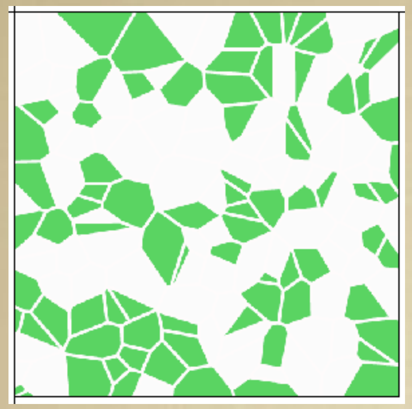
$< \mathcal{R} >$

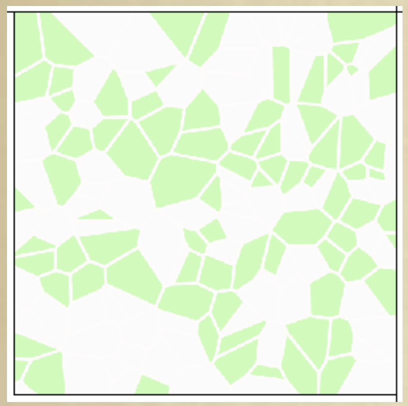
THE AVERAGE INTERPHASE CURVATURE RADIUS



$< \mathcal{R}_2 >$

THE AVERAGE GRAIN SIZE





Coarsening by diffusion across same phase interfaces

=

fast

Coarsening by diffusion across different phases

=

slow

Karato

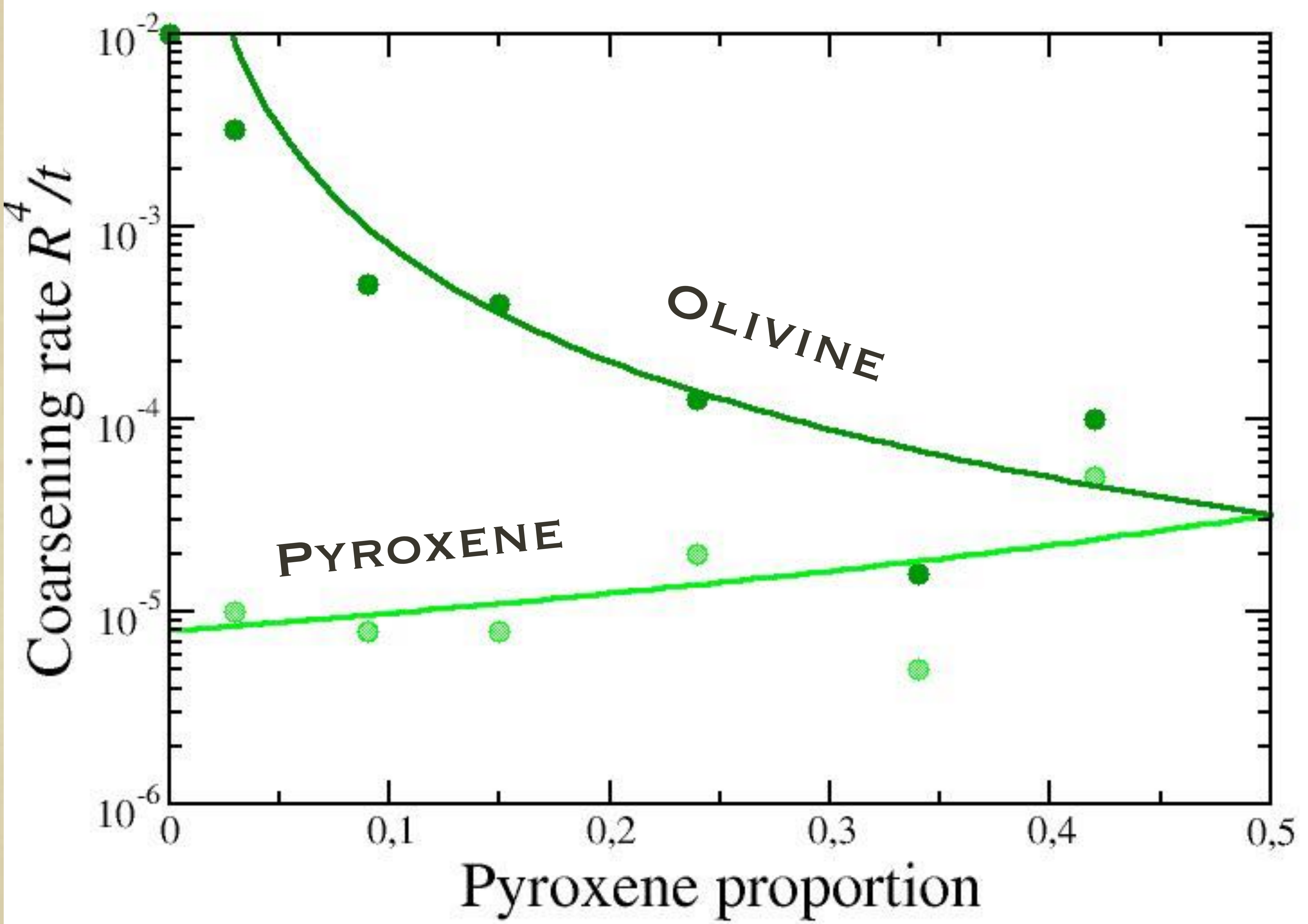
$$\frac{d\overline{R}_i}{dt} = \frac{G_i}{p\overline{R}_i^{p-1}} Z_i$$

Geometrical factor

$$Z_i = 1 - (1 - \phi_i)\frac{\overline{R}_i^2}{r^2}$$

$$\frac{d\overline{r}}{dt} = \frac{G'}{q\overline{r}^{q-1}}$$

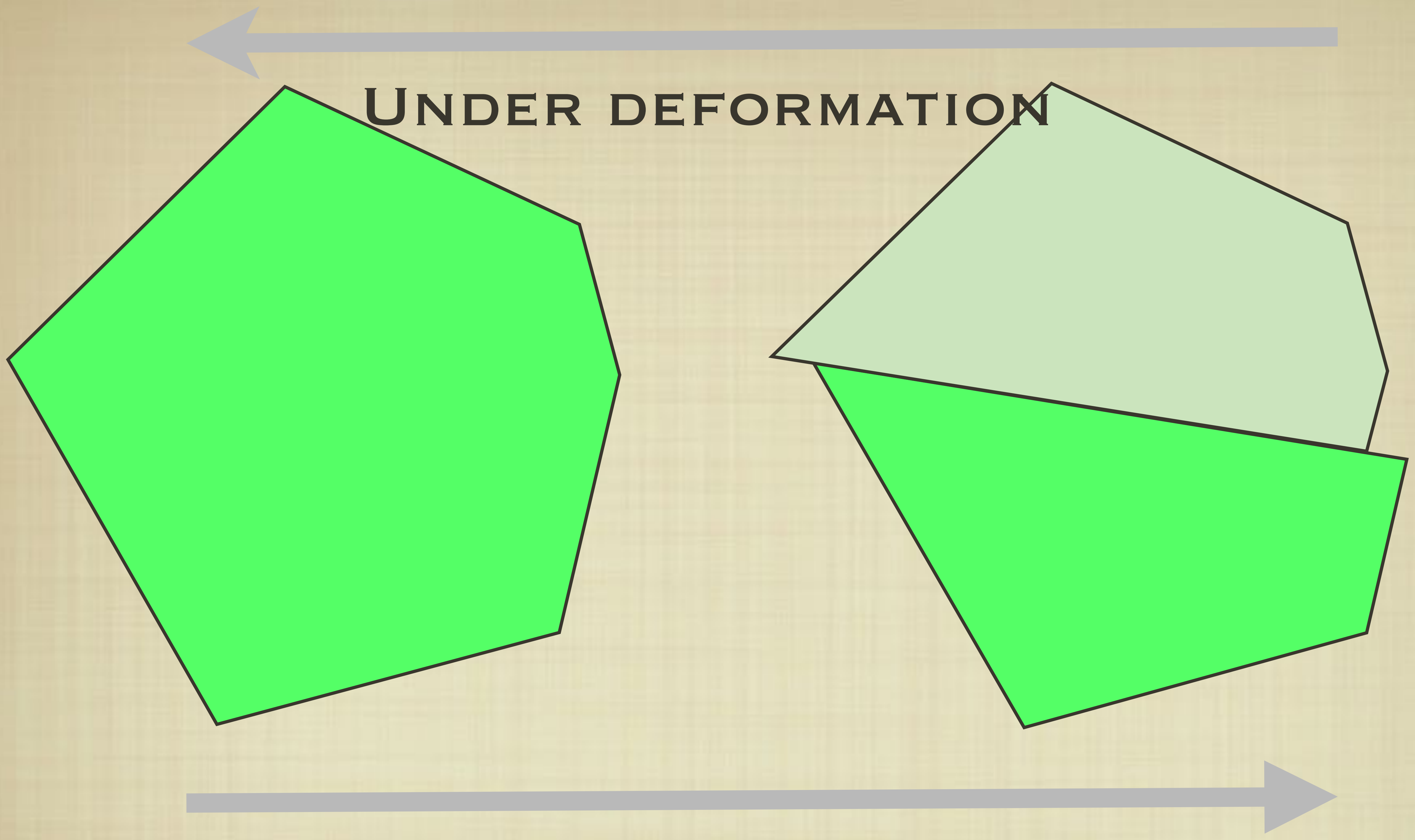
Experiment from Hiraga



Bercovici and Ricard, 2012

But all that was without applied stresses

$$\underline{\tau} : \underline{\dot{\epsilon}} - \gamma \frac{D\alpha}{Dt} \geq 0$$



Formation of subgrains/grain fractures/ recystallization...

$$\gamma \frac{D\alpha}{Dt} \leq \underline{\tau} : \underline{\dot{\epsilon}}$$

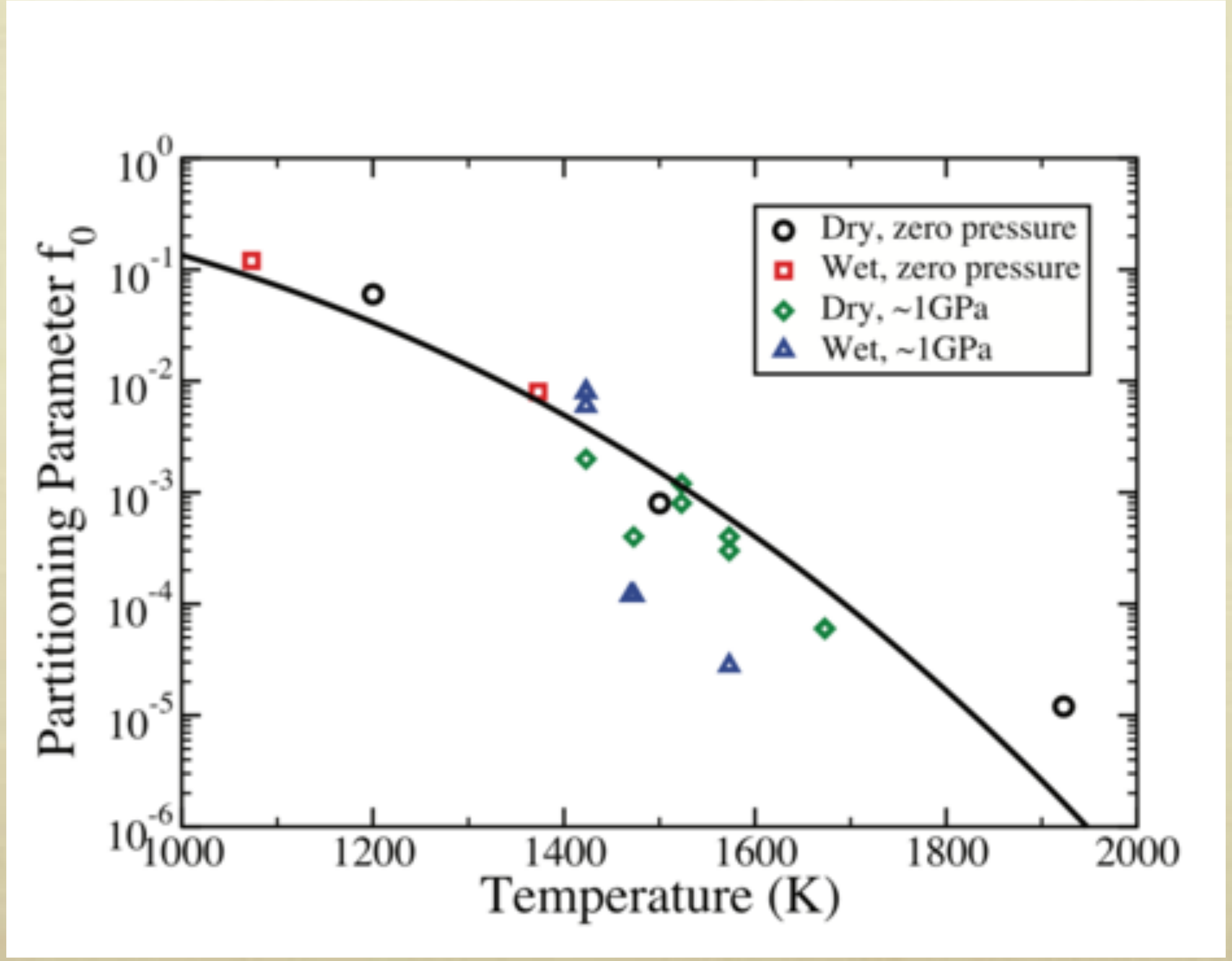
Coarsening (healing)

gain reduction (dammage)

we choose

$$\frac{d\overline{R}}{dt} = \frac{G}{p\overline{R}^{p-1}} - f\frac{\overline{R^2}}{\gamma}\underline{\tau} : \underline{\dot{\epsilon}}$$

$$0 \leq f \leq 1$$



Post, Ross, Van der wal, Karato

At lithospheric temperature about 1%-0.1% of the input power is not dissipated as heat but converted into surface energy reducing grain size

$$\frac{D\mathcal{R}_i}{Dt} = \frac{G_i}{p\mathcal{R}_i^{p-1}}\mathcal{Z}_i - \frac{\lambda_3}{\lambda_2}\frac{\mathcal{R}_i^2}{3\gamma_i}\mathfrak{f}_{\mathrm{G}}(1-\mathfrak{f}_{\mathrm{I}})\Psi_i\mathcal{Z}_i^{-1}$$

$$\frac{Dr}{Dt} = \frac{\eta G_{\mathrm{I}}}{qr^{q-1}} - \frac{r^2}{\eta\gamma_{\mathrm{I}}}\mathfrak{f}_{\mathrm{I}}\overline{\Psi}$$

Each phase grainsize

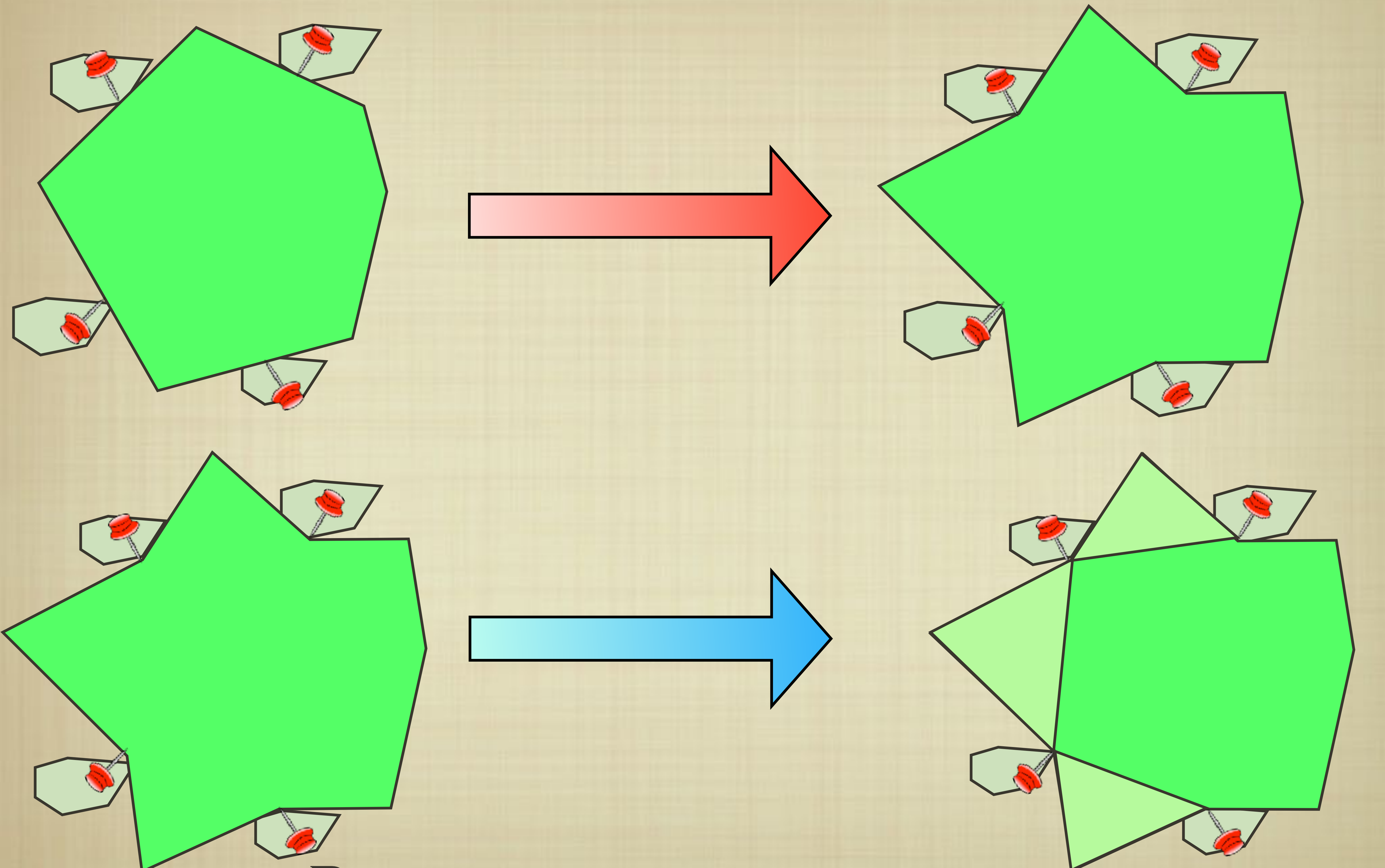
Interface curvature

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

Zener pinning

The deformation mixes the phases (raisonnable but guessed)

Corsening more difficult



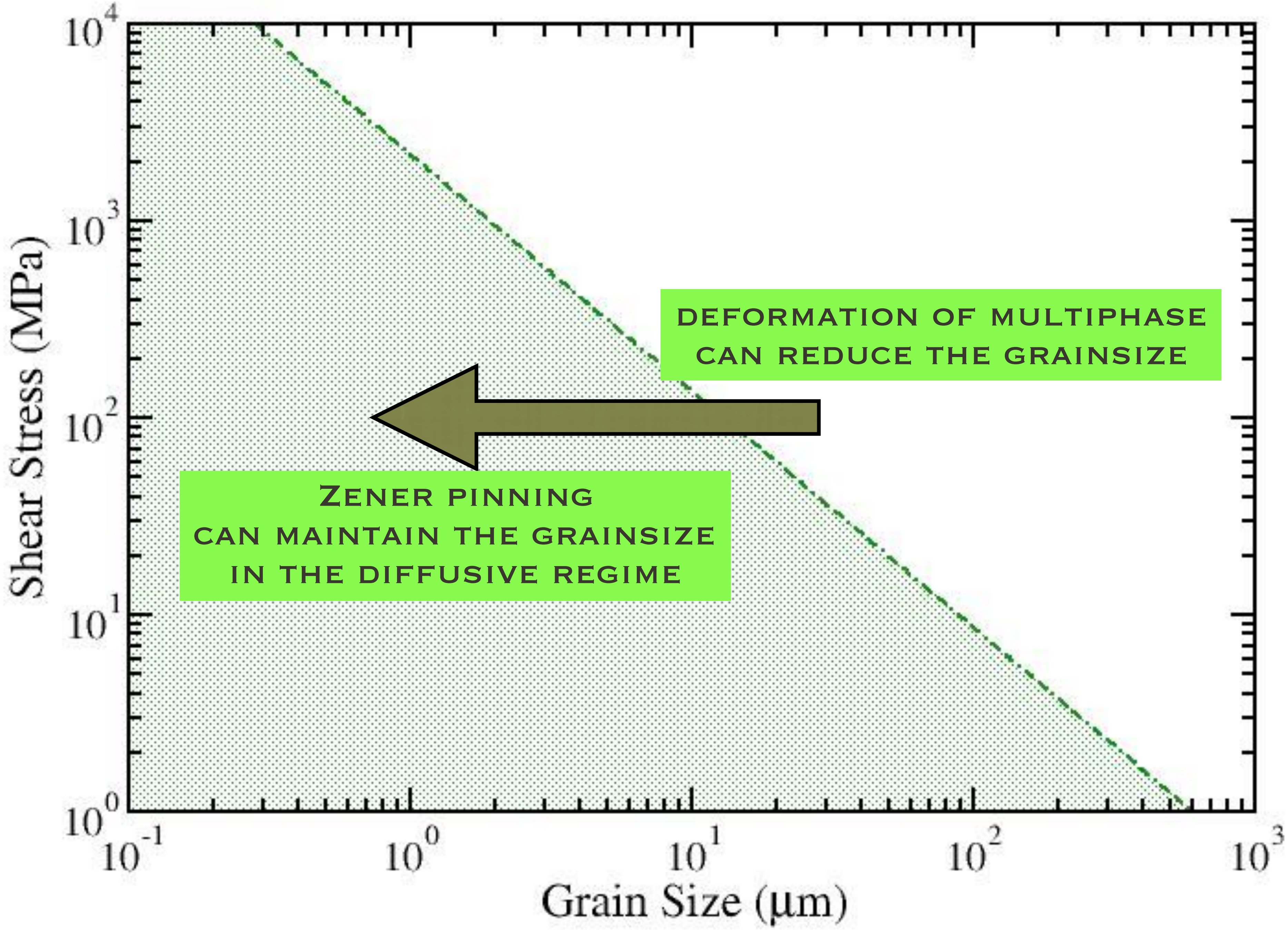
Recrystallization easier

A mechanism to localize deformation:

Deformation mixes the different phases and stirs the interphase boundary

This increases the pinning obstacles

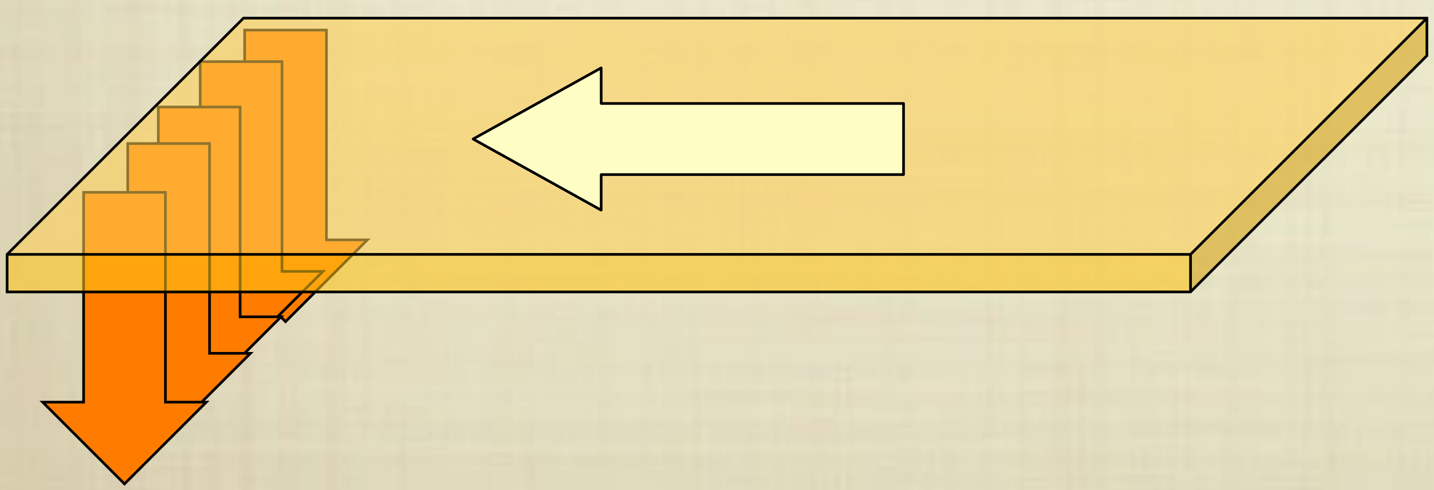
And maintains the grains into a weak grain-size dependent rheology over geological times

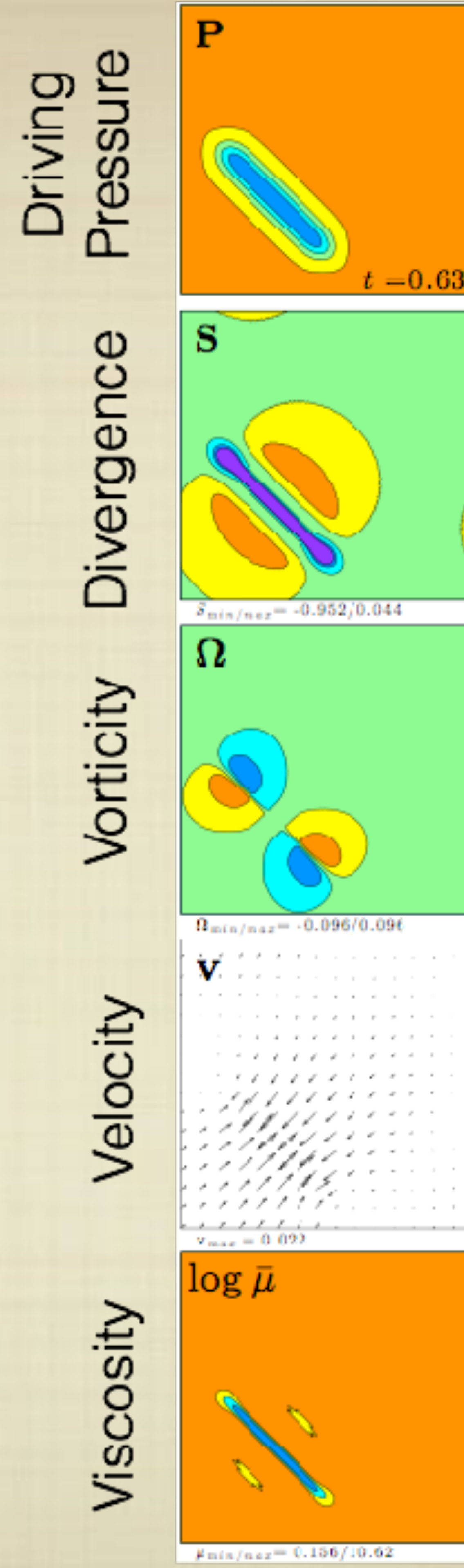


DEFORMATION OF MULTIPHASE
CAN REDUCE THE GRAINSIZE
ZENER PINNING
CAN MAINTAIN THE GRAINSIZE
IN THE DIFFUSIVE REGIME
Shear Stress (MPa)
Grain Size (μm)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3

Is this rheology leading to plates?

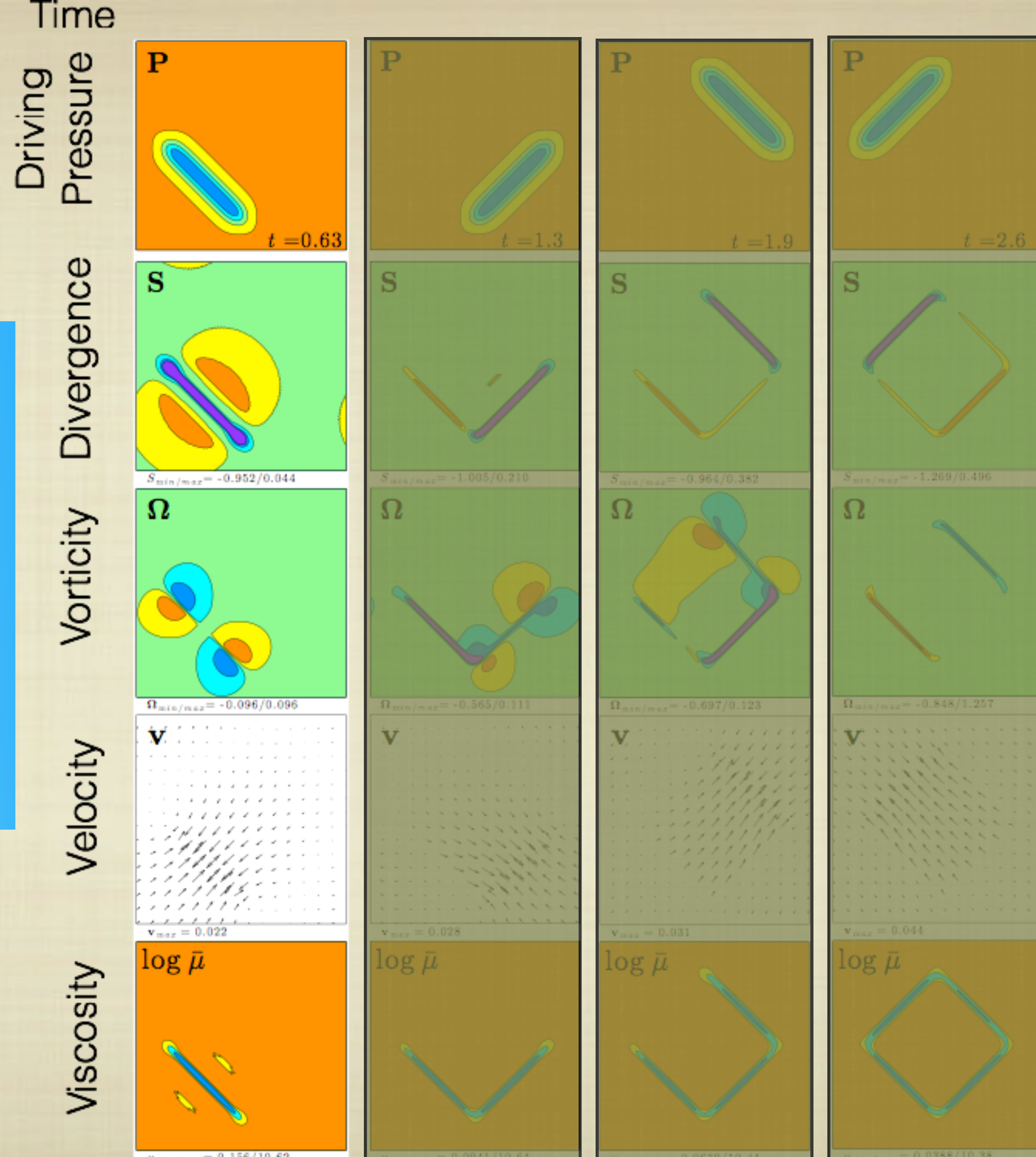
Time-dependent downwelling and damage: An idealized model





Earth case

Low healing
High damage

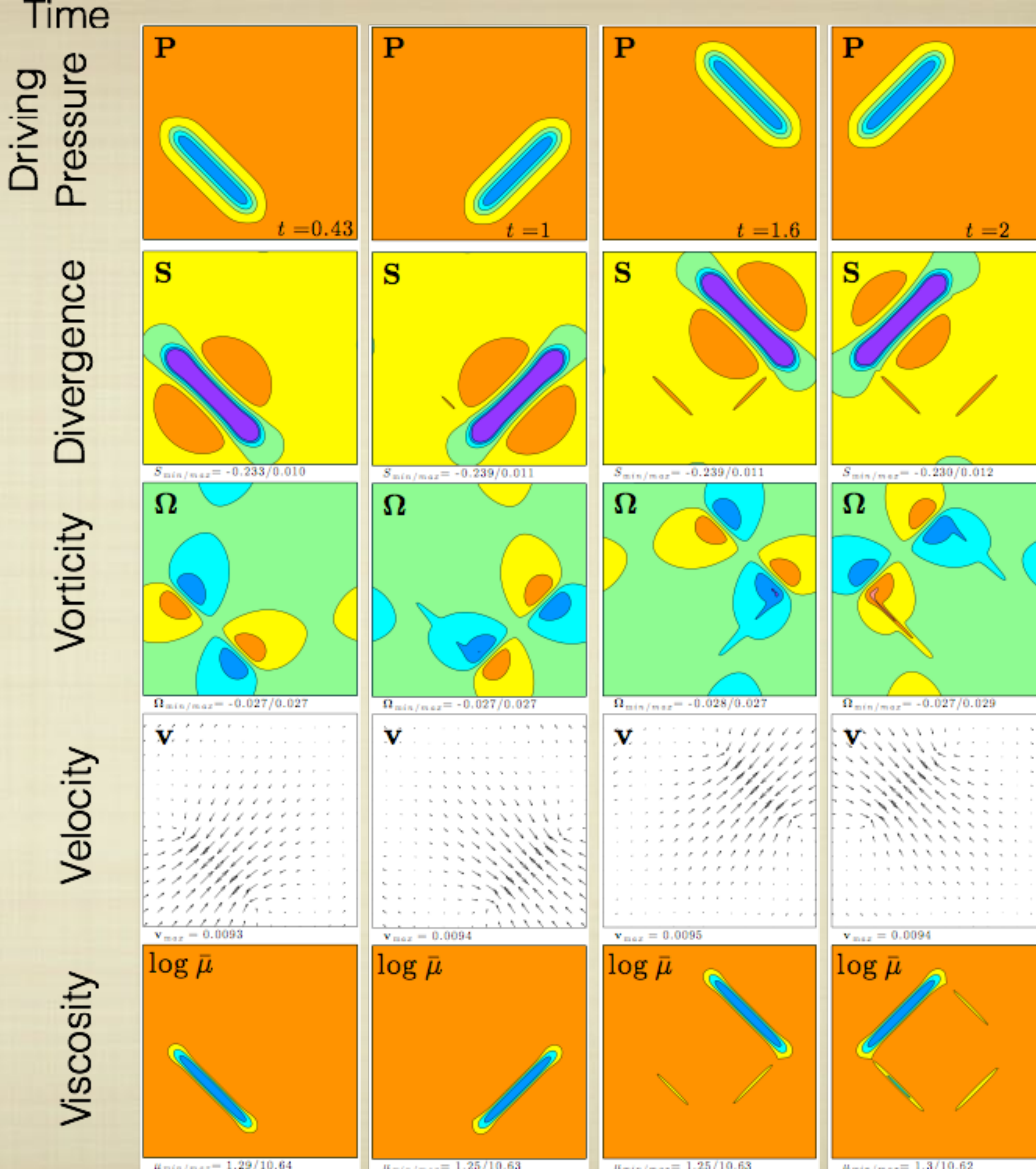


Increased Temperature

Venus case

High healing x10

Low damage ÷10



100 kyrs 100 Myrs 1 Byrs

Damage time << Convection time << healing time

Earth : Plate Tectonics

1 Myrs 100 Myrs 100 Myrs

Damage time < Convection time = healing time

Venus : No Plate Tectonics

Phase interaction may provide both localization and long term memory necessary for plate tectonics

Simple phase coarsening laws are most probably not very usefull for the Earth

Rheology measured in a laboratory is not at grain-size equilibrium

Two phase coarsening experiments are needed!!

Possible effects leading to localisation

-Temperature

-Surface temperature

-Non linear rheology

-Composition

-Water

-Anisotropy

-Grain-size