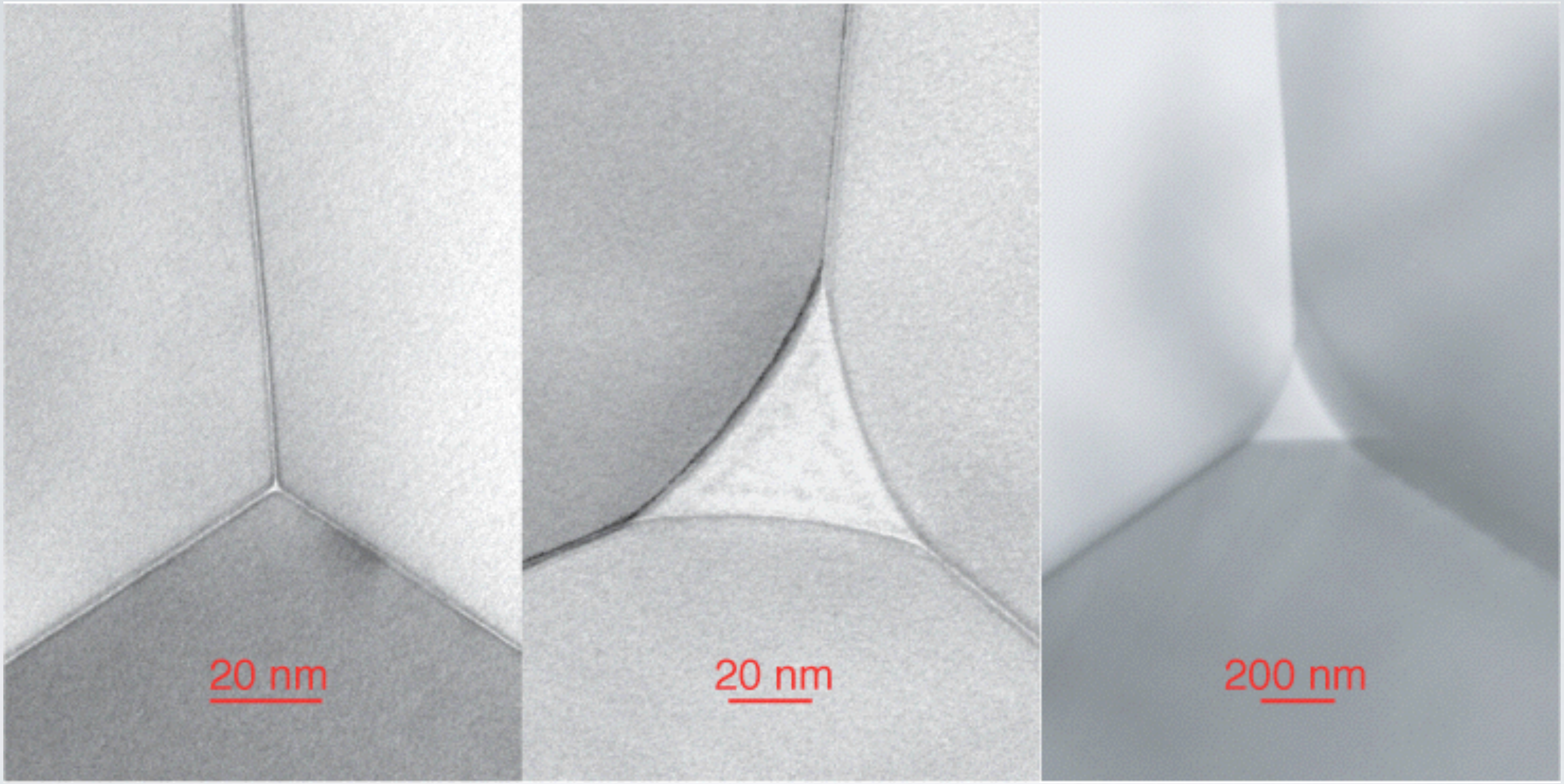
Rheology cont.: Influence of melt

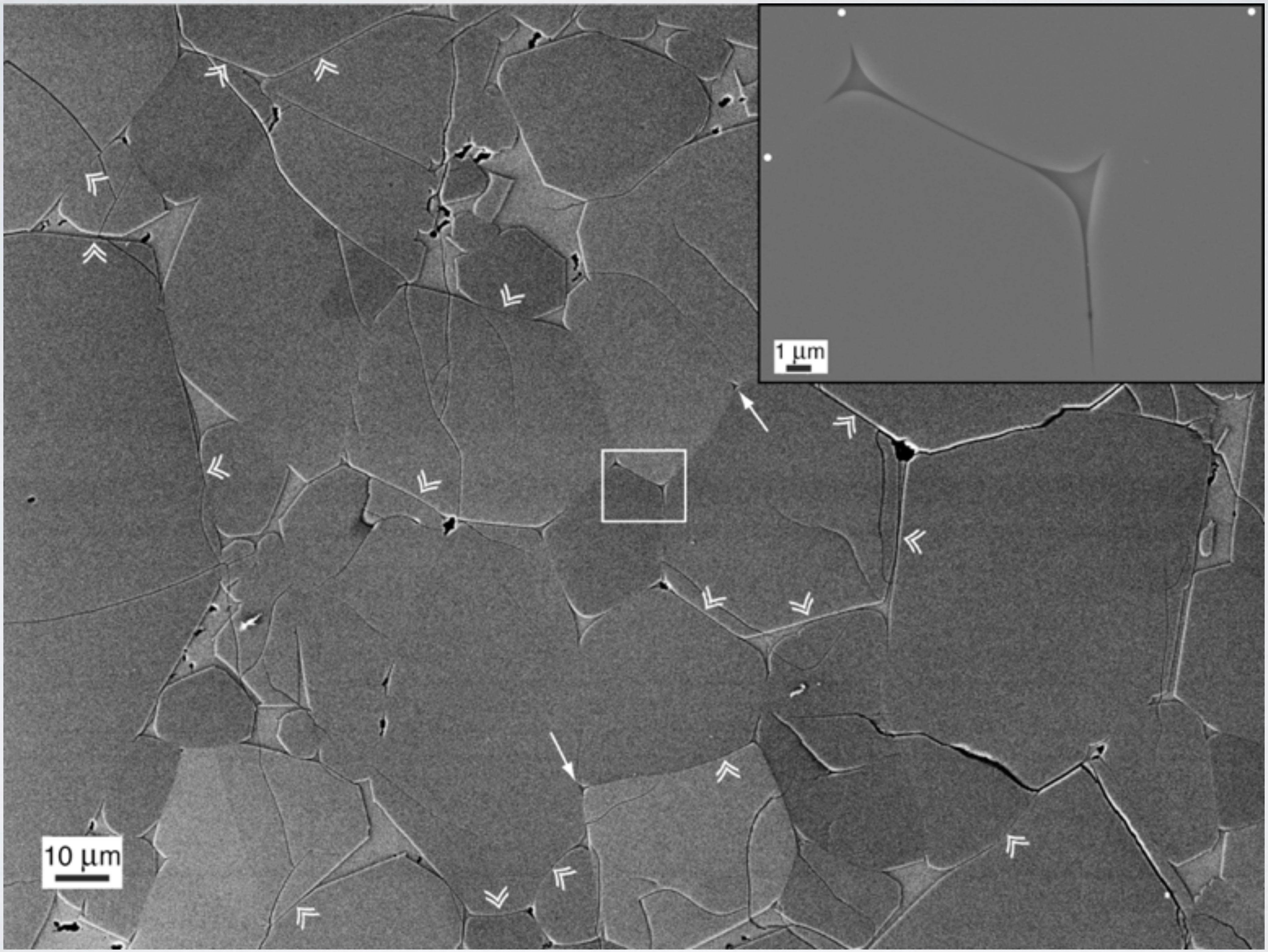
TEM images of three-grain edges



Solgel olivine

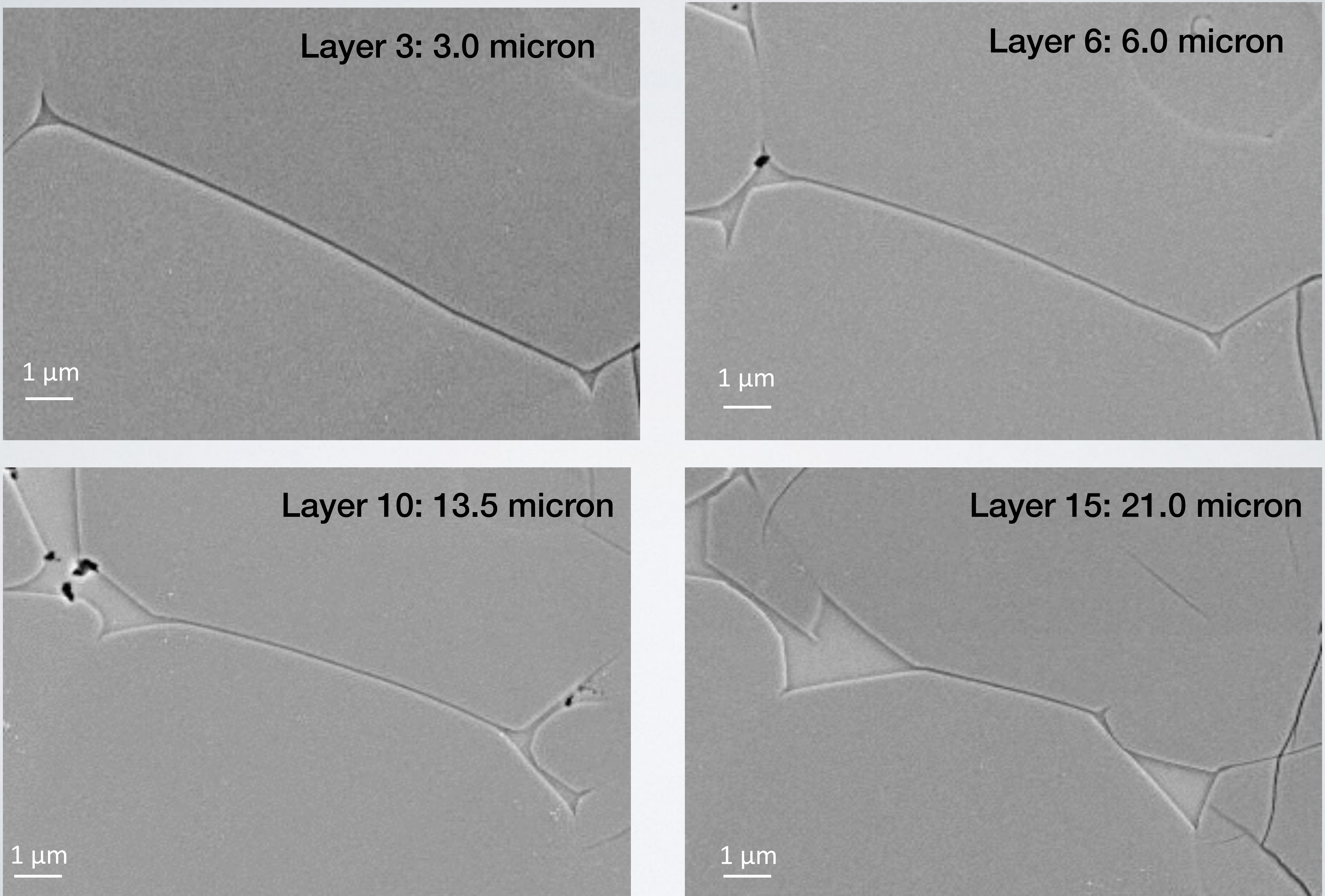
San Carlos olivine

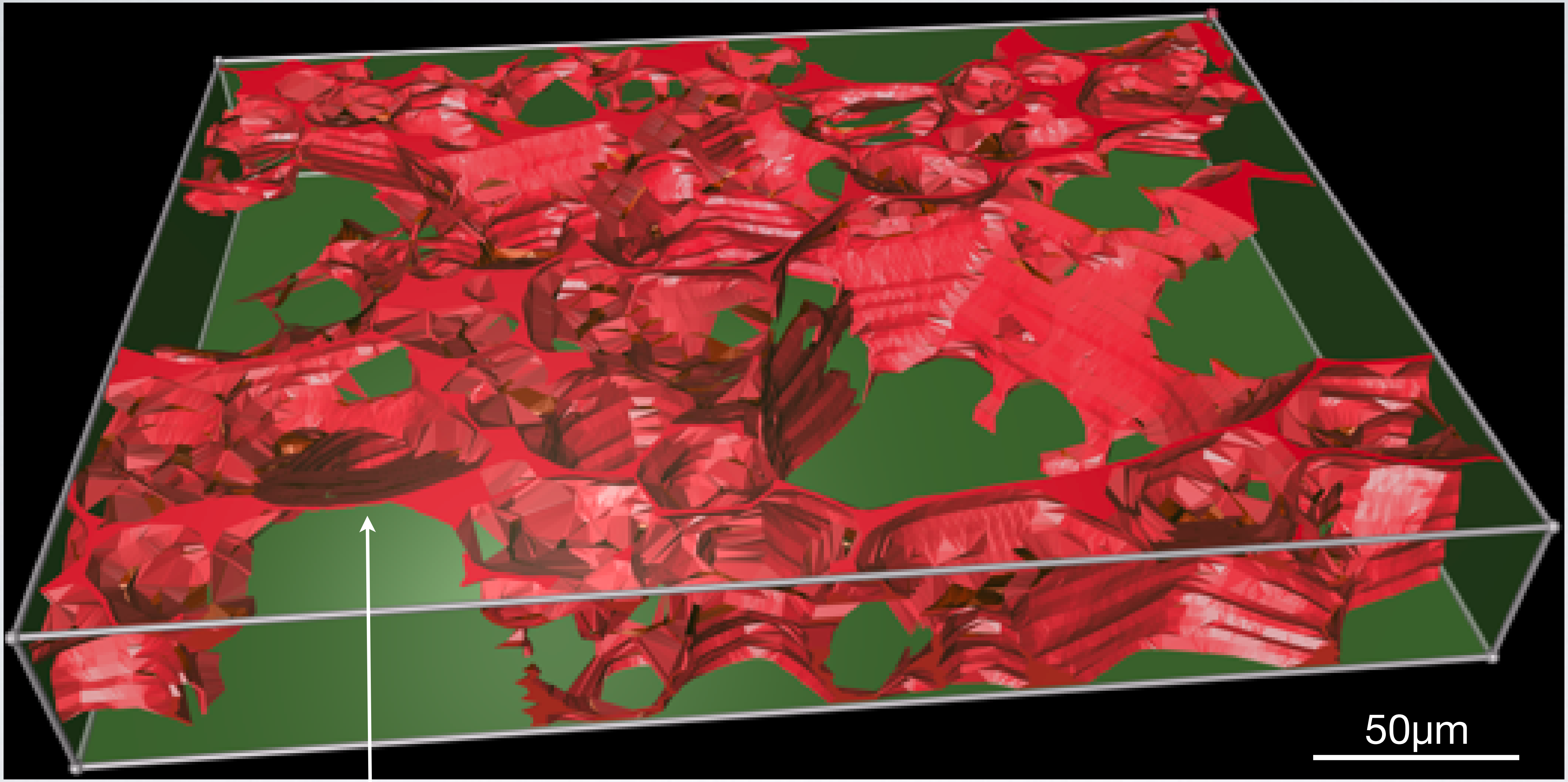
Melt distribution in polycrystalline olivine

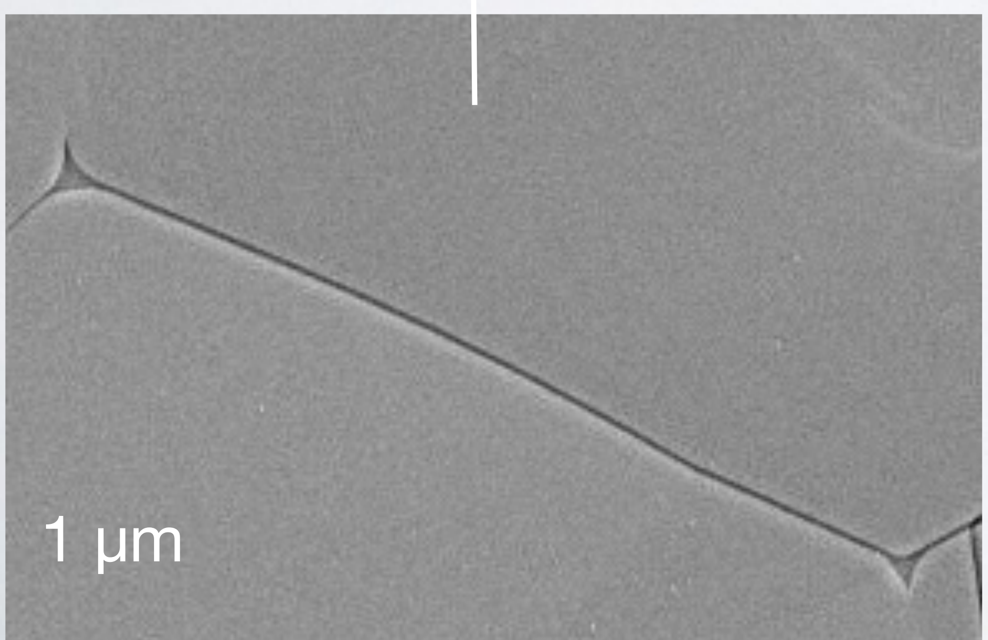


P = 1 GPa, 1350ºC, 432 hours

Serial sectioning + high res. imaging: Thin (~100 nm) layers on two-grain boundaries





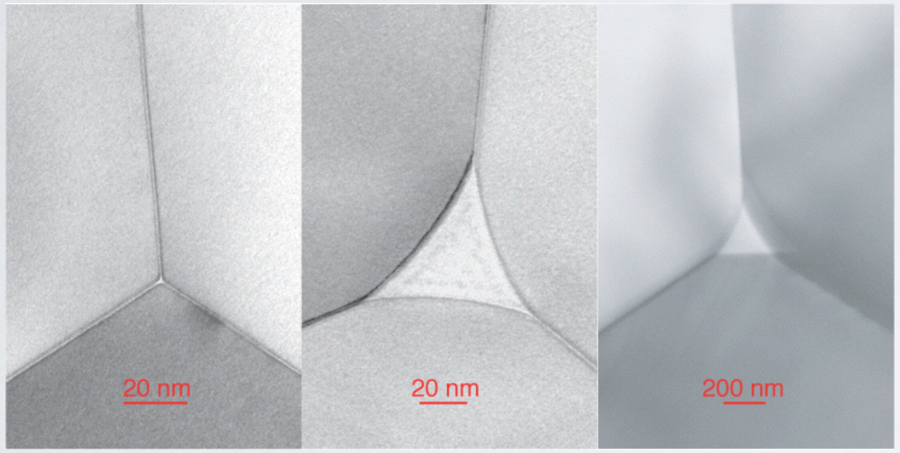


3-D view of the melt distribution
3.6% melt, 30 µm grain size

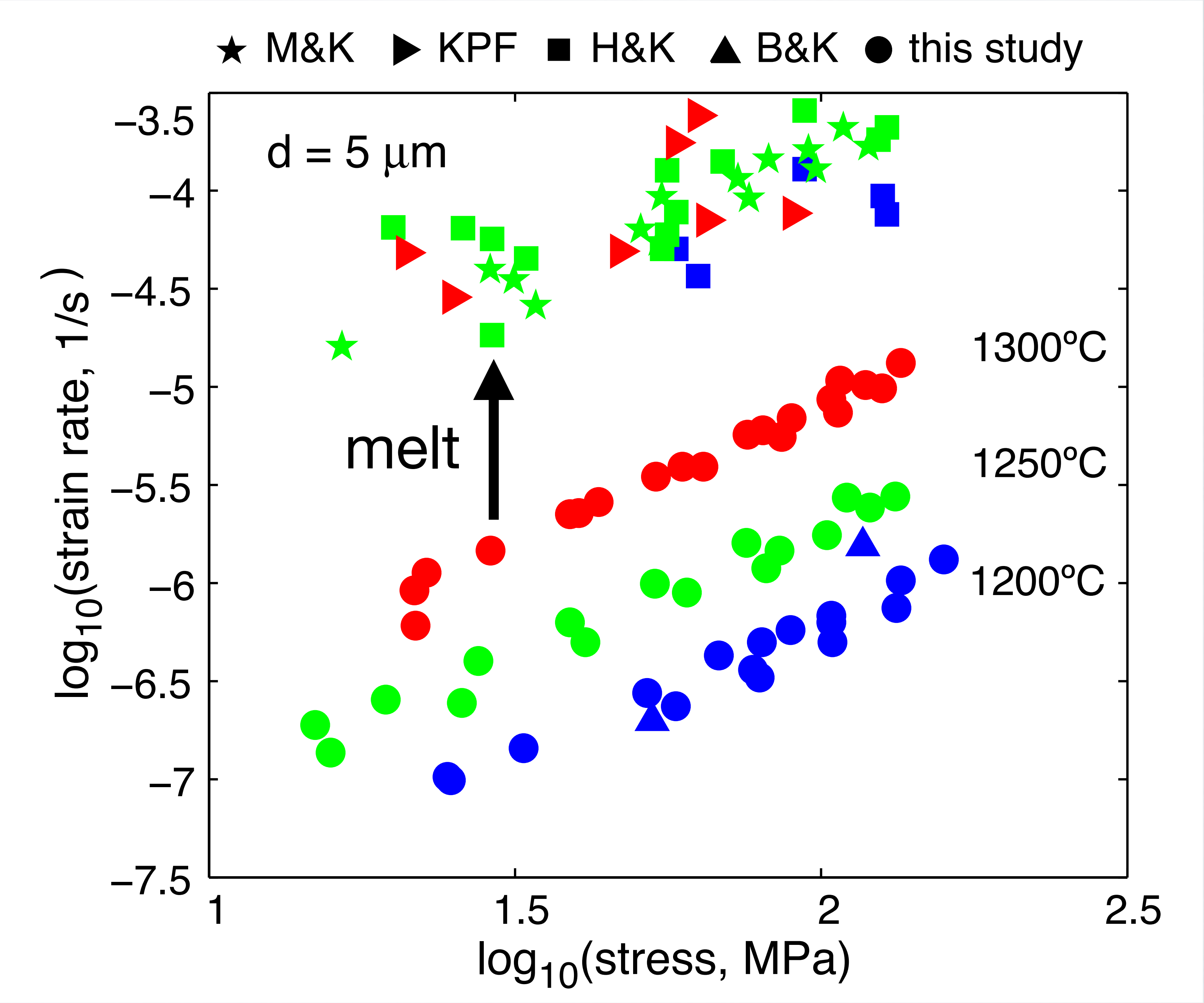
Garapić, Faul and Brisson, G^3, 2013

Influence of melt on rheology

Small amount (1%) of melt enhances strain rate by ~ 1.5 orders of magnitude

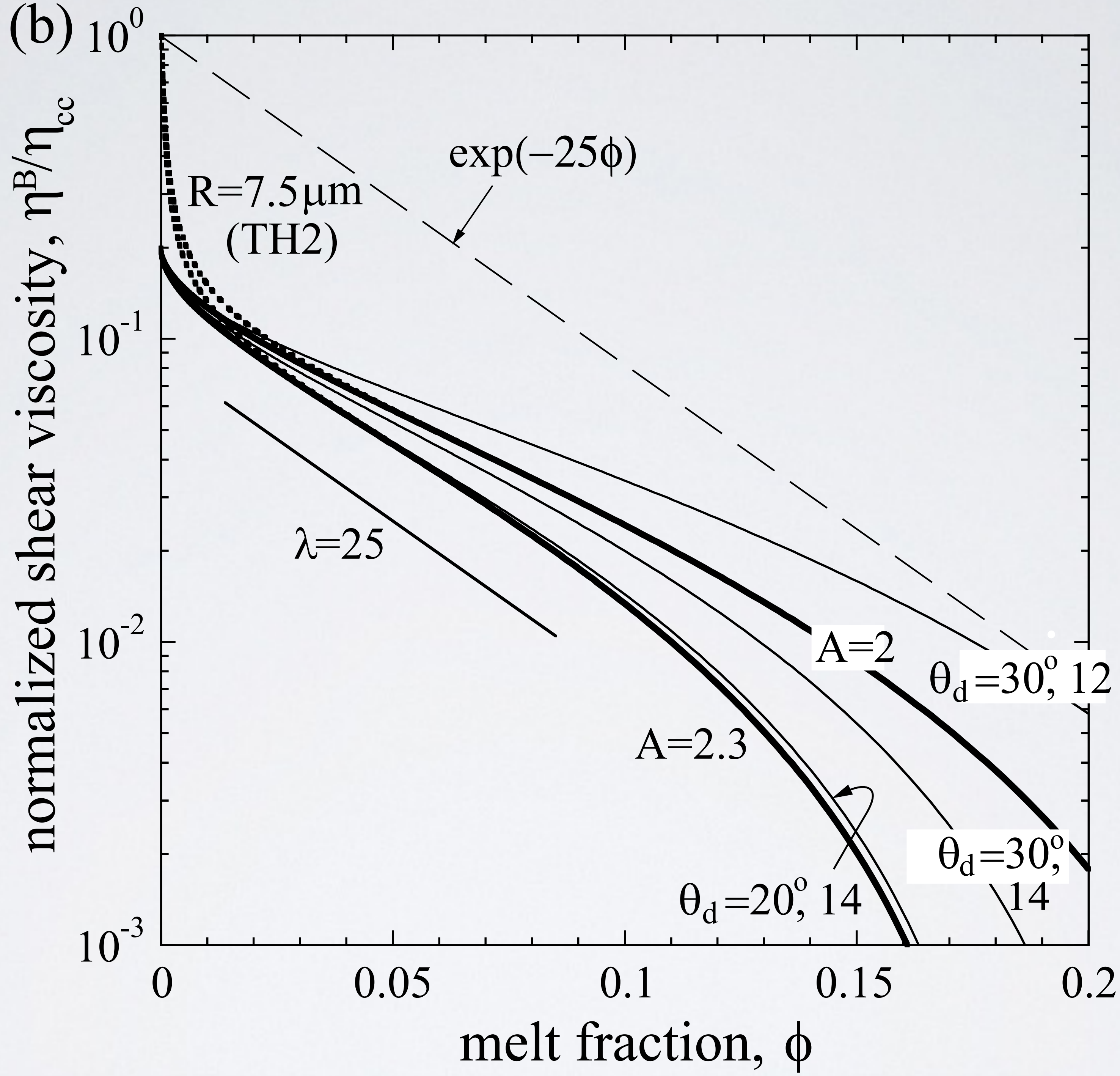


connected melt produces short circuit diffusion paths



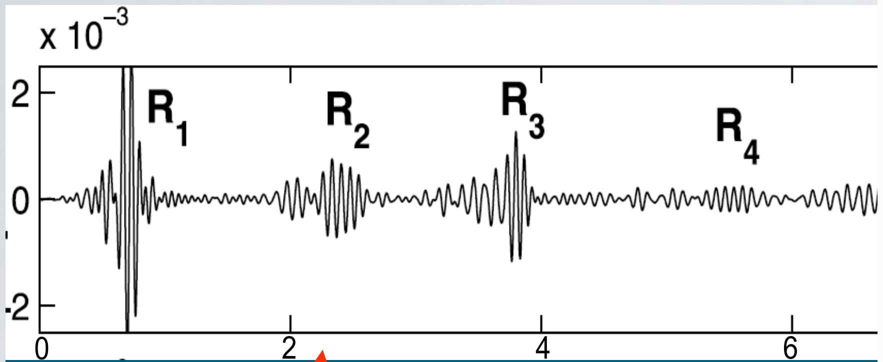
Faul and Jackson, 2007

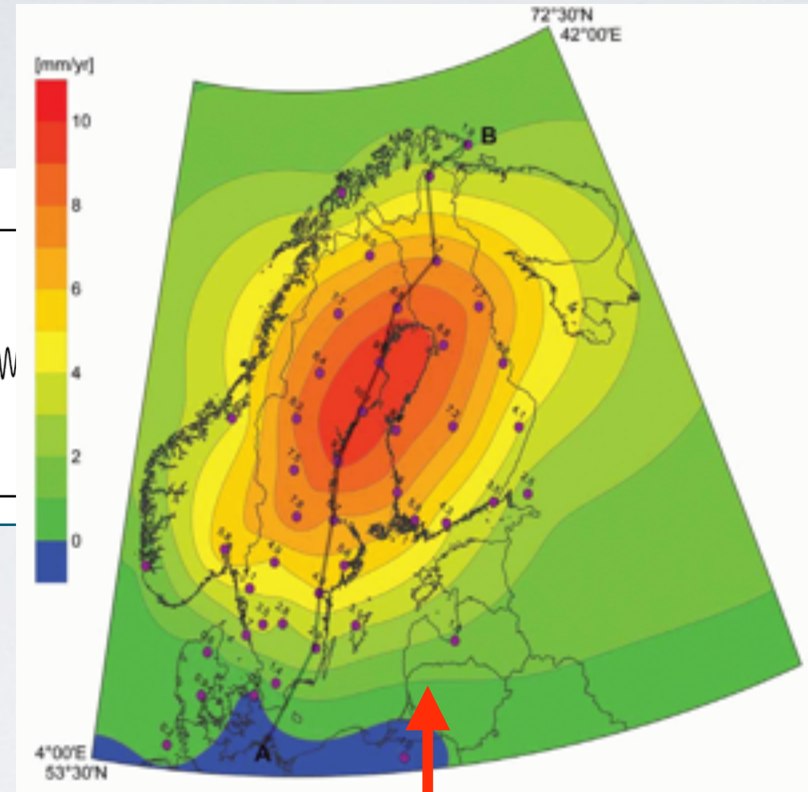
Theoretically predicted viscosity reduction due to melt

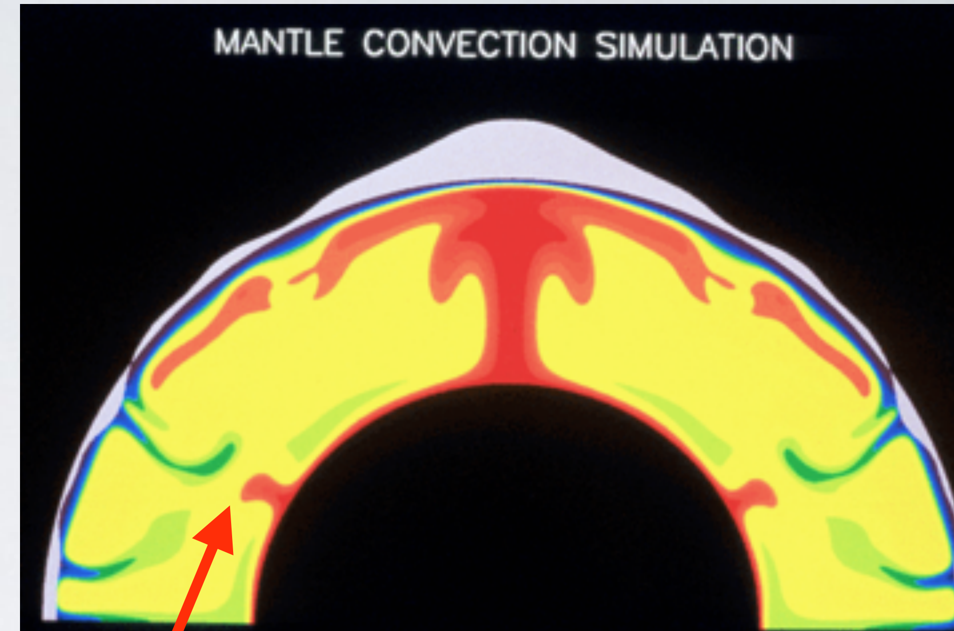


Takei & Holtzman, 2009

Deformation at a range of time scales

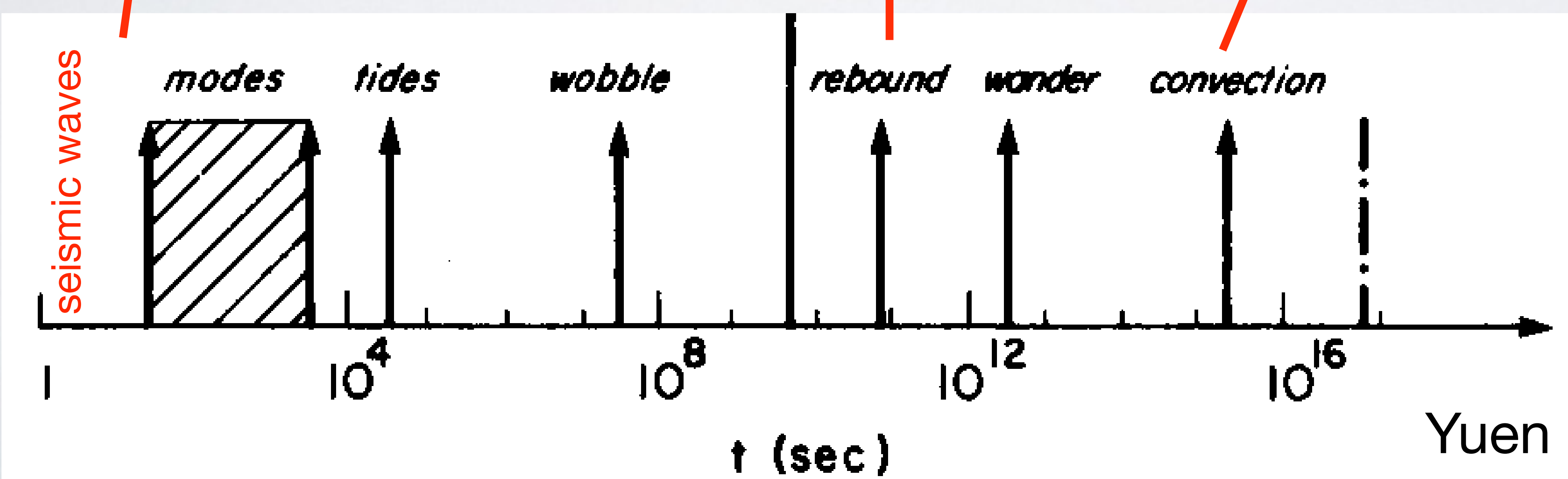






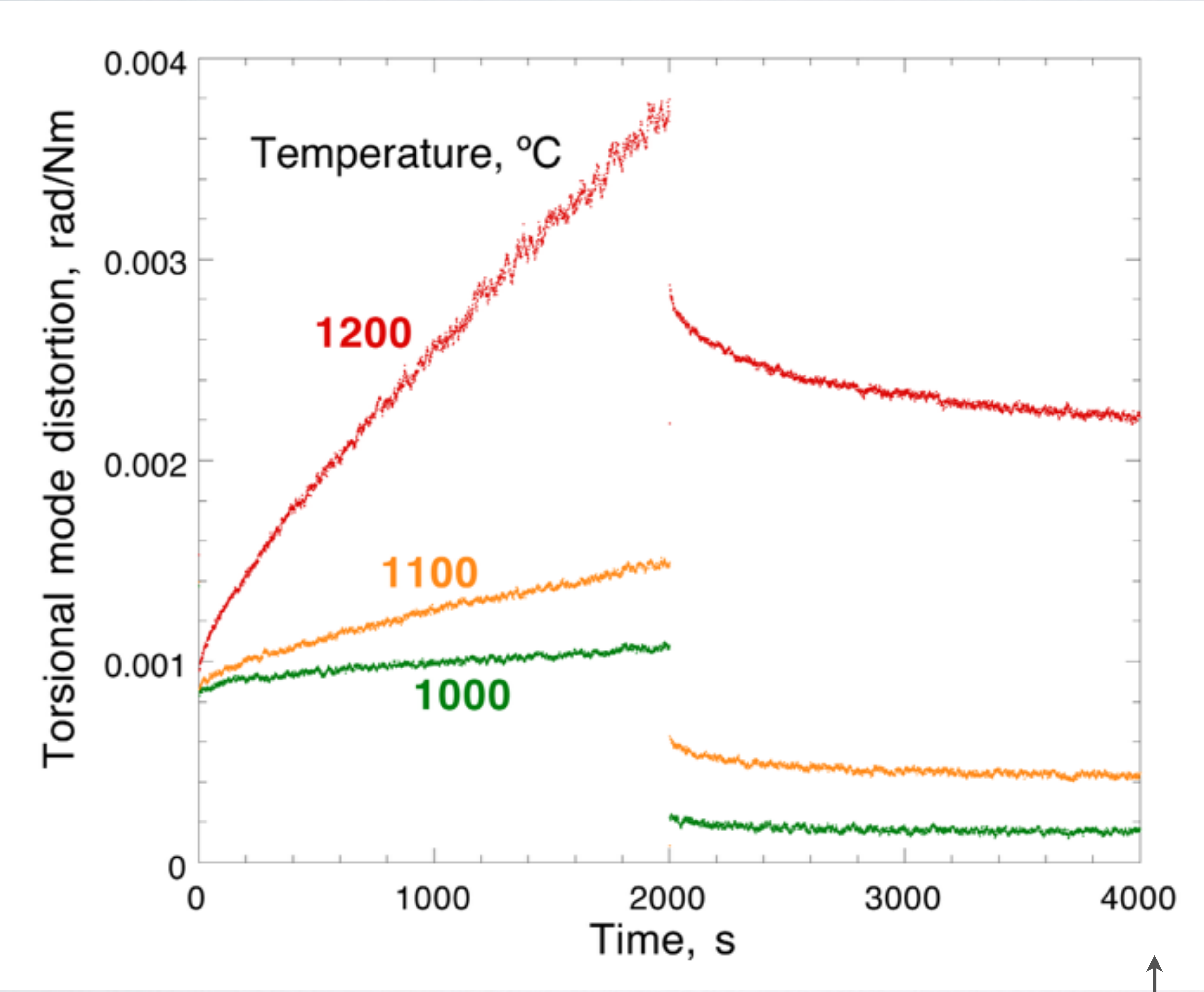
$\varepsilon < 10^{-4}$

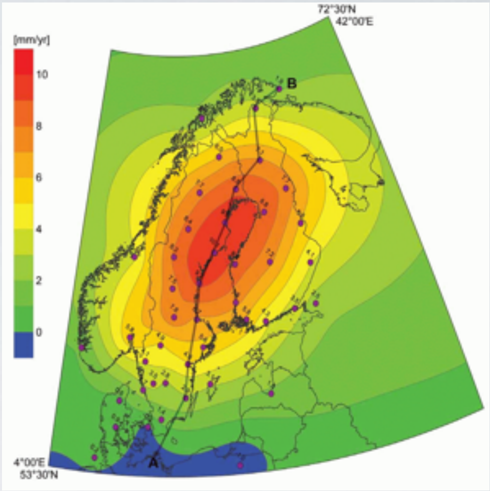
$\varepsilon >> 1$



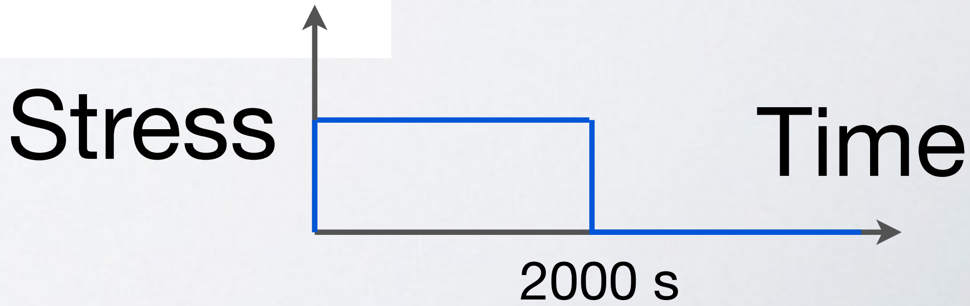
Yuen & Peltier, 1982

Microcreep experiments (time domain)

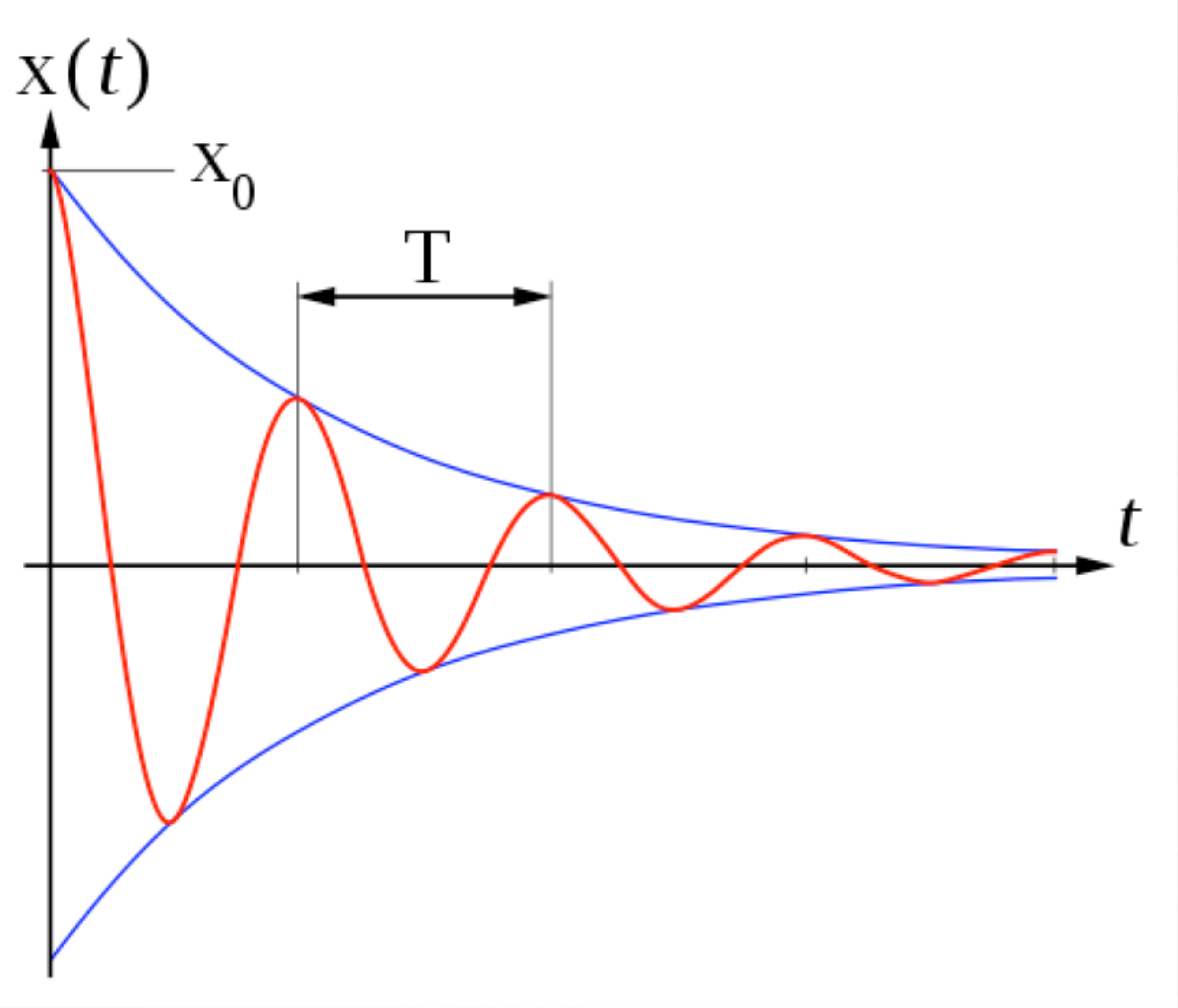




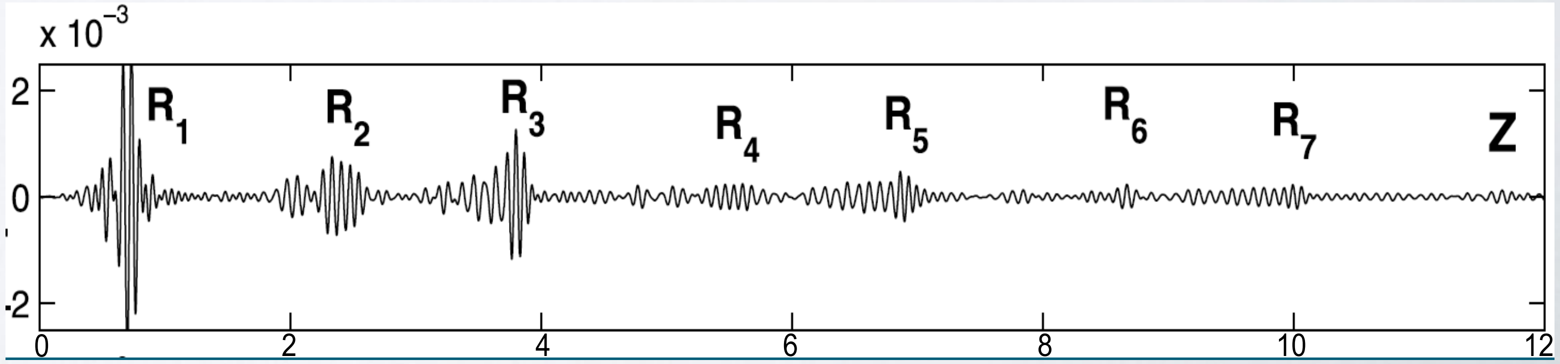
$\varepsilon < 10^{-4}$



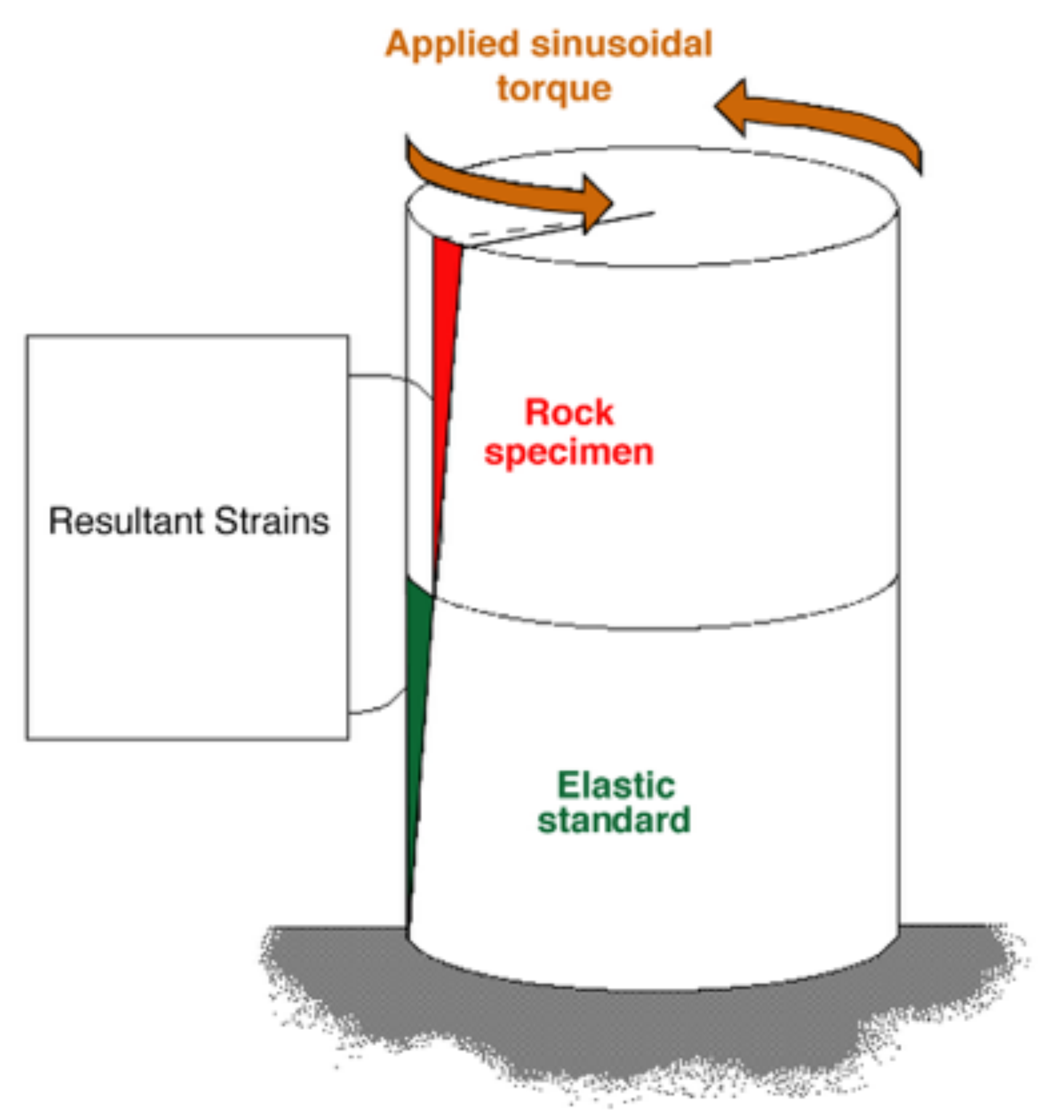
Attenuation/dissipation (frequency domain)
amplitude decreases with each cycle



Q^{-1} = δE/E * 1/2π



Experiments: Measurement of shear modulus (G) and attenuation (1/Q)



Research School of Earth Sciences, Australian National University

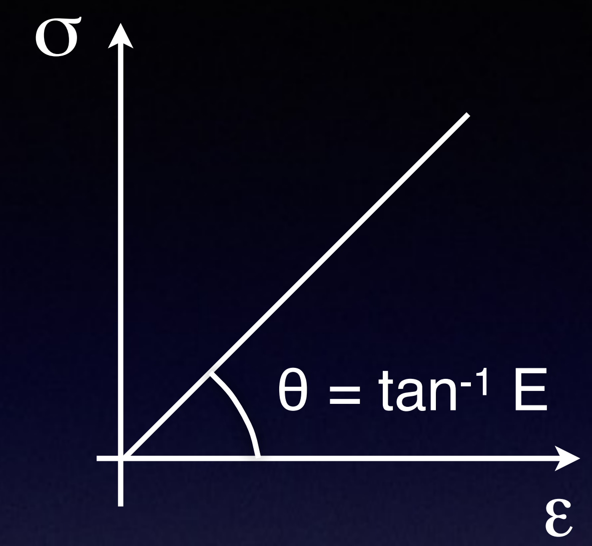
Experiments at
- temperatures to 1300°C
- periods 1 - 1000s
- 200 MPa confining pressure

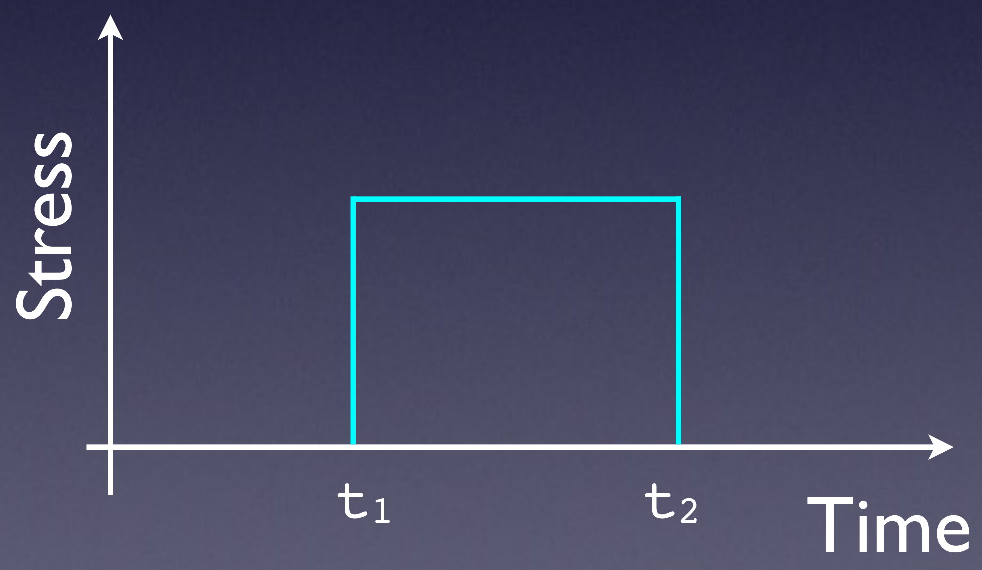
Measure shear modulus G and dissipation/attenuation

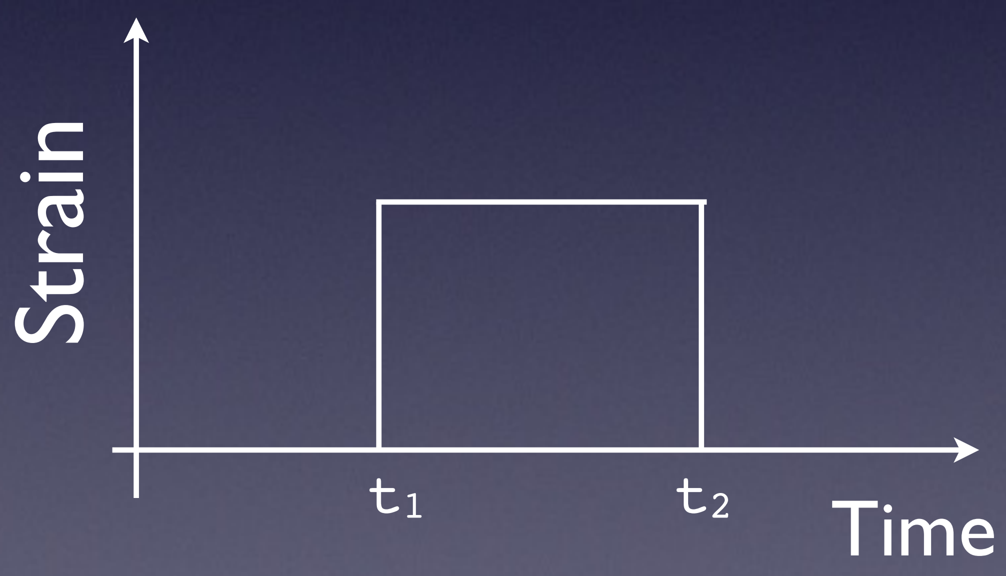
Attenuation (1/Q): energy loss per cycle

Elastic behavior (Spring): Hooke's Law

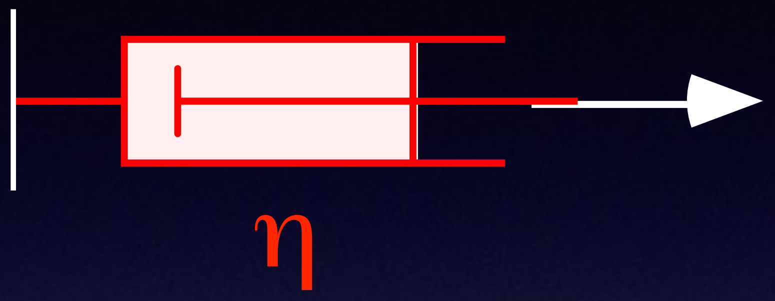
$$\sigma = E\,\varepsilon$$





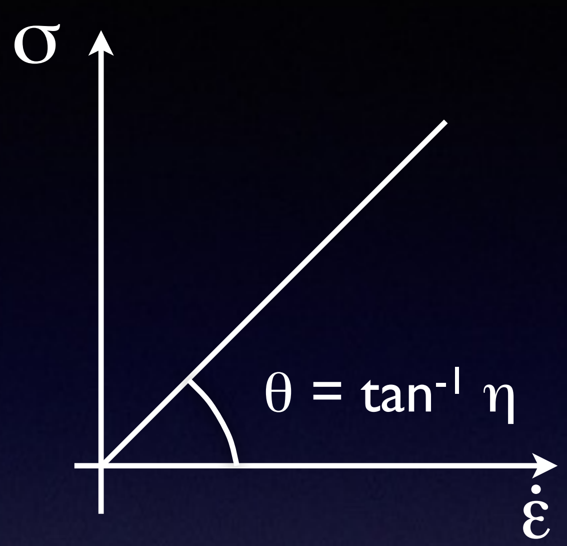


Viscous behavior (leaky dashpot)

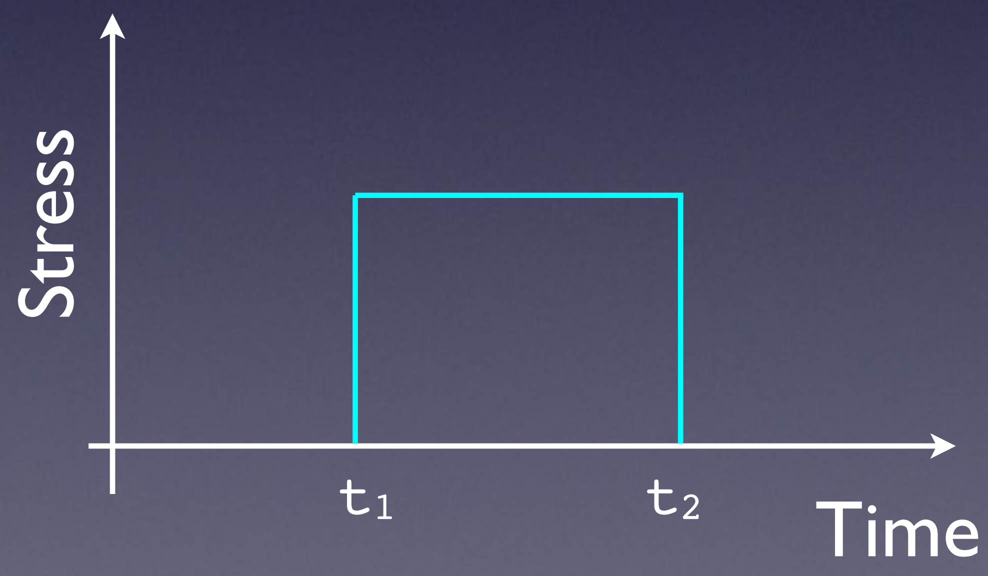


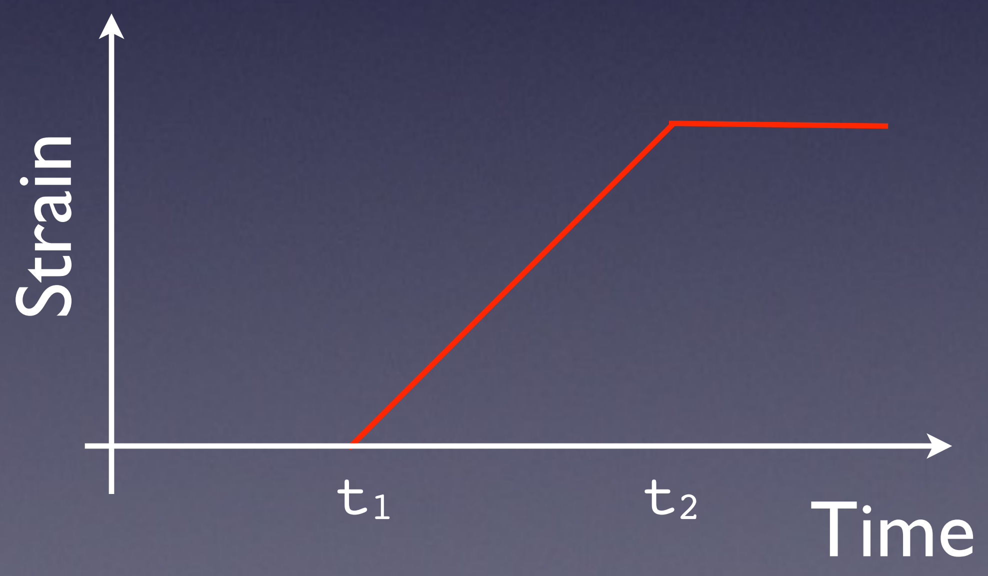
$$\sigma = \eta\,\dot{\varepsilon}$$

increasing strain rate results in increasing stress, with viscosity constant of proportionality

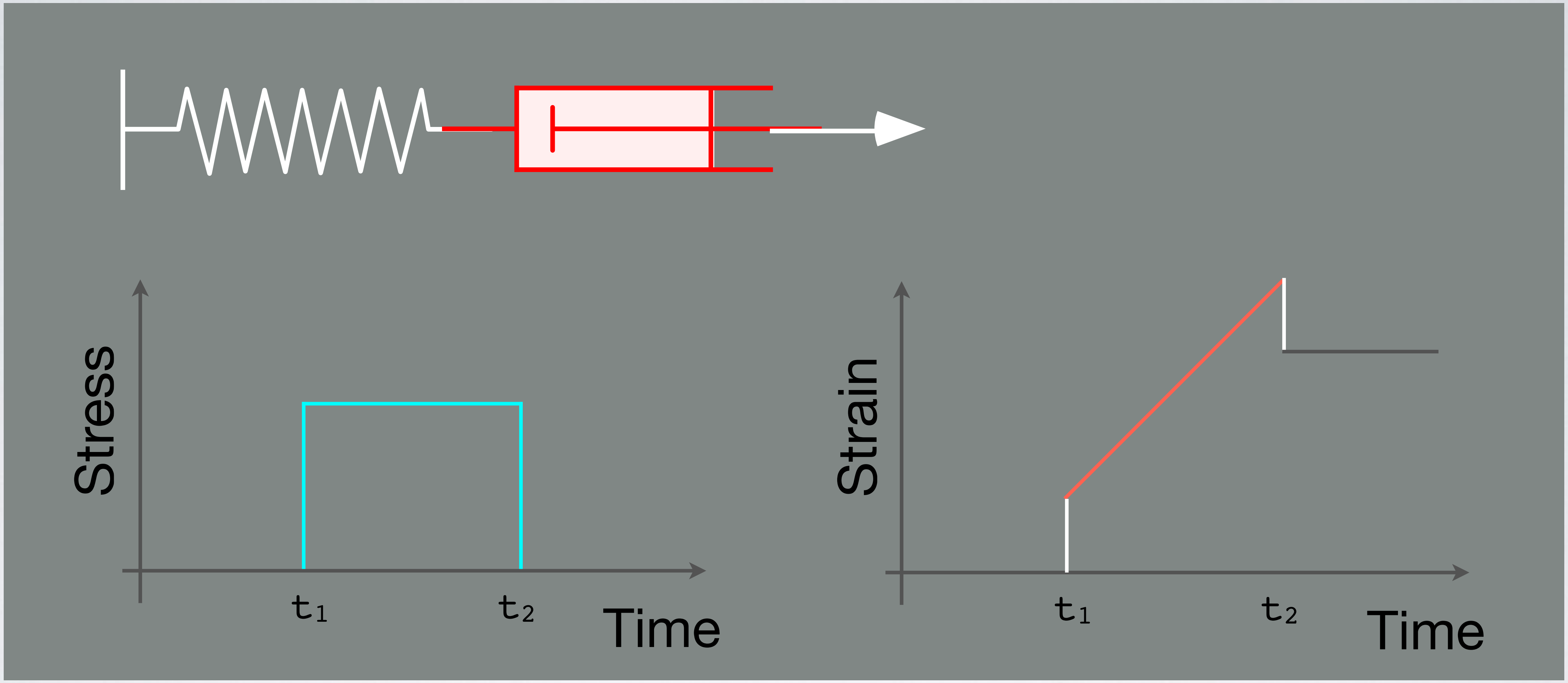


For a step function application of stress:



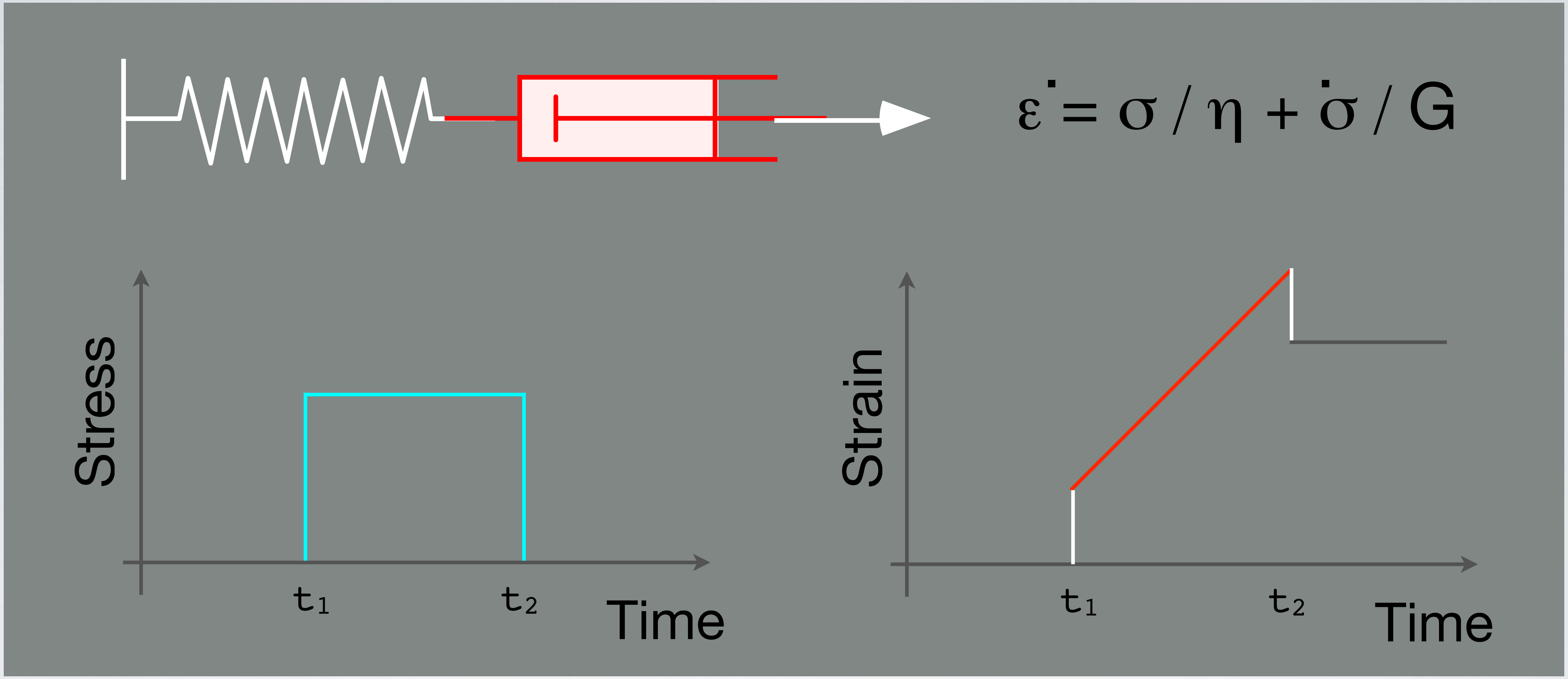


Maxwell body: viscoelastic



relevant elastic modulus for deformation of solid Earth is shear modulus G

Maxwell body

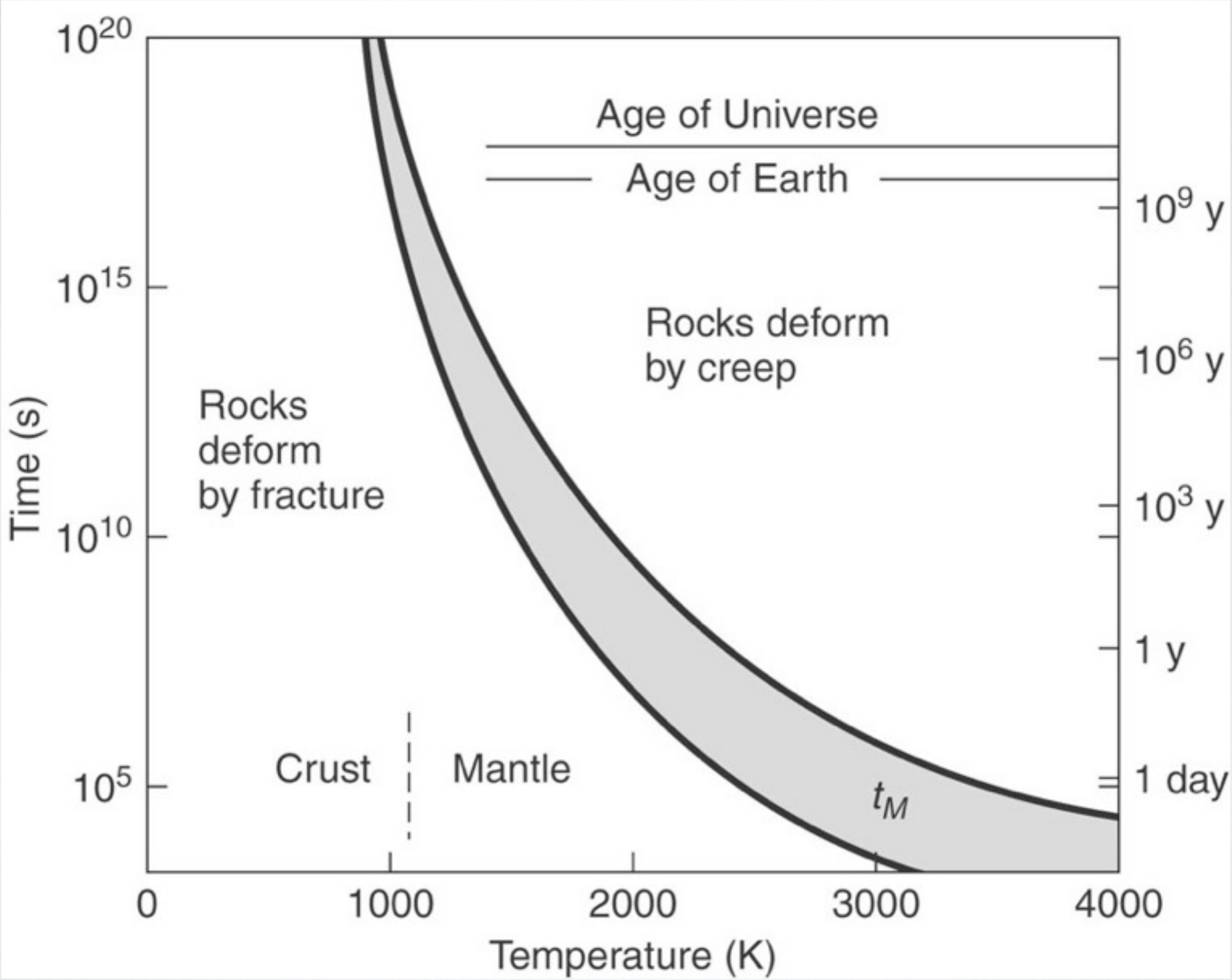


relevant elastic modulus for deformation of solid Earth is shear modulus G

For constant strain:

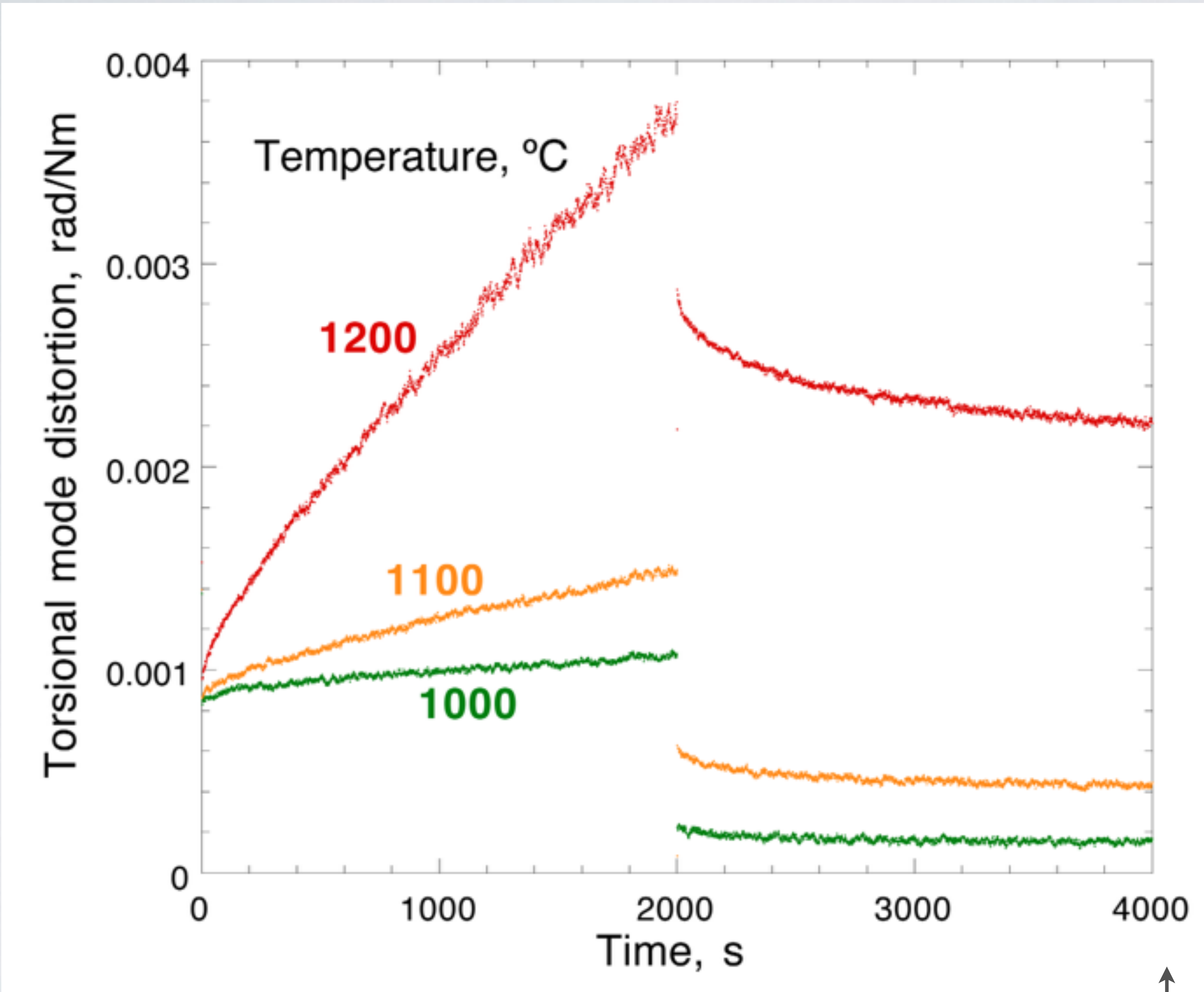
with $\dot{\varepsilon} = 0$: $\sigma = \sigma_0 \exp(-(G/\eta)\, t)$, exponential decay of stress with Maxwell relaxation time $\tau_M = \eta/G$

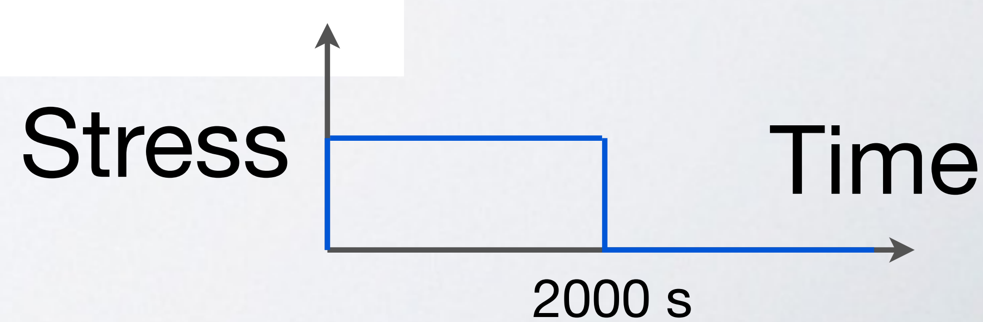
Maxwell relaxation time: how quickly does stress decay in the Earth?



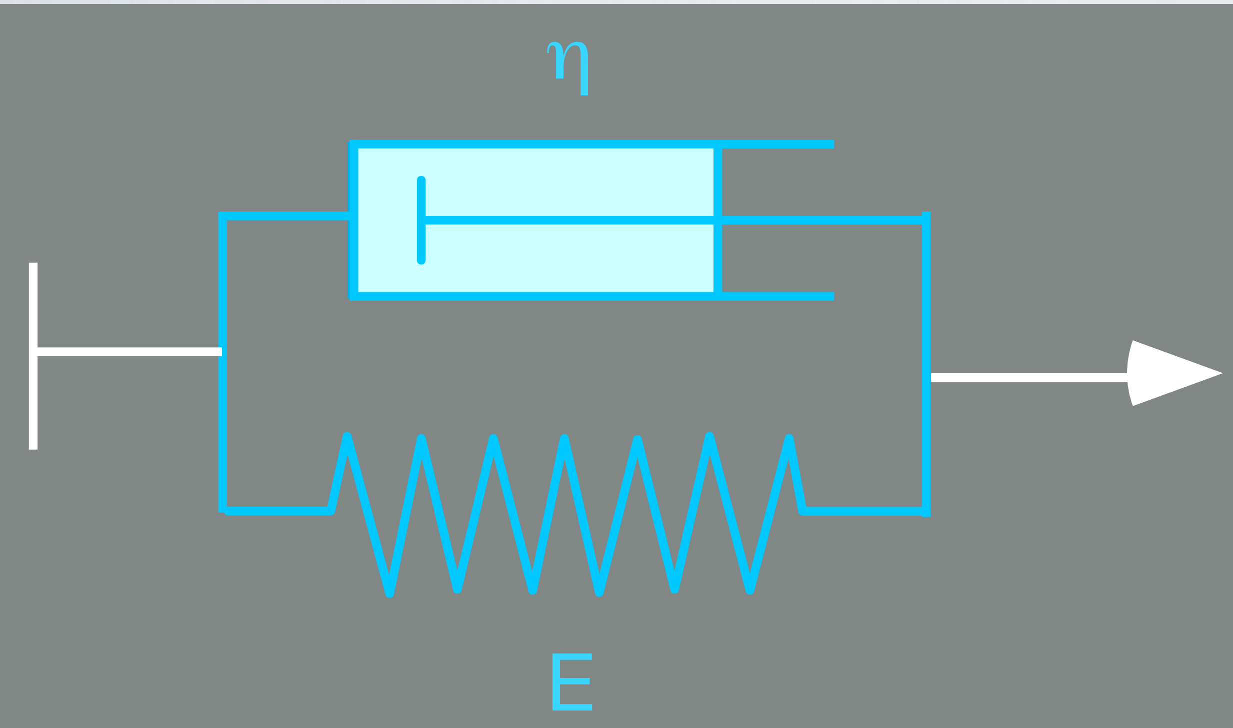
Microcreep experiments

$\varepsilon < 10^{-4}$

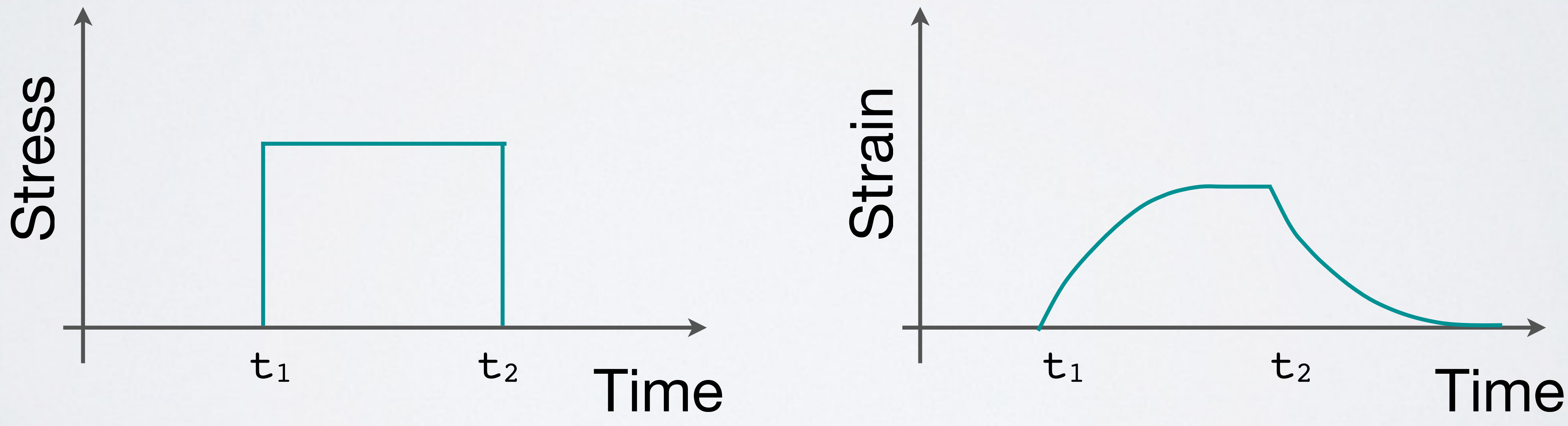




Anelastic behavior (transient creep)

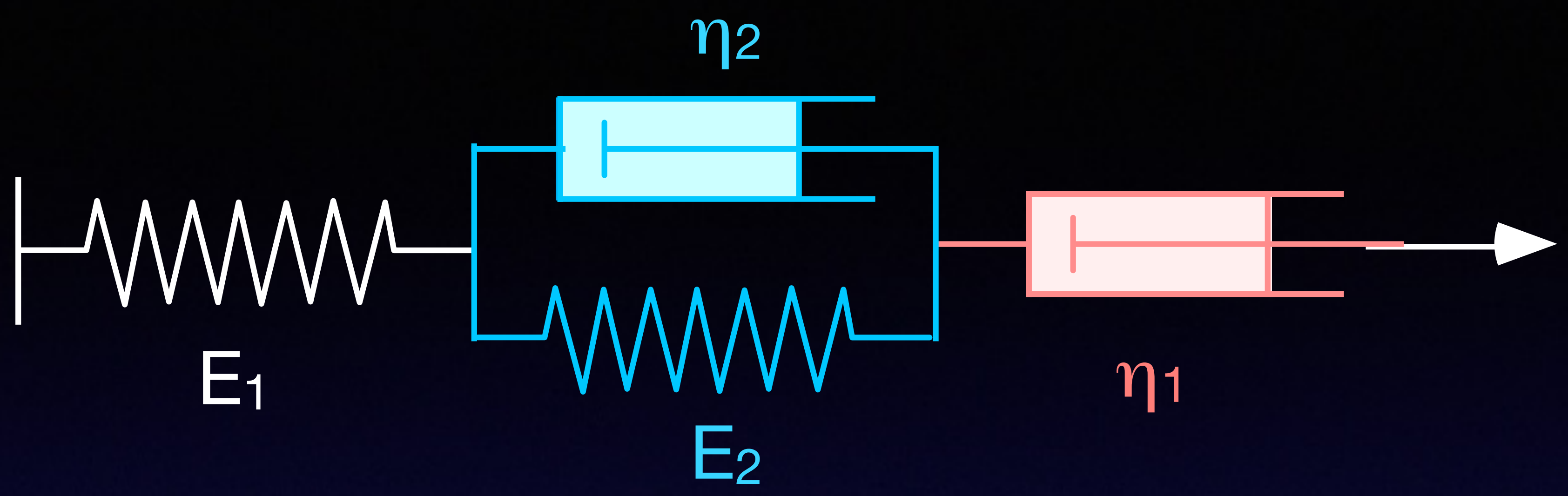


$$\sigma = \eta\, \dot{\varepsilon} + G\, \varepsilon$$

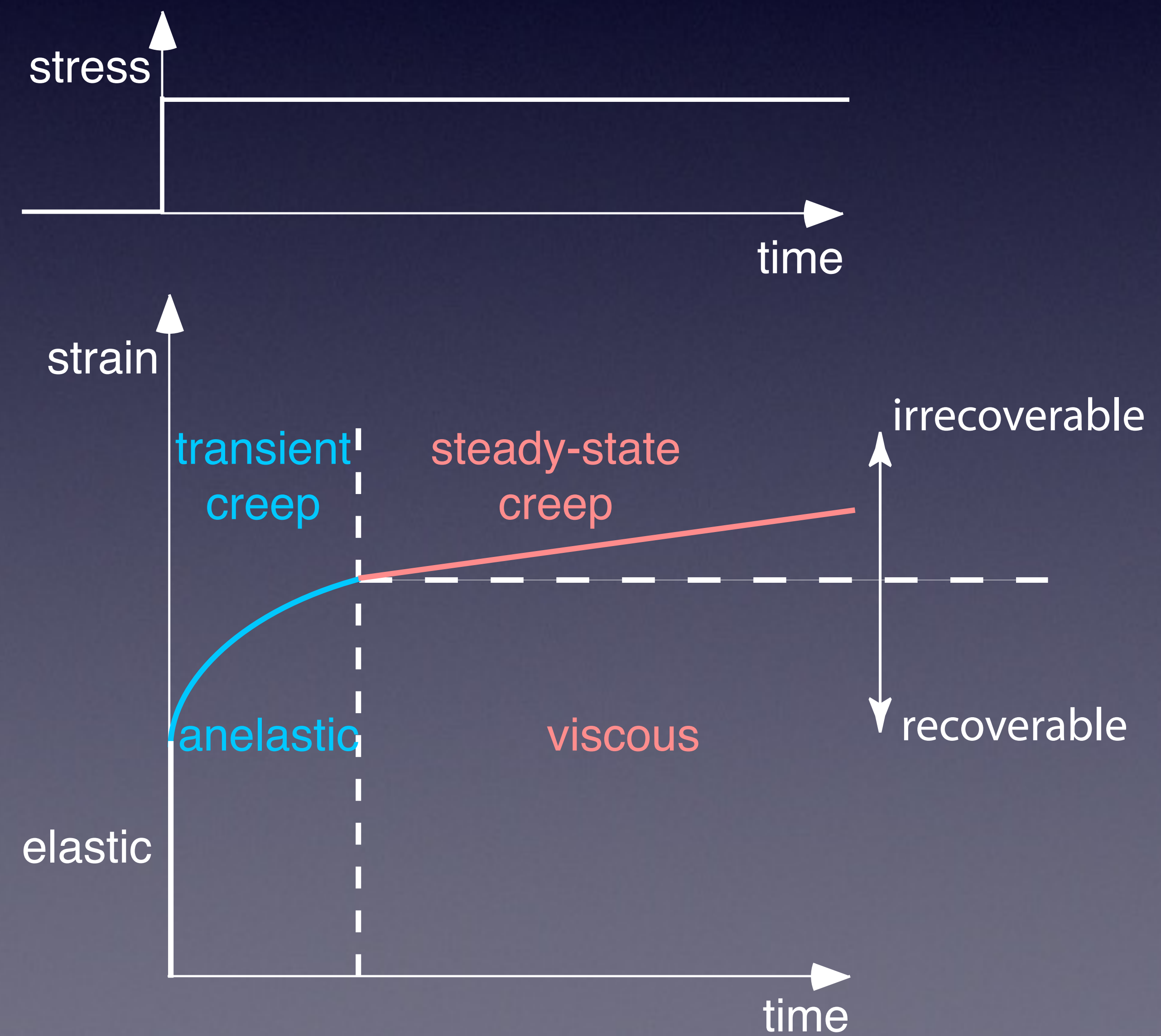


time-dependent, unique equilibrium, recoverable

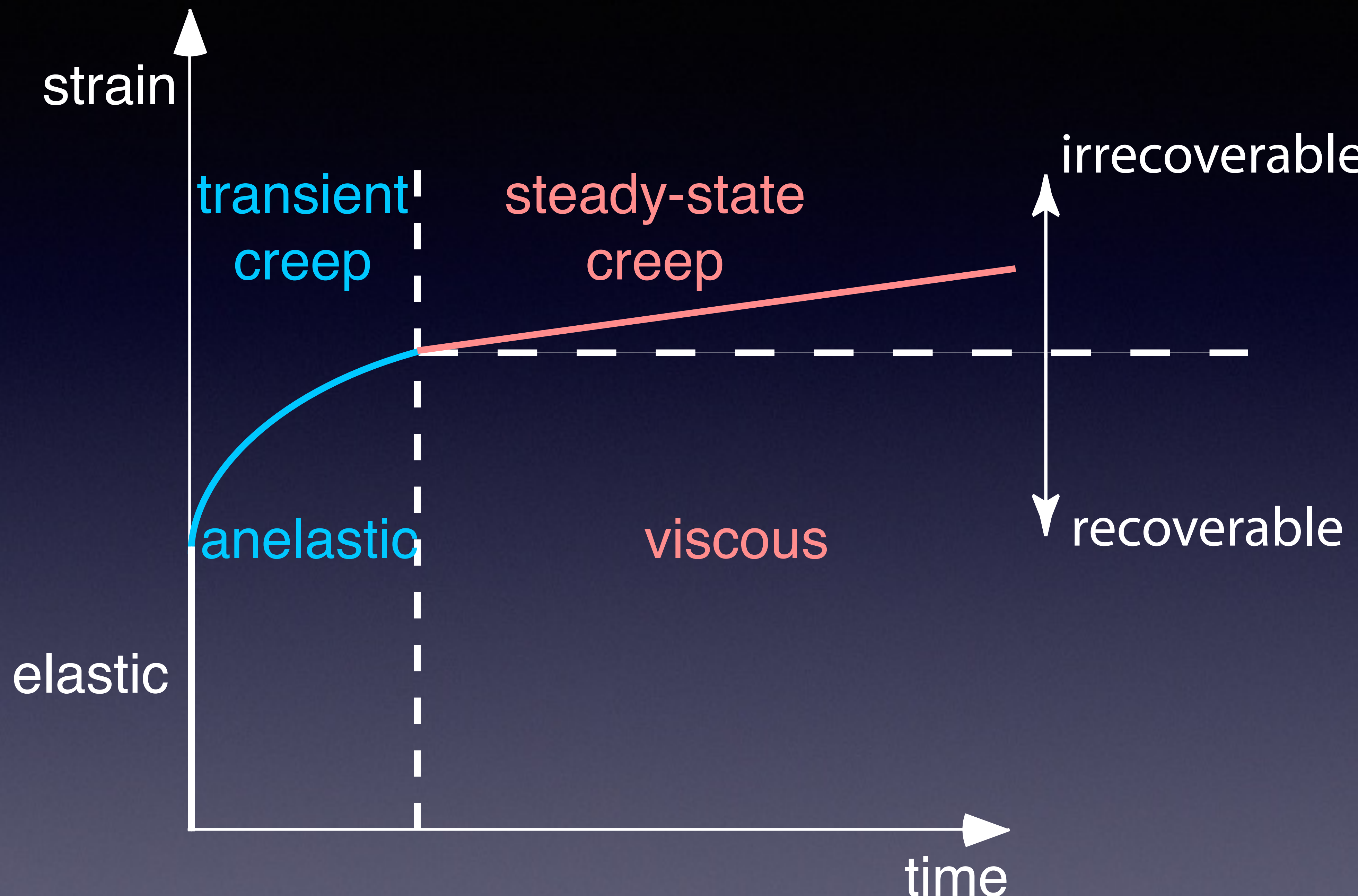
Viscoelastic behavior: Burgers Model



$$\varepsilon(t) = \varepsilon_e + \varepsilon_t(t) + \dot{\varepsilon}t$$

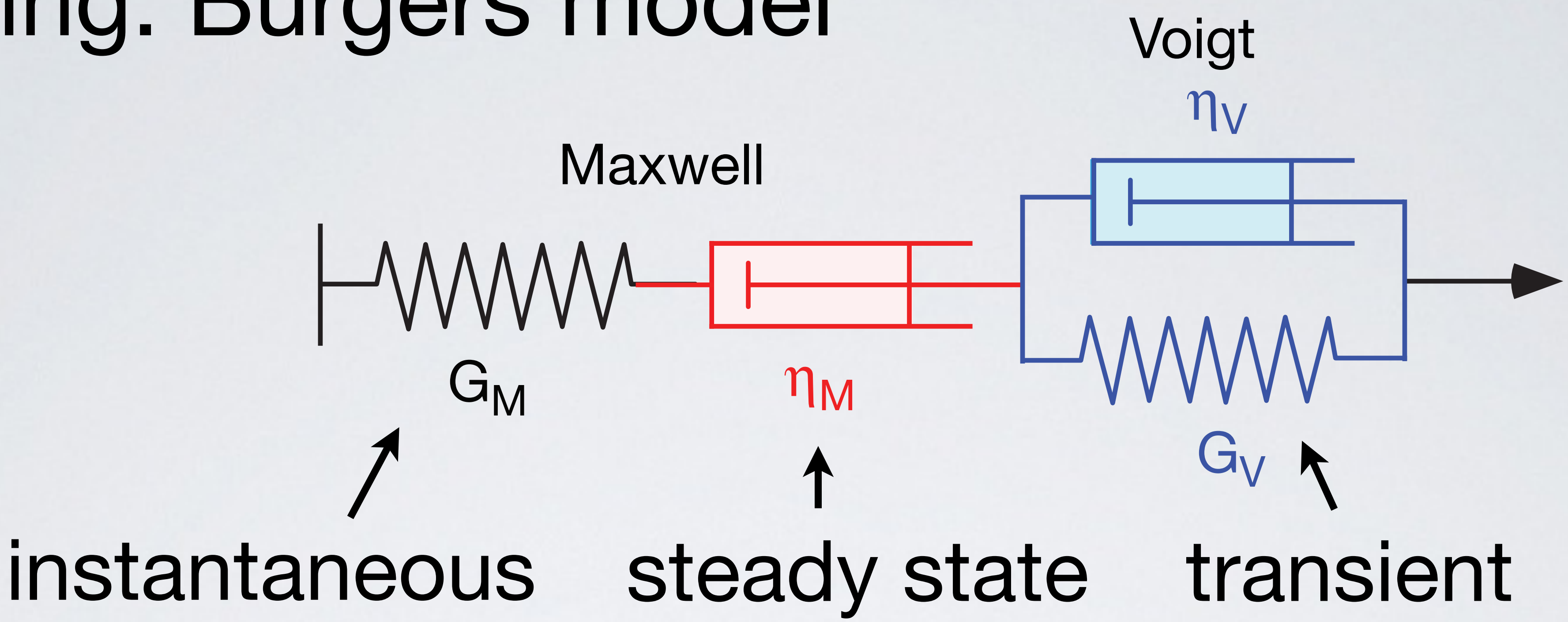


Timescales of deformation in the Earth



(Earth-quakes) Seismic waves Post-glacial rebound Mantle convection

Data fitting: Burgers model



Time domain: strain as a function of time (creep function)

$$J(t) = J_M + t/\tau_M + J_V\,(1 - \exp(-t/\tau_V))$$

$J_M = 1/G_M$; $\tau_{M,V}$ relaxation times

Frequency domain:

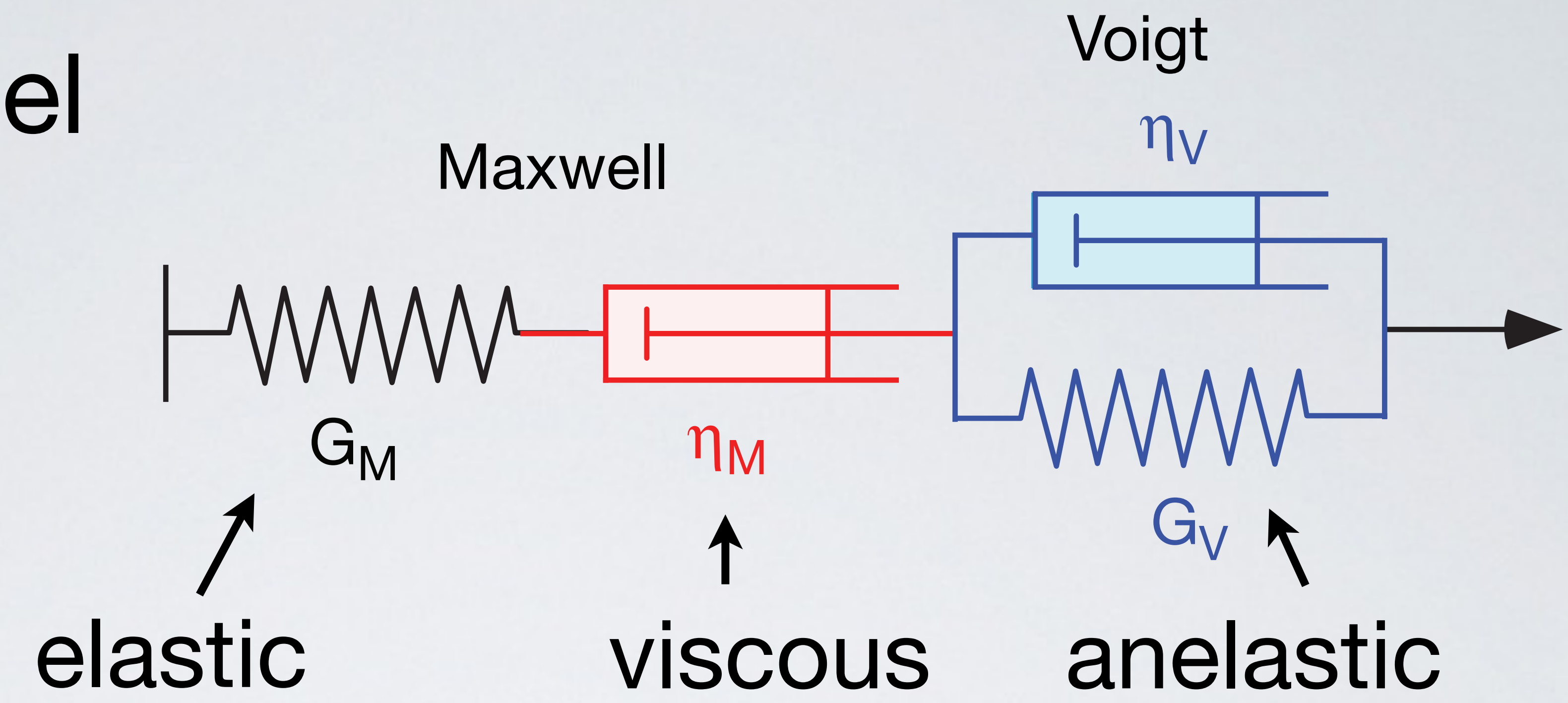
$$J^*(w) = J_1(\omega) + i\,J_2(\omega)$$

$$J_1(\omega) = J_M + J_V\,/(1 + \omega^2\tau_V^2),$$

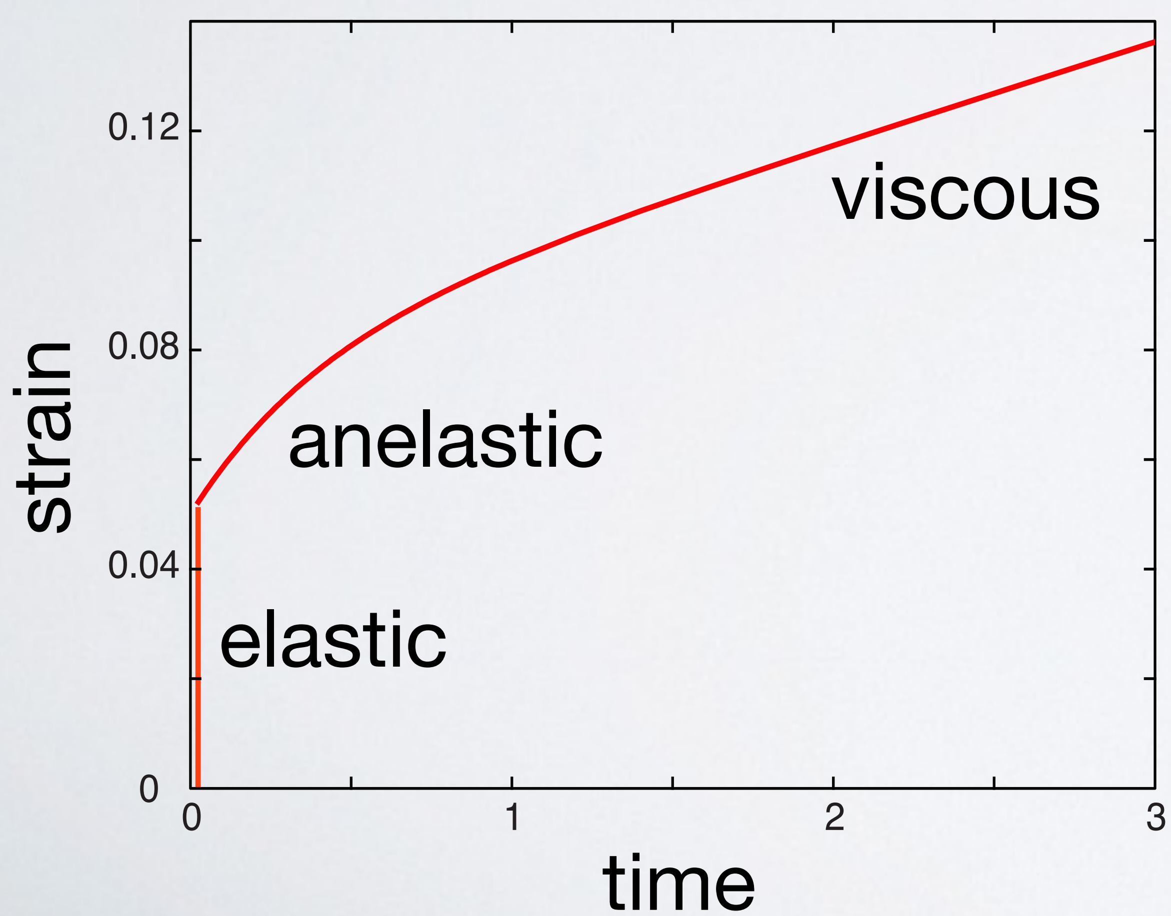
$$J_2(\omega) = J_V\,\omega\tau_V/(1 + \omega^2\tau_V^2) + 1/\omega\tau_M$$

$$G(\omega) = [J_1^2(\omega) + J_2^2(\omega)]^{-1/2} \quad Q(\omega) = J_1(\omega)/J_2(\omega)$$

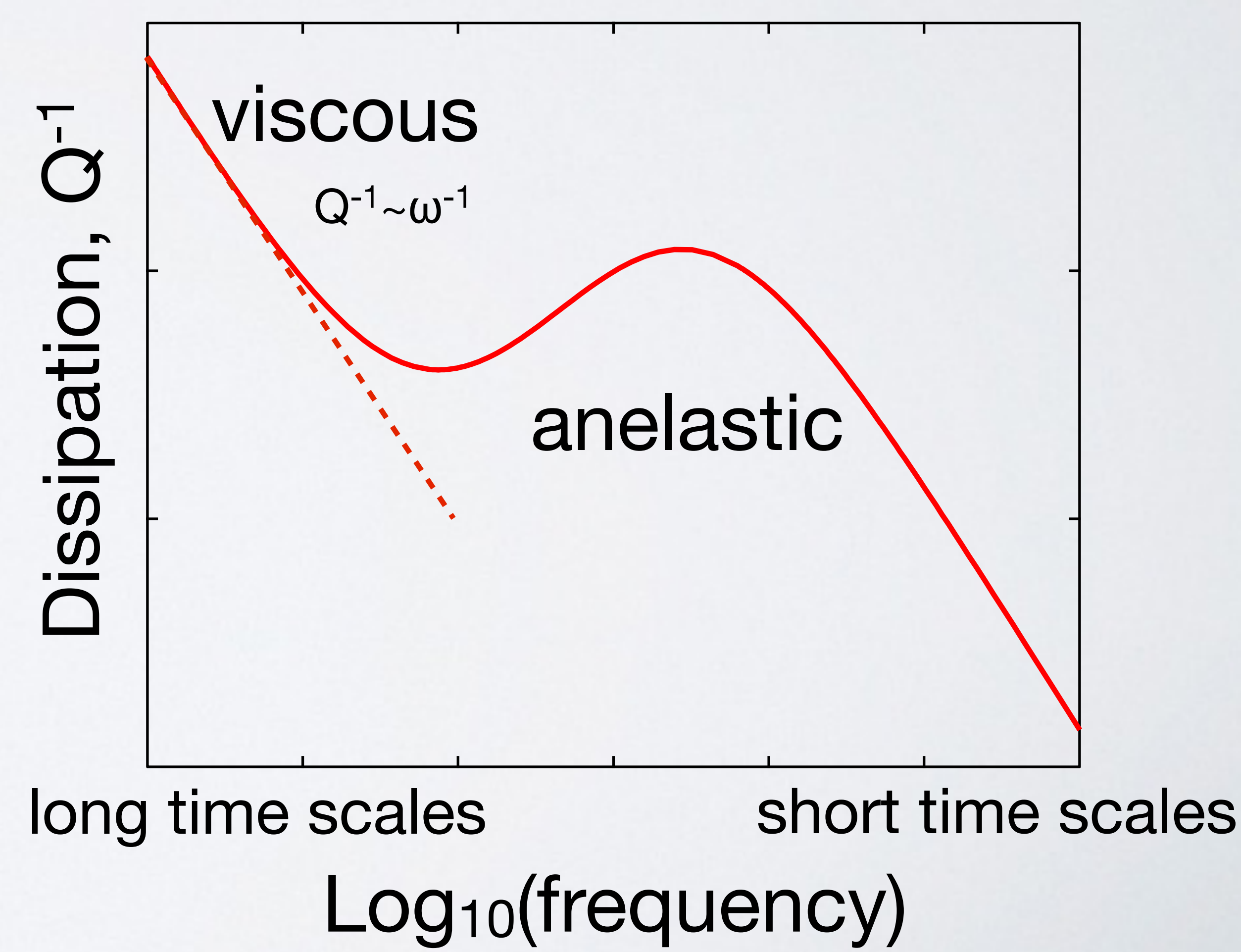
Burgers model



time domain

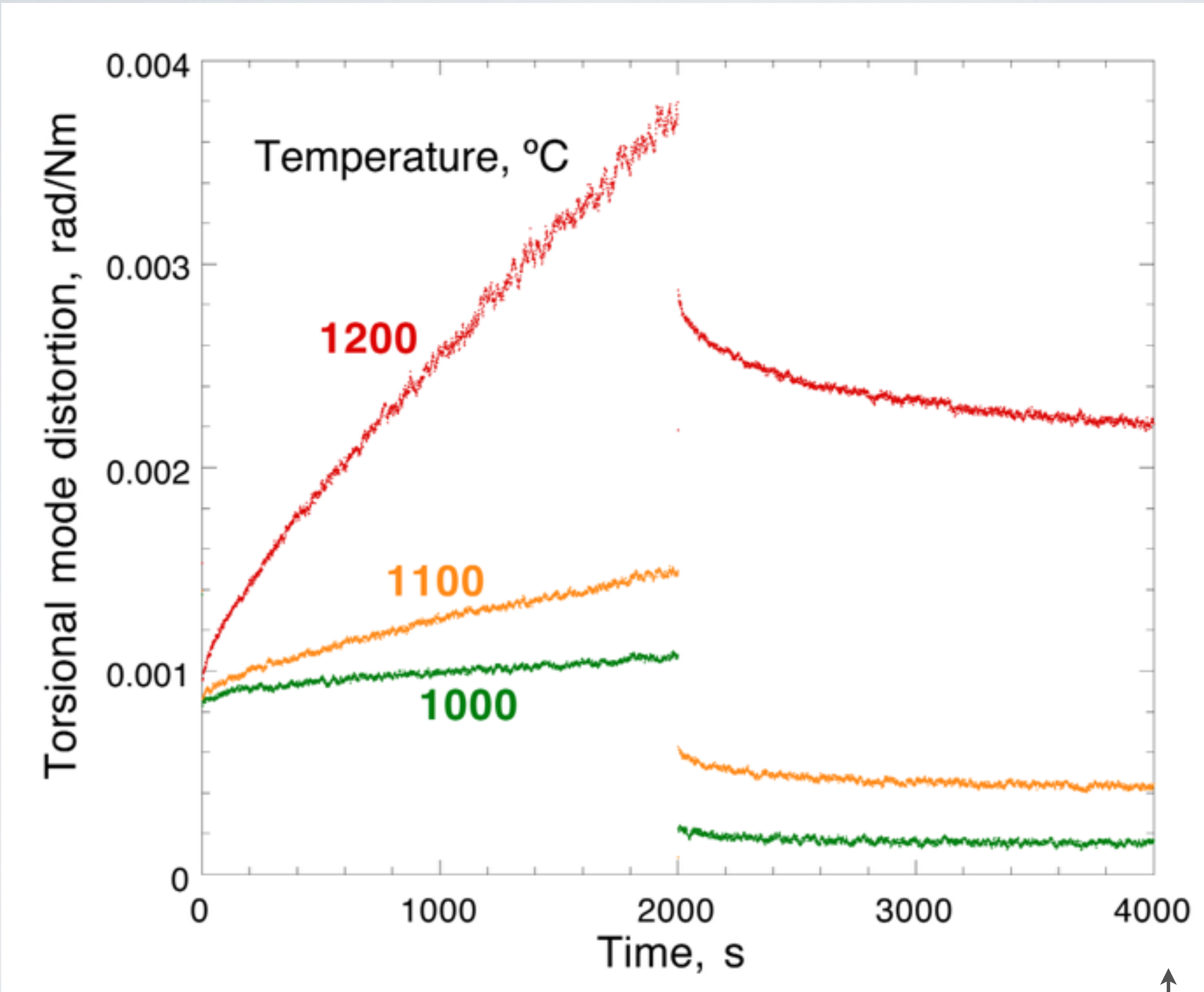


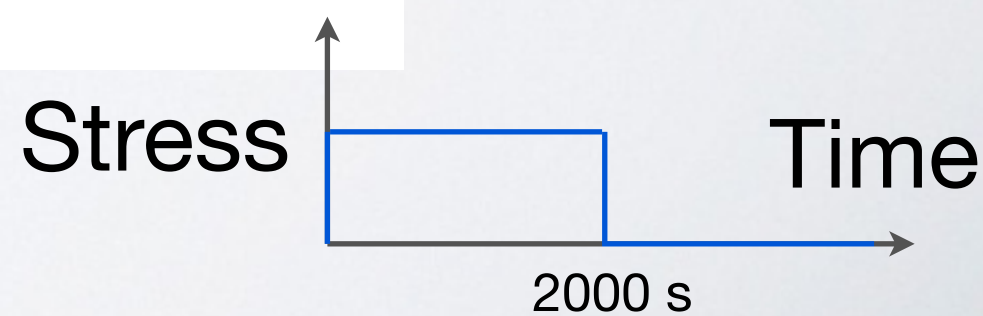
frequency domain



Burgers model replicates experimental observations

$\varepsilon < 10^{-4}$

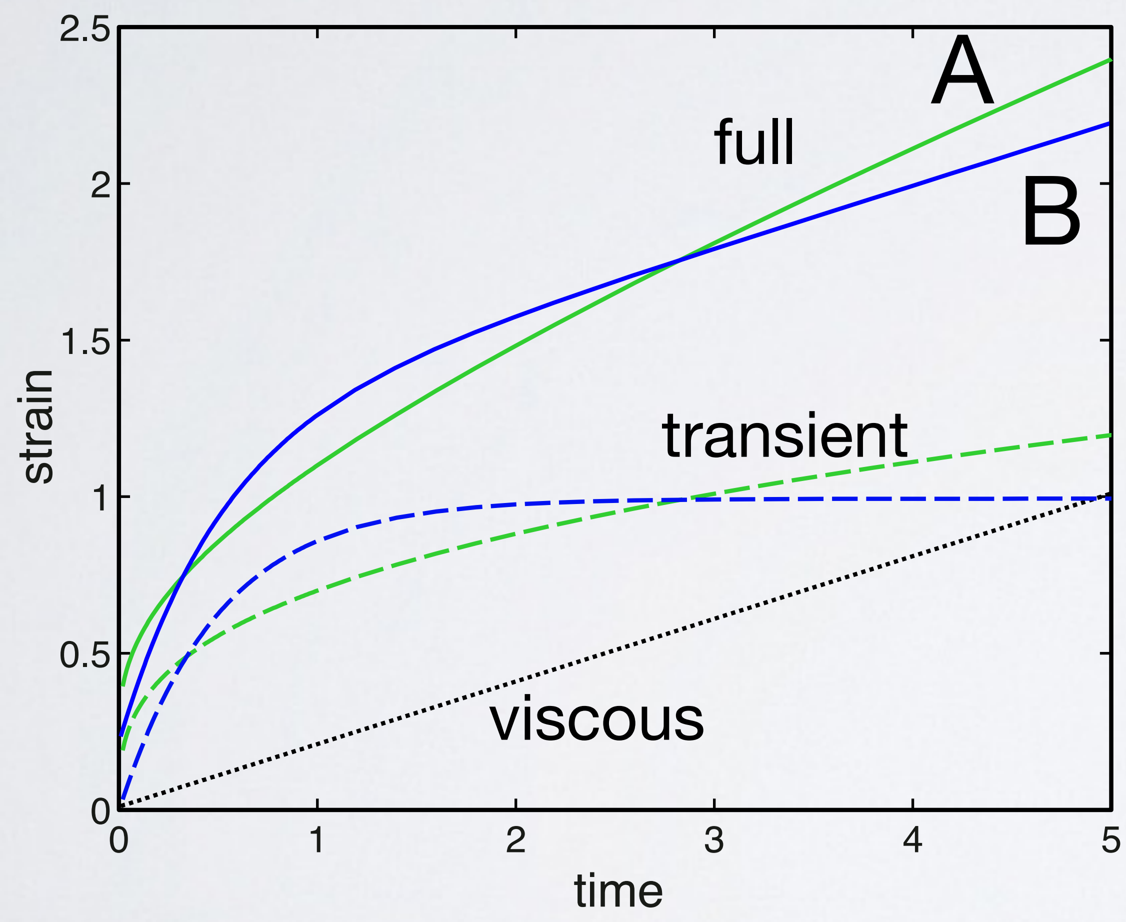


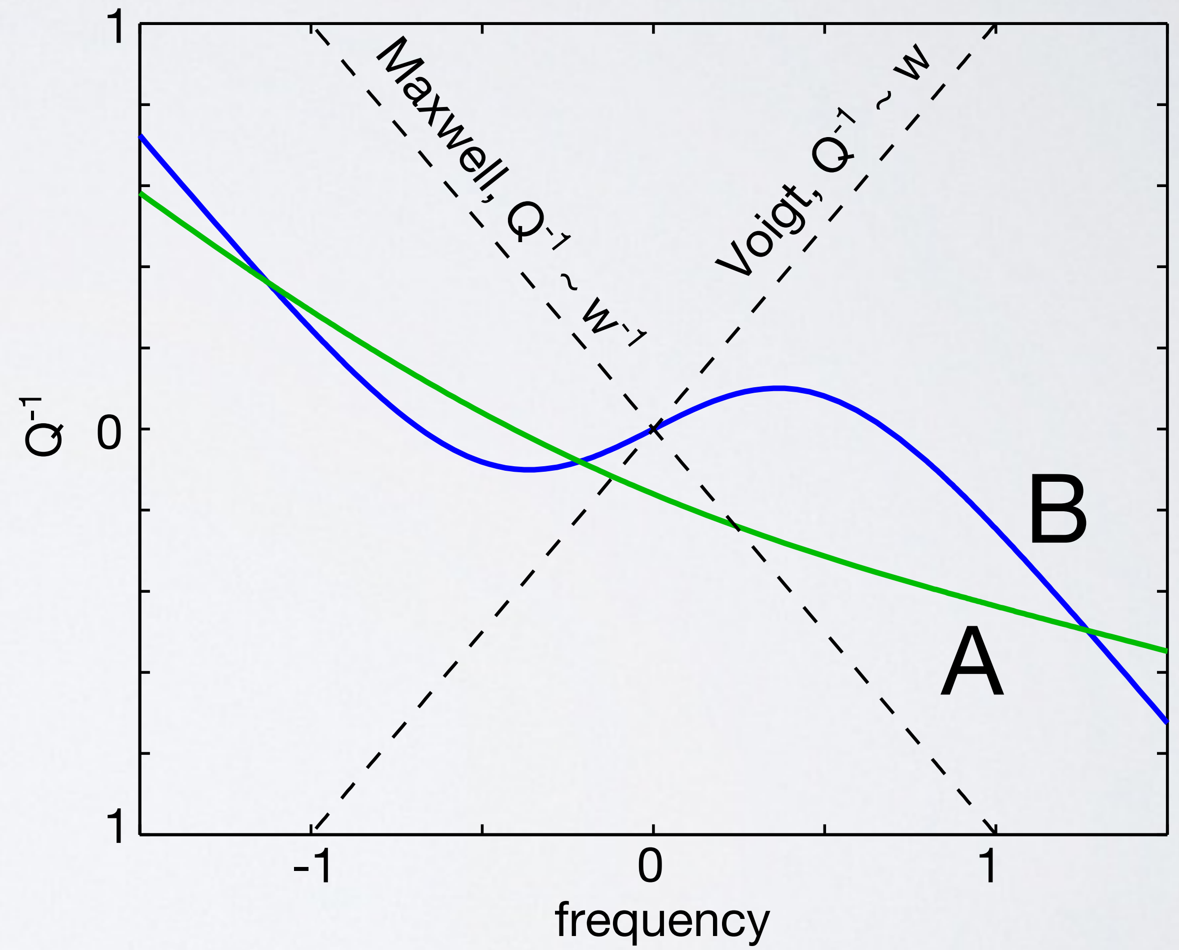


Alternative models for transient creep

Burgers model $J(t) = J_M(1 + t/\tau_M) + J_V(1 - exp(-t/\tau_V))$

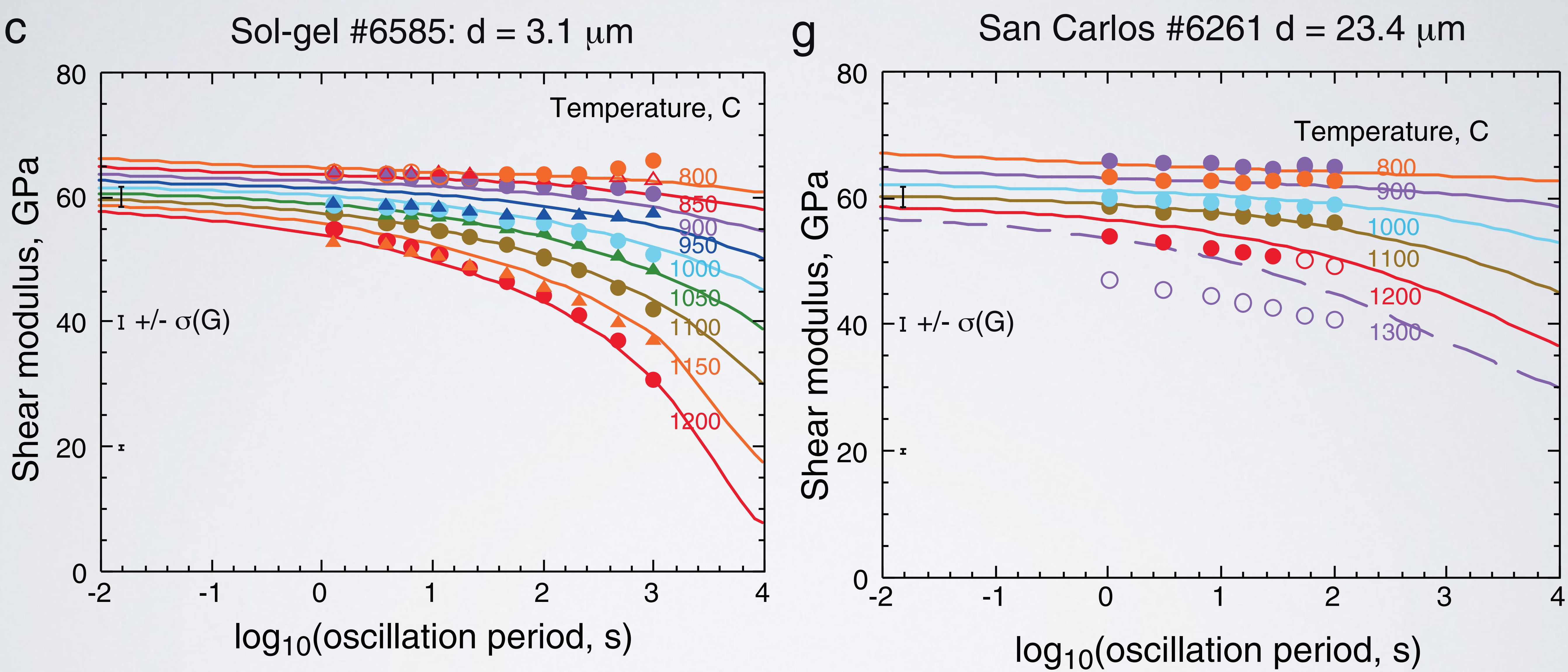
Andrade model $J(t) = J_M(1 + t/\tau_M) + \beta t^n$



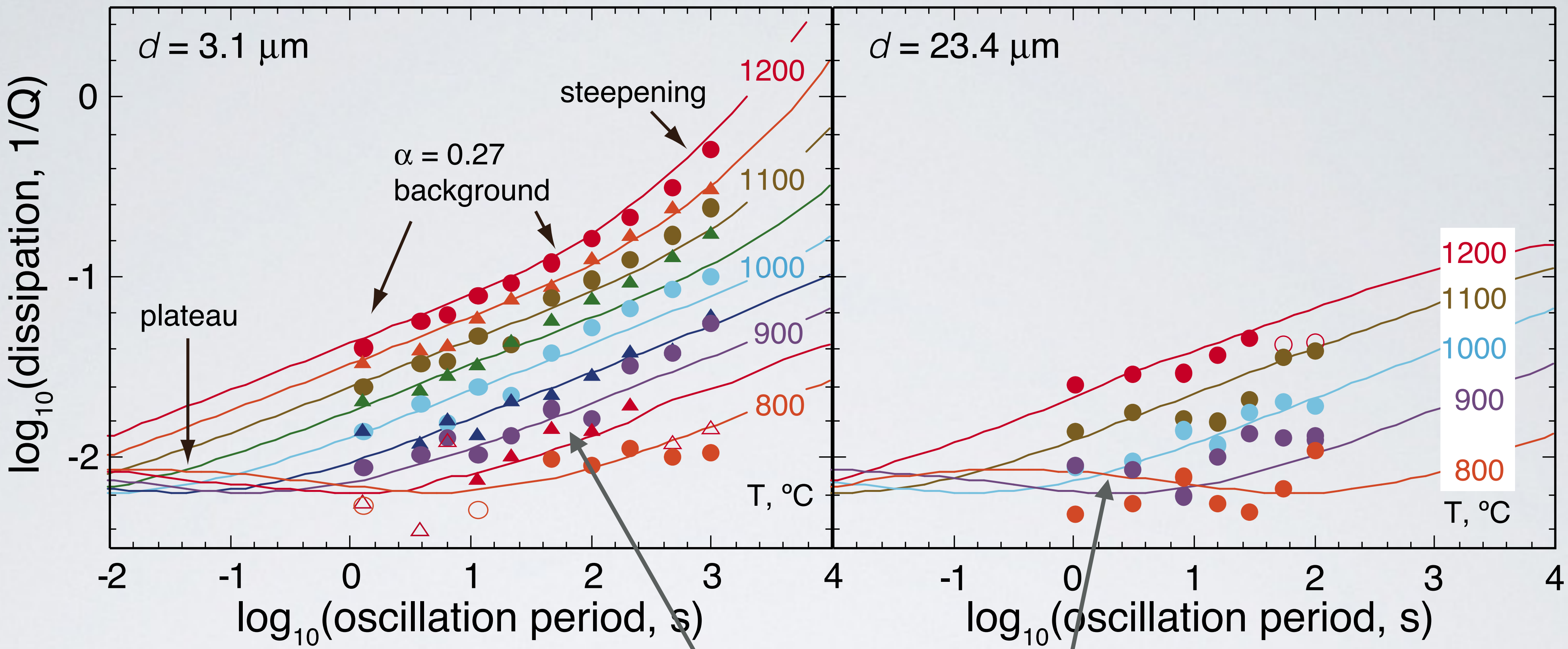


Transient term of Andrade model contributes indefinitely,
unsuitable for extrapolation

Forced torsional oscillation (frequency domain): Temperature, grain size and frequency dependence of dry, melt-free polycrystalline olivine



Jackson and Faul, 2010



distribution of relaxation times

plateau

$$J_1(\omega) = J_U \left\{ 1 + \frac{\alpha \Delta_B}{\tau_H^\alpha - \tau_L^\alpha} \int_{\tau_L}^{\tau_H} \frac{\tau^{\alpha-1}}{1+\omega^2\tau^2} d\tau \right.$$
$$\left. + \frac{1}{\sigma\sqrt{(2\pi)}} \Delta_P \int_0^\infty \frac{1}{\tau} \frac{exp\left(\frac{-[ln(\tau/\tau_P)/\sigma]^2}{2}\right)}{1+\omega^2\tau^2} d\tau \right\}$$

$$J_2(\omega) = J_U \left\{ \frac{\omega \alpha \Delta_B}{\tau_H^\alpha - \tau_L^\alpha} \int_{\tau_L}^{\tau_H} \frac{\tau^{\alpha}}{1+\omega^2\tau^2} d\tau \right.$$
$$\left. + \frac{\omega}{\sigma\sqrt{(2\pi)}} \Delta_P \int_0^\infty \frac{exp\left(\frac{-[ln(\tau/\tau_P)/\sigma]^2}{2}\right)}{1+\omega^2\tau^2} d\tau + \frac{1}{\omega\tau_M} \right\}$$

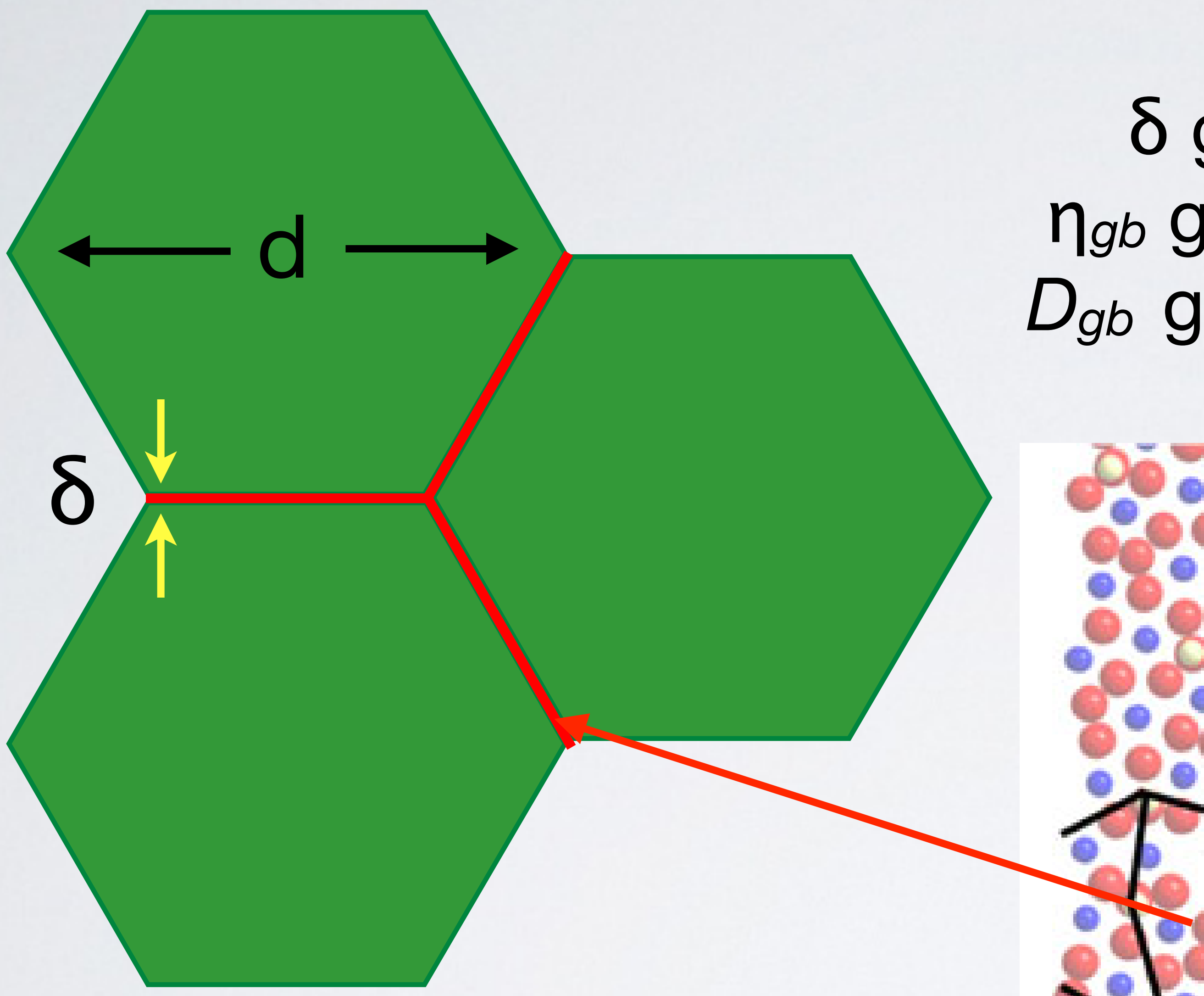
Physical Model?
-needs to account for:

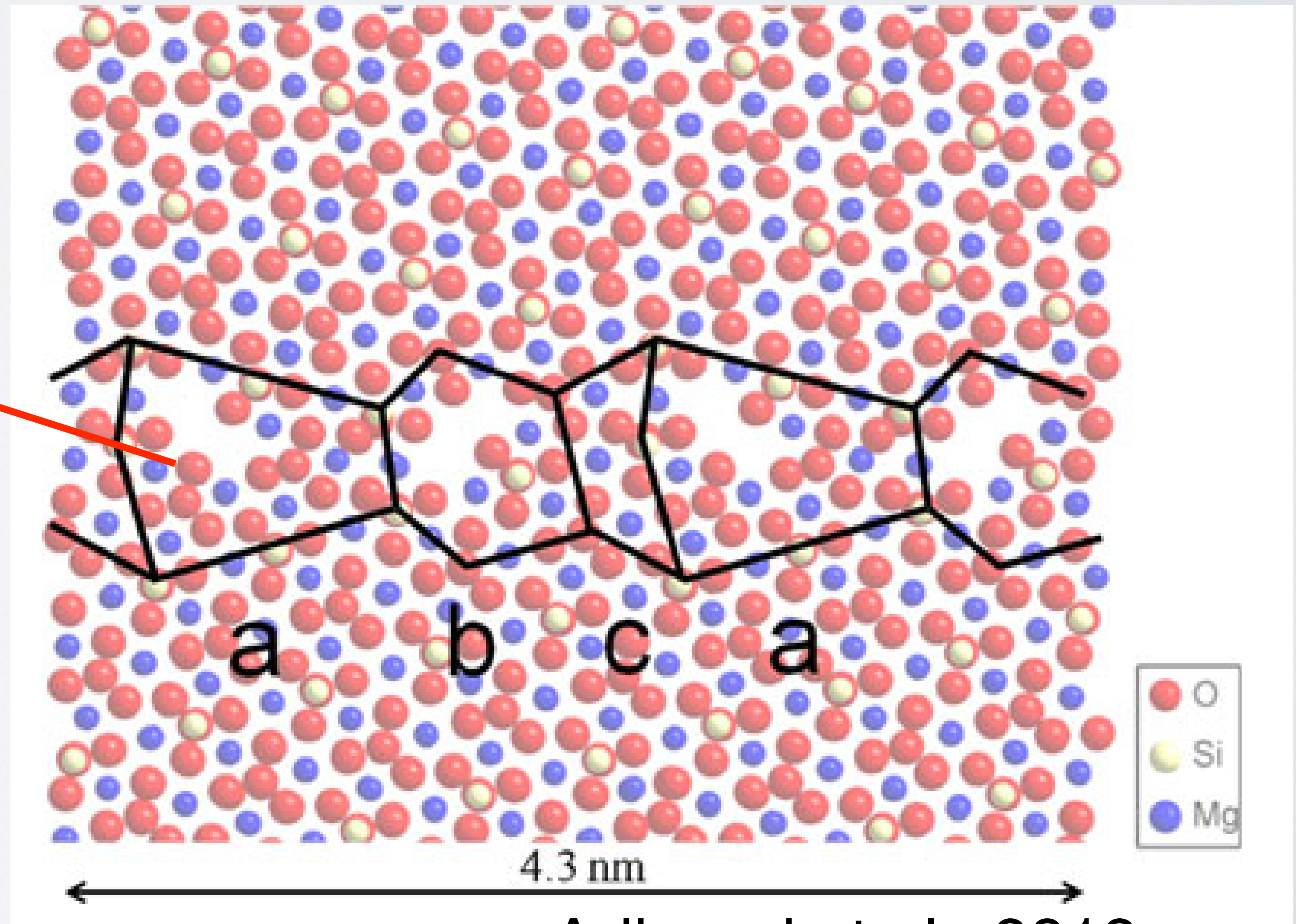
- grain size dependence
- temperature dependent
- different frequency regimes:

broad region w. mild frequency dependence, i.e. absorption band; plateau/broad peak; transition to viscous behavior

Grain size-dependent dissipation mechanism: Grain boundary sliding

parameters:
d grain size,
δ grain boundary width
η_{gb} grain boundary viscosity
D_{gb} grain boundary diffusivity

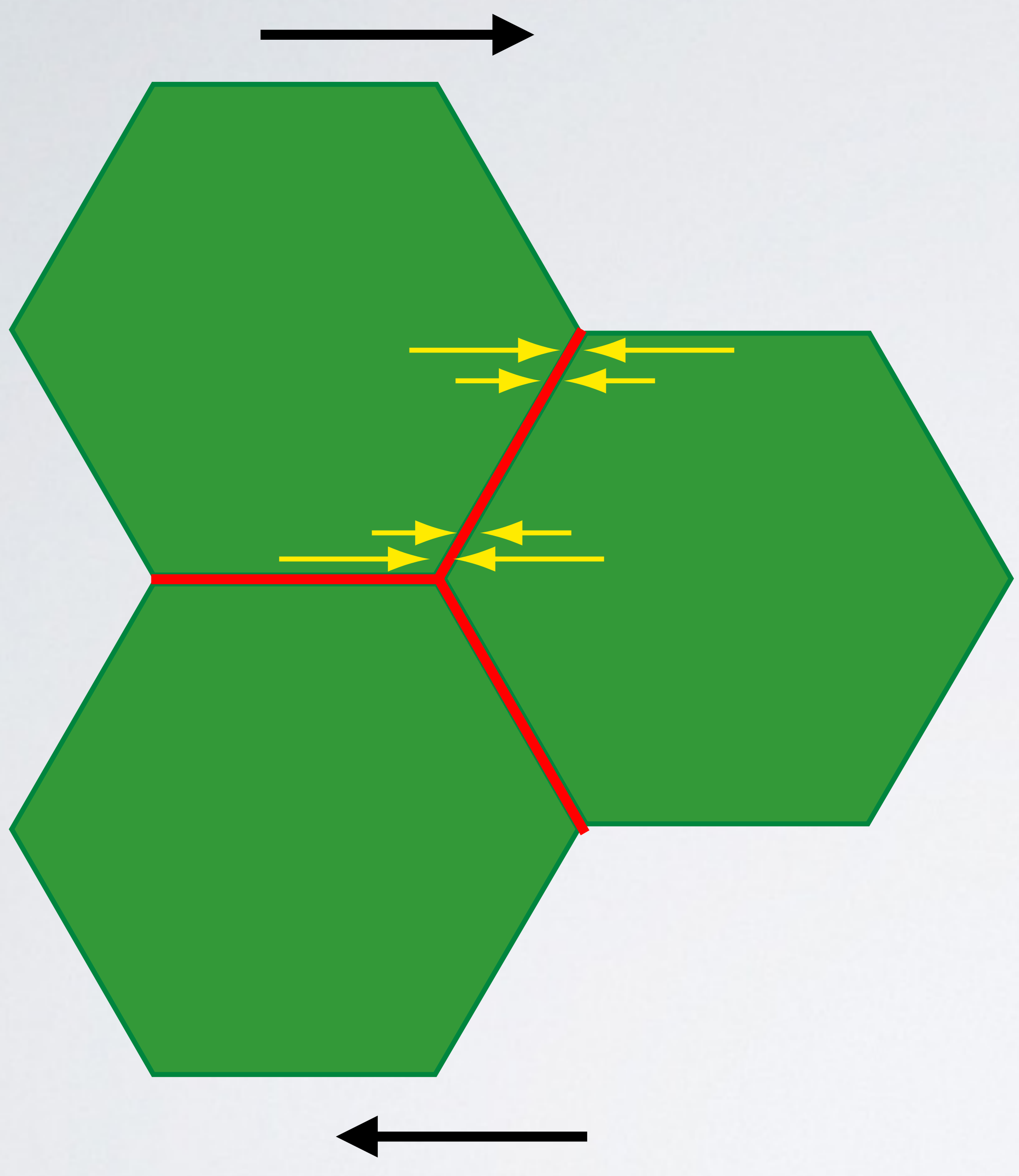




Adjaoud et al., 2012

results in three distinct processes:

1. Elastically accommodated sliding



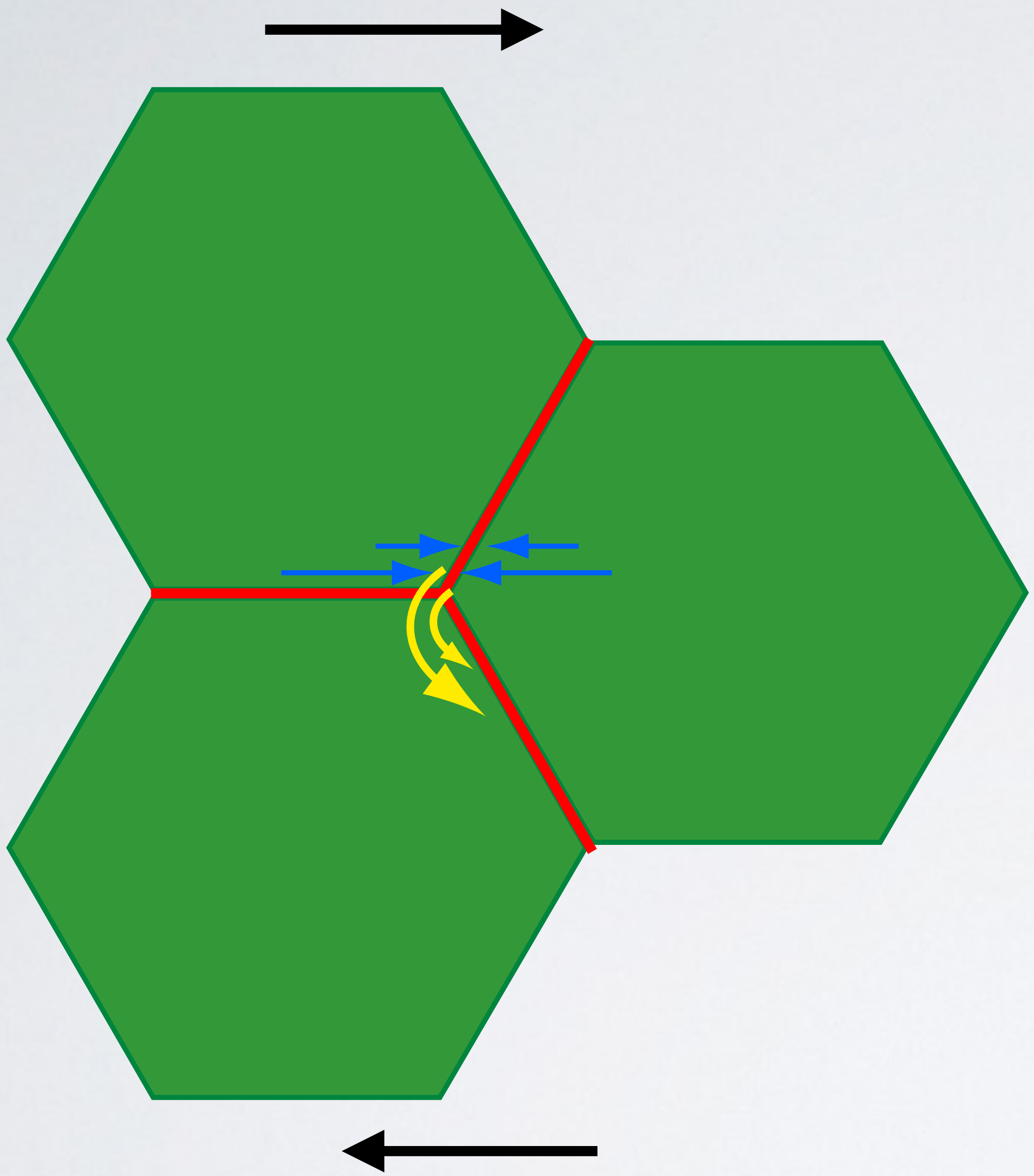
viscous sliding of grain boundaries leads to elastic stress concentrations at grain corners

time scale: $\tau_E = \eta_{gb}\, d/G\, \delta$

recoverable strain, anelastic process, dissipation peak

After Raj and Ashby, 1971; Raj, 1975

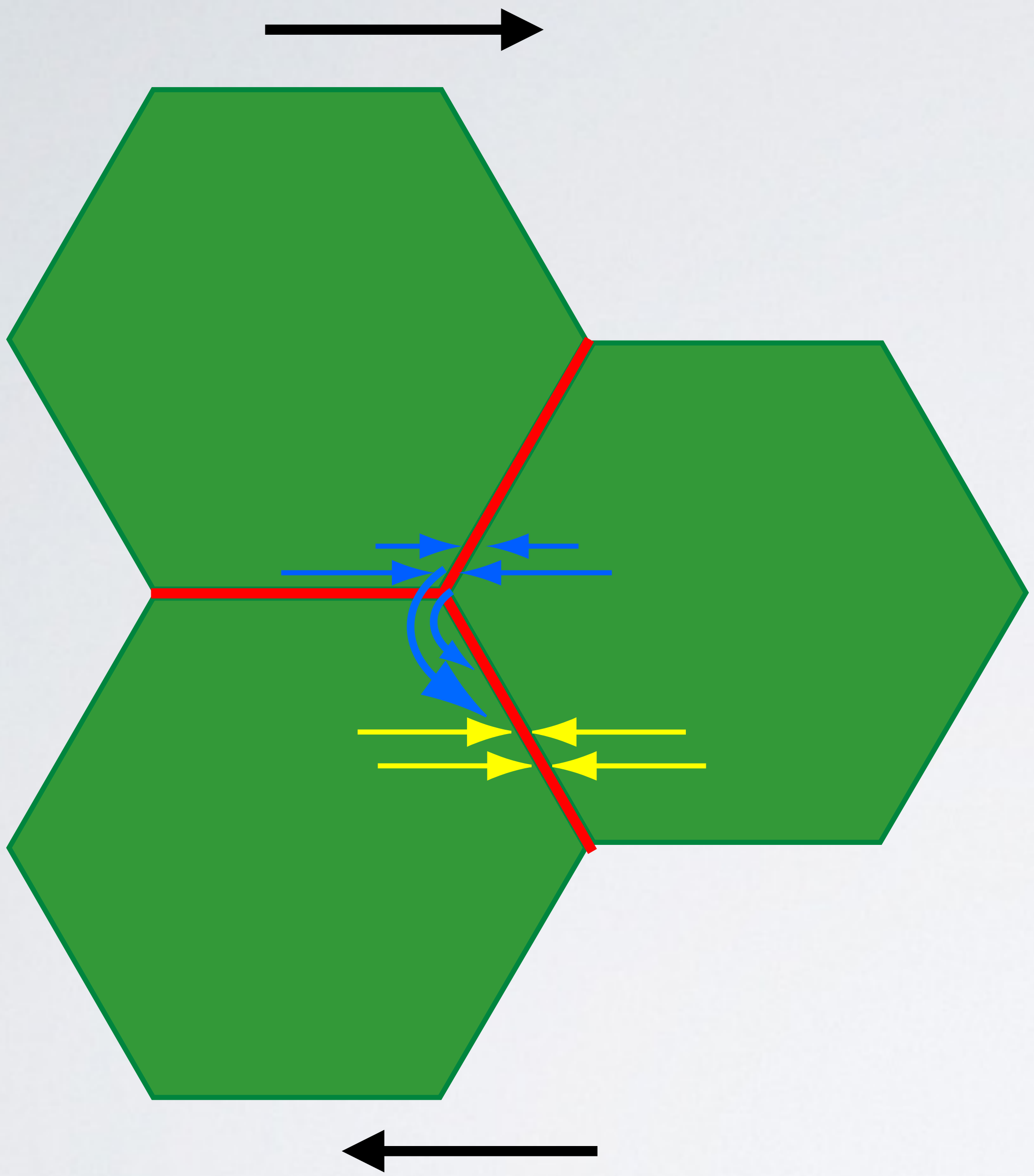
2. Diffusionally assisted sliding

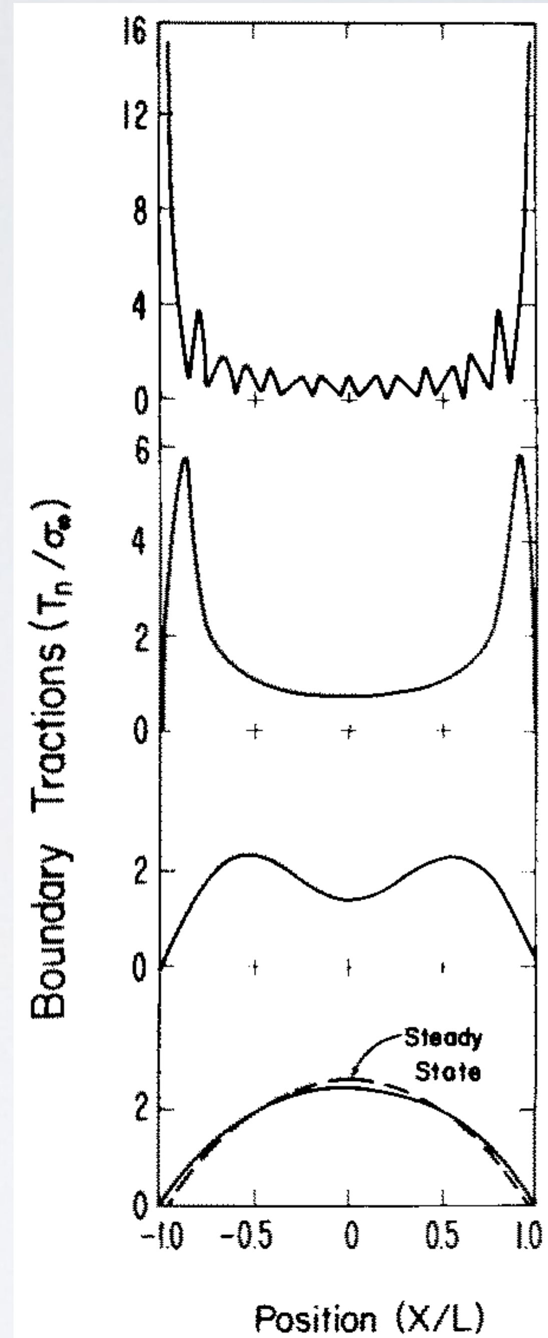


- stress concentrations cause diffusion away from corners
- transient phase is characterised by diffusion over increasing length scales

distribution of relaxation times, transient, recoverable

3. Diffusionally accommodated sliding (steady state)





1. end of elastically accommodated sliding

2. diffusionally assisted sliding

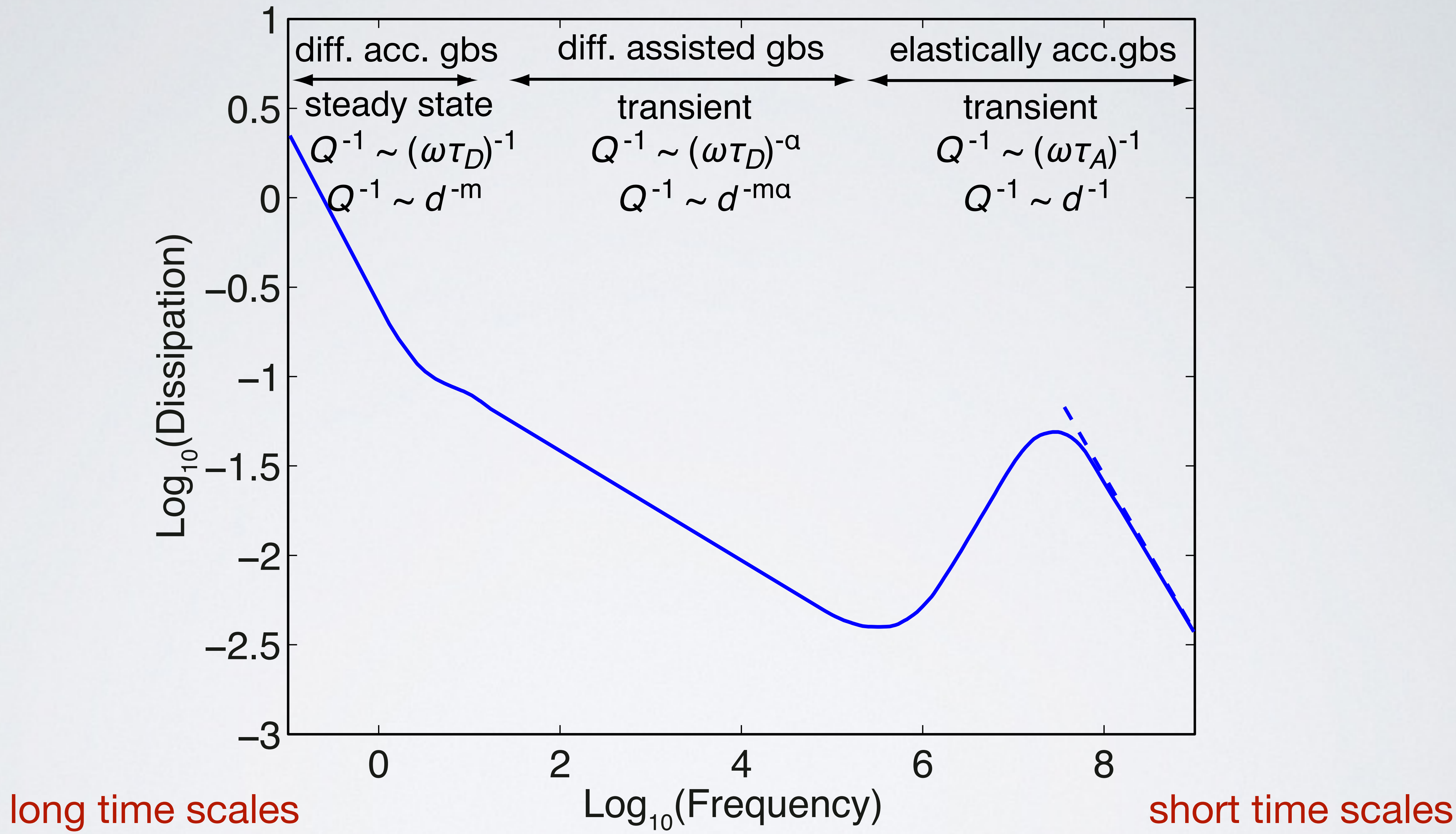
3. steady state creep

Raj 1975,
Gribb and Cooper, 1998

time scale: $\tau_D \sim \; T\, d^3/G\, \delta\, D_{gb}$

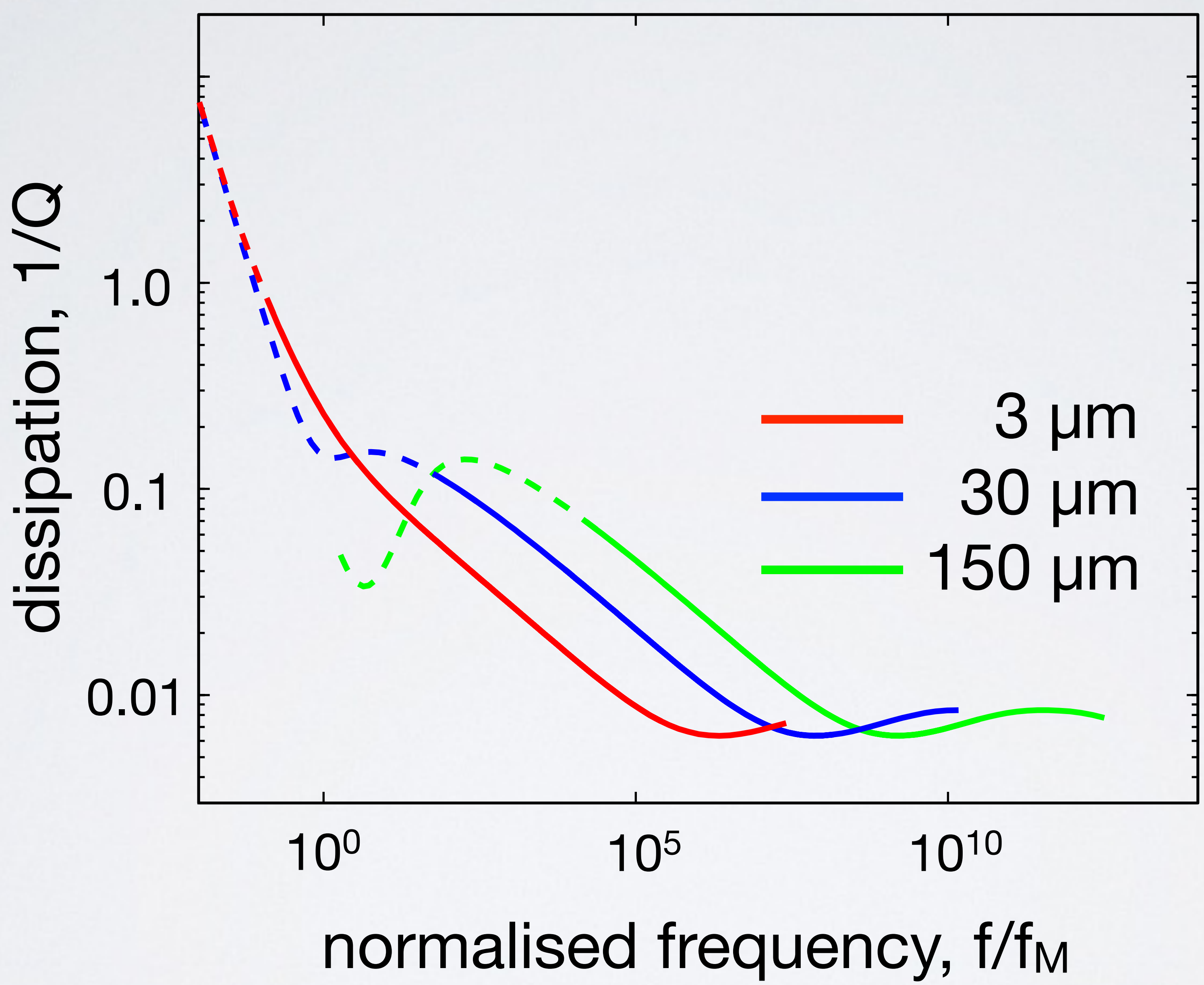
gb normal stresses are highest in center between grain corners (steady state diffusion creep)

Frequency domain model
(Morris and Jackson, 2009, Lee et al., 2011)

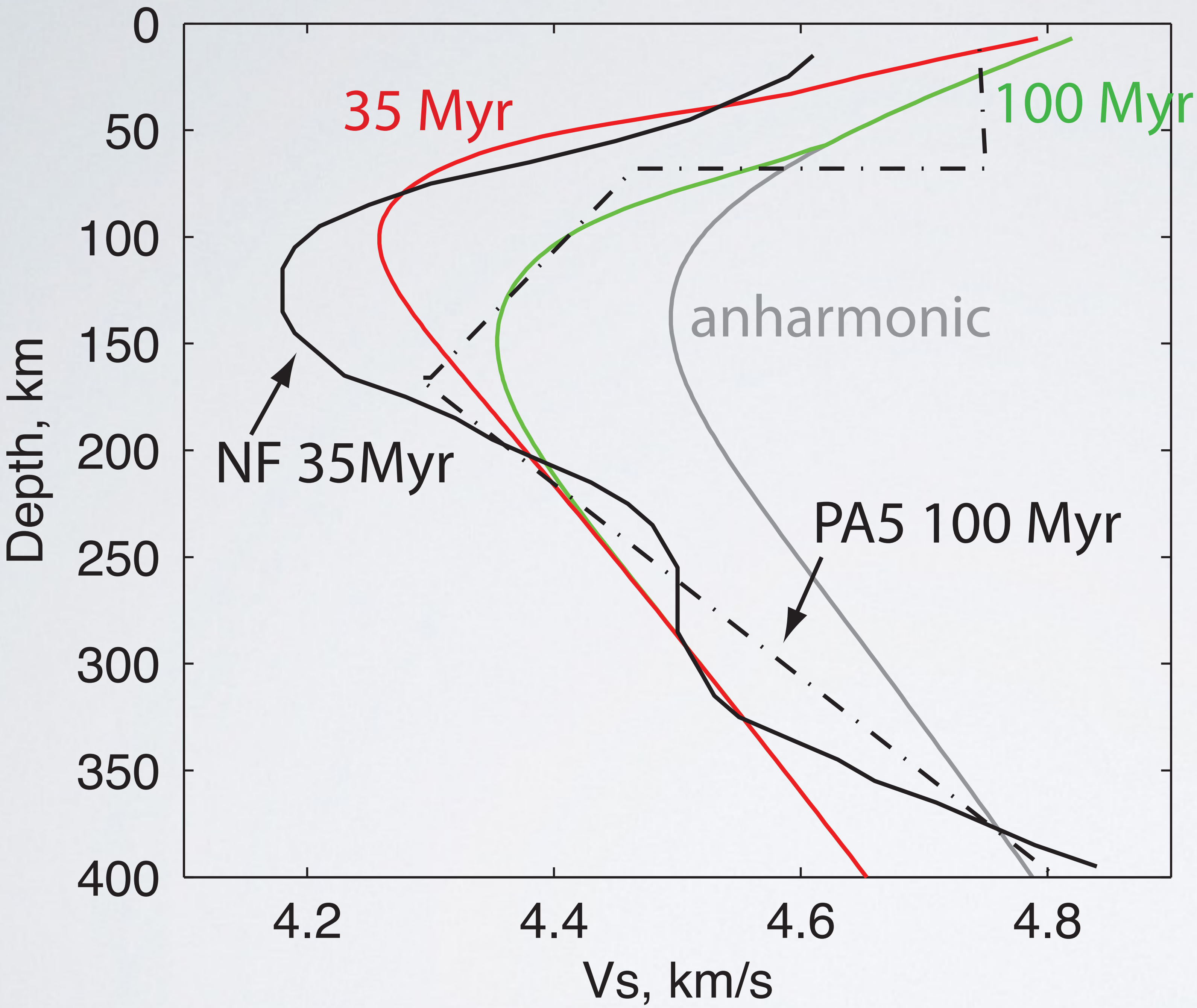


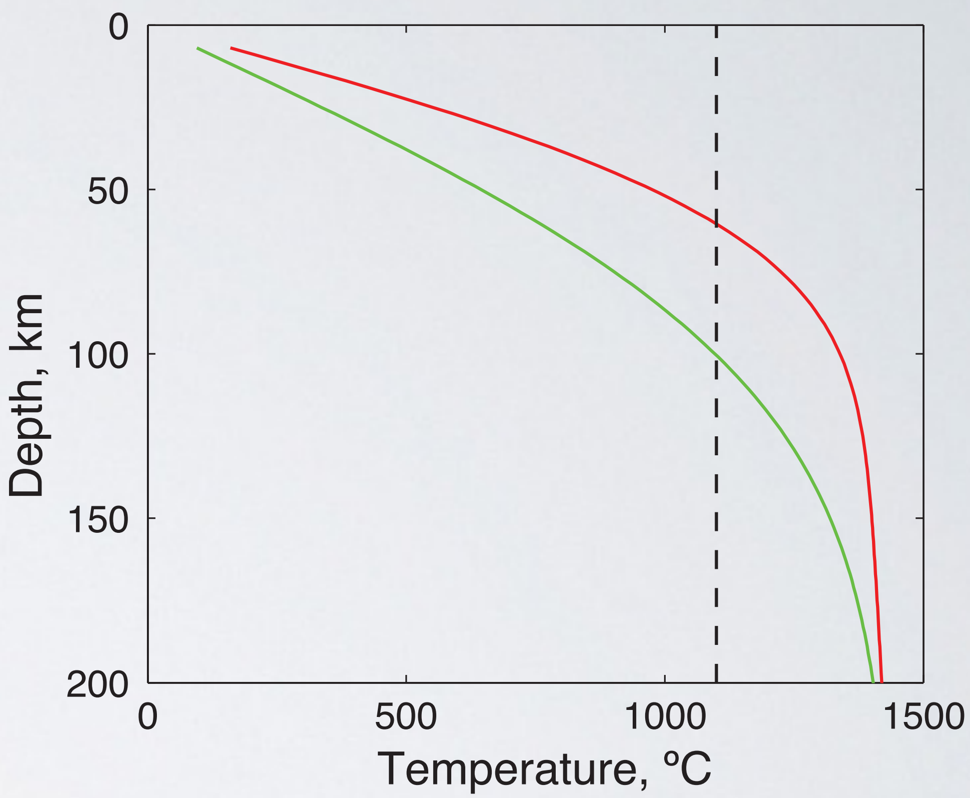
grain size dependence changes from
~ linear (transient) to cubic (steady state)

Extended Burgers model fit to forced oscillation data for olivine



Application to the Upper Mantle
Comparison with velocity models for the Pacific

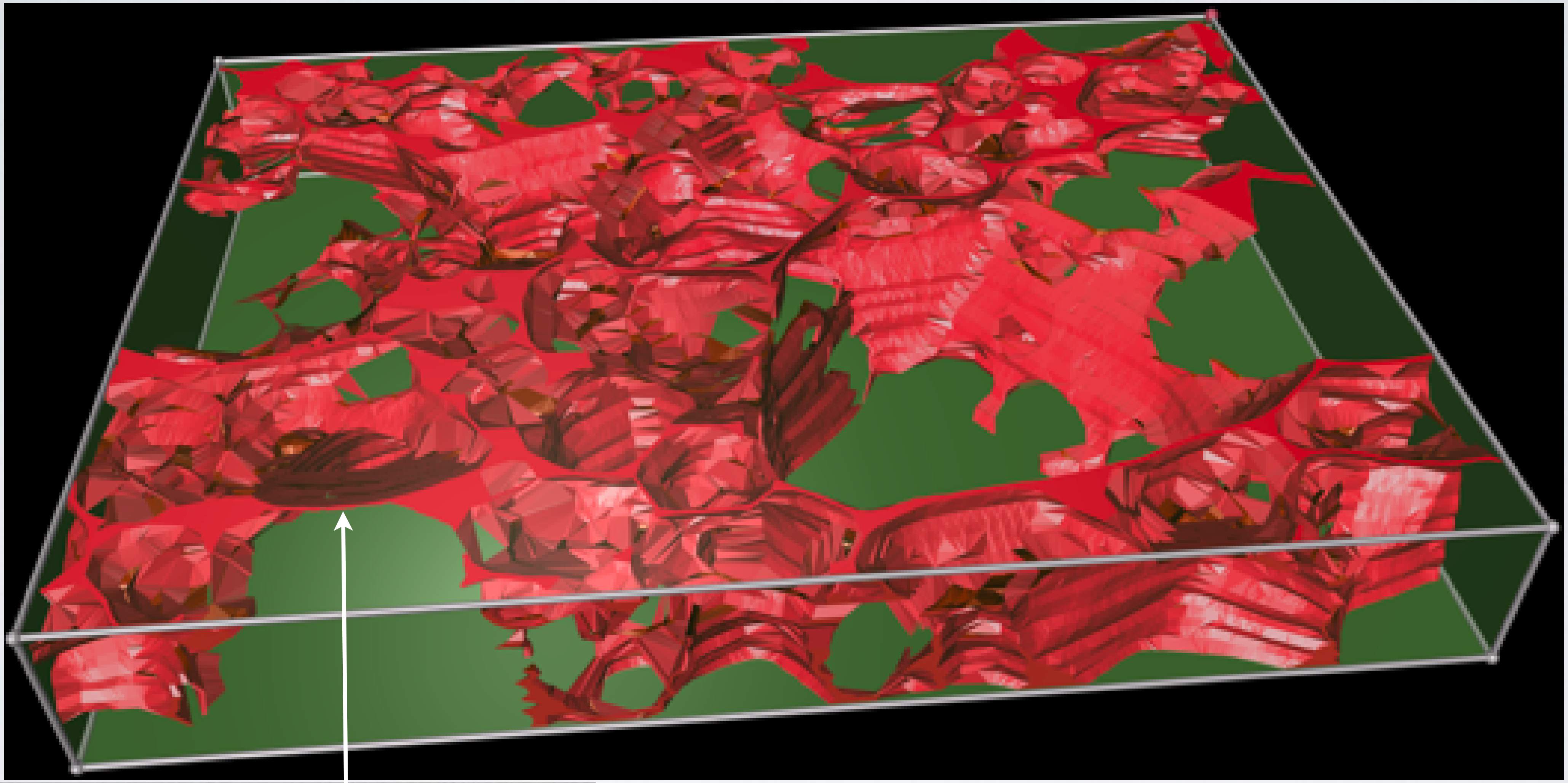


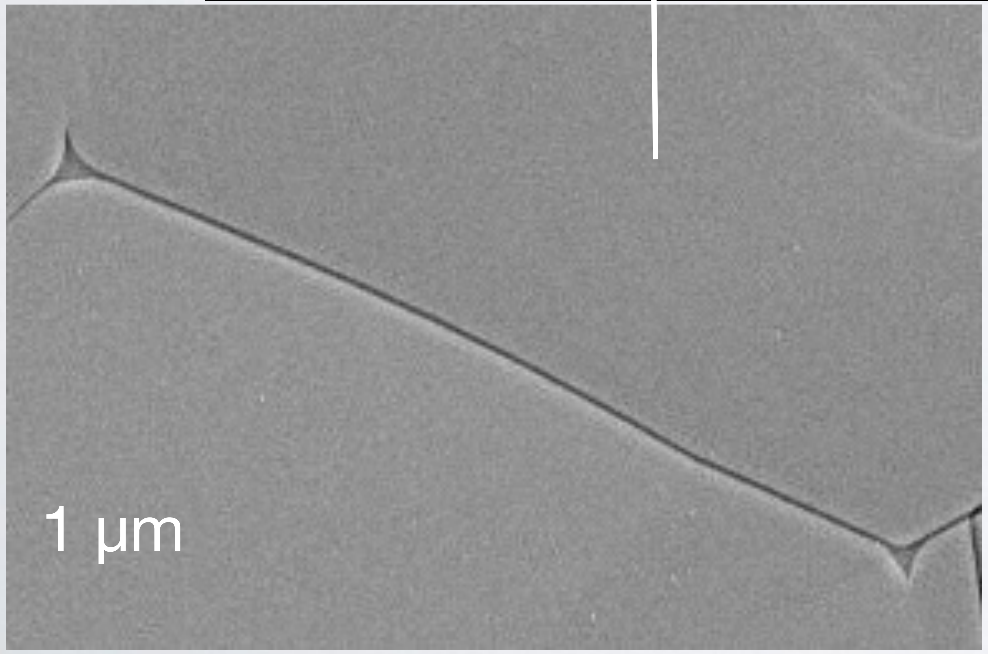


d = 1 cm, Tp = 1350ºC

Nishimura & Forsyth, 1989
Gaherty et al., 1996

Additional mechanism for velocity reduction and attenuation: melt

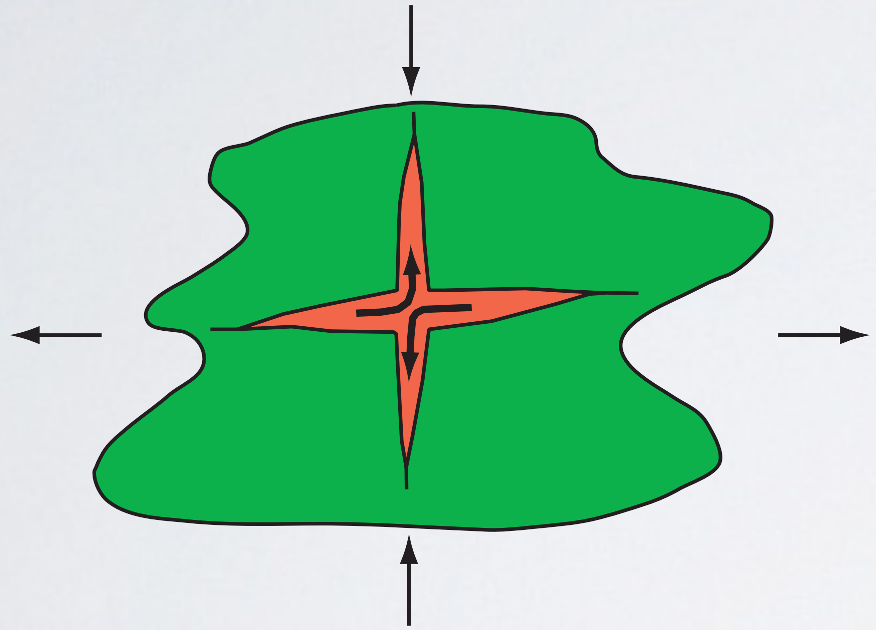




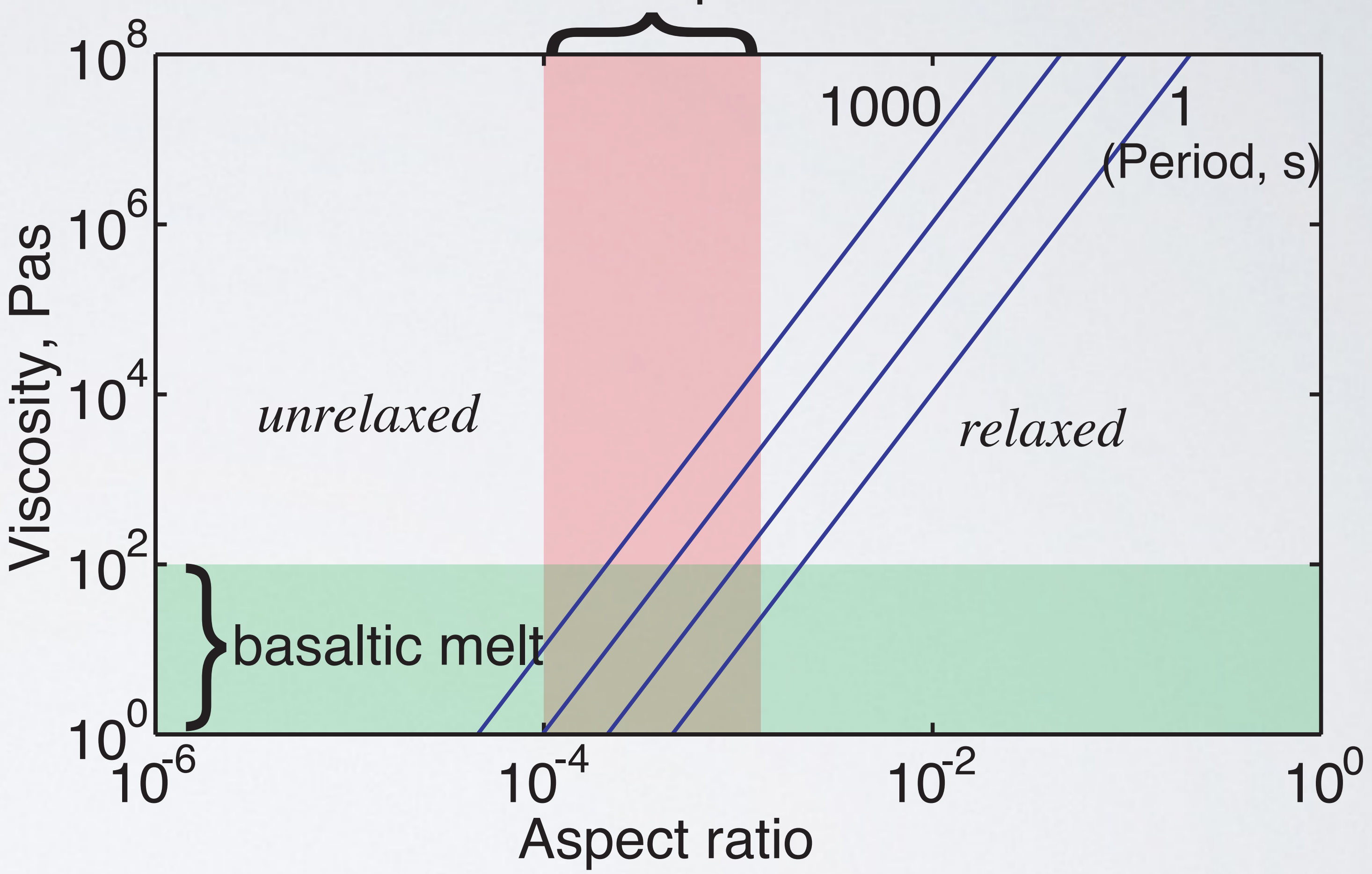
Grain-scale melt network, Garapić, Faul and Brisson, G^3 2013

Partially molten rocks: melt 'squirt' as dissipation mechanism

Melt squirt:
pressure driven melt flow



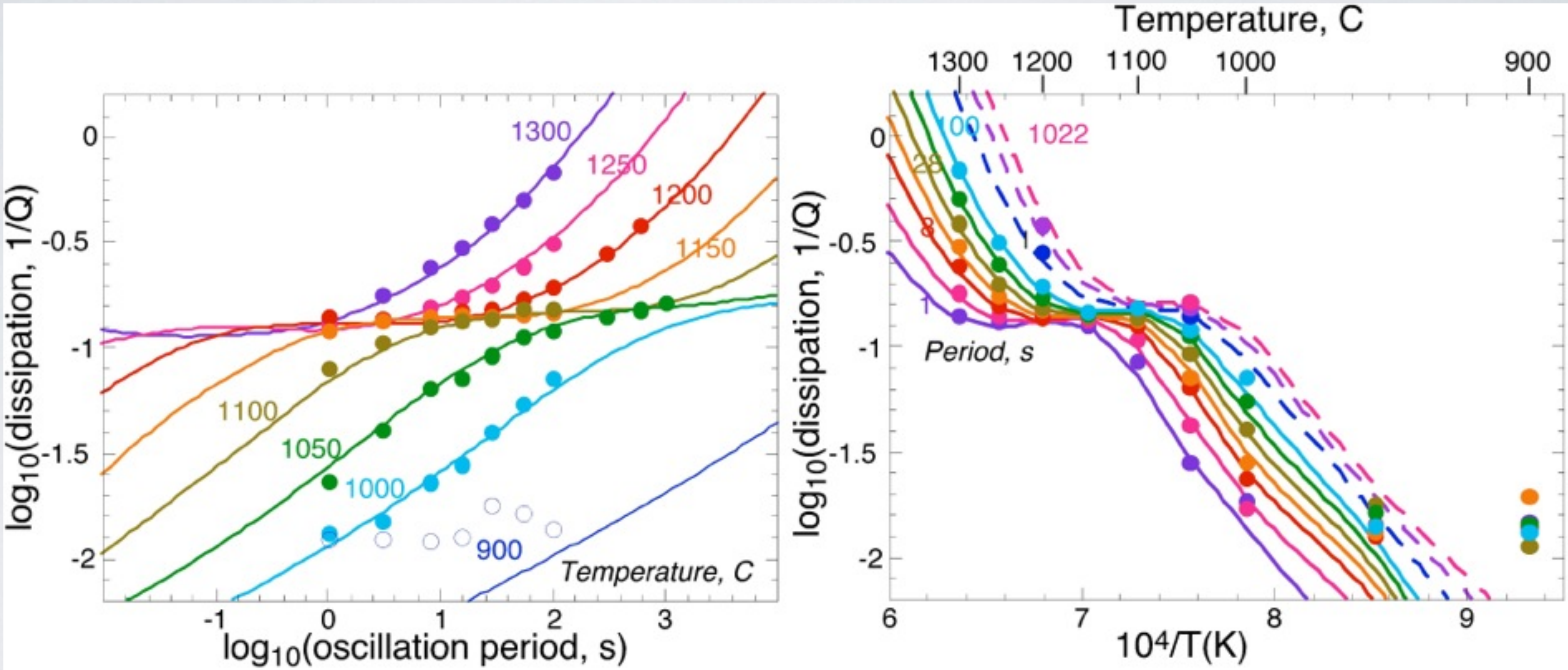
after Mavko and Nur, 1975



After Schmeling (1985)

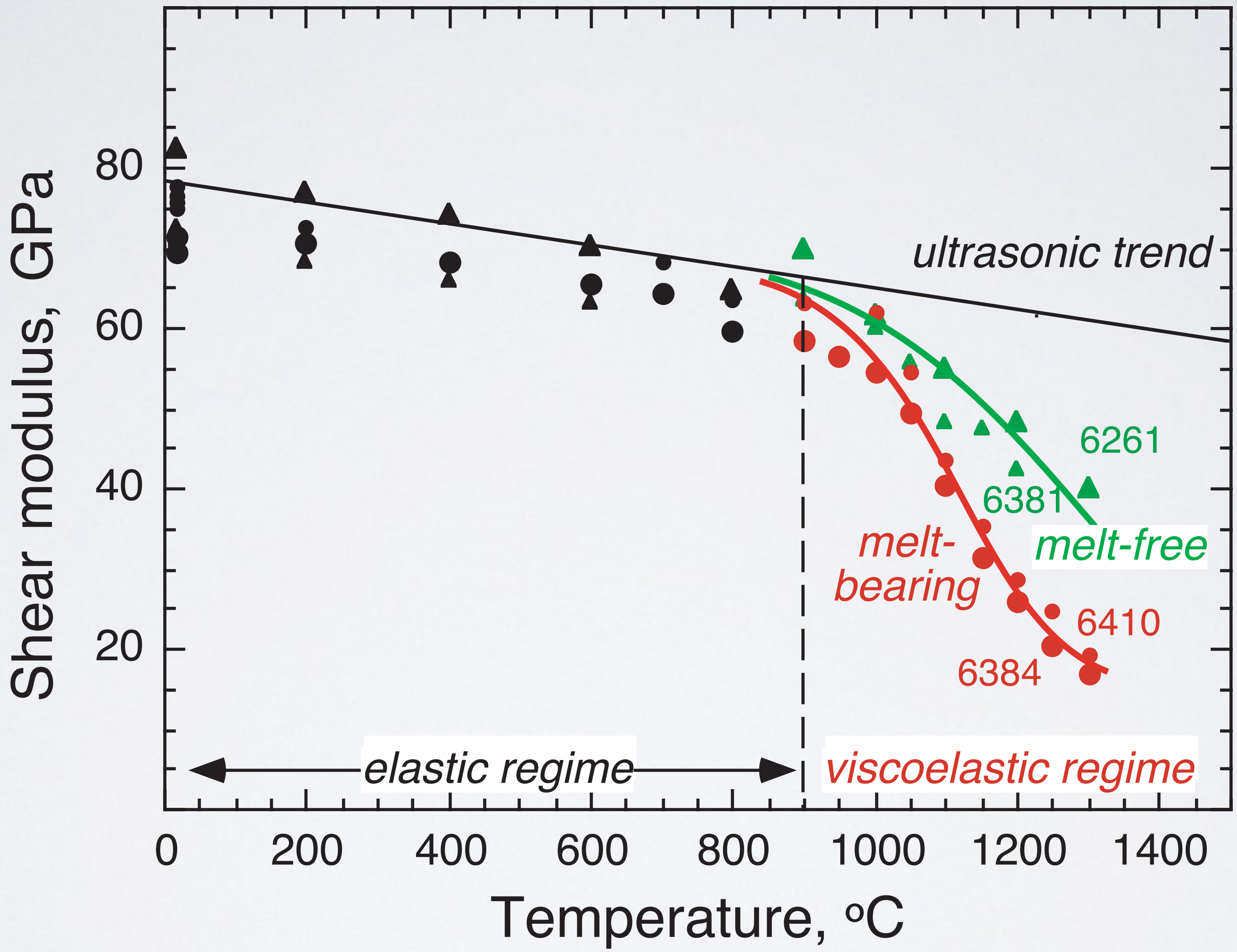
dissipation maximum at a particular frequency

Melt present: dissipation peak due to melt 'squirt'



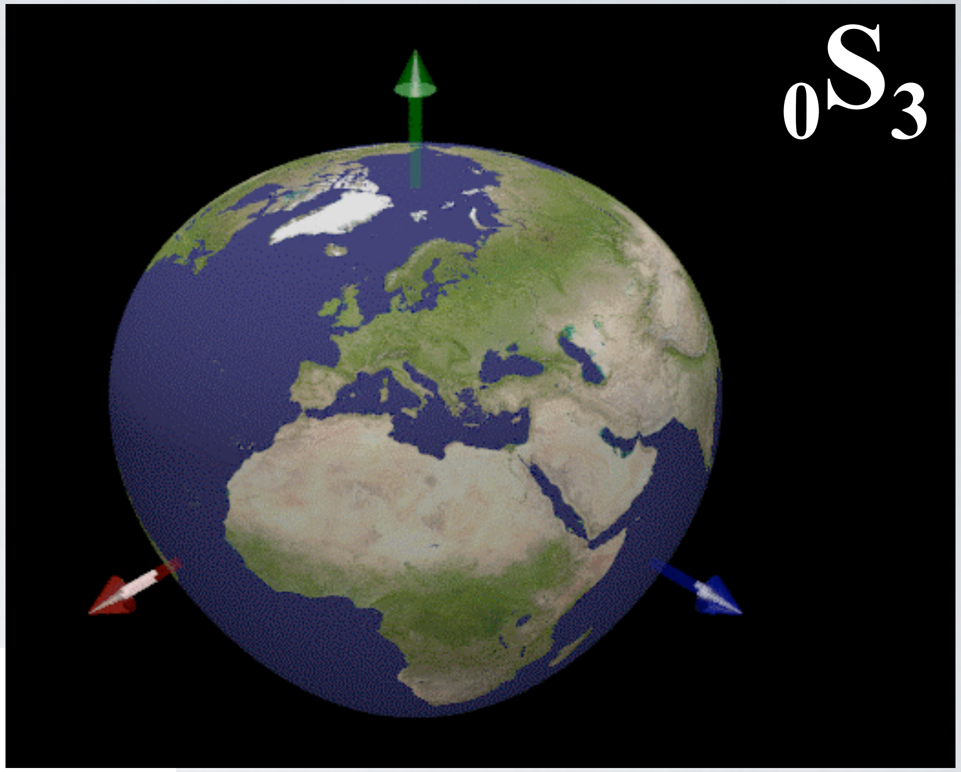
Jackson et al., 2004, Faul et al., 2004

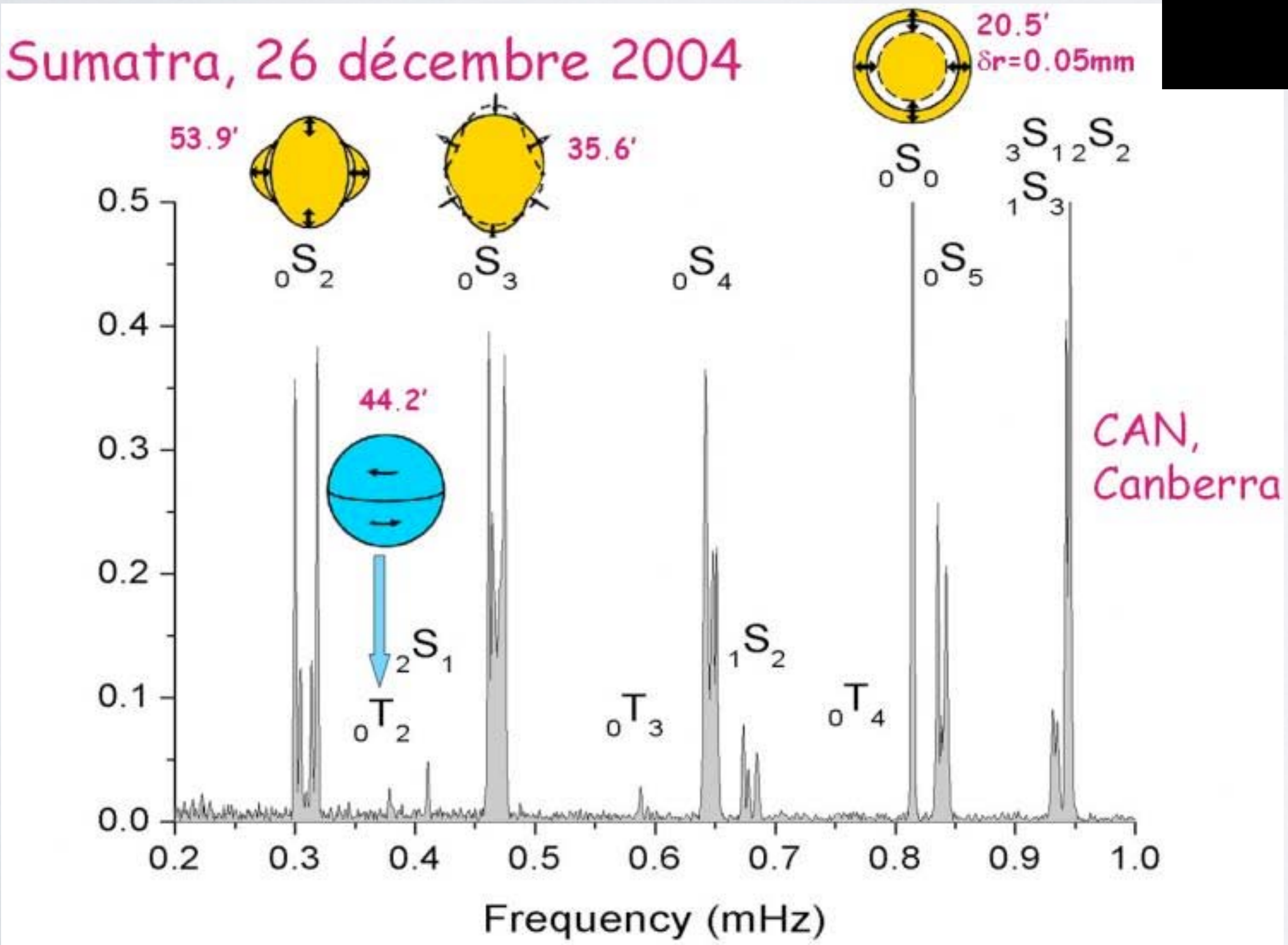
Shear modulus reduction due to melt



Jackson et al., 2004

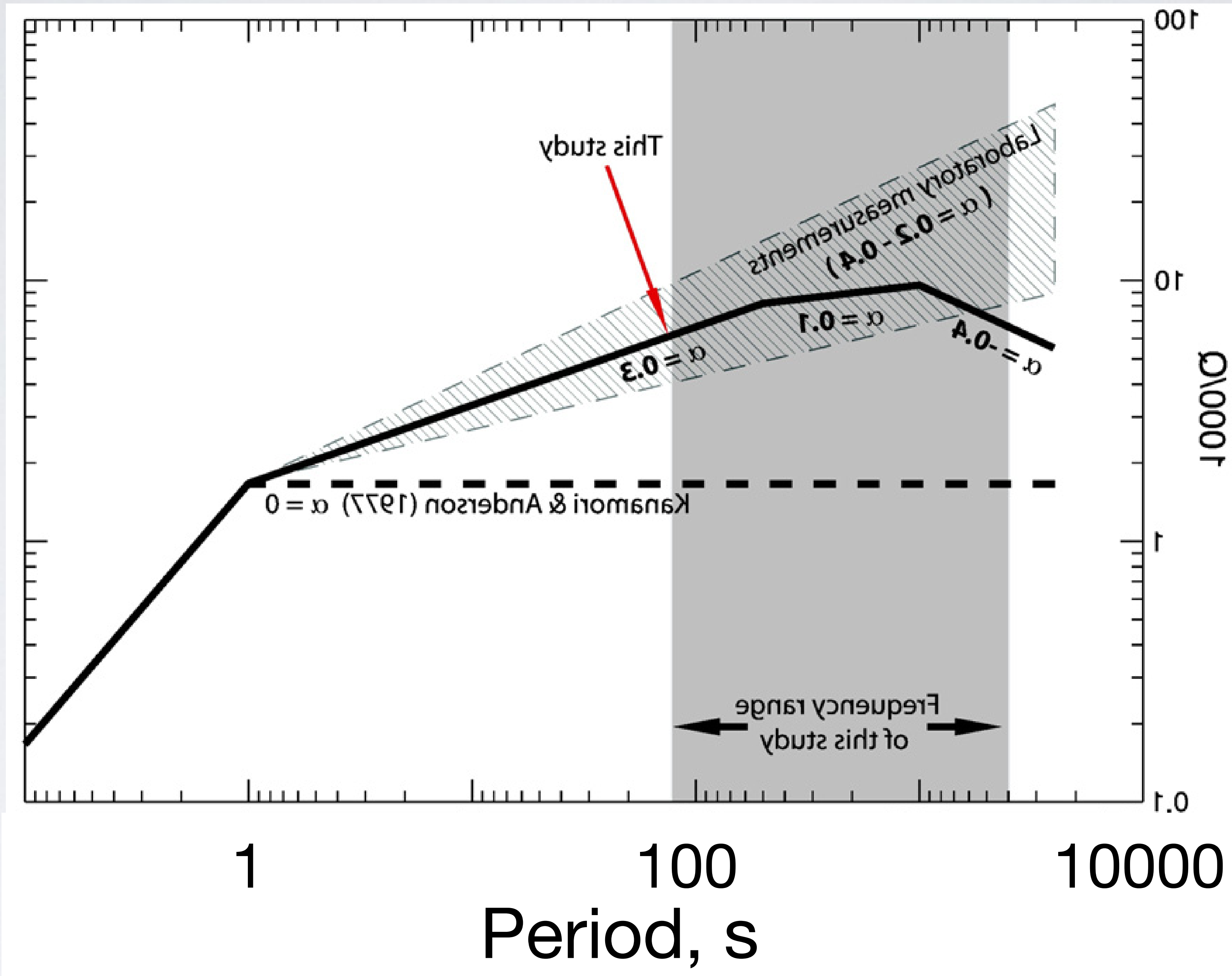
At longer periods: normal modes - whole Earth deformation





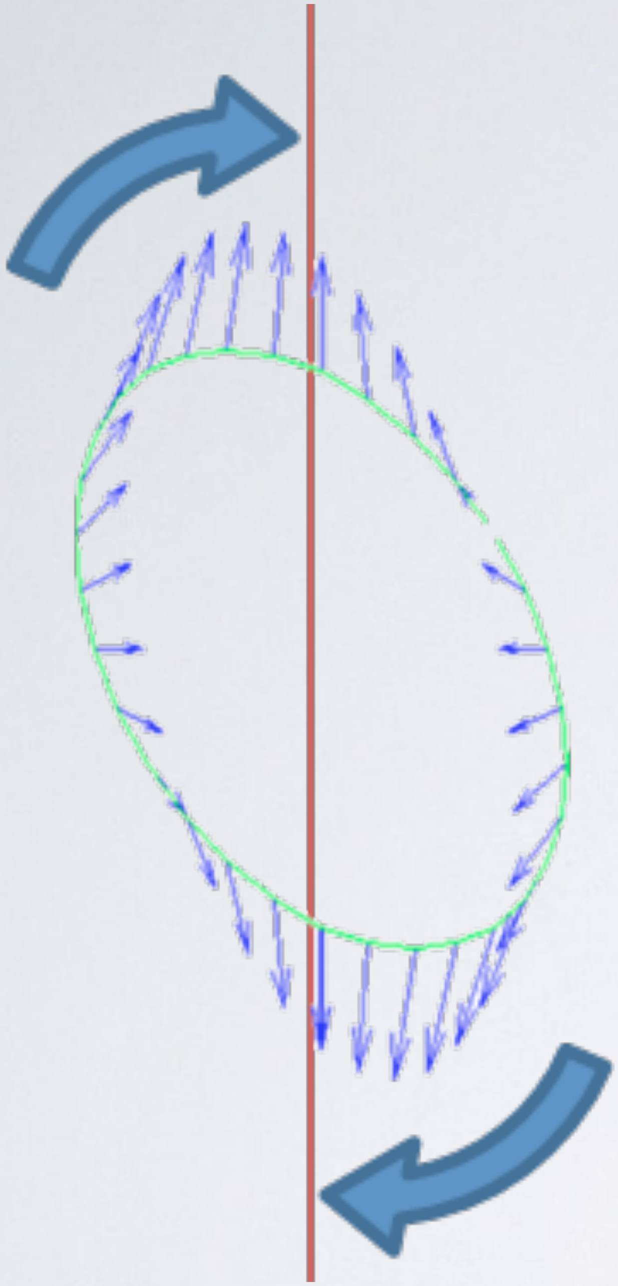
Park et al., 2005

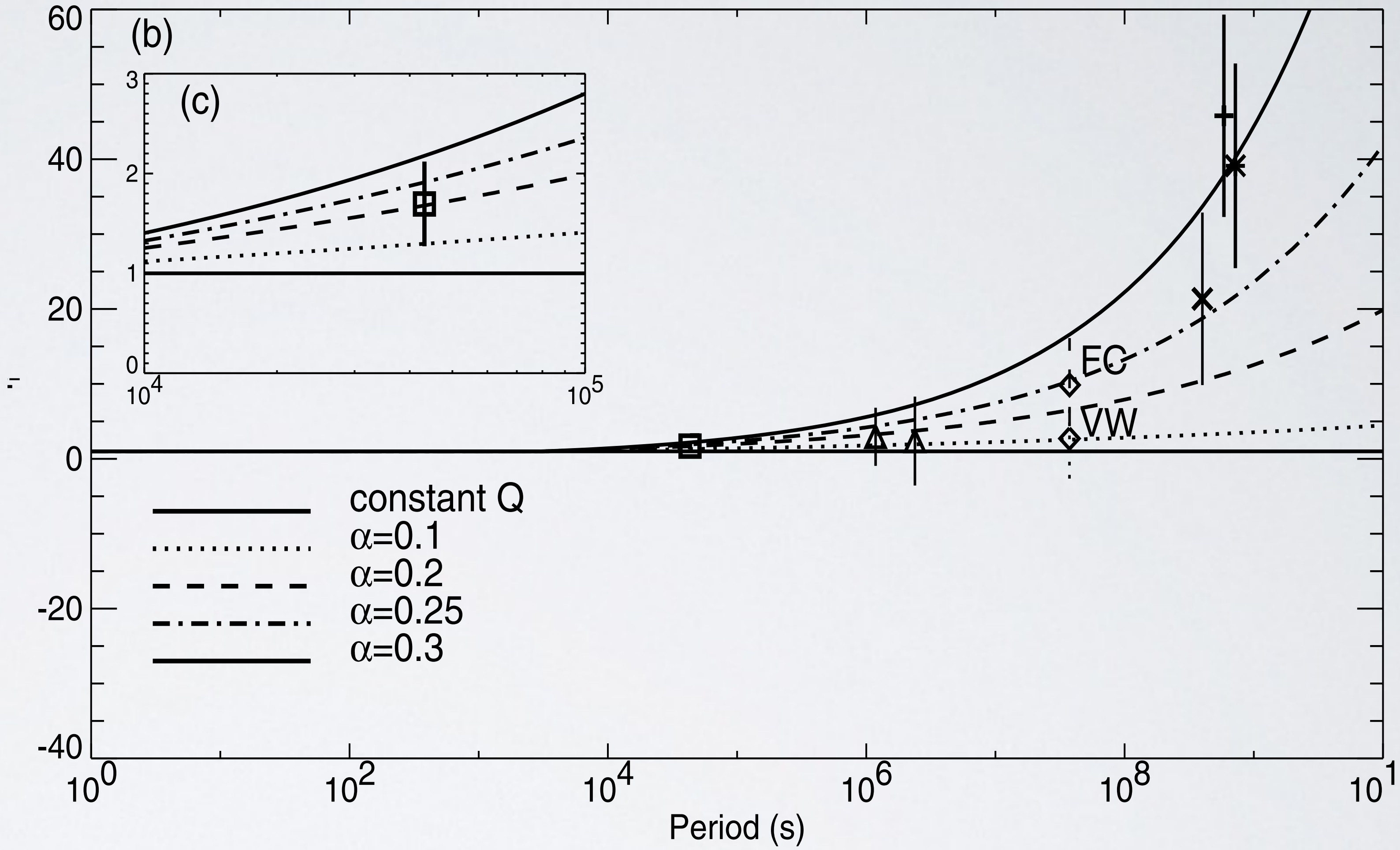
Lekic et al., 2009:
absorption band from surface waves, normal modes



attenuation decreases again at periods > 1000 s

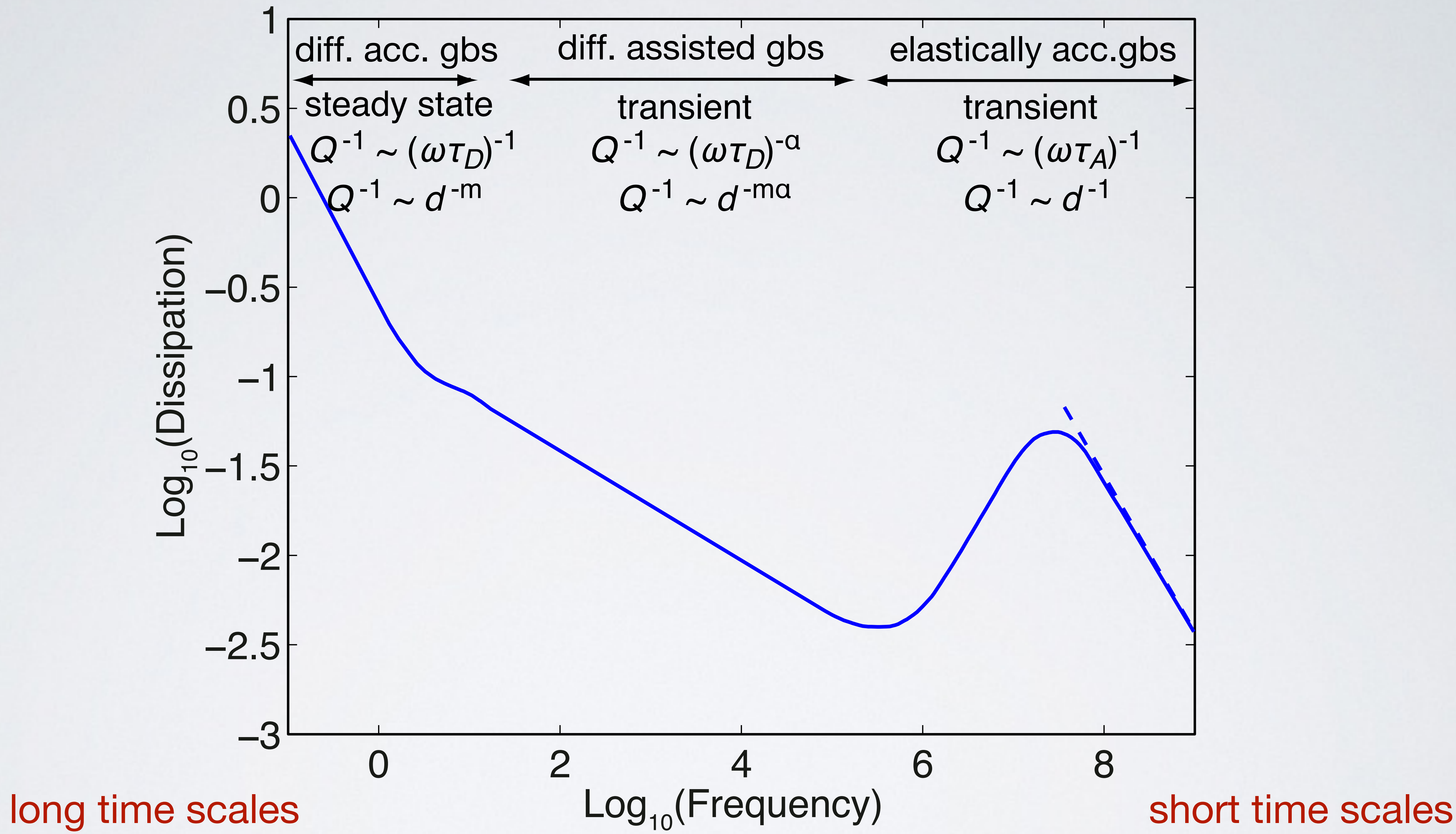
At even longer periods: tidal dissipation





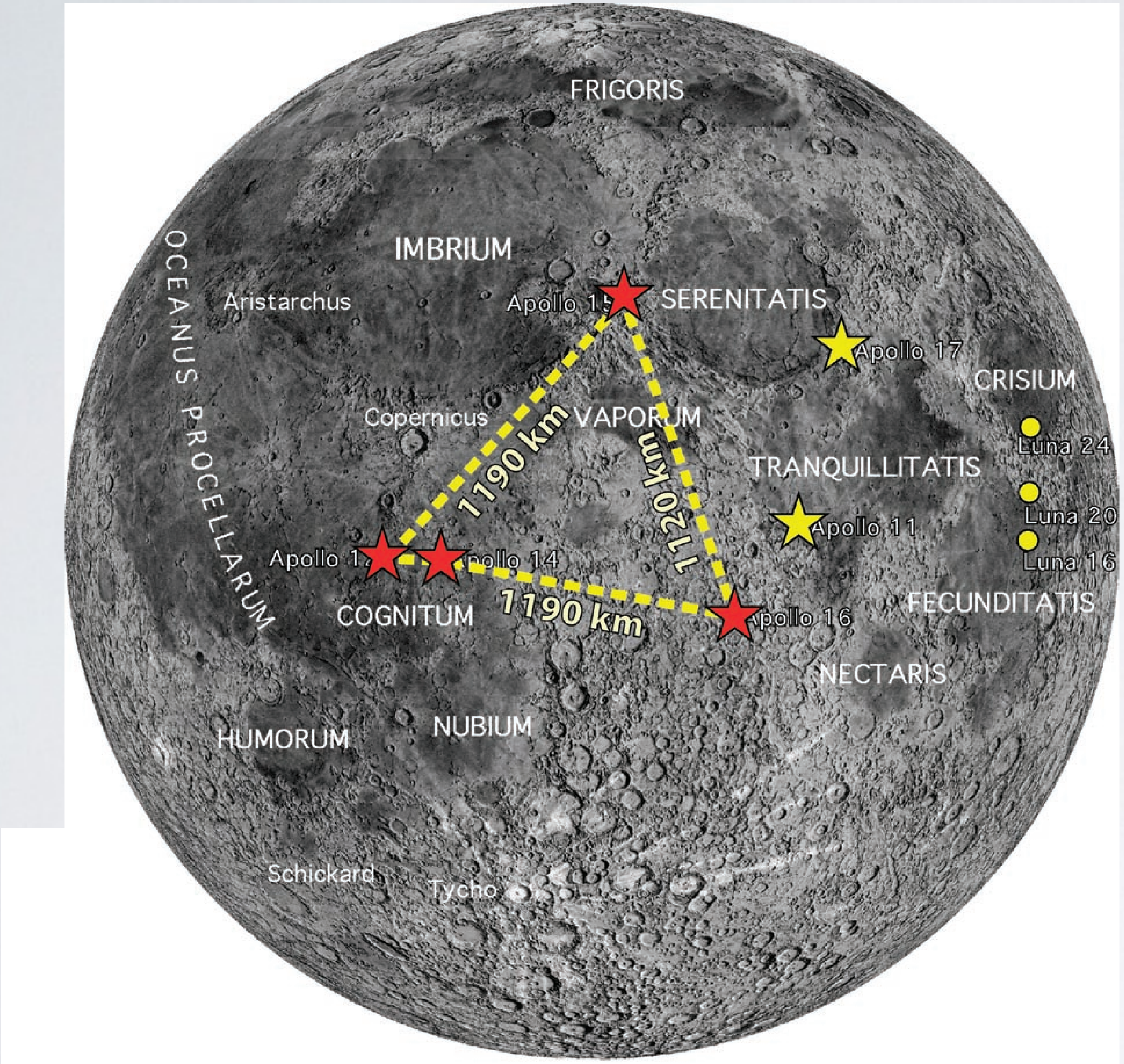
Benjamin et al., 2006:
attenuation becomes frequency dependent
and increases at > 10000s

Frequency domain model
(Morris and Jackson, 2009, Lee et al., 2011)



grain size dependence changes from
~ linear (transient) to cubic (steady state)

Application to other planetary bodies: Moon



Wieczorek, 2009

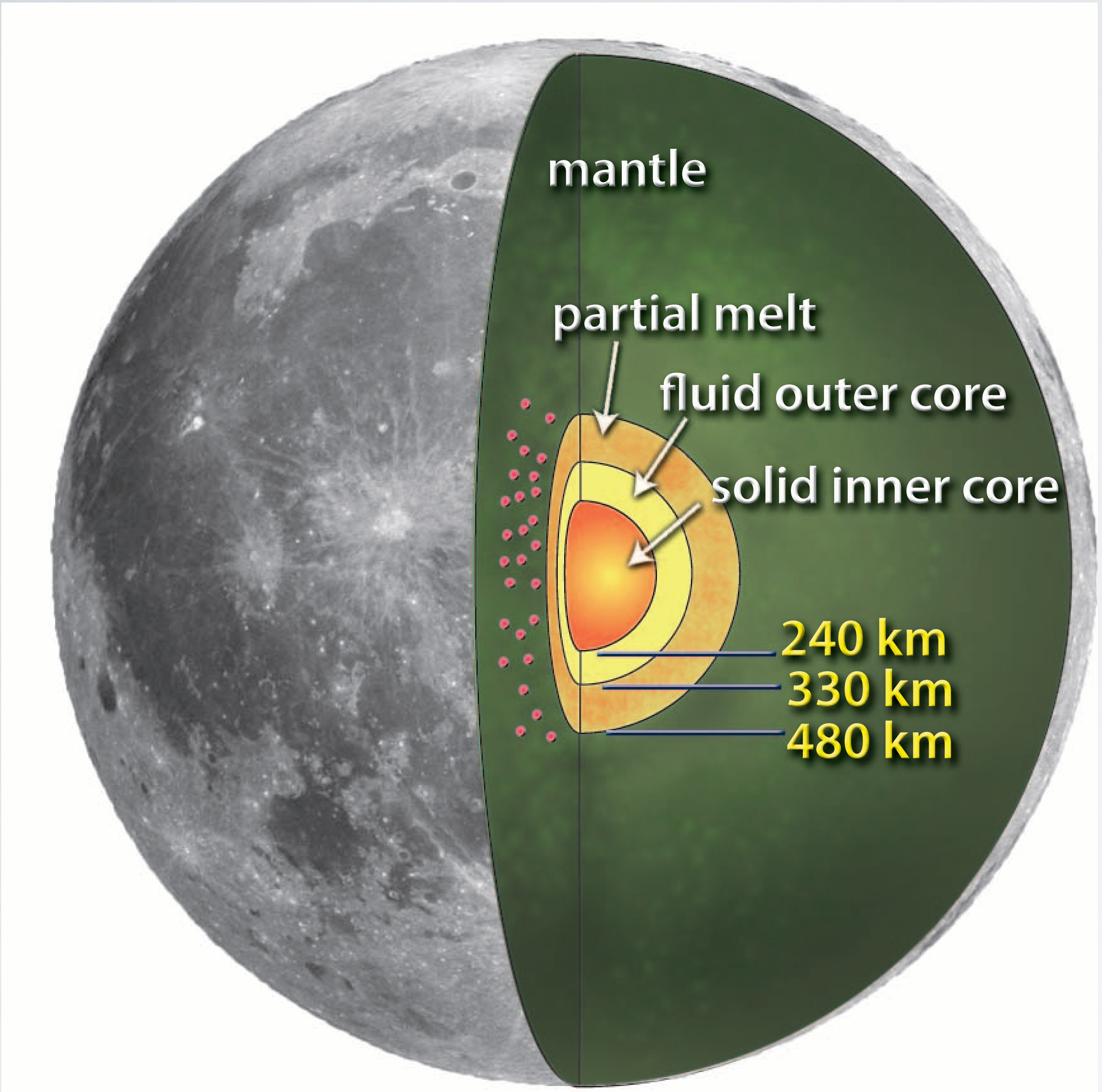
Configuration of the Apollo seismic network

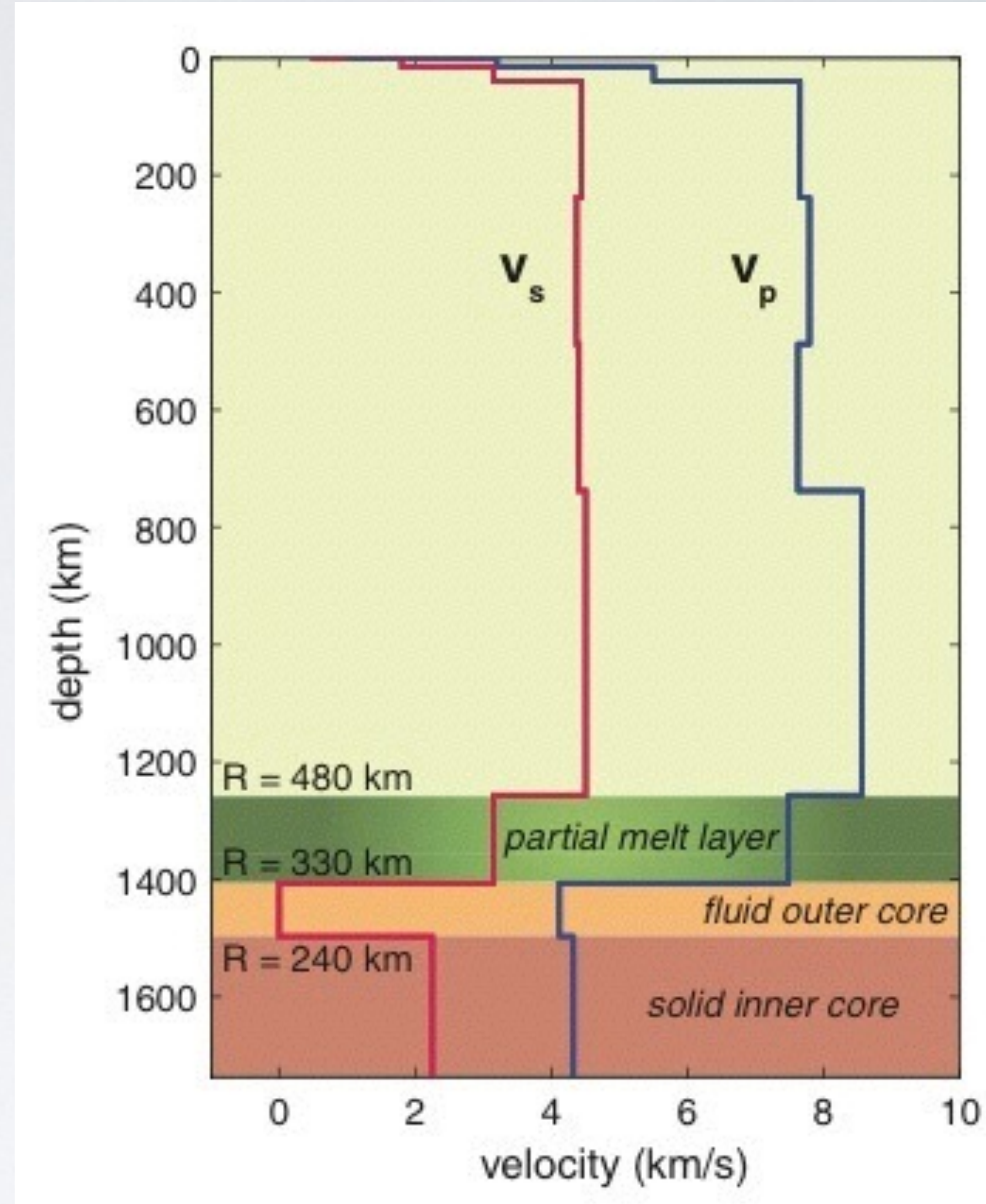
seismic data

phase lag of pole of rotation

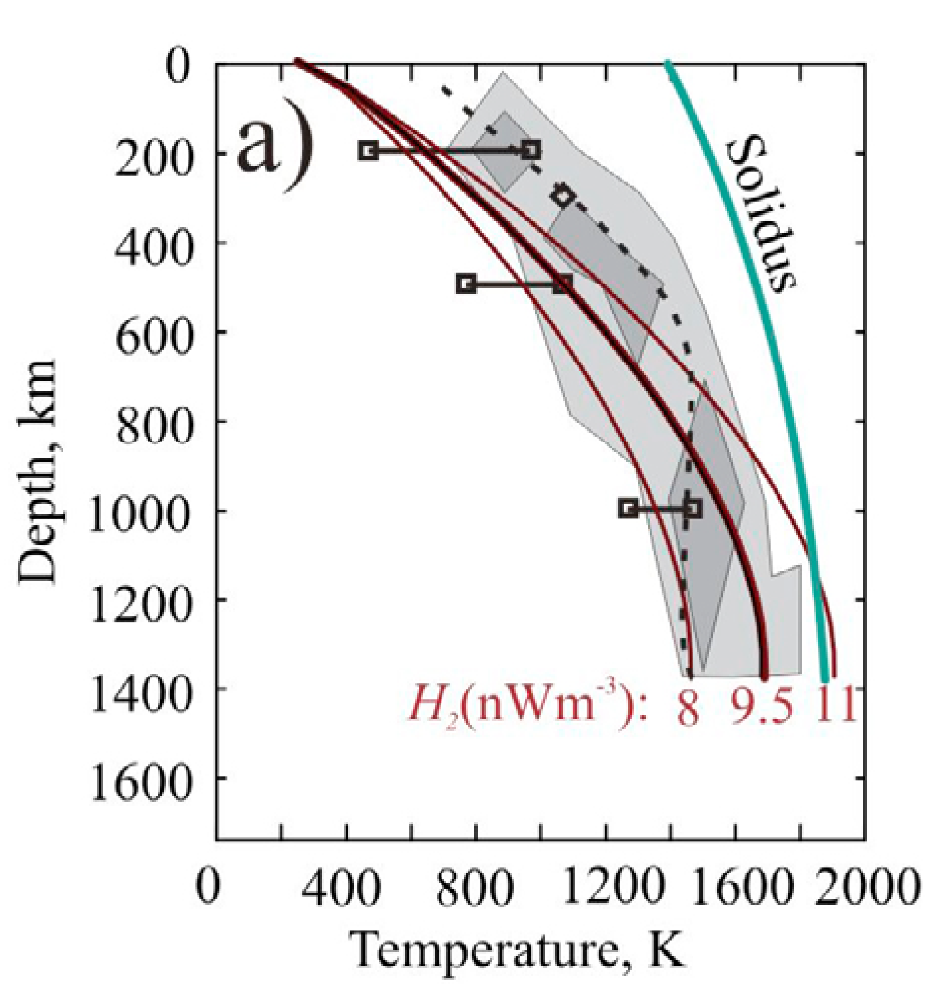
tidal Love number k_2

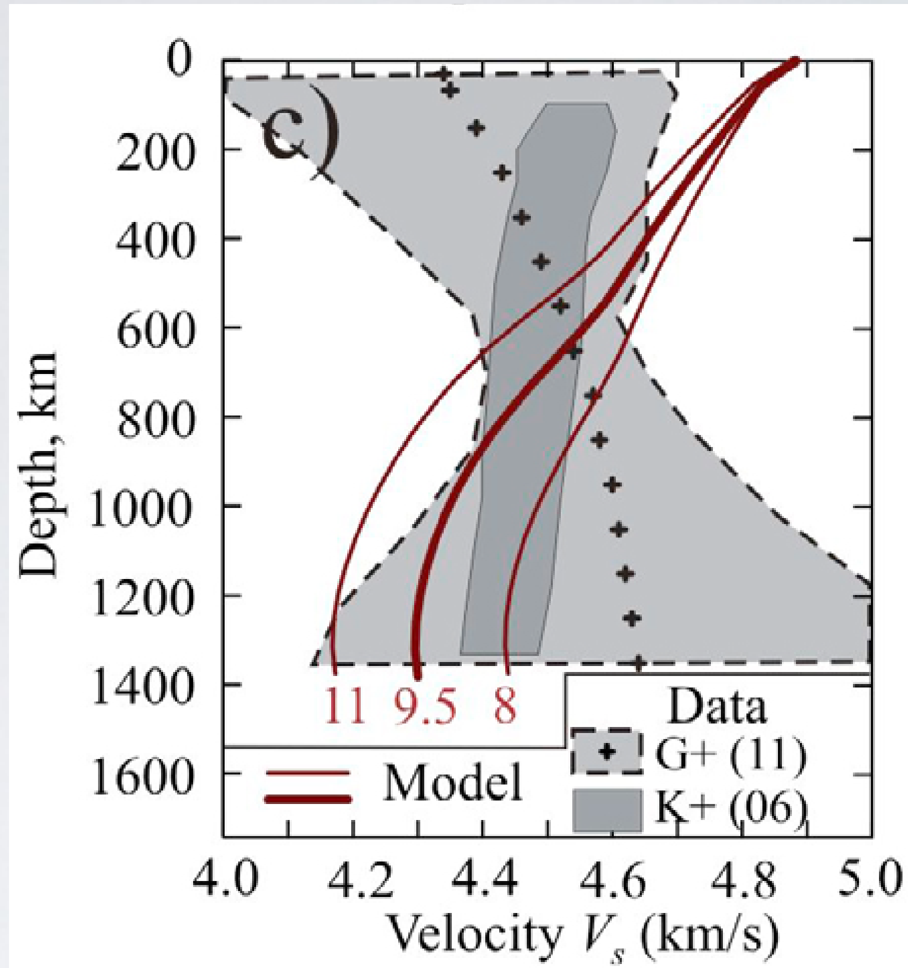
Model from seismic data



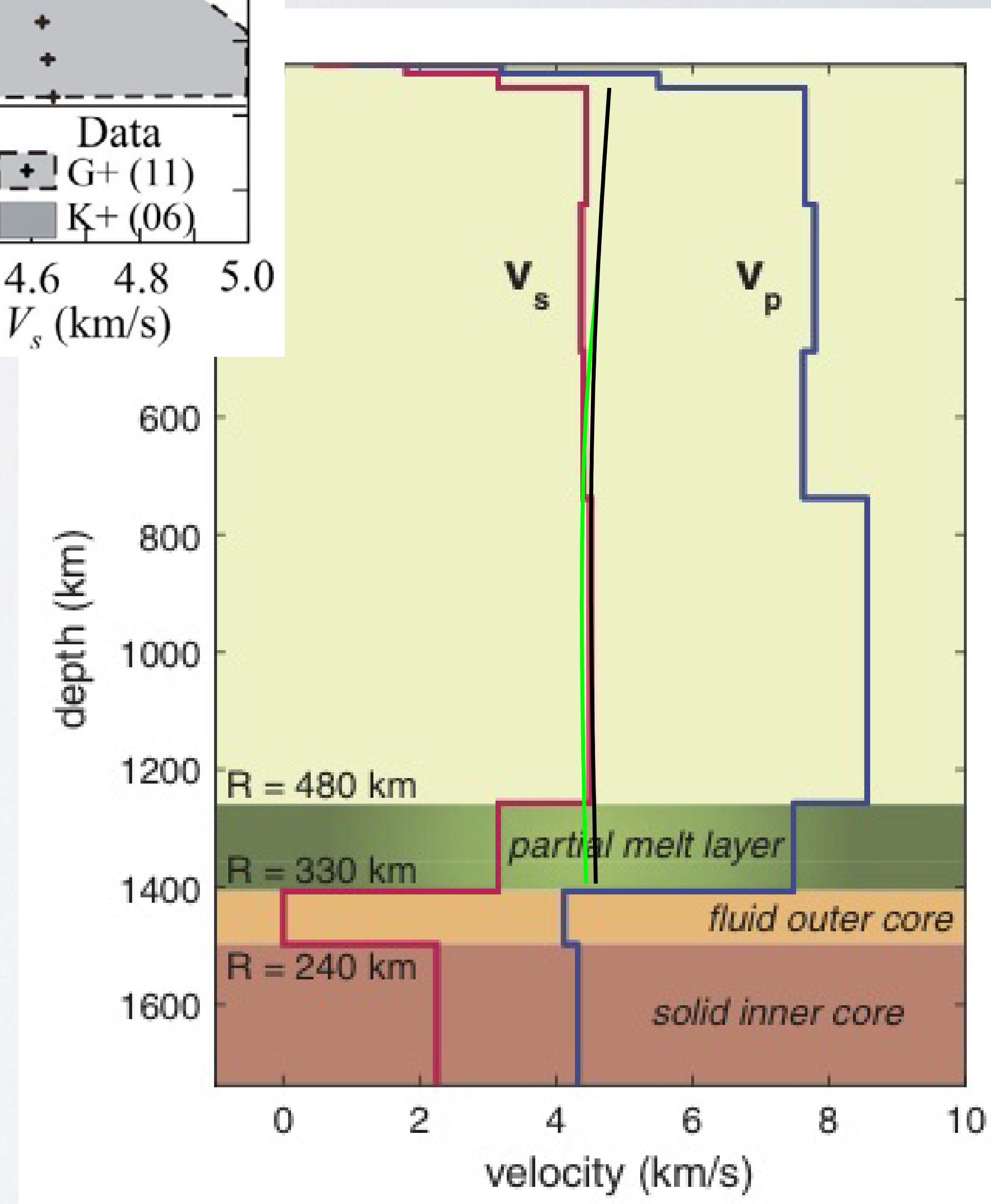


Weber et al., 2011



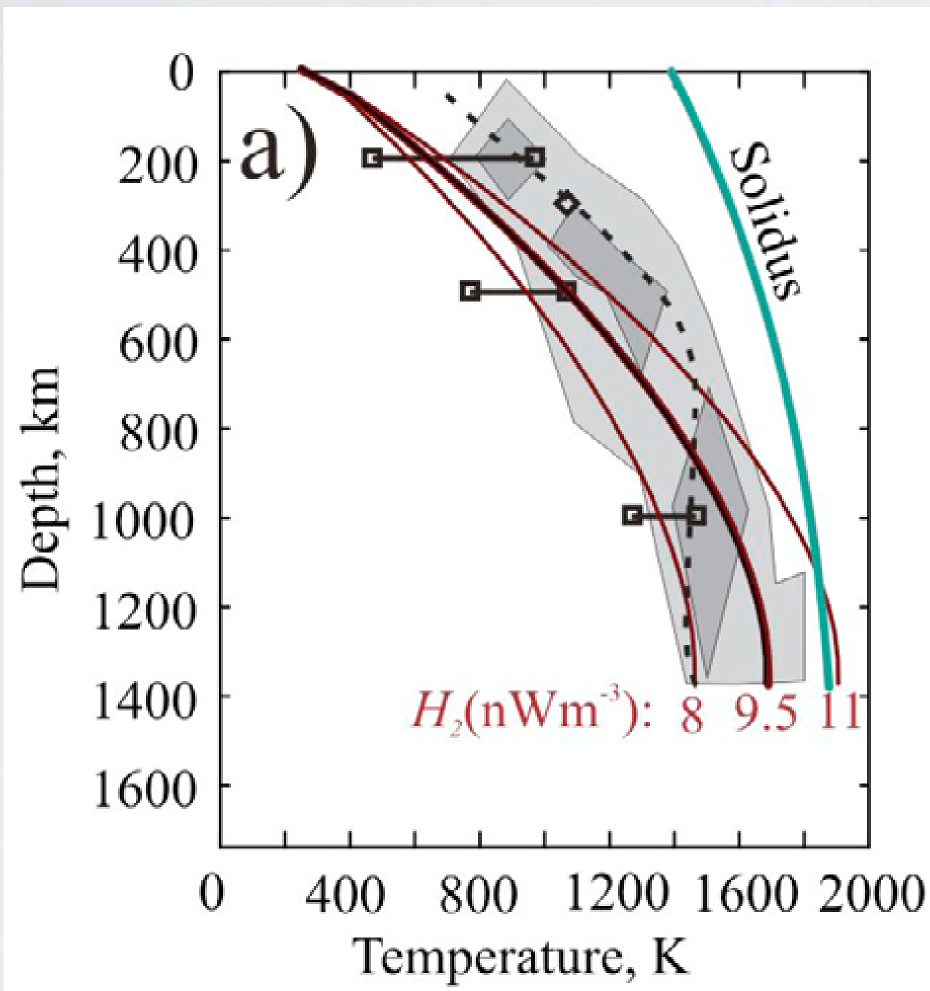


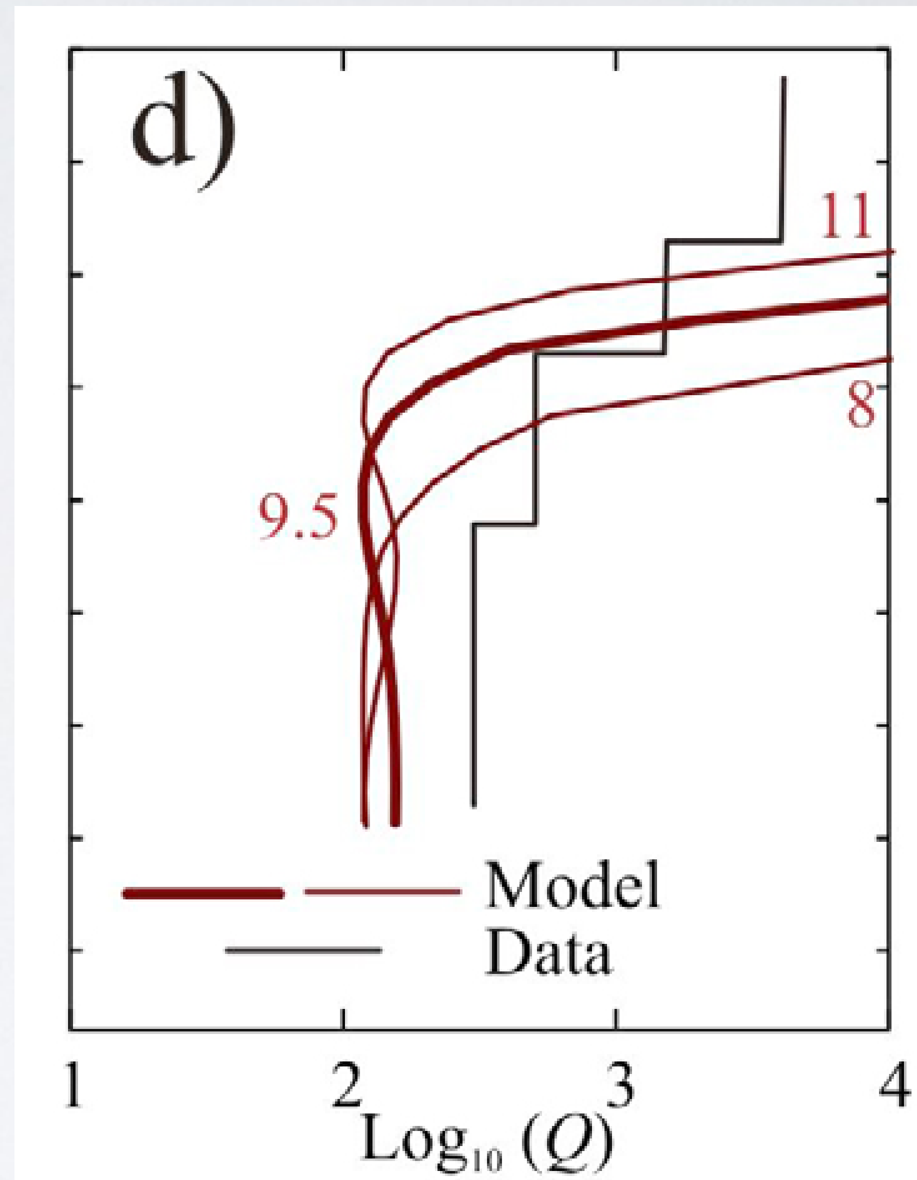
Nimmo, Faul & Garnero, 2012



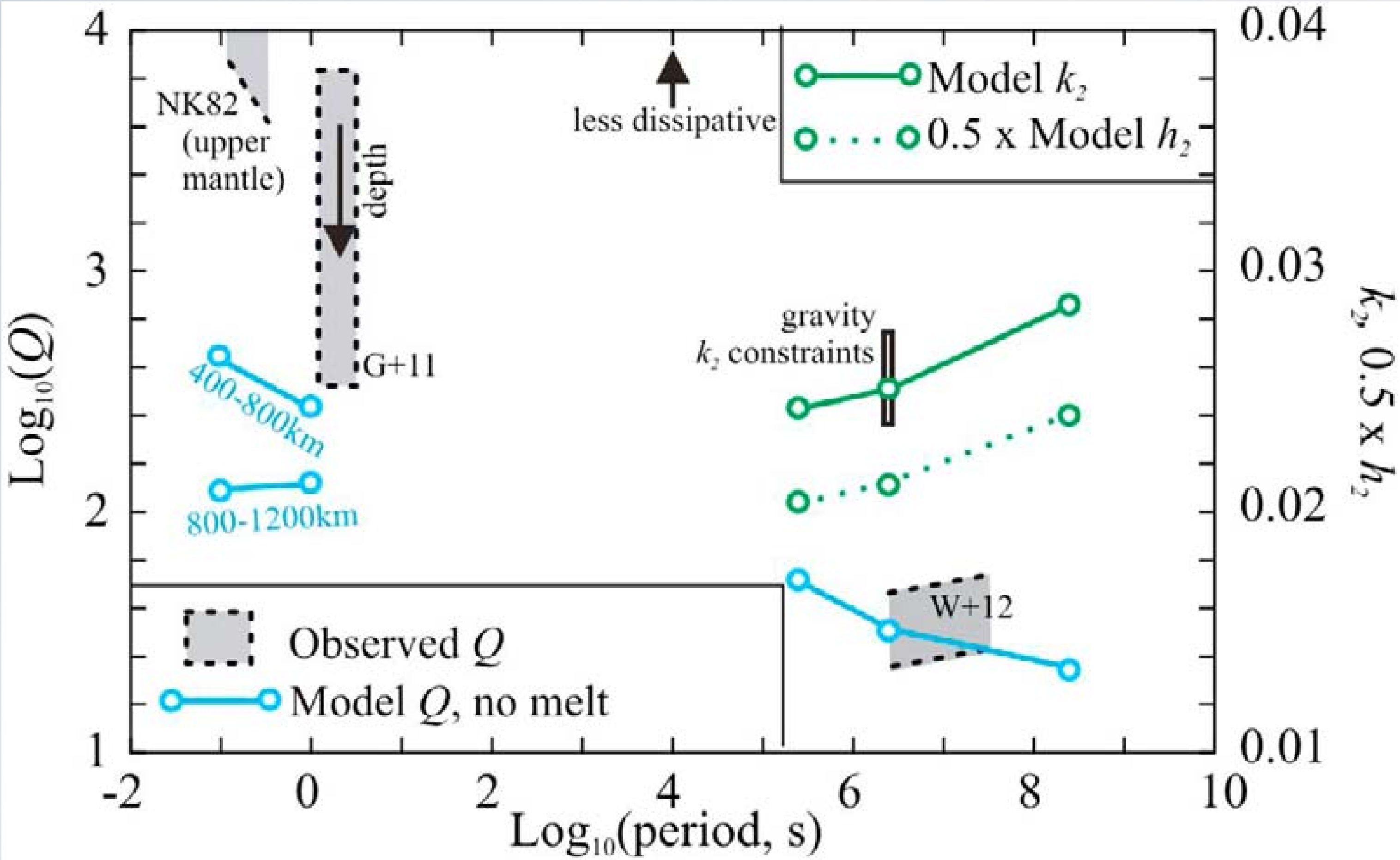
temperature increases - velocity has to decrease for fixed composition

Attenuation: no melt required



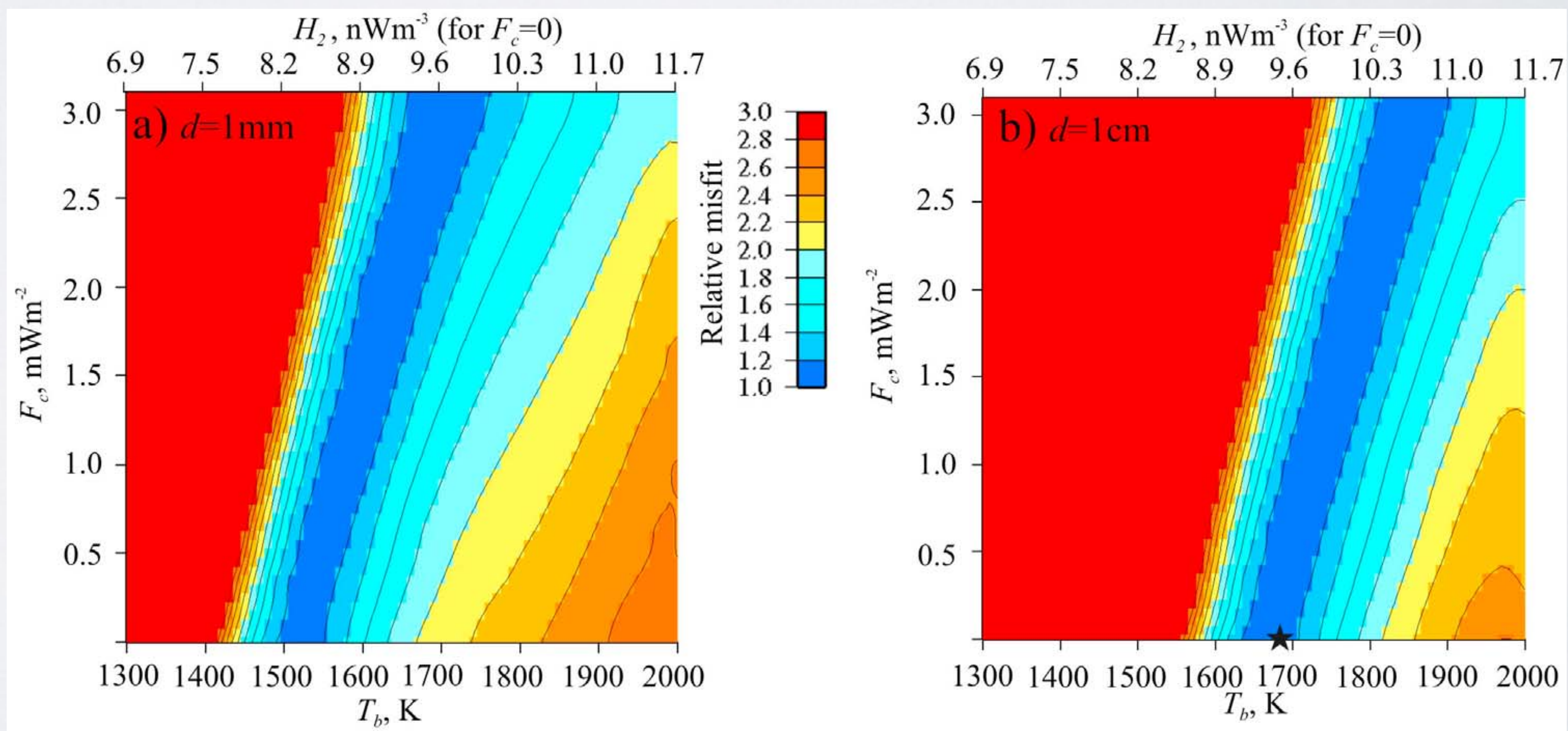


geodetic and dissipation data and model

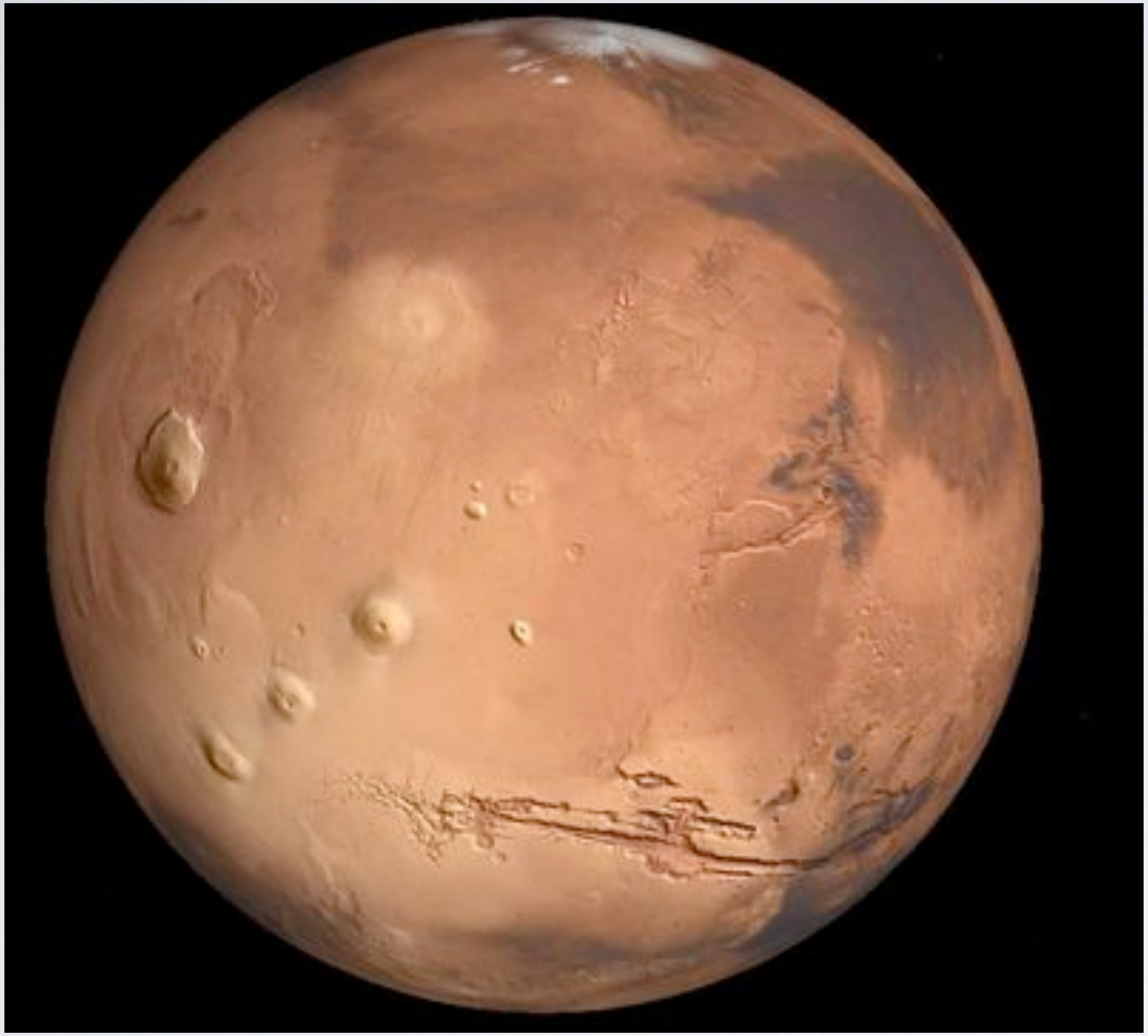


inferred temperature

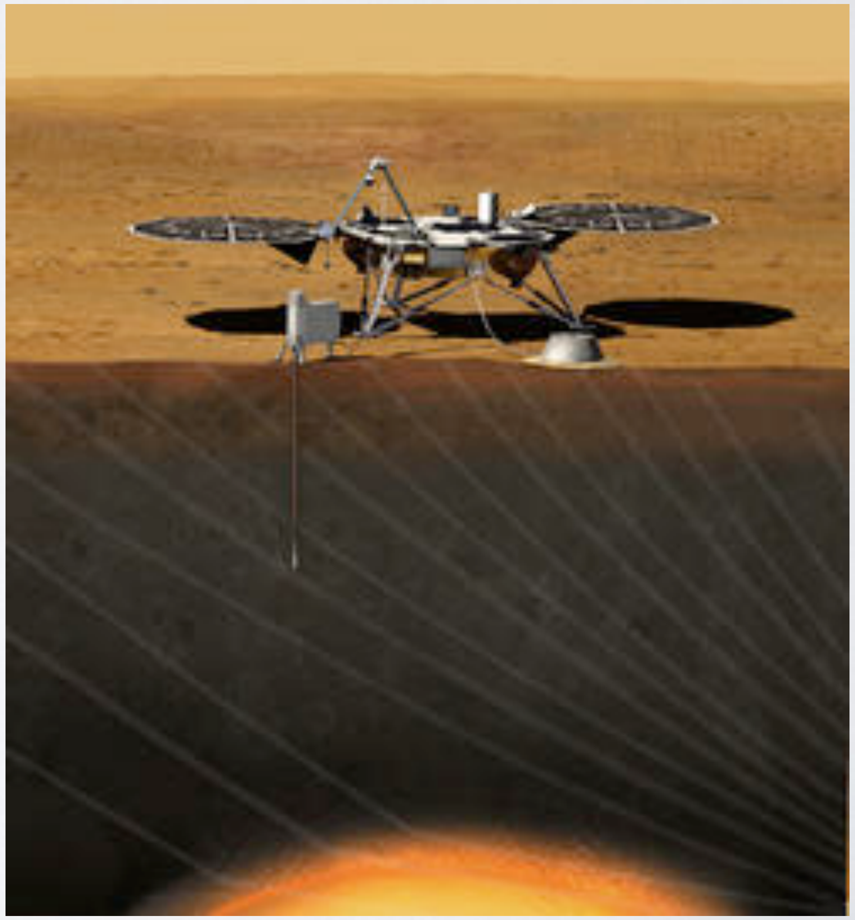
Core heat flux



T at base of mantle (~1400 km depth)

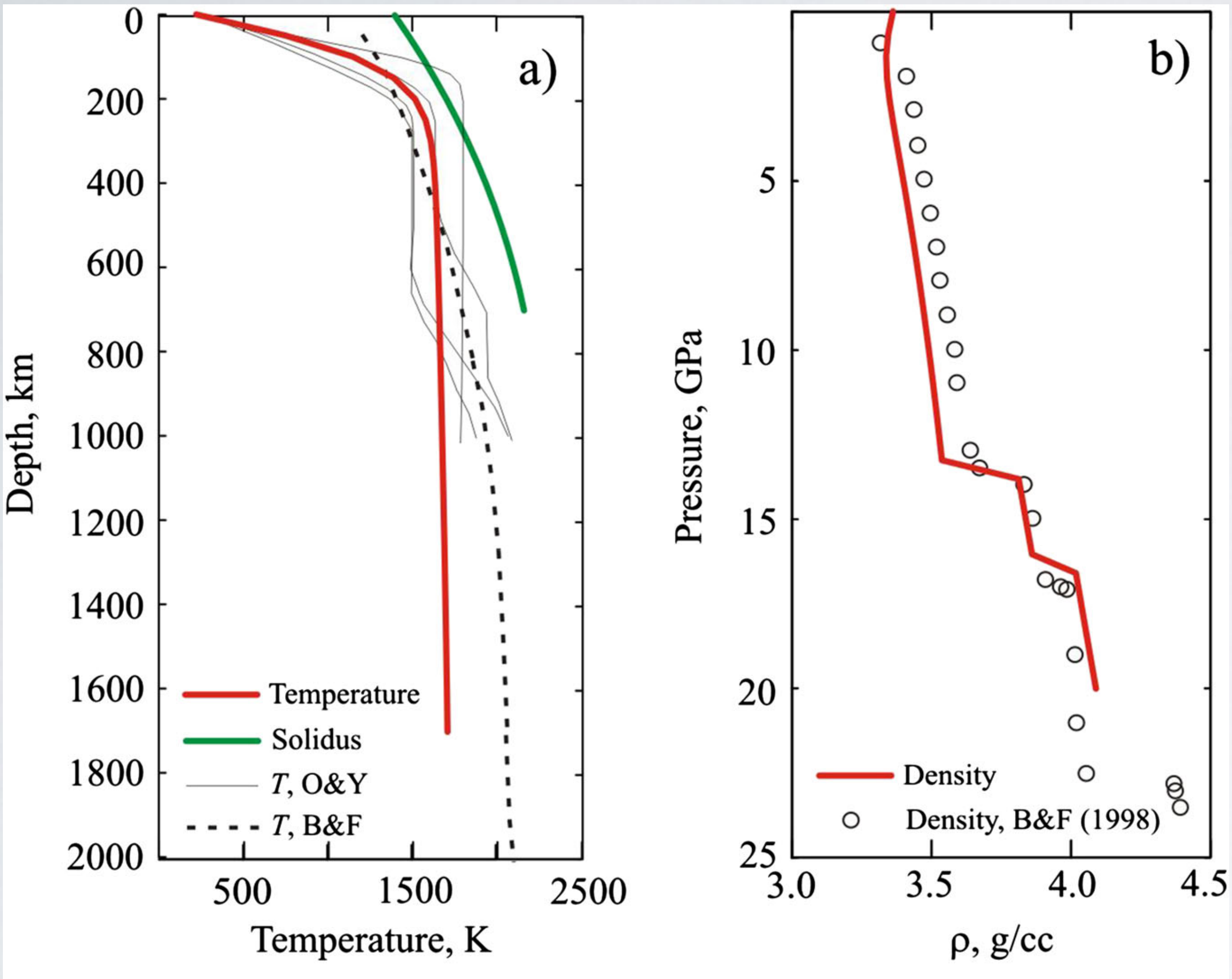


Mars

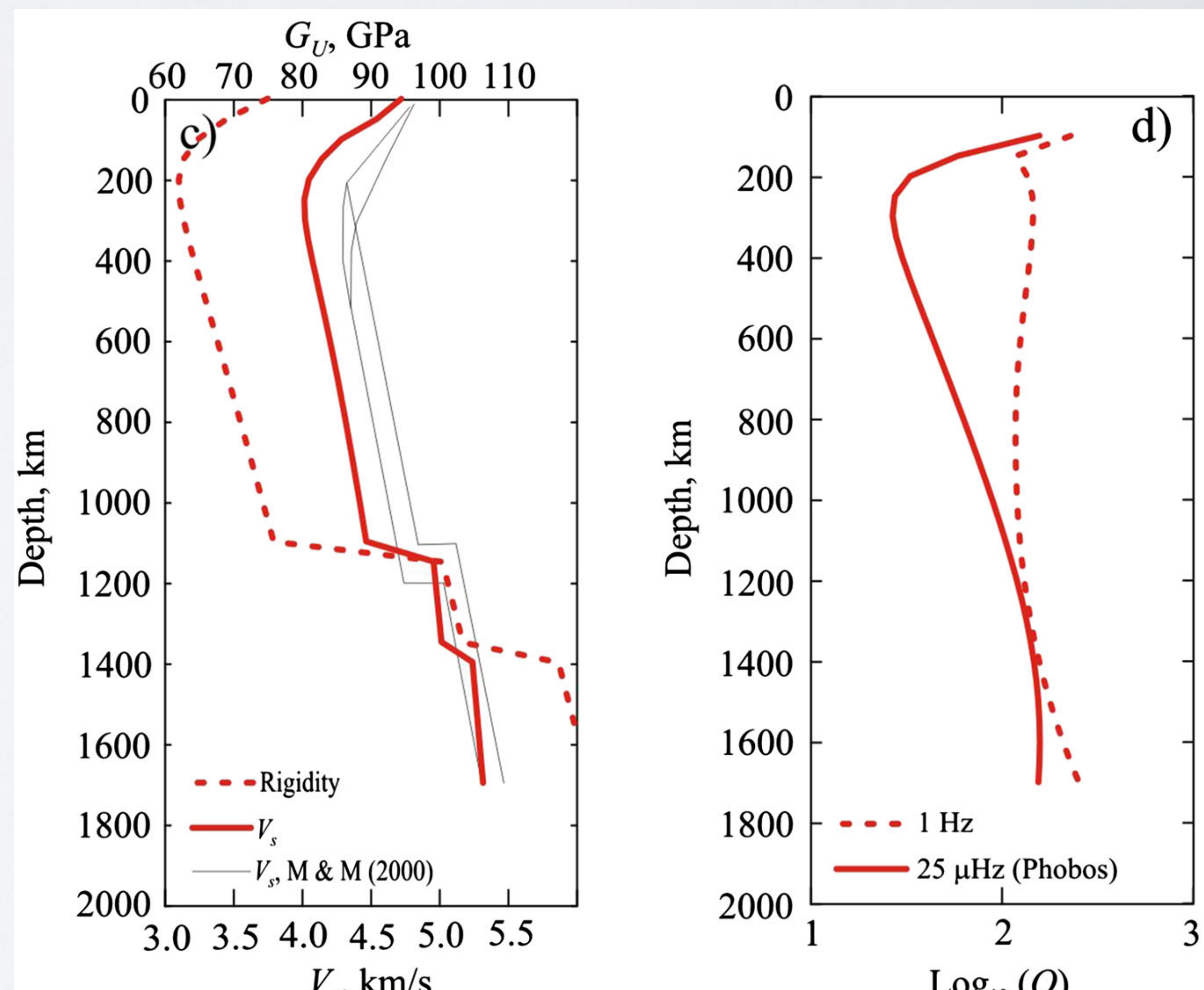


Geophysical lander in 2016
(InSight mission),
including a seismometer

Existing data provides constraints on density, composition etc.

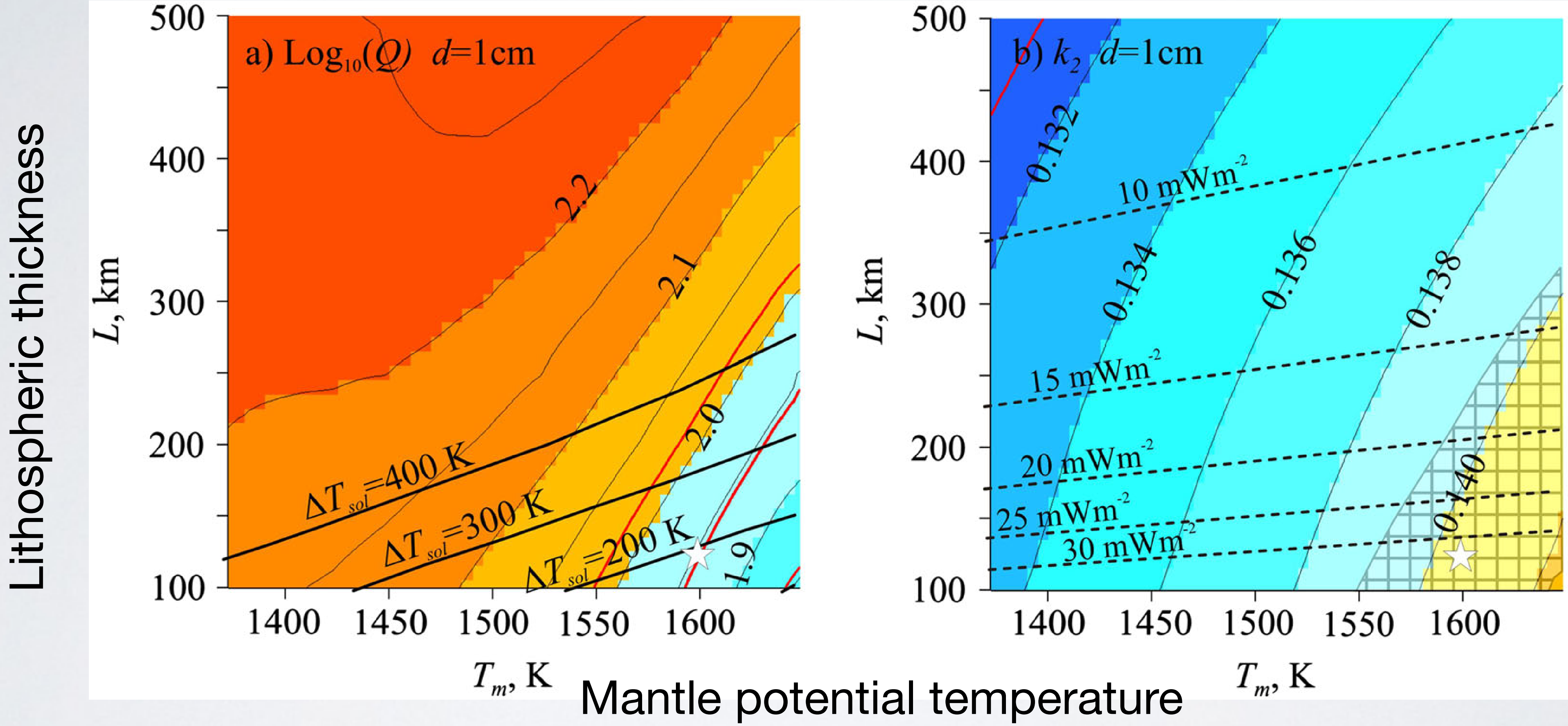


allows forward modelling of temperature, seismic properties



Nimmo & Faul 2013

Tidal deformation (Phobos) places constraints on Q and k2



As for Moon, tidal deformation indicates overall moderate temperatures in the interior, substantially below solidus