Experimental Observation of Transient Creep of Upper Mantle Rocks

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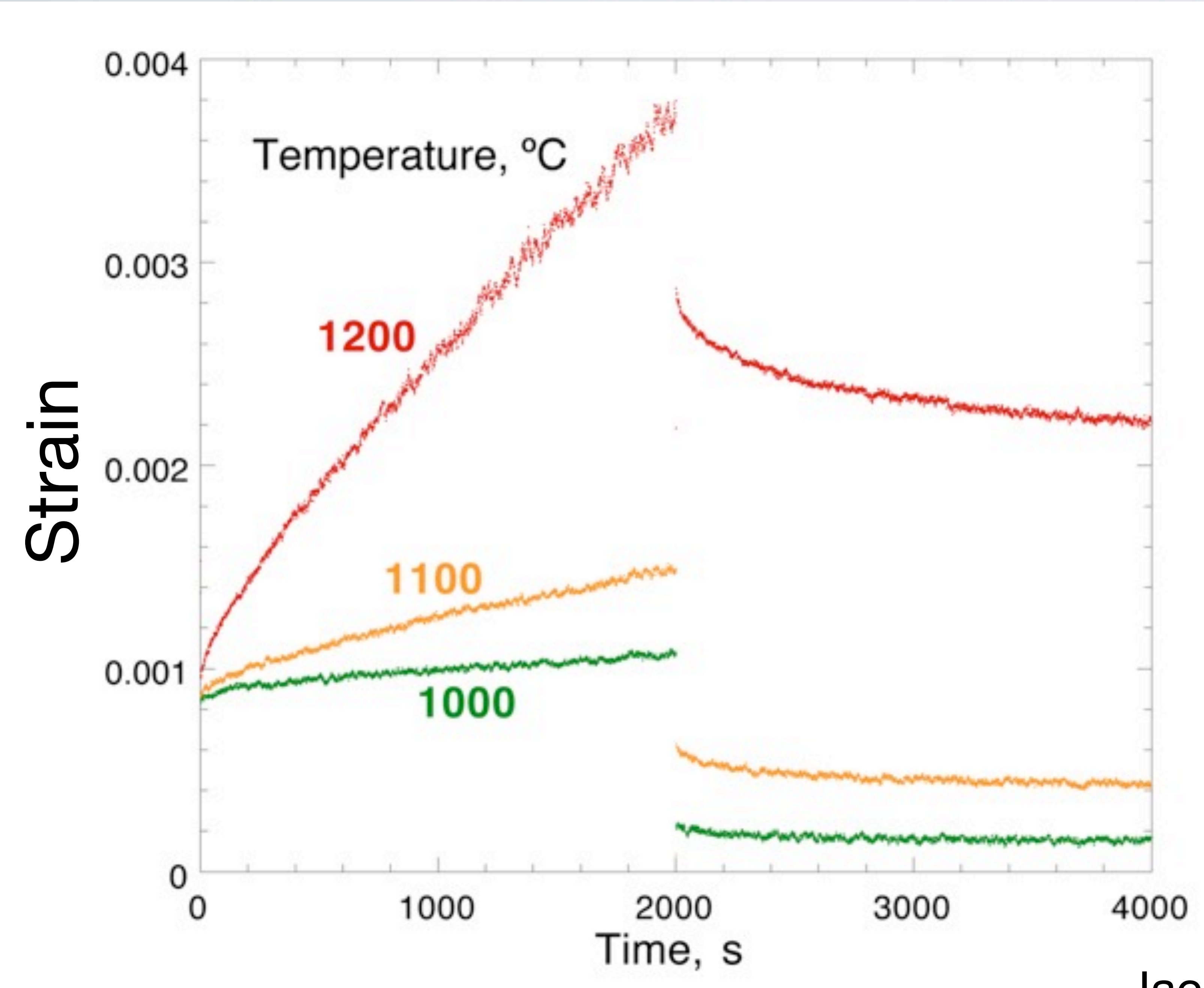
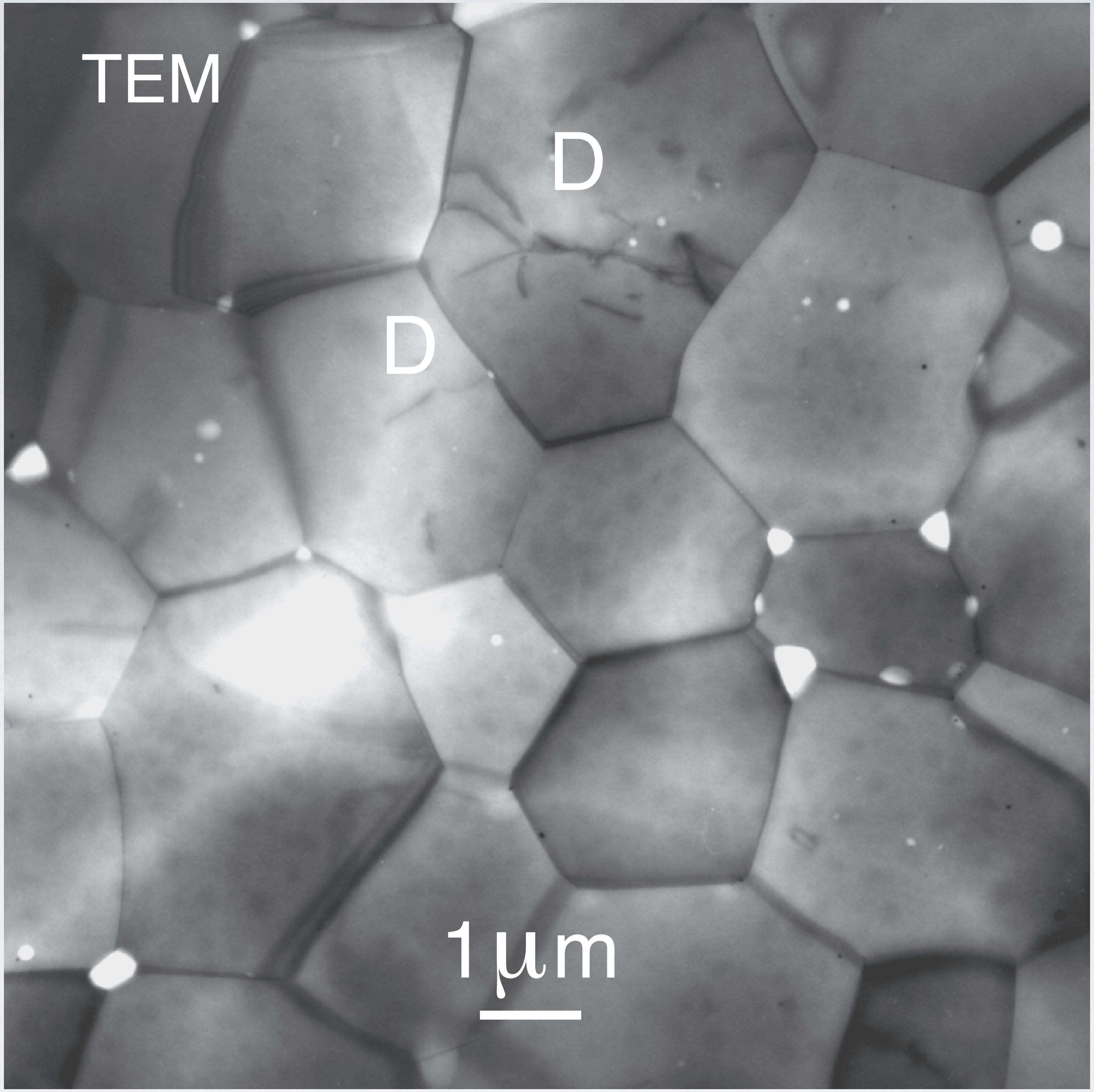
Microcreep in response to application of a step function stress



Jackson et al., 2002

response: elastic + transient + viscous

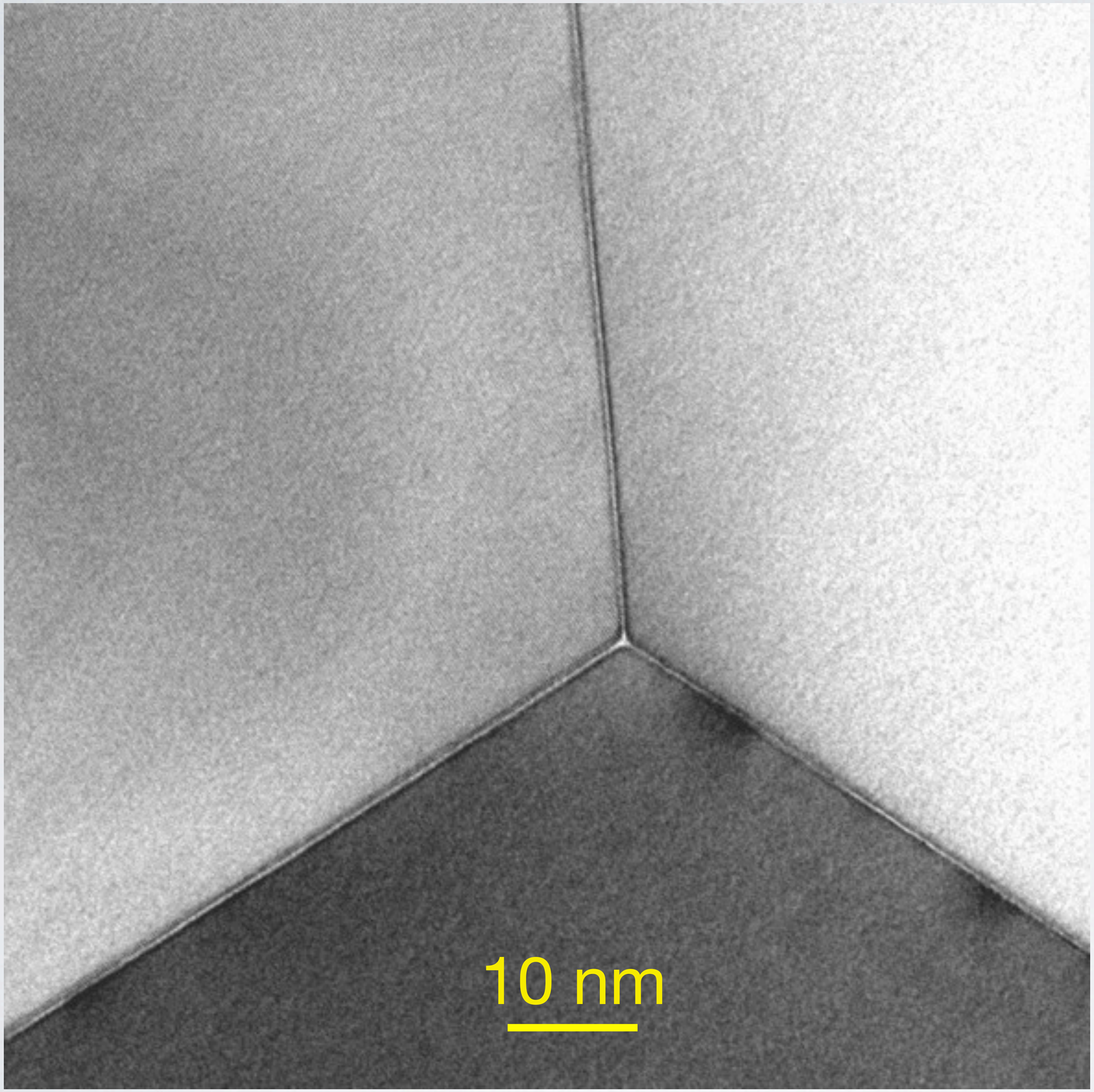
Microstructure: melt-free polycrystalline olivine



Jackson et al., 2002

defects: grain boundaries, dislocations

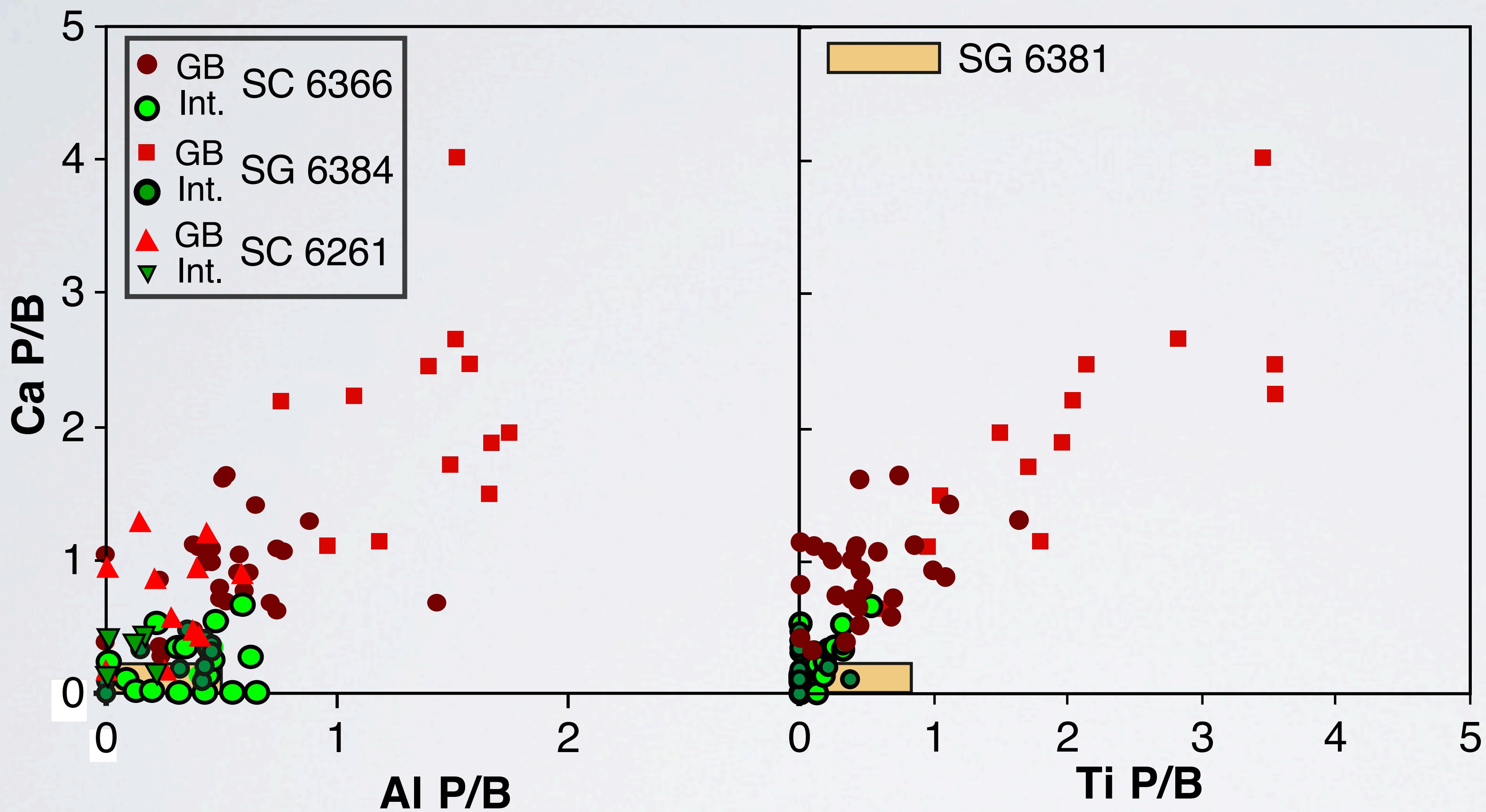
A closer look at grain boundaries:

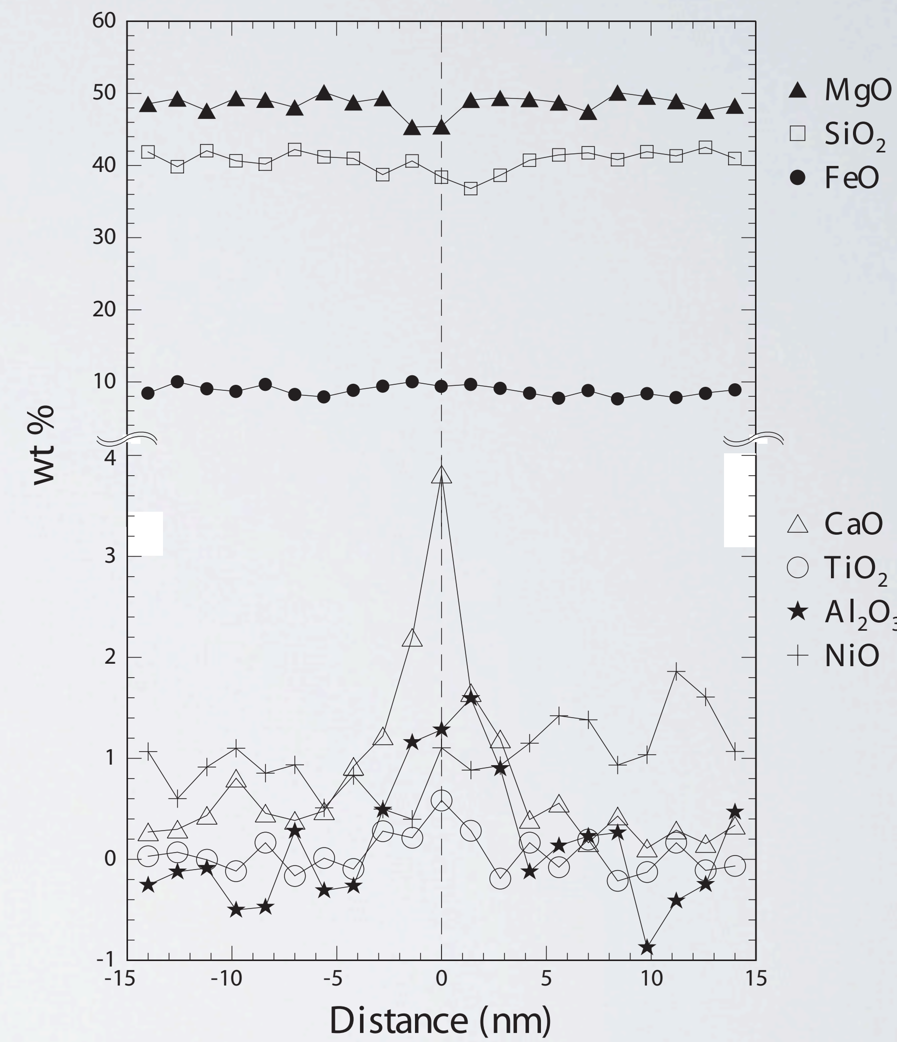


TEM image of triple junction of melt-free olivine. Grain boundaries oriented parallel to the beam.

Faul et al., 2004

TEM-EDS analyses of high angle grain boundaries



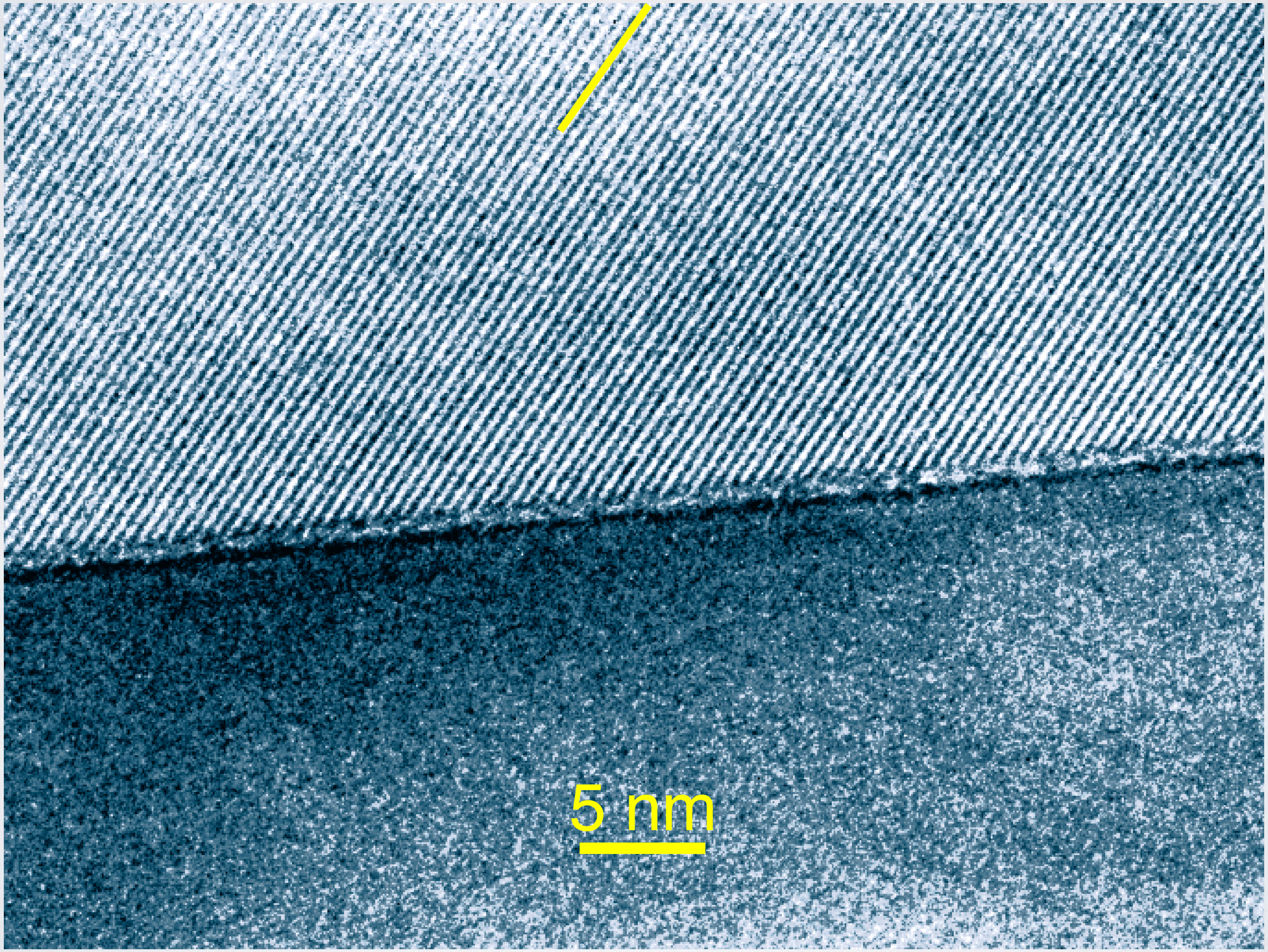


Hiraga et al., 2003

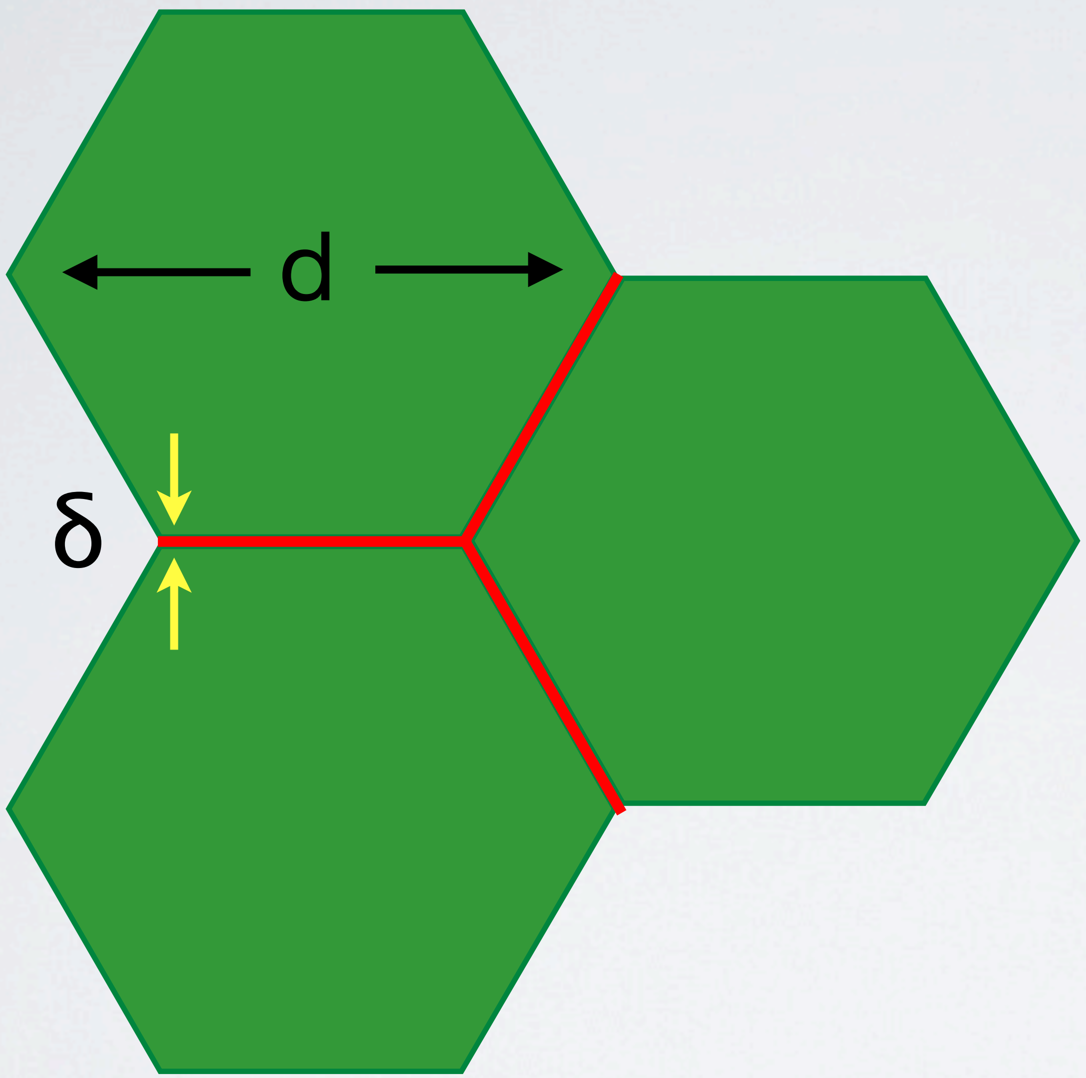
Grain boundaries are trace element enriched relative to grain interiors

High angle (general) grain boundaries in olivine: smooth (no evidence of steps or dislocation structures), structurally distinct, ~ 1nm wide, chemically enriched

(010)



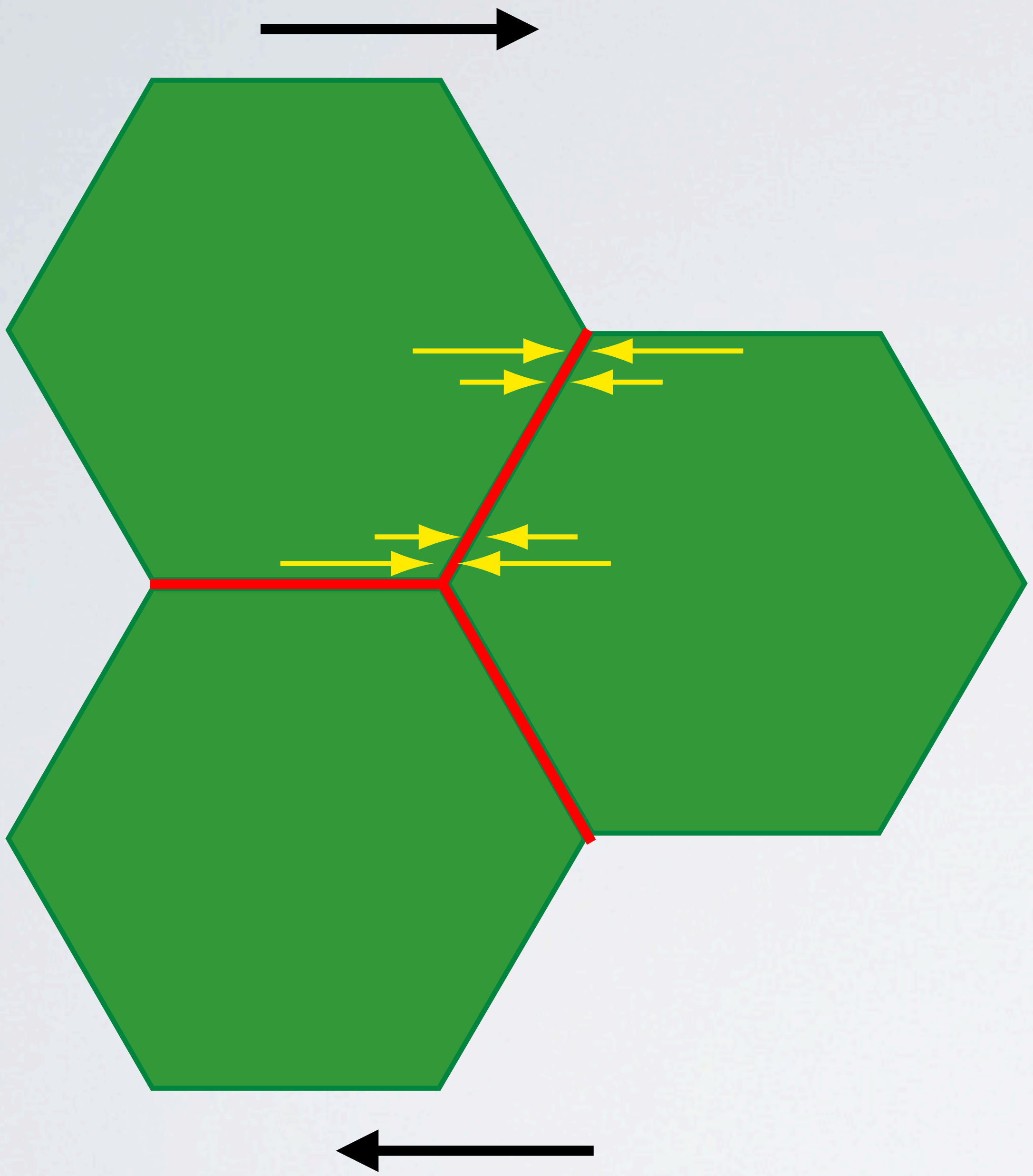
Grain boundary sliding due to shear stress



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

results in three distinct processes:

1. Elastically accommodated sliding



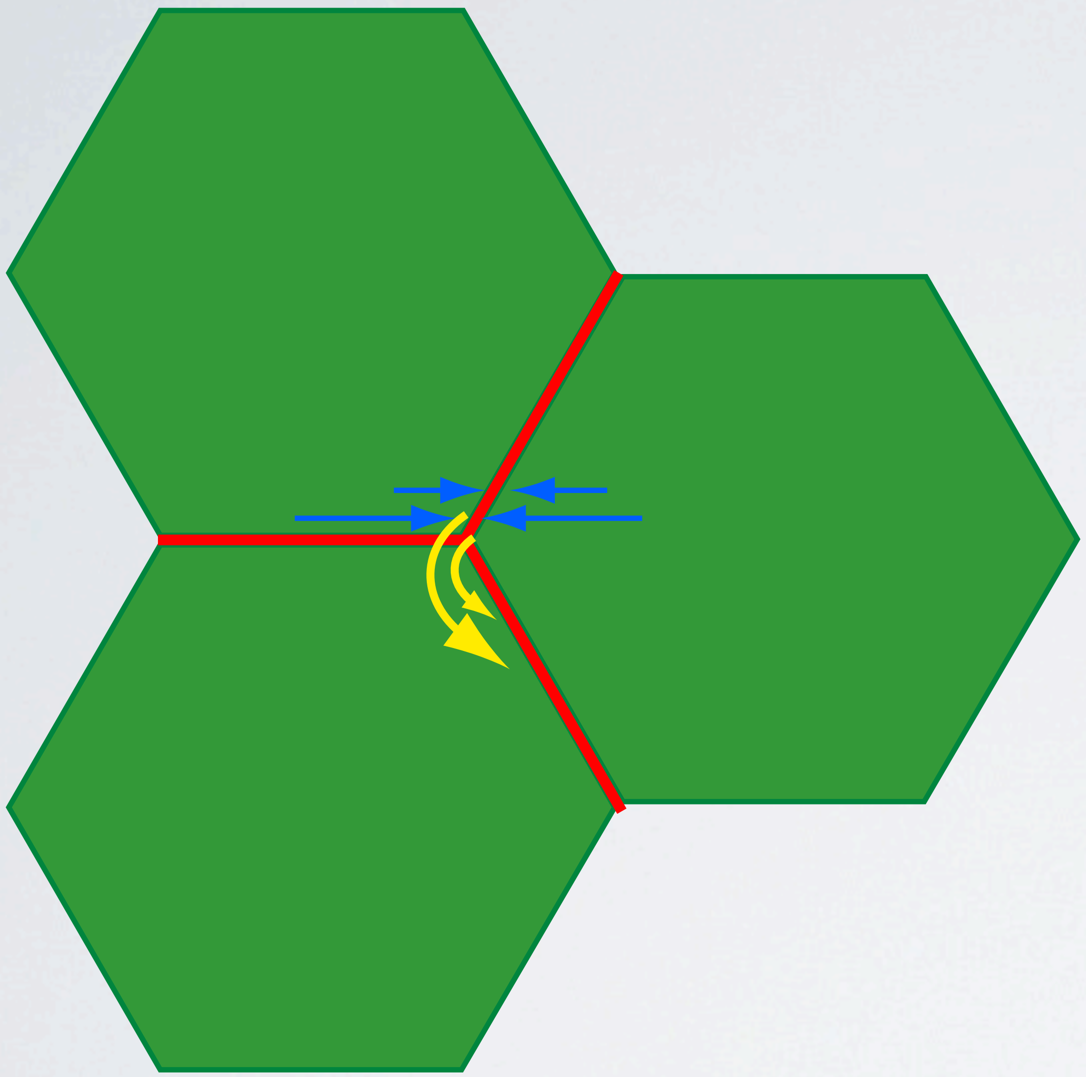
viscous sliding of grain boundaries leads to elastic stress concentrations at grain corners

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

recoverable strain, anelastic process

After Raj and Ashby, 1971; Raj, 1975

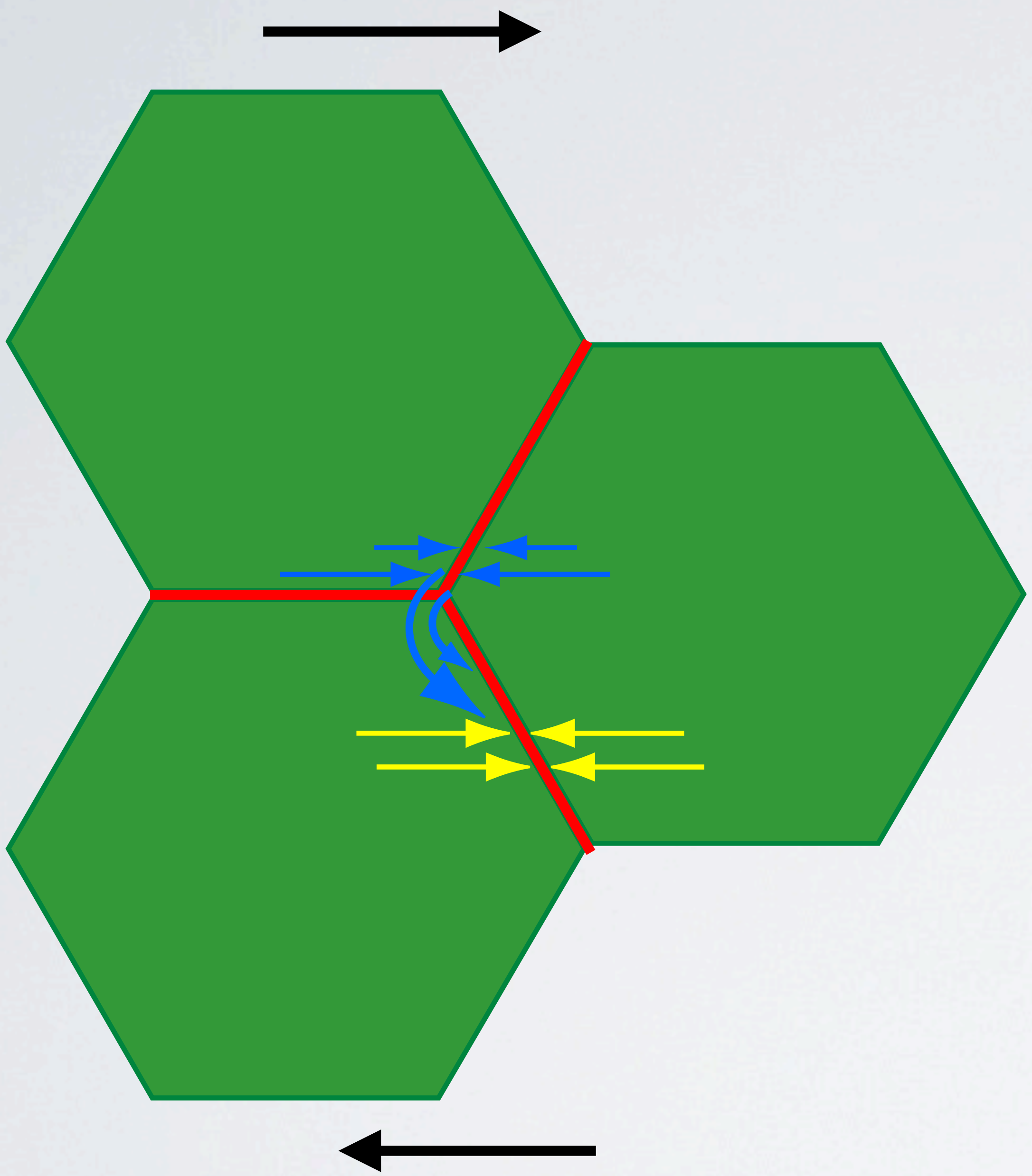
2. Diffusionally assisted sliding

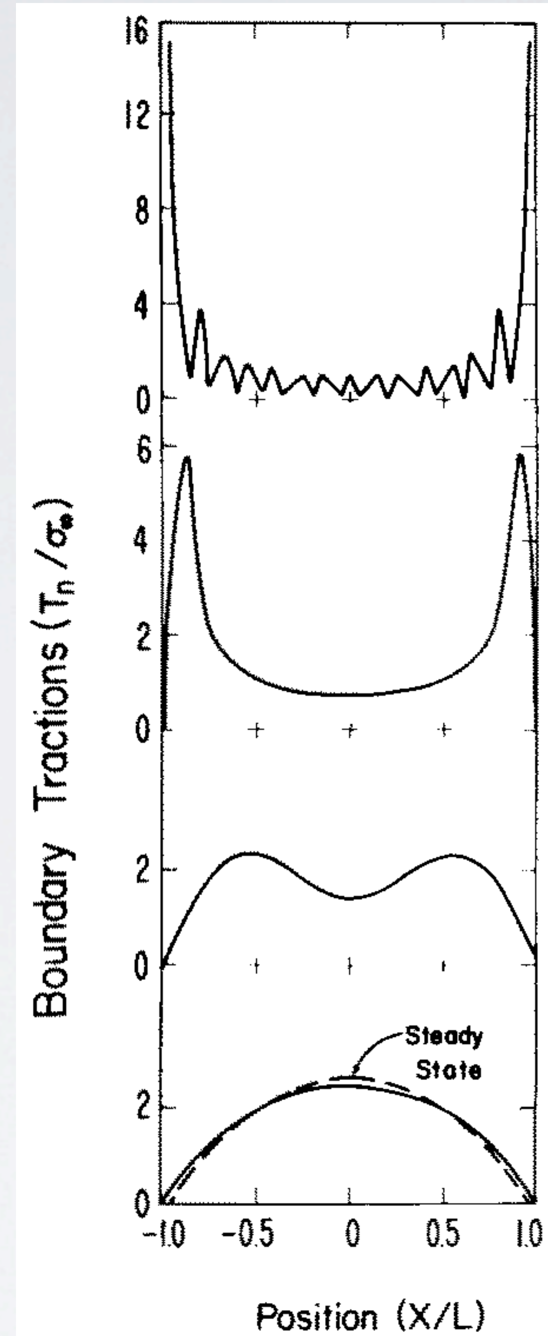


- stress concentrations cause diffusion away from corners
- transient phase is characterised by diffusion over increasing length scales

transient but ‘viscous’ process

3. Diffusionally accommodated sliding (steady state)



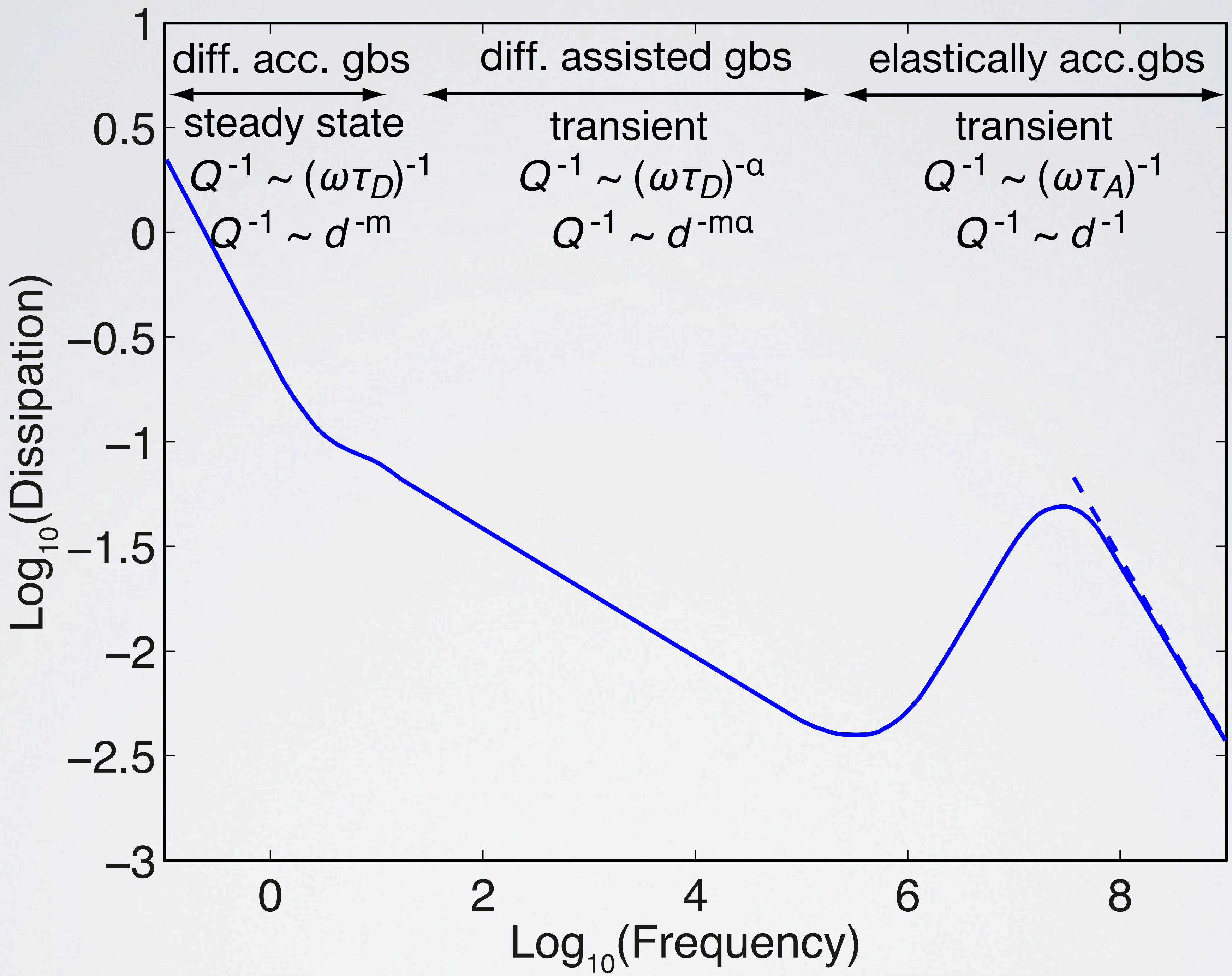


Raj 1975, Gribb & Cooper, 1998

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

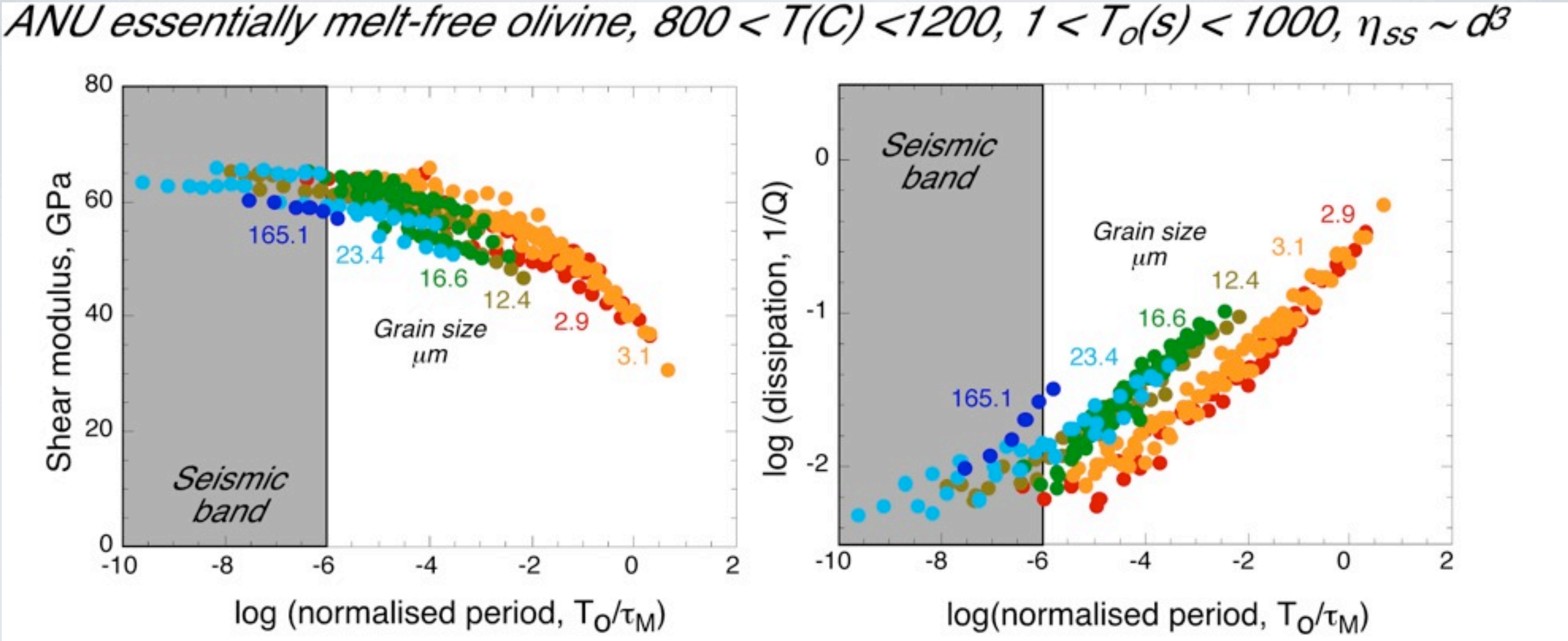
gb normal stresses are highest in center between grain corners (steady state diffusion creep)

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



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

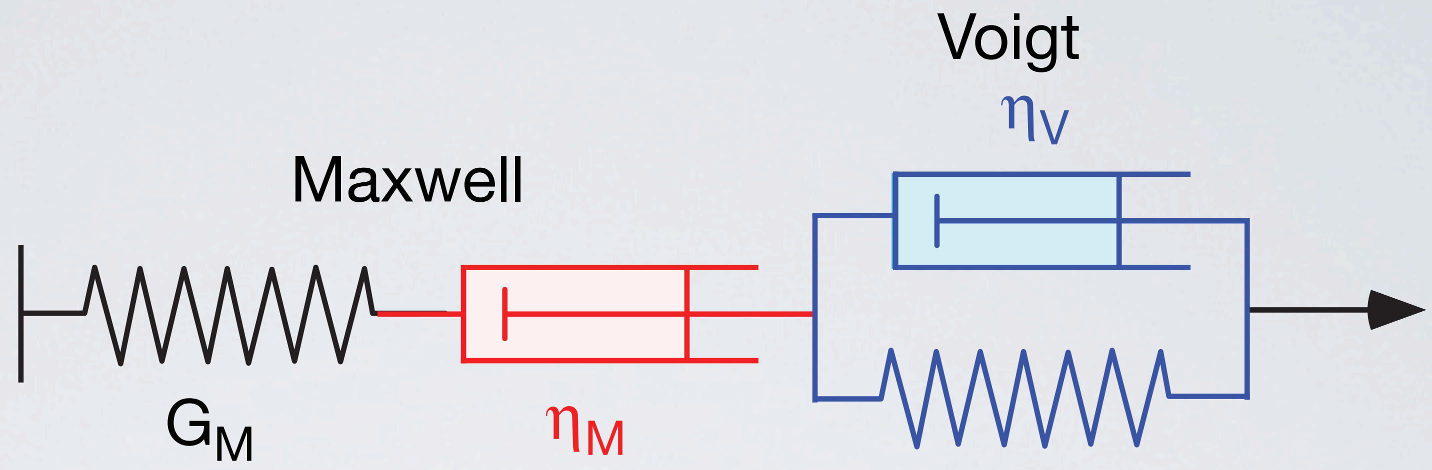
DEPARTURES FROM THE MASTER CURVE



Q^{-1} is more mildly grain-size sensitive than expected from scaling with the Maxwell time $\tau_M = \eta_{SS}/G_U \sim d^3 \exp(E/RT)$ for Coble creep

-> transient close to linear in grain size dependence

Data fitting: (extended) Burgers model



instantaneous steady state transient

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

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

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

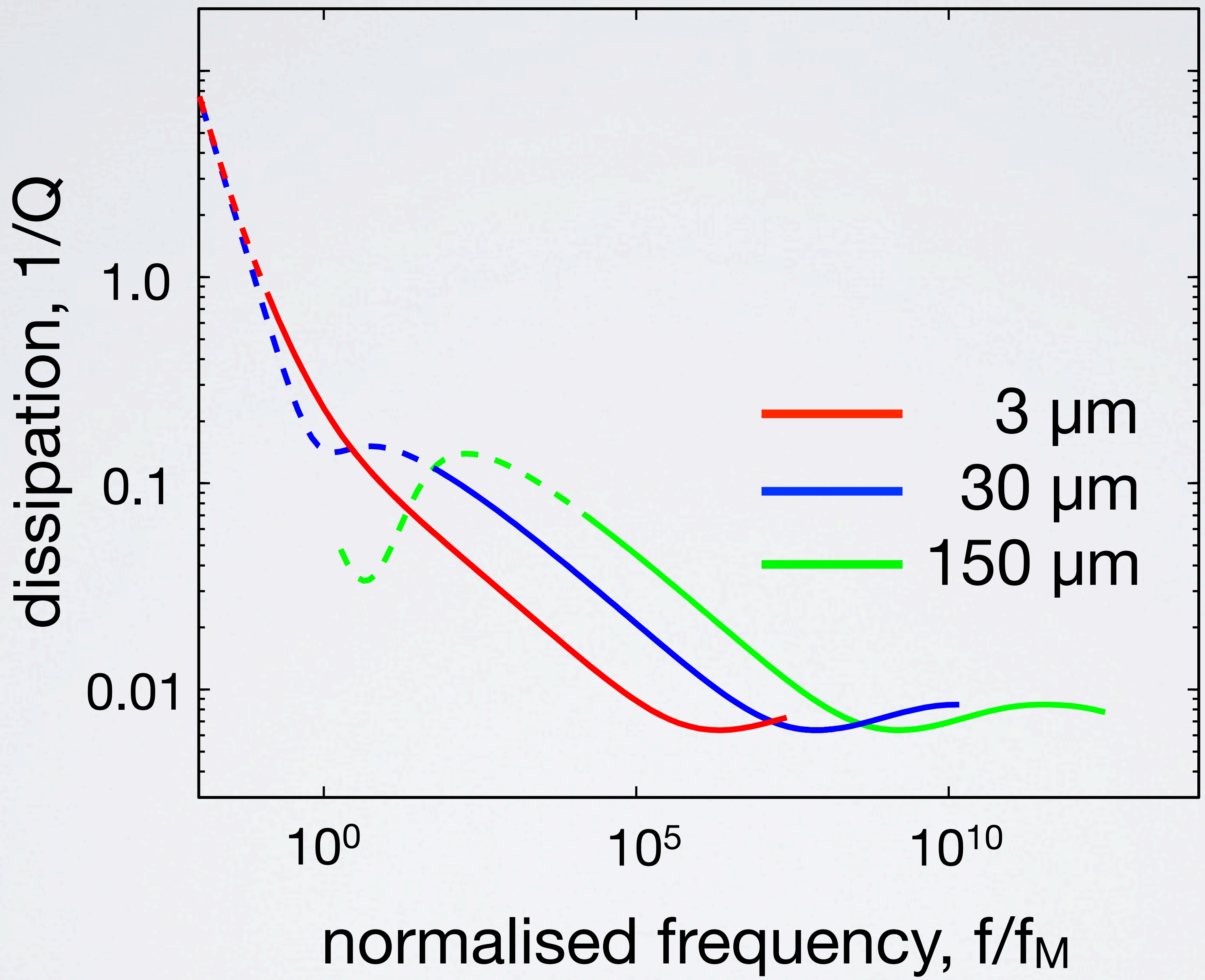
Frequency domain:

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

$$J^*(w) = J_1(\omega) + i\,J_2(\omega) \qquad J_2(\omega) = J_V\,\omega\tau_V/(1 + \omega^2\tau_V^2) + 1/\omega\tau_M$$

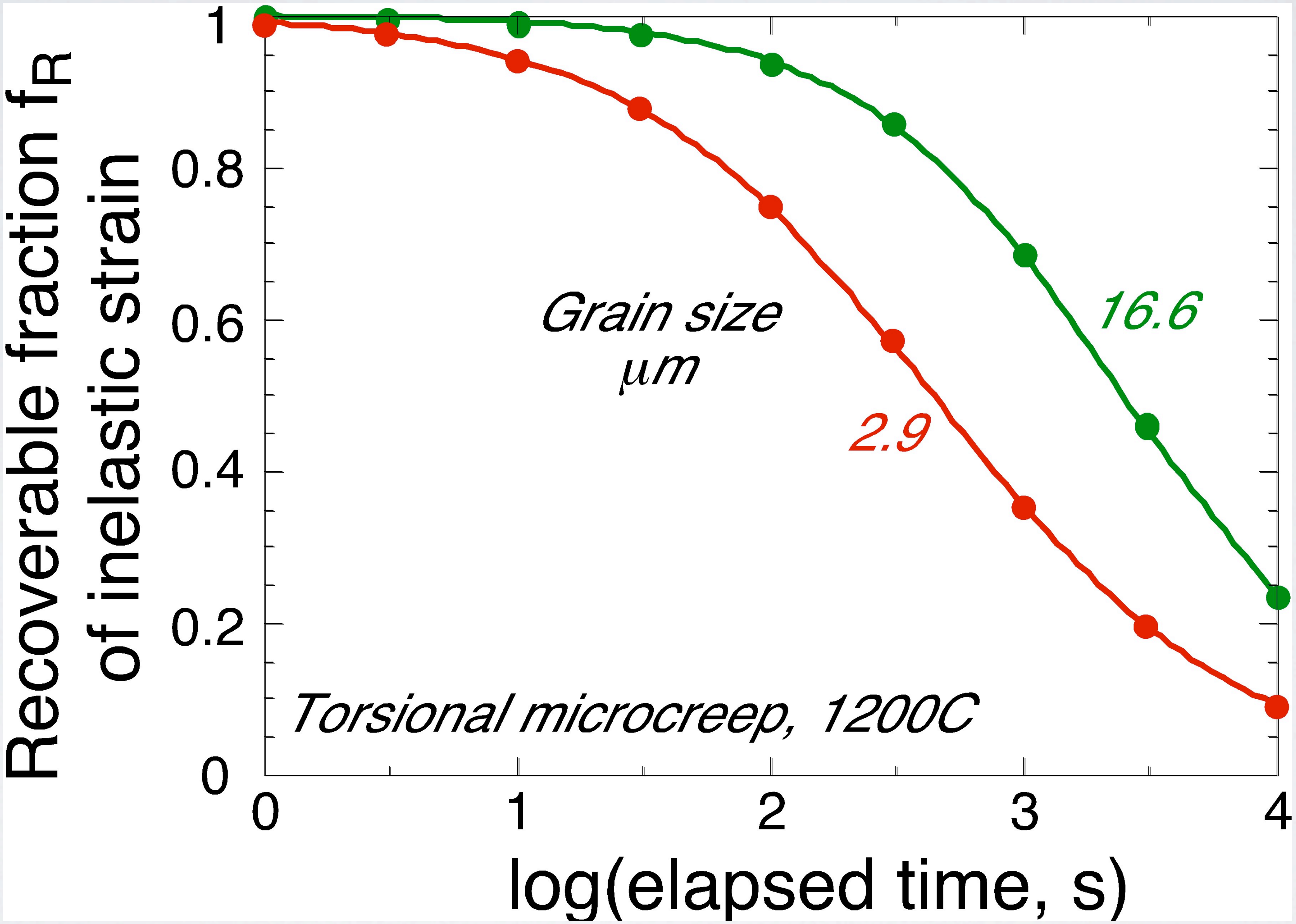
$$G(\omega) = [J_1^2(\omega) + J_2^2(\omega)]^{-1/2} \qquad Q(\omega) = J_1(\omega)/J_2(\omega)$$

Extended Burgers model fit to forced oscillation data for olivine



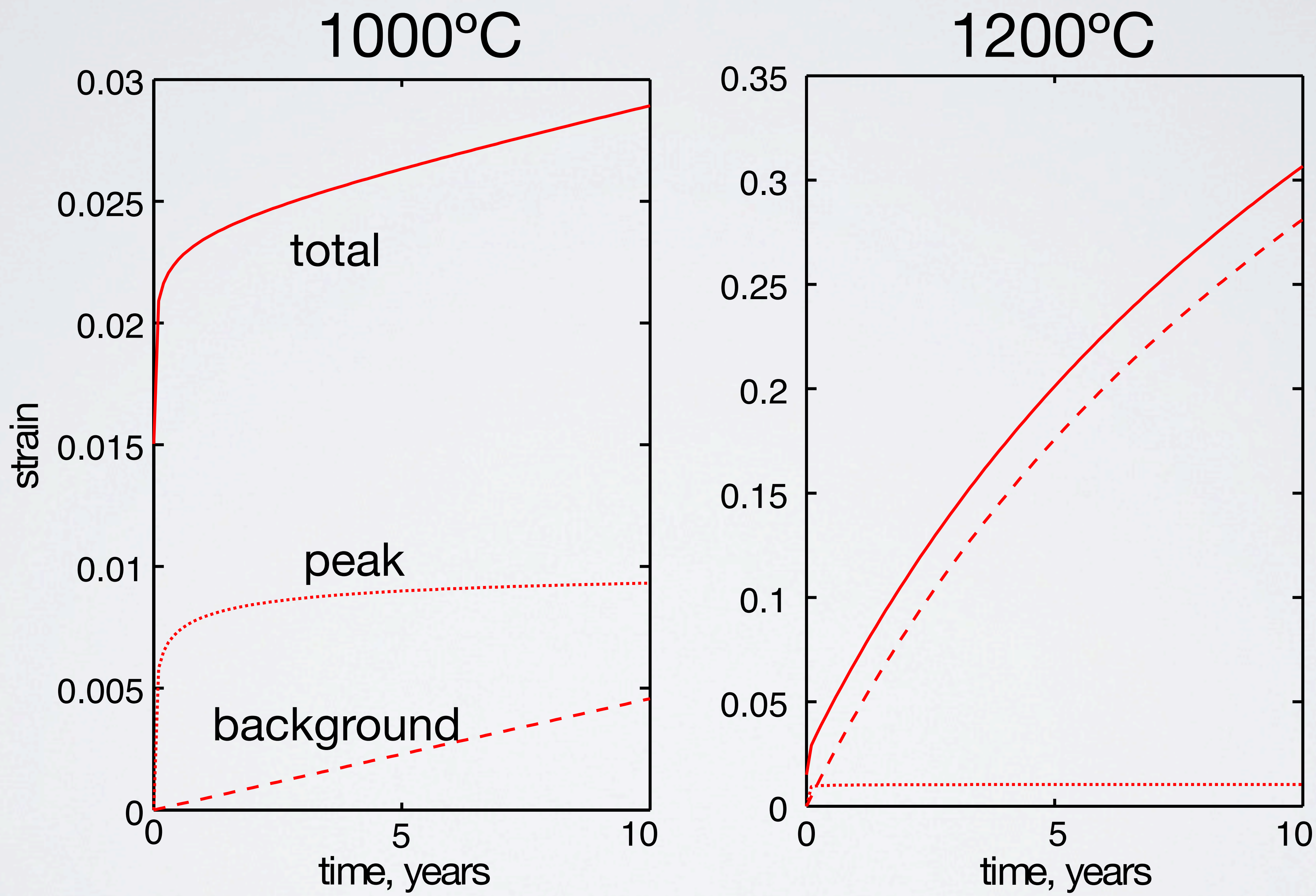
curves 'collapse' in Maxwell regime ($f < f_M$); spread due to linear grain size dependence in transient regime

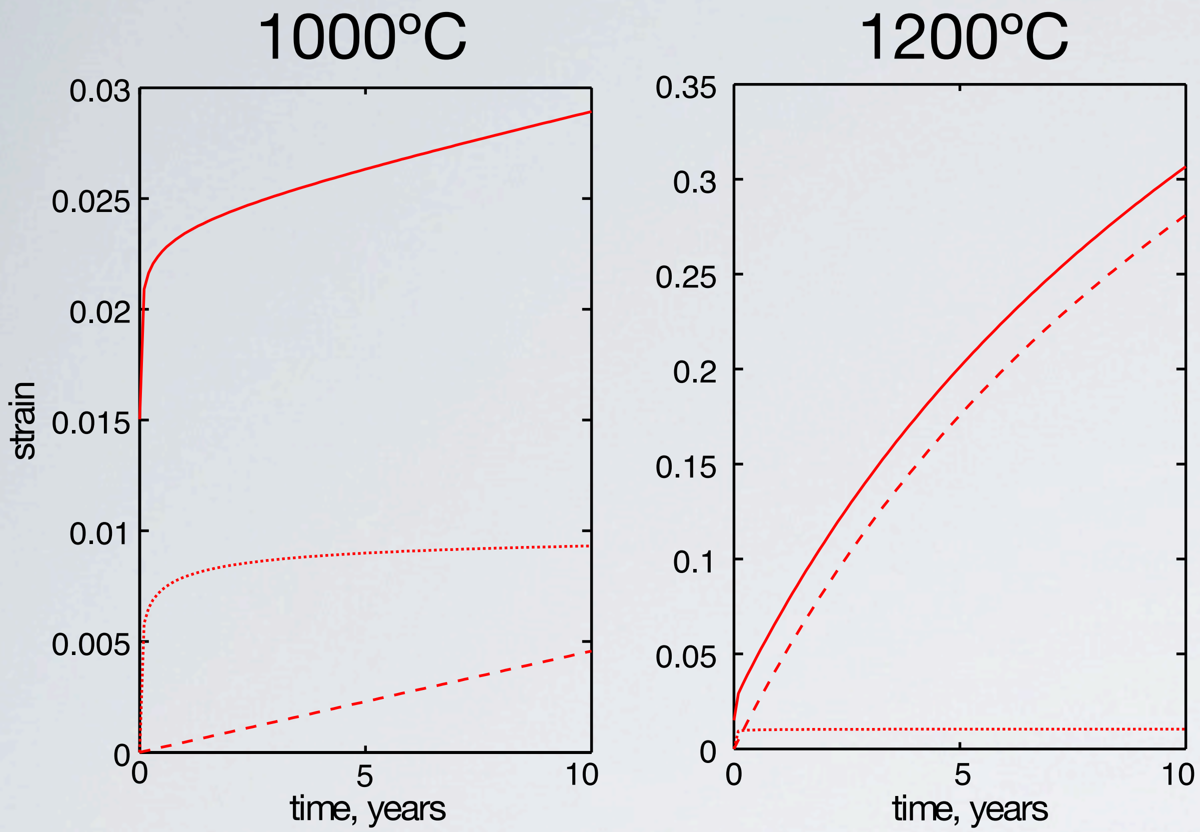
Microcreep records:
Recoverable (elastic + anelastic) portion of strain decreases with time



transient is (near linearly) grain size dependent

Extended Burgers model calculation of transient strain, extrapolated to 1 cm grain size

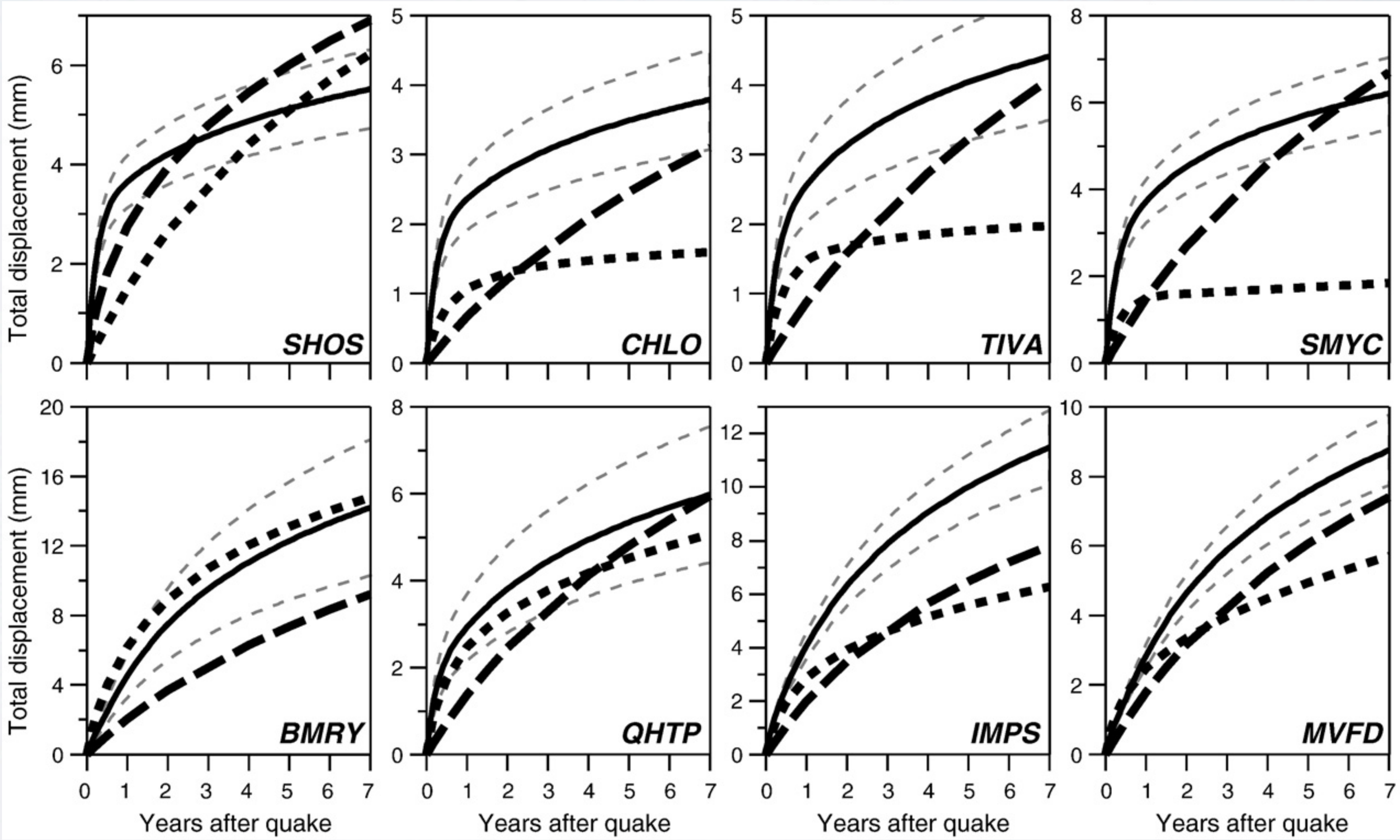




Comparison with creep observed by GPS in Southern California

applicable at small strains (far field)

Freed et al., 2010



solid lines: observations
dashed: steady state creep models