Dislocations and dislocation creep...

1. Introduction: a) Observations of textures associated with dislocation creep
b) MOVIES of dislocations in metals.

2. How do dislocations move?: single dislocations: stress, energy and motion.
Orowan's equation. Frank-Read sources, Work Hardening
(Fatigue, paper clips)

3. Recovery and Recrystallization:
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Steady state grain size

4. Fabric development
Grain rotation (LPO development)

5. Flow laws and Deformation Mechanism Maps

**First, lay out the complexity that is observed in nature,
that we want to understand !**

**THEN, deconstruction:
simple - - - - > complex
small scale (single dislocation) ----- > larger scale (behavior of ensembles)**

MOVIE of analog dislocations in ball bearings

MOVIES of dislocations in metals

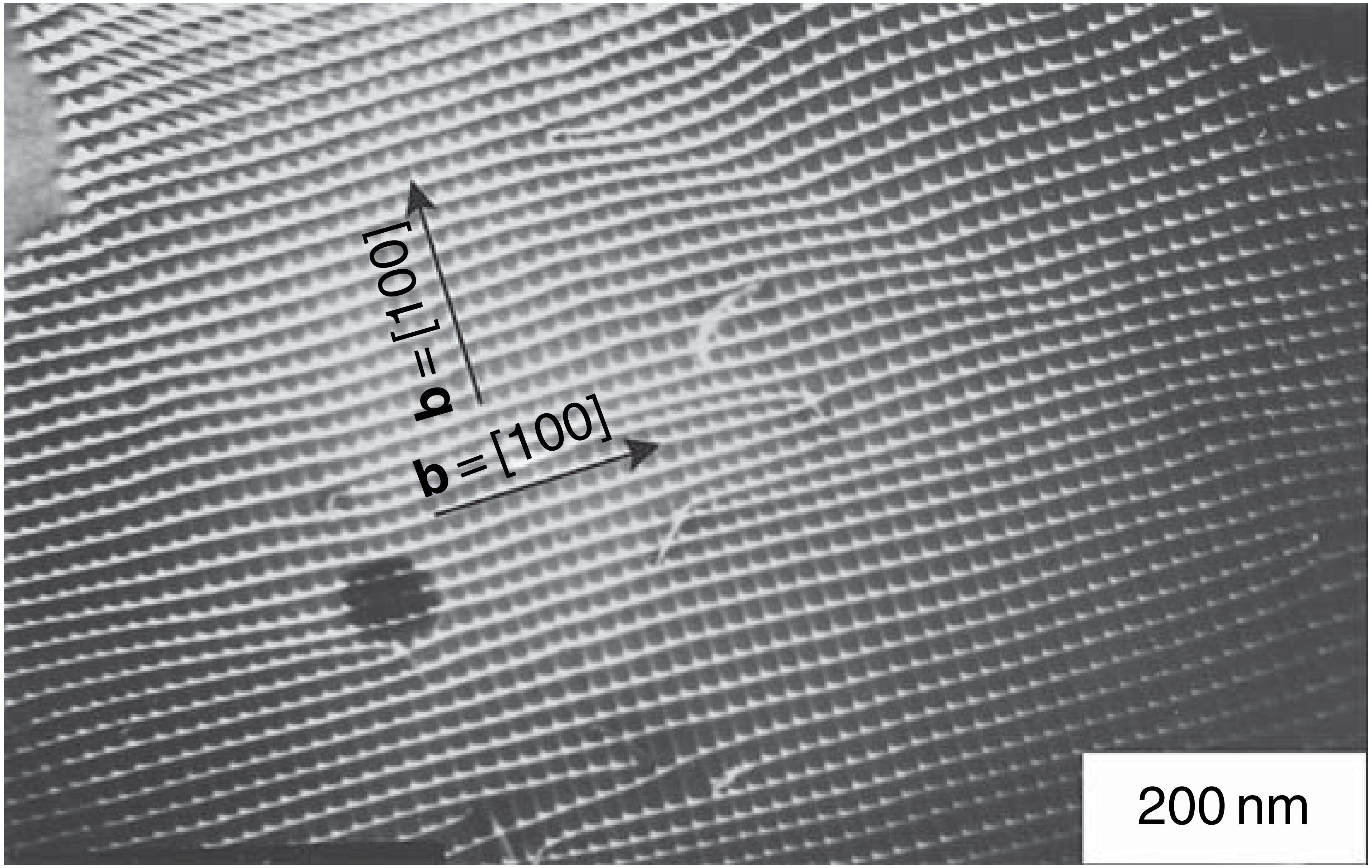


Figure 6 Dark-field transmission electron micrograph of two orthogonal sets of screw dislocations, one with **b** = [100] and the other with **b** = [001], forming a low-angle twist boundary in the (010) plane of olivine. The boundary is very

Dislocation creep regimes in quartz aggregates

Journal of Structural Geology, Vol. 14, No. 2, pp. 145 to 159, 1992

GREG HIRTH and JAN TULLIS

regimes determined by relative rates of

1. dislocation production
2. dislocation climb
3. grain boundary migration (GBM)

these rates are a function of stress, temperature and water content

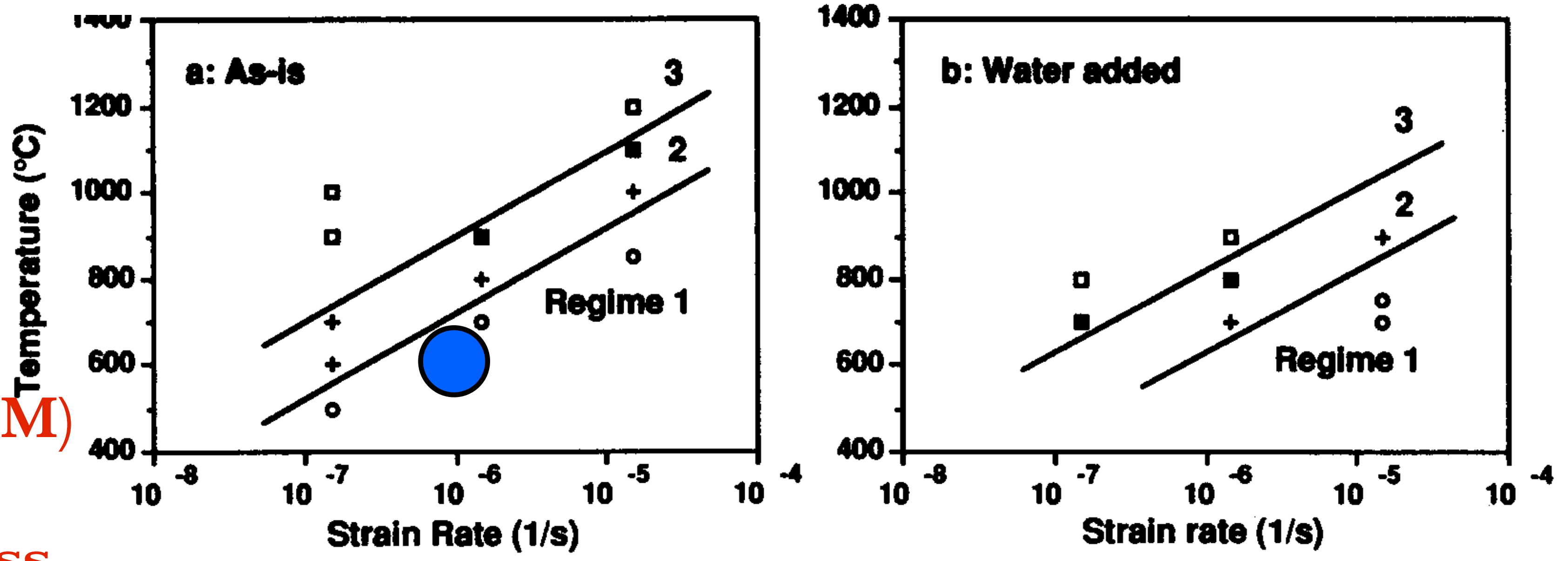
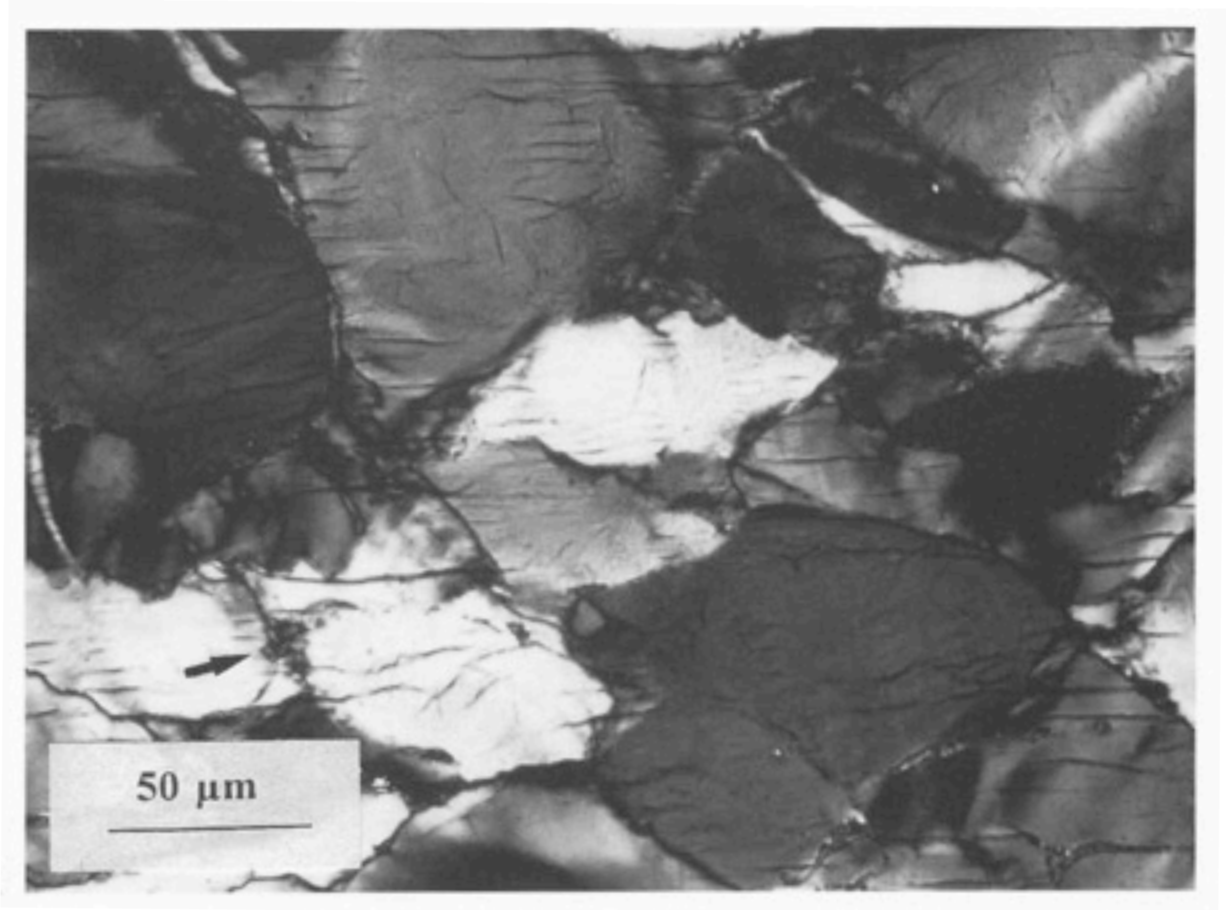


Fig. 2. Plots of temperature vs strain rate showing the location of the dislocation creep regimes for quartz aggregate deformed (a) 'as-is' and (b) with 0.17 wt% water added. The boundaries between the regimes are gradational. Open circle represent regime 1, plus symbols represent regime 2, open squares represent regime 3, and a plus inside a square represent gradational between regimes 2 and 3.

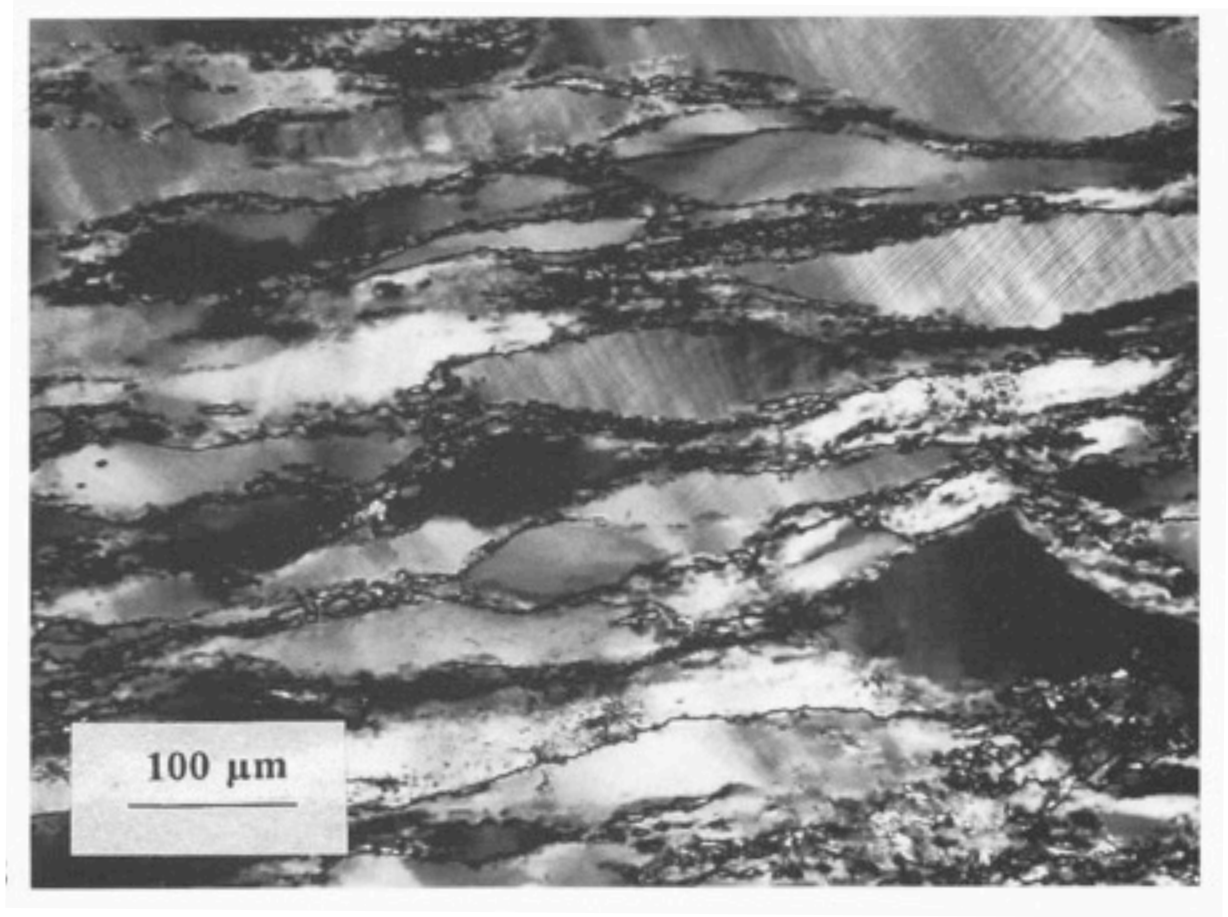
Regime 1

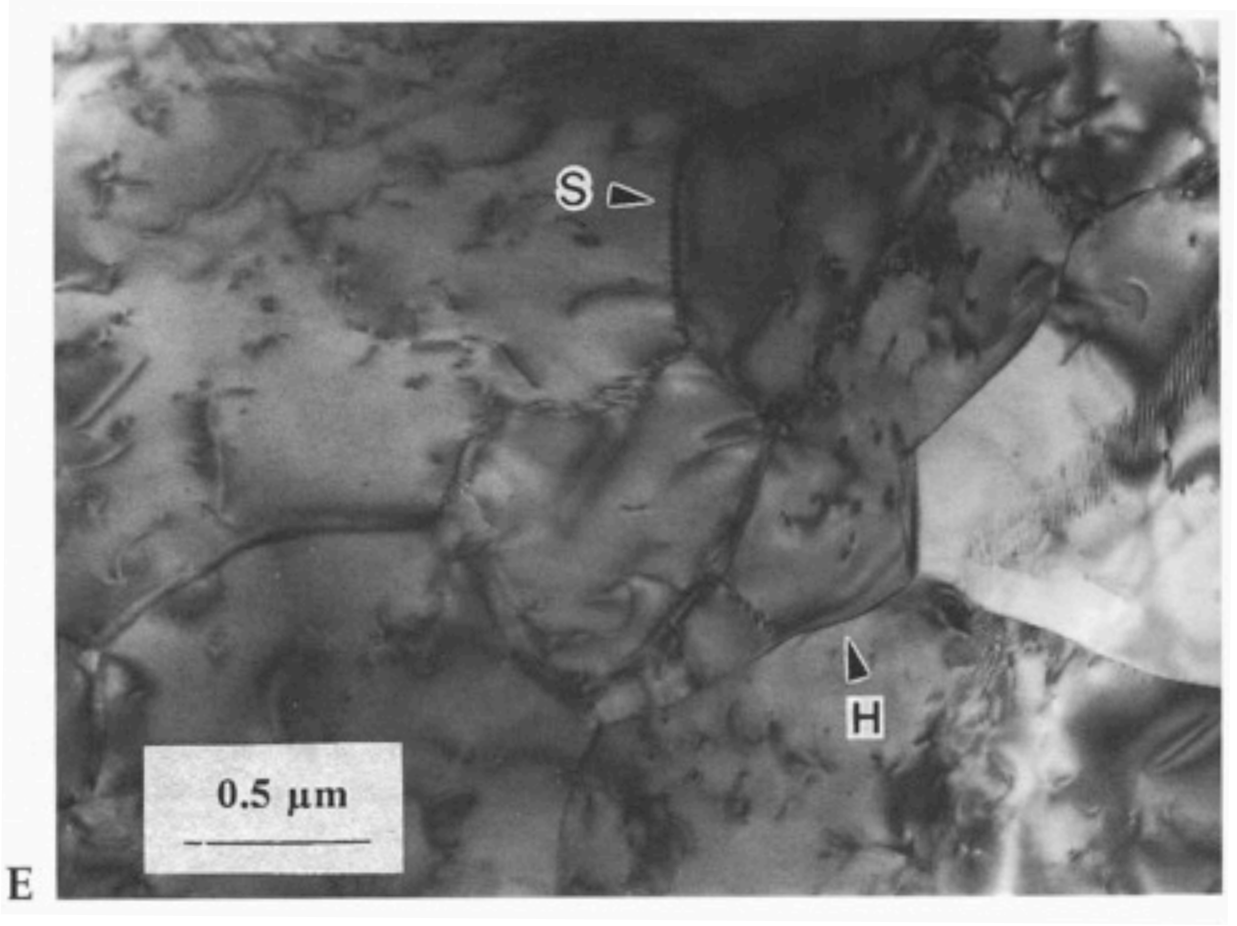


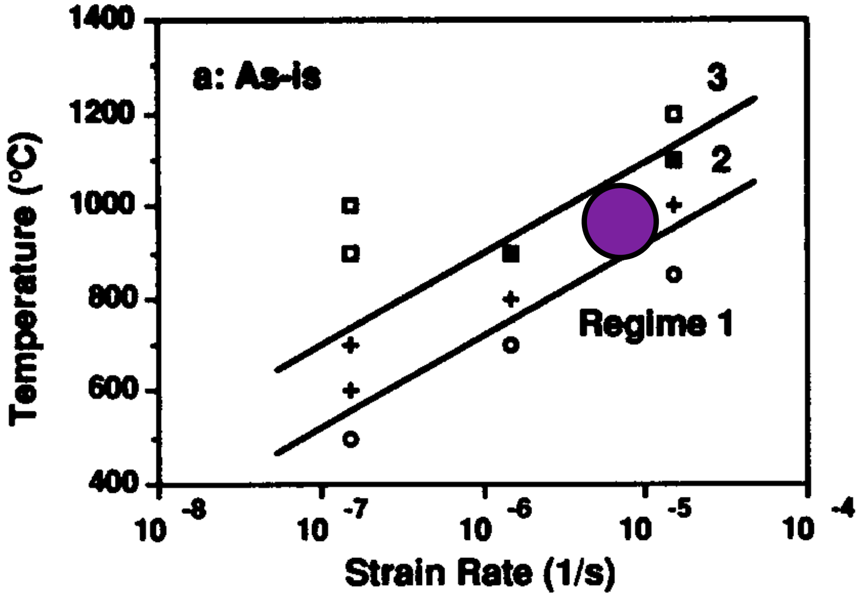
R1 (high stress, low T): production fast, recovery by climb and GBM slow

Experimentally deformed:

Regime 2



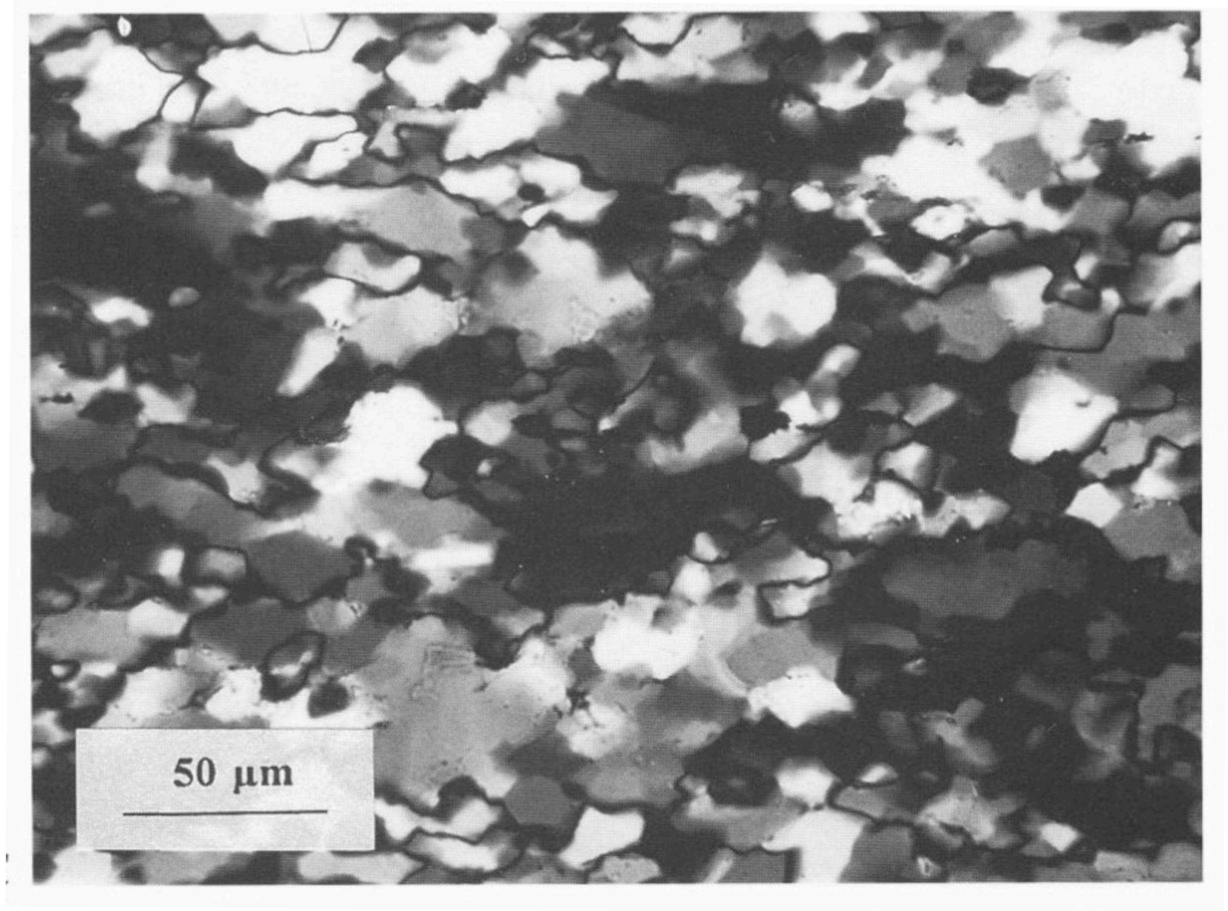


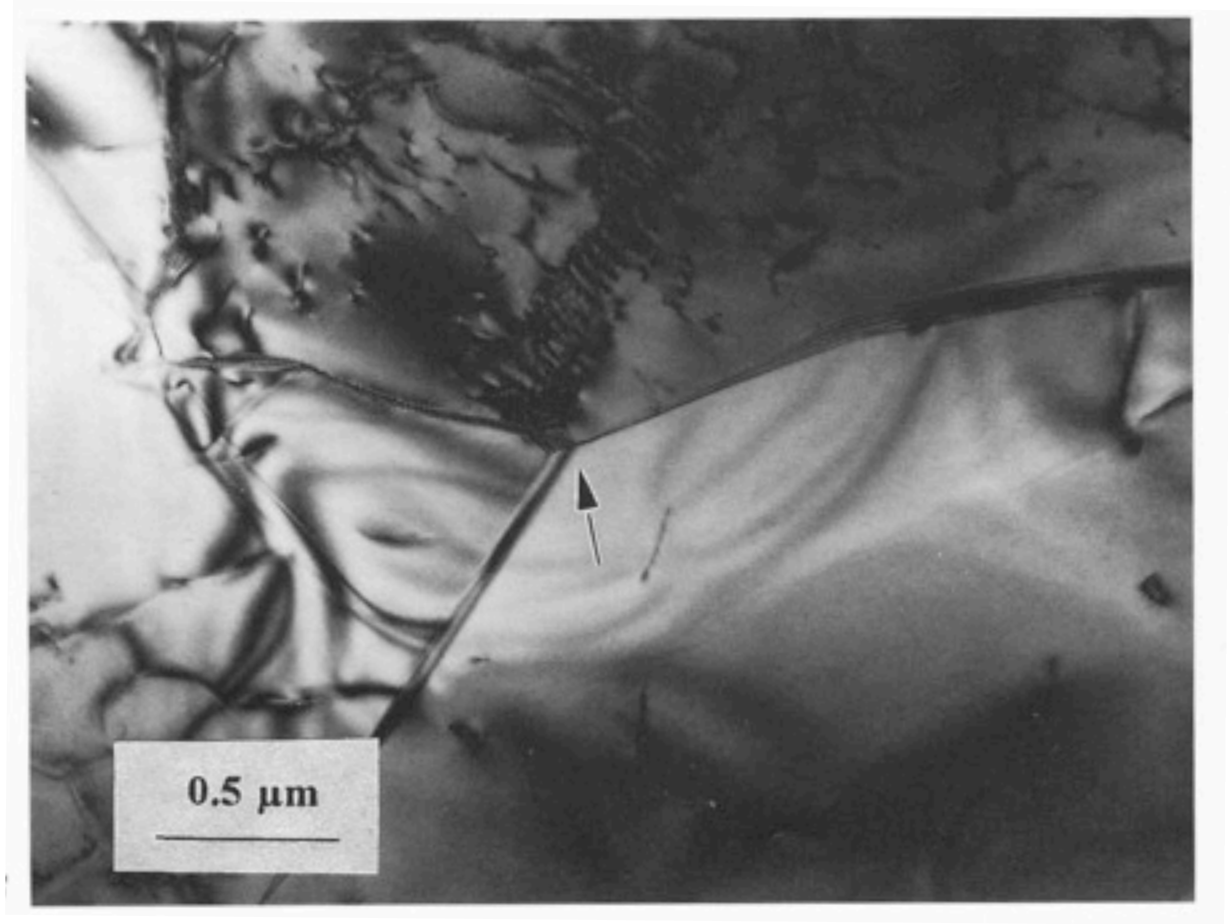


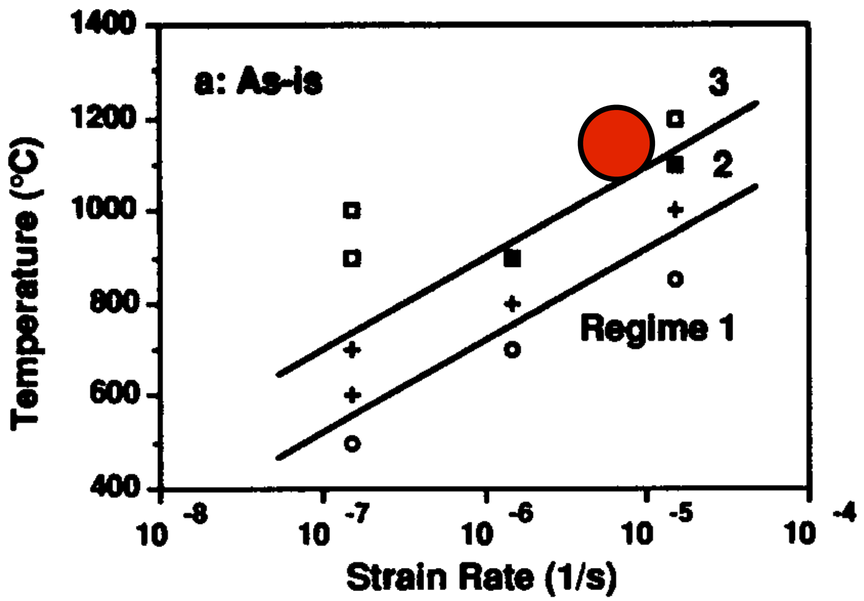
R2 (lower stress, higher T): recovery by climb moderate, but GBM slow, so recrystallization occurs by subgrain rotation (requiring climb)

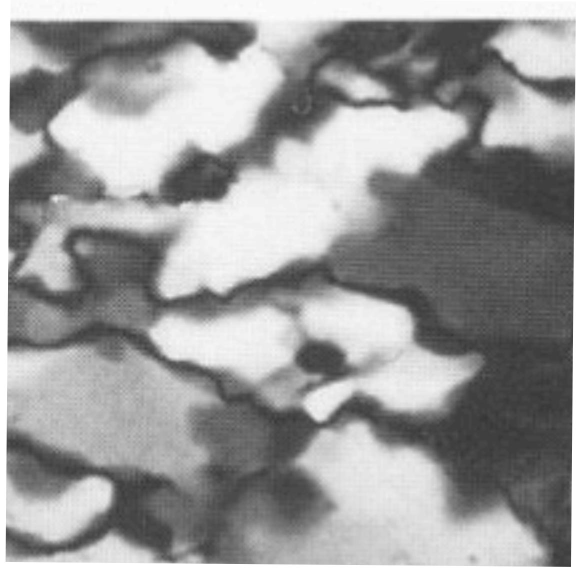
Experimentally deformed:

Regime 3









R3 (low stress, high T): recovery by climb fast, but Grain Boundary Migration is also fast, so complete recrystallization occurs by both subgrain rotation and GBM.

Thermomechanical evolution of a ductile duplex

TECTONICS, VOL. 16, NO. 6, PAGES 983-1000, DECEMBER 1997

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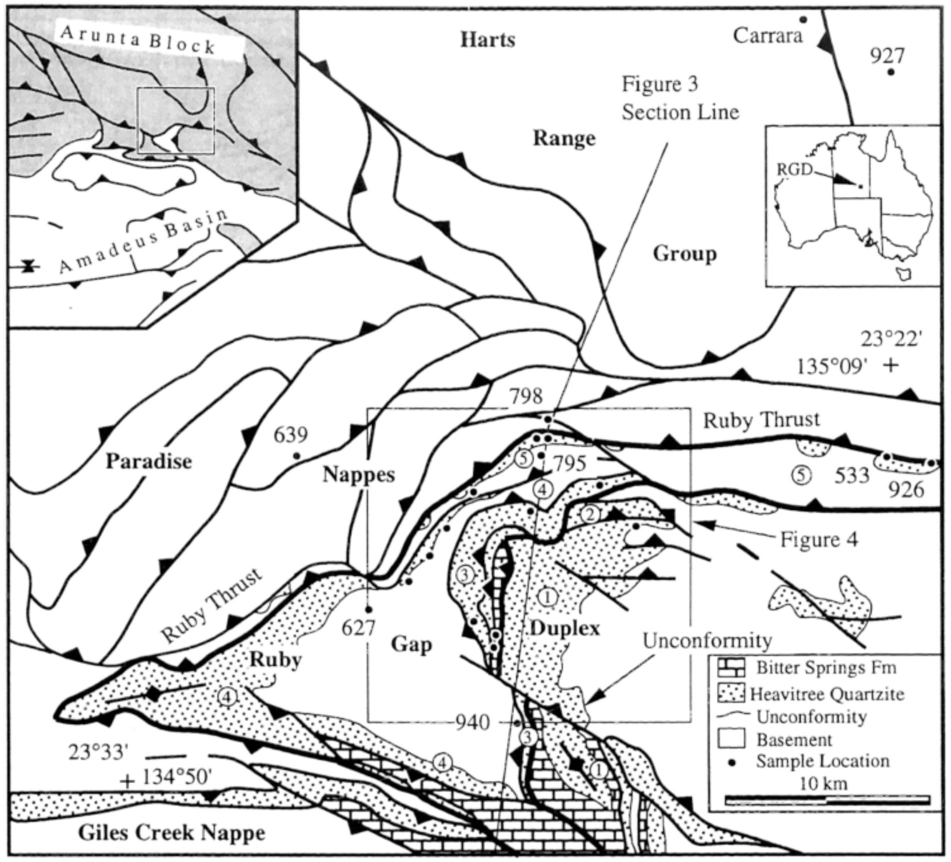
McLean Laboratory, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

C. Teyssier
Department of Geology and Geophysics, University of Minnesota, Minneapolis



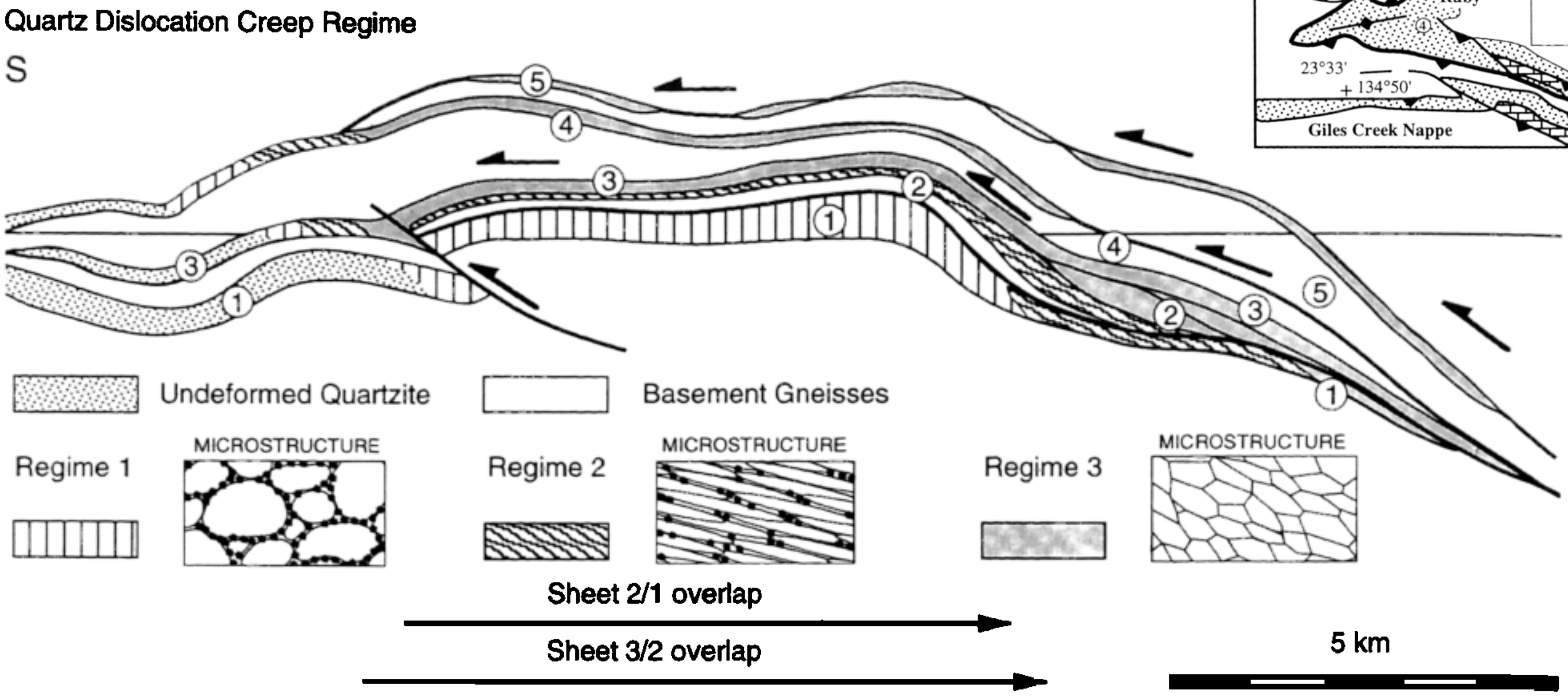
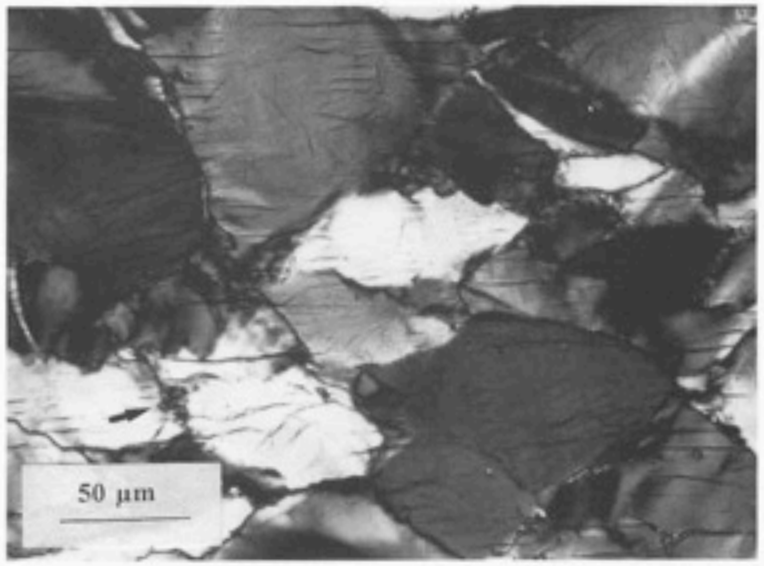


Figure 5. Cross section of the Ruby Gap duplex showing the distribution of dislocation creep regimes in quartzite. Only the quartzite is ornamented; the basement and carbonate are unornamented. The pattern is constrained by about 100 thin-section analyses. Insets show schematic characteristic microstructures at about 500 µm scale. Thrust duplication of the regime 1-3 microstructures probably occurred after microstructural freezing. If this is the case, then the overlap in the microstructures can be removed as indicated by the arrows at the bottom of the diagram. Thrust sheet numbers are shown as numbers within circles.

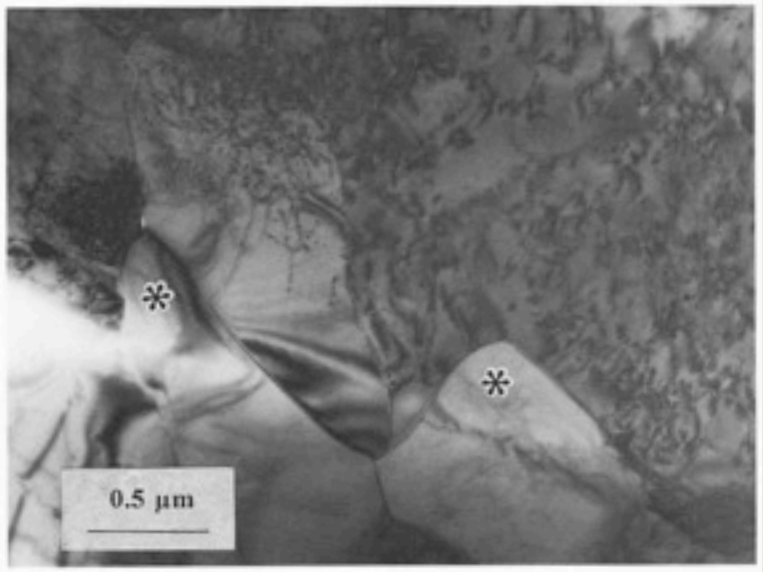
from: “Atlas”

Experimentally deformed:

Regime 1

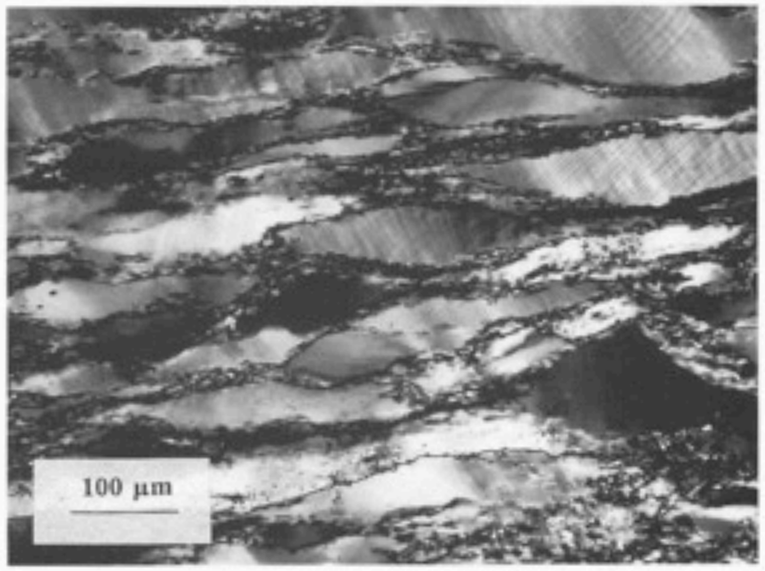


146 A

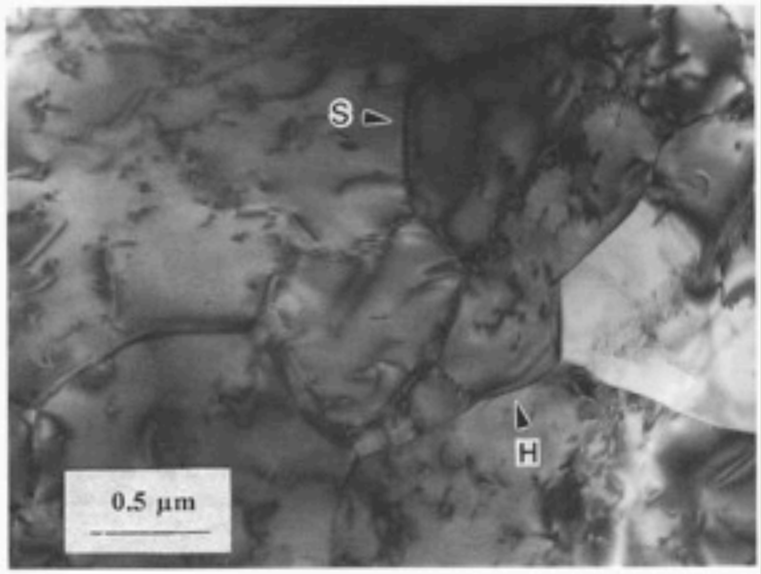


46 D

Regime 2

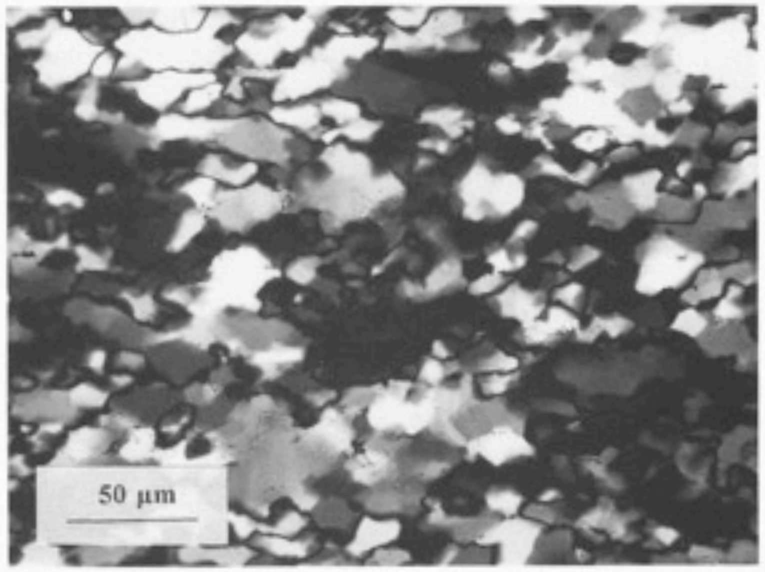


146 B

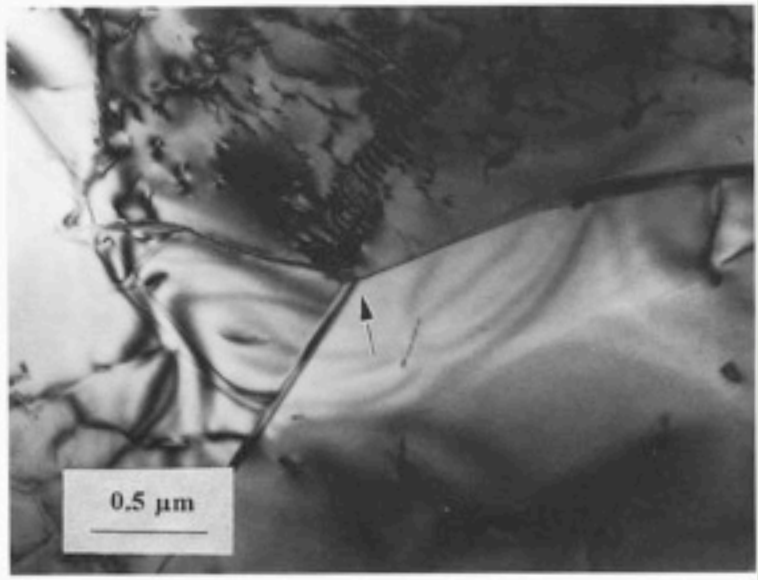


146 E

Regime 3

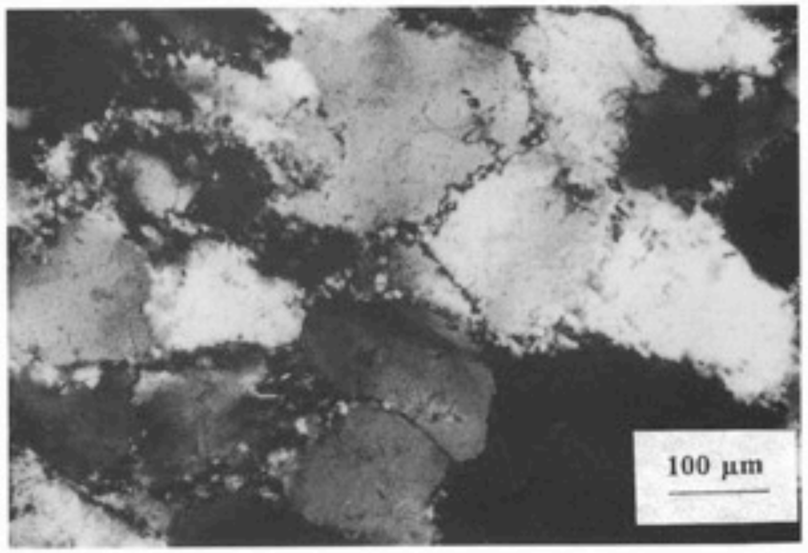


146 C

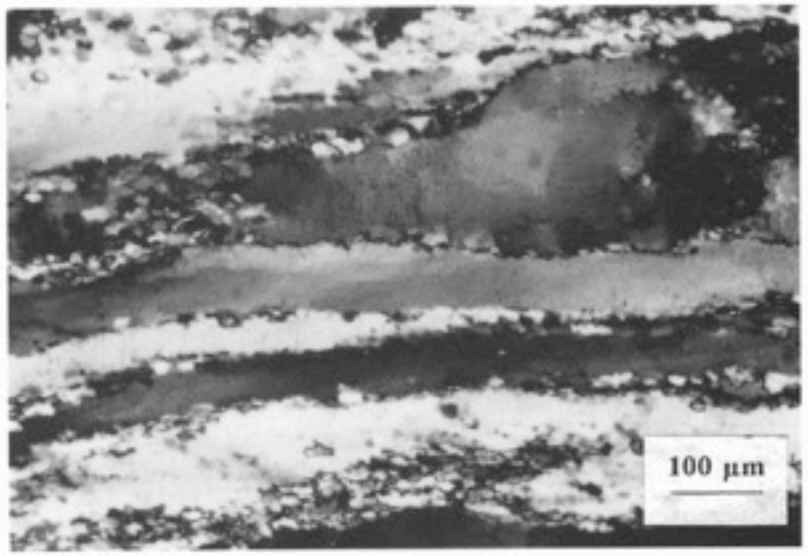


146 F

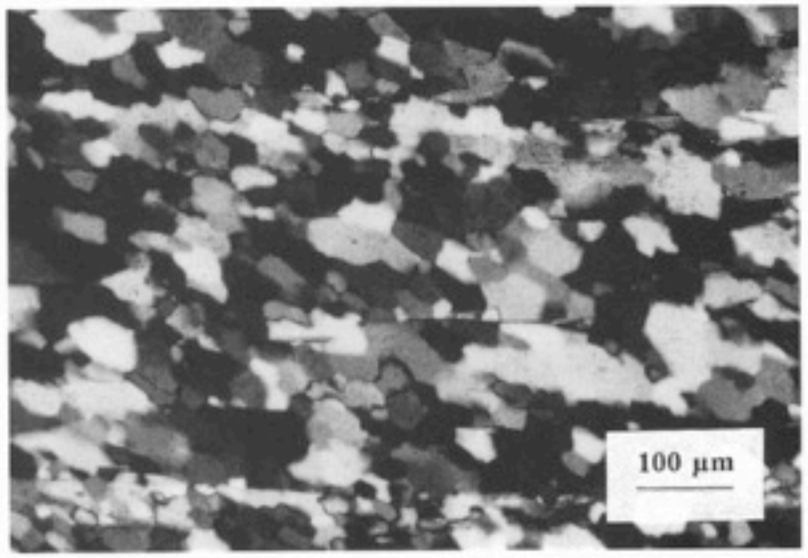
Naturally deformed



147 A



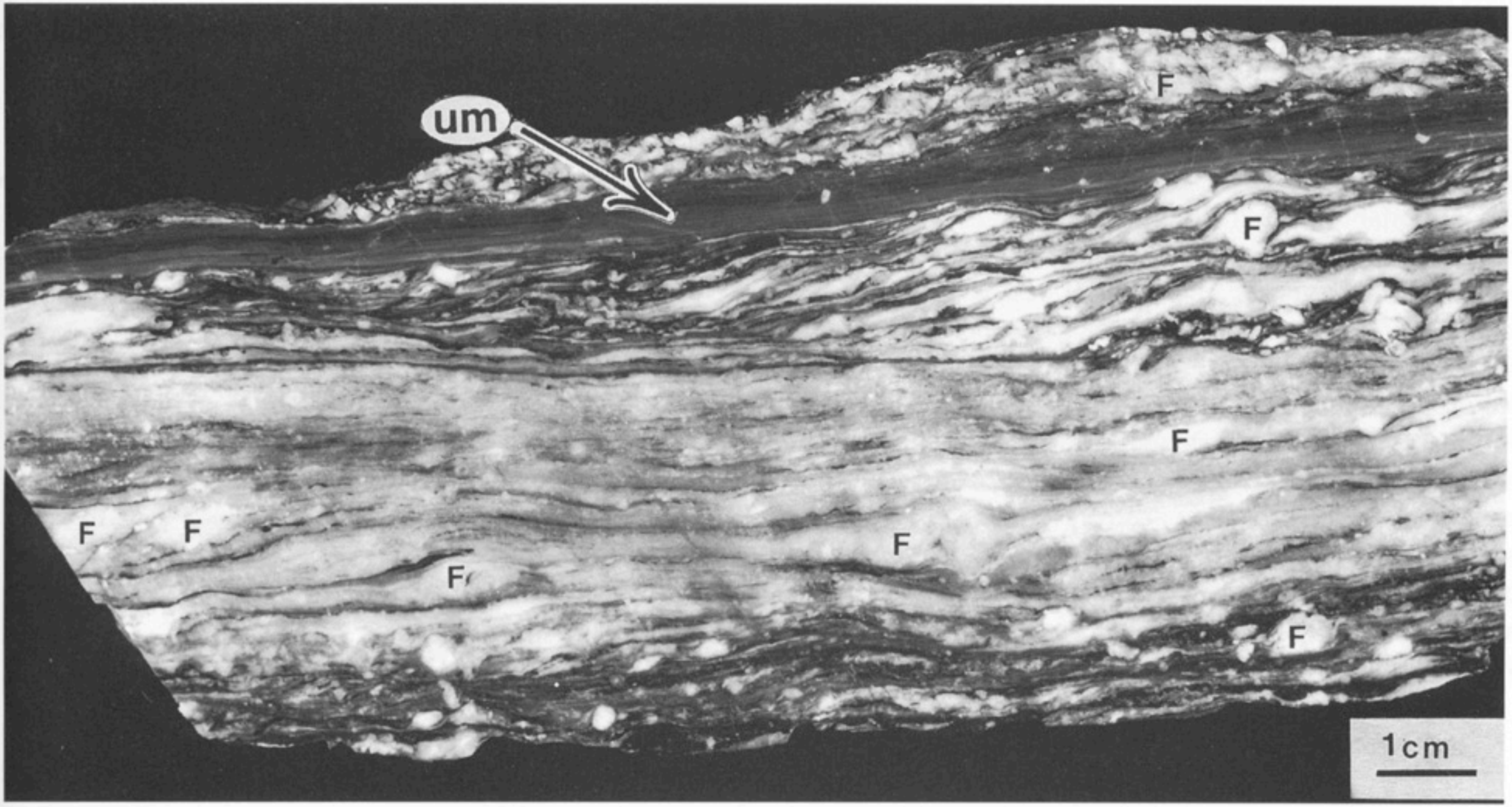
14 B



14 C

MOVIES of grain boundary migration in deforming ice:
<u>http://virtualexplorer.com.au/special/meansvolume/contribs/wilson/introduction.html</u>

Win means movies



64

from: “Atlas”

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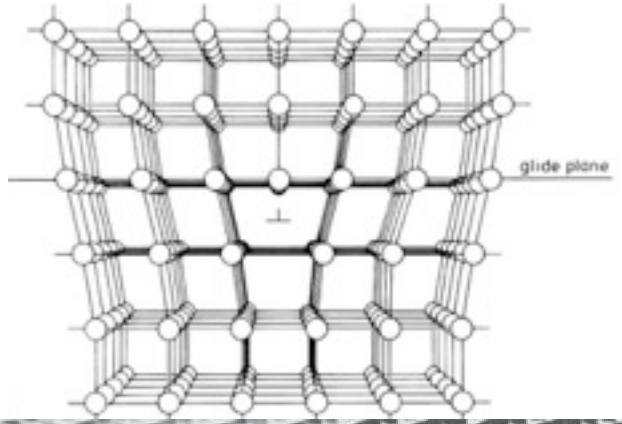
Theoretical strength crisis:
1934: Polyani, Orowan, Taylor hypothesized dislocations….

an olivine crystal full of dislocations:



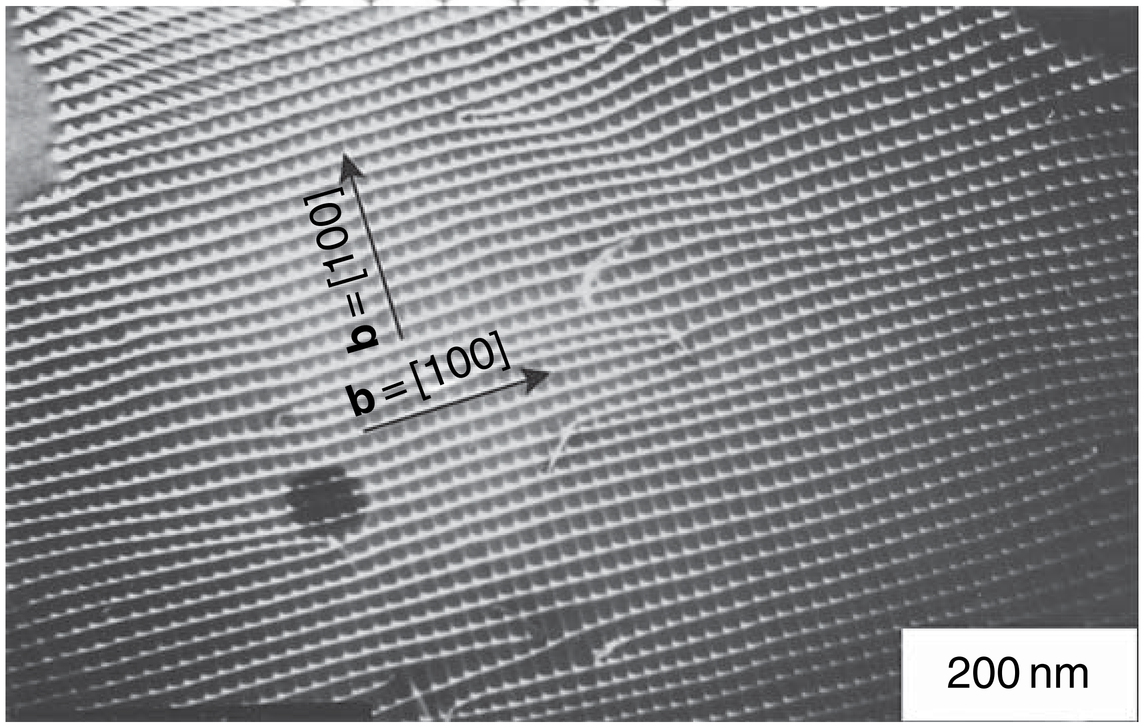
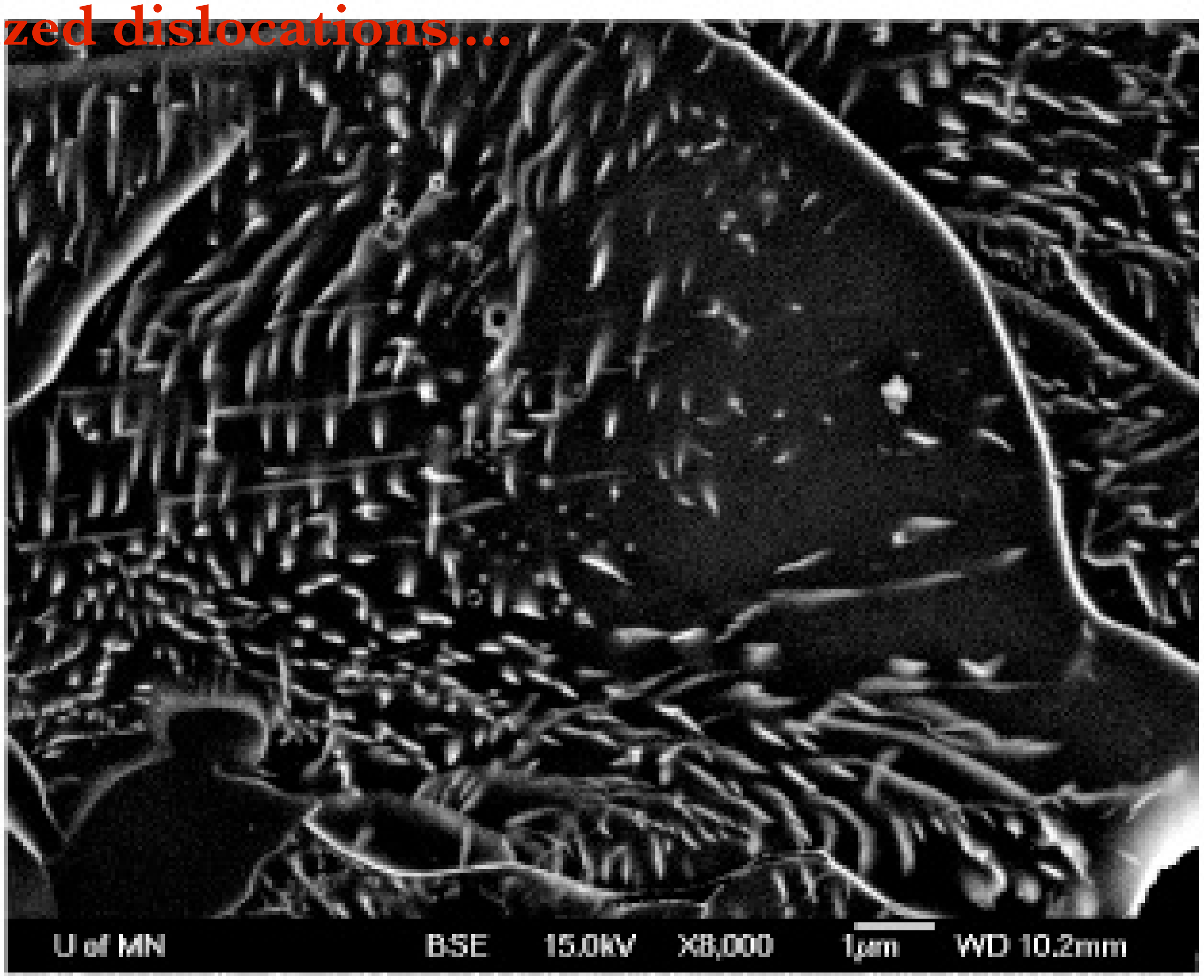
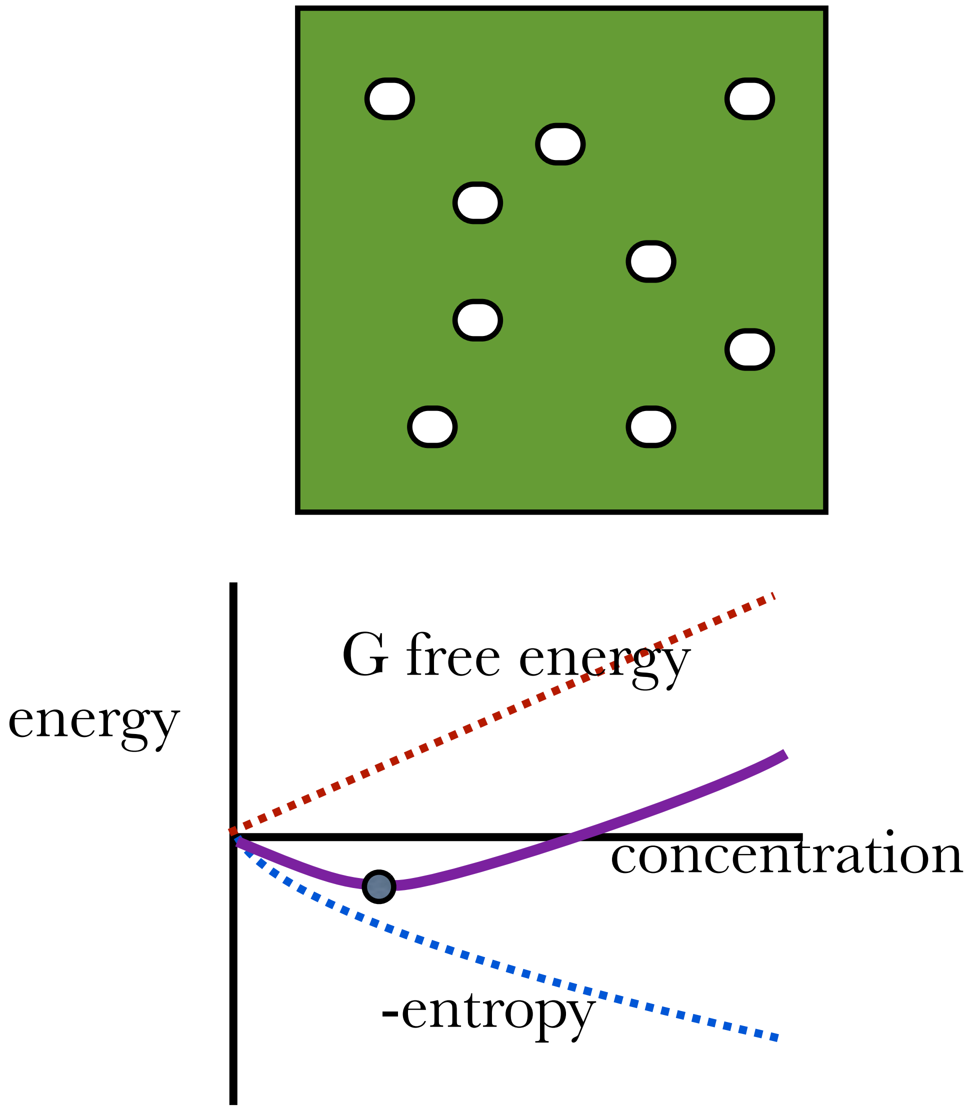
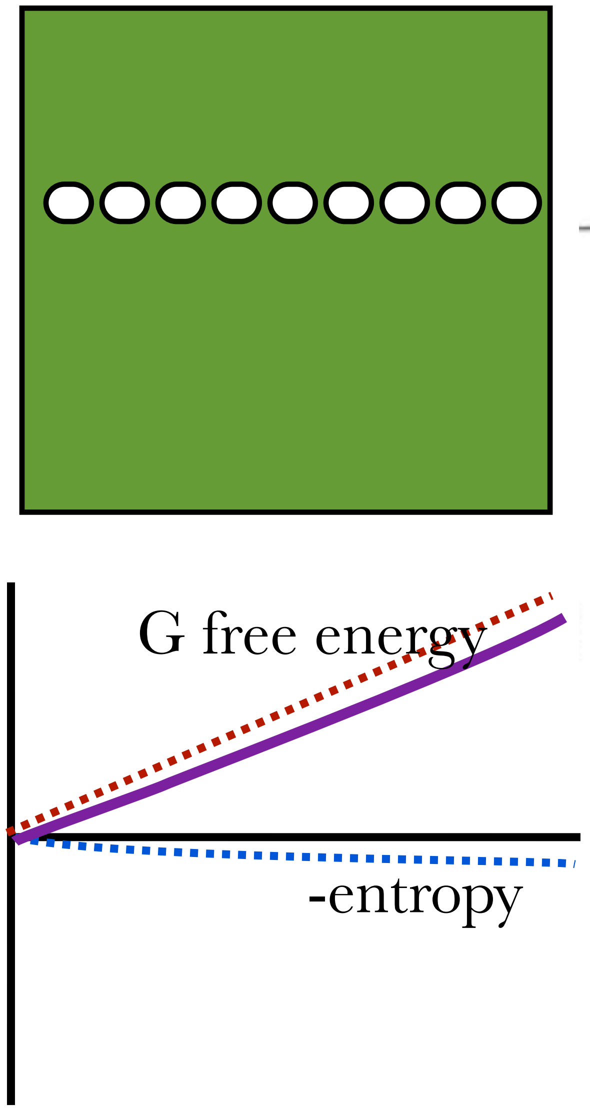


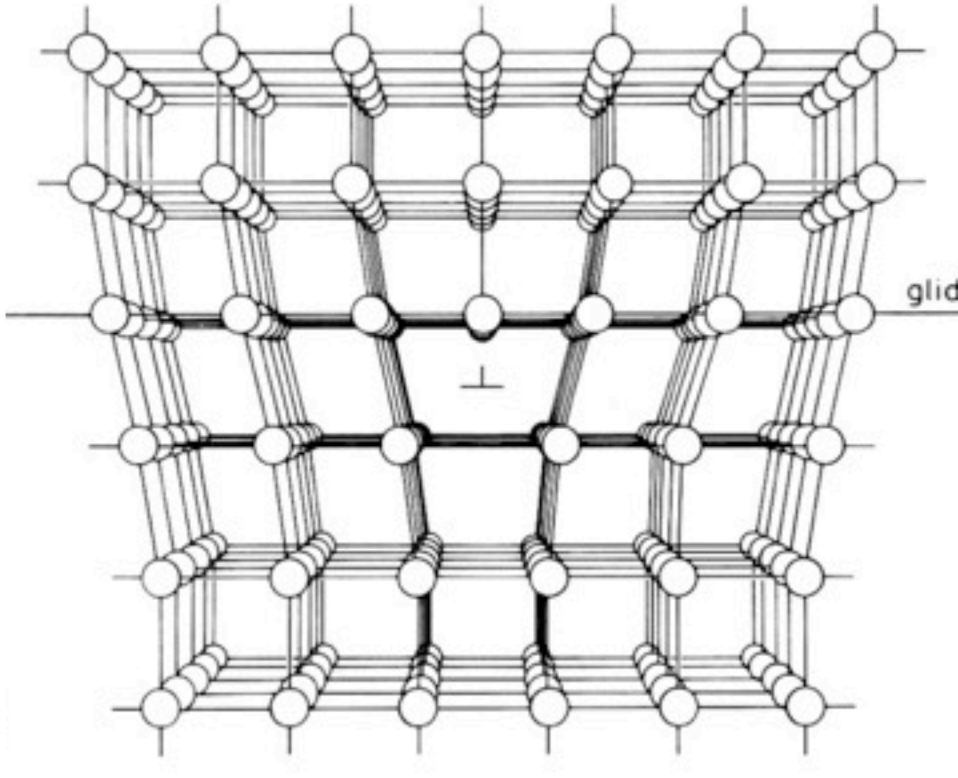
Figure 6 Dark-field transmission electron micrograph of two orthogonal sets of screw dislocations, one with **b** = [100] and the other with **b** = [001], forming a low-angle twist boundary in the (010) plane of olivine. The boundary is very nearly parallel to the plane of the figure. Adapted from Ricoult DL and Kohlstedt DL (1983a) Structural width of low-angle grain boundaries in olivine. *Physics and Chemistry of Minerals* 9: 133–138. Ricoult DL and Kohlstedt DL (1983b) Low-angle grain boundaries in olivine. In: Yan MF and Heuer AH (eds.) *Advances in Ceramics*, *Character of Grain Boundaries*, vol. 6, pp. 56–72. Columbus: American Ceramic Society.



2. Single dislocations







Unlike for vacancies, there is no equilibrium concentration of dislocations, because the aligned vacancies do not increase the entropy as much as isolated vacancies do.

Because there is not an equilibrium concentration, and because each dislocation produces a very small strain, there must be constant production of dislocations… called a “Frank-Read source” (1950, Charles Frank and Thornton Read)

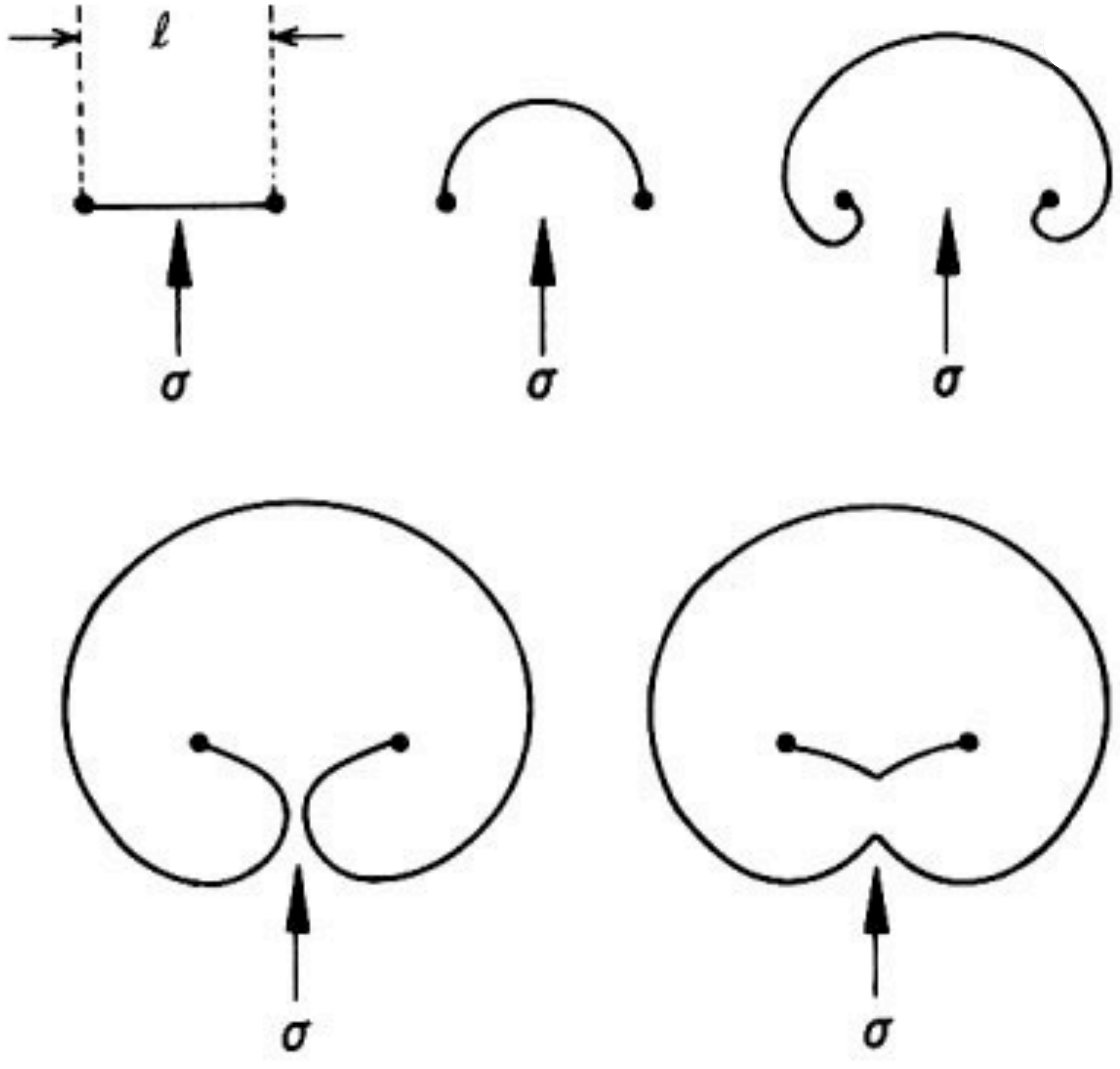
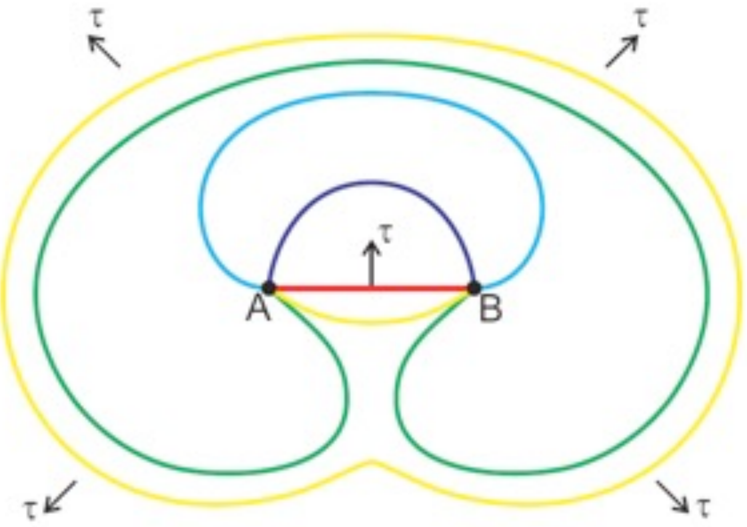


Figure 3-3. Representation of dislocation movement in a Frank-Read dislocation source under stress σ. Multiplication of dislocation pinned at a distance l.



Peach-Koehler Force:

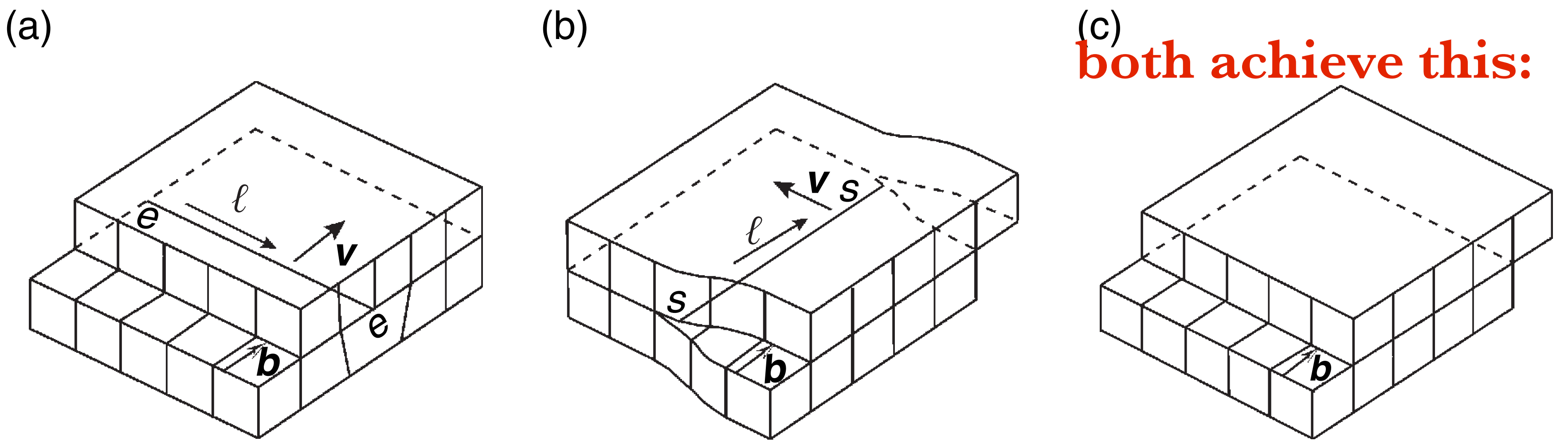
$$F_{PK} = \sigma b x$$

tension on growing dislocation = Gb^2

$$\sigma_{FR} \approx \frac{2Gb}{l}$$

~ several MPa

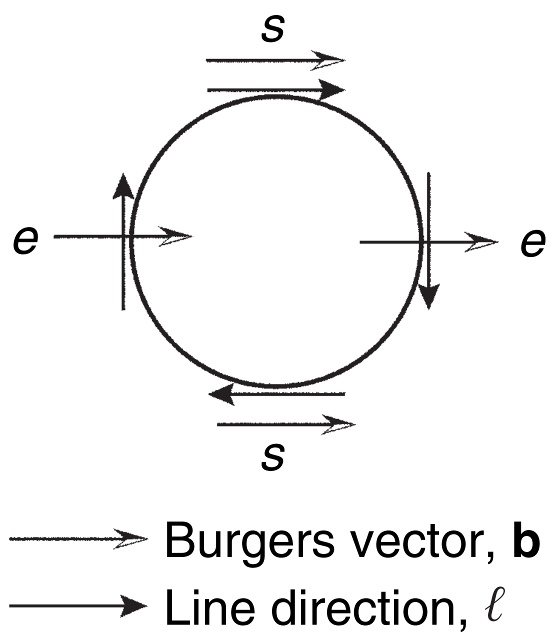
a crystal dislocation is a slipped surface, exactly like the ruptured surface on a fault

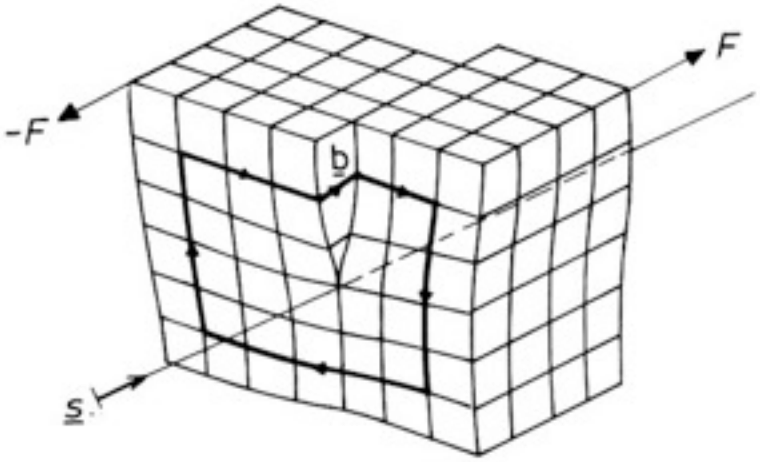


both achieve this:

edge dislocation

screw dislocation





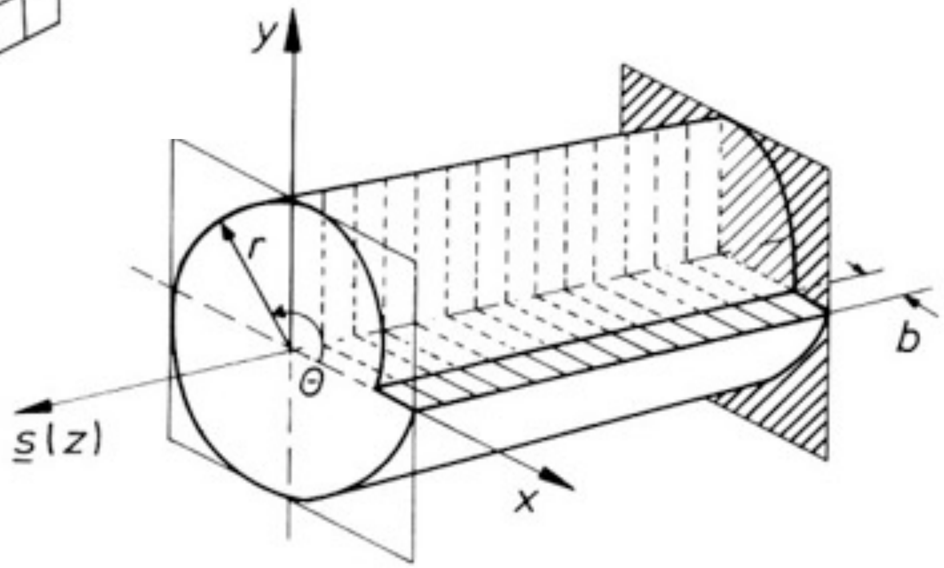
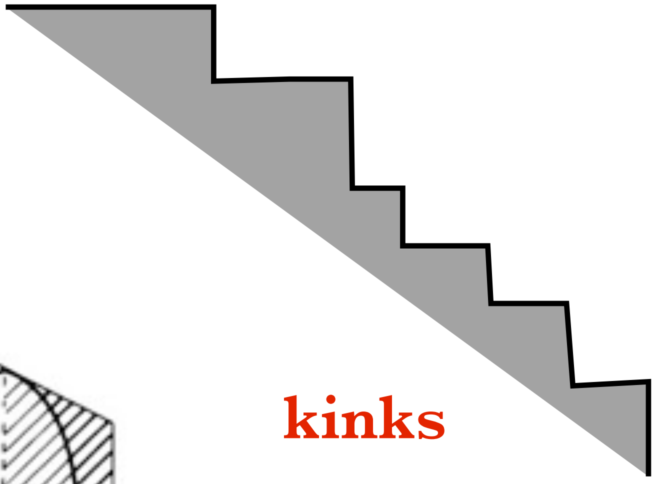
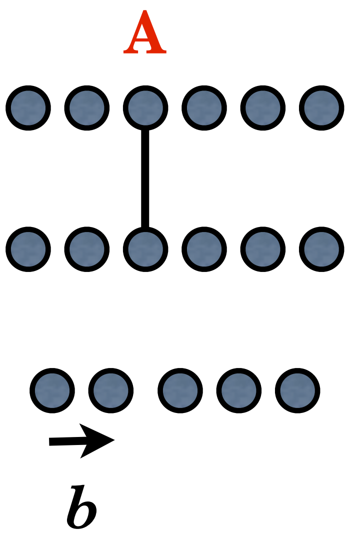


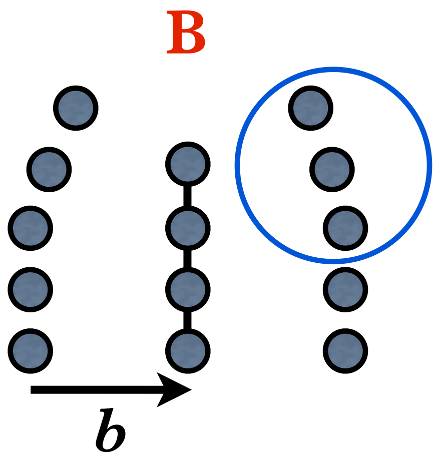
Figure 3-10. Strain geometry of an edge dislocation.



kinks

Slip system: (slip plane)[burger’s vector]





the slip system with the shorter burger’s vector and longer atomic distance normal to the slip plane will be “easier”: A dislocations move more easily (at lower stress, or faster at the same stress) than B dislocations.

This leads to anisotropy in dislocation motion and eventually to the creation of lattice preferred orientation…

Peierle's stress…

$$\tau_{\mathrm{PN}} = G e^{-2\pi W/b}$$

$$W = \frac{a}{1-\nu} =$$

dislocation width (or really, the elastic strain field around it)

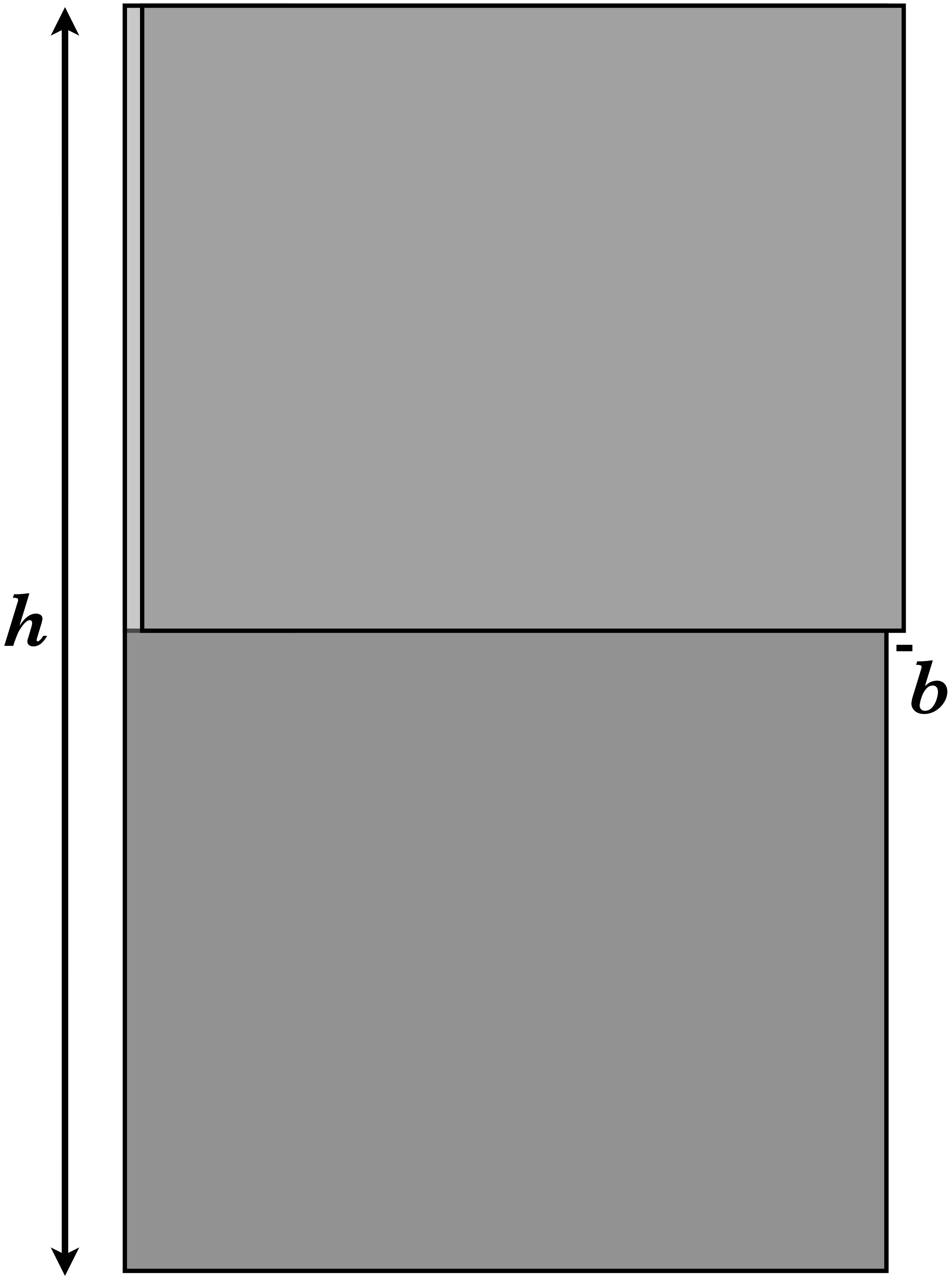
G = shear modulus

ν = Poisson's ratio

b = interatomic spacing

a = interplanar spacing

MAKING LARGE STRAINS WITH DISLOCATIONS:



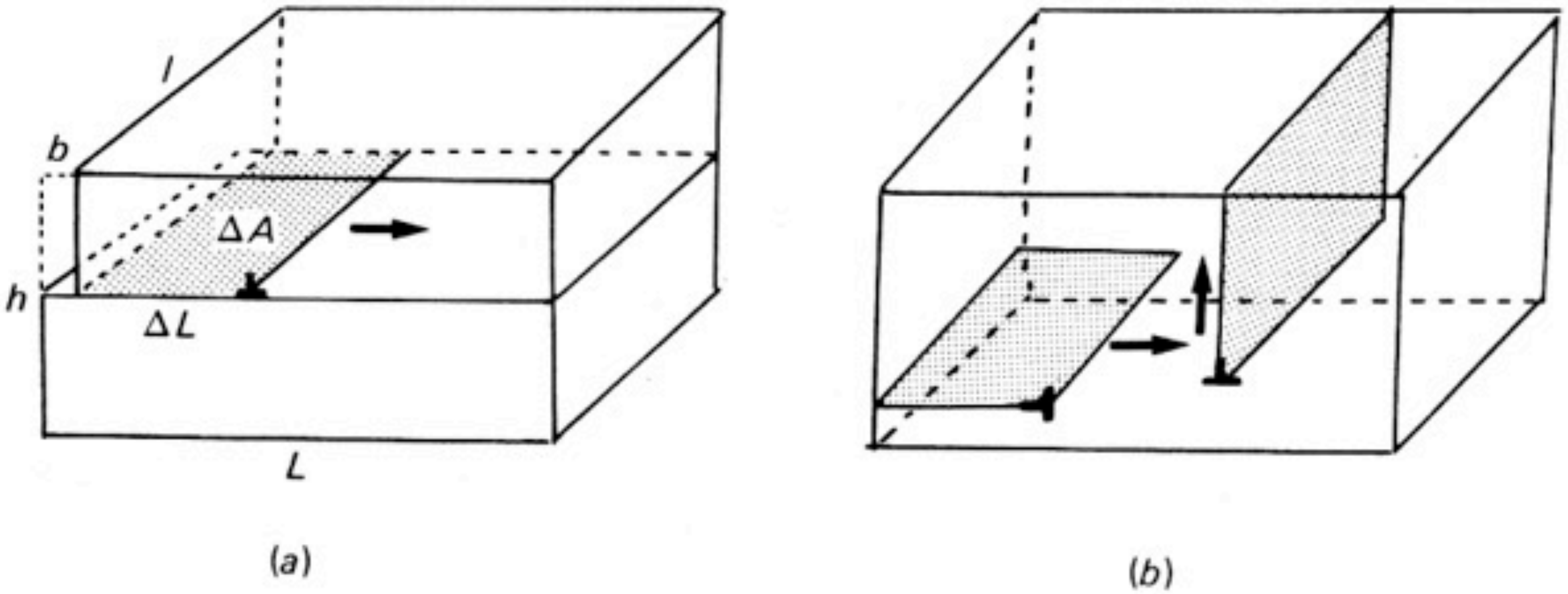
strain ~ b/h

$$\varepsilon = \frac{b}{h}$$

**one dislocation makes
a minuscule strain..
so to enable strain,
many must be produced
and move through the crystal**

OROWAN Equation (from Poirier, 1985, p 62) and Kohlstedt ToG, p 400:

Fig. 2.15. Orowan's equation. (*a*) A straight edge dislocation, sweeping its glide plane over ΔL creates shear strain $\varepsilon = b\Delta L/hL$. (*b*) Two straight edge dislocations create a pure shear strain by climbing in opposite senses.



$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} = \rho b \bar{v}_d$$

ρ **dislocation density = length / m^3 or # / m^2**

$$\bar{v}_d(\sigma, P, T, X) \propto \sigma^{1+}$$

avg. disl. velocity

disl. density

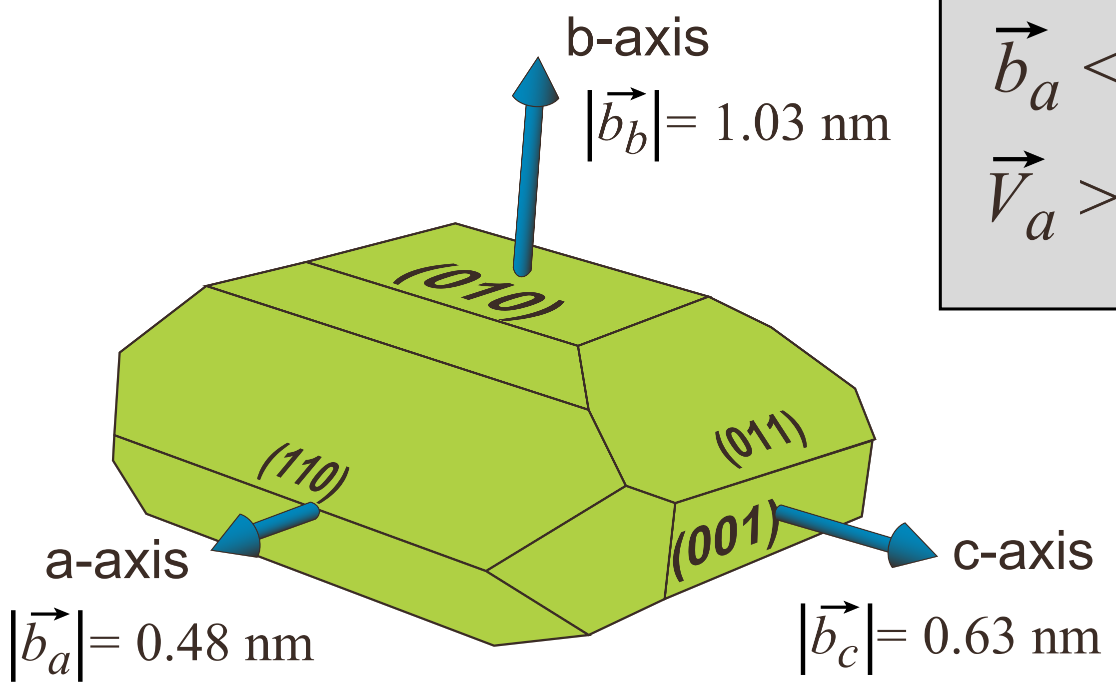
$$\rho(\sigma) \propto \sigma^2$$

$$\boxed{\dot{\varepsilon} \propto \sigma^{3+}}$$

most of the complexity comes in the dislocation velocity term...

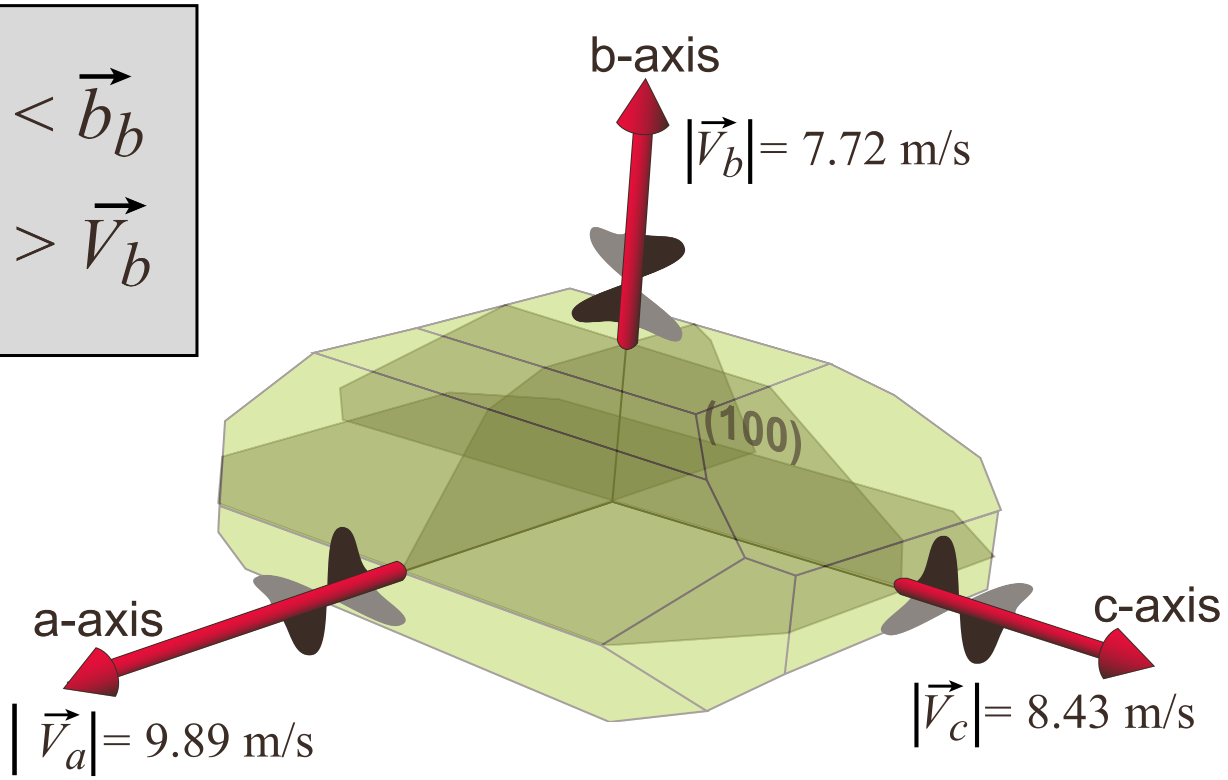
Olivine: (010)[100] is easiest, followed by (010)[001]

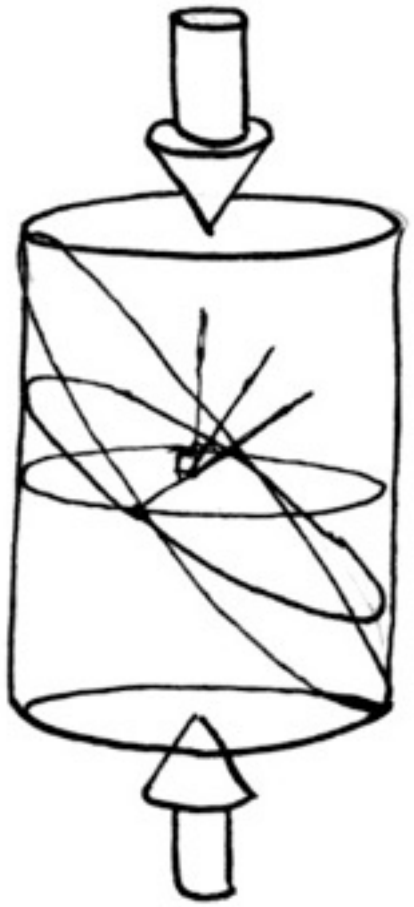
“Miller indexes” = (slip plane)[slip direction]



$$\vec{b}_a < \vec{b}_c < \vec{b}_b$$

$$\vec{V}_a > \vec{V}_c > \vec{V}_b$$





Goetze & Evans, single crystal experiments..

PAPER CLIPS deformation:

1. work hardening…

2. Bauschinger effect (hysteresis: unbending is easier than bending, because the dislocations push against each other)

3. Heat the deformed bit. What happens?

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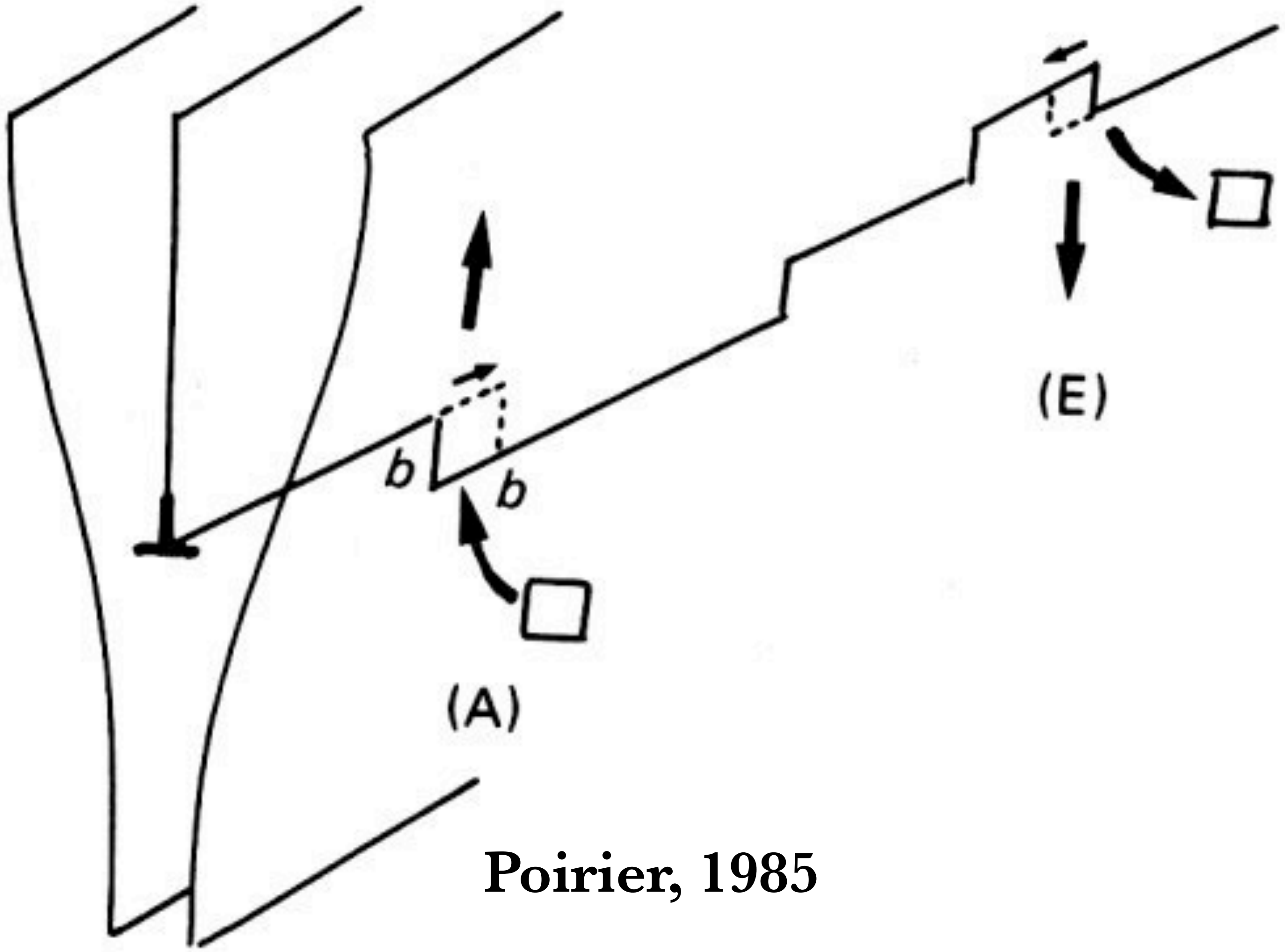
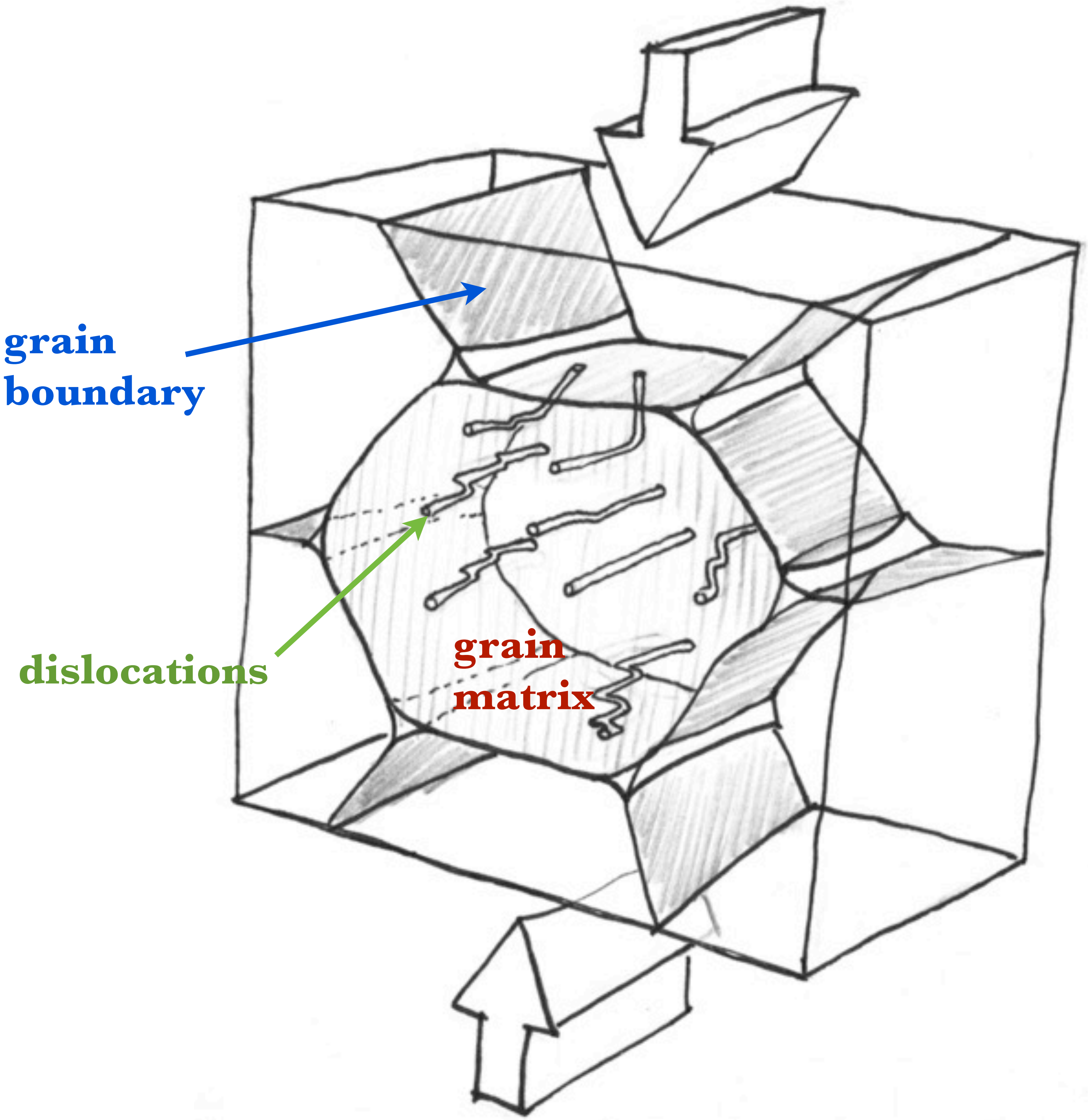
Large strains cannot occur without recovery...

Fig. 2.14. Climb of an edge dislocation: the dislocation line climbs by an interatomic distance when a jog travels along its length by absorbing (A) or emitting (E) vacancies.

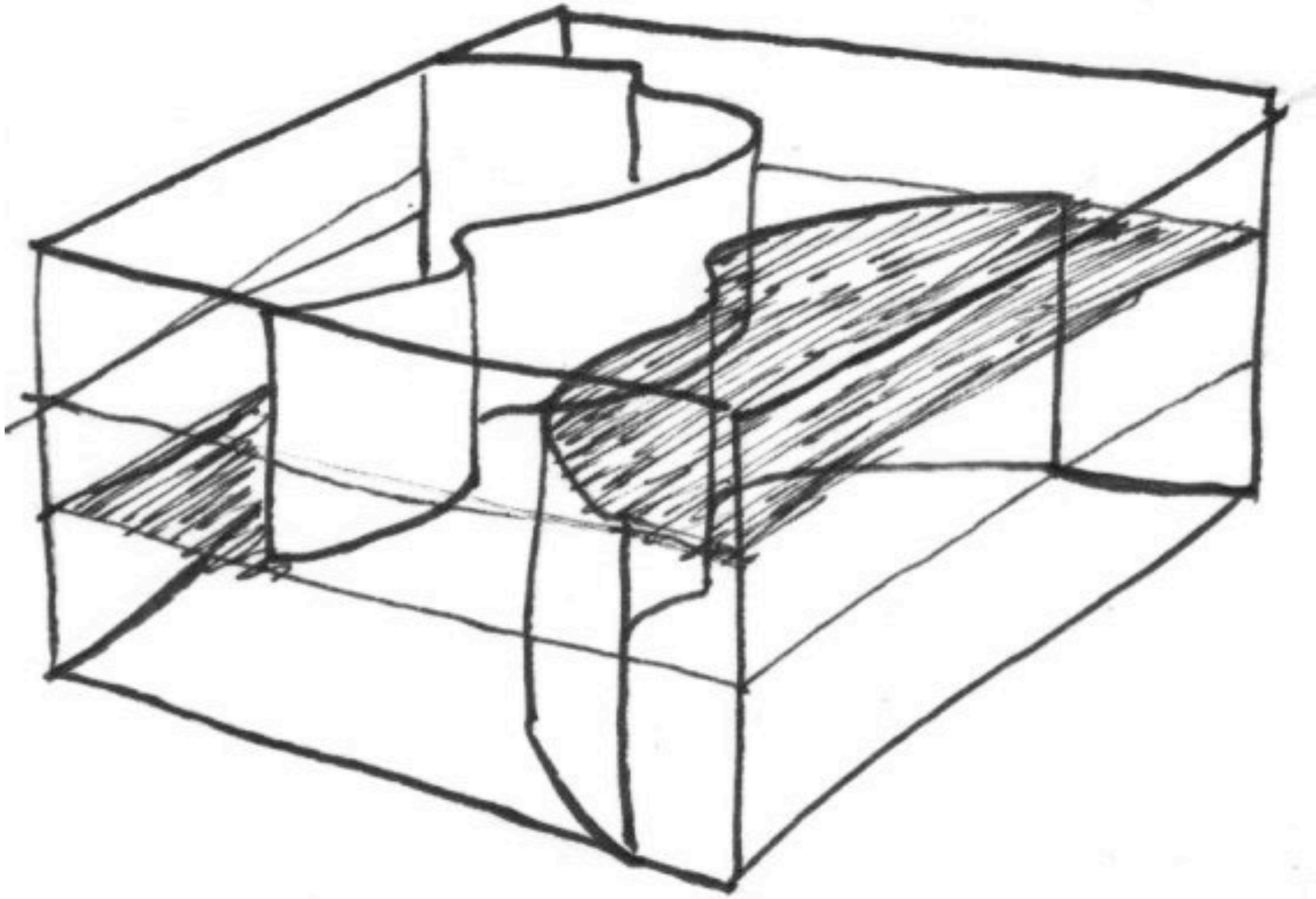


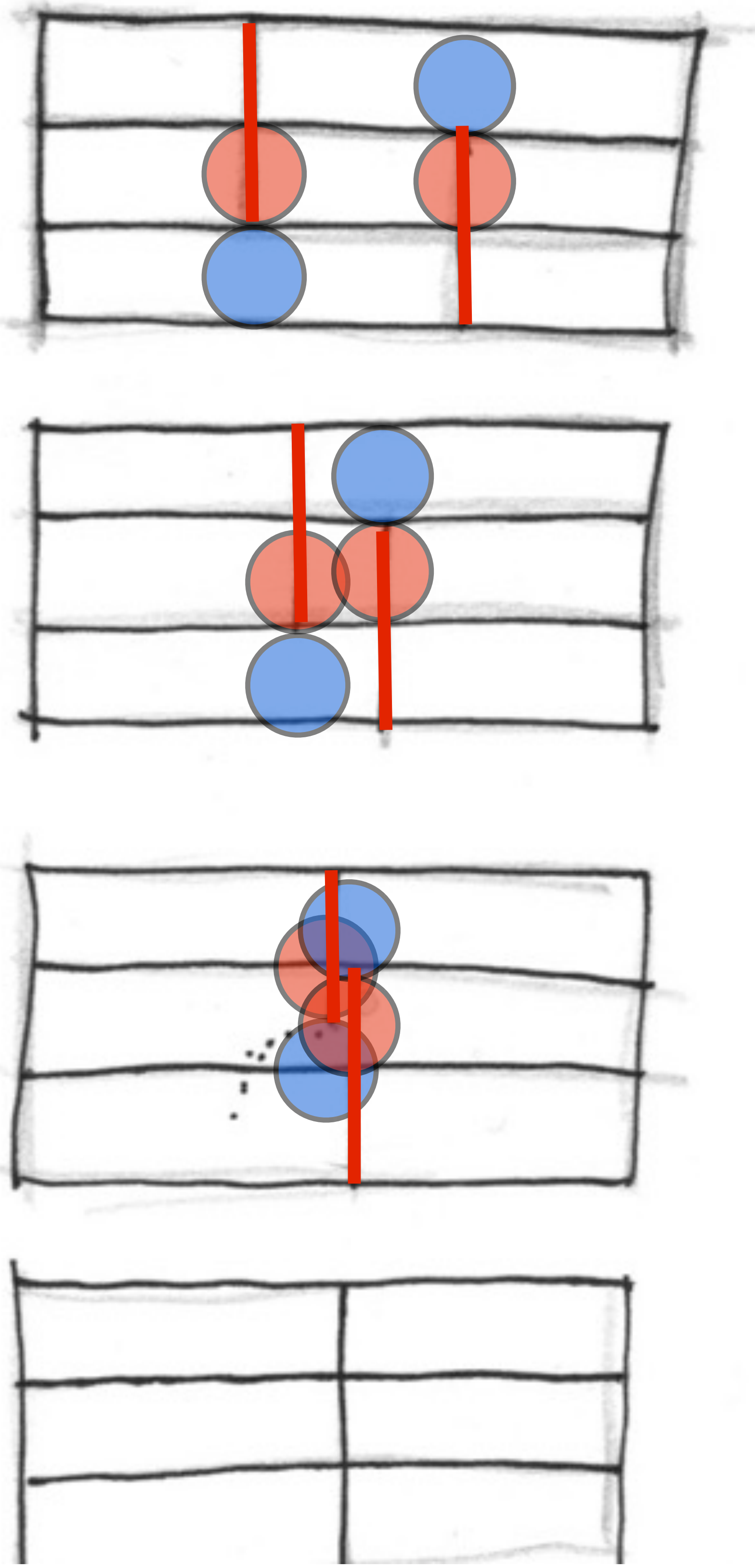
Poirier, 1985

Climb is a thermally activated diffusive process..
This is where the temperature dependence of dislocation creep comes from.

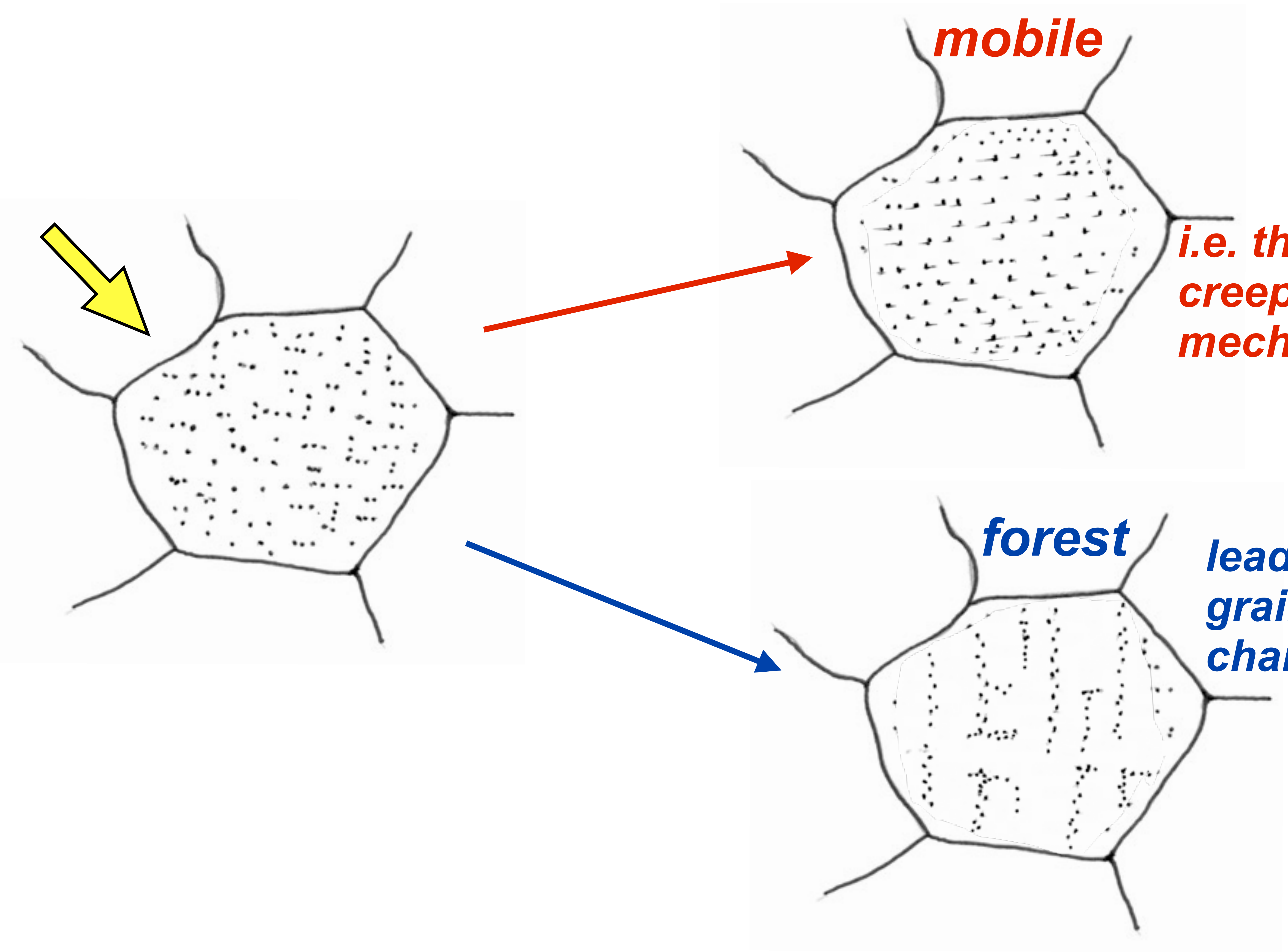


diffusion through dislocations = “pipe diffusion”





mobile and forest dislocations



mobile

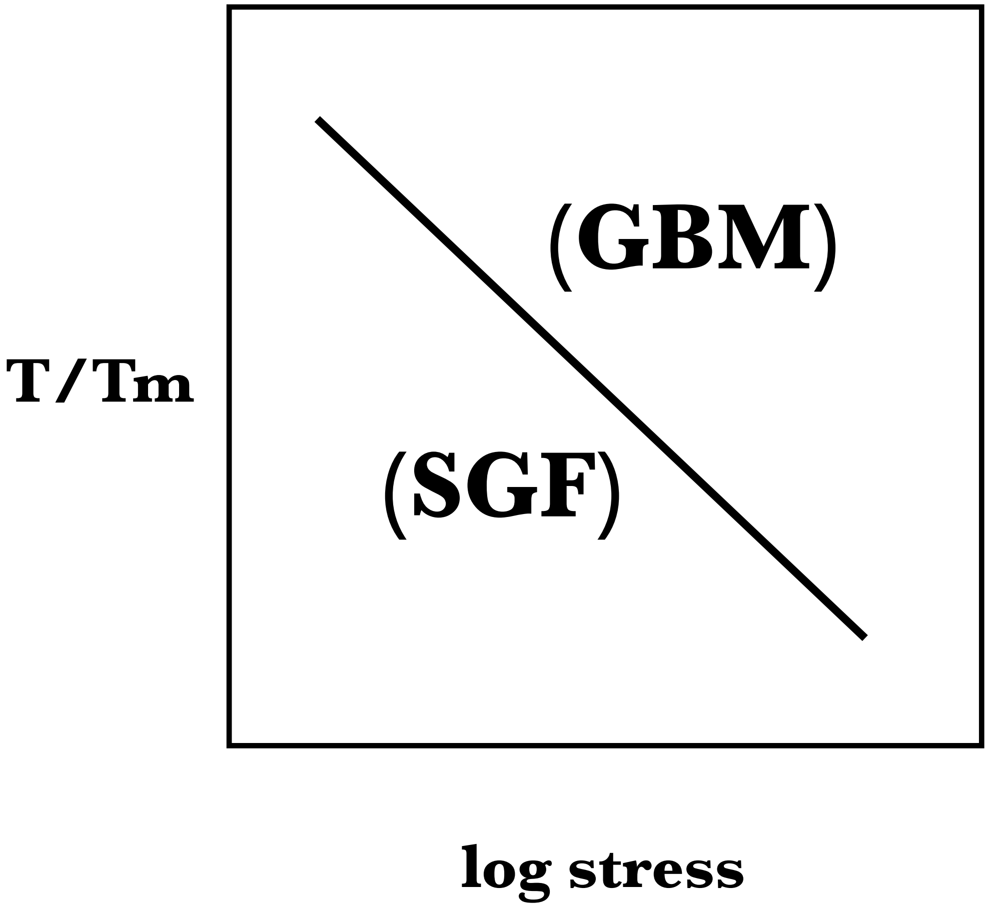
i.e. the creep mechanism

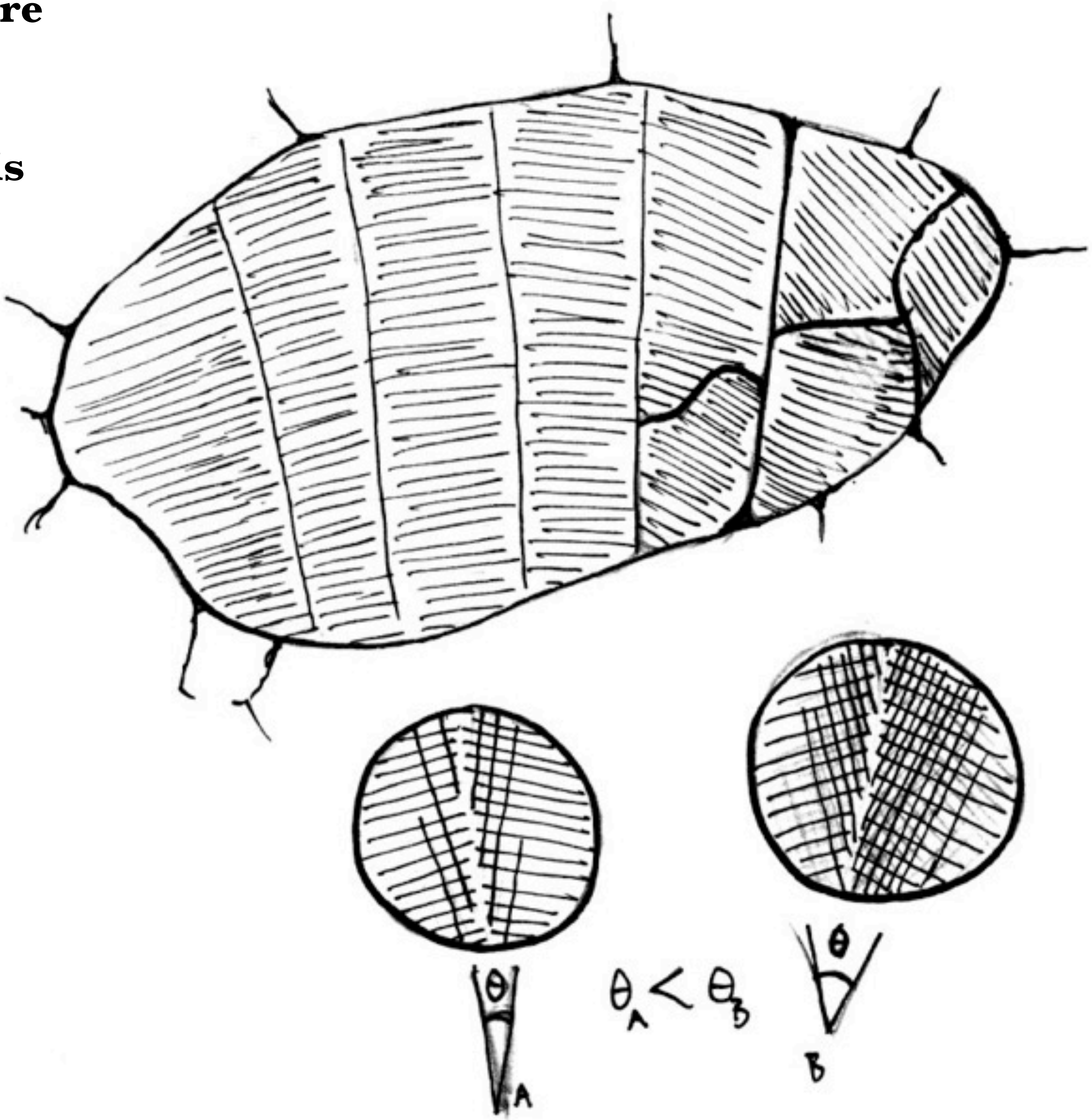
forest

lead to grain size change

Recovery by sub grain formation (SGF)

-associated with lower temperature because diffusion length scale is shorter and and lower stress conditions because driving force is smaller

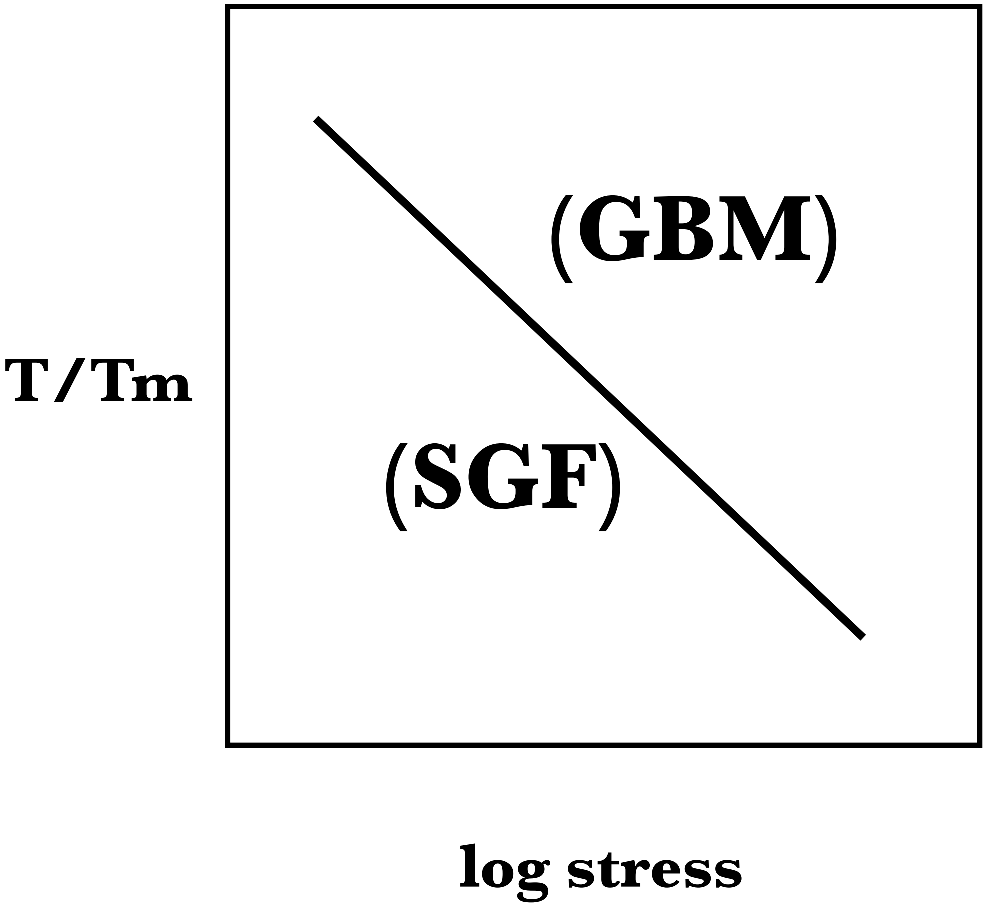


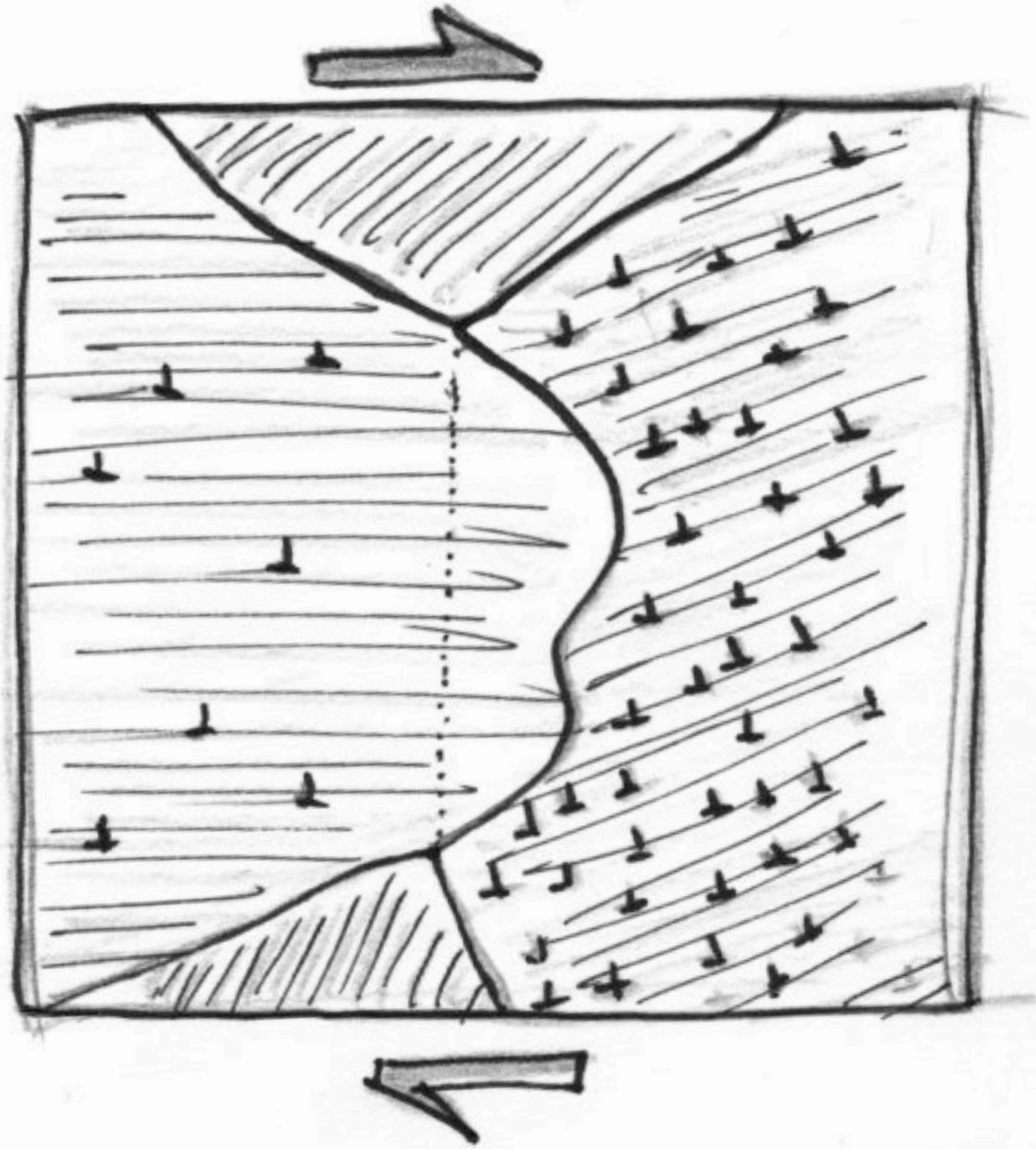


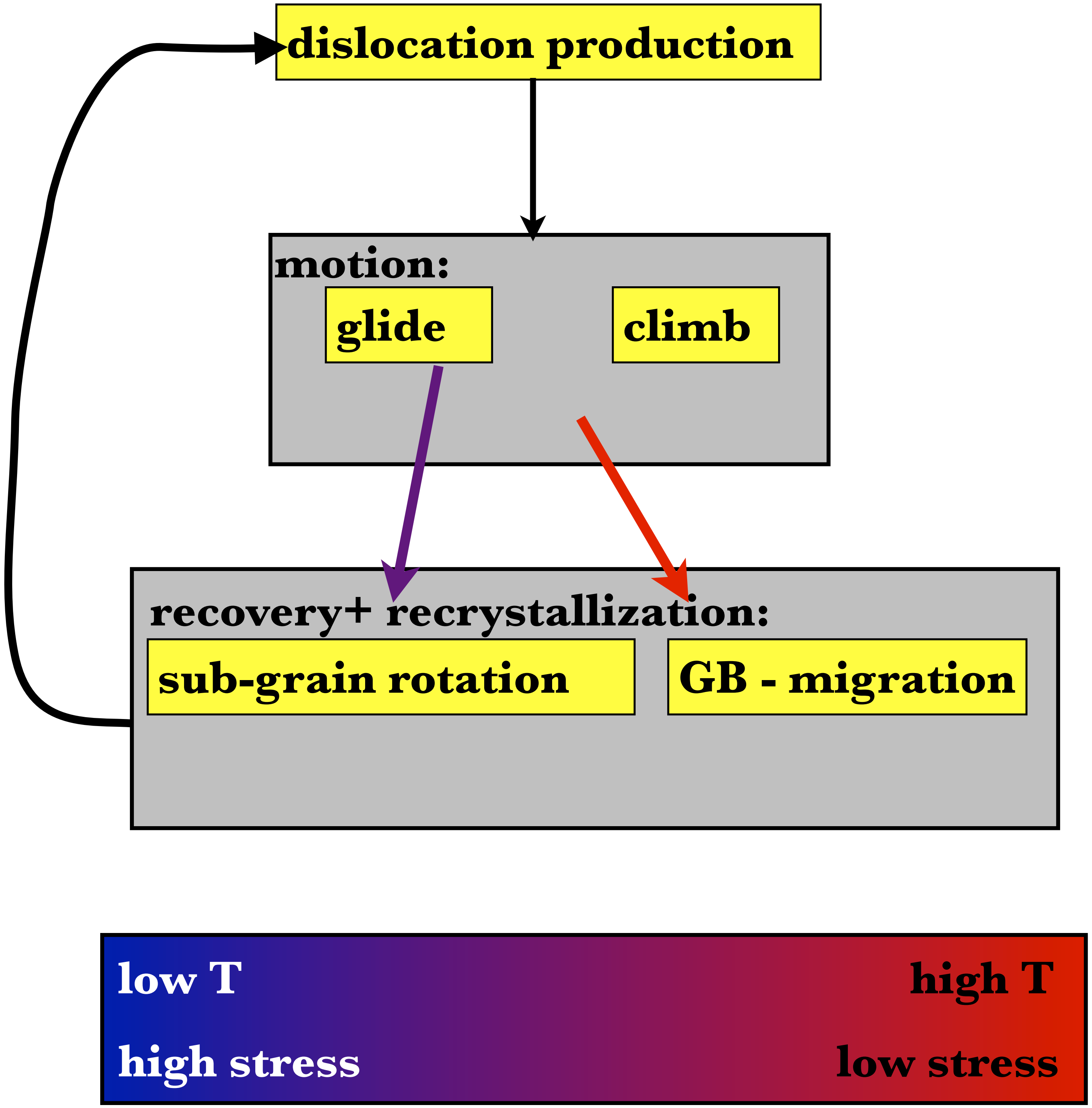
Recovery by grain boundary migration

-associated with higher temperature conditions (only because necessary diffusion length scale is greater than for SGR)

-associated with higher stress because necessary driving force is higher (at constant T)







dislocation production

motion:

glide

climb

recovery+ recrystallization:

sub-grain rotation

GB - migration

low T

high T

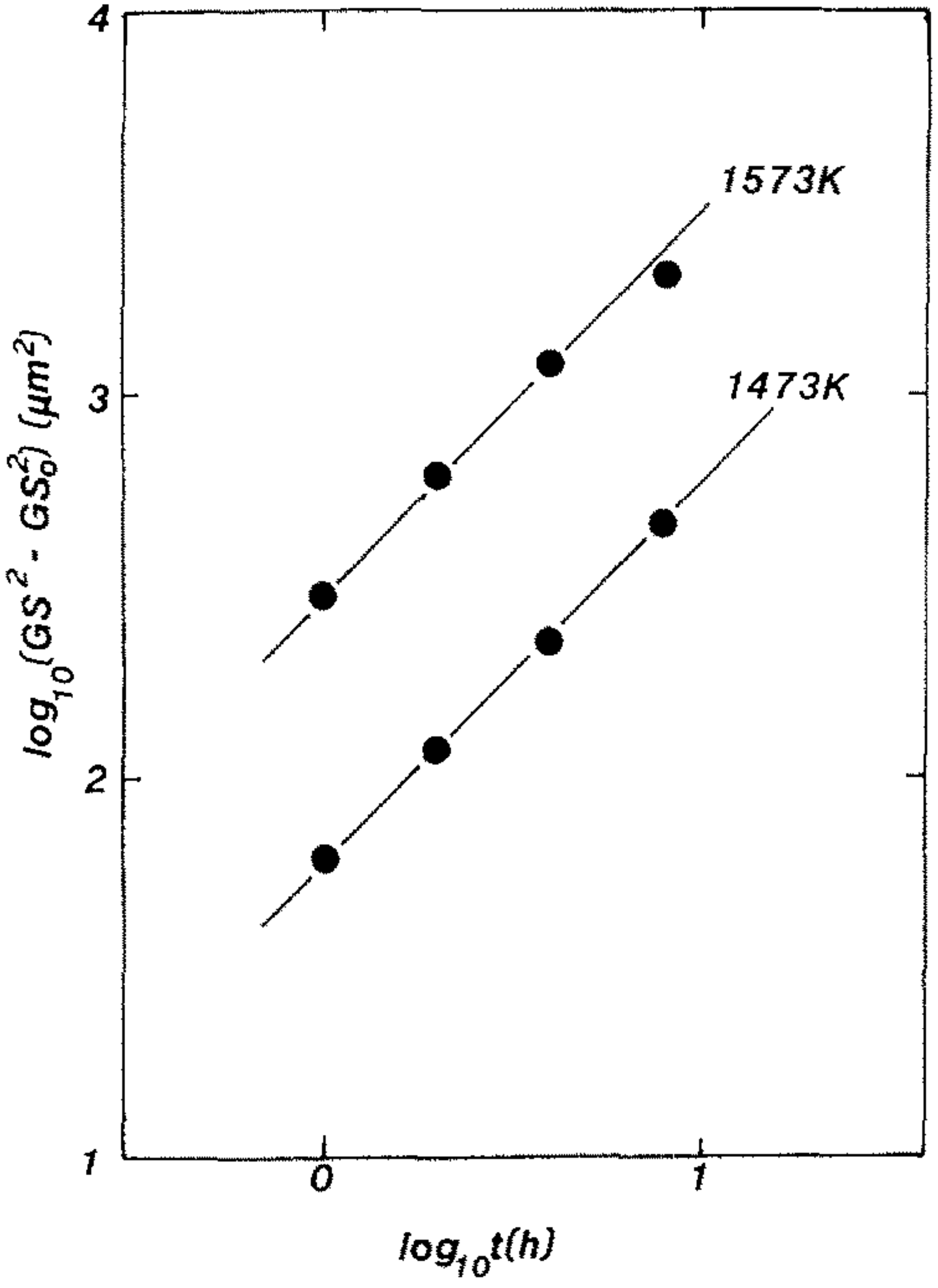
high stress

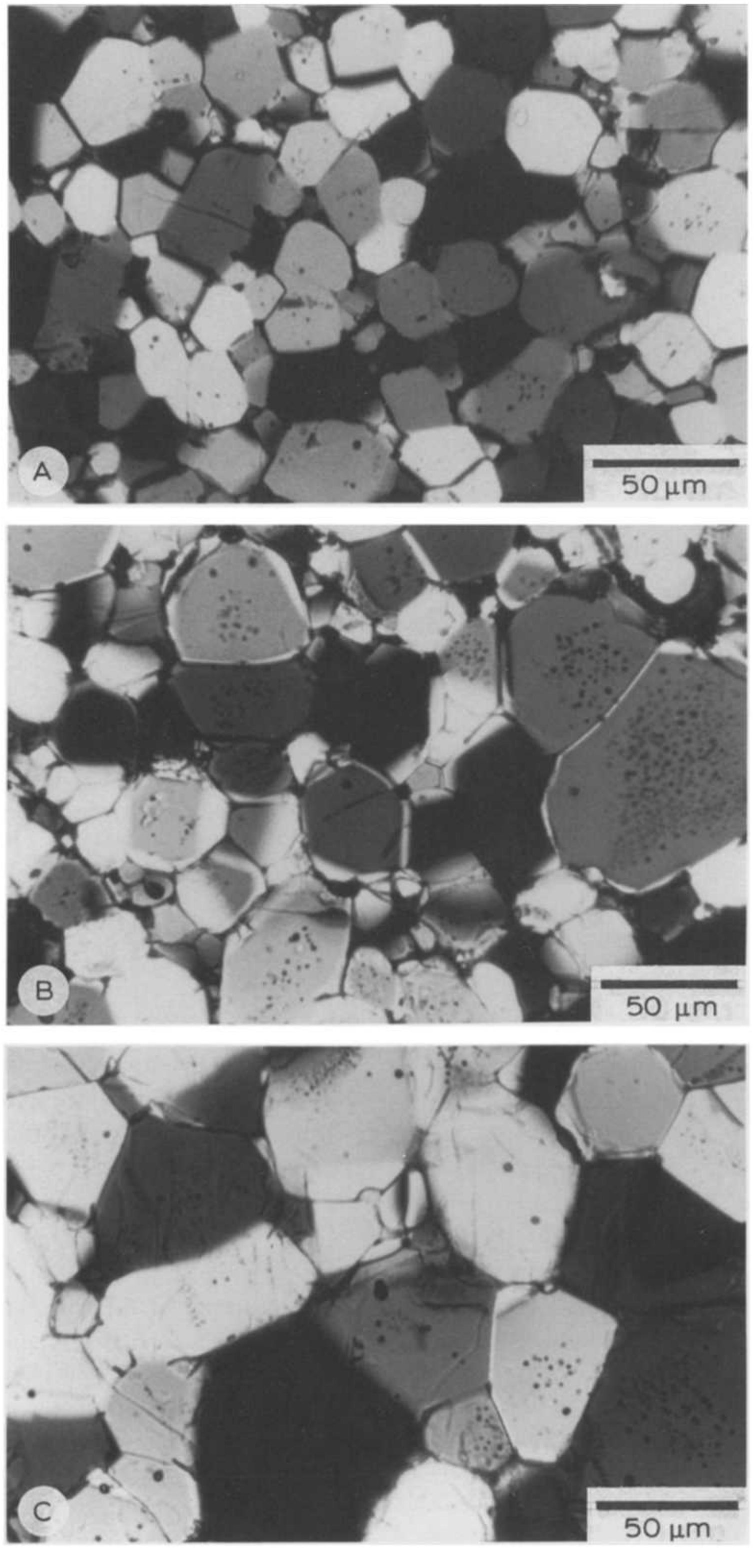
low stress

Static grain growth

Karato, S. (1989). Grain growth kinetics in olivine aggregates. *Tectonophysics*, *168*, 255–273.

$$\dot{d}_{gg} = A_{gg}\exp(-Q_{gg}/RT)d^{1-p}/p$$



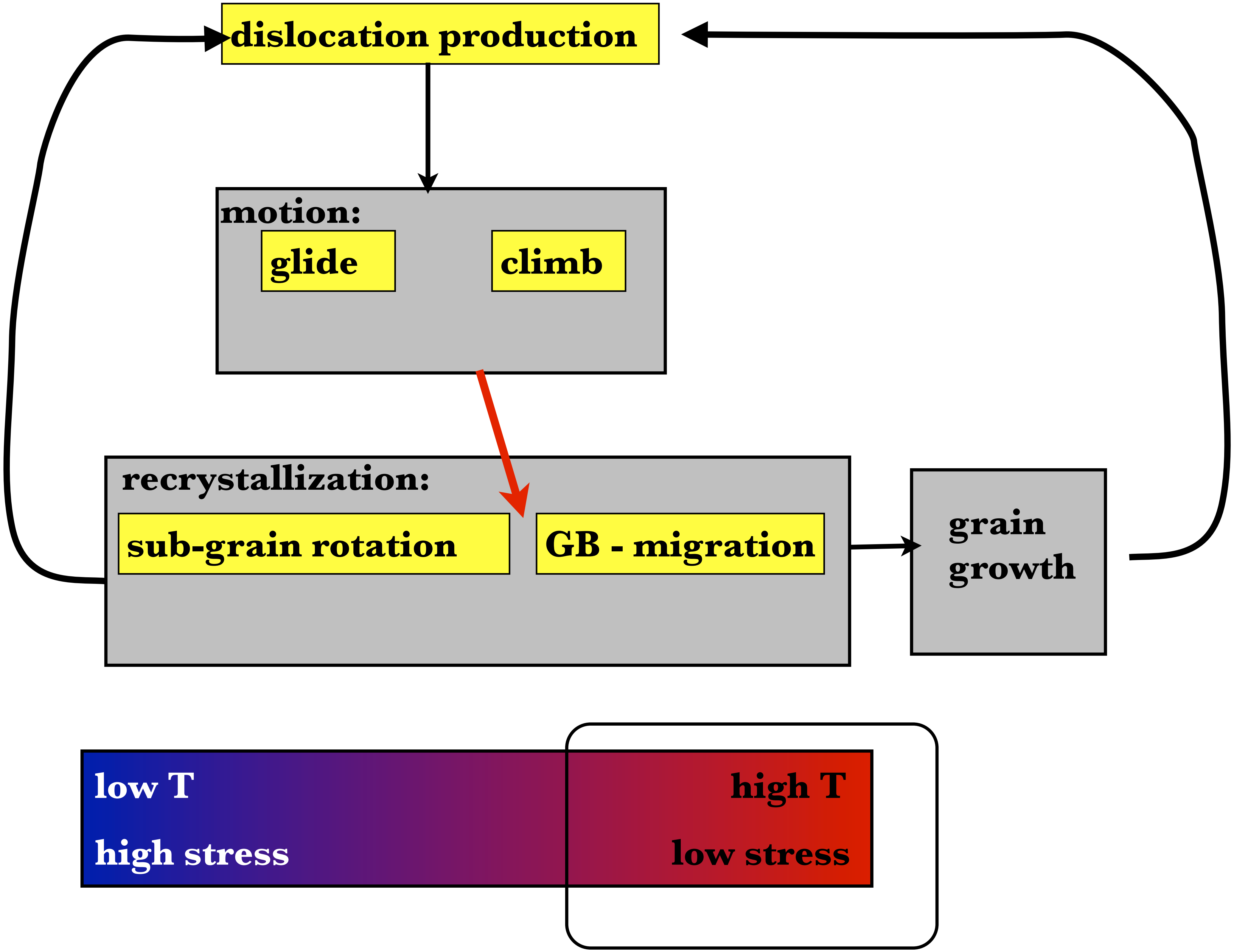


other factors:

pinning by other phases (pyroxenes)? (some say melt)

enhancement of growth rates by melt and by water..

enhancement of growth rate by variations in internal energy due to dislocation density? (can deformation enhance growth rate?)



dislocation production

motion:

glide

climb

recrystallization:

sub-grain rotation

GB - migration

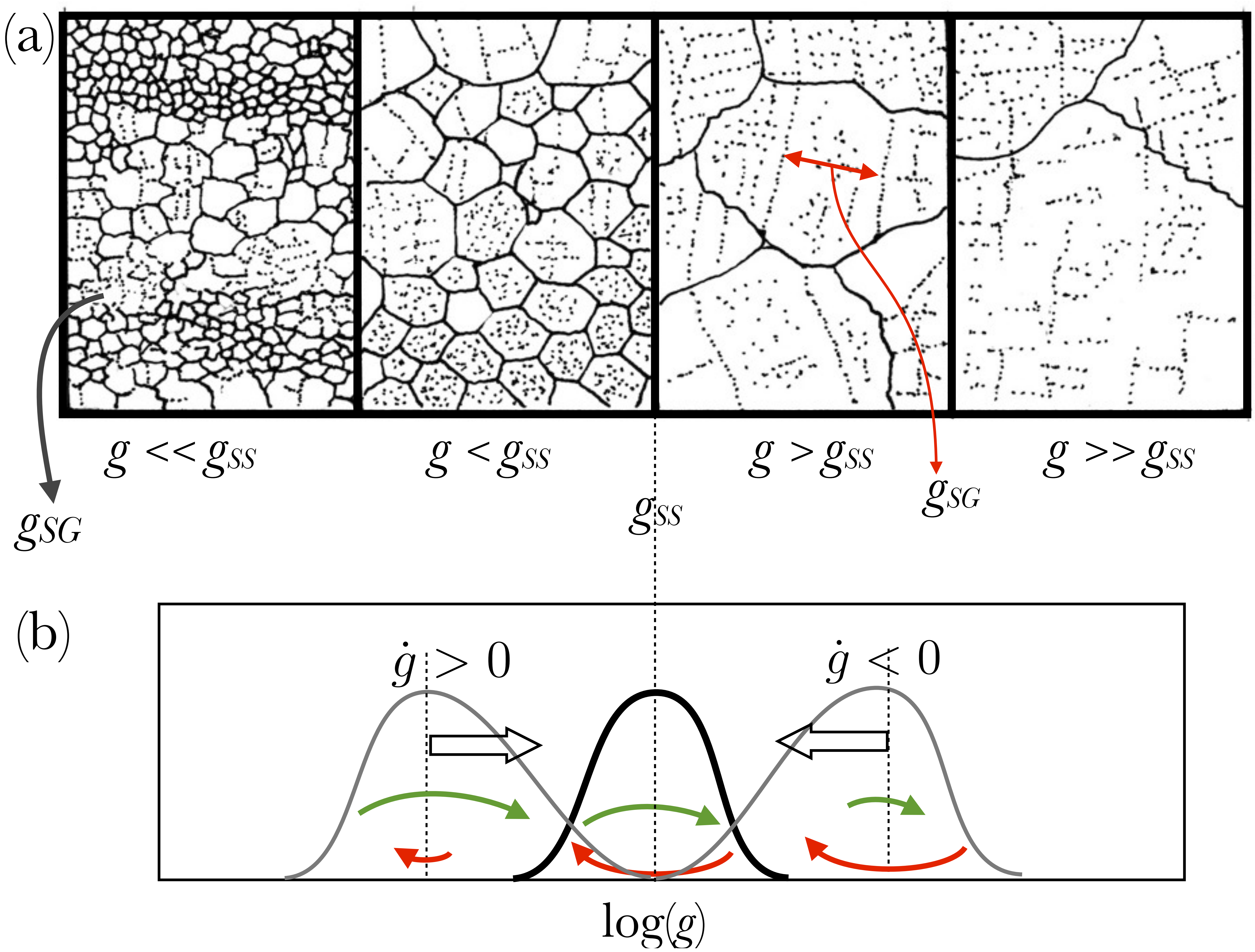
grain growth

low T

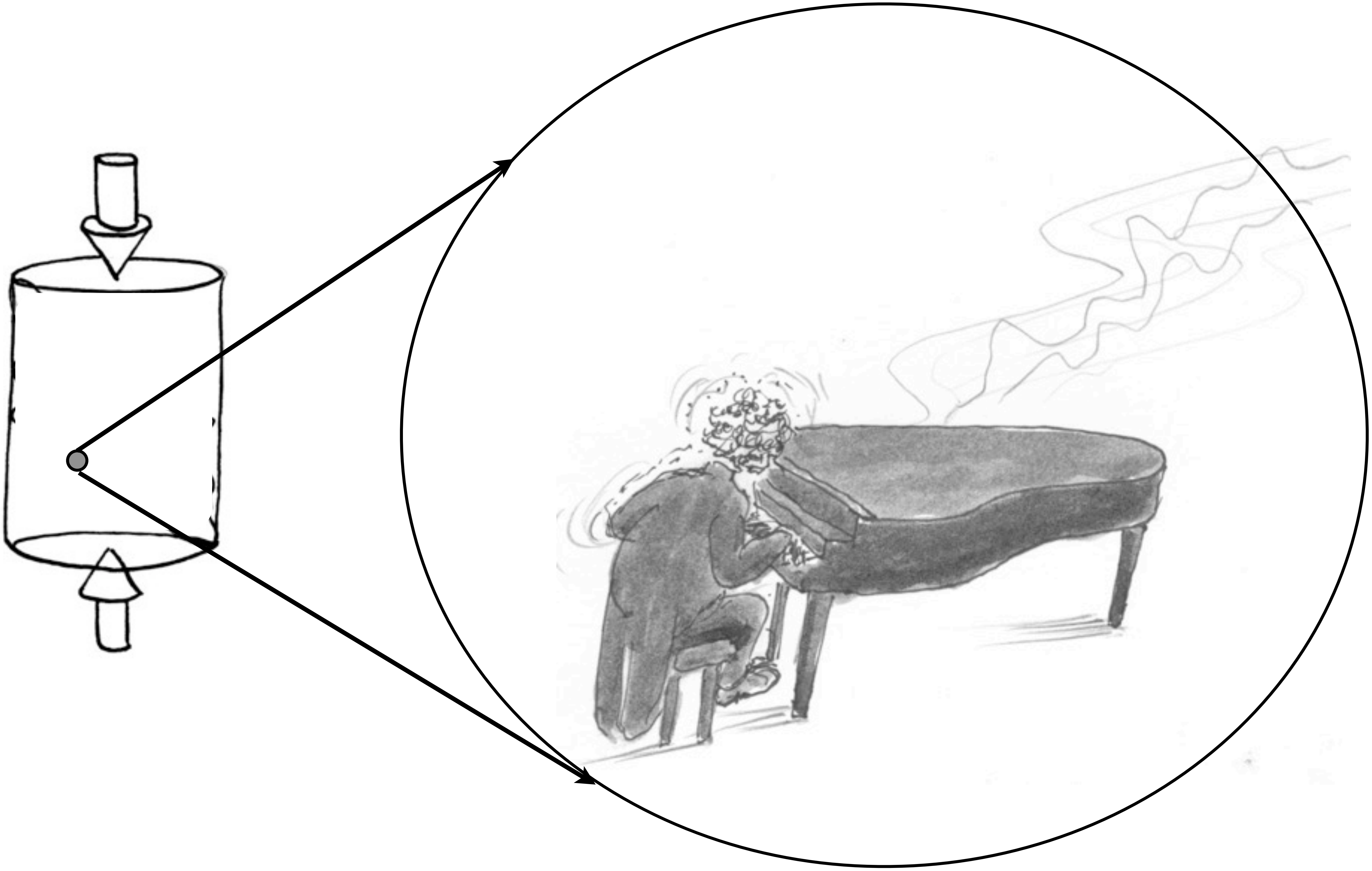
high stress

high T

low stress


(a)
$g << g_{SS}$
$g < g_{SS}$
$g > g_{SS}$
$g >> g_{SS}$
g_{SG}
g_{SS}
g_{SG}
(b)
$\dot{g} > 0$
$\dot{g} < 0$
log(g)

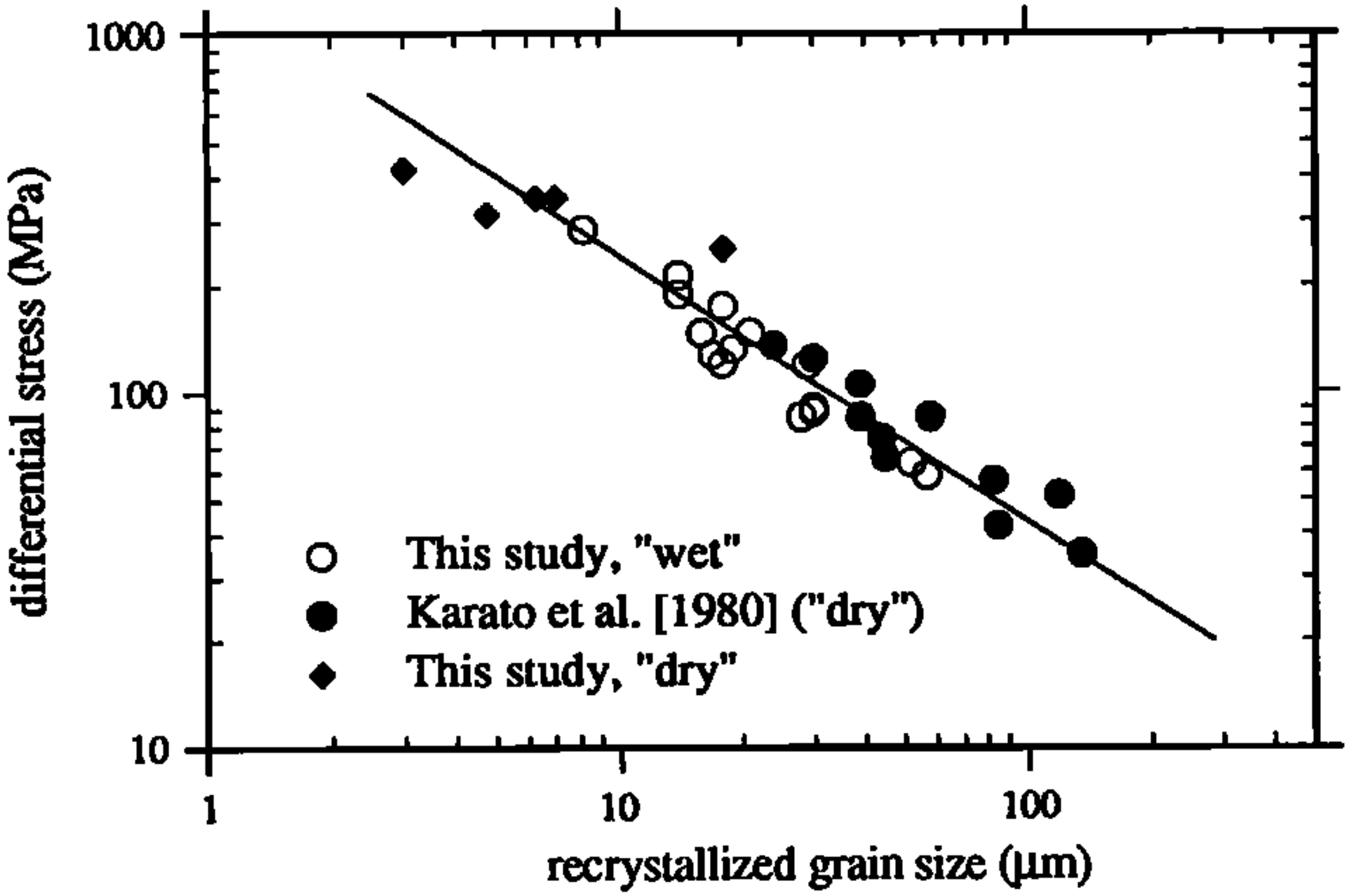
orowan to scholz:
“you can only measure the displacement...
for all you know, there is a guy inside playing the piano...”



RELATIONSHIPS BETWEEN DYNAMICALLY RECRYSTALLIZED GRAIN SIZE AND DEFORMATION CONDITIONS IN EXPERIMENTALLY DEFORMED OLIVINE ROCKS

Dirk Van der Wal [1,2], Prame Chopra [3], Martyn Drury [2] and John Fitz Gerald [2]

GEOPHYSICAL RESEARCH LETTERS, VOL. 20, NO. 14, PAGES 1479-1482, JULY 23, 1993



$$D_g = 0.015^{+0.0004}_{-0.0003} (\sigma)^{-1.33 \pm 0.09} \quad R = 0.96$$

Grain size:

$$\delta_g = A_g b \left(\frac{\sigma}{\mu} \right)^{-n_g}$$

piezometer (stress-meter) is meaningful for steady state deformation (i.e. time scale longer than the transient time).

in principle and empirical observation, the steady state lengthscale is proportional to the stress (rate of production = rate of annihilation and self-stress = applied stress)

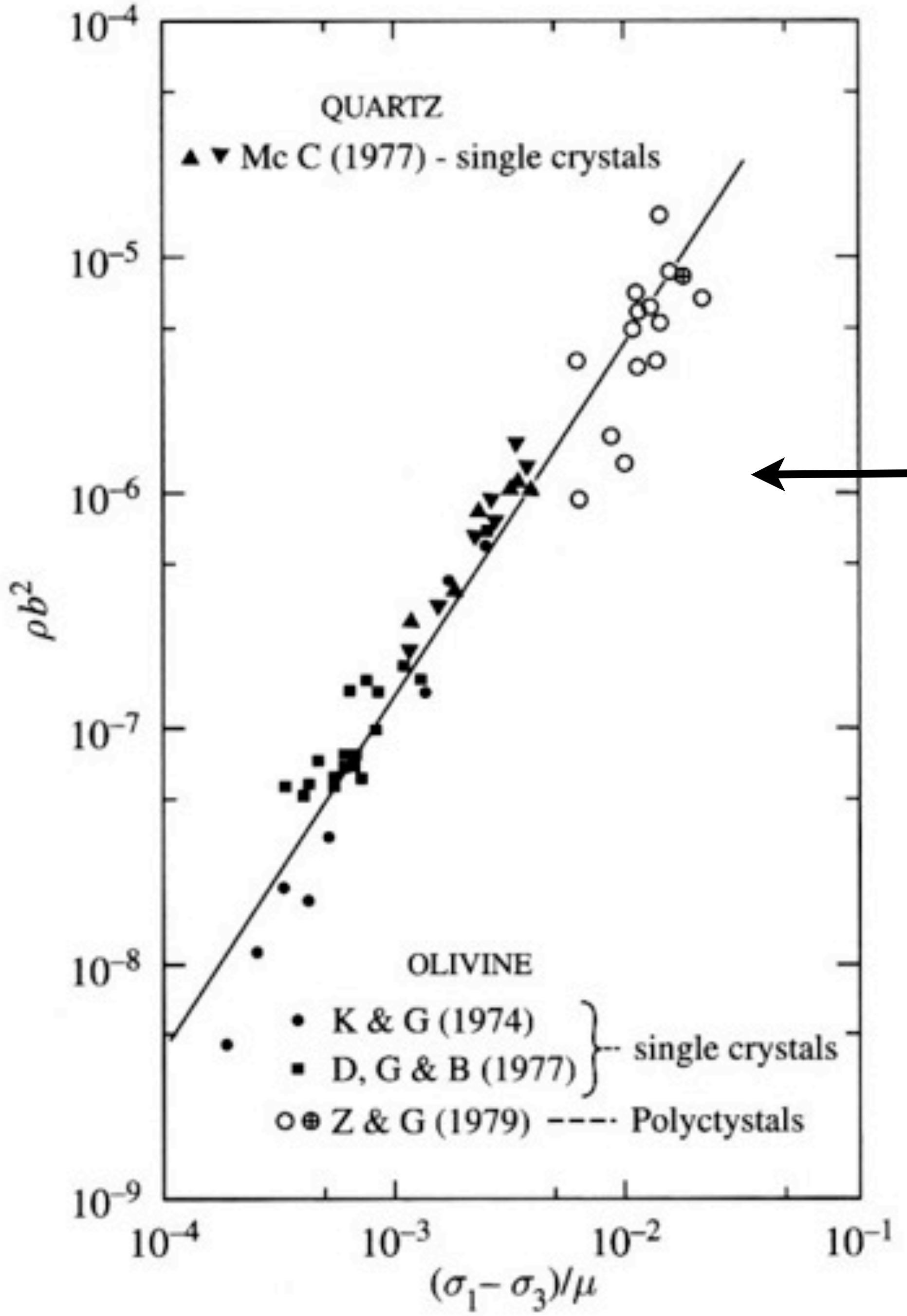


FIGURE 5.7 The dislocation density versus stress relationship (after Kohlstedt and Weathers, 1980).

Dislocation density:

$$\rho = A_1 b^{-2} \left(\frac{\sigma}{\mu}\right)^{+n_1}$$

or Dislocation spacing:

$$\delta_d = A_d b \left(\frac{\sigma}{\mu}\right)^{-n_d}$$

Subgrain size:

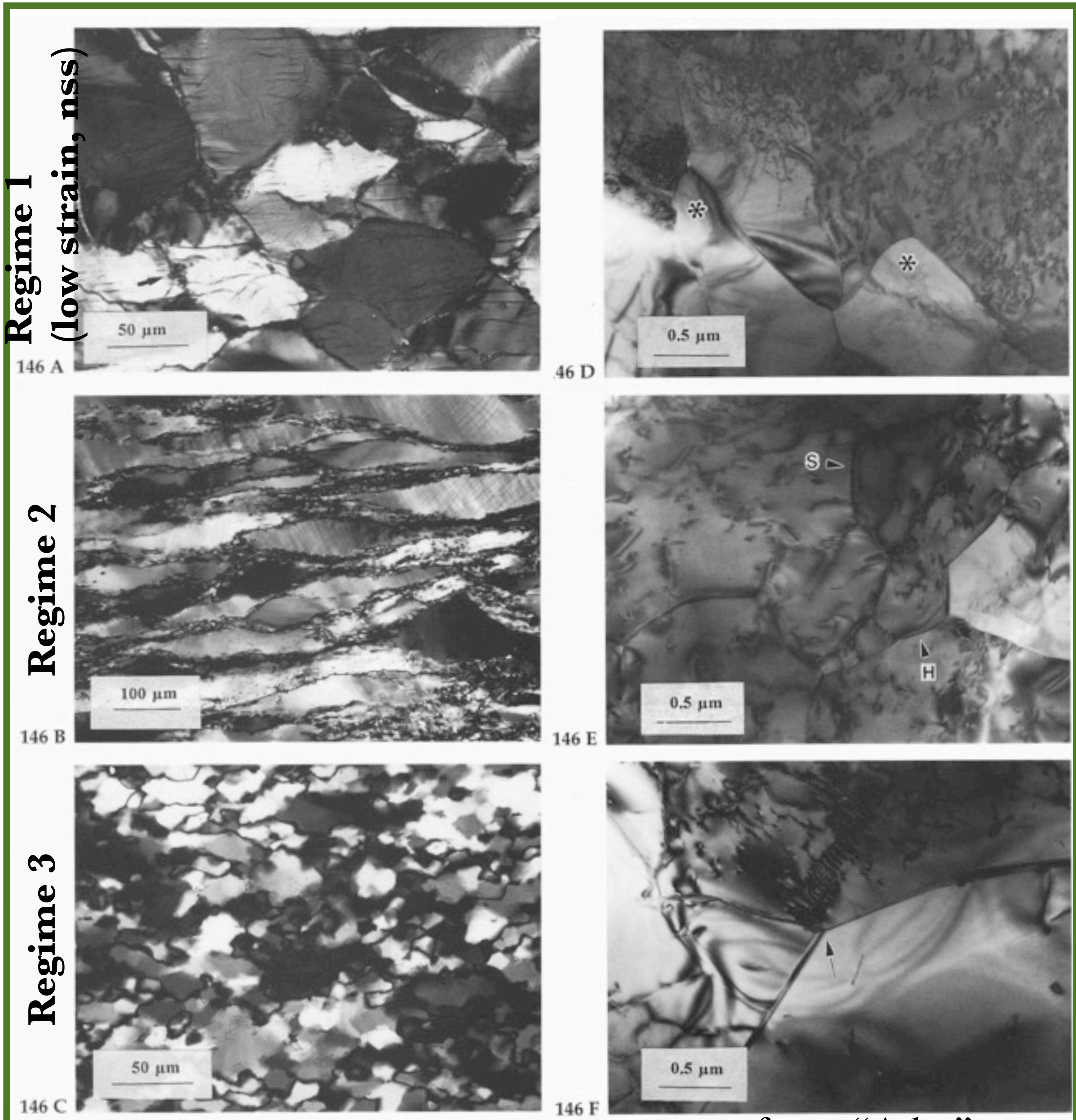
$$\delta_{sg} = A_{sg} b \left(\frac{\sigma}{\mu}\right)^{-n_{sg}}$$

Grain size:

$$\delta_g = A_g b \left(\frac{\sigma}{\mu}\right)^{-n_g}$$

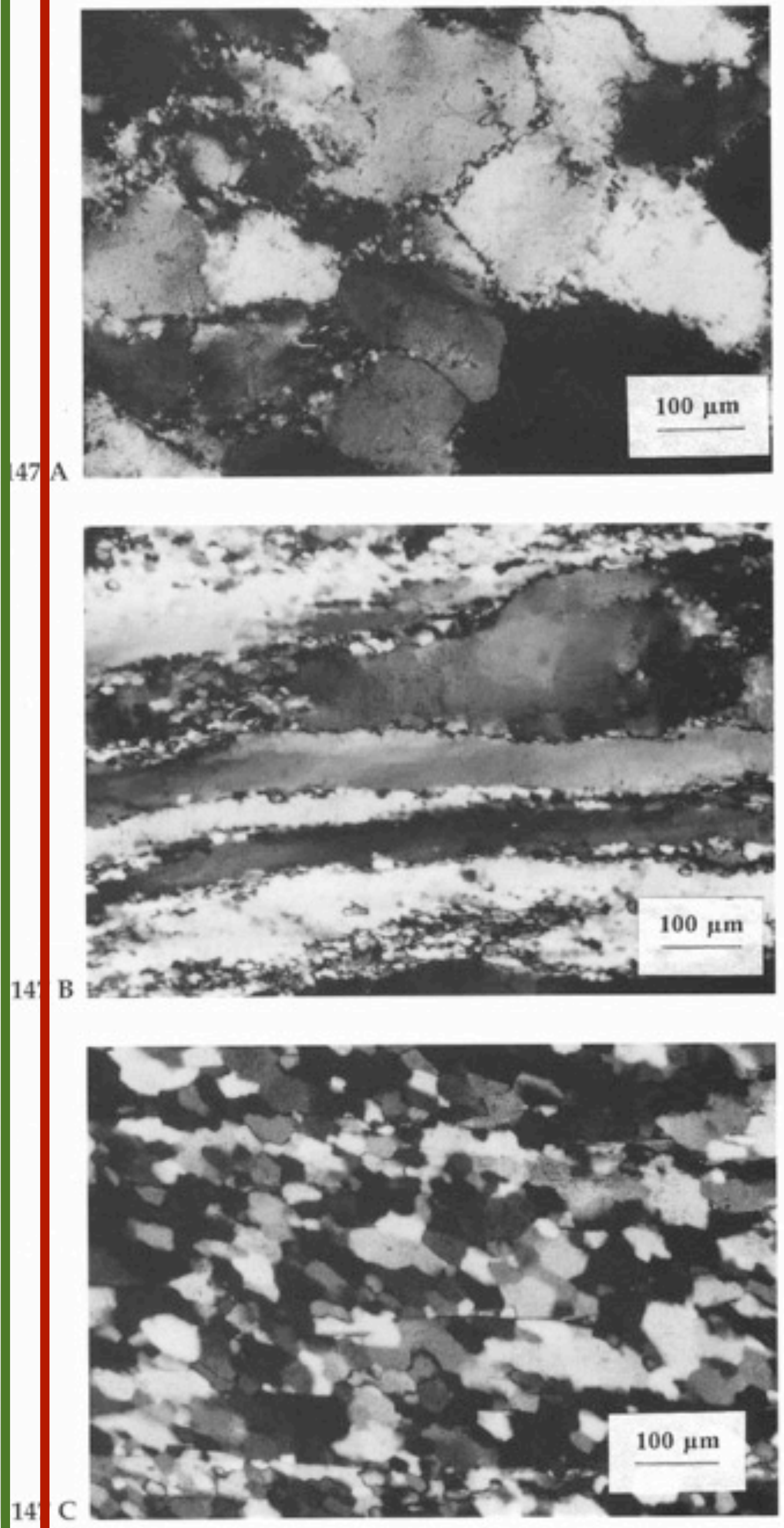
1. REVISIT Intro: Observations

Experimentally deformed:



from: “Atlas”

Naturally deformed



regimes determined by relative rates of

1. dislocation production
2. dislocation climb
3. grain boundary migration

these rates are a function of stress, temperature and water content

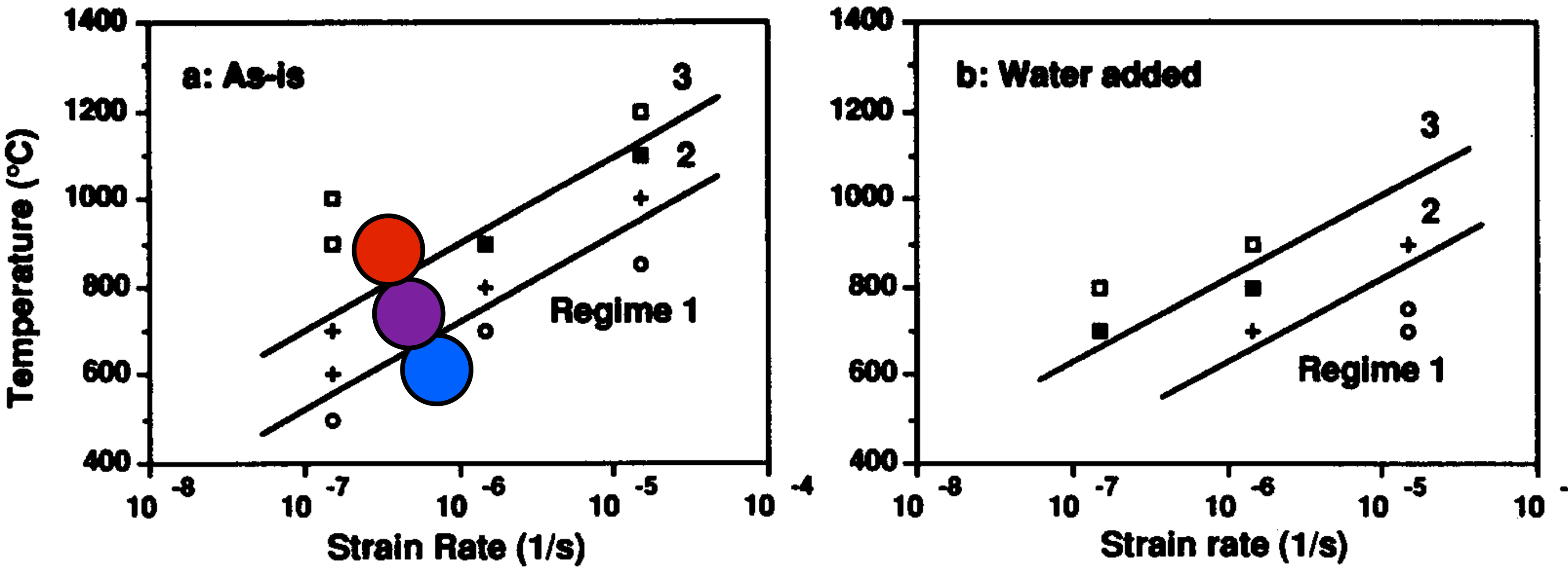


Fig. 2. Plots of temperature vs strain rate showing the location of the dislocation creep regimes for quartz aggre deformed (a) 'as-is' and (b) with 0.17 wt% water added. The boundaries between the regimes are gradational. Open c represent regime 1, plus symbols represent regime 2, open squares represent regime 3, and a plus inside a square repre gradational between regimes 2 and 3.

● R1 (high stress, low T): production fast, recovery by climb and GBM slow

● R2 (lower stress, higher T): recovery by climb moderate, but GBM slow, so recrystallization occurs by subgrain rotation (requiring climb)

● R3 (low stress, high T): recovery by climb fast, but Grain Boundary Migration is also fast, so complete recrystallization occurs by both subgrain rotation and GBM. (see relatively uniform grain size)

Summary

1. dislocations move through crystals to reduce elastic strain energy and cause deformation

2. each one causes only very small displacement… so many must be produced and move through the crystal to cause strain. The production is caused by stress acting on a "Frank-Read Source".

3. The motion of dislocations depends on the anisotropy of the lattice, and the orientation of the lattice relative to the stress.

4. The strain rate is a non-linear function of the stress, due to the rate of production, the density and the velocity of dislocations. The velocity depends on the ease of climb, which is a thermally activated diffusive process, so dislocation creep has the exp(-Q/RT) dependence.

5. Large strains require recovery, which can be achieved by sub-grain rotation, grain boundary migration recrystallization.

6. Regimes defined by microstructures depend on the relative rates of these processes of dislocation production and recovery

Dislocations and dislocation creep...

1. Introduction: a) Observations of textures associated with dislocation creep
b) MOVIES of dislocations in metals.

2. How do dislocations move?: single dislocations: stress, energy and motion.
Orowan's equation. Frank-Read sources, Work Hardening
(Fatigue, paper clips)

3. Recovery and Recrystallization:
Dislocation climb,
Subgrain formation, Grain boundary migration
Grain Growth
Steady state grain size

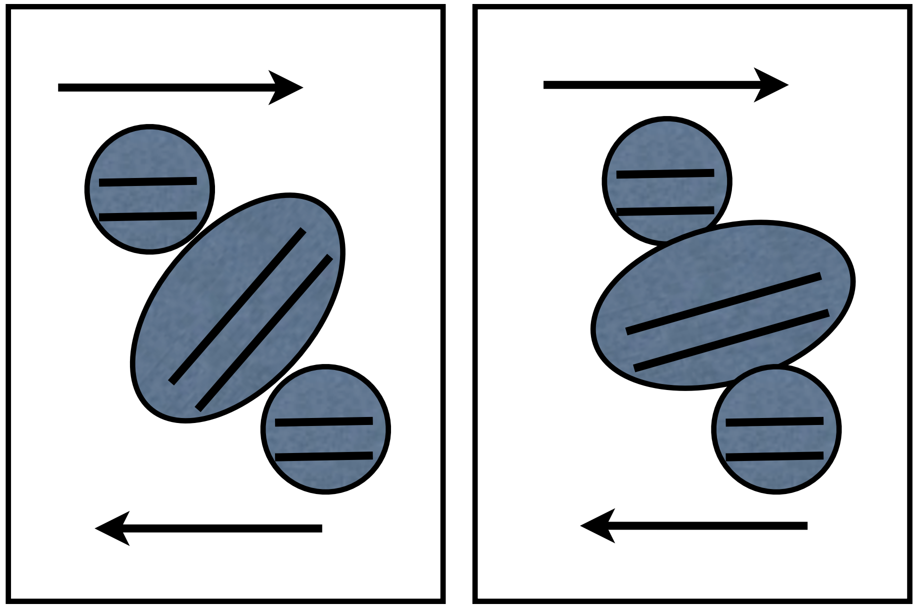
4. Fabric development
Grain rotation (LPO development)

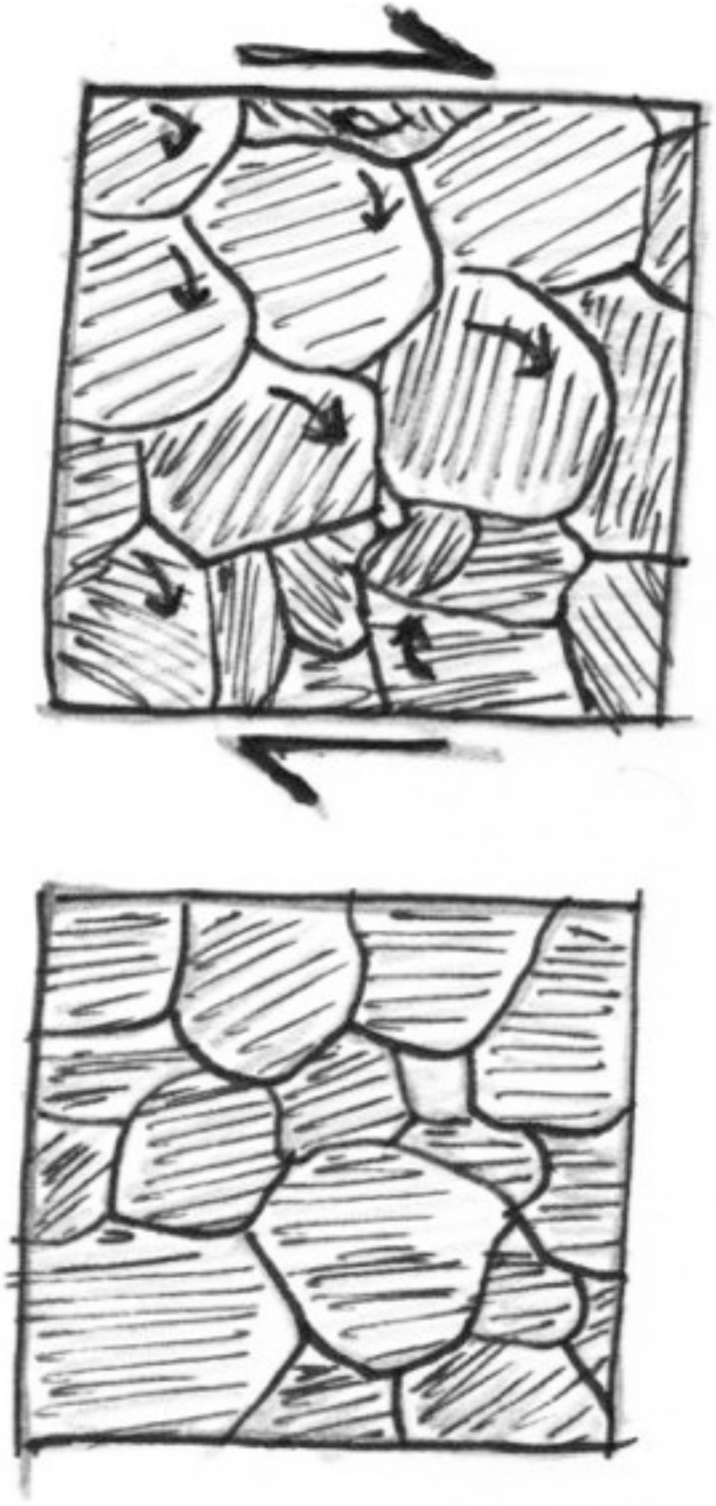
5. Flow laws and Deformation Mechanism Maps

4. Fabric (Lattice preferred orientation) Development

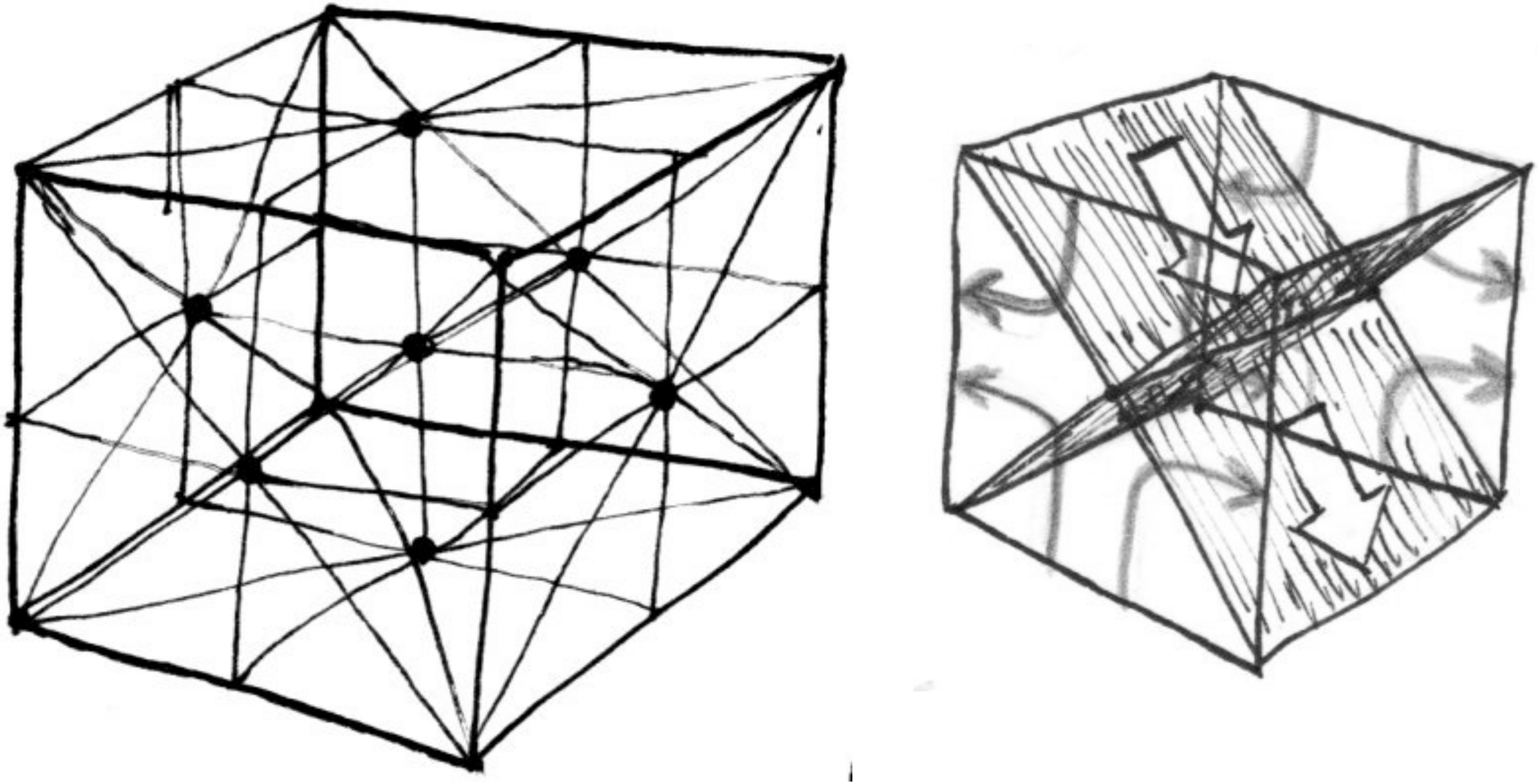
When anisotropic crystals (i.e. slip systems with significantly different strengths) are sheared, grains can rotate by a range of mechanisms, including:

1. **rigid body rotation**
2. **recrystallization by GBM, in which well-oriented grains consume poorly oriented grains,**
3. **subgrain rotation recrystallization…**


rigid body rotation



von mises criterion

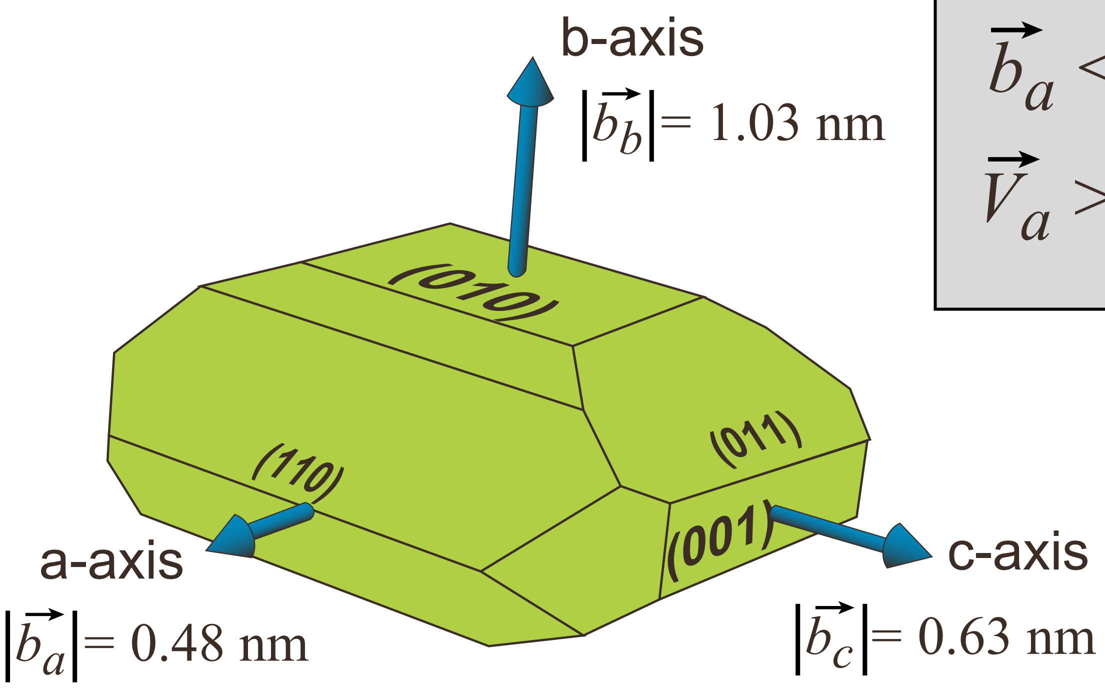


complete strain compatibility for an arbitrary deformation requires FIVE slip systems to be active (6 strain components + constant volume constraint). However, this strict requirement can be relaxed by grain boundary sliding and diffusion creep... so the strength more closely reflects the weakest slip system than the strongest.

ADD VON MISES MATH

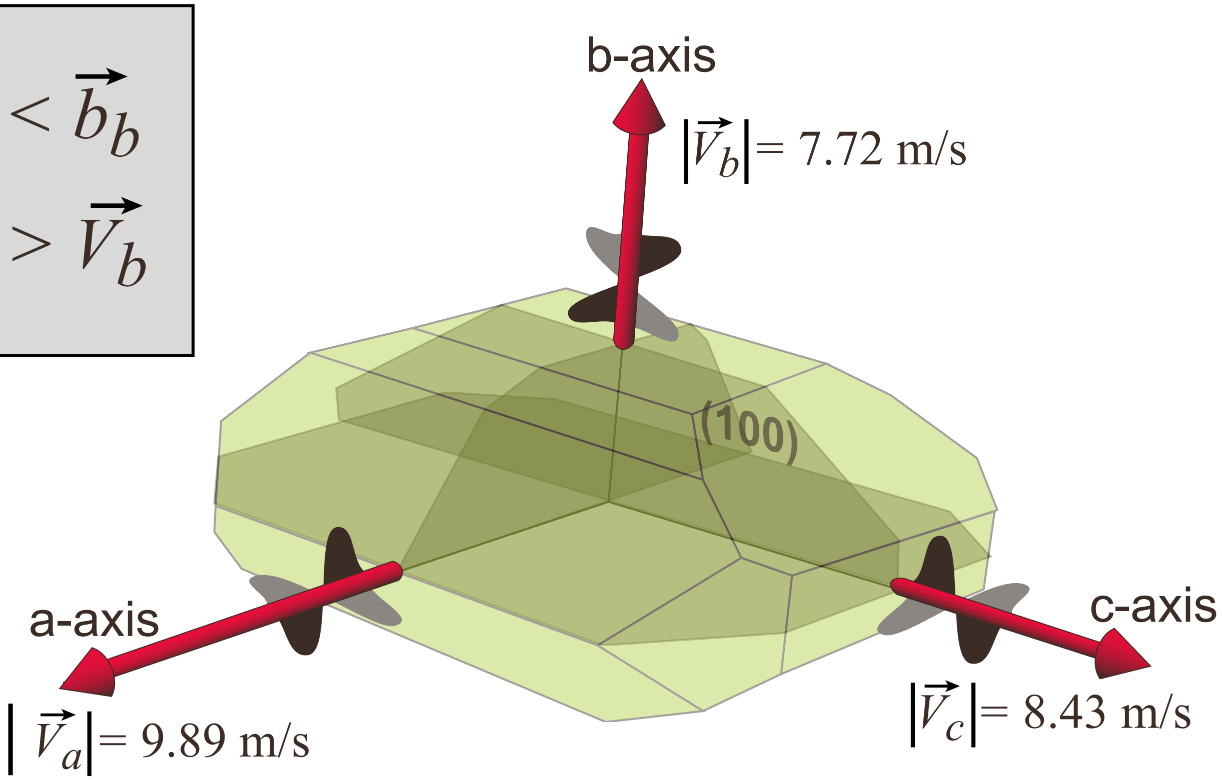
Olivine: (010)[100] is easiest, followed by (010)[001]

“Miller indexes” = (slip plane)[slip direction]



$$\vec{b}_a < \vec{b}_c < \vec{b}_b$$

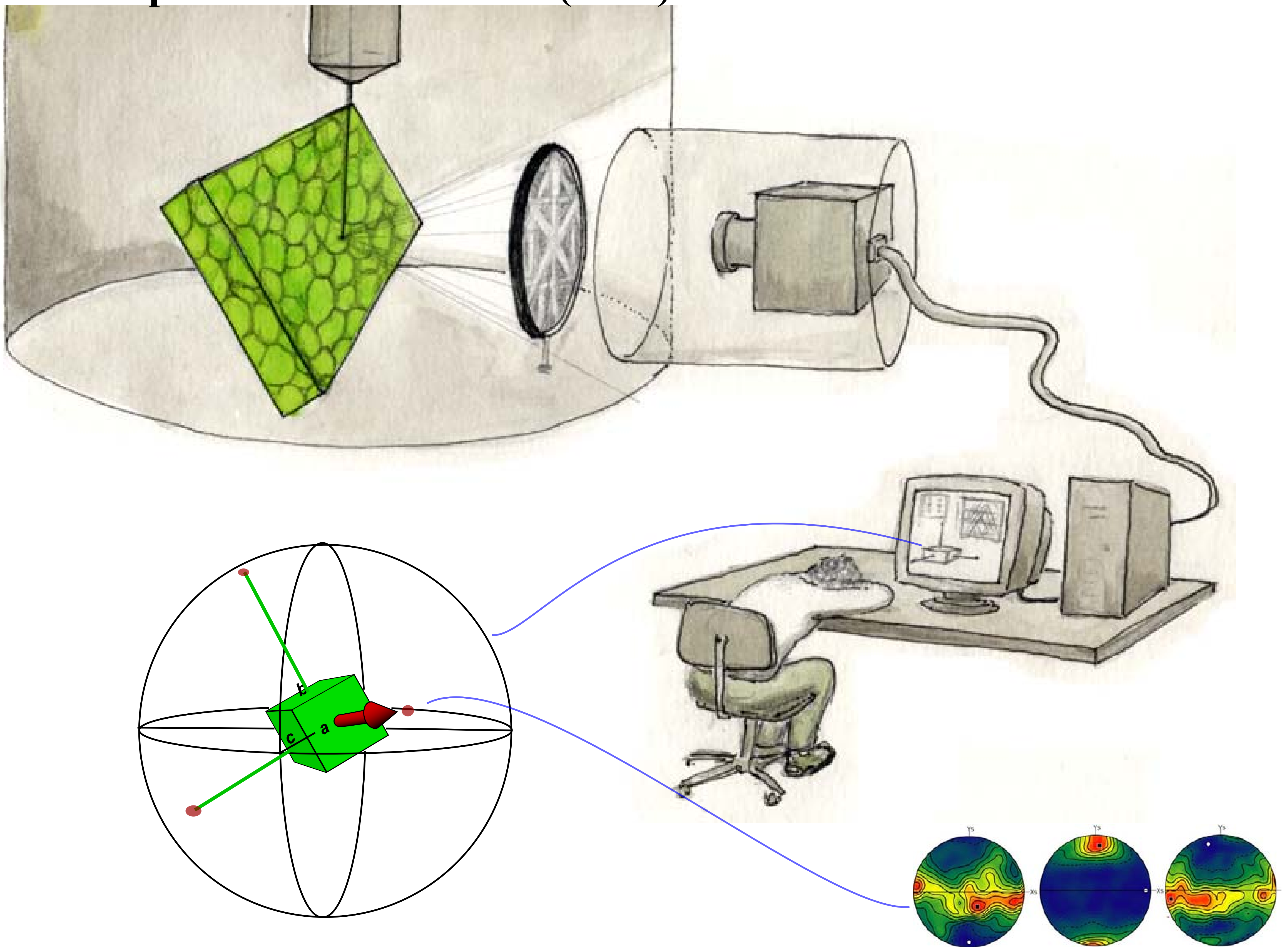
$$\vec{V}_a > \vec{V}_c > \vec{V}_b$$



The “von Mises criterion” says that you need 5 independent slip systems to accommodate any arbitrary strain in a polycrystalline material.

If the material can access other mechanisms such as grain boundary sliding, this requirements can be relaxed.

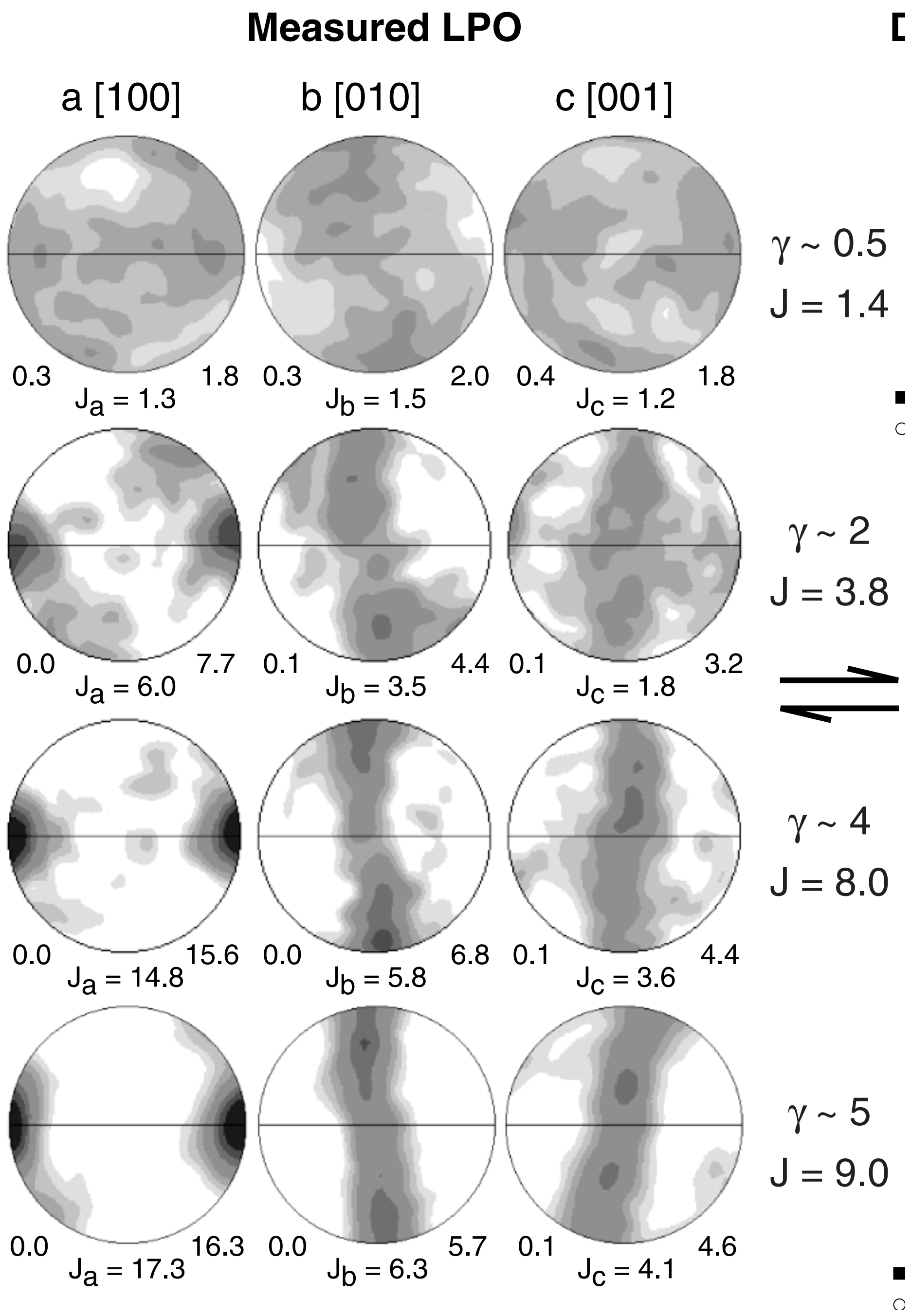
The principles of electron back-scatter diffraction (EBSD) pattern analysis and lattice preferred orientations (LPO)

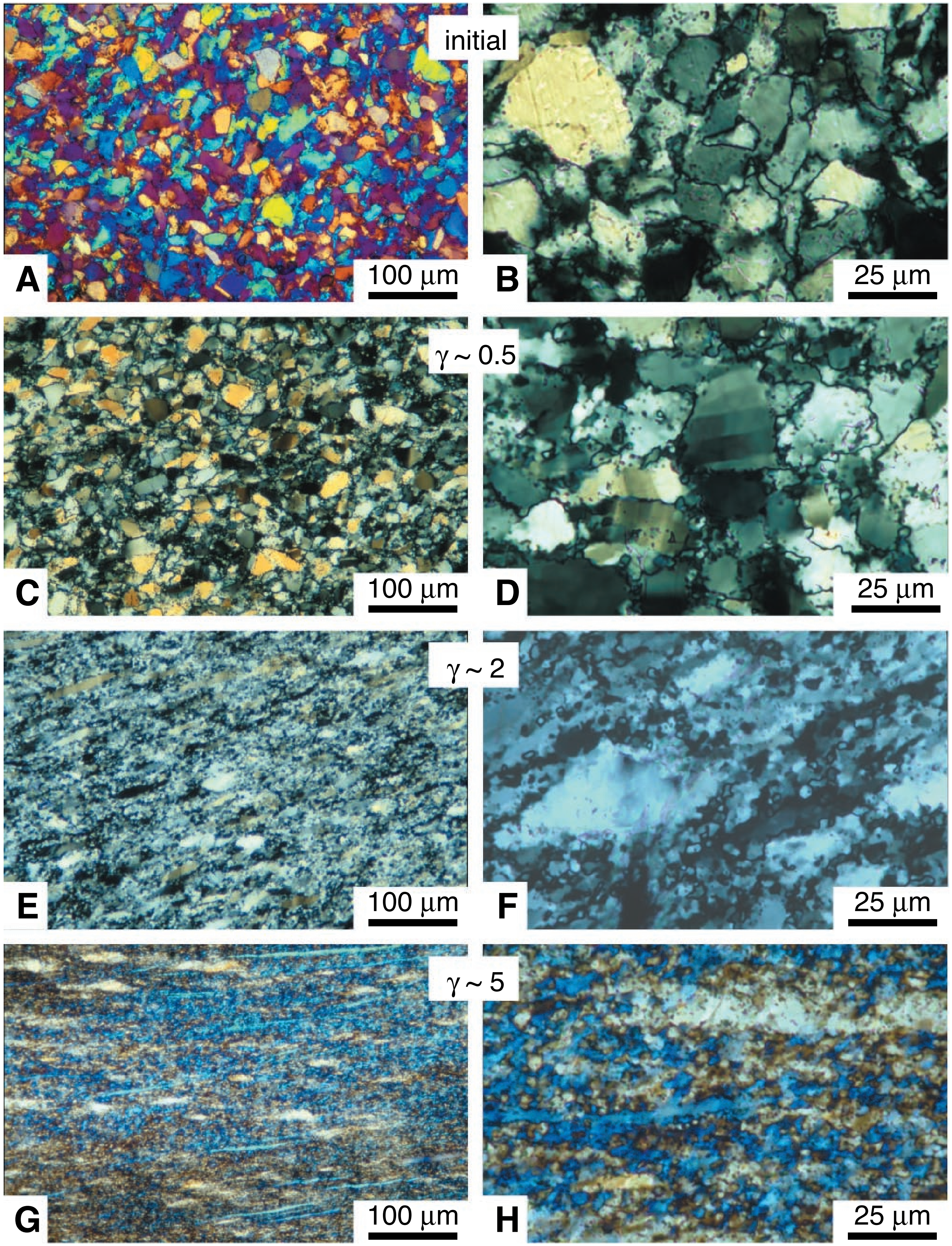


High Shear Strain of Olivine Aggregates: Rheological and Seismic Consequences

M. Bystricky,* K. Kunze, L. Burlini, J.-P. Burg

24 NOVEMBER 2000 VOL 290 SCIENCE



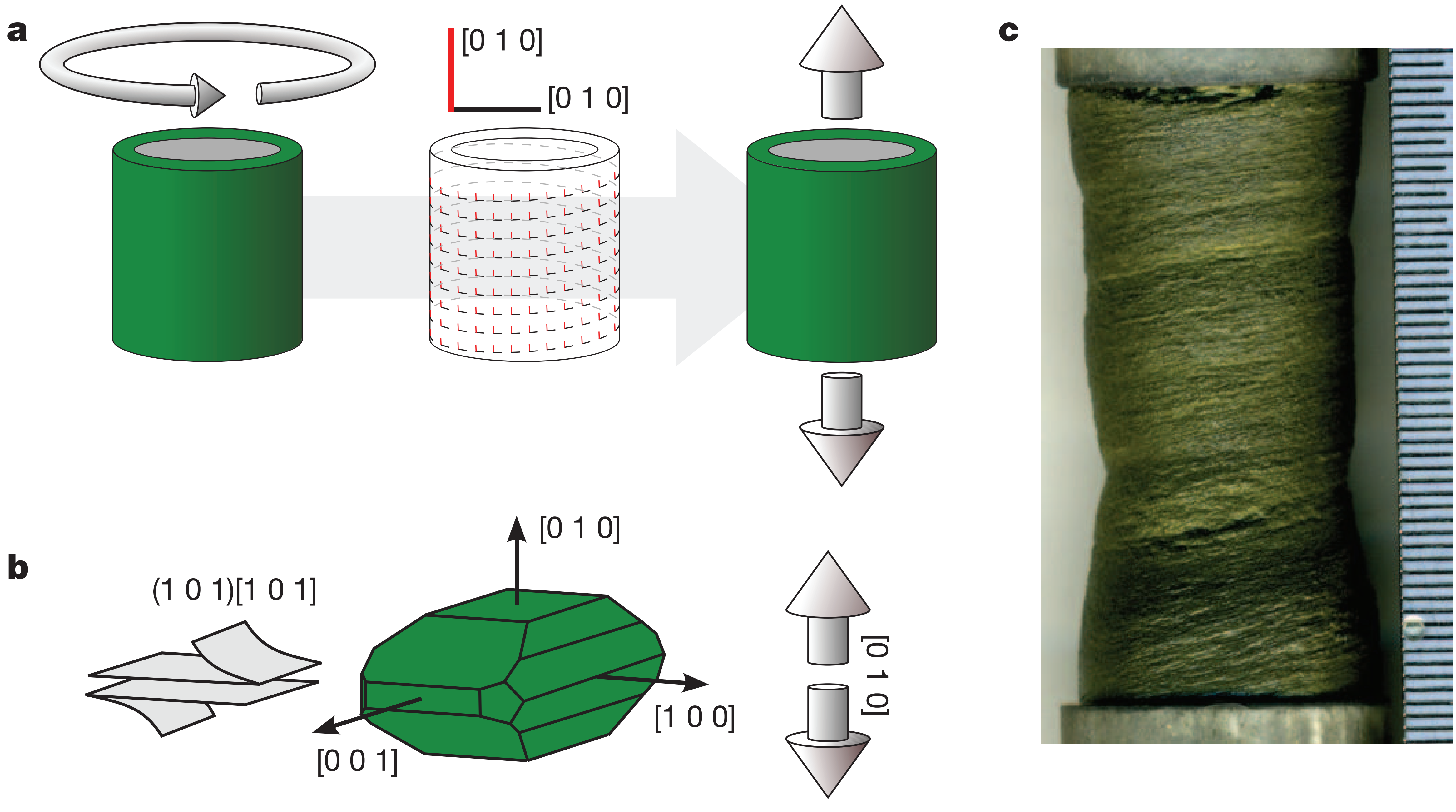


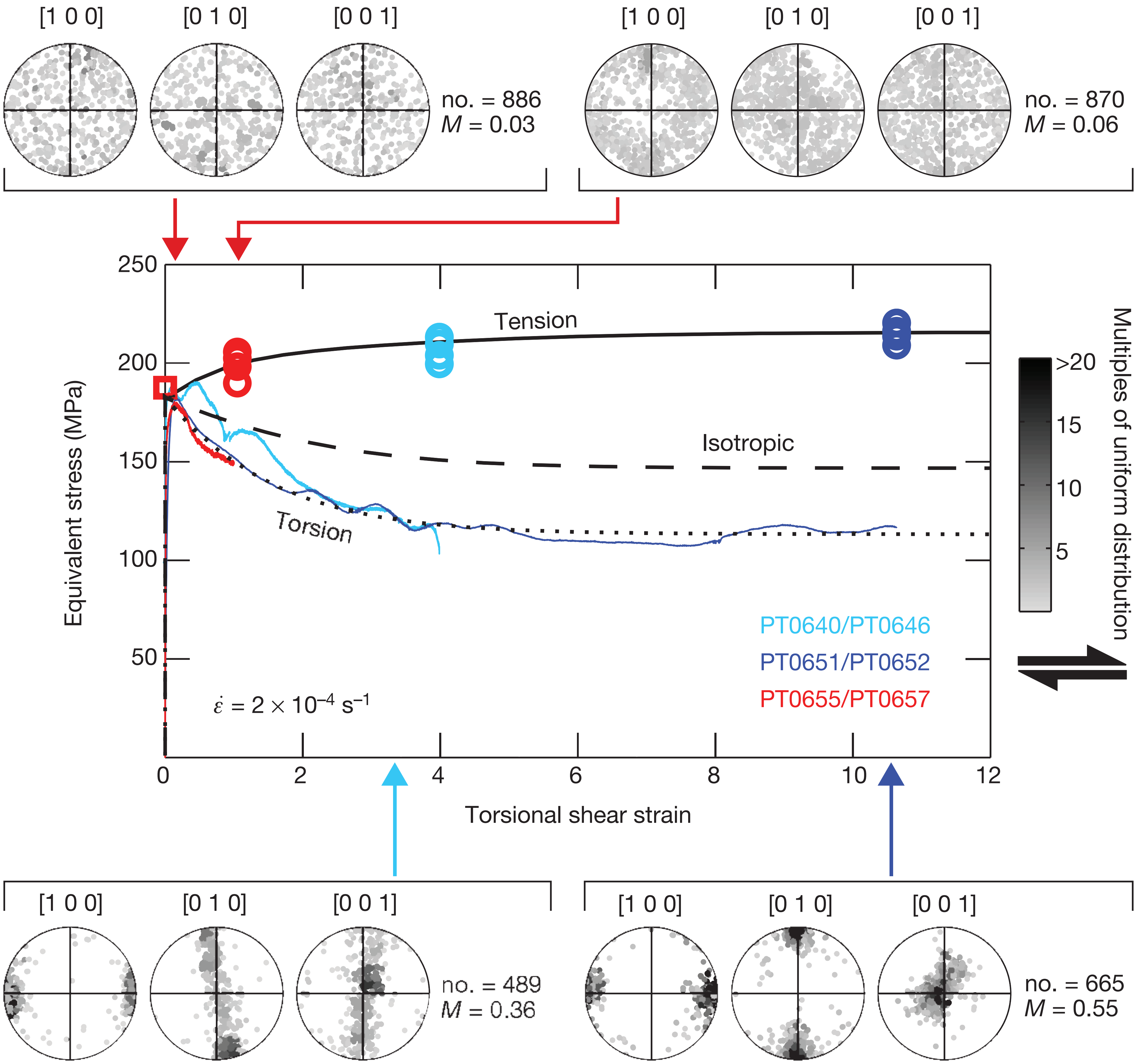
also, shape preferred orientation (SPO)

Laboratory measurements of the viscous anisotropy of olivine aggregates

L. N. Hansen[1]†, M. E. Zimmerman[1] & D. L. Kohlstedt[1]

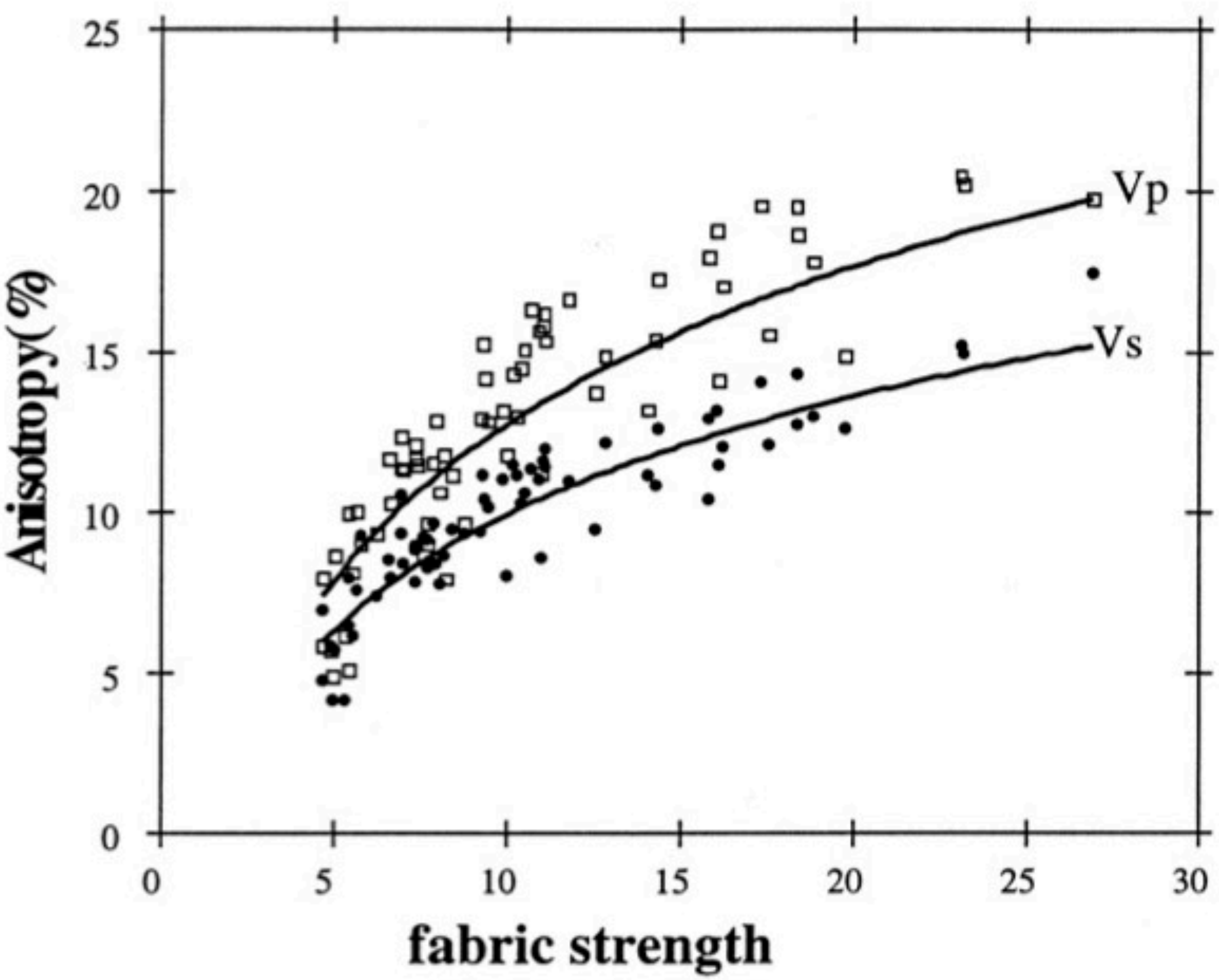
20/27 DECEMBER 2012 | VOL 492 | NATURE | 415

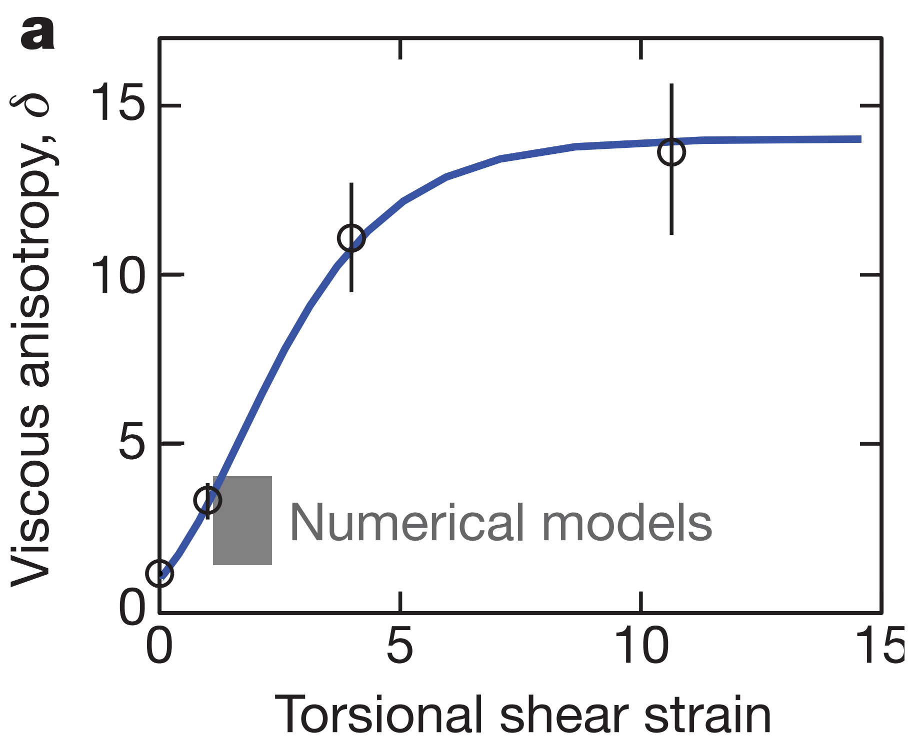



[1 0 0]
[0 1 0]
[0 0 1]
no. = 886
M = 0.03
[1 0 0]
[0 1 0]
[0 0 1]
no. = 870
M = 0.06
250
200
150
100
50
Equivalent stress (MPa)
Tension
Isotropic
Torsion
$\dot{\varepsilon} = 2 \times 10^{-4}\ \mathrm{s}^{-1}$
PT0640/PT0646
PT0651/PT0652
PT0655/PT0657
0
2
4
6
8
10
12
Torsional shear strain
>20
15
10
5
Multiples of uniform distribution
[1 0 0]
[0 1 0]
[0 0 1]
no. = 489
M = 0.36
[1 0 0]
[0 1 0]
[0 0 1]
no. = 665
M = 0.55

An olivine fabric database:
an overview of upper mantle fabrics and seismic anisotropy

Walid Ben Ismaïl, David Mainprice [*] Tectonophysics 296 (1998) 145–157



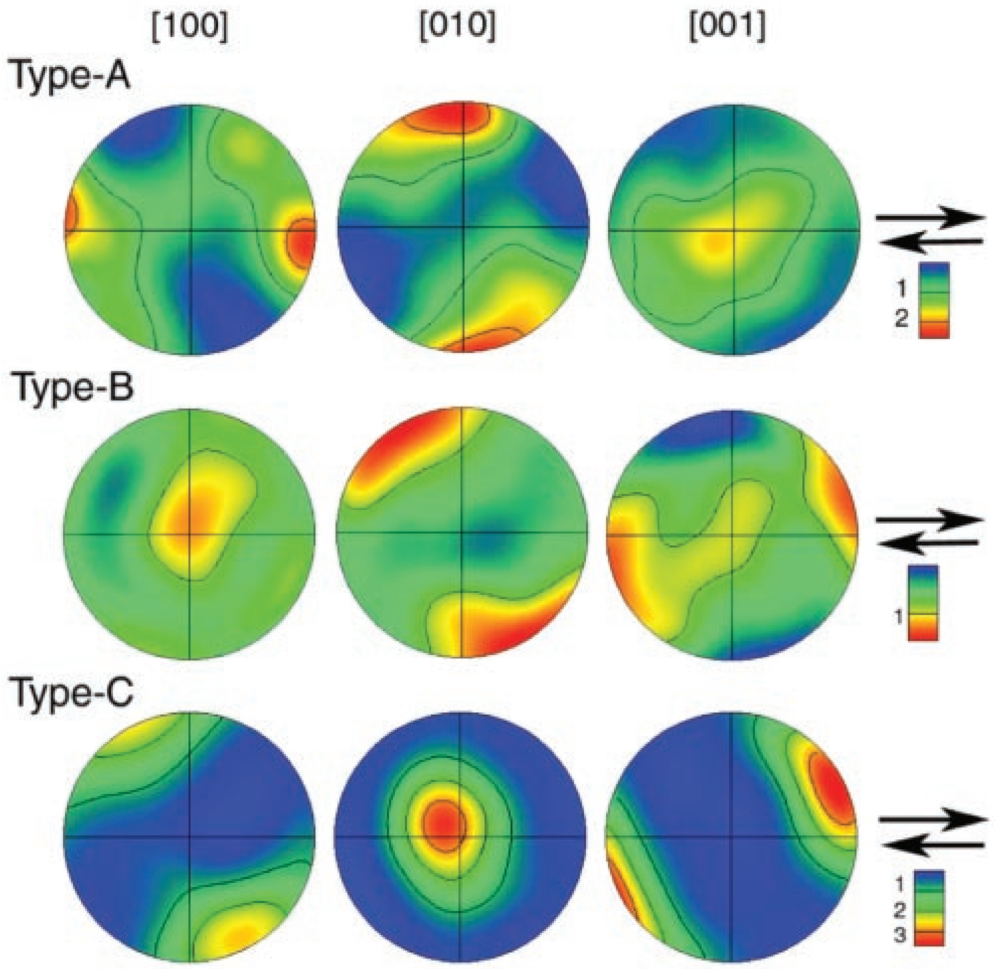


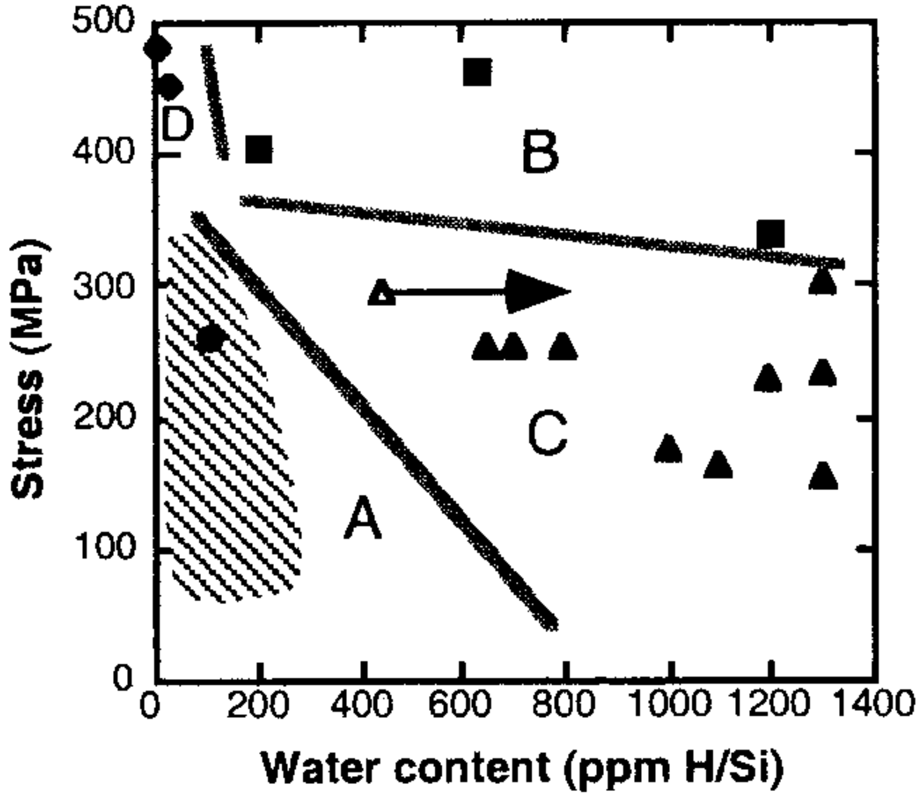
Other effects on LPO:

1) grain size and shape: new experiments show that grain shape can cause an LPO during diffusion creep-- crystals will align with long axes in shear direction. (Miyazake et al., Nature 2013)

2) dissolved water and elevated stress may affect slip systems (Jung and Karato, 2001 etc.); elevated stress and pressure may affect slip systems (Couvy et al., Nature 2005)

3) Melt affects LPO. Aligned and segregated melt affect LPO (BH et al., Science, 2003)





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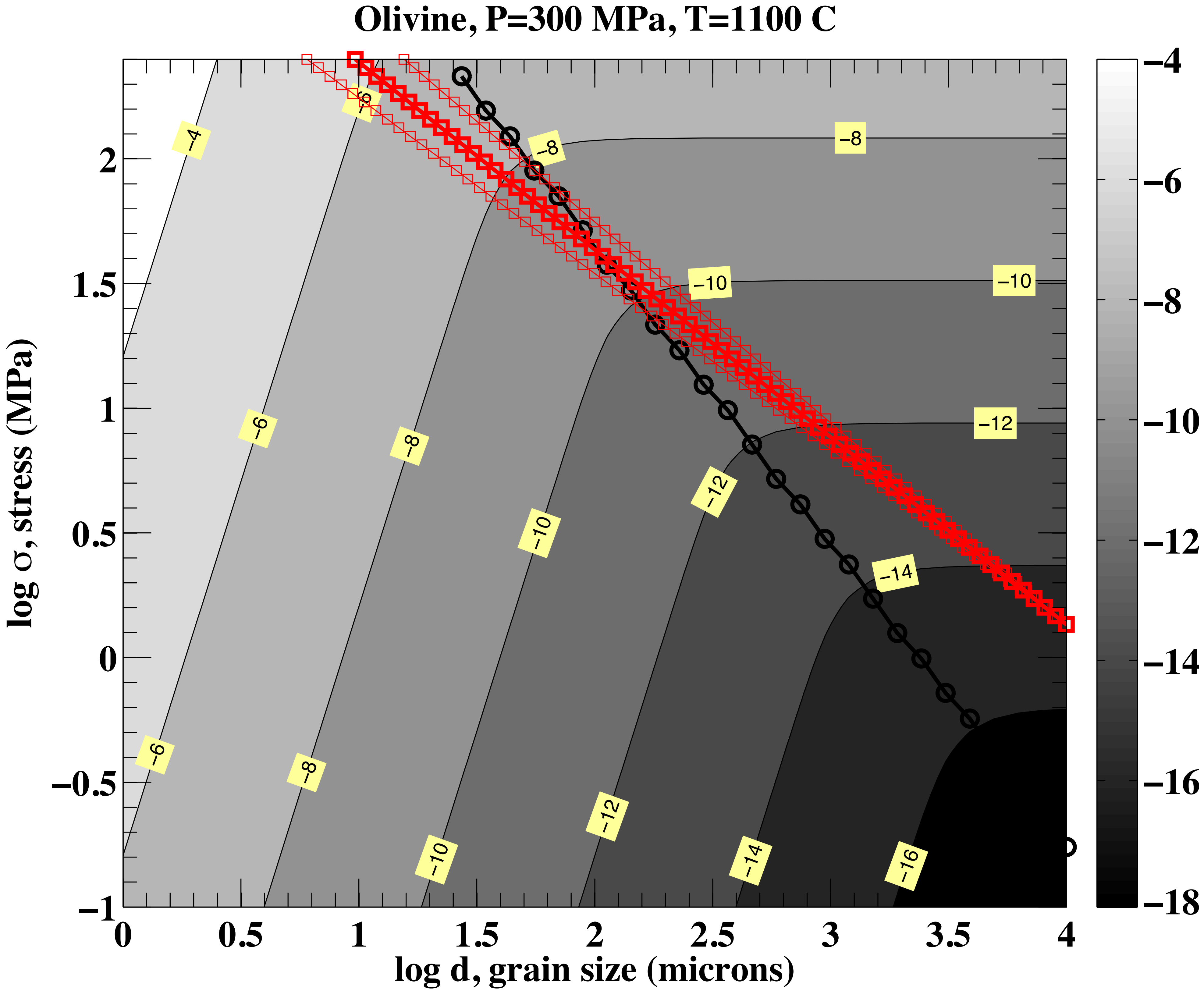
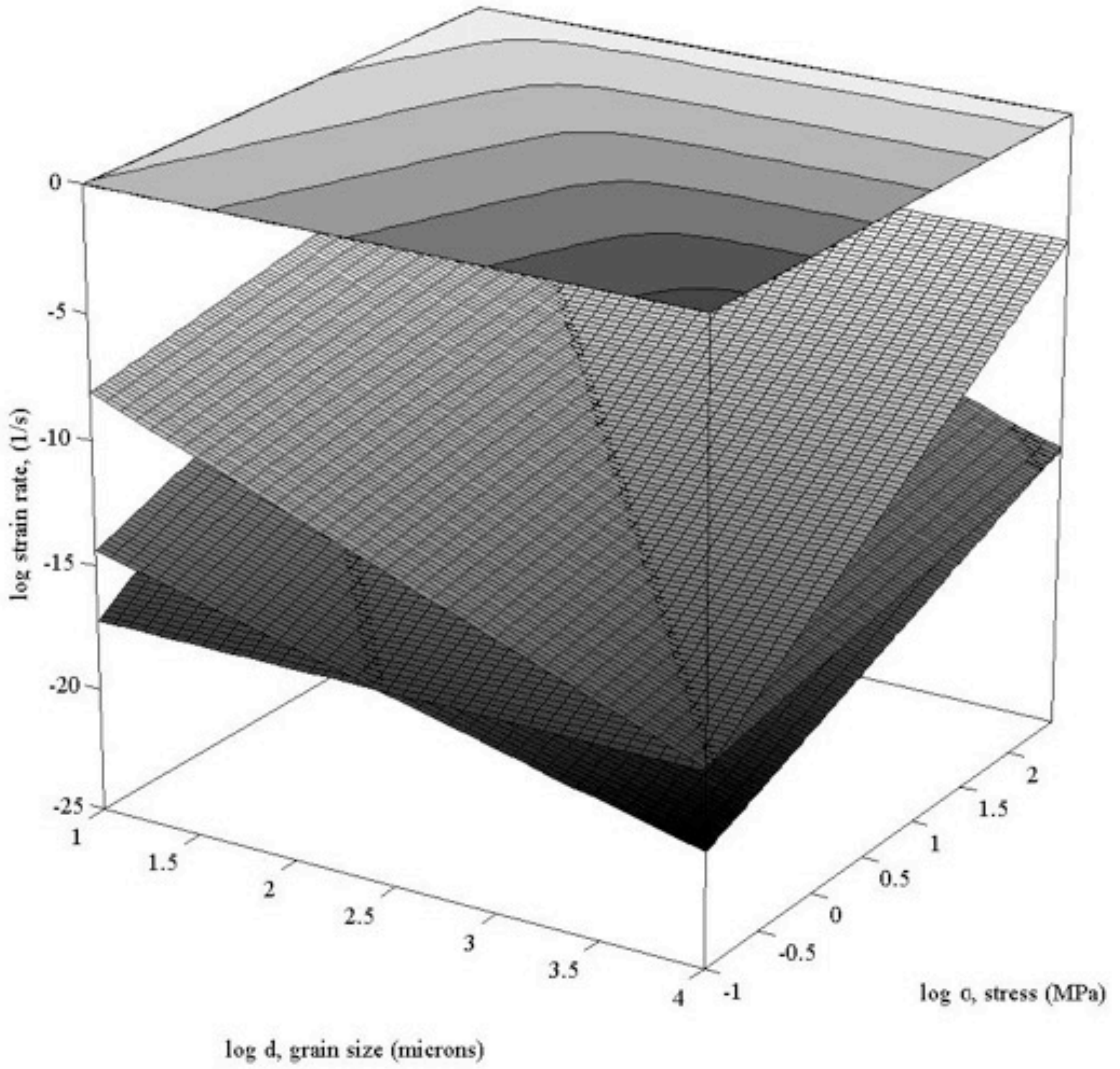
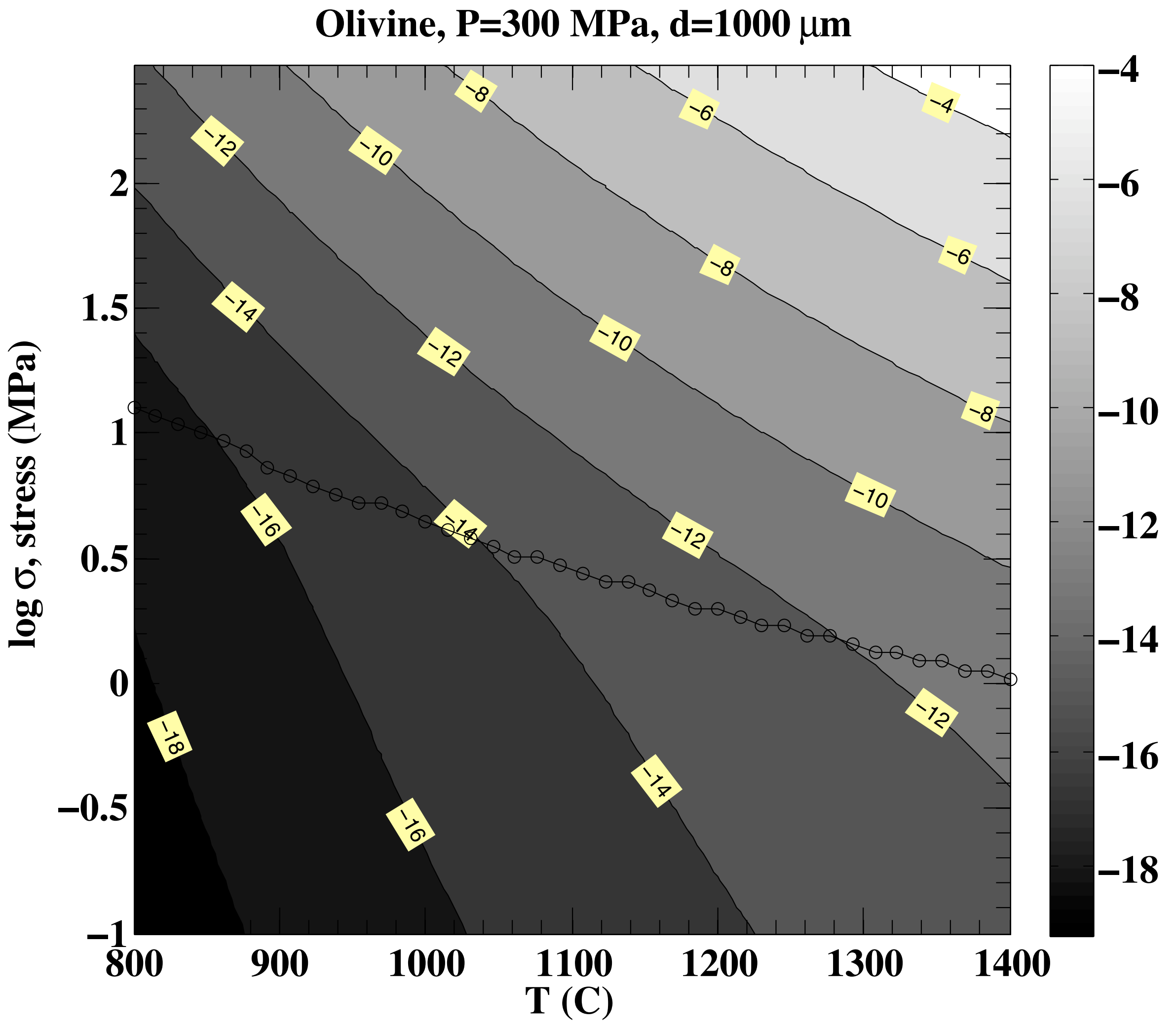
$$\dot{\varepsilon}_i(\sigma, d, T, P) = A_i \sigma^{n_i} d^{-p_i} \exp(-Q_i/RT) \qquad \dot{\varepsilon} = \sum_i \dot{\varepsilon}_i$$

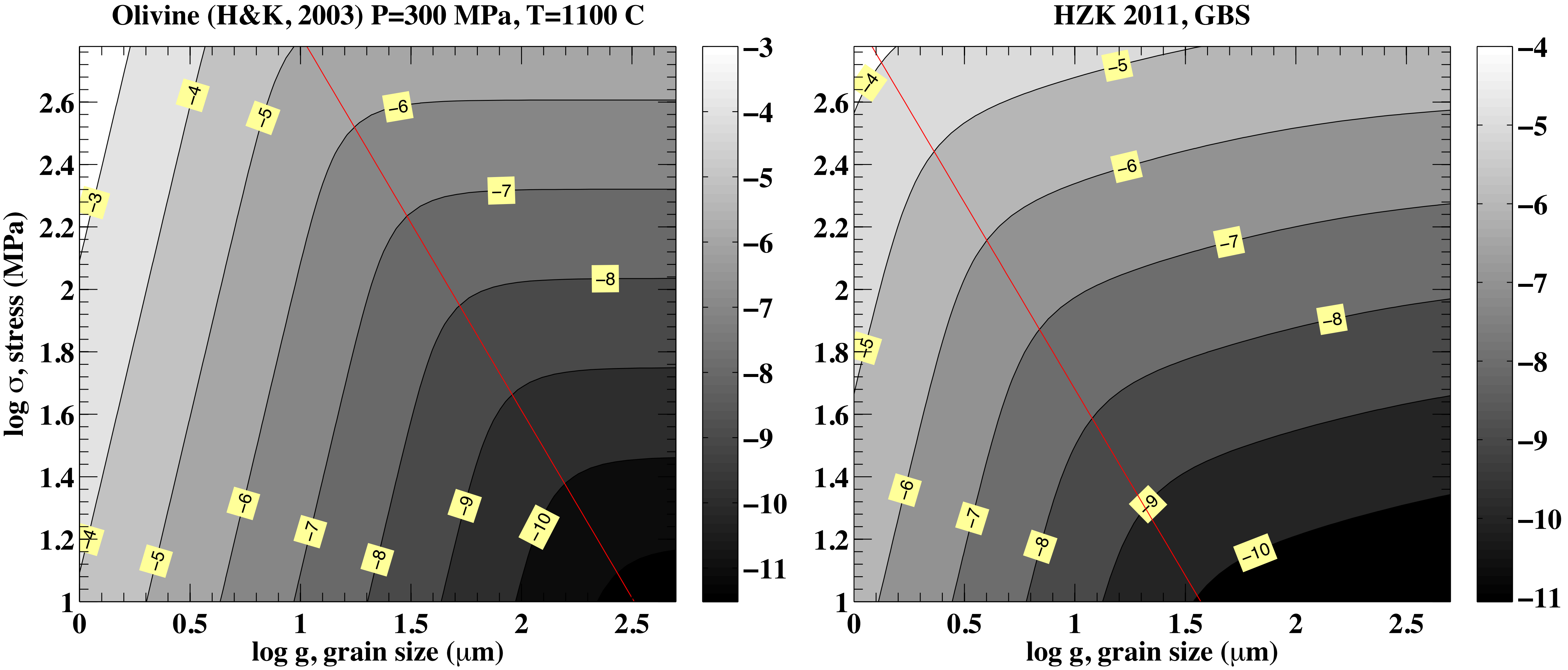





Olivine, P=300 MPa, d=1000 μm

i, Mechanism:	A_i	n_i	m_i	E_i
H & K, 2003				
1: diffusion	1.5e9	1	3	375e3
2: dislocation	1.1e5	3.5	0	530e3
3: disl-GBS[1]	6500	3.5	2	400e3
Hansen et al., 2011				
1: diffusion	4e7	1	3	375e3
2: dislocation	1.1e5	3.5	0	530e3
3: disl-GBS	6.3e4	2.9	0.73	400e3

Table 1: Flow law parameters. disl-GBS = dislocation creep-accommodated grain boundary sliding. Units of A_i are $(\mu m^p/MPa^n/s)$. The activation volume term is not used here. [1] values for $T \leq 1250^\circ$ C.


Olivine (H&K, 2003) P=300 MPa, T=1100 C
HZK 2011, GBS
log σ, stress (MPa)
log g, grain size (μm)
log g, grain size (μm)
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
0
0.5
1
1.5
2
2.5
−3
−4
−5
−6
−7
−8
−9
−10
−11
−4
−5
−6
−7
−8
−9
−10
−11

Summary 2

1. Lattice preferred orientation (and shape preferred orientation) are a consequence of recovery mechanisms during dislocation creep, but diffusion creep and grain rotation can also contribute.

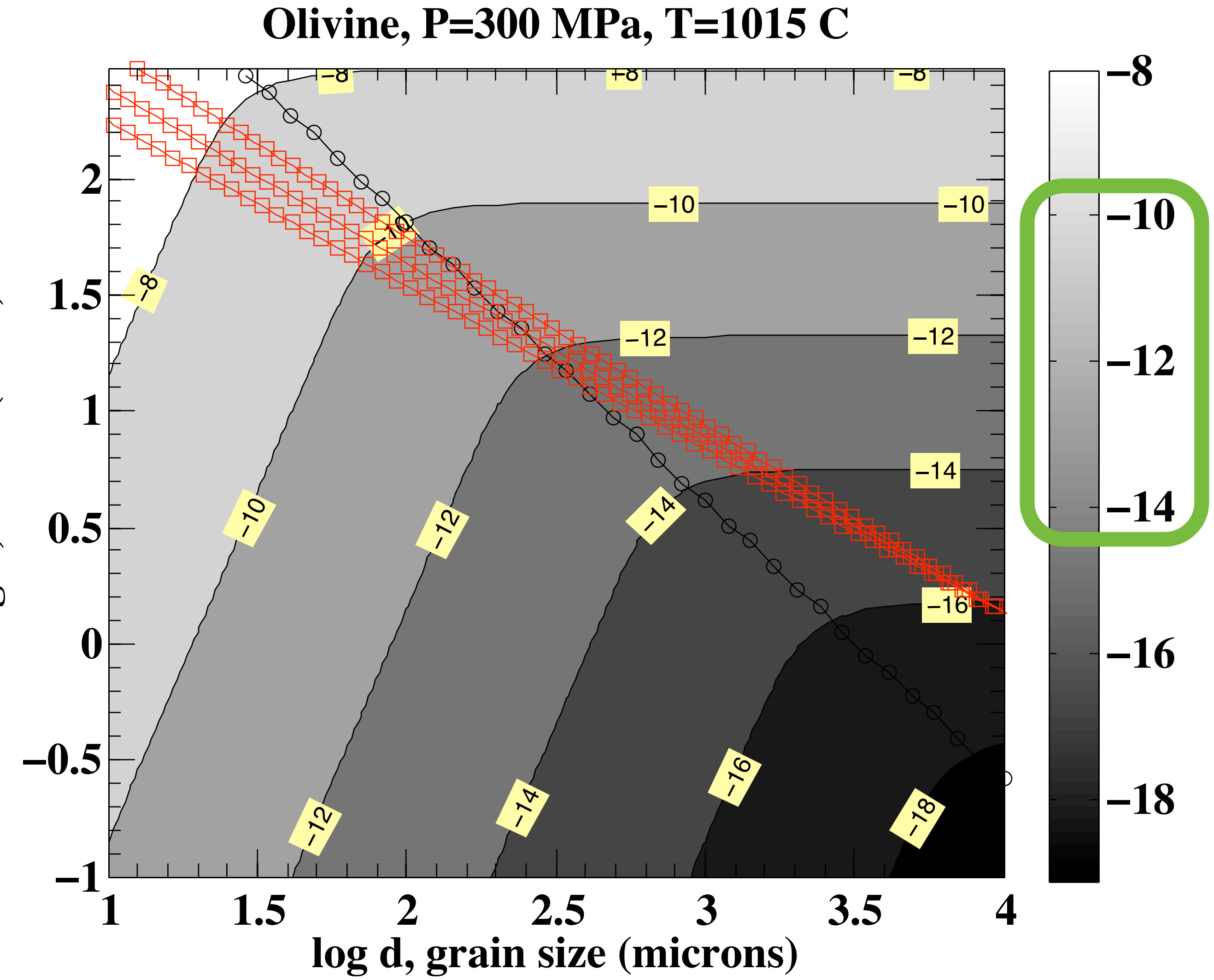
2. Localization by grain size reduction occurs through a feedback-- grain size reduces into grain size-sensitive creep field, strain concentrates in that zone because it is weaker, and so grain size remains small… How does grain size reduce further? Still an open question…

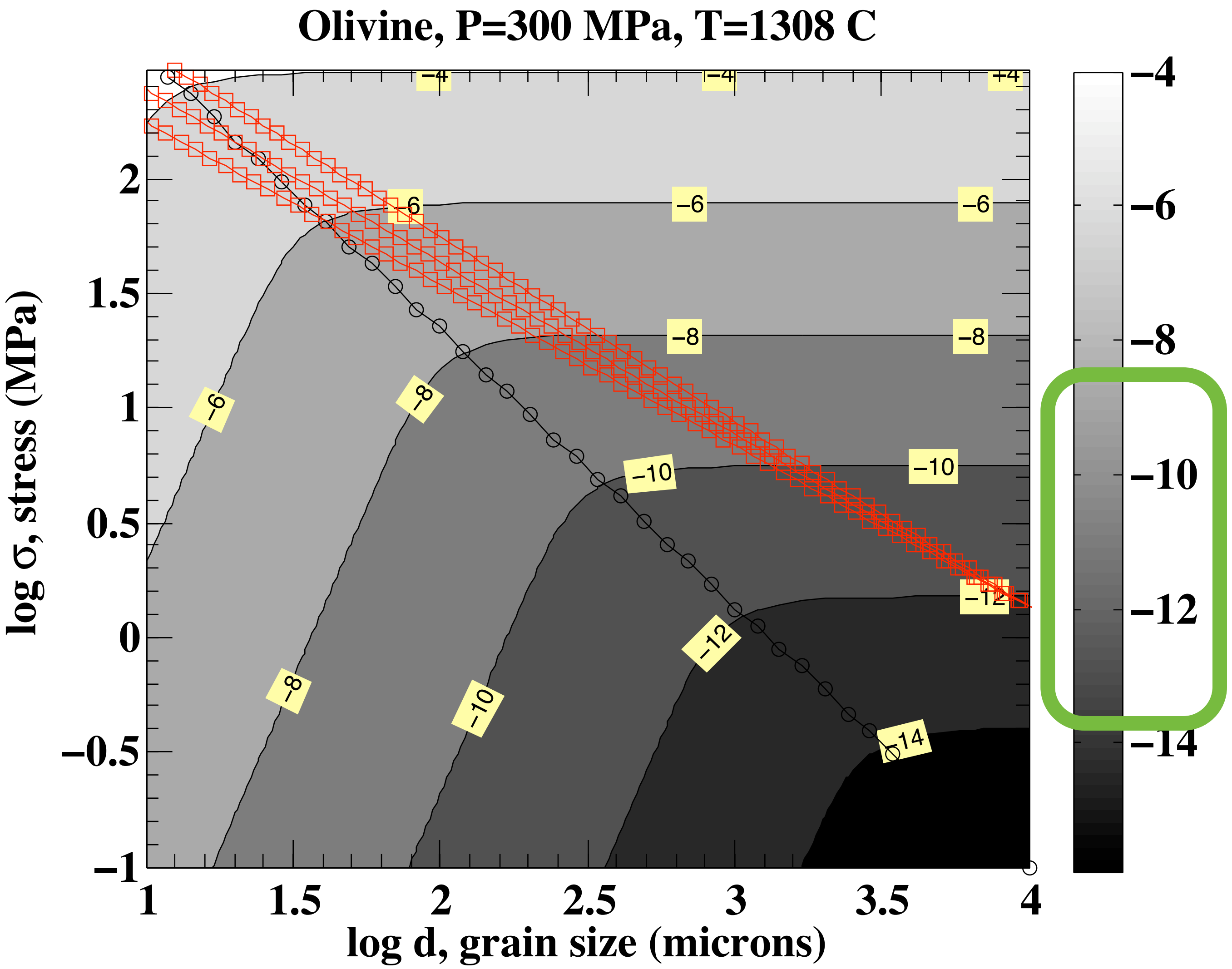
3. Empirical flow laws can be represented as deformation mechanism maps, that synthesize all of the above…

EXTRA

low T (~1000 C): piezometer is near the field boundary (at geologic strain rates)

high T (~1000 C): piezometer is far into dislocation creep field (at geologic strain rates)

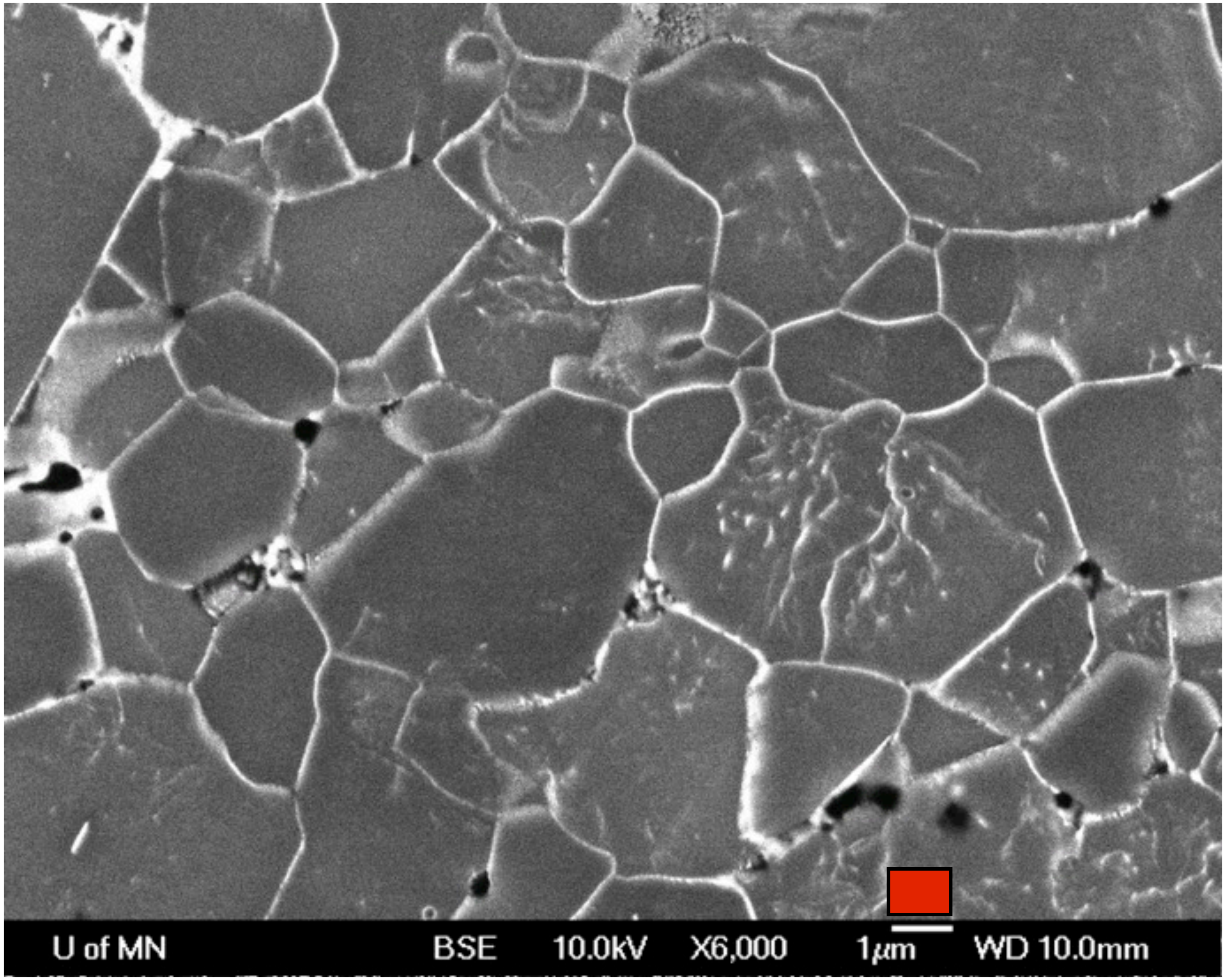




this is still not understood !

**olivine,
8 micron
average
grain size**

🟥
~ 1 um



the transient time is related to the lengthscale of the microstructural property, ie dislocation density < subgrain size < grain size.

an example of transients:

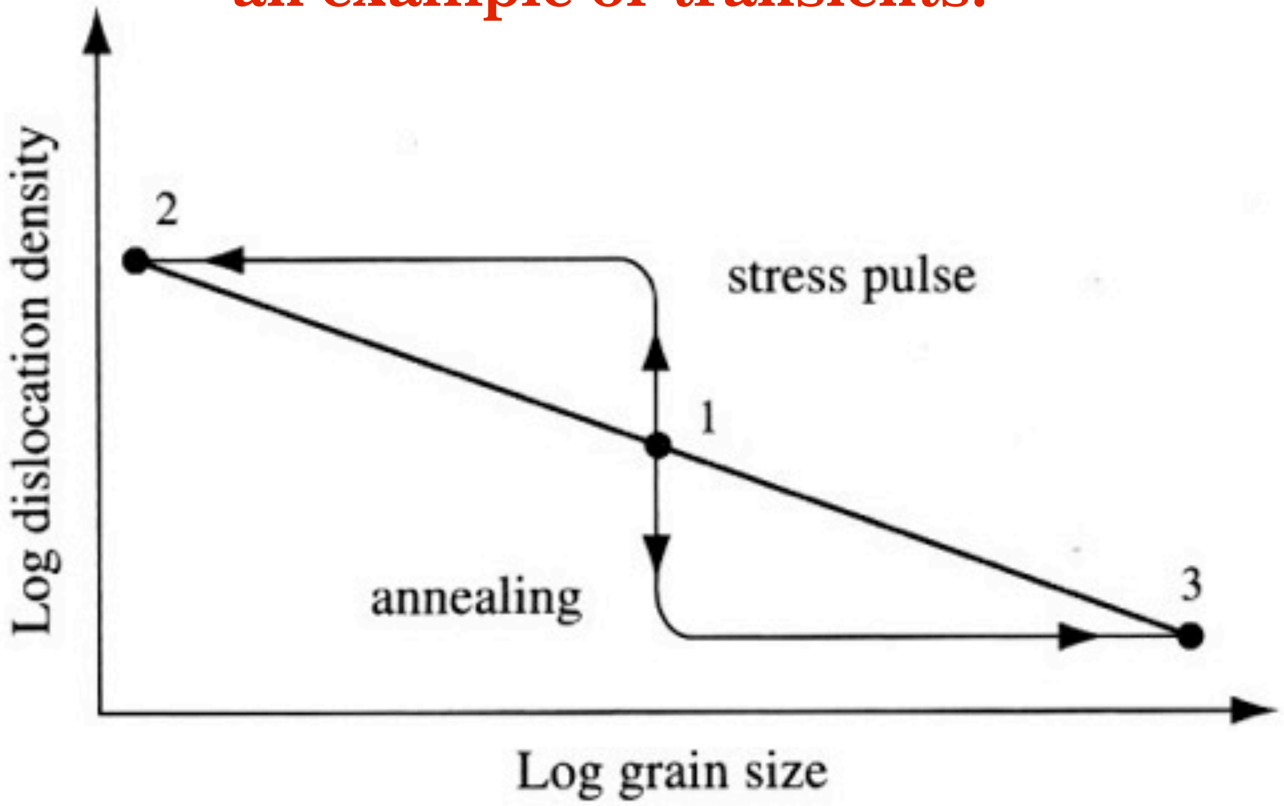


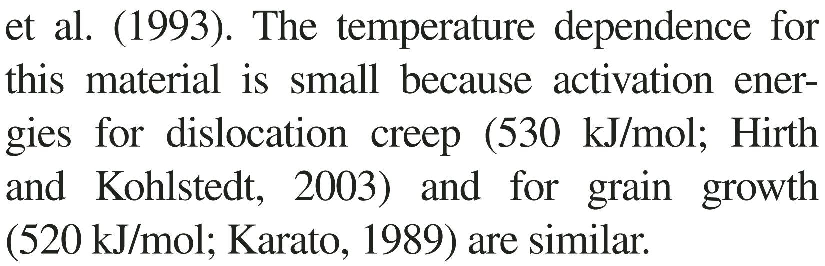
FIGURE 13.16 A dislocation density versus dynamically recrystallized grain size plot. If both dislocation density and recrystallized grain size correspond to a steady state, then the data should fall on a single line. Deviations from this line indicate non-steady-state deformation such as a stress pulse and/or static annealing.

for dislocation density:
olivine: 1% strain
quartz: 3% strain

for grain size,
closer to 100% strain

Karato, p 249 (idea from Goetze, 1975; Weathers et al., 1979)

Why the independence from temperature, water content, melt fraction ?



et al. (1993). The temperature dependence for this material is small because activation energies for dislocation creep (530 kJ/mol; Hirth and Kohlstedt, 2003) and for grain growth (520 kJ/mol; Karato, 1989) are similar.

Austin & Evans, 2007

$$\delta_g = C\varepsilon_c\left(\frac{v_{gbm}}{\dot{\varepsilon}}\right)$$

Derby & Ashby, 1987

C is a slightly temperature sensitive constant

ε_c is the critical strain for nucleation

v_{gbm} is the velocity for grain boundary migration

$\dot{\varepsilon}$ is the strain rate

if those parameters affect the factors in the ratio approximately equally, the ratio will not change !

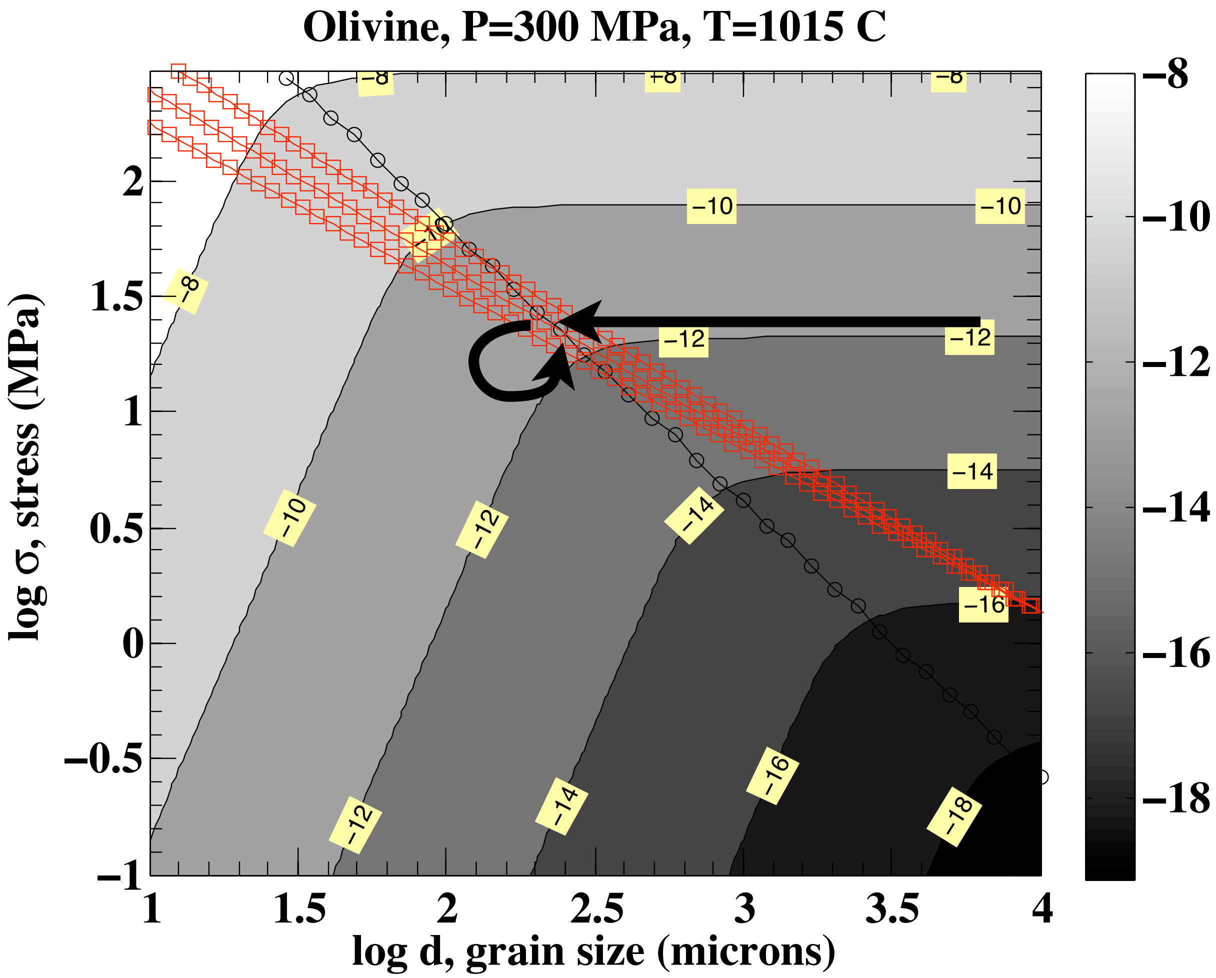
Field boundary hypothesis (de Bresser et al., 2001)

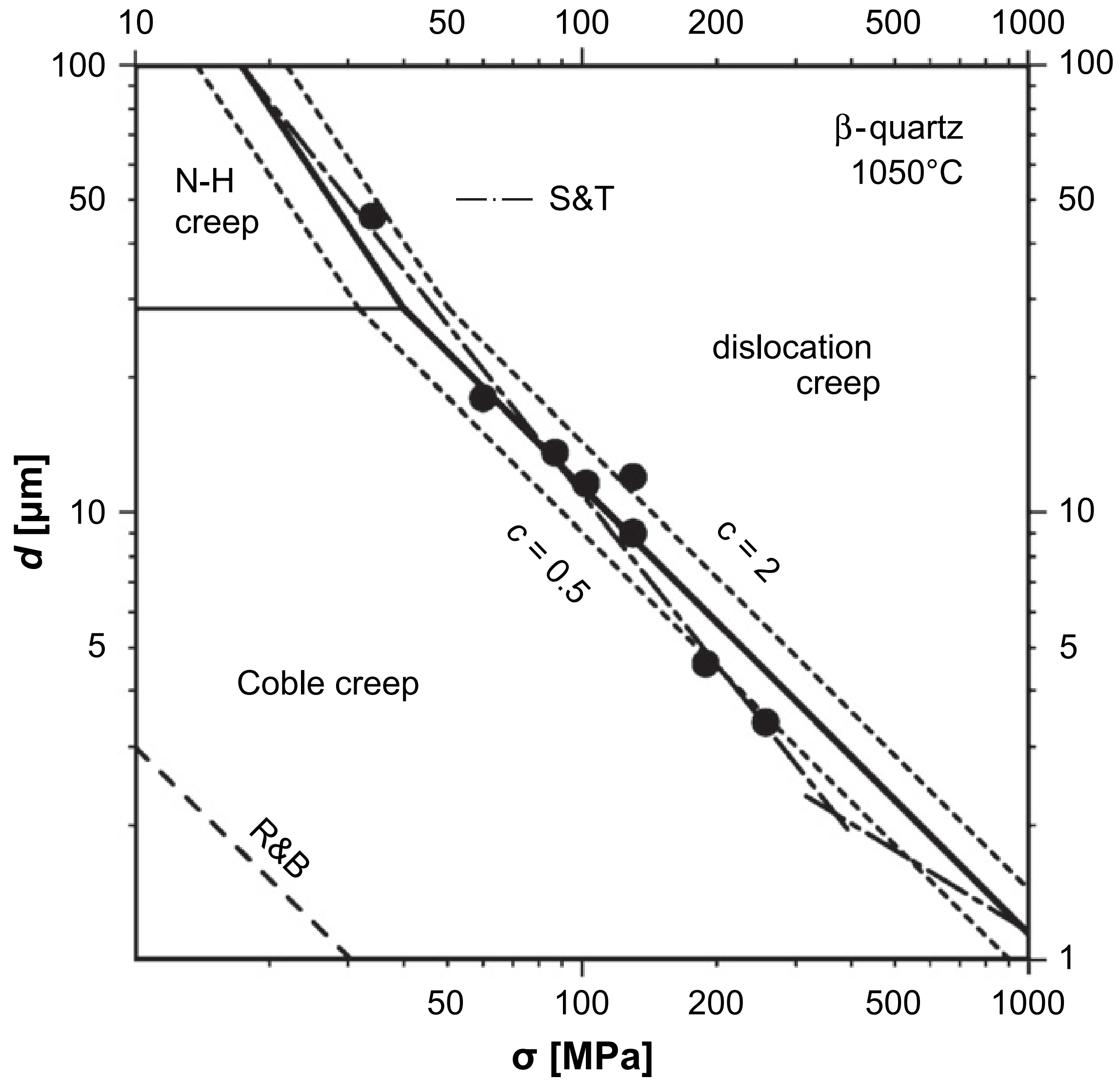
J.H.P. De Bresser · J.H. Ter Heege · C.J. Spiers

Grain size reduction by dynamic recrystallization: can it result in major rheological weakening?

Int J Earth Sciences (Geol Rundsch) (2001) 90 : 28–45

quartz:


Olivine, P=300 MPa, T=1015 C



gs reduction -> diff creep field ->
grain growth -> disl. field -> gs reduction

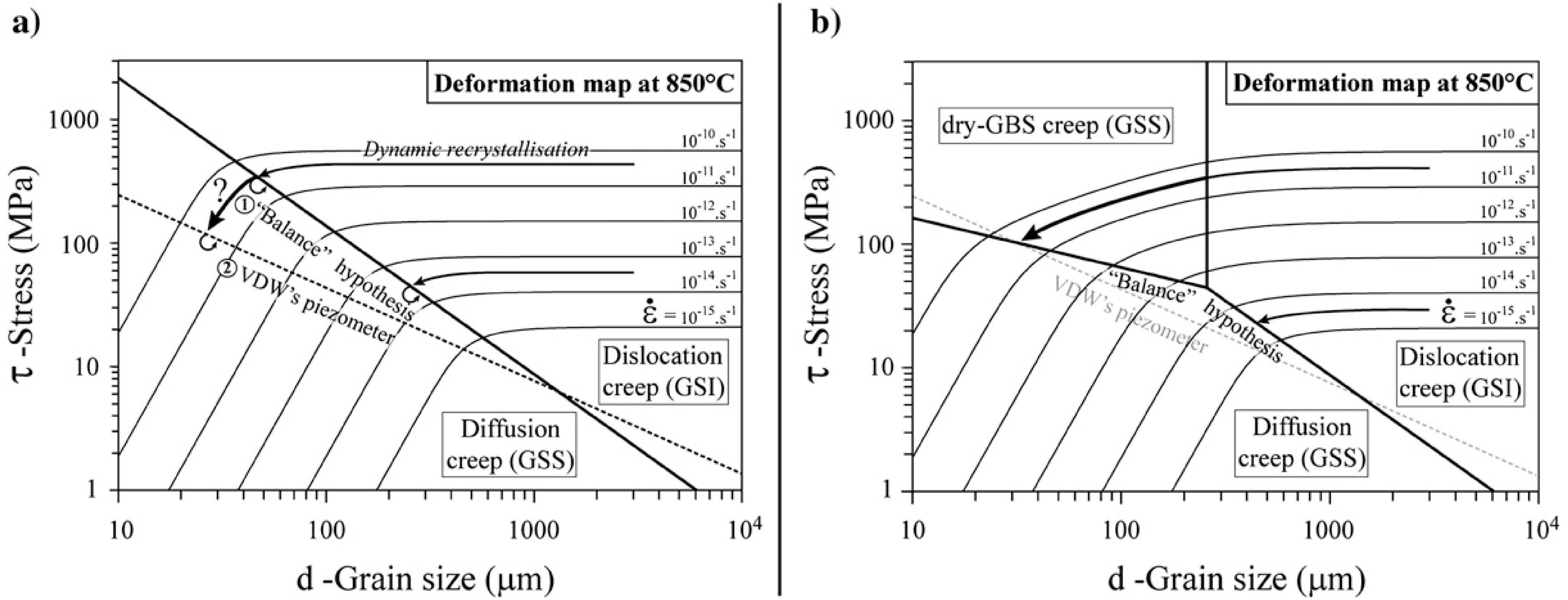
Theories and applicability of grain size piezometers: The role of dynamic recrystallization mechanisms

I. Shimizu*

Journal of Structural Geology 30 (2008) 899–917

olivine:

diff-disl creep only **+ disl. accommodated GBS field:**



VDW *= Van Der Wal (Van der Wal et al., 1993)* ***; GBS*** *= Grain Boundary Sliding* ***; GSS*** *= Grain Size Sensitive ;* ***GSI*** *= Grain Size Insensitive*

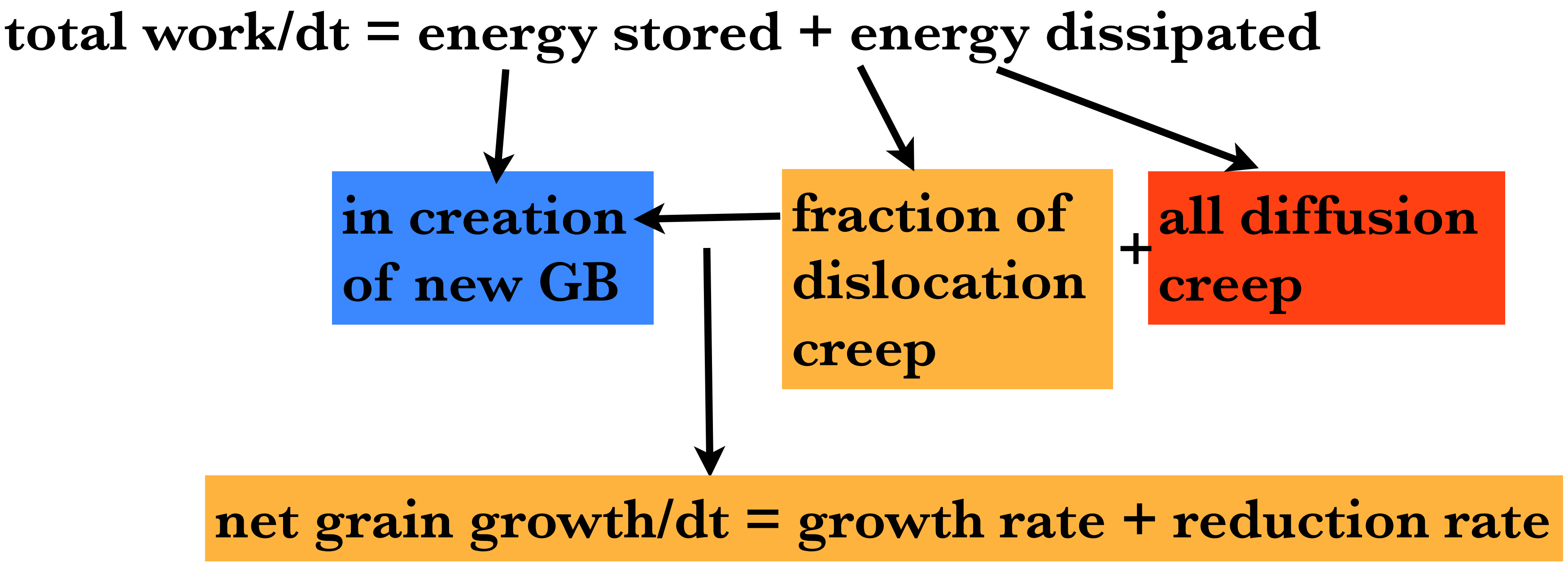
Strain localisation in the subcontinental mantle — a ductile alternative to the brittle mantle

J. Precigout [a,*], F. Gueydan [a], D. Gapais [a], C.J. Garrido [b], A. Essaifi [c]

Tectonophysics 445 (2007) 318 – 336

and/or, an alternative idea: the "Wattmeter"
grain size is proportional to the dissipated energy, not just the stress.

based on ideas from non-equilibrium thermodynamics: the recrystallized grain size represents the budget of energy being stored in grain boundaries and energy dissipated by flow.

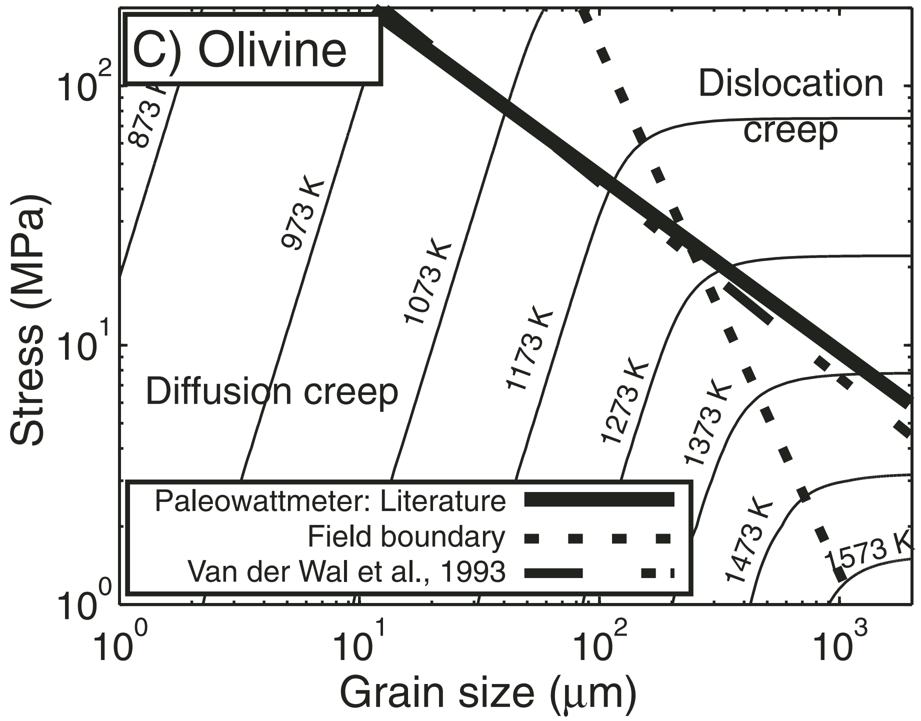


total work/dt = energy stored + energy dissipated

in creation of new GB

fraction of dislocation creep + **all diffusion creep**

net grain growth/dt = growth rate + reduction rate



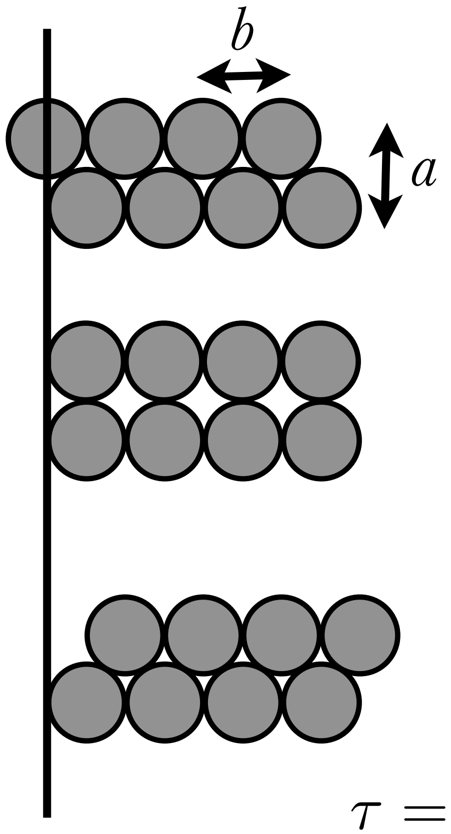
Paleowattmeters: A scaling relation for dynamically recrystallized grain size

Nicholas J. Austin*
Brian Evans*

GEOLOGY, April 2007

Periodic model, theoretical strength (Frenckel derivation...)

1934: Polyani, Orowan, Taylor hypothesized dislocations....



$$E = Fx$$

$$F = \frac{dE}{dx}$$

$$\tau = \frac{F}{A}$$

$$\tau = \tau_{max} \sin 2\pi \frac{x}{b}$$

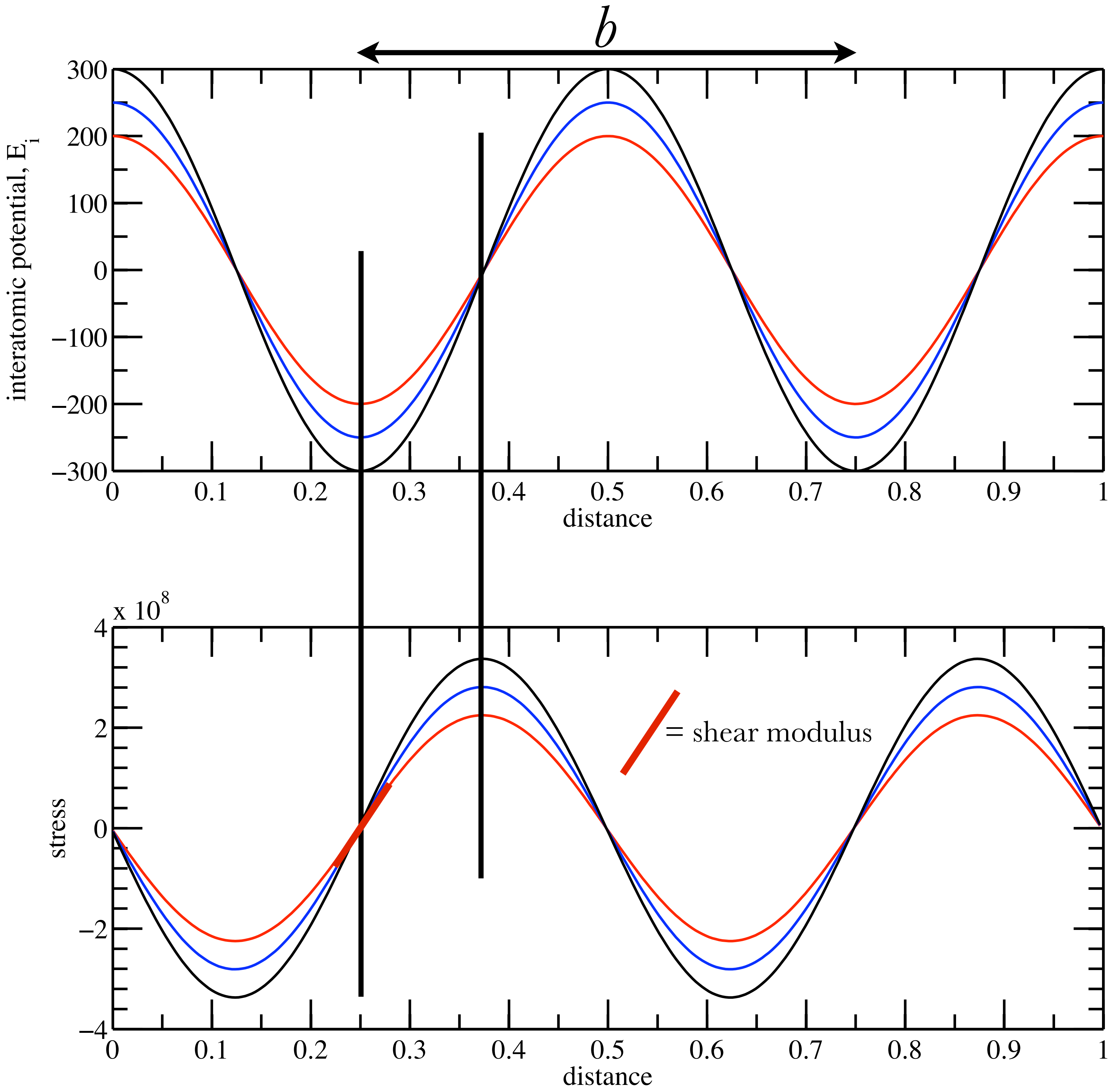
$$\tau \approx \tau_{max} 2\pi \frac{x}{b}$$

$$\tau = \mu\gamma$$

$$\gamma \approx \frac{x}{a}$$

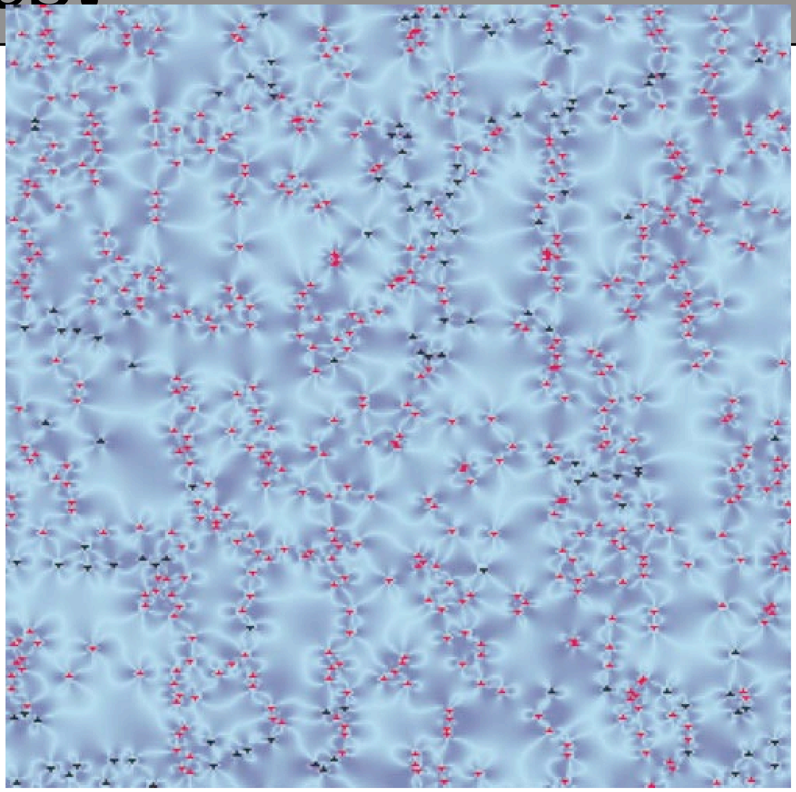
$$\tau_{max} = \frac{\mu}{2\pi}\frac{b}{a}$$

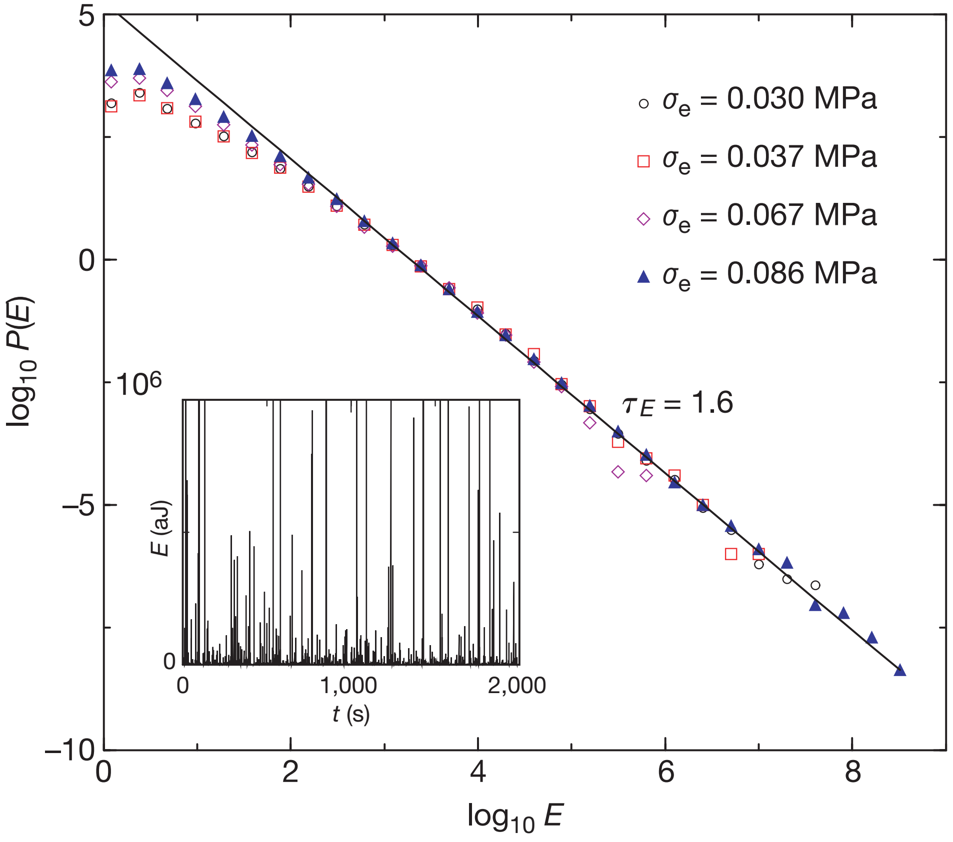
$$\tau_{max} \approx \frac{\mu}{2\pi}$$



~ 10 GPa, way too strong

higher order structures : strain waves?





Intermittent dislocation flow in viscoplastic deformation

M.-Carmen Miguel*†, Alessandro Vespignani*, Stefano Zapperi‡, Jérôme Weiss§ & Jean-Robert Grasso‖

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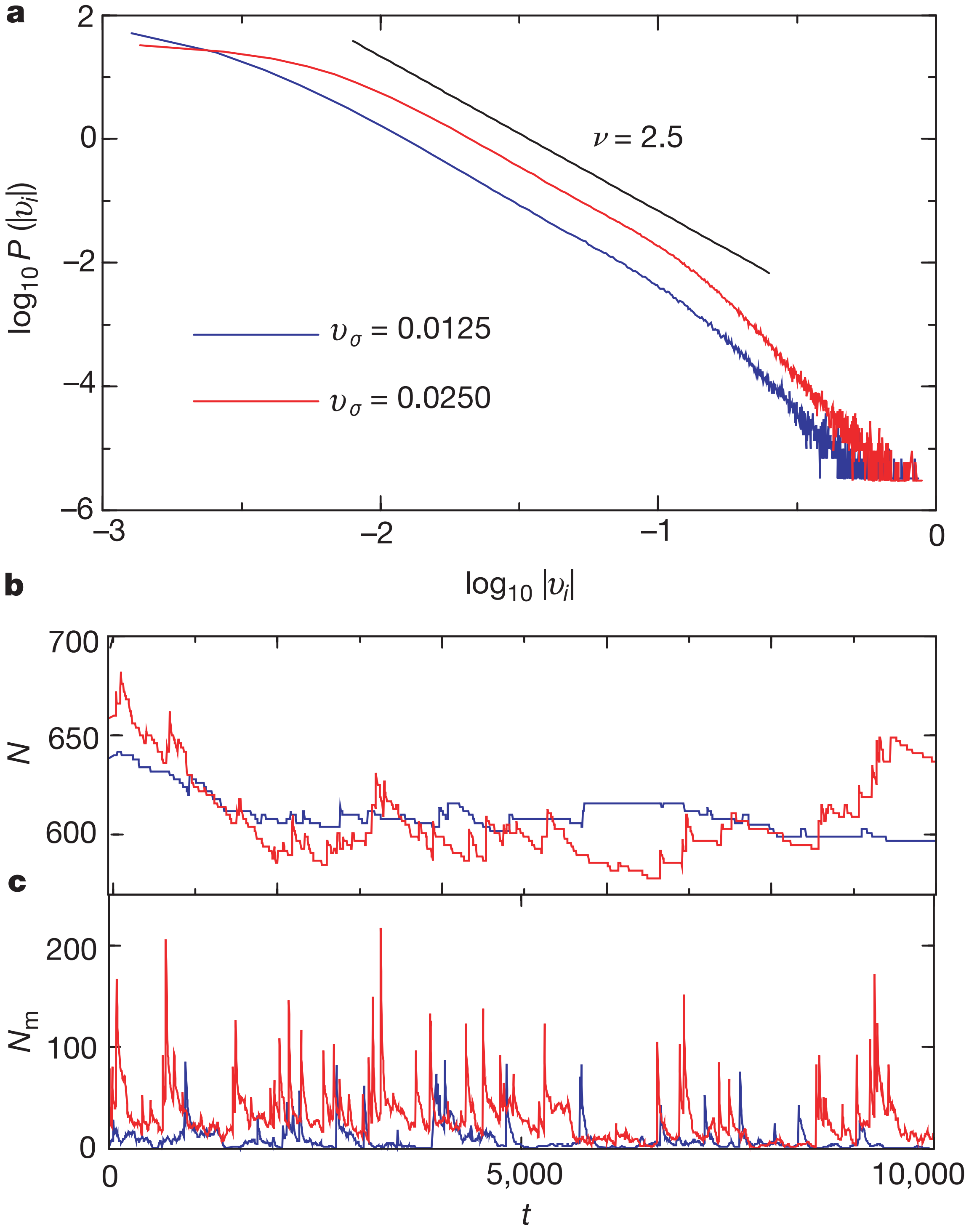
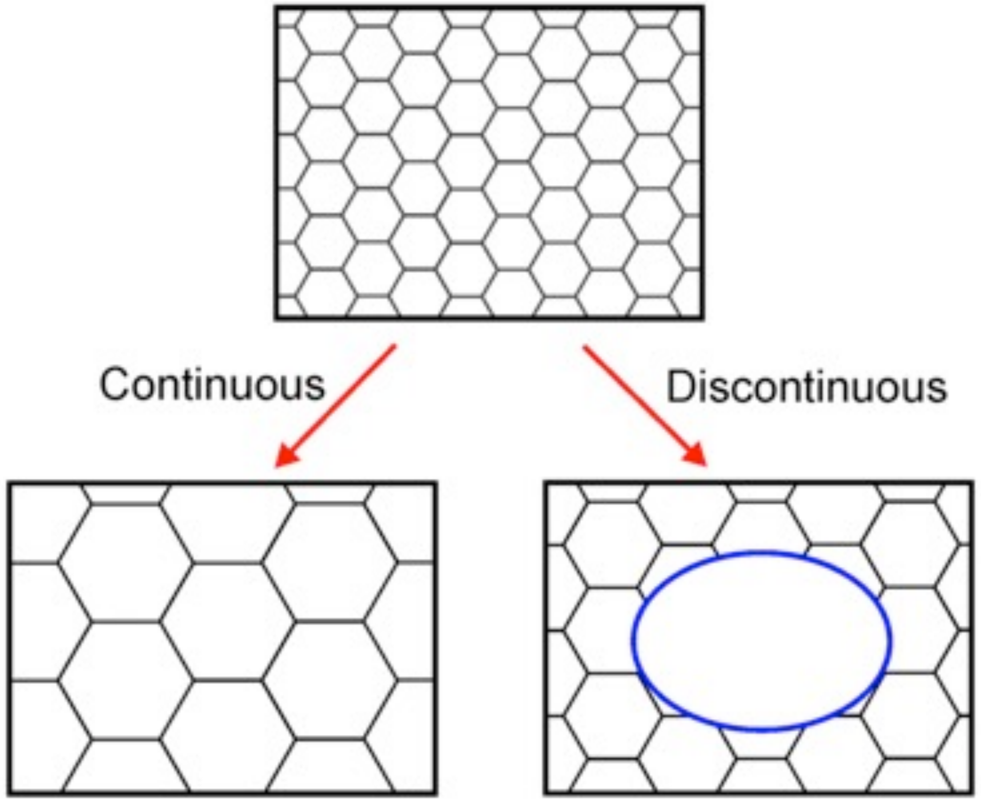


http://www.nature.com/nature/journal/v410/n6829/extref/410667a0_S1.htm small grains get consumed faster.

static grain growth is driven by the reduction of surface energy of grain boundaries (proportional to the curvature, that locally drives diffusion.

$$d^n - d_0^n = kt$$
$$n = 2+$$



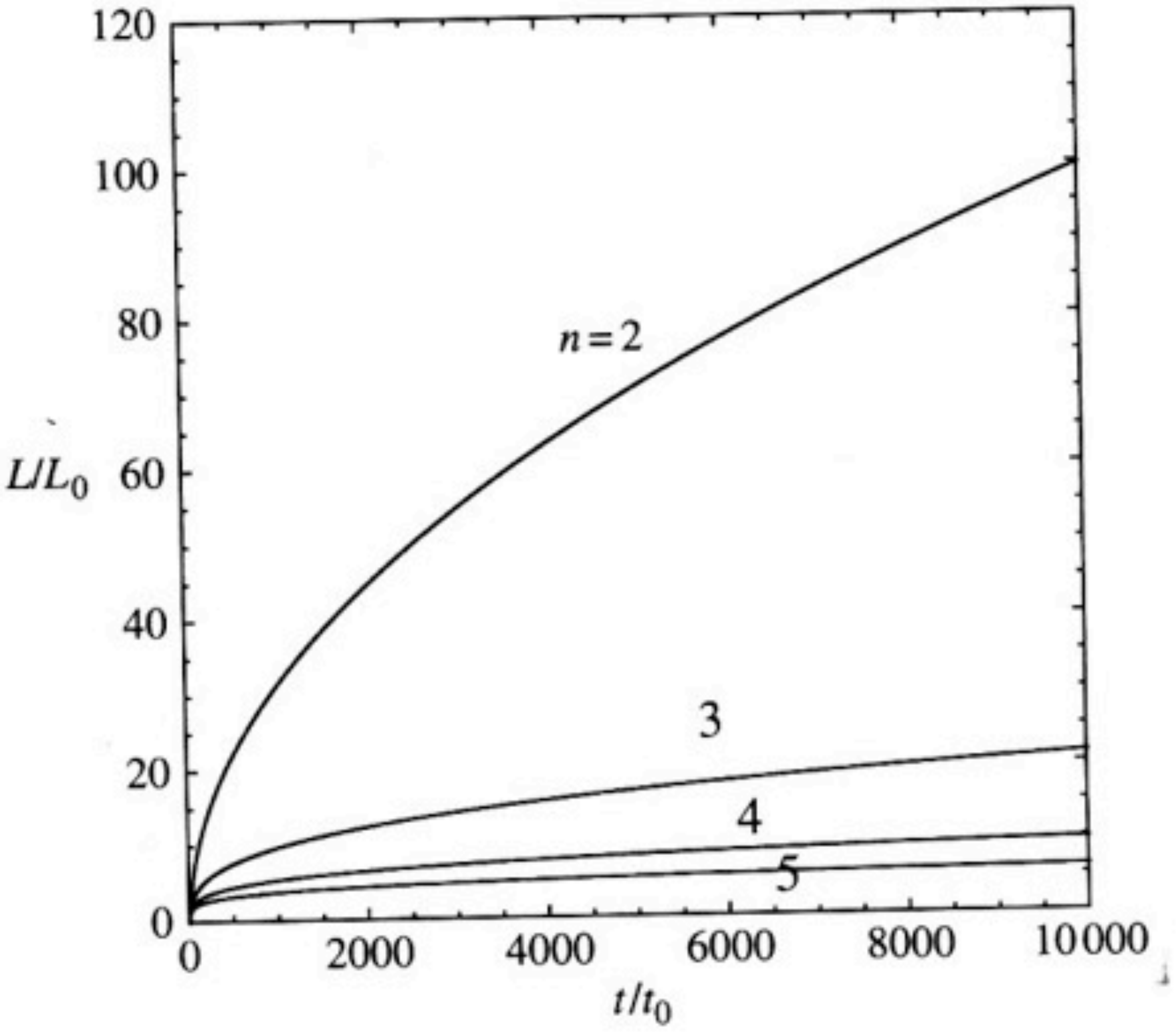


FIGURE 13.7 A plot of the grain size versus the time relation for various n ($t_0 \equiv L_0^n/k_n$).

[illegible] second phases

in reality, muck and second phases slow grain growth...