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: dislocation climb, subgrain formation

4. Recrystallization: Fabric development and grain size evolution
Grain rotation (LPO development)
Reduction: Mechanisms of recrystallization
Growth: forces driving grain growth... ----> Localization
REVISIT THE QUARTZ regimes

5. Grain Growth: static and dynamic ?

Thursday:
6. Piezometers and Wattmeters
Empirical Piezometers (dislocations, subgrain and grain size).
Stress in the lithosphere from xenoliths (Mercier)
Stress across shear zones (Kohlstedt and Weathers)
The WATTMETER

1. Intro: Observations

First, ALL the complexity that we want to understand !

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

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

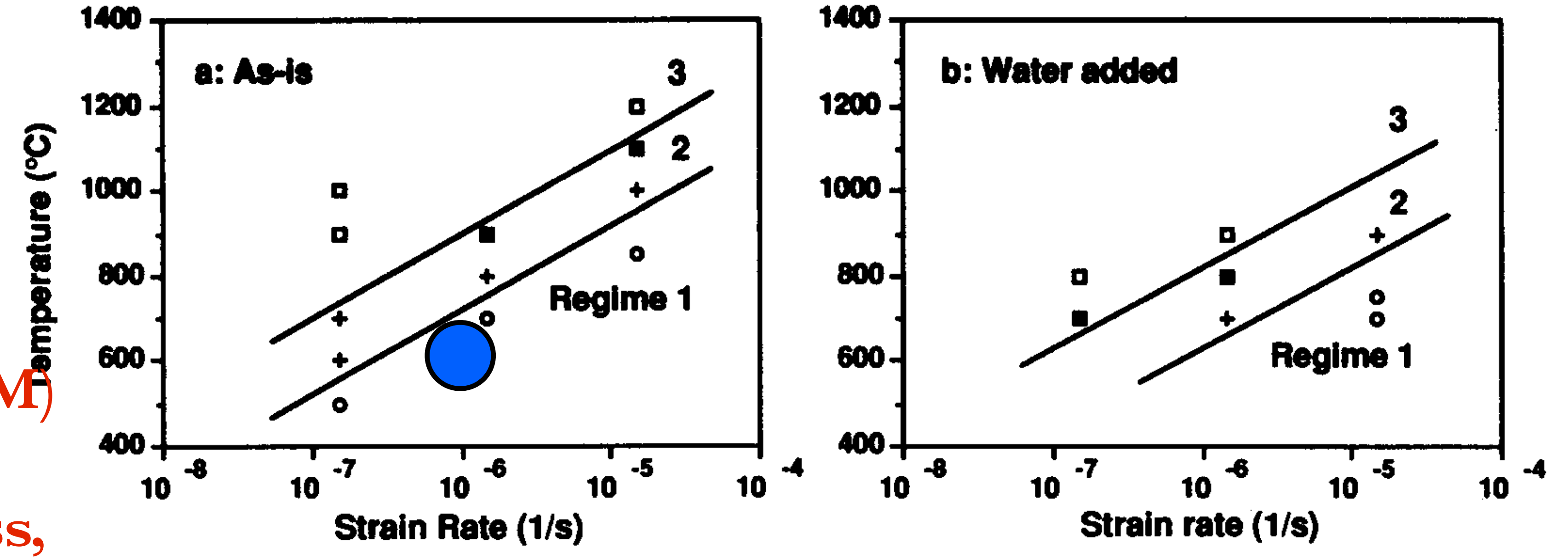
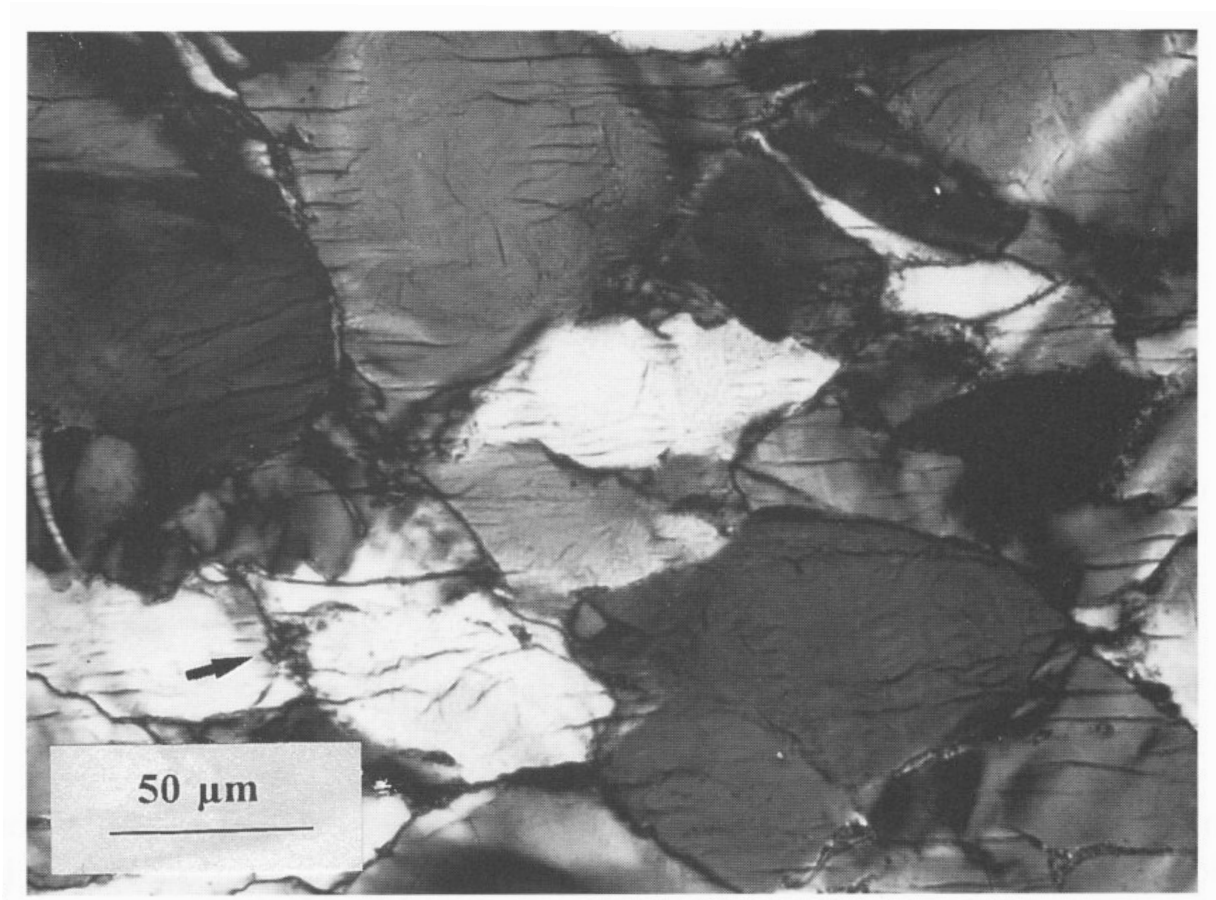


Fig. 2. Plots of temperature vs strain rate showing the location of the dislocation creep regimes for quartz aggrega deformed (a) 'as-is' and (b) with 0.17 wt% water added. The boundaries between the regimes are gradational. Open circ represent regime 1, plus symbols represent regime 2, open squares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

Regime 1



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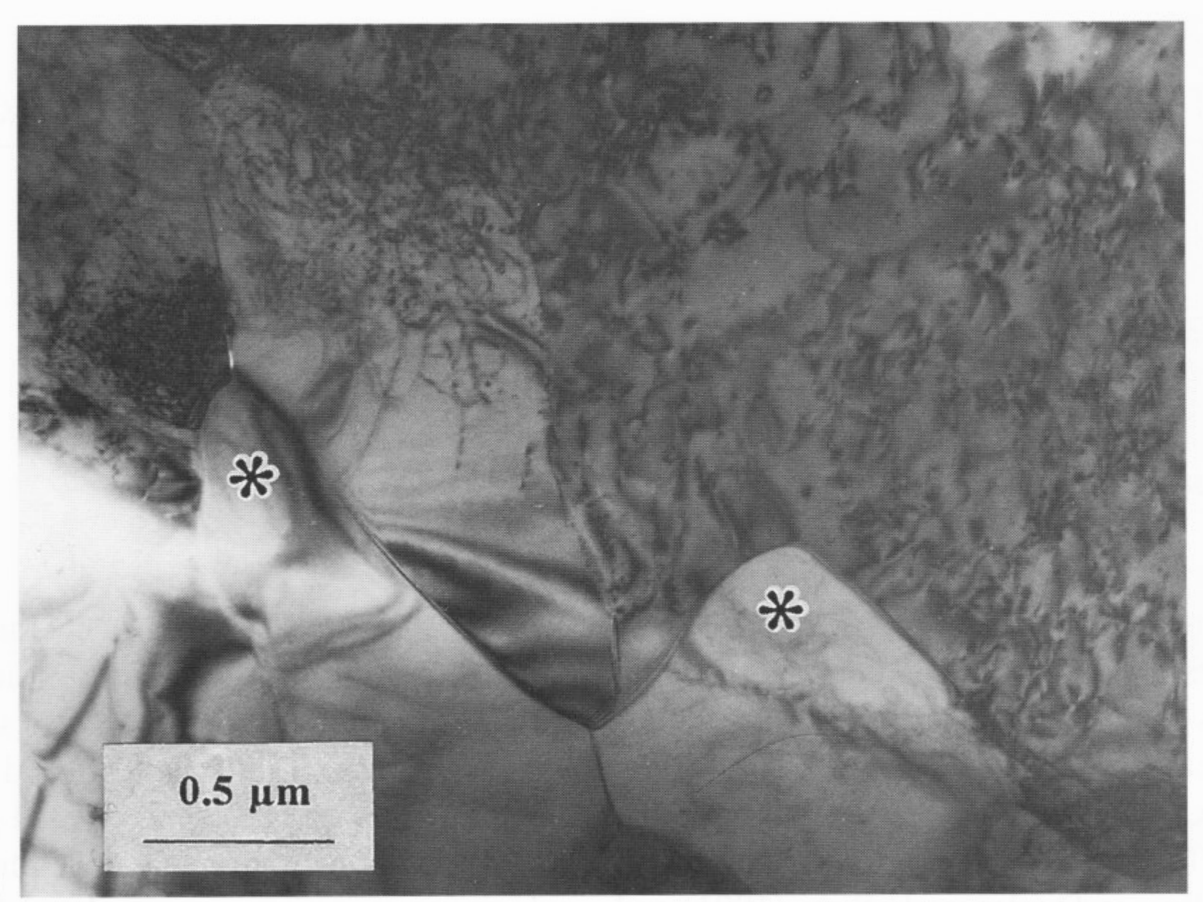
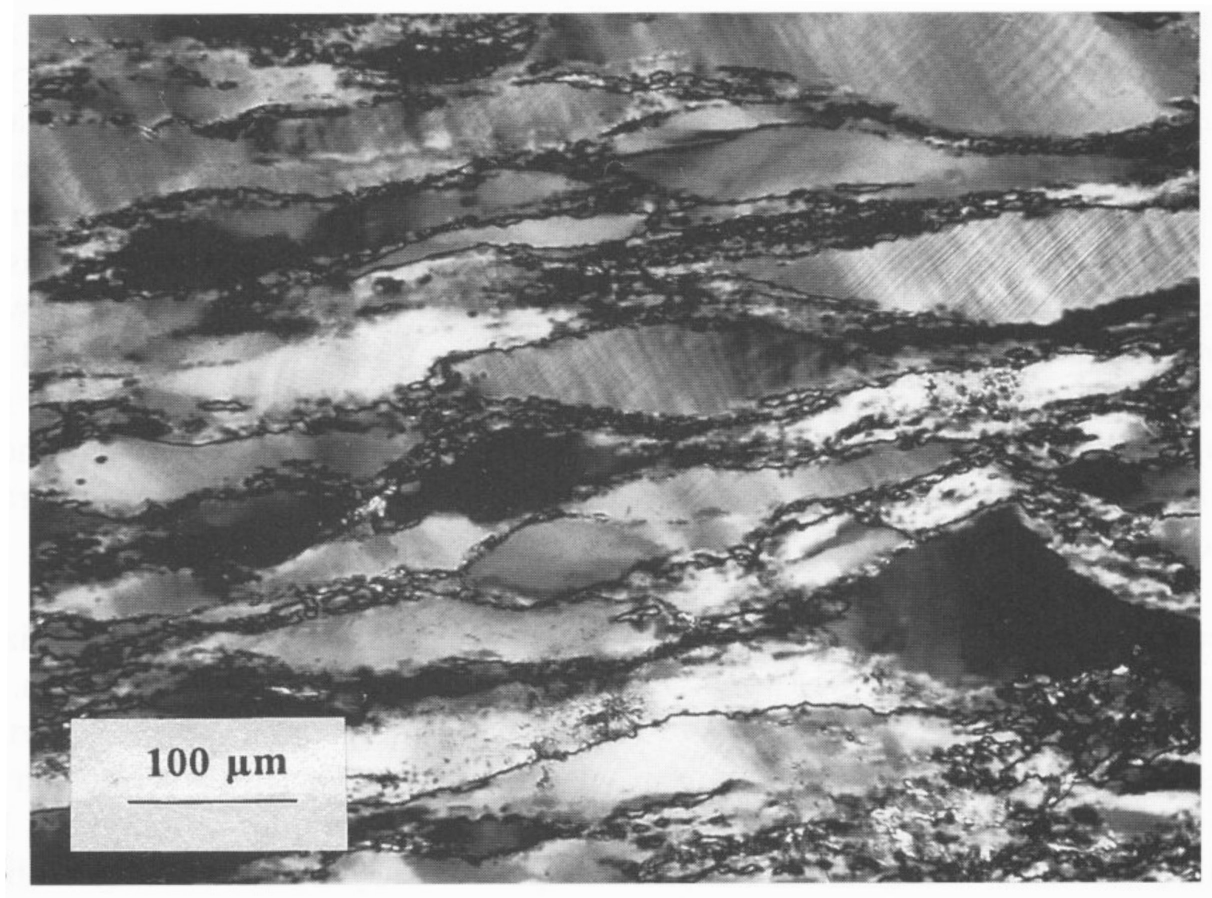
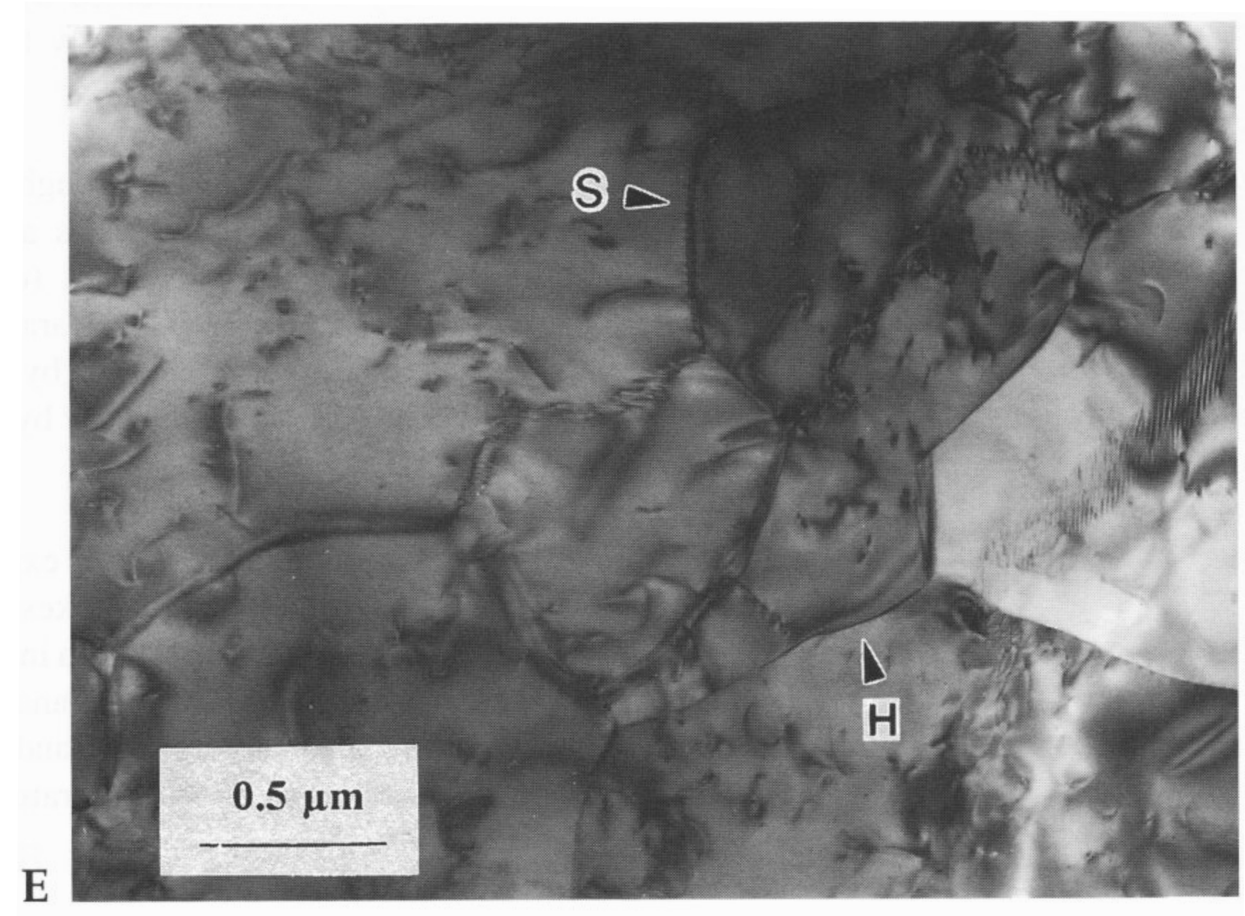


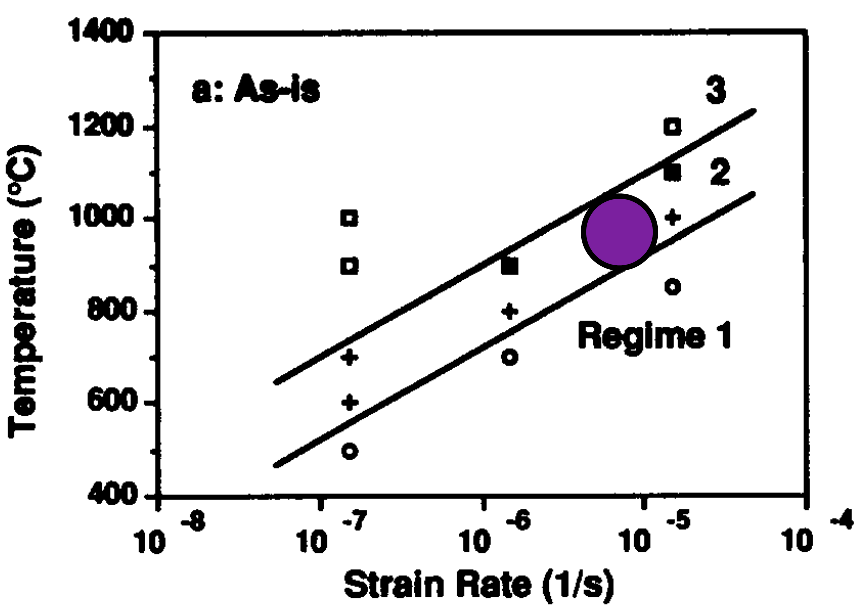
R1 (high stress, low T): production fast, recovery by climb and GBM slow

Experimentally deformed:

Regime 2



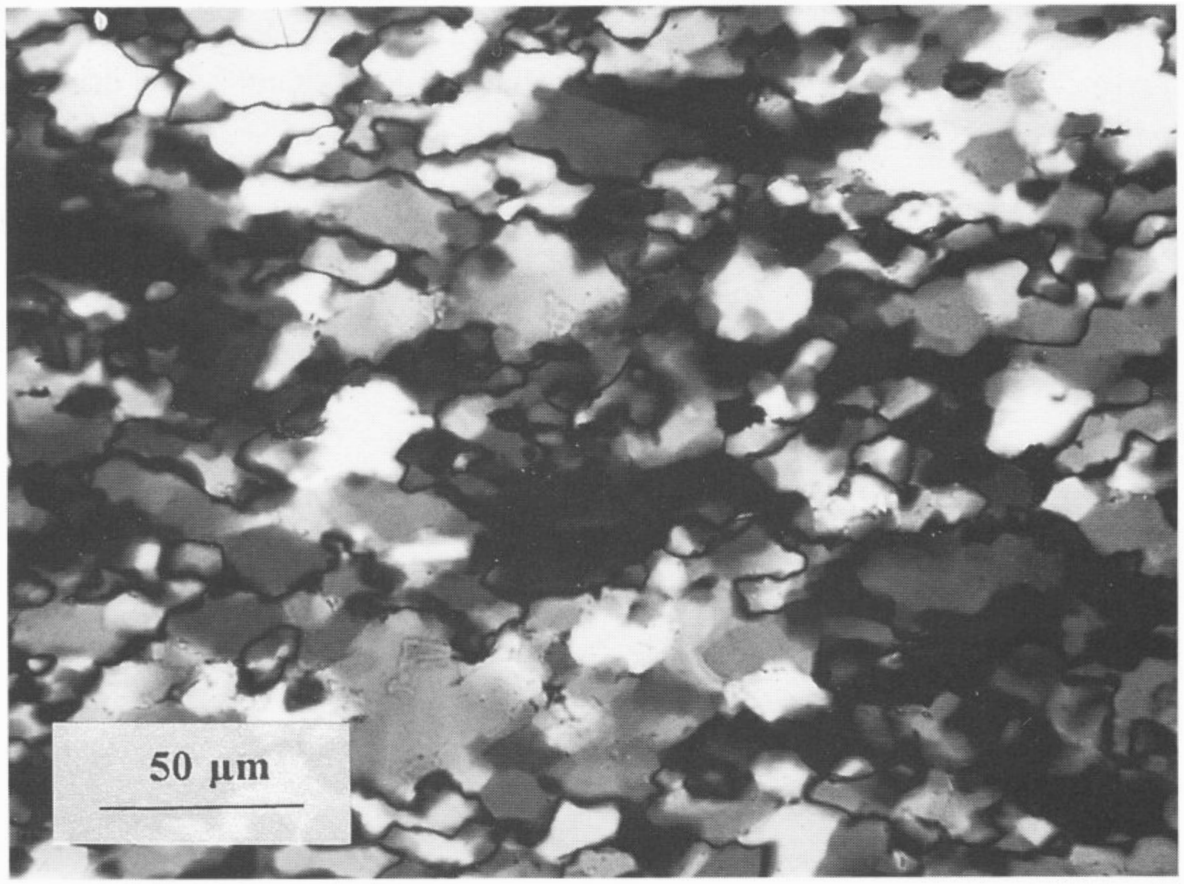


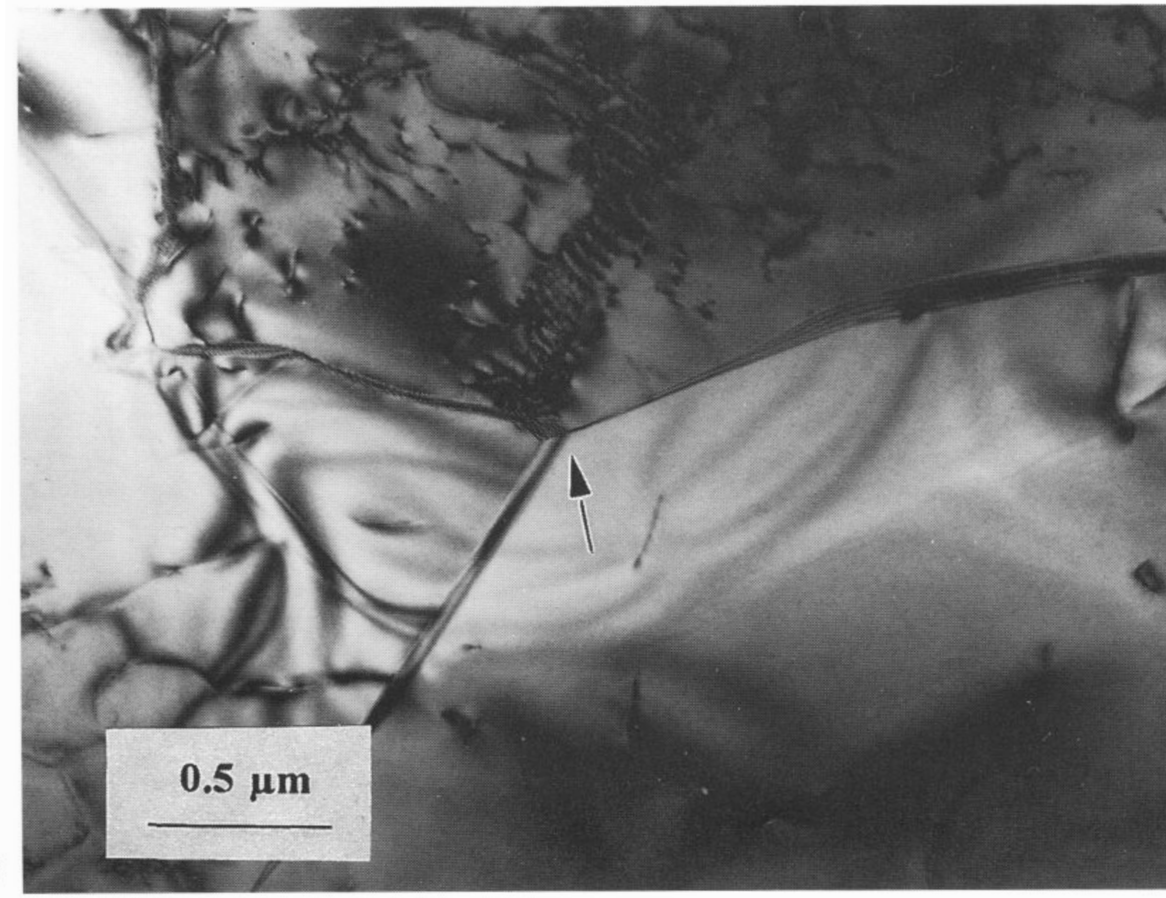


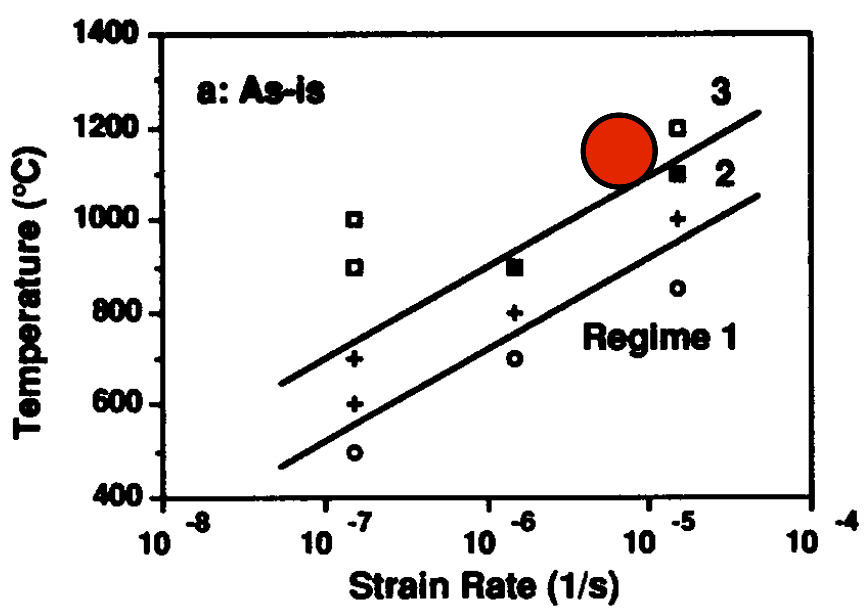
R2 (lower stress, higher T): recovery by climb moderate, but GBM slow, so recrystallization occurs by subgrain rotation (requiring climb)

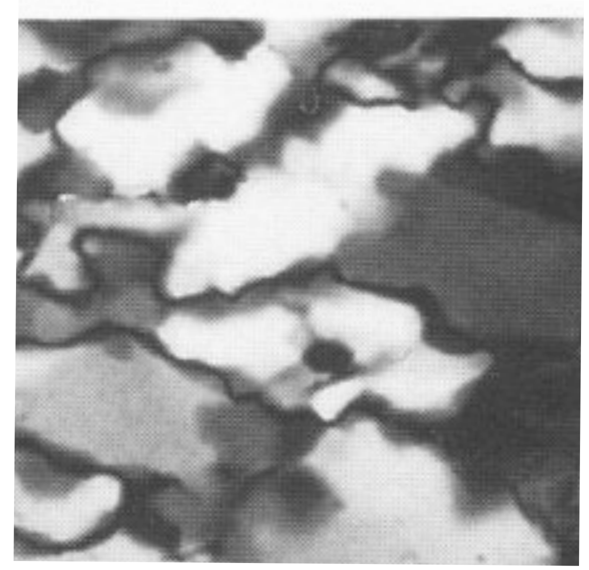
Experimentally deformed:

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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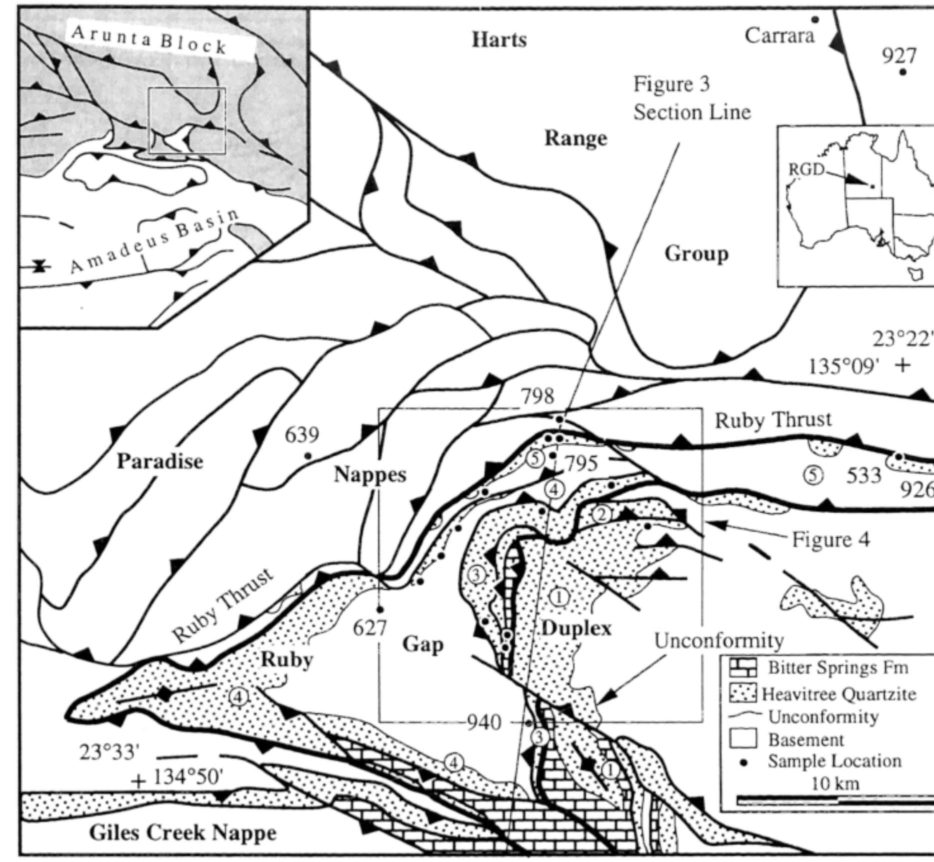


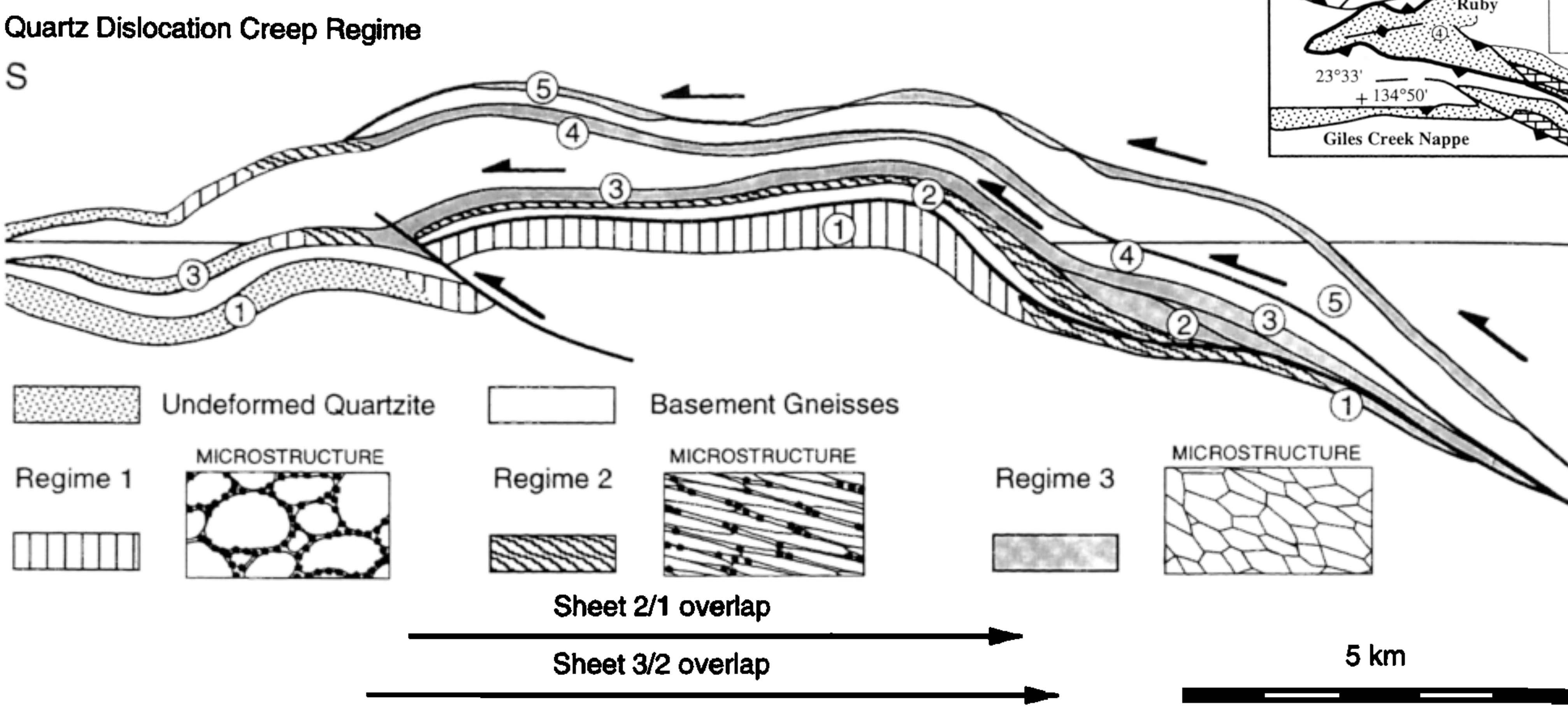
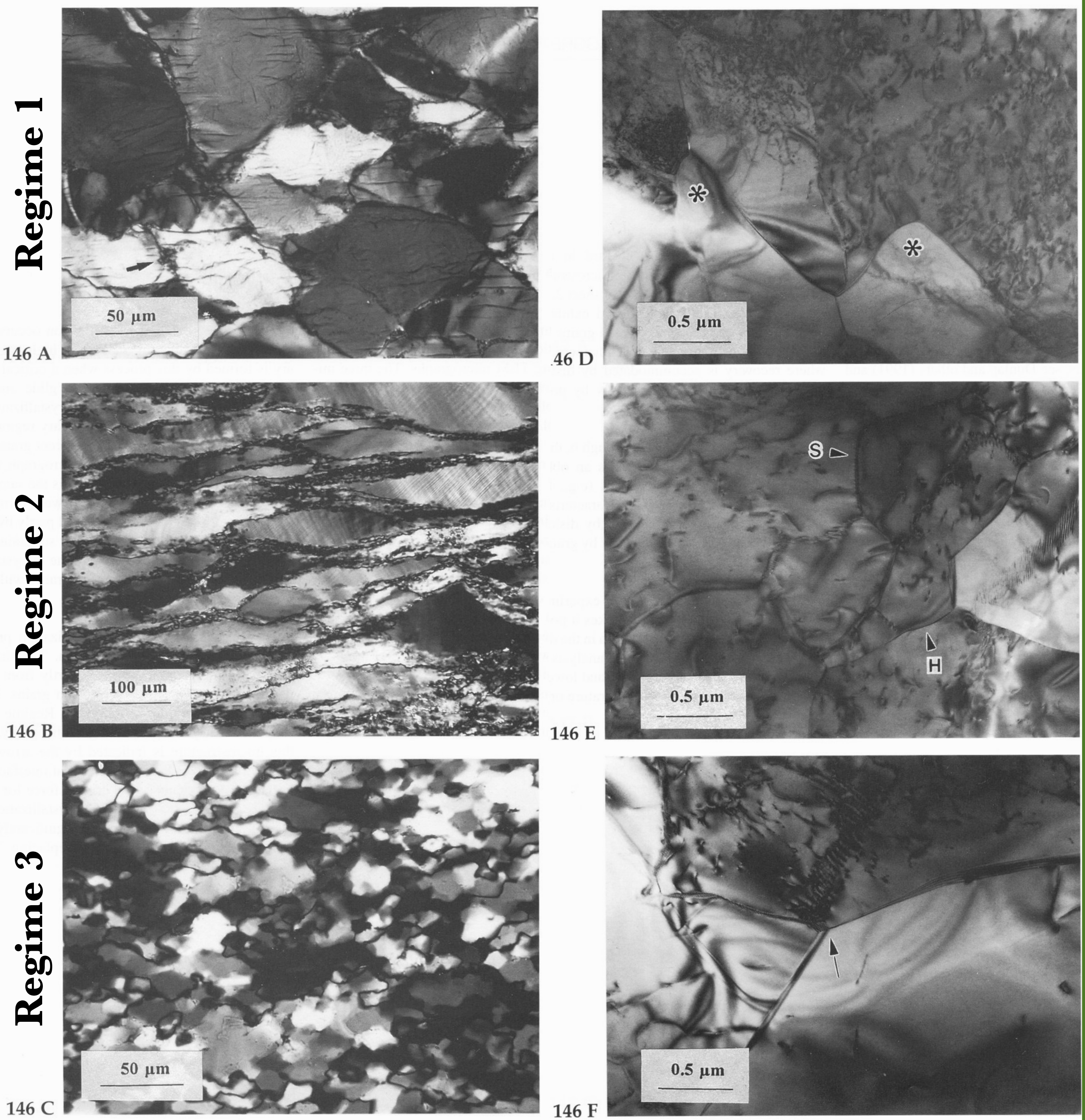


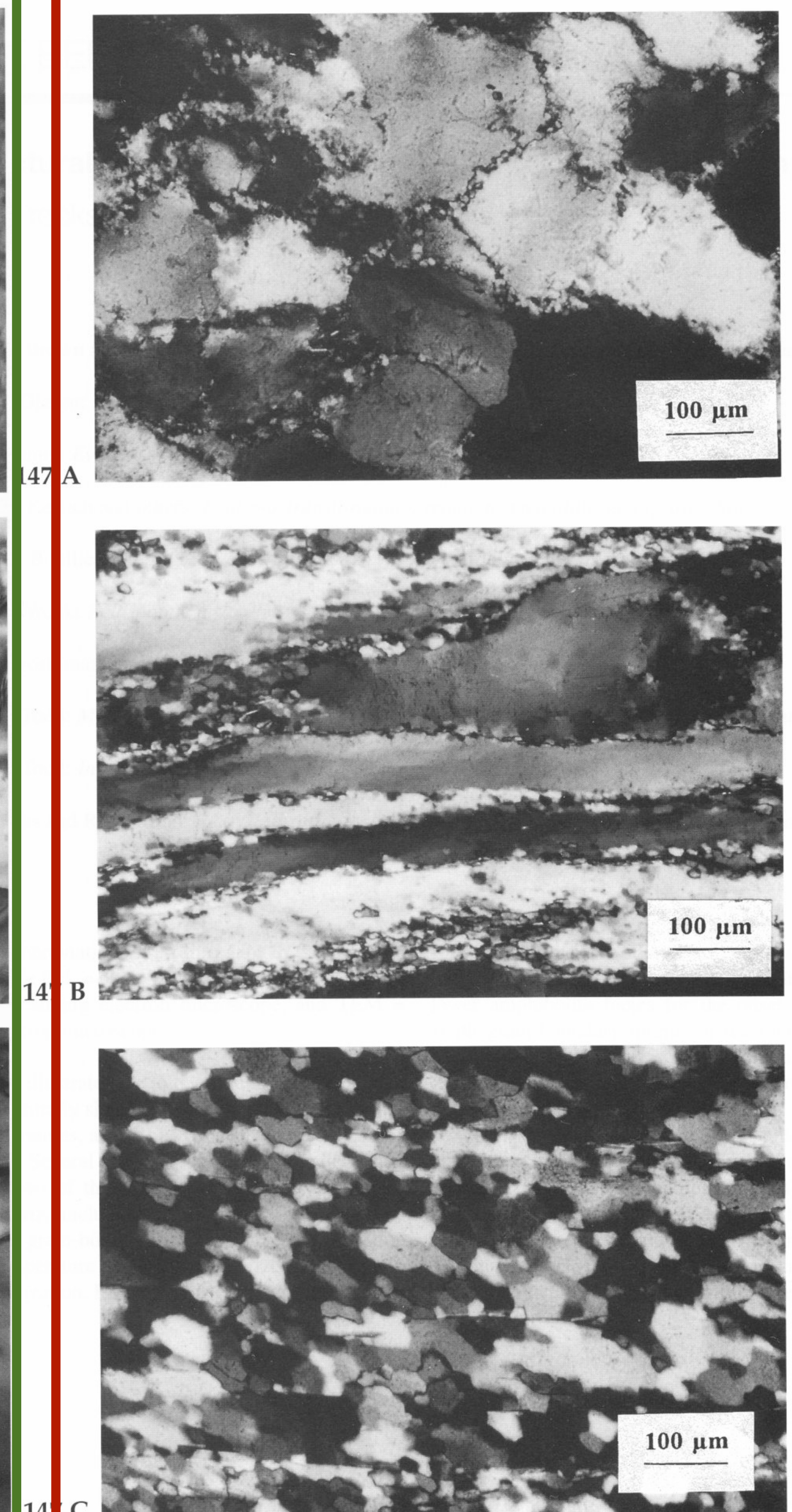
Figure 5. Cross section of the Ruby Gap duplex showing the distribution of dislocation creep regimes in quartzite. Only the quartzite is ornamented; the basement and carbonate are unornamented. The pattern is constrained by about 100 thin-section analyses. Insets show schematic characteristic microstructures 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.

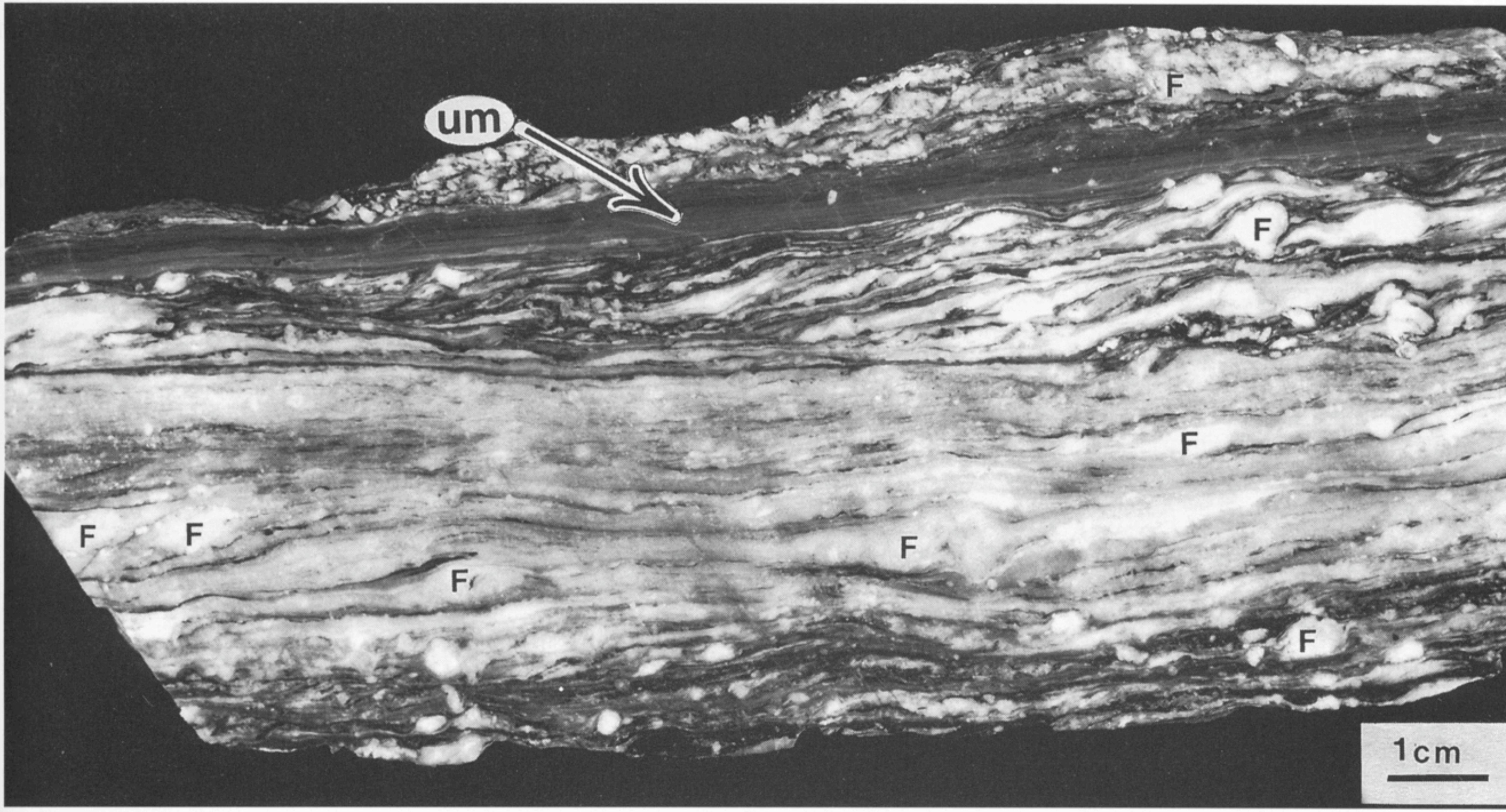
from: “Atlas”

Experimentally deformed:



Naturally deformed





from: “Atlas”

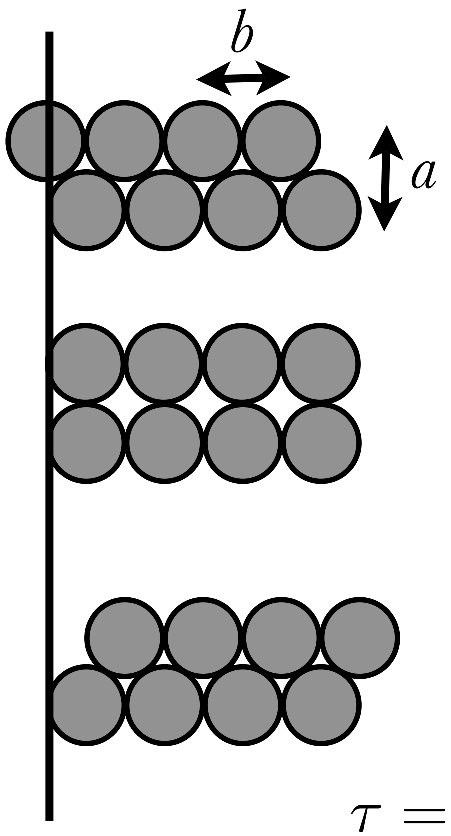
MOVIES of dislocations in metals

MOVIES of grain boundary migration in deforming ice:

http://virtualexplorer.com.au/special/meansvolume/contribs/wilson/introduction.html

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

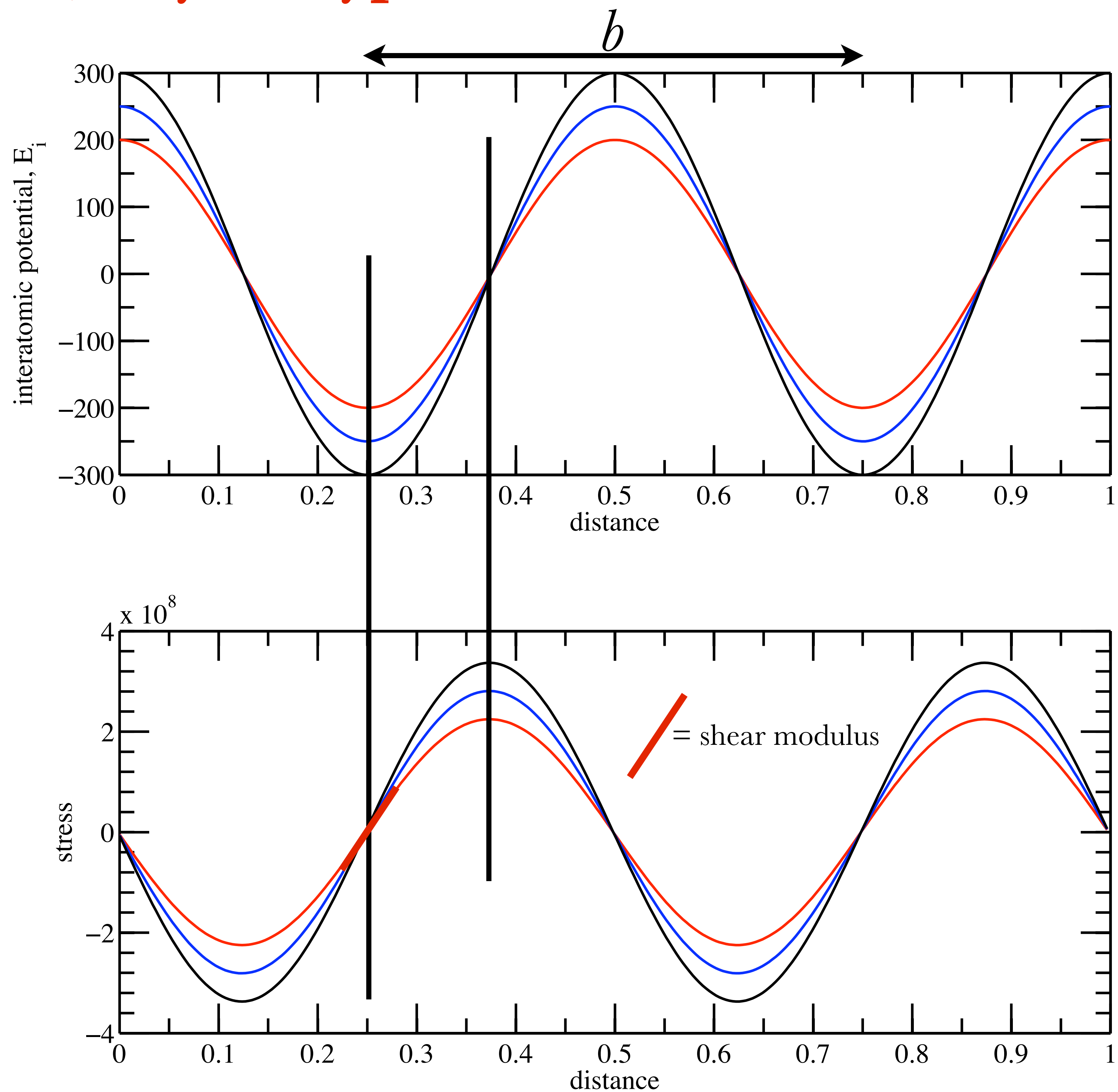
1934: Polyani, Orowan, Taylor hypothesized dislocations....



$$E = Fx$$

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

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



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

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

$$\tau = \mu\gamma$$

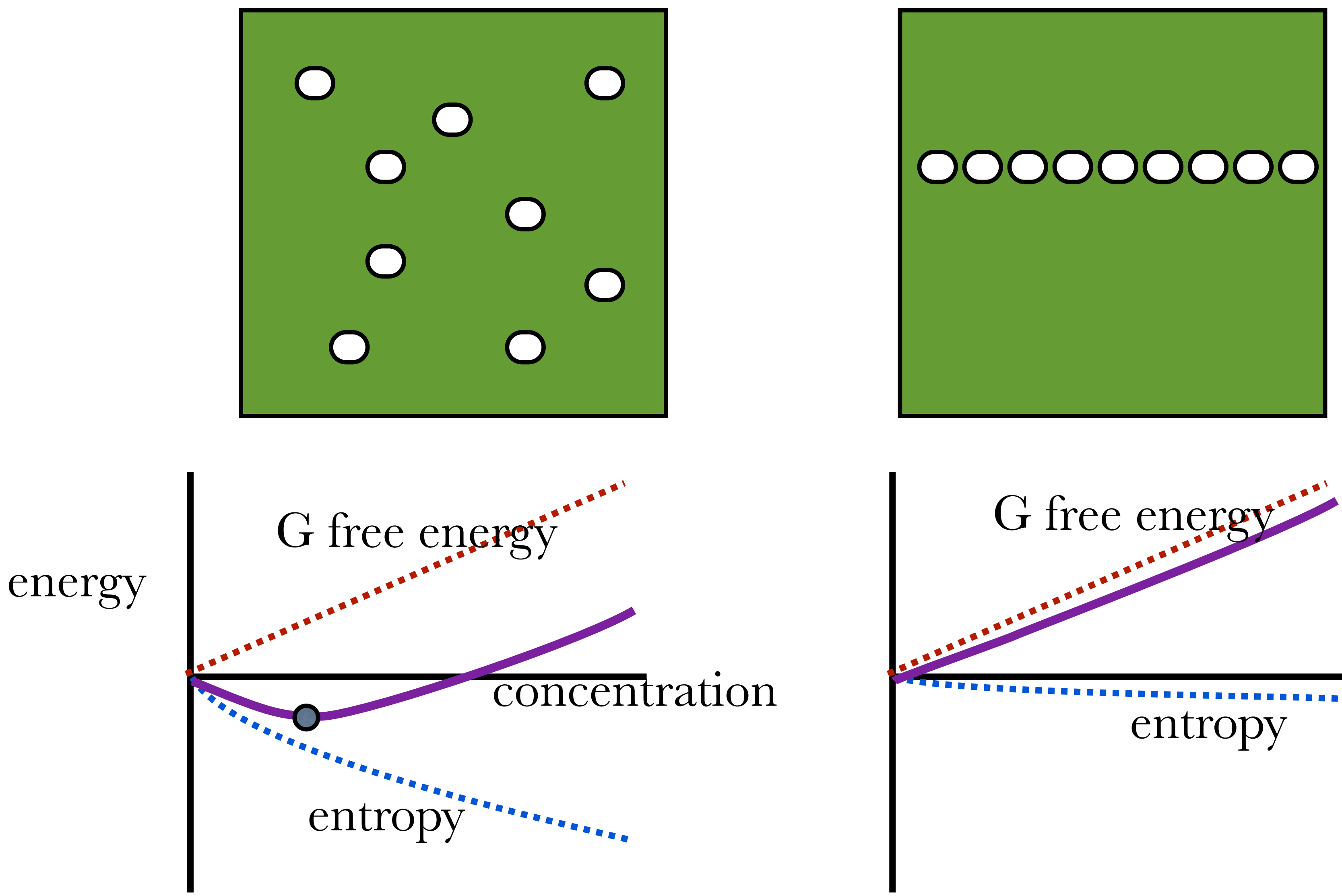
$$\gamma \approx \frac{x}{a}$$

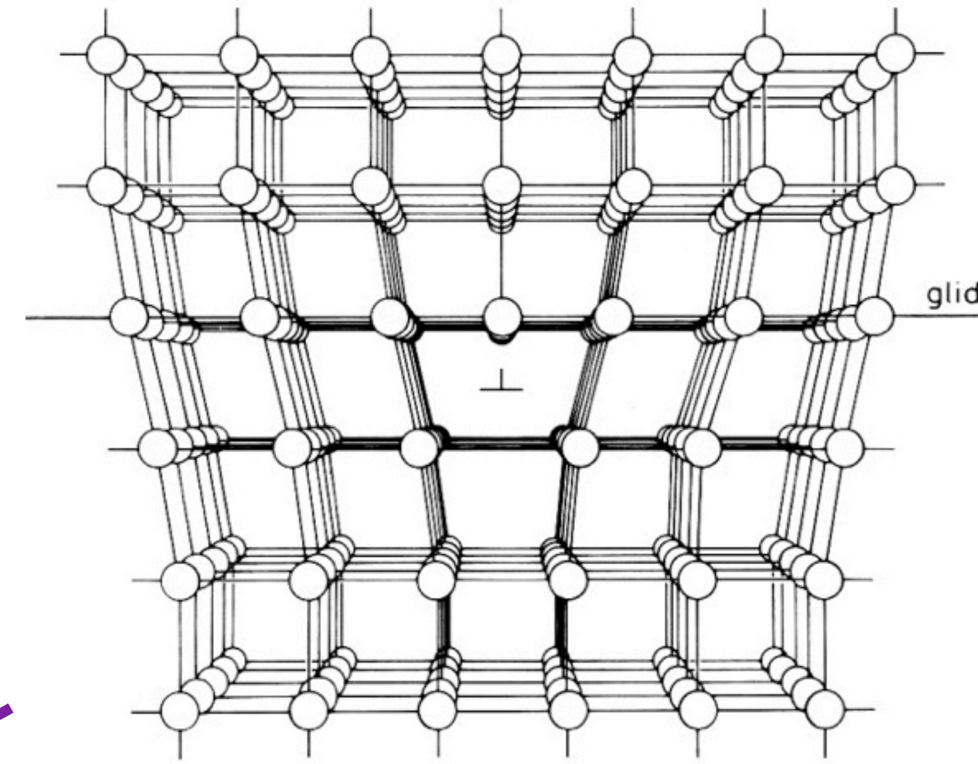
$$\tau_{max} = \frac{\mu}{2\pi}\frac{b}{a}$$

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

~ 10 GPa, way too strong

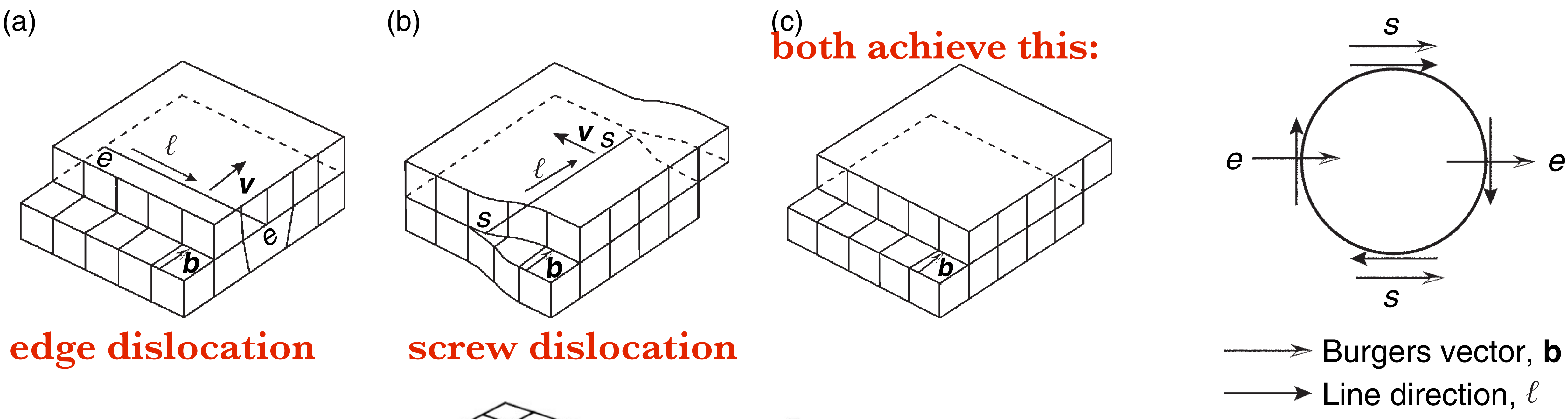
2. Single dislocations

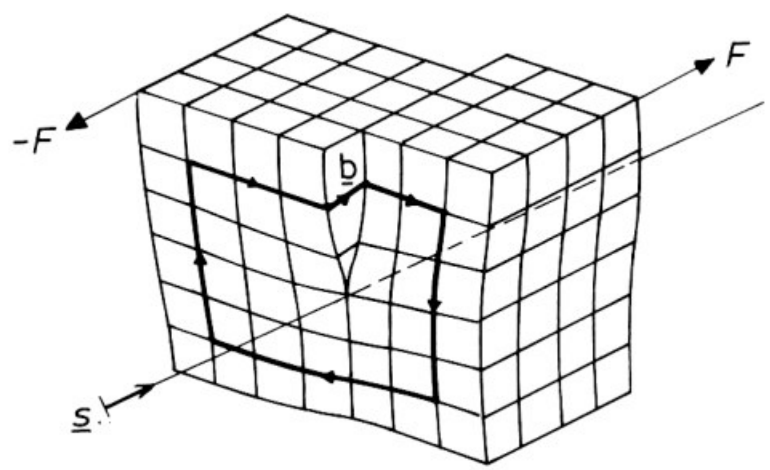


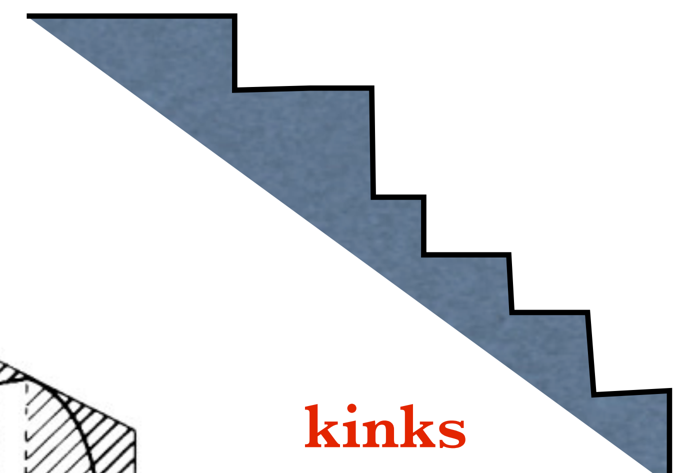


Unlike for vacancies, there is no equilibrium concentration of dislocations, because the aligned vacancies do not increase the entropy as much as isolated vacancies do.

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







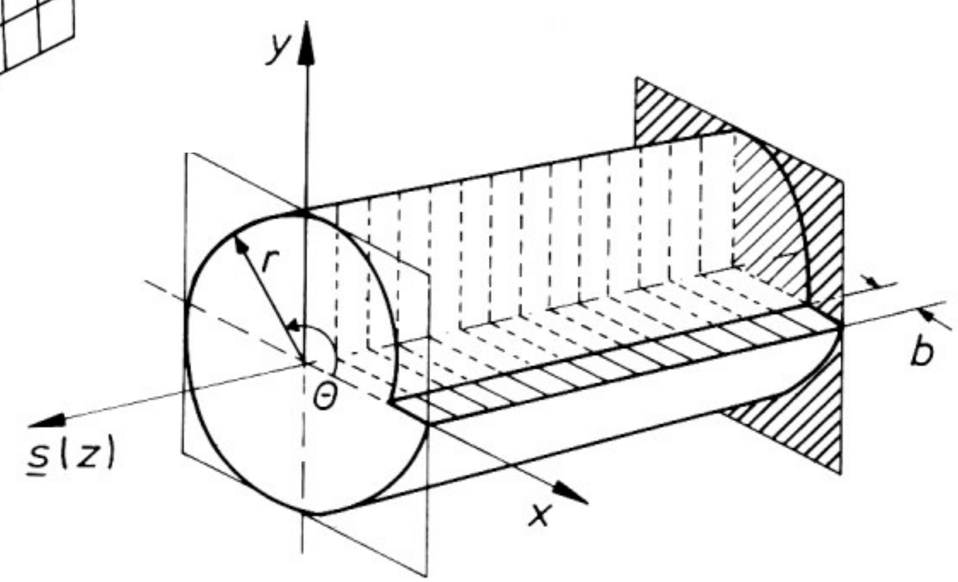
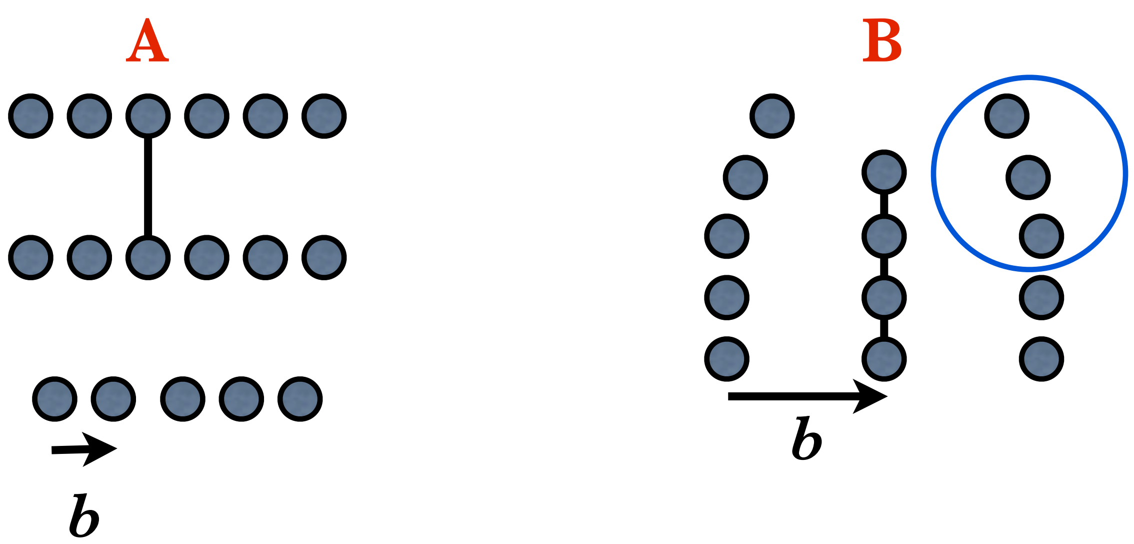


Figure 3-10. Strain geometry of an edge dislocation.

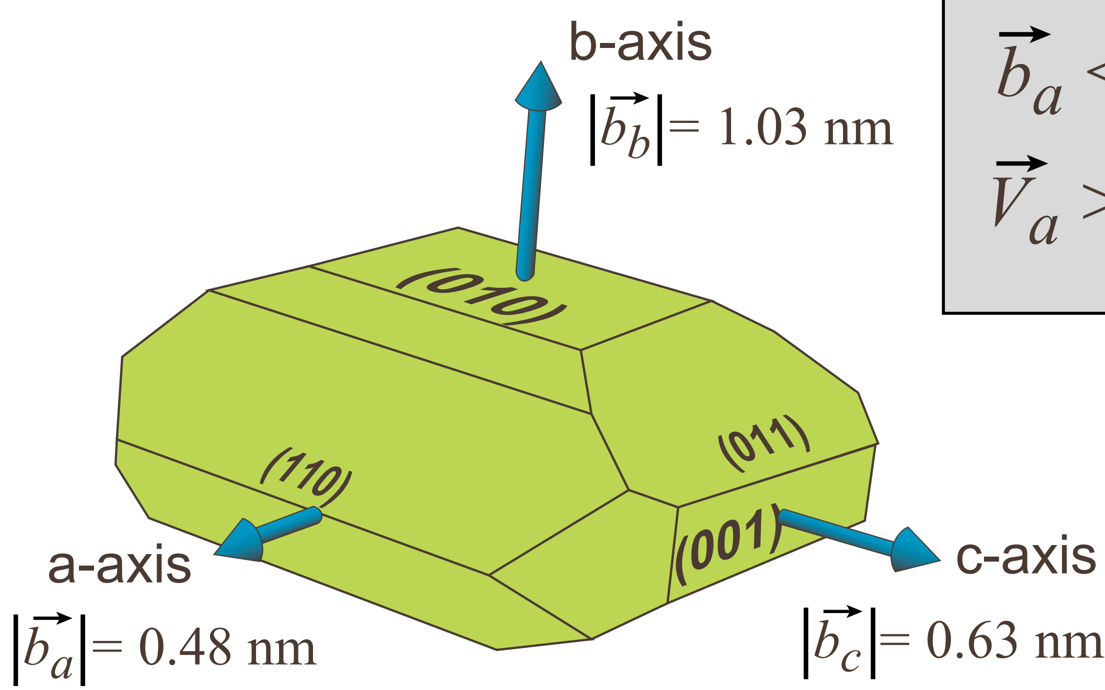
Slip system: **(slip plane)[burger's vector]**



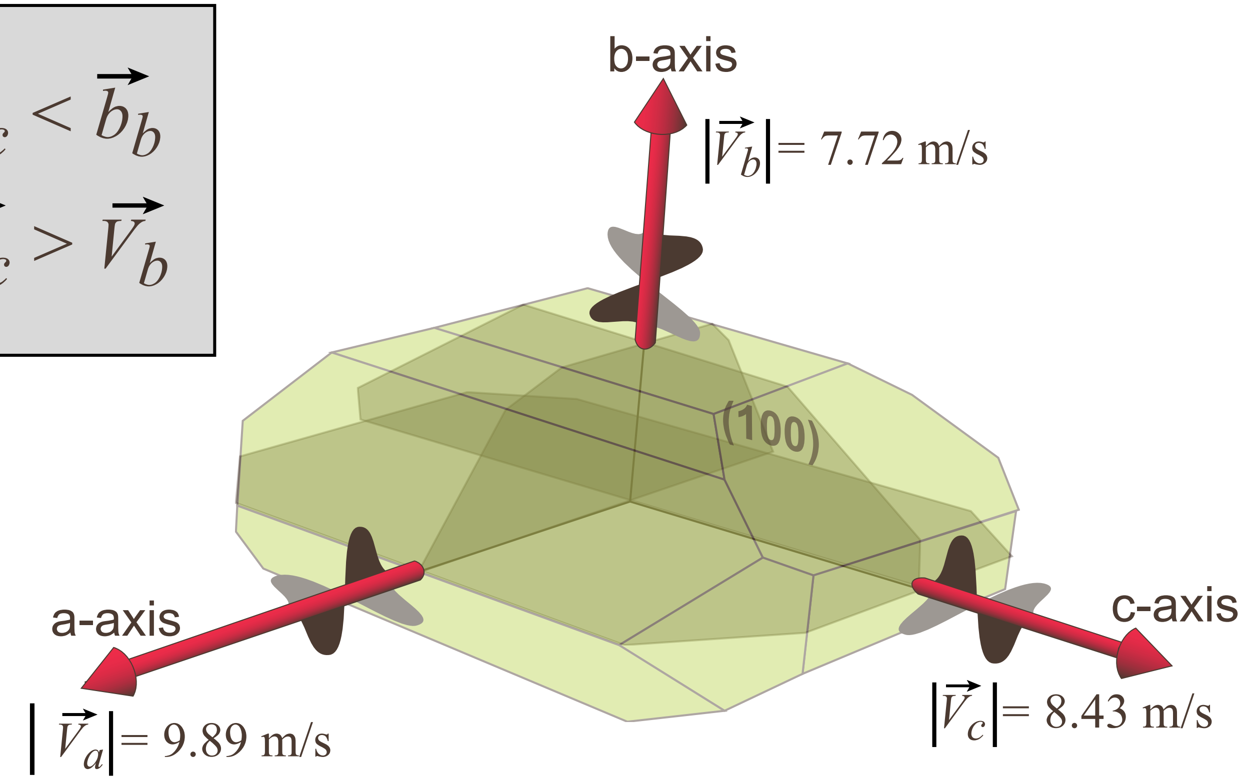
the slip system with the shorter burger's vector and longer atomic distance normal to the slip plane will be "easier": A dislocations move more easily (at lower stress, or faster at the same stress) than B dislocations.

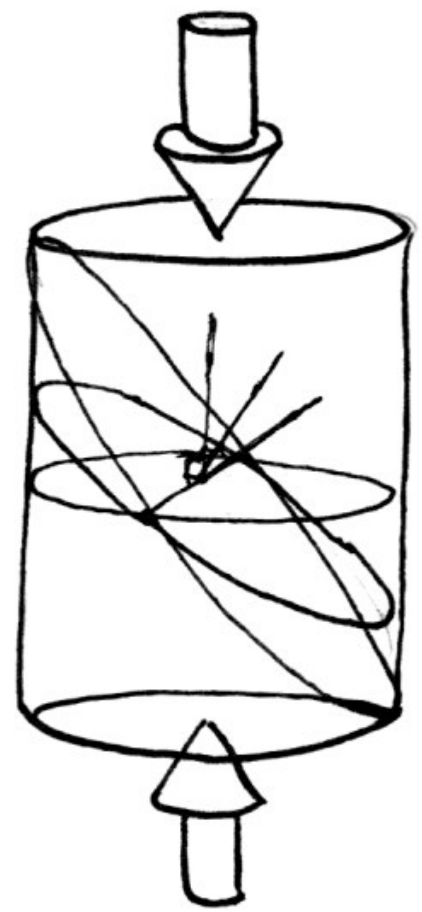
This leads to anisotropy in dislocation motion and eventually to the creation of lattice preferred orientation...

Olivine: **(010)[100] is easiest, followed by (010)[001] ("Miller indexes")**



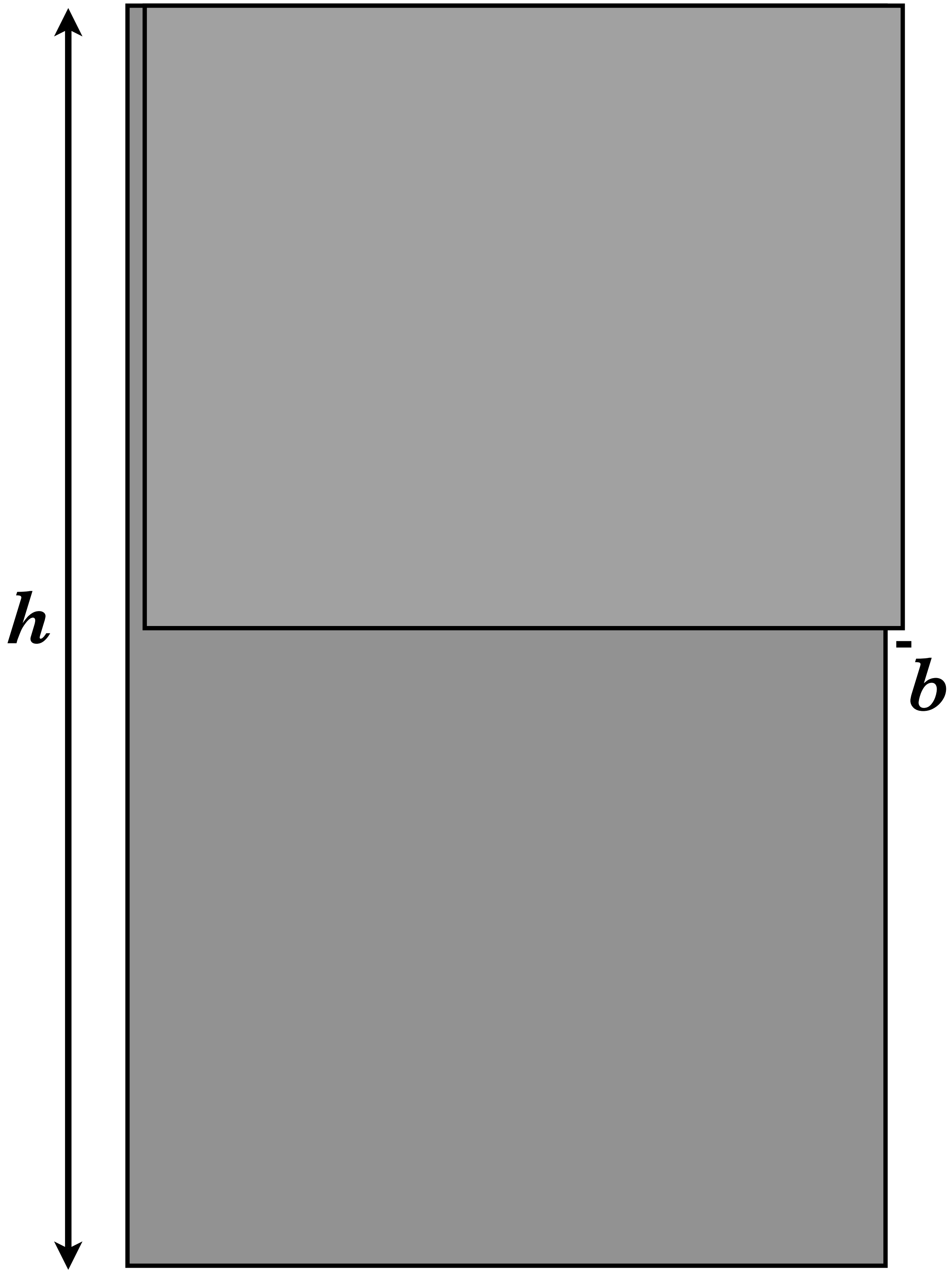
$$\vec{b}_a < \vec{b}_c < \vec{b}_b$$
$$\vec{V}_a > \vec{V}_c > \vec{V}_b$$





Goetze & Evans, single crystal experiments..

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

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)

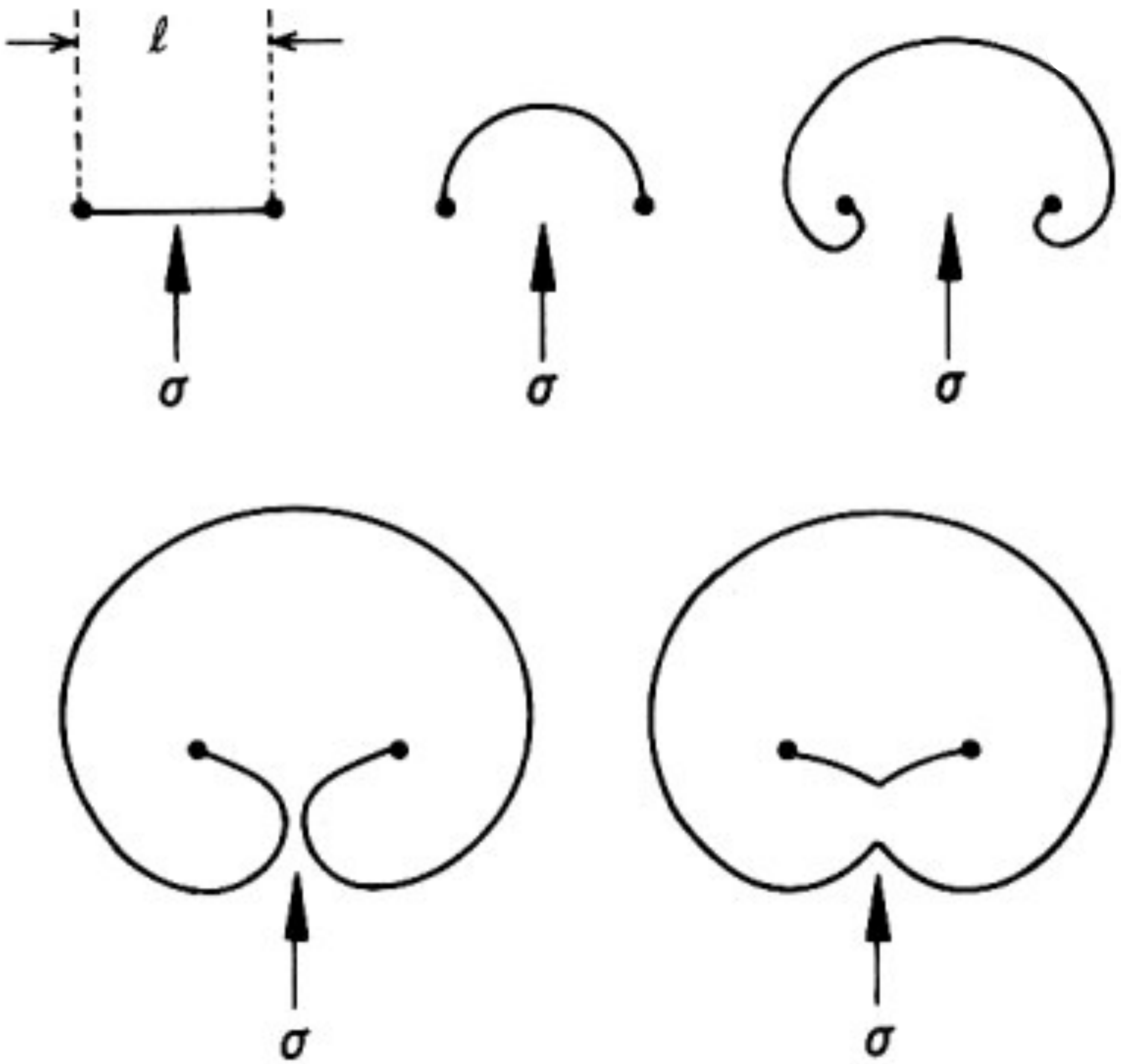
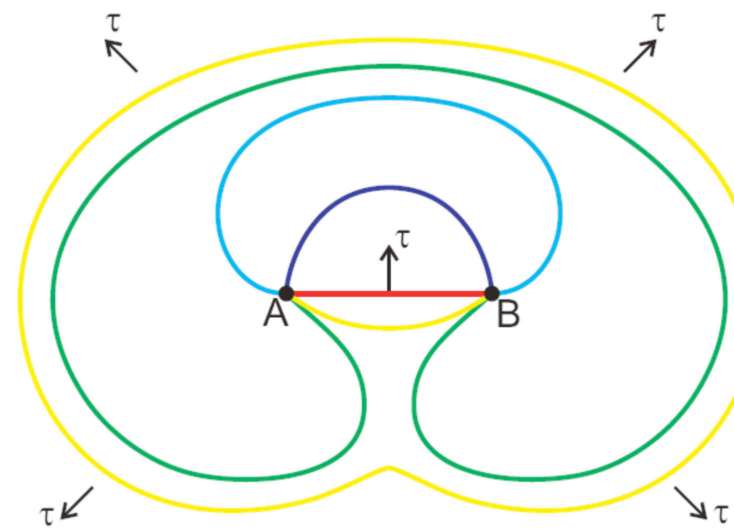


Figure 3-3. Representation of dislocation movement in a Frank-Read dislocation source under stress σ. Multiplication of dislocation pinned at a distance *l*.



Peach-Koehler Force:

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

tension on growing dislocation = Gb^2

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

~ several MPa

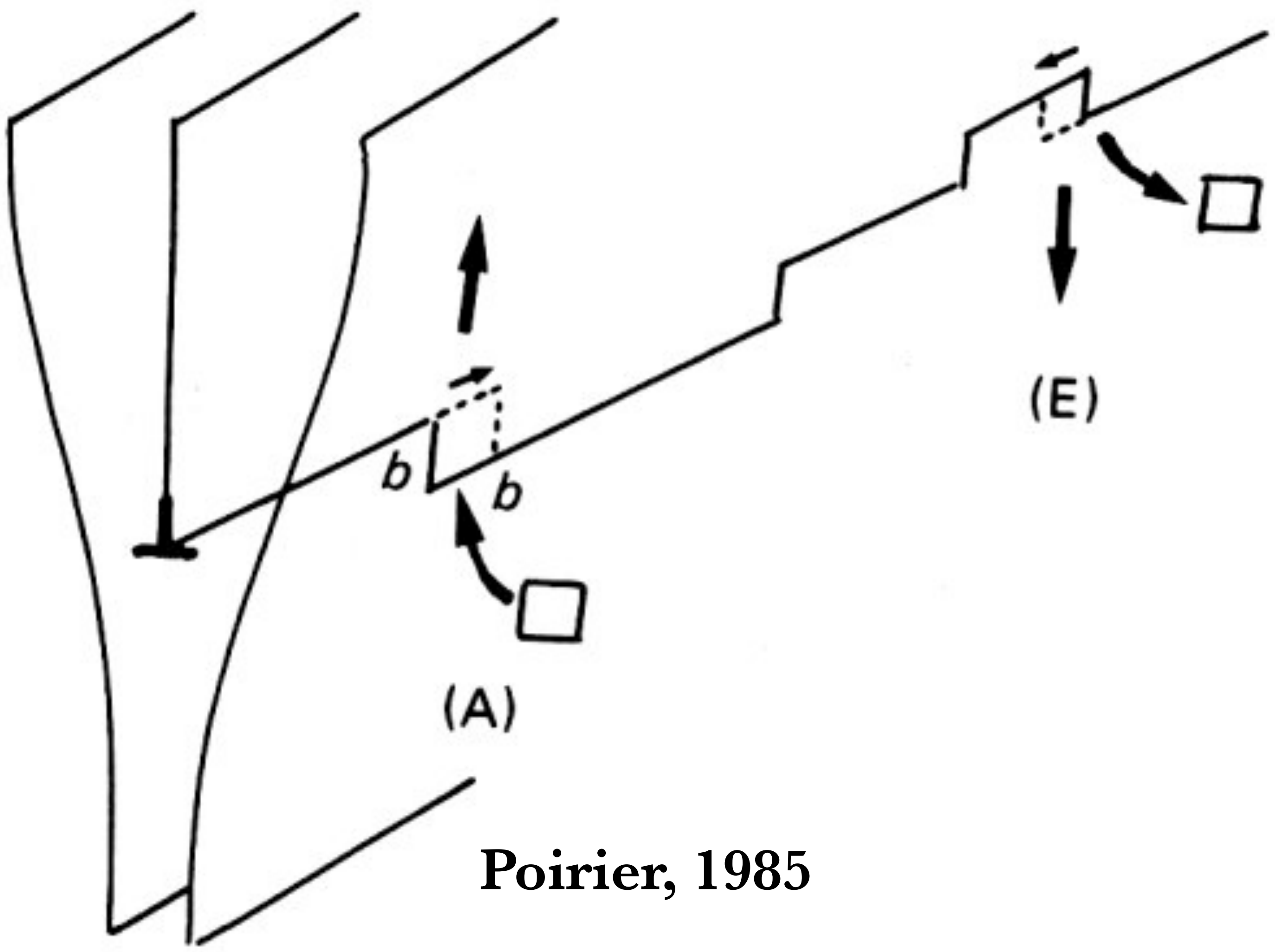
PAPER CLIPS deformation:

1. work hardening,
2. Bauschinger effect (hysteresis: unbending is easier than bending, because the dislocations push against each other)
3. Luder's bands: localization before rupture

3. Recovery

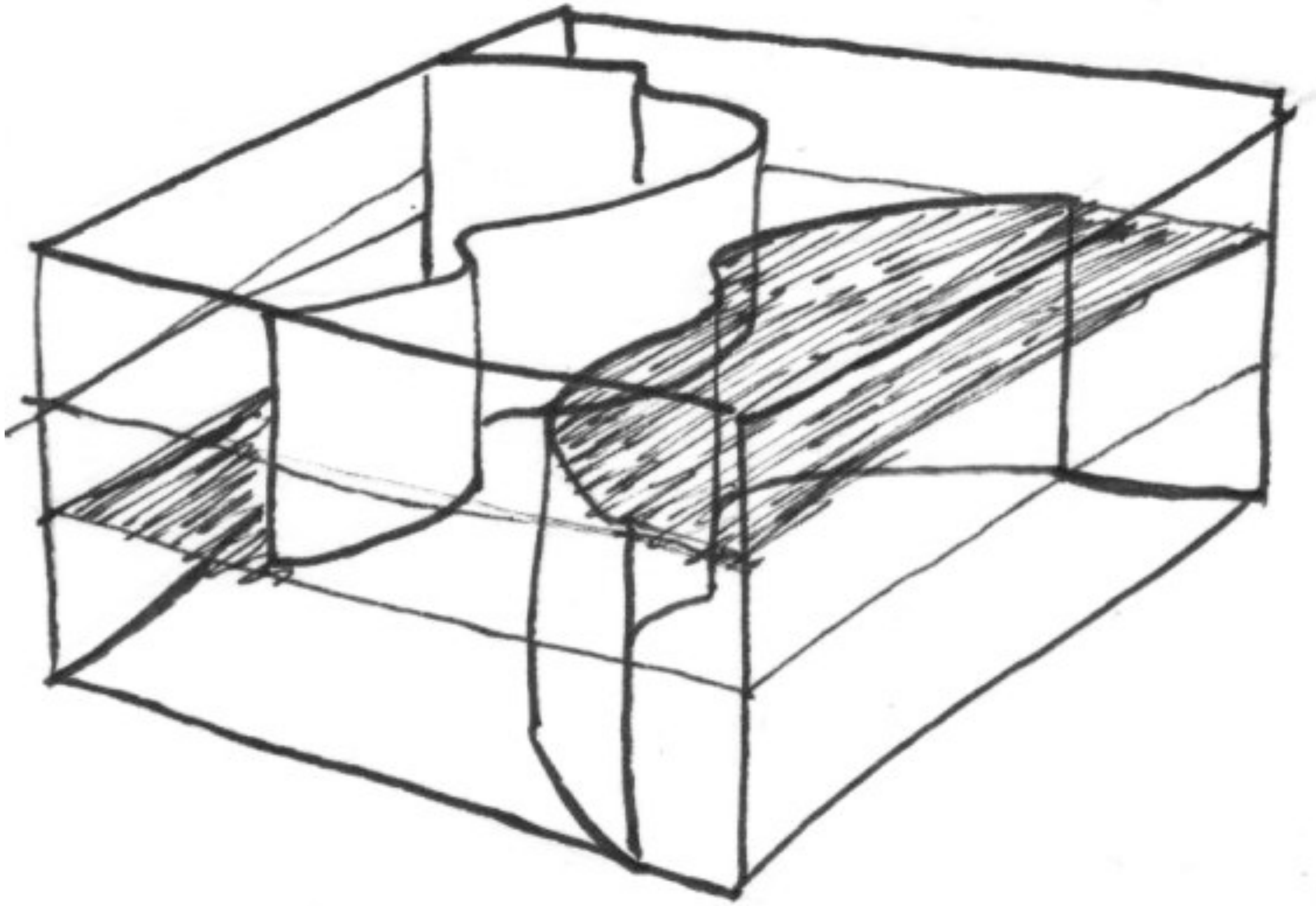
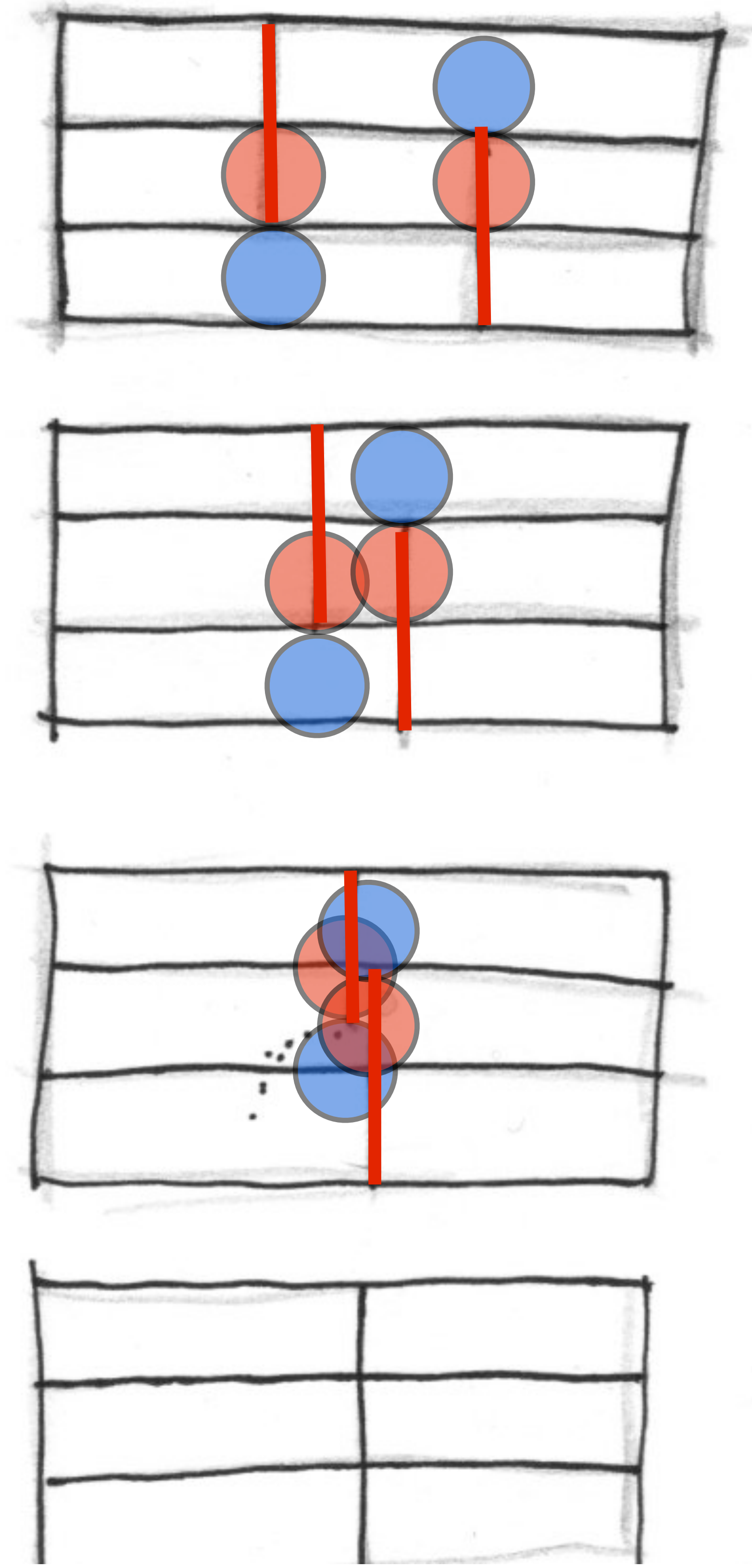
Large strains cannot occur without recovery...

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.



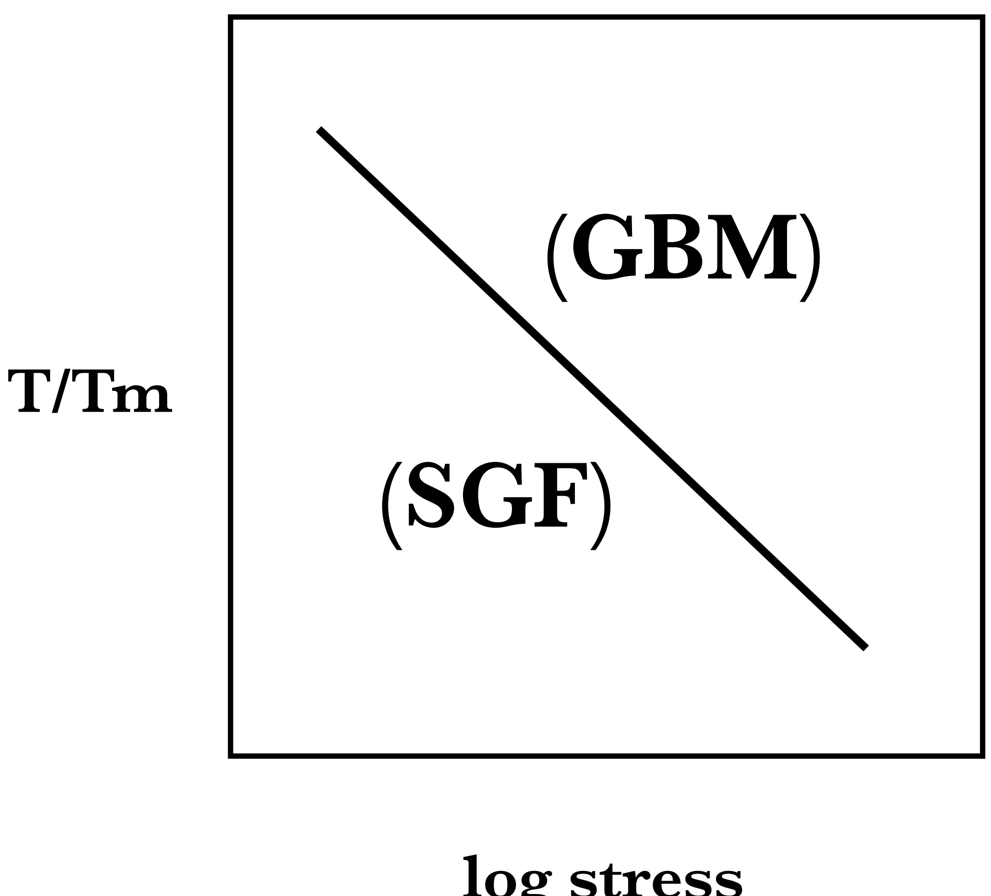
Poirier, 1985

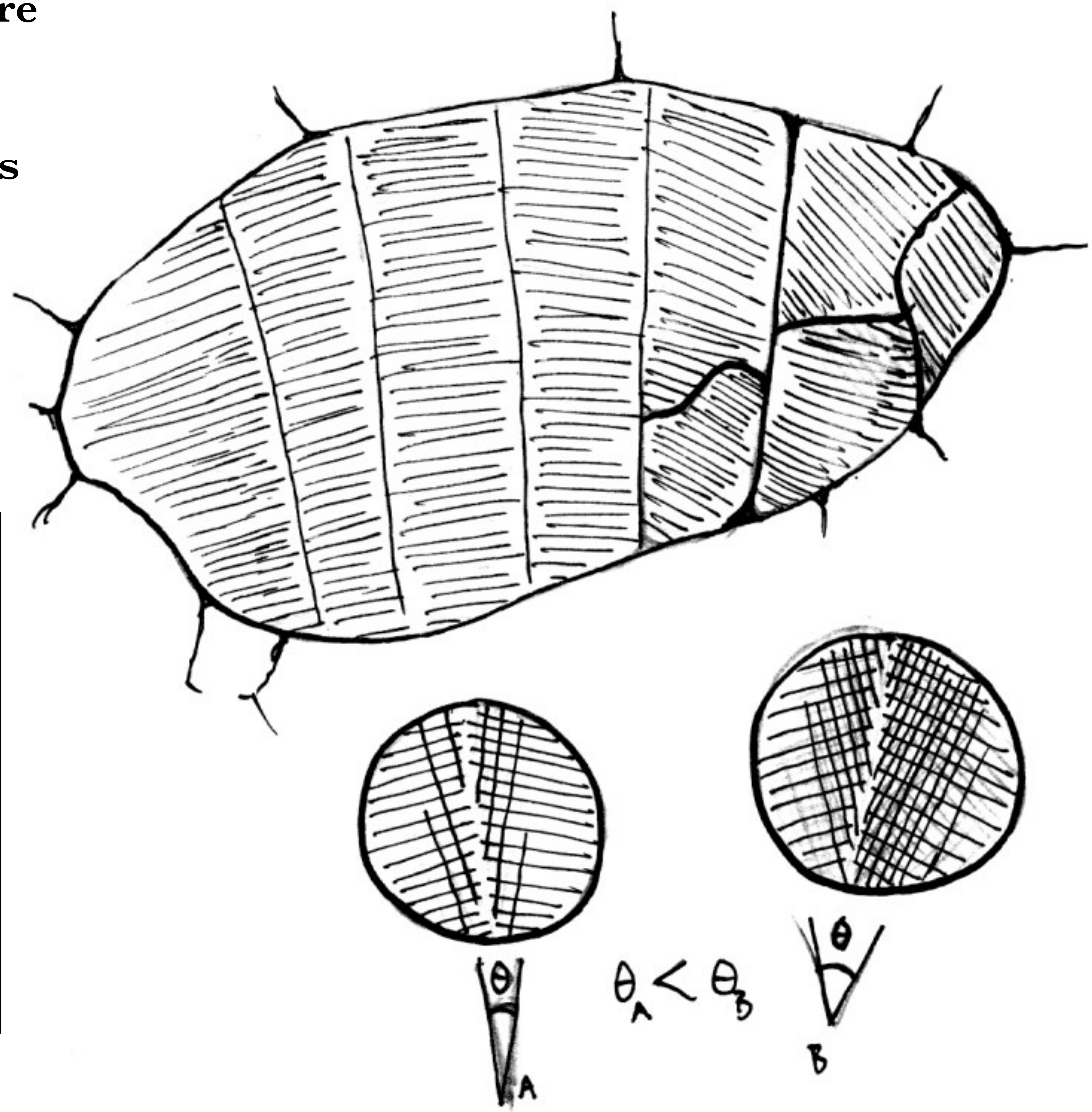
Climb is a thermally activated diffusive process..
This is where the temperature dependence of dislocation creep comes from.

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

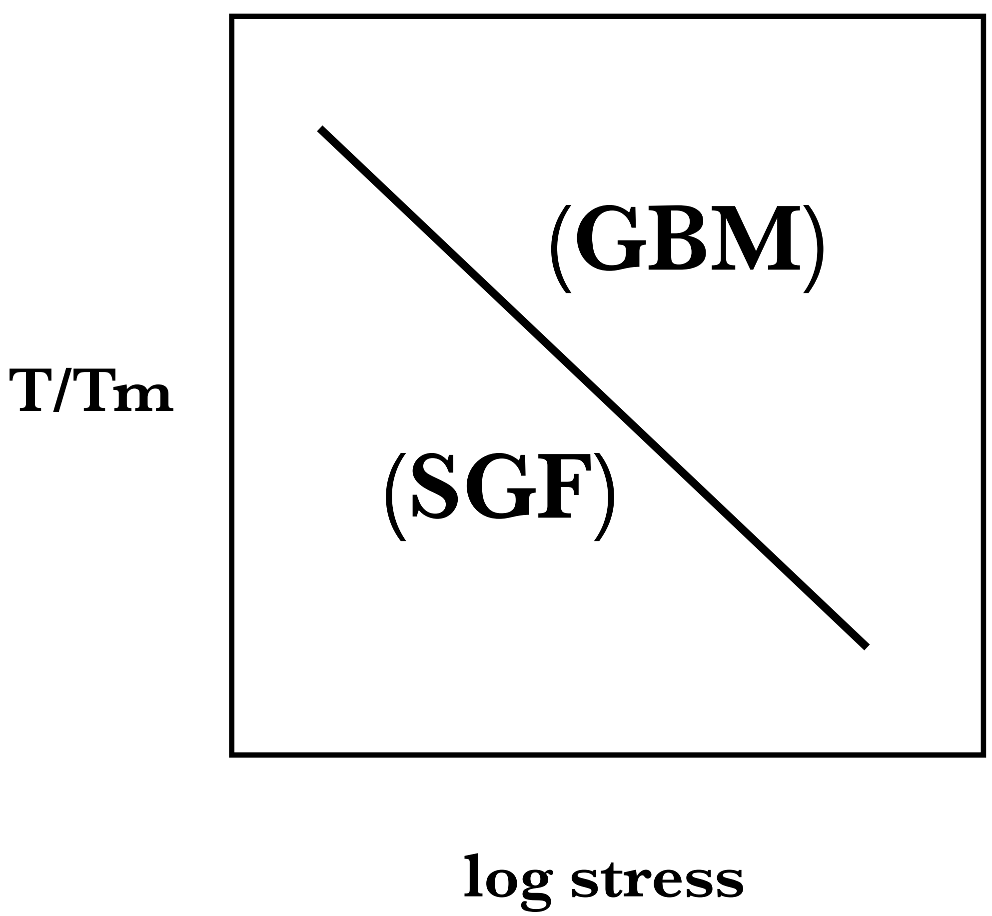




Recovery by grain boundary migration

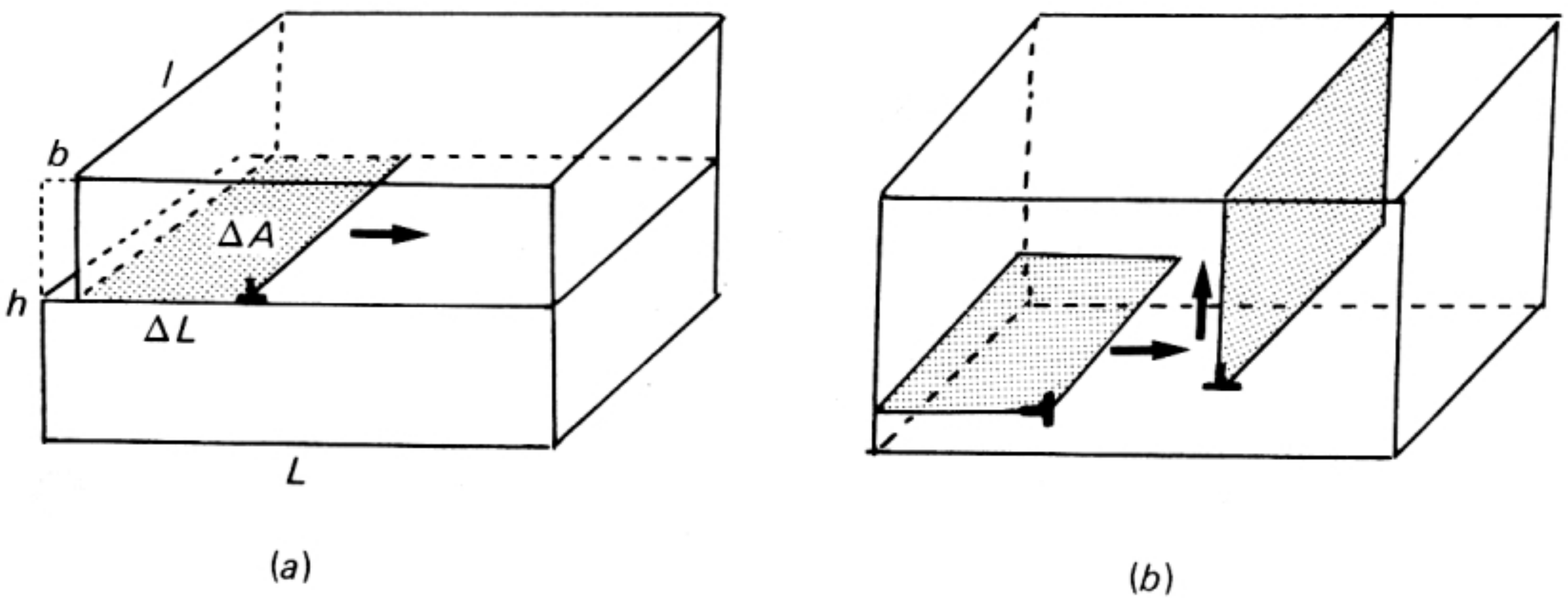
-associated with higher temperature conditions (only because necessary diffusion length scale is greater than for SGR)

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



OROWAN Equation (from Poirier, 1985, p 62):

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.



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

if disl. only sweeps ΔL

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

and for N dislocations

$$\varepsilon = N\frac{b}{h}\frac{\Delta L}{L}$$

$$(V = Llh)$$

$$\varepsilon = \frac{Nl}{V} b\Delta L$$

$$(\rho = (Nl)/V)$$ **disl. density**

$$\varepsilon = \rho b \Delta L$$

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

avg. disl. velocity

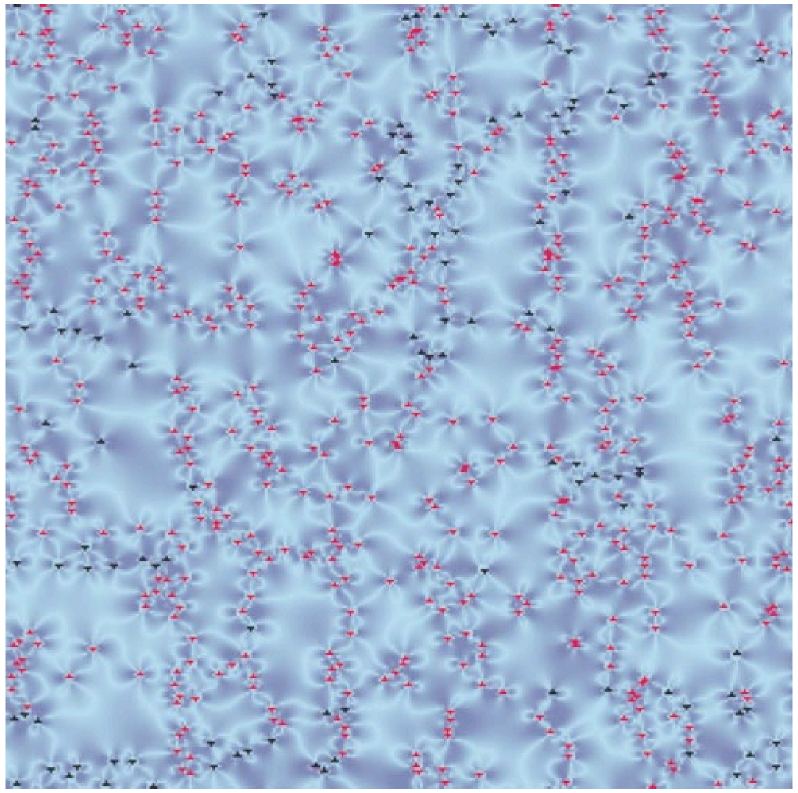
$$\bar{v}_d(\sigma, P, T, X) \propto \sigma^{1+}$$

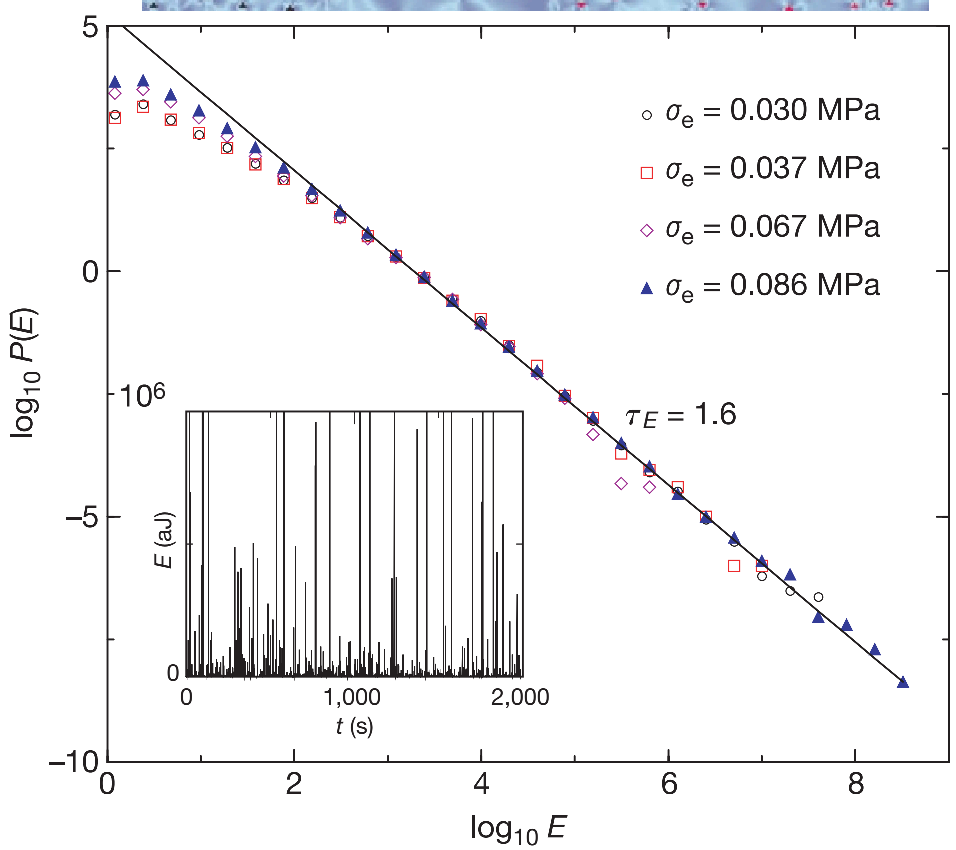
$$\rho(\sigma) \propto \sigma^2$$

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

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

higher order structures : strain waves?

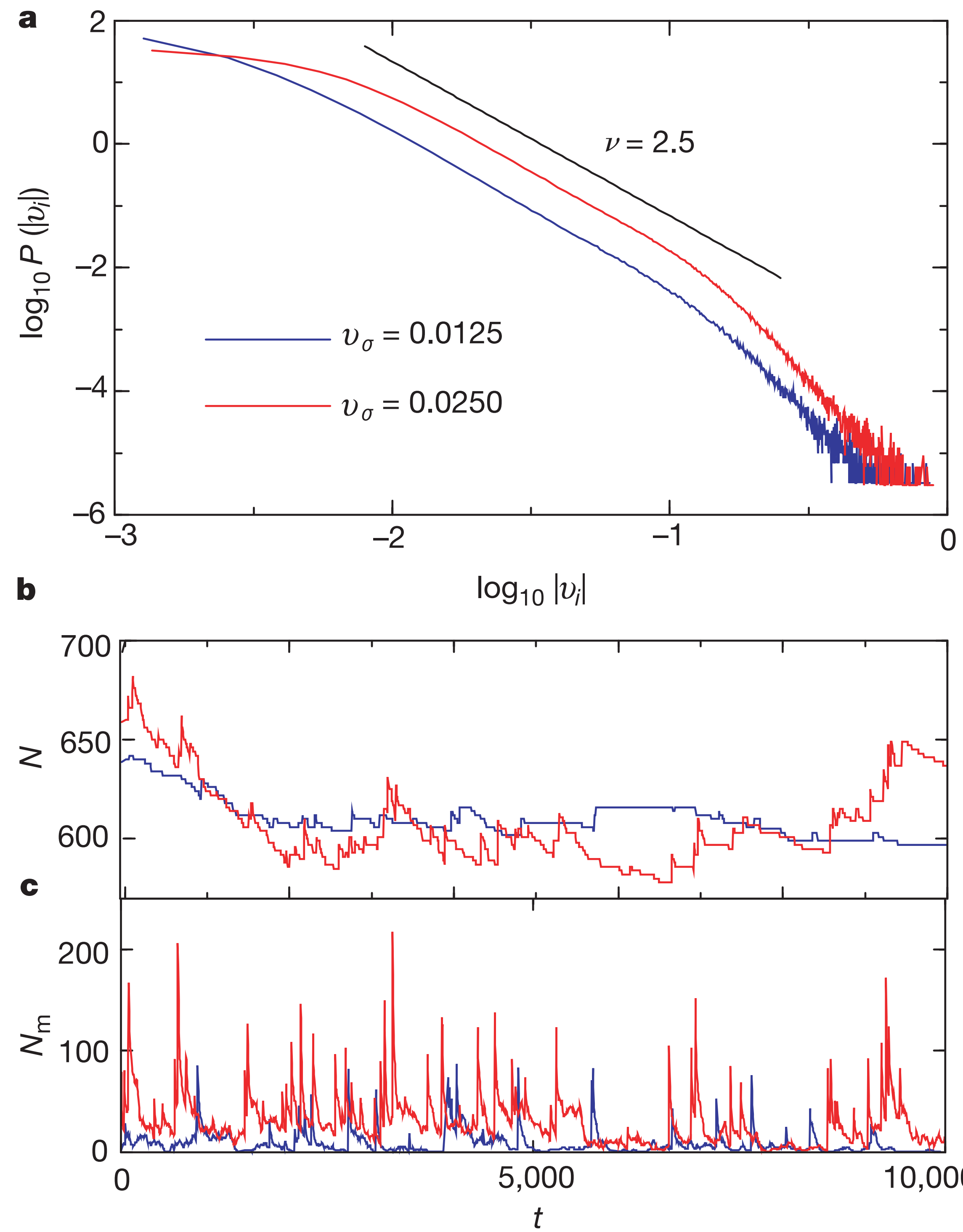




Intermittent dislocation flow in viscoplastic deformation

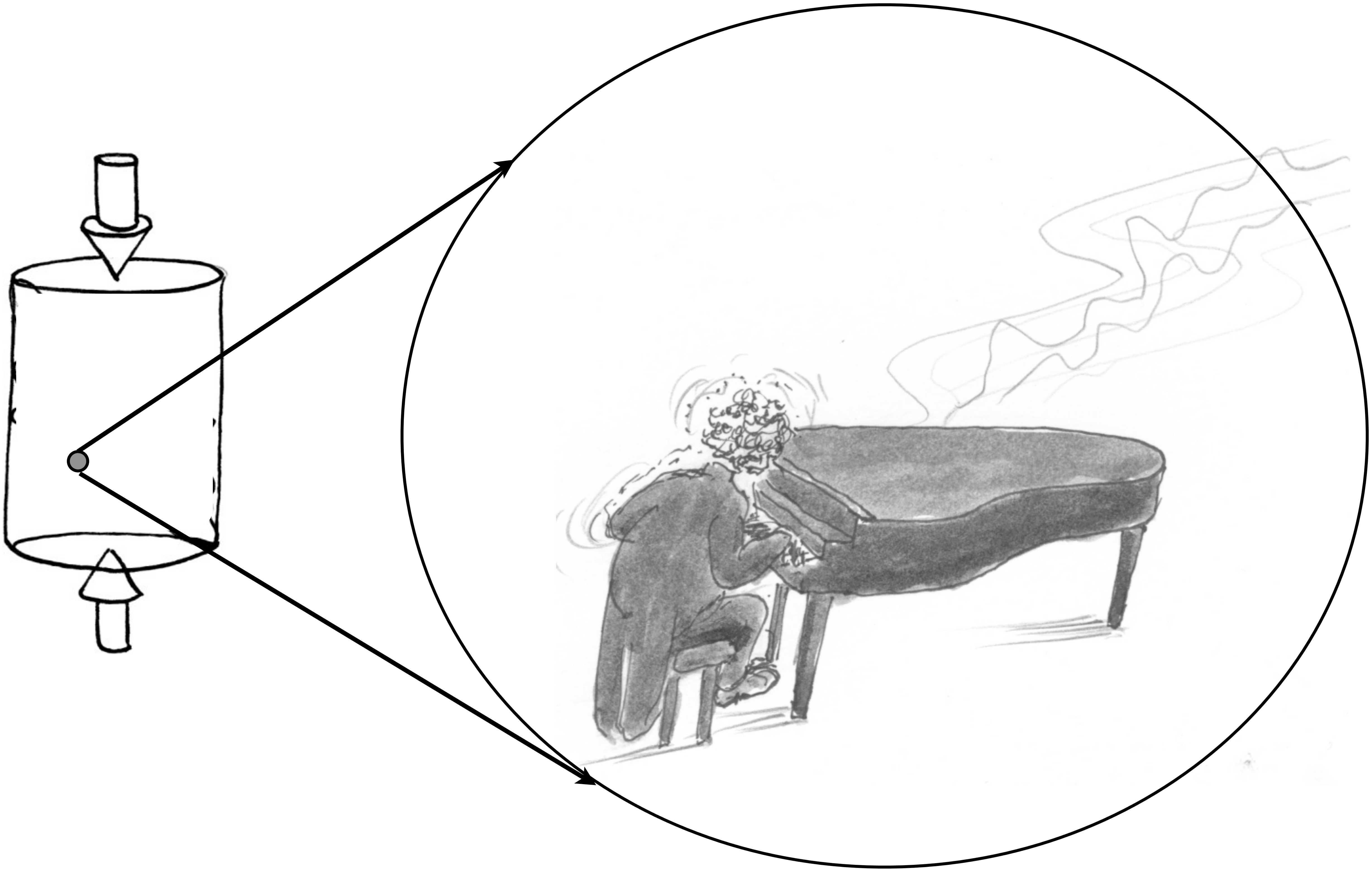
M.-Carmen Miguel*†, Alessandro Vespignani*, Stefano Zapperi‡, Jérôme Weiss§ & Jean-Robert Grasso||

NATURE | VOL 410 | 5 APRIL 2001 |

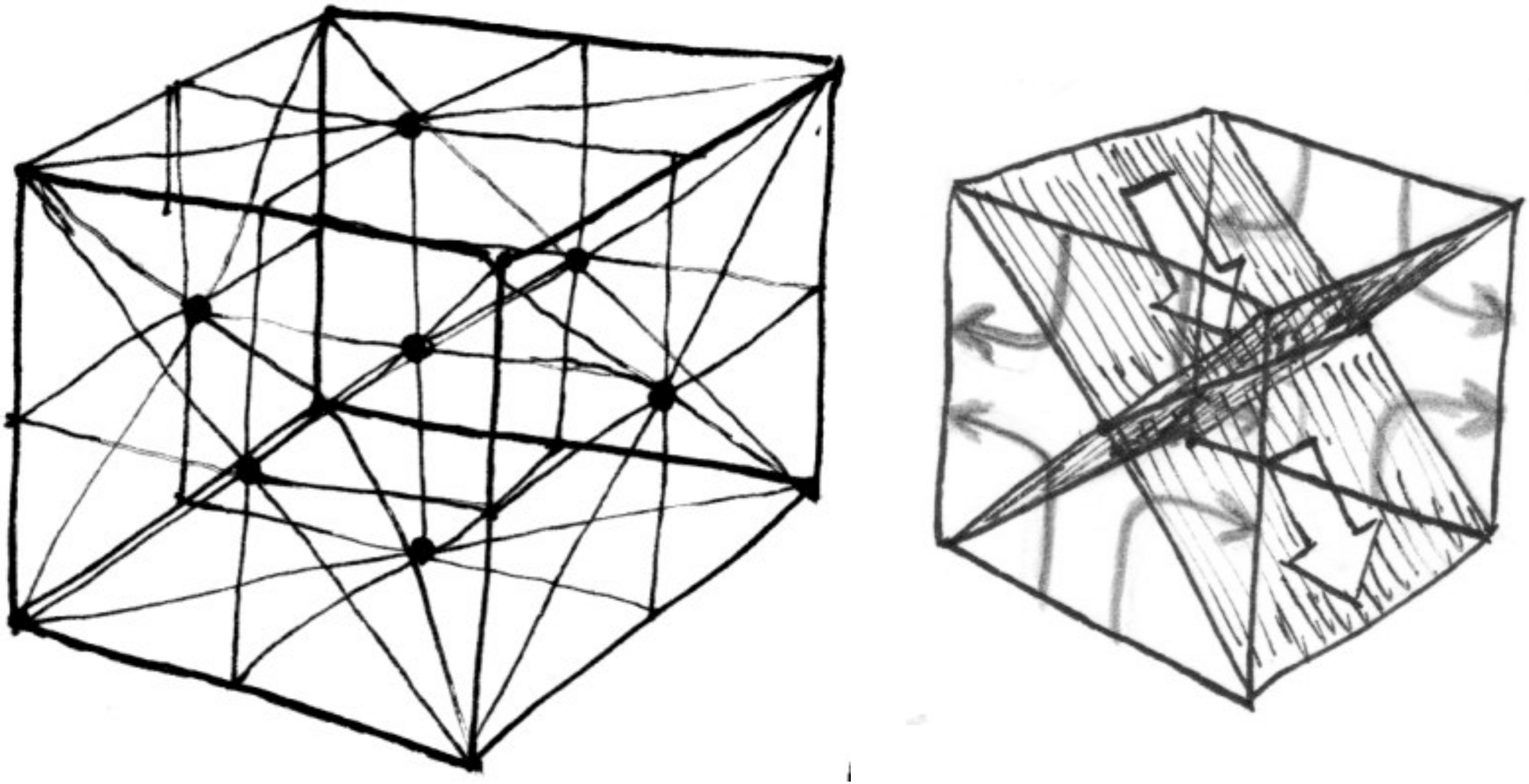


http://www.nature.com/nature/journal/v410/n6829/extref/410667a0_S1.htm

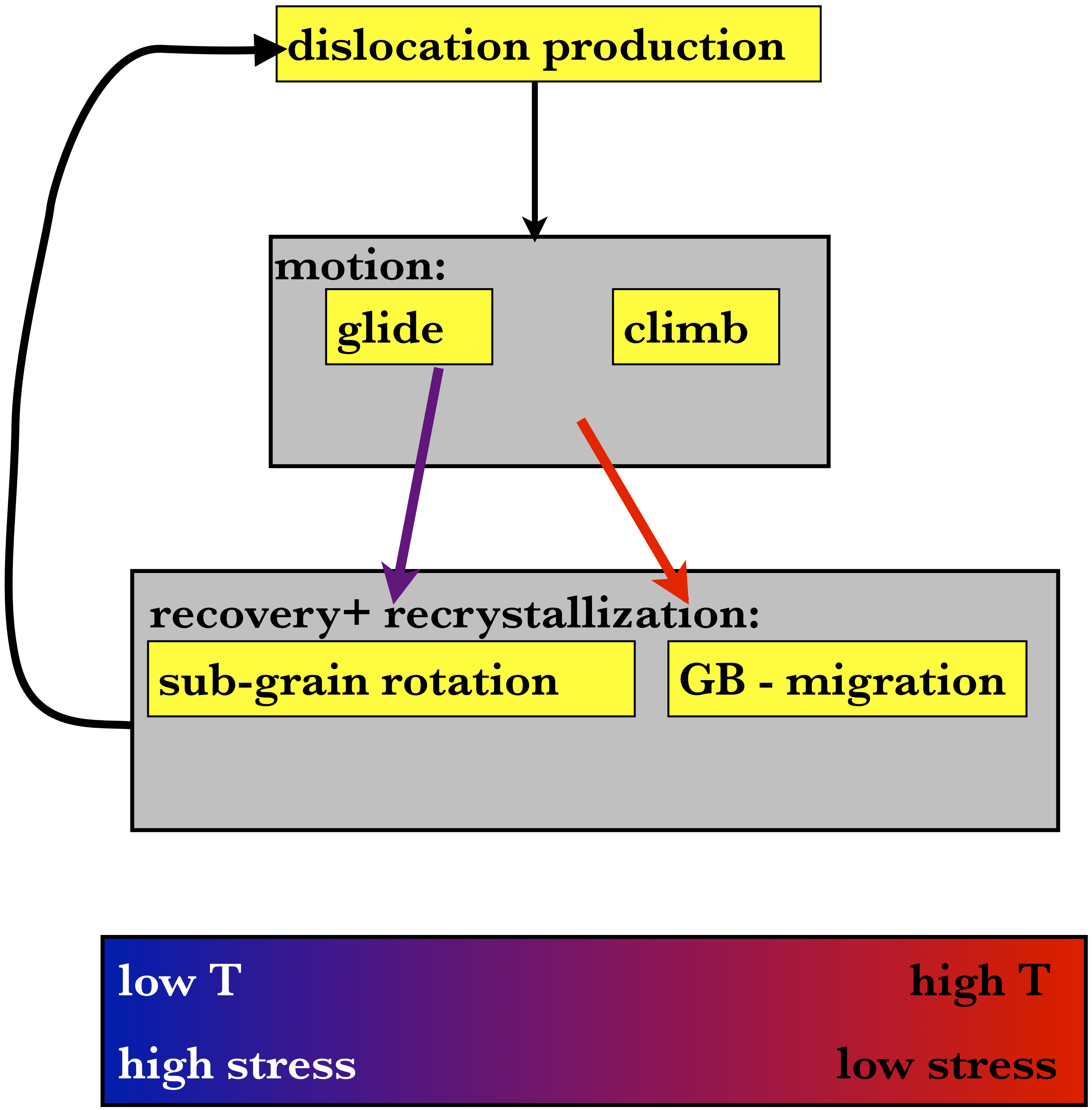
orowan to scholz:
"you can only measure the displacement...
for all you know, there is a guy inside playing the piano..."



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.

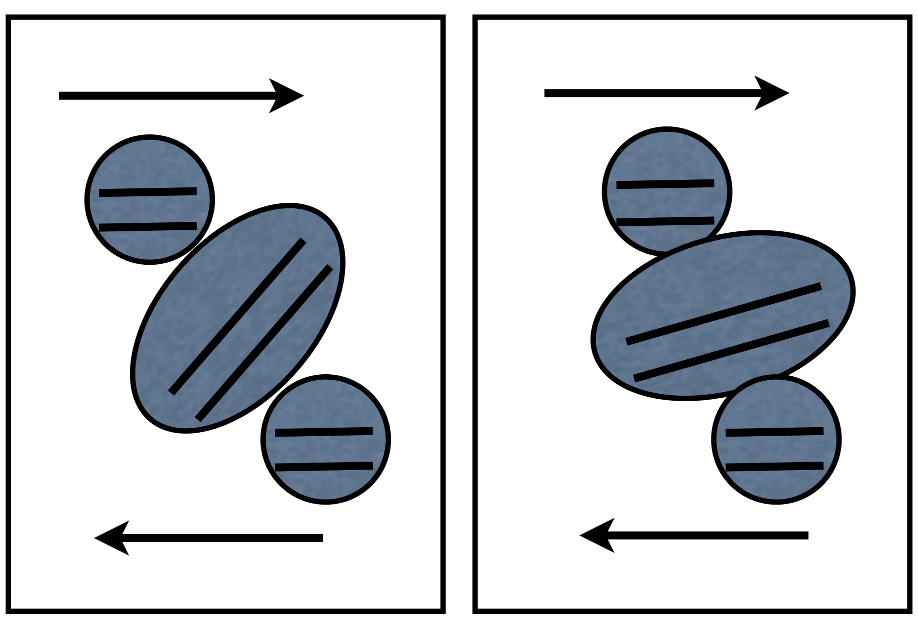

dislocation production
motion:
glide
climb
recovery+ recrystallization:
sub-grain rotation
GB - migration
low T
high T
high stress
low stress

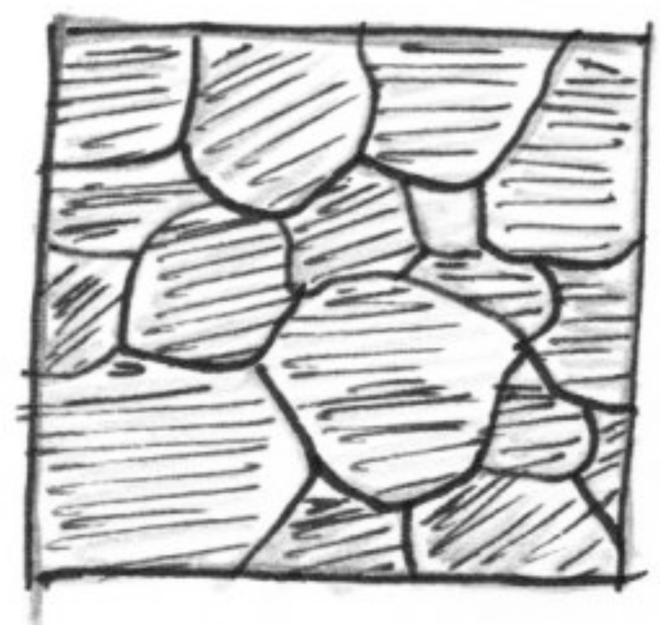
4. Fabric (Lattice preferred orientation) Development

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 recystallization...

rigid body rotation

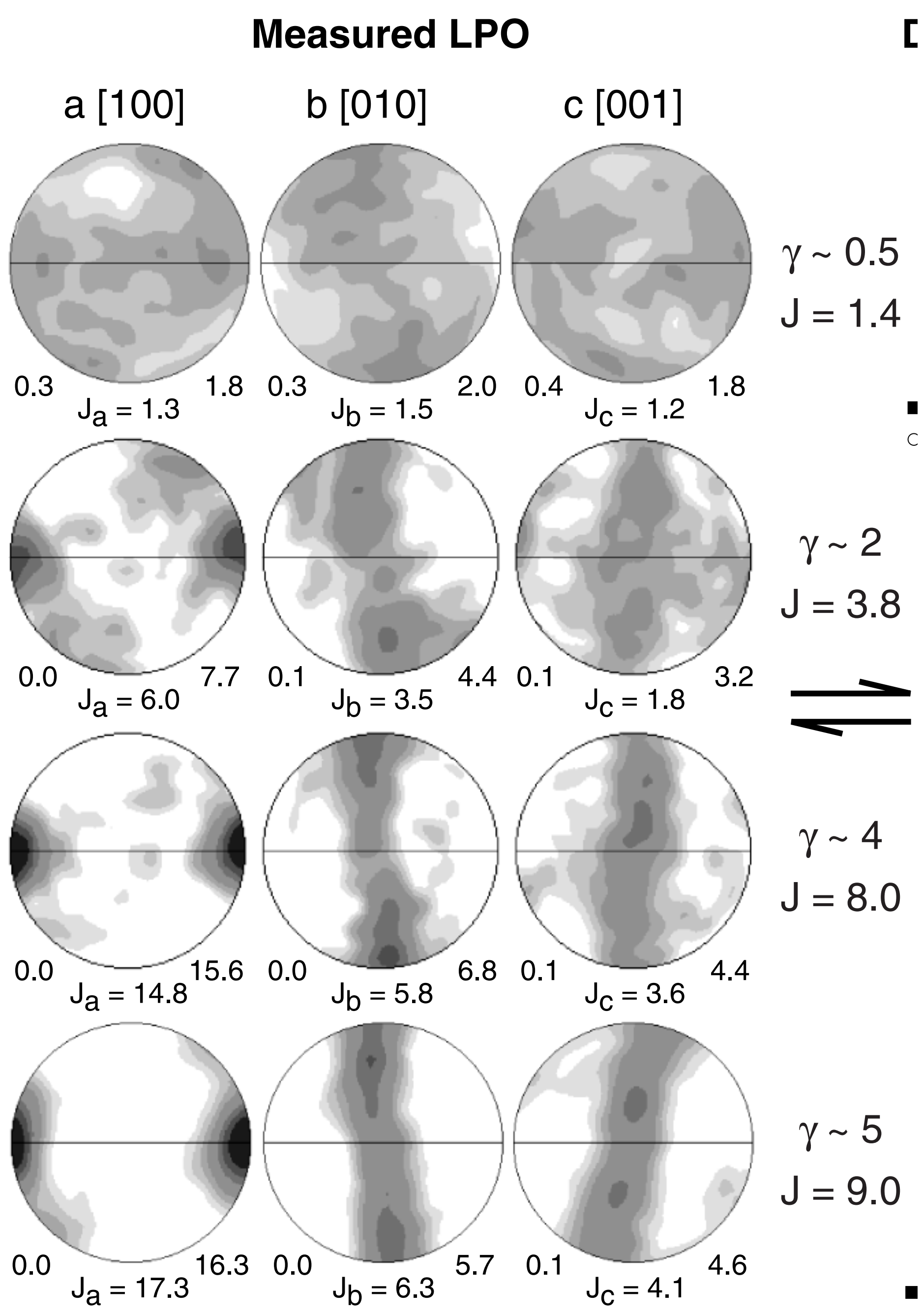


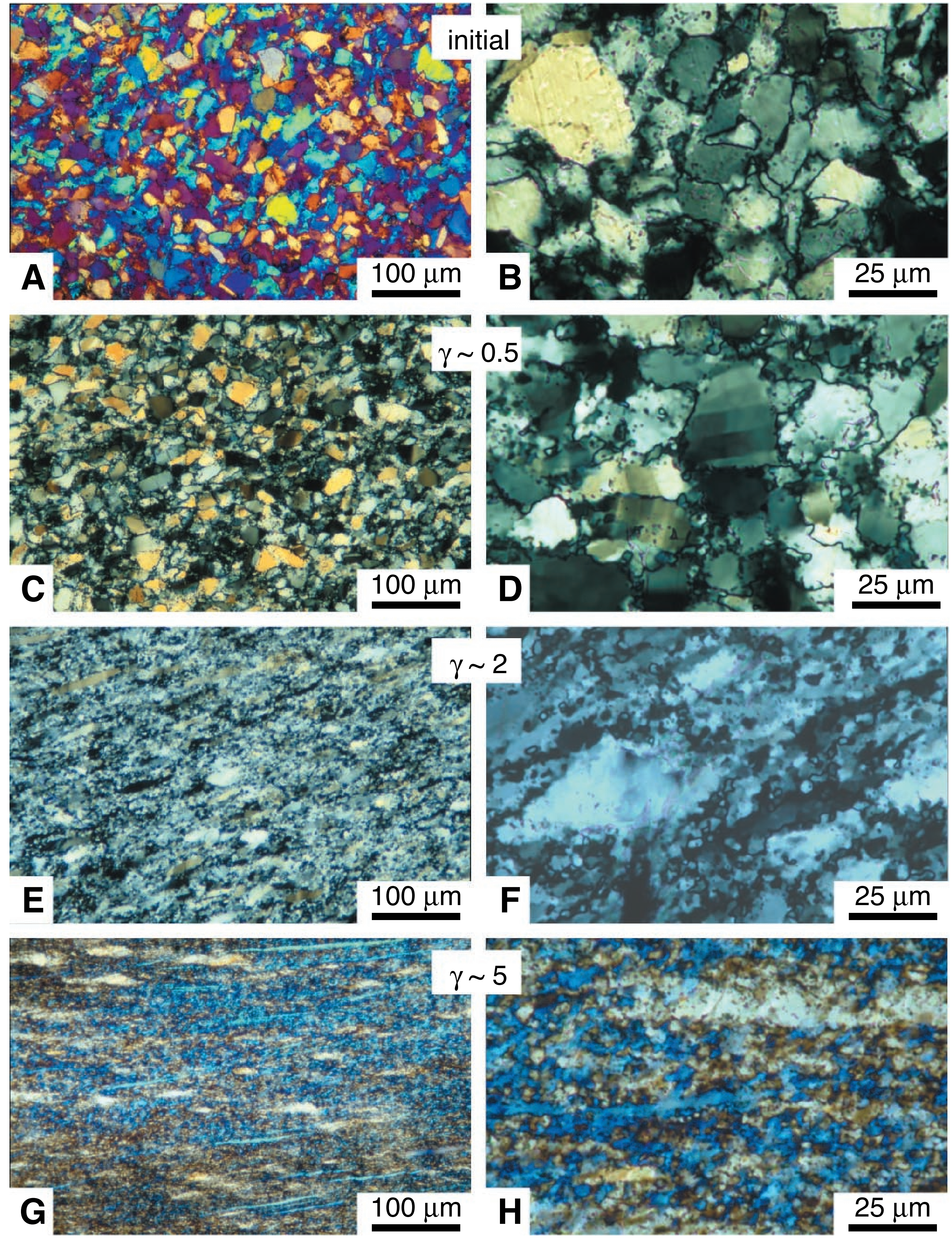


High Shear Strain of Olivine Aggregates: Rheological and Seismic Consequences

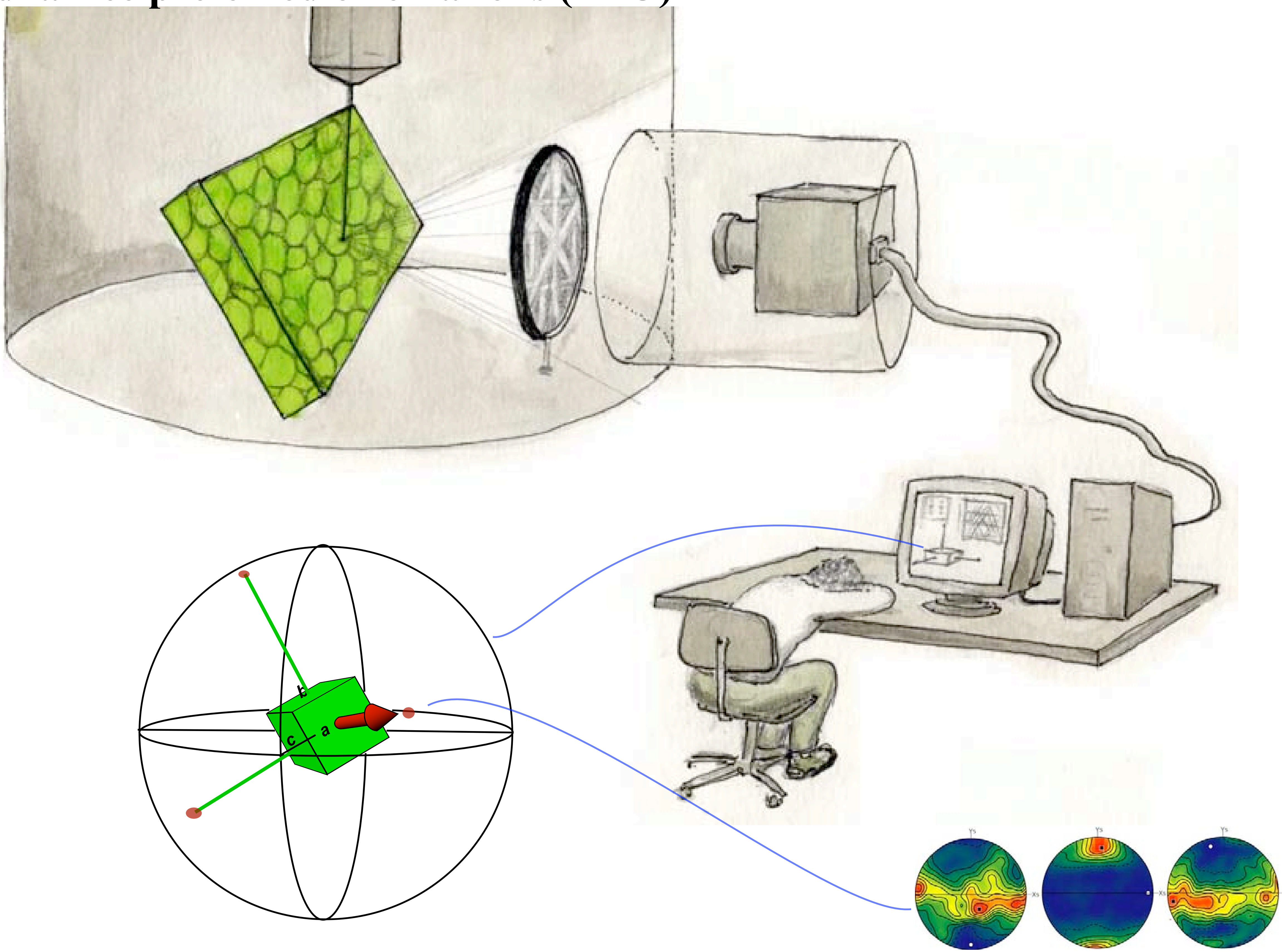
M. Bystricky,* K. Kunze, L. Burlini, J.-P. Burg

24 NOVEMBER 2000 VOL 290 SCIENCE





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

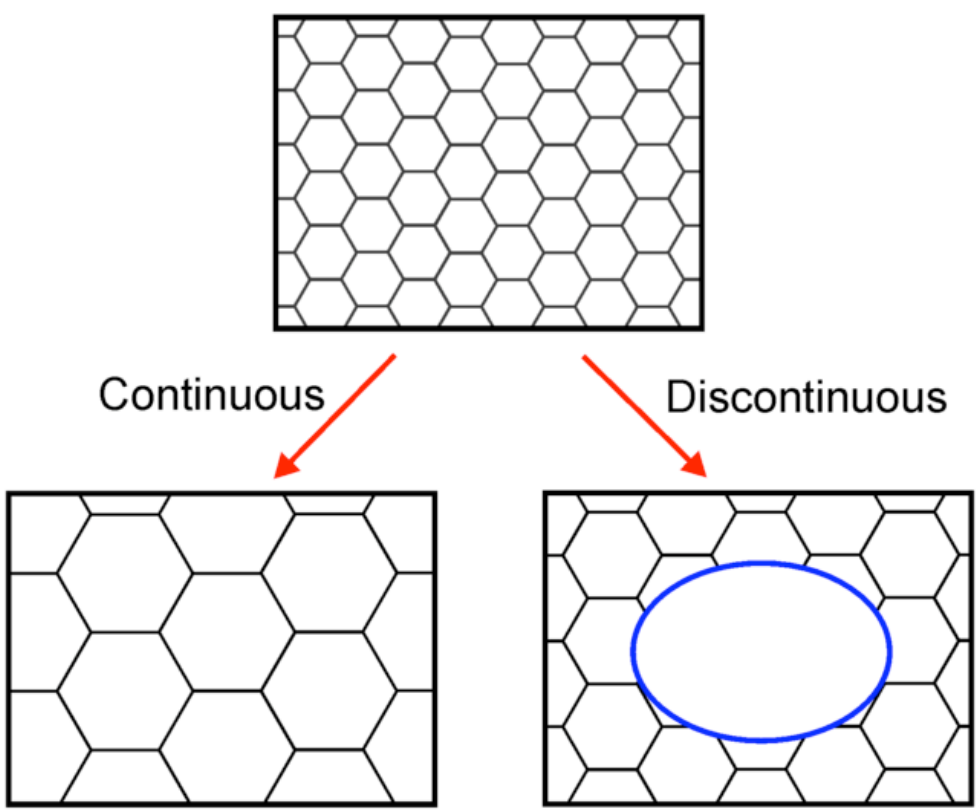


5. Grain Growth

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.

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



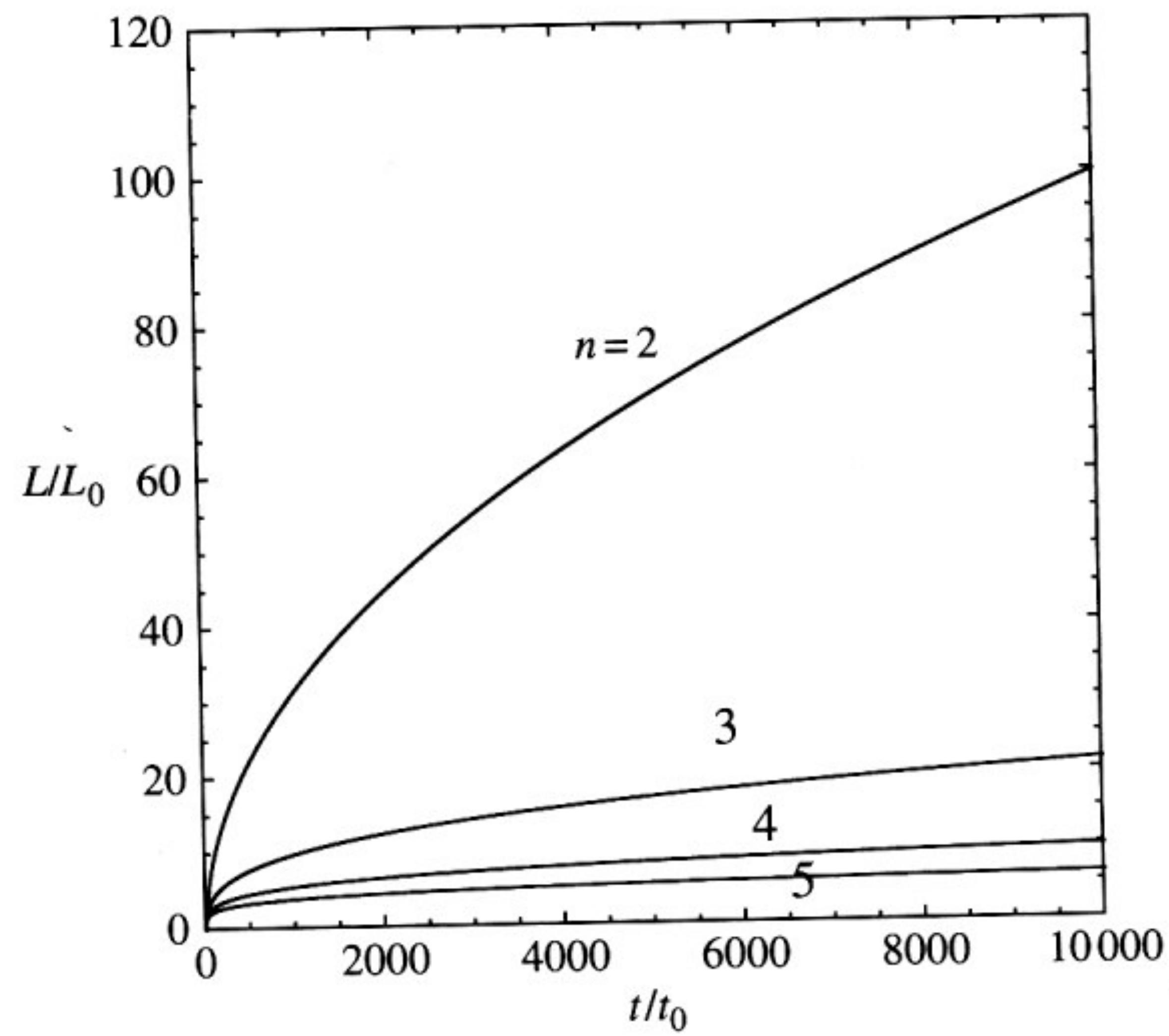
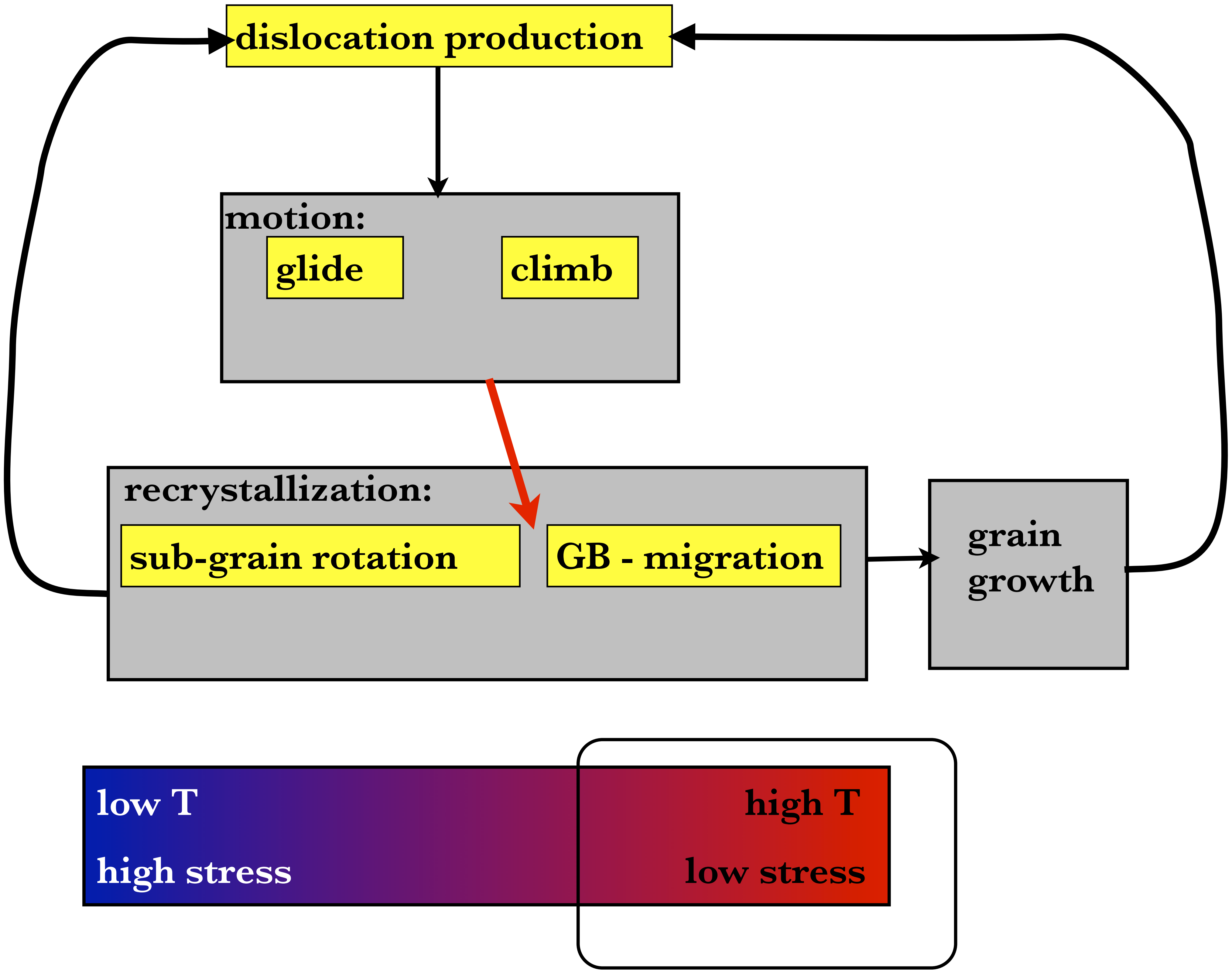


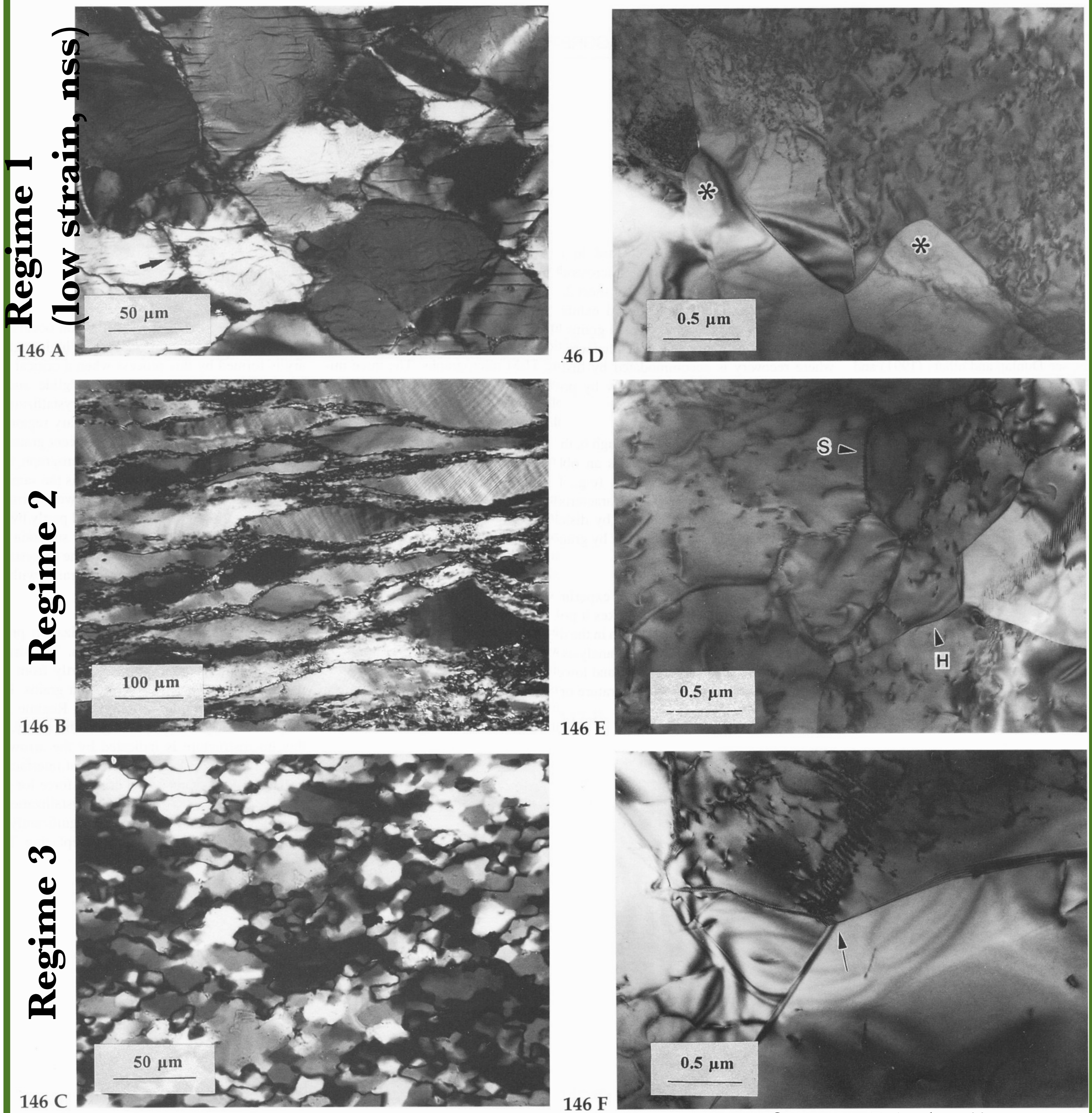
FIGURE 13.7 A plot of the grain size versus the time relation for various n $(t_0 \equiv L_0^n/k_n)$.

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

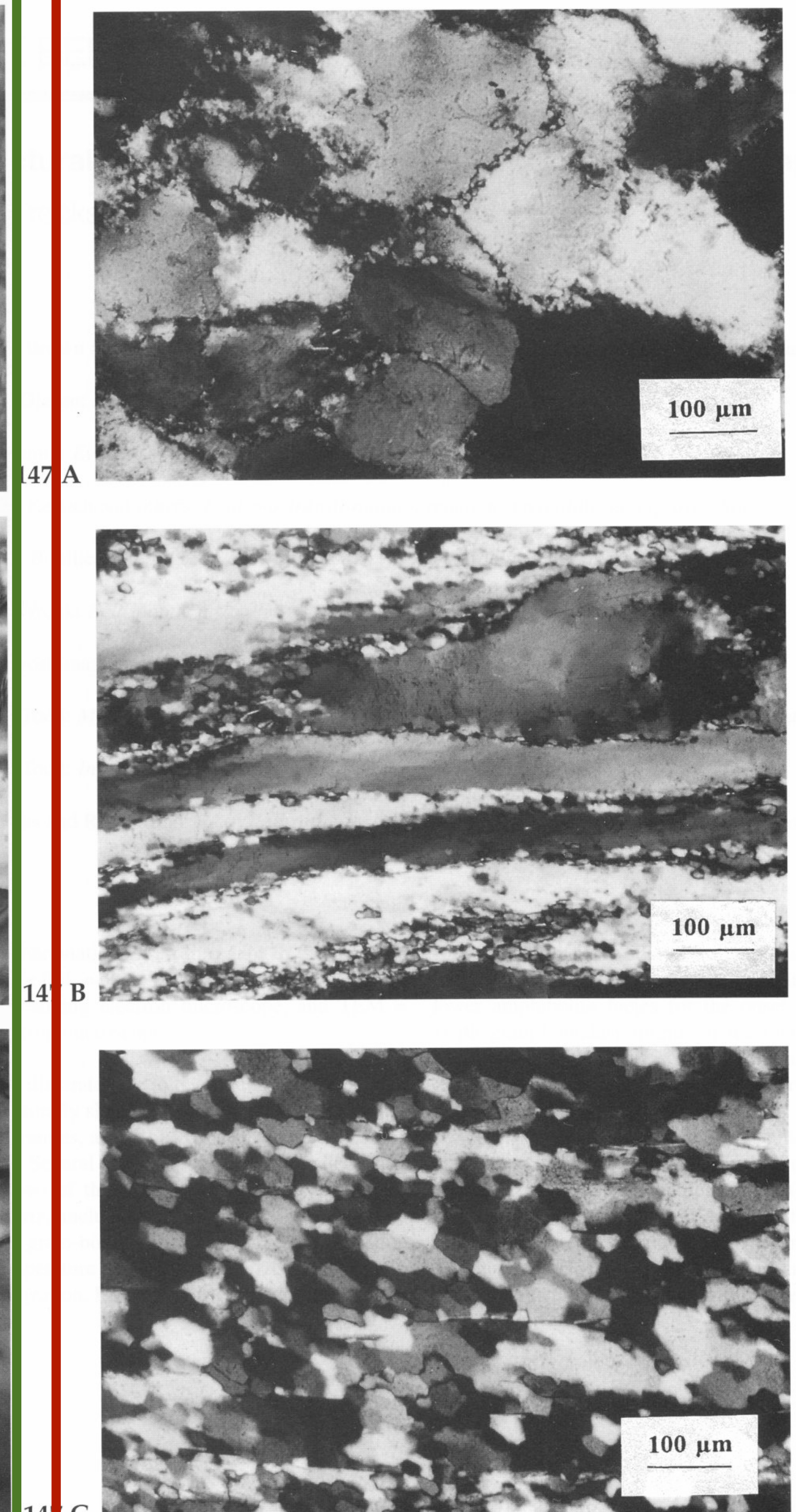

dislocation production
motion:
glide
climb
recrystallization:
sub-grain rotation
GB - migration
grain
growth
low T
high stress
high T
low stress

1. REVISIT Intro: Observations

Experimentally deformed:



Naturally deformed



from: “Atlas”

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

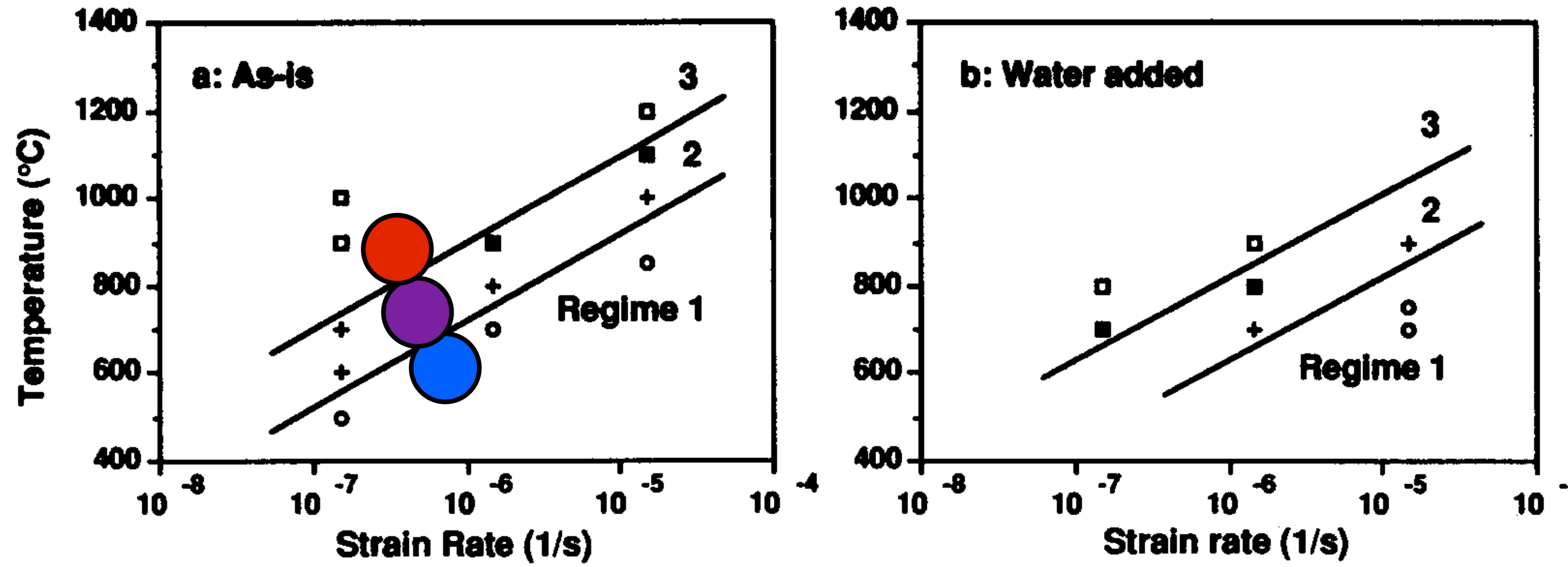
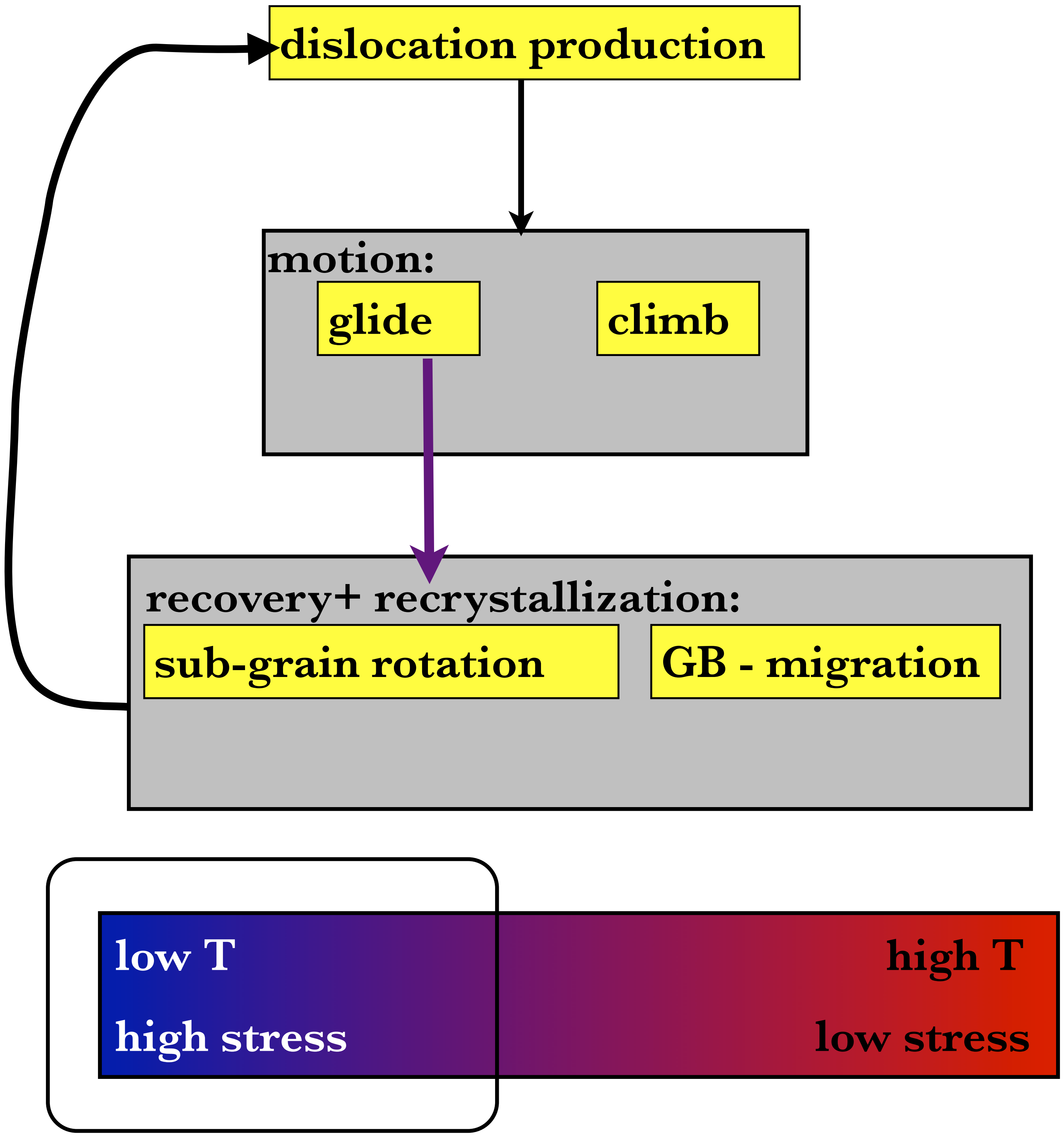


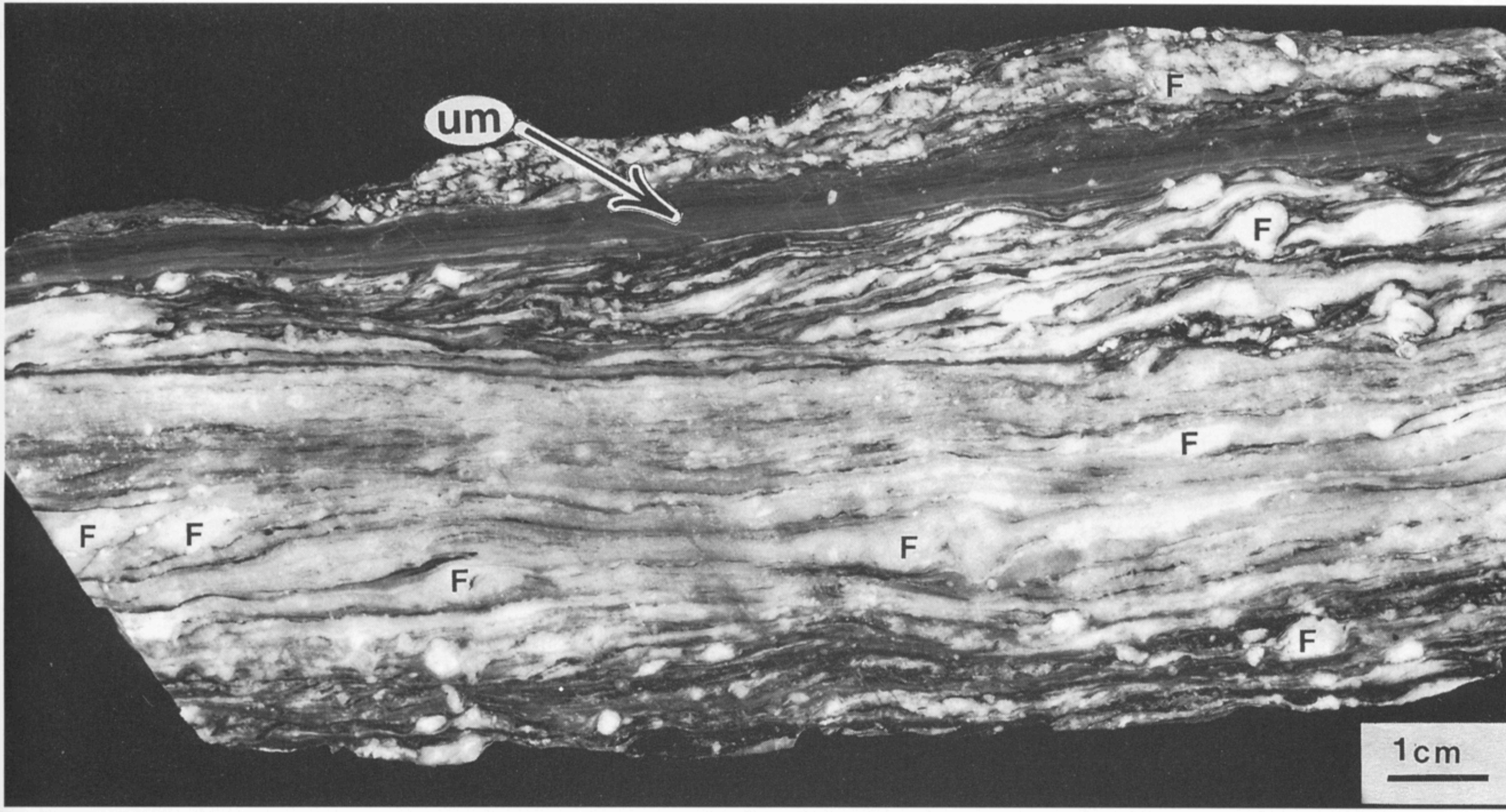
Fig. 2. Plots of temperature vs strain rate showing the location of the dislocation creep regimes for quartz aggre deformed (a) 'as-is' and (b) with 0.17 wt% water added. The boundaries between the regimes are gradational. Open c represent regime 1, plus symbols represent regime 2, open squares represent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


dislocation production
motion:
glide
climb
recovery+ recrystallization:
sub-grain rotation
GB - migration
low T
high stress
high T
low stress



from: “Atlas”

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 effected 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

6. PIEZOMETERS

1. Empirical Piezometers (dislocations, subgrain and grain size), for olivine and quartz. Independent of T, water content, melt.

2. Theory(?): Why should these be independent of temperature and water?

3. The WATTMETER

Where this is going: Stress across shear zones (Kohlstedt and Weathers)
Stress in the lithosphere from xenoliths (Mercier)

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)

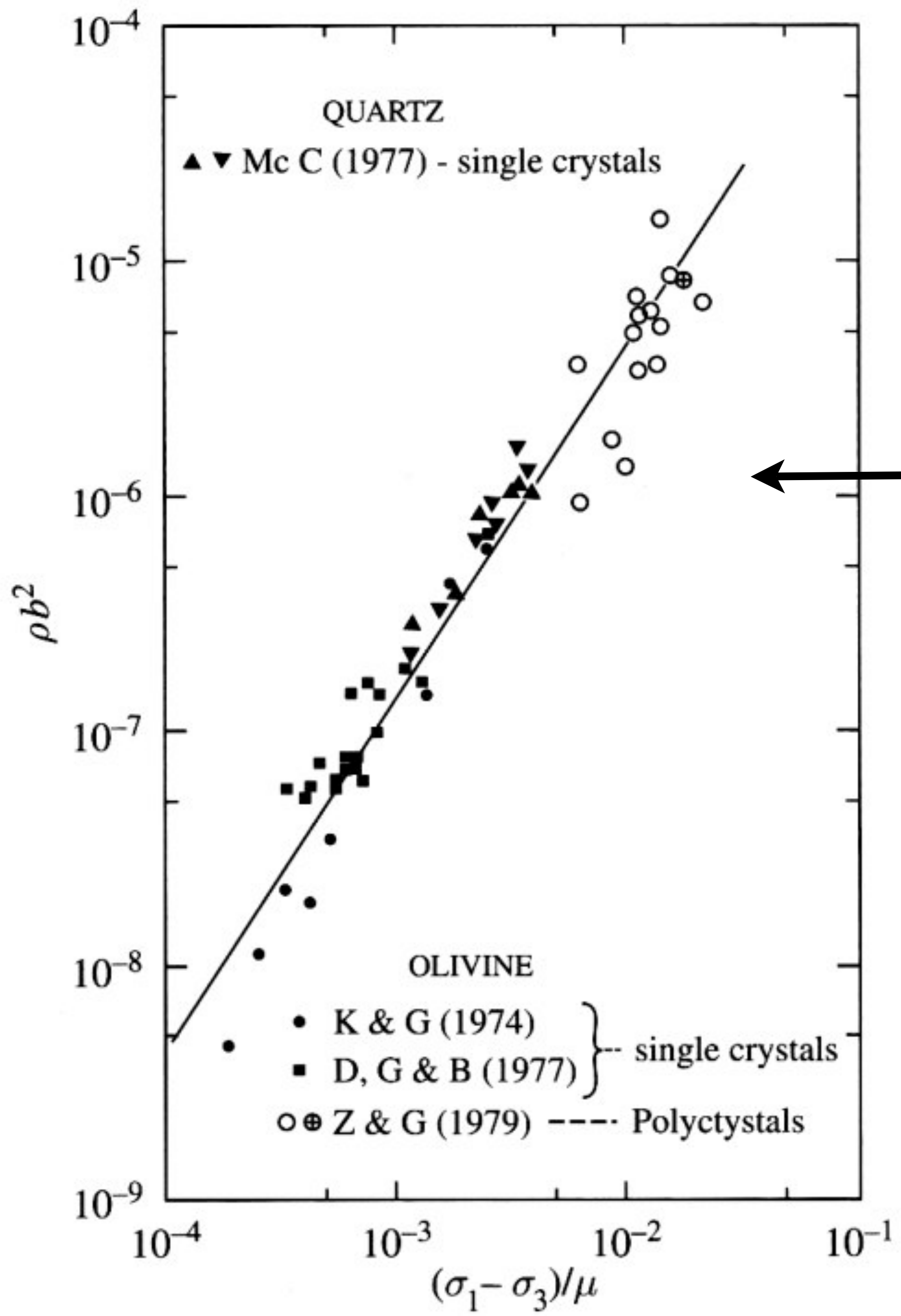


FIGURE 5.7 The dislocation density versus stress relationship (after Kohlstedt and Weathers, 1980).

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:

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

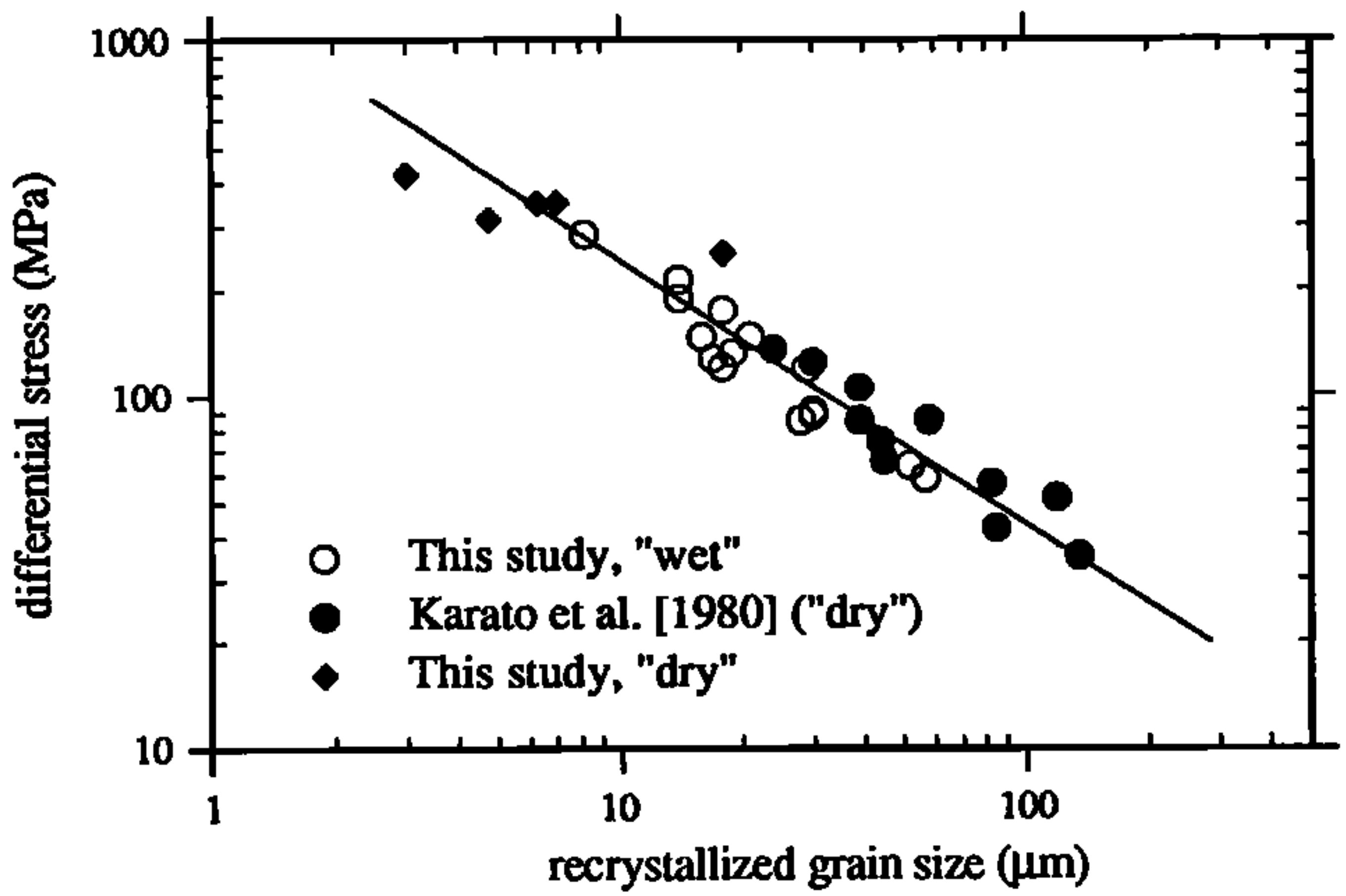
Grain size:

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

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:

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

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

an example of transients:

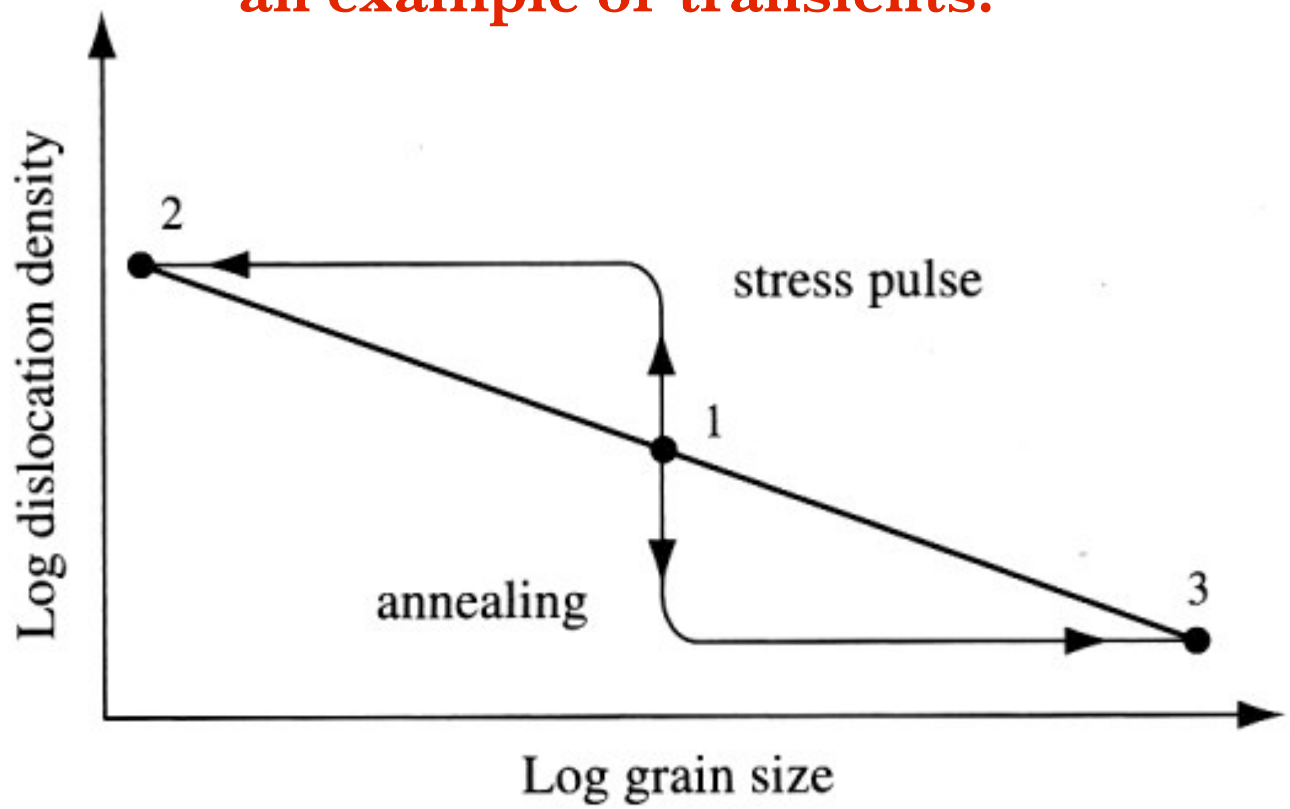


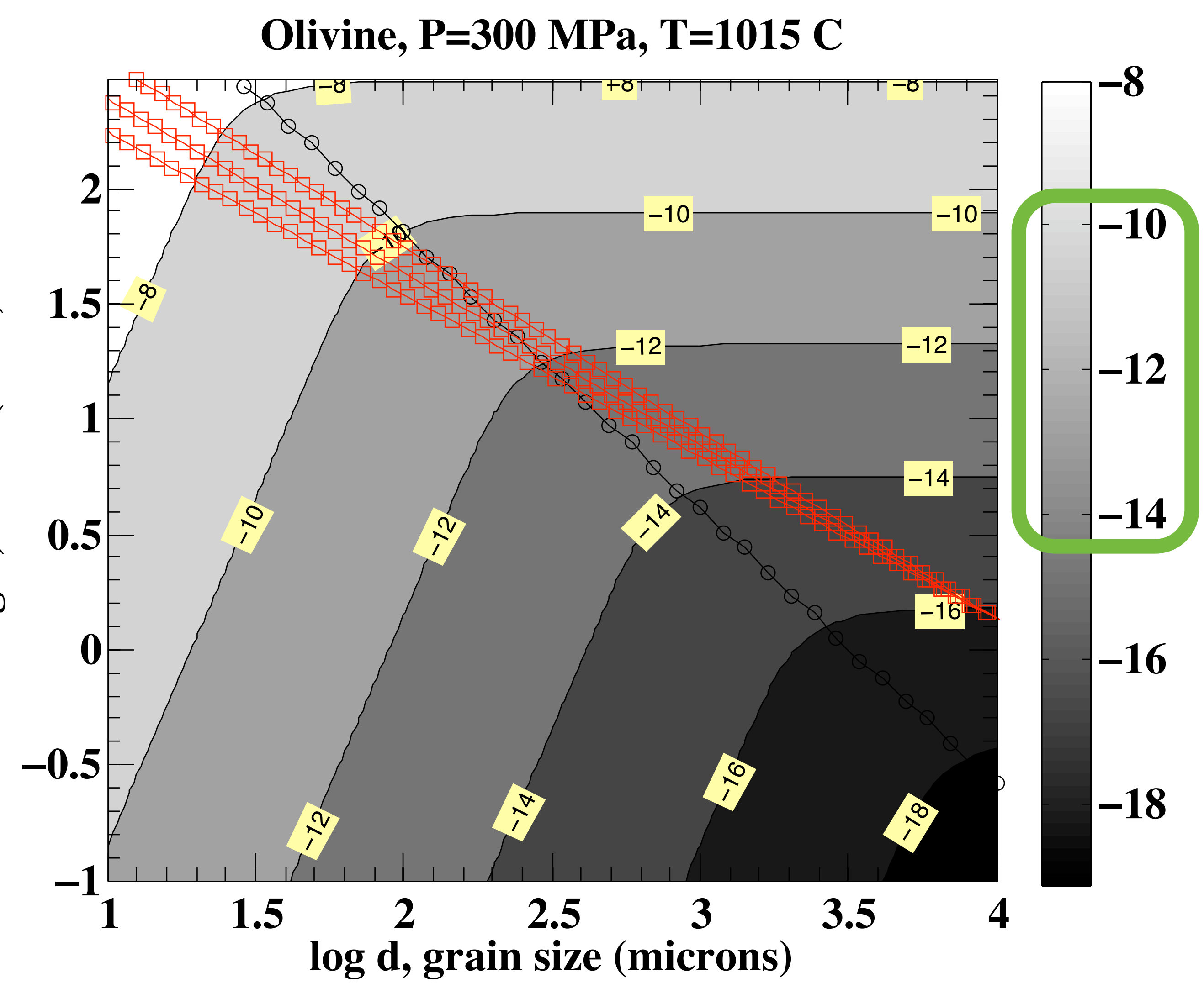
FIGURE 13.16 A dislocation density versus dynamically recrystallized grain size plot. If both dislocation density and recrystallized grain size correspond to a steady state, then the data should fall on a single line. Deviations from this line indicate non-steady-state deformation such as a stress pulse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

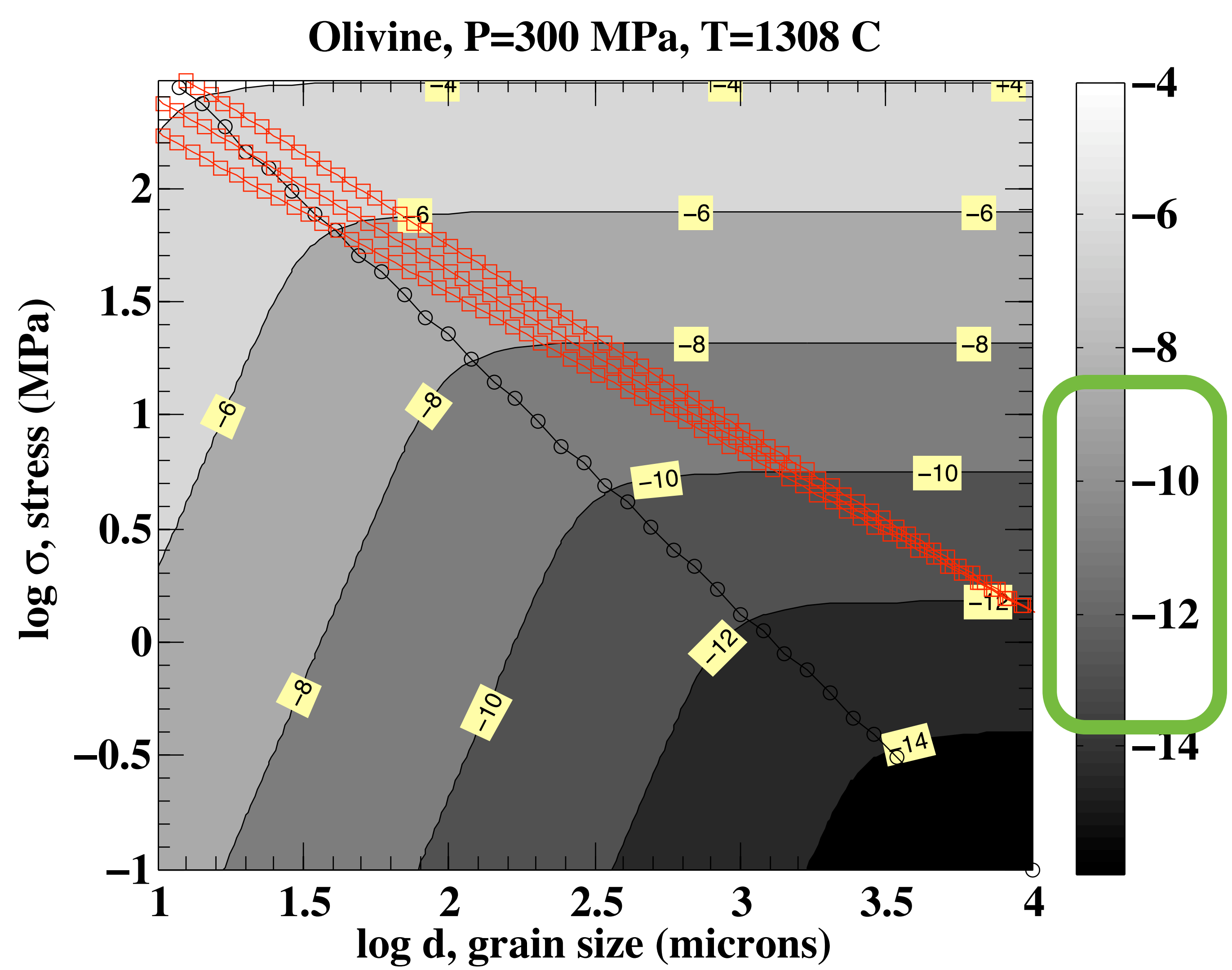
for dislocation density:
olivine: 1% strain
quartz: 3% strain

for grain size,
closer to 100% strain

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





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

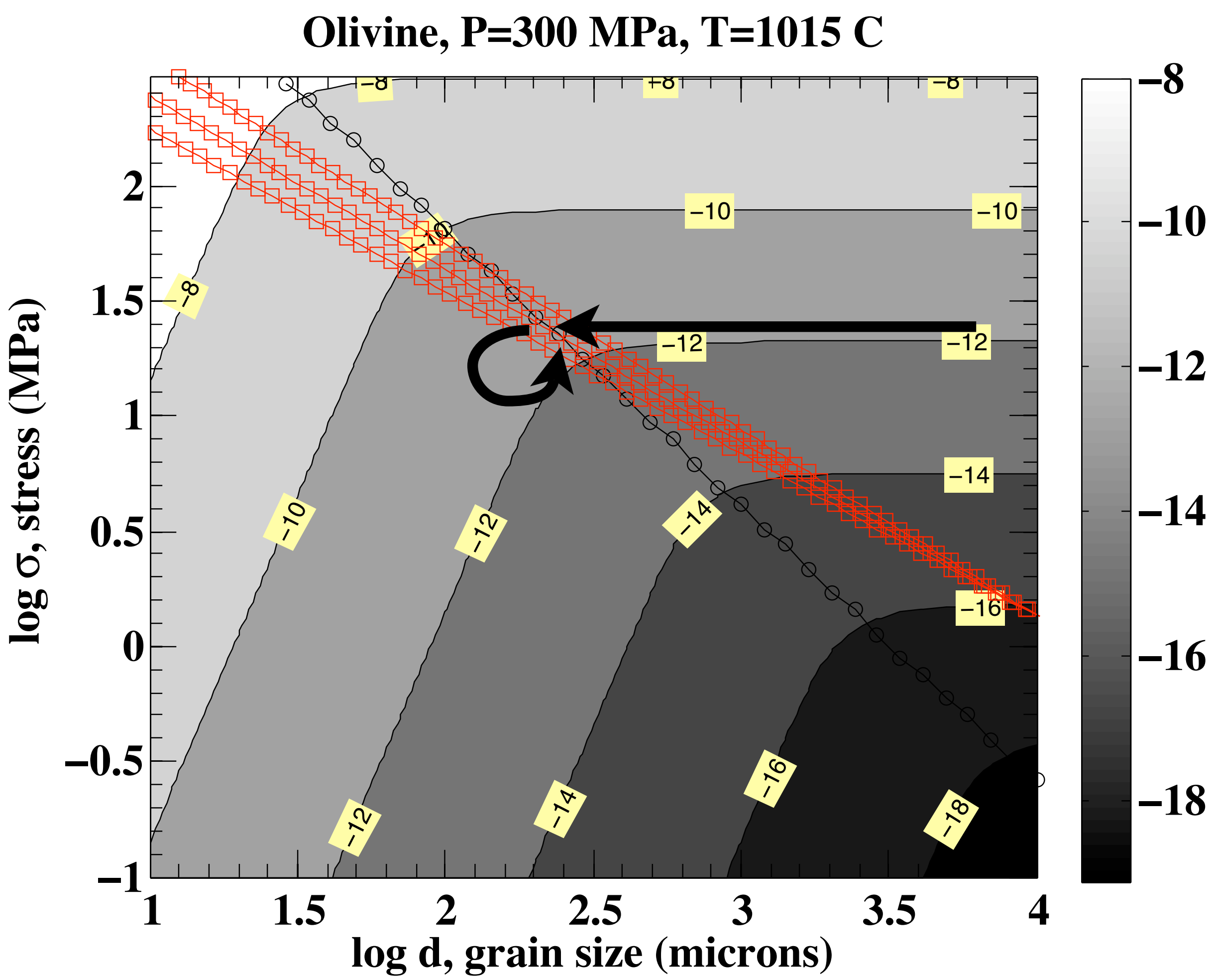
if those parameters affect the factors in the ratio approximately equally, the ratio will not change !

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

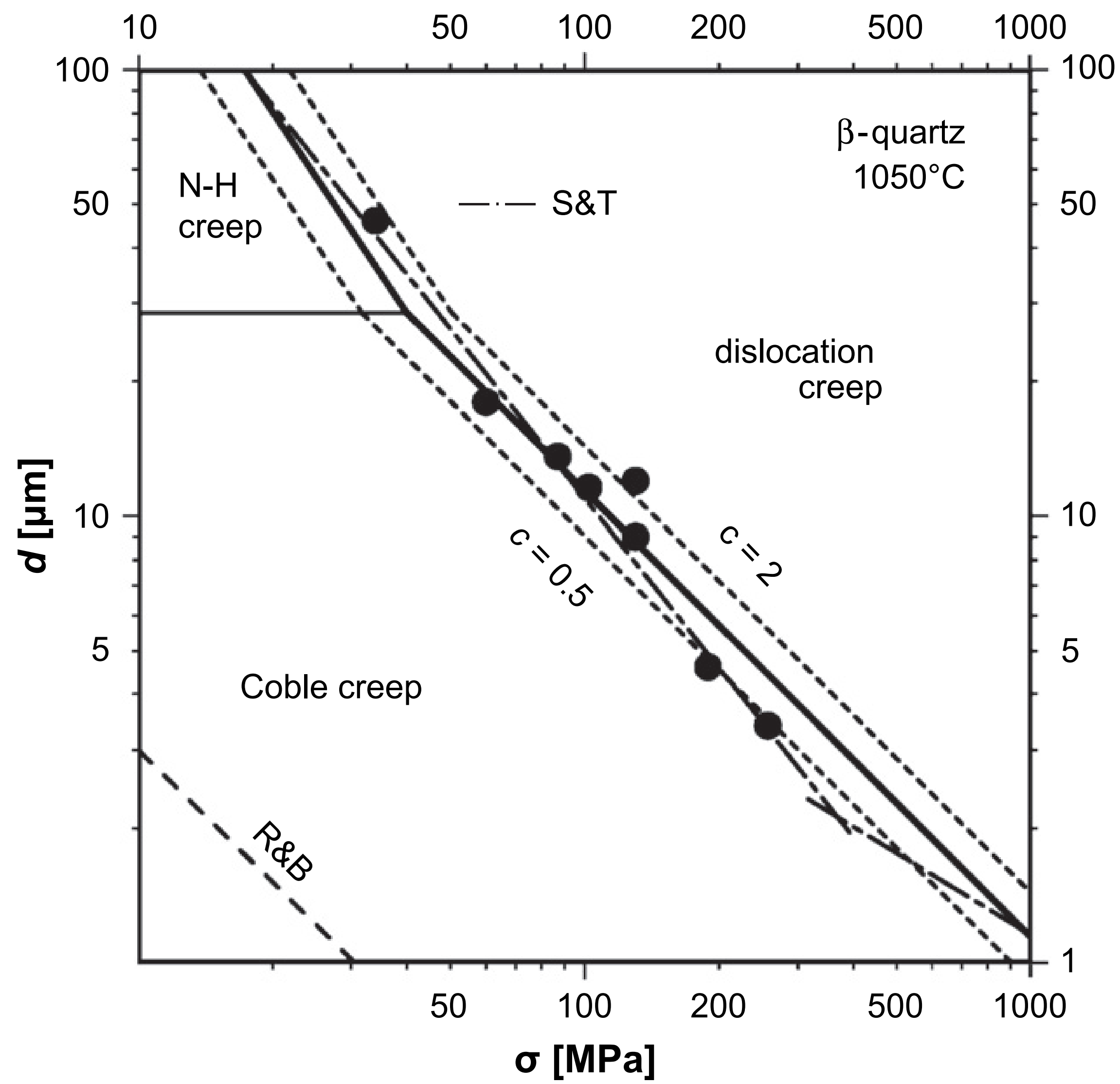
J.H.P. De Bresser · J.H. Ter Heege · C.J. Spiers

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

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



quartz:



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

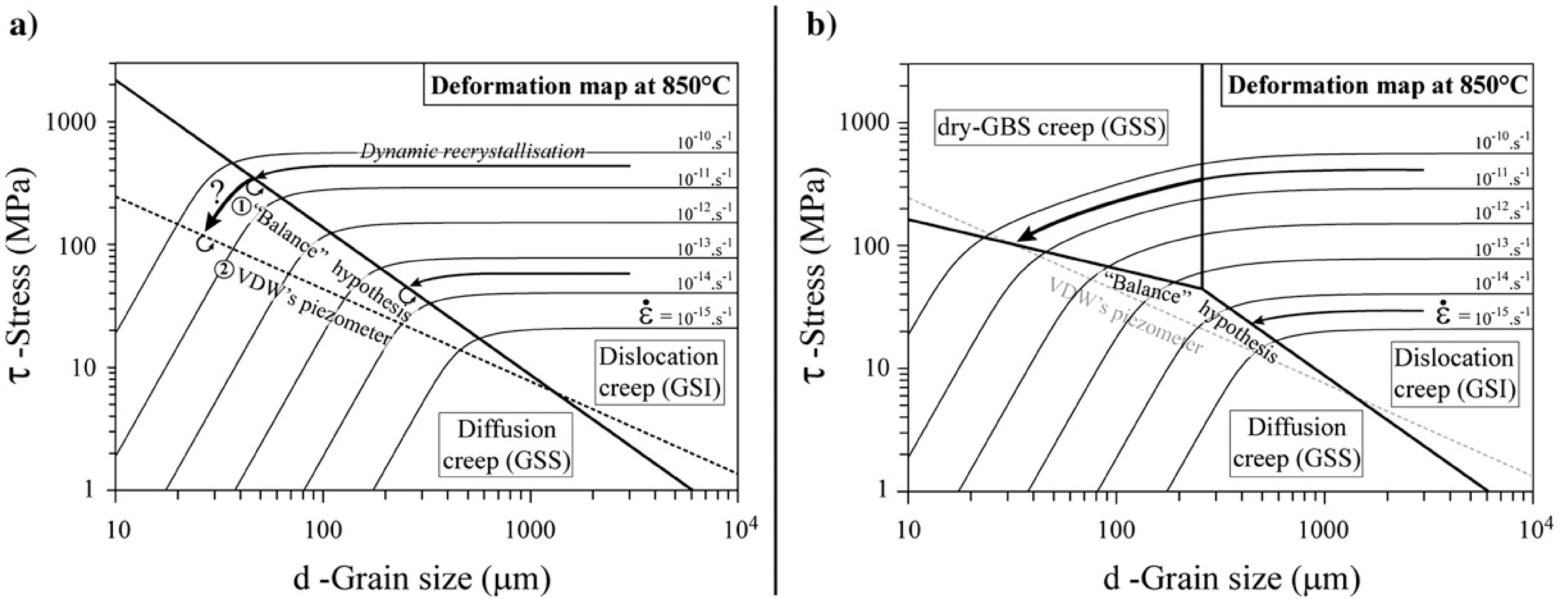
Theories and applicability of grain size piezometers: The role of dynamic recrystallization mechanisms

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.

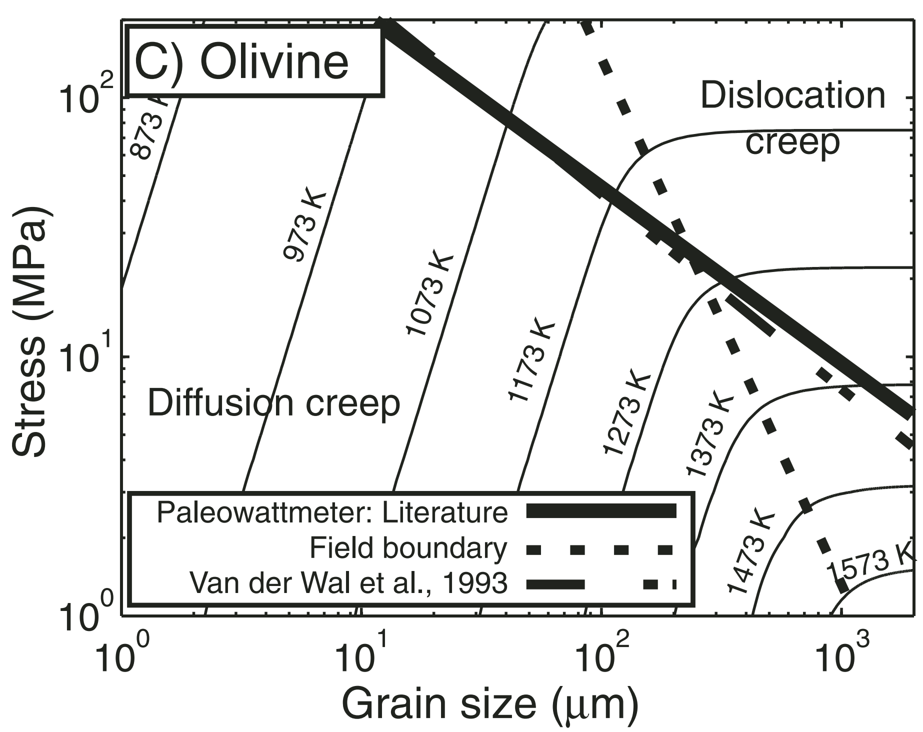
based on ideas from non-equilibrium thermodynamics: the recrystallized grain size represents the budget of energy being stored in grain boundaries and energy dissipated by flow.

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