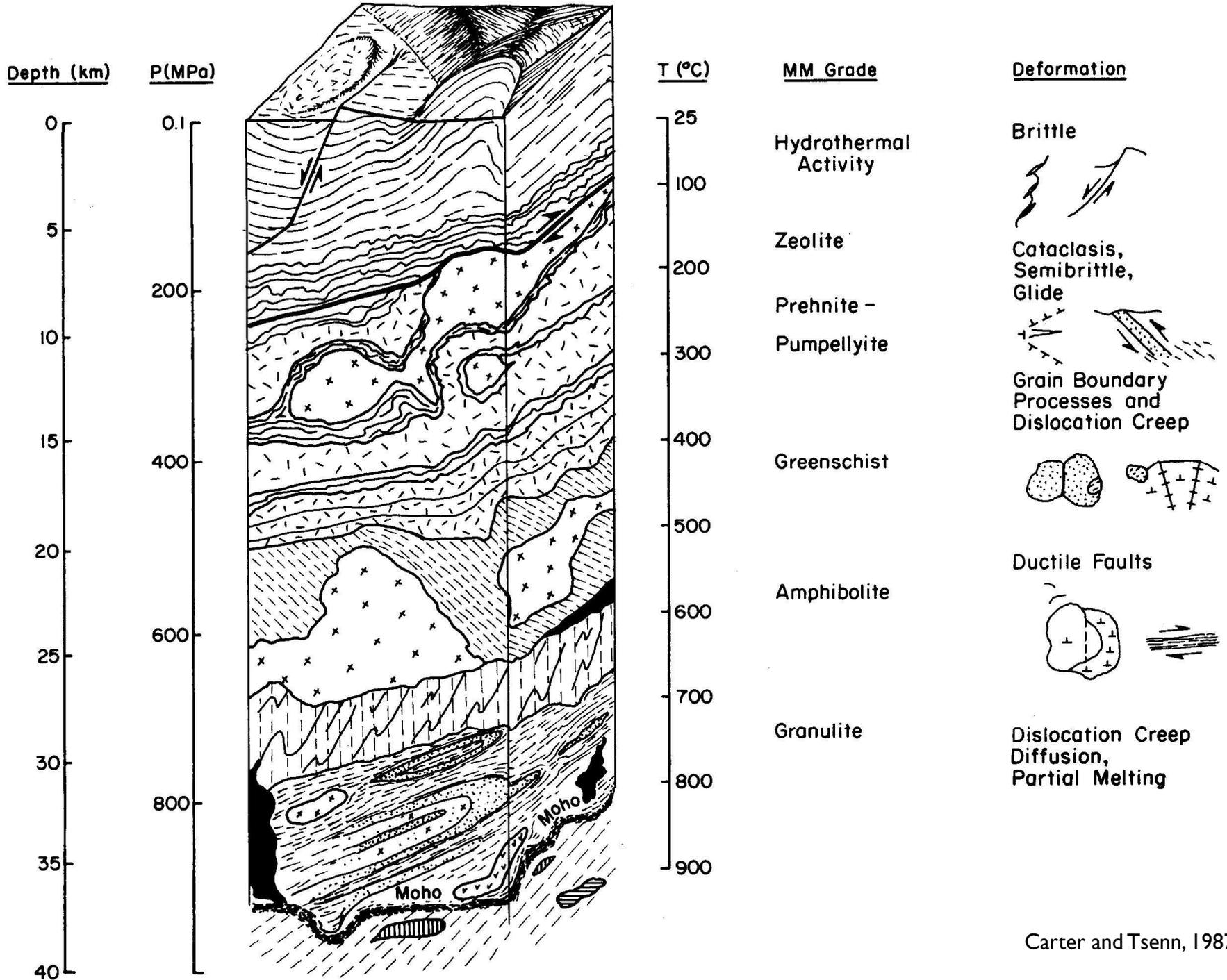
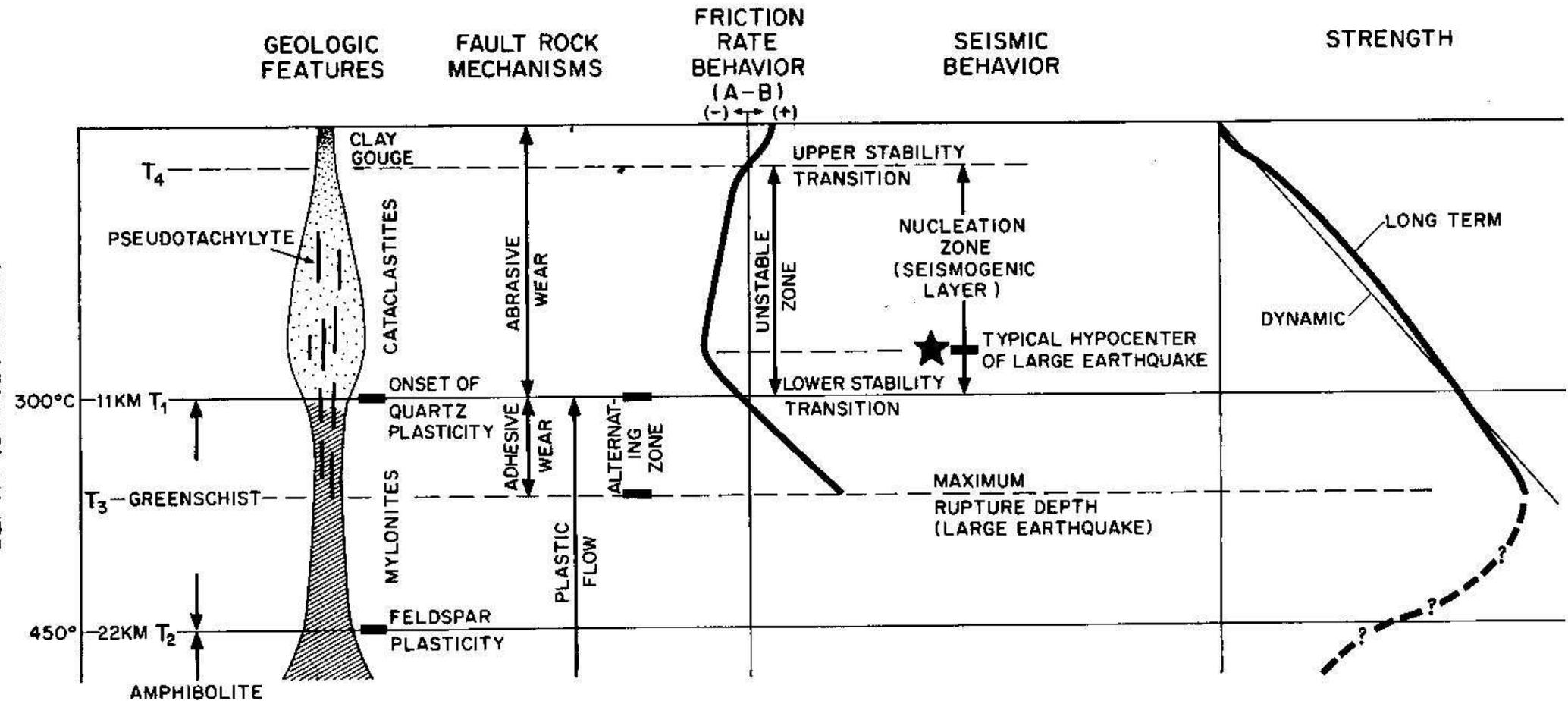


Figure 6-10 Brittle-to-ductile transition of pyroxenite. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression. (After Kirby, 1980.)

CONTINENTAL CRUST



Seismo-structural section through the San Andreas fault



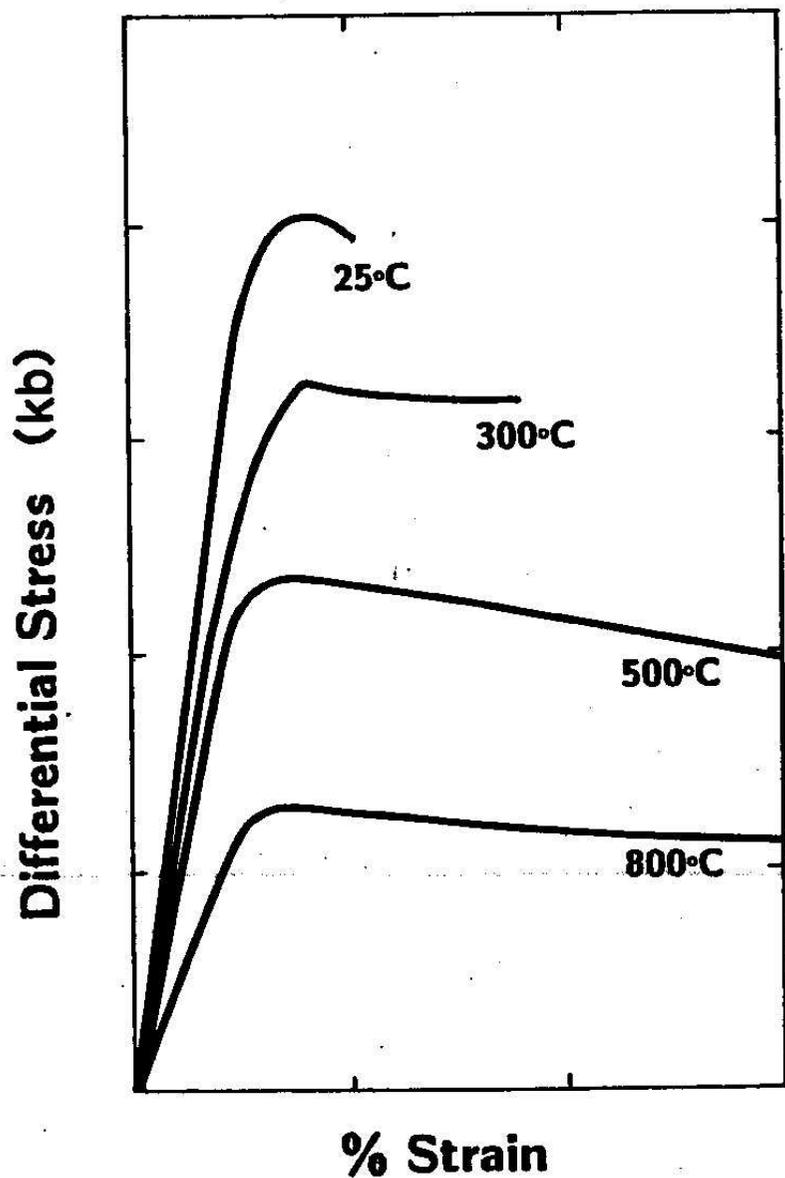


Figure 6-11 Temperature effects on the behavior of granite tested in compression. (After Heard, 1960.)

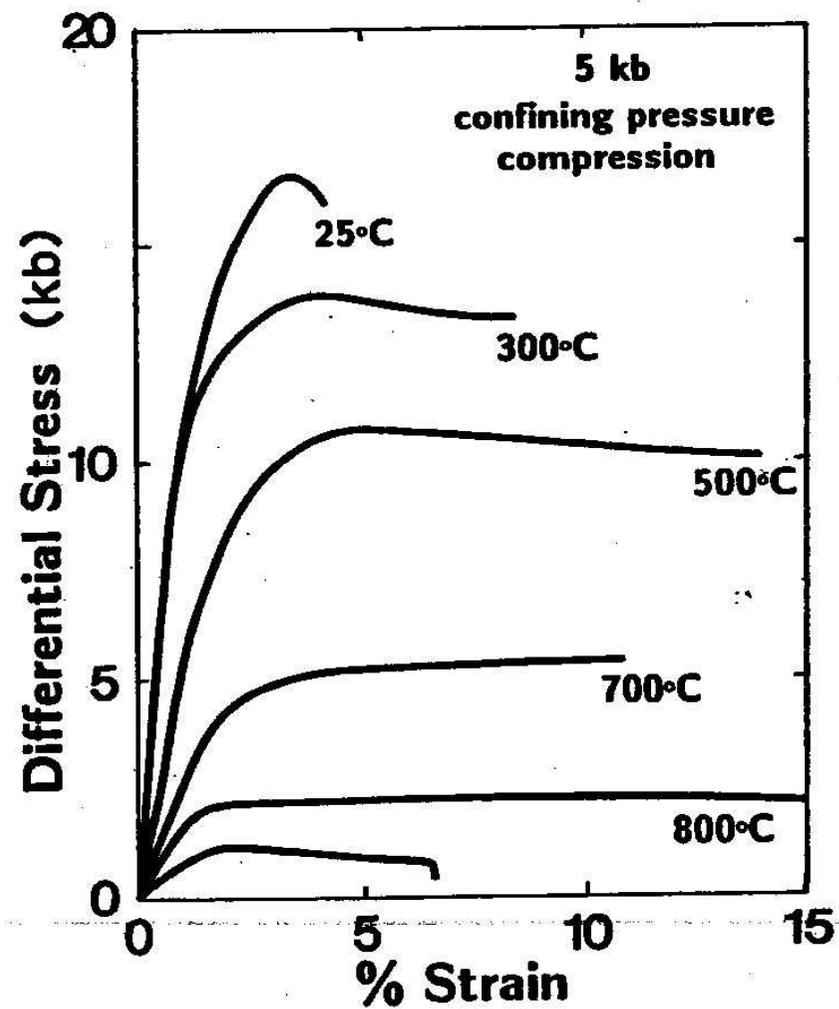
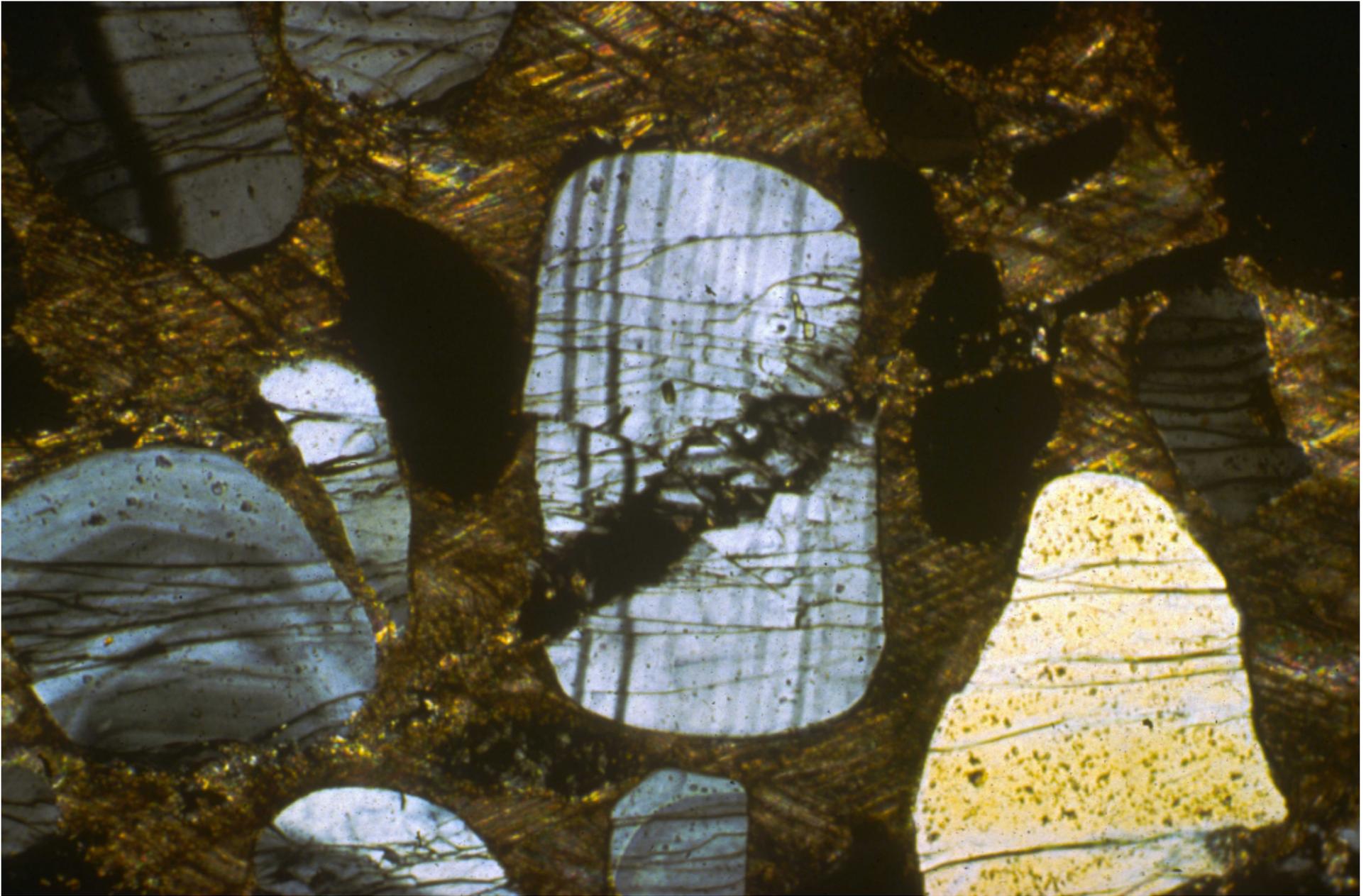


Figure 6-12 Temperature effects on the behavior of basalt tested in compression. (After Heard, 1960.)

Brittle deformation in calcite-cemented quartz sandstone.



Experimental cataclastic shear



video by Winn Means

Low-Temperature Crystal Plasticity

Processes that depend more on differential stress than on temperature, and that change a mineral's shape without melting, fracturing or faulting.

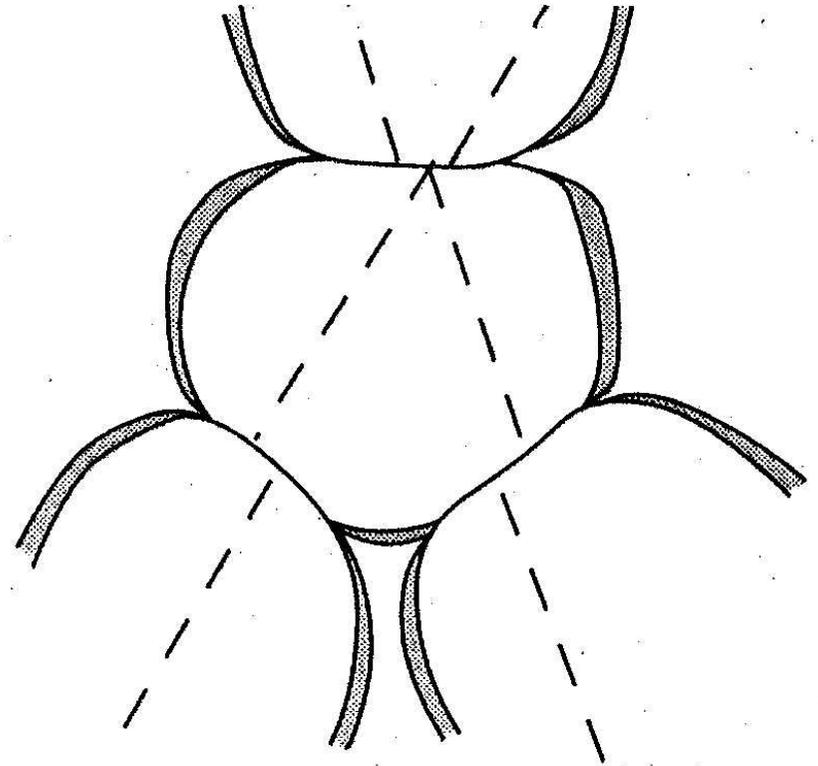
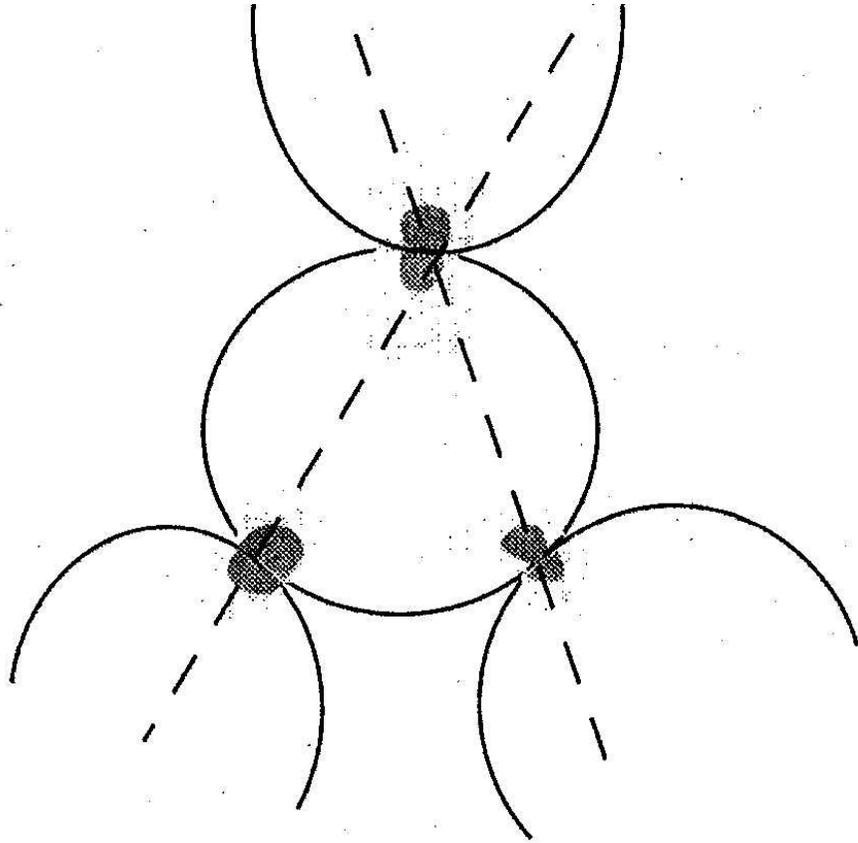
- Pressure solution
- Kinking
- Dislocation glide
- Mechanical twinning

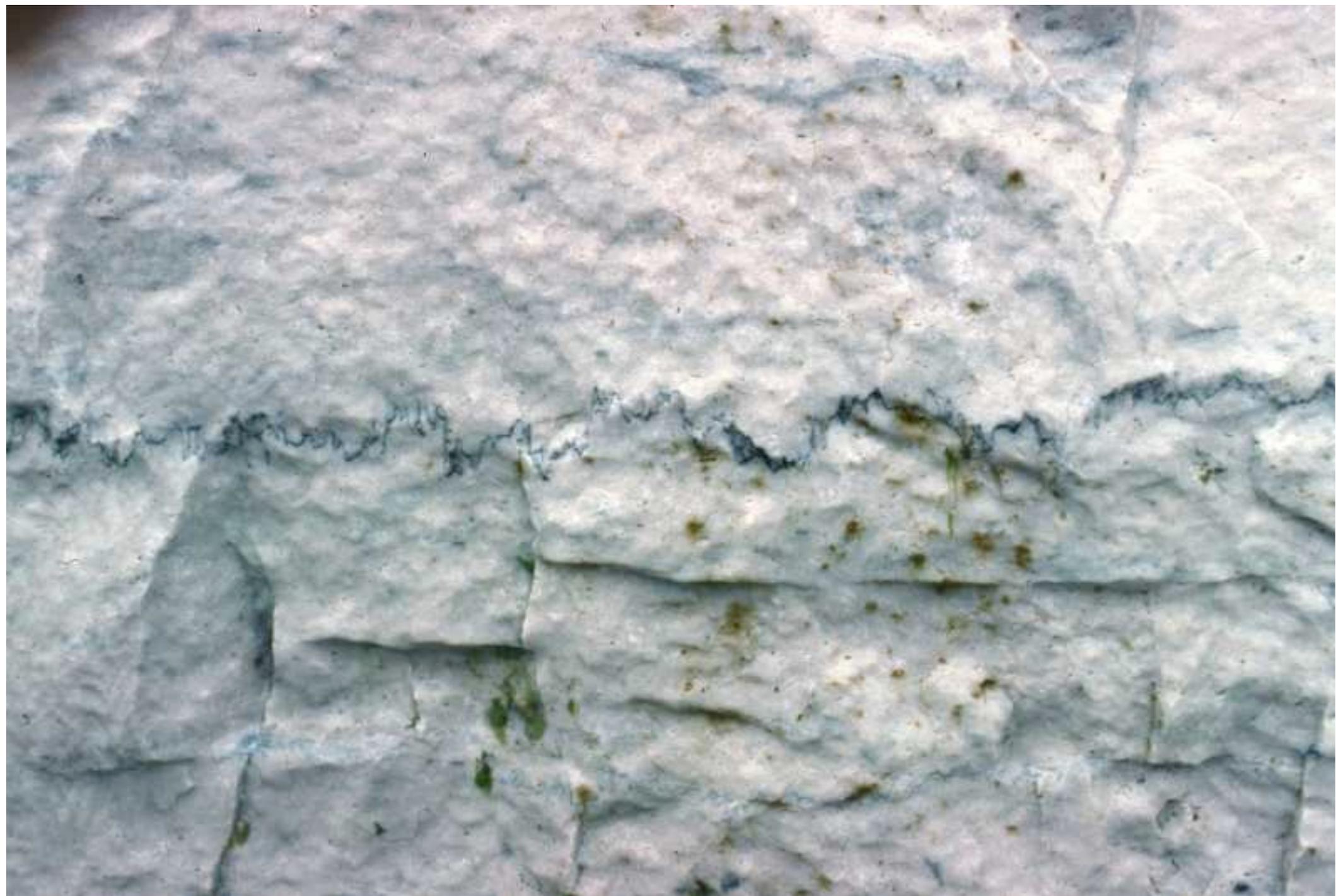
Low-Temperature Crystal Plasticity

Processes that depend more on differential stress than on temperature, and that change a mineral's shape without melting, fracturing or faulting.

- Pressure solution

Pressure solution





Low-Temperature Crystal Plasticity

Processes that depend more on differential stress than on temperature, and that change a mineral's shape without melting, fracturing or faulting.

- Pressure solution
- Kinking

Development of kink bands

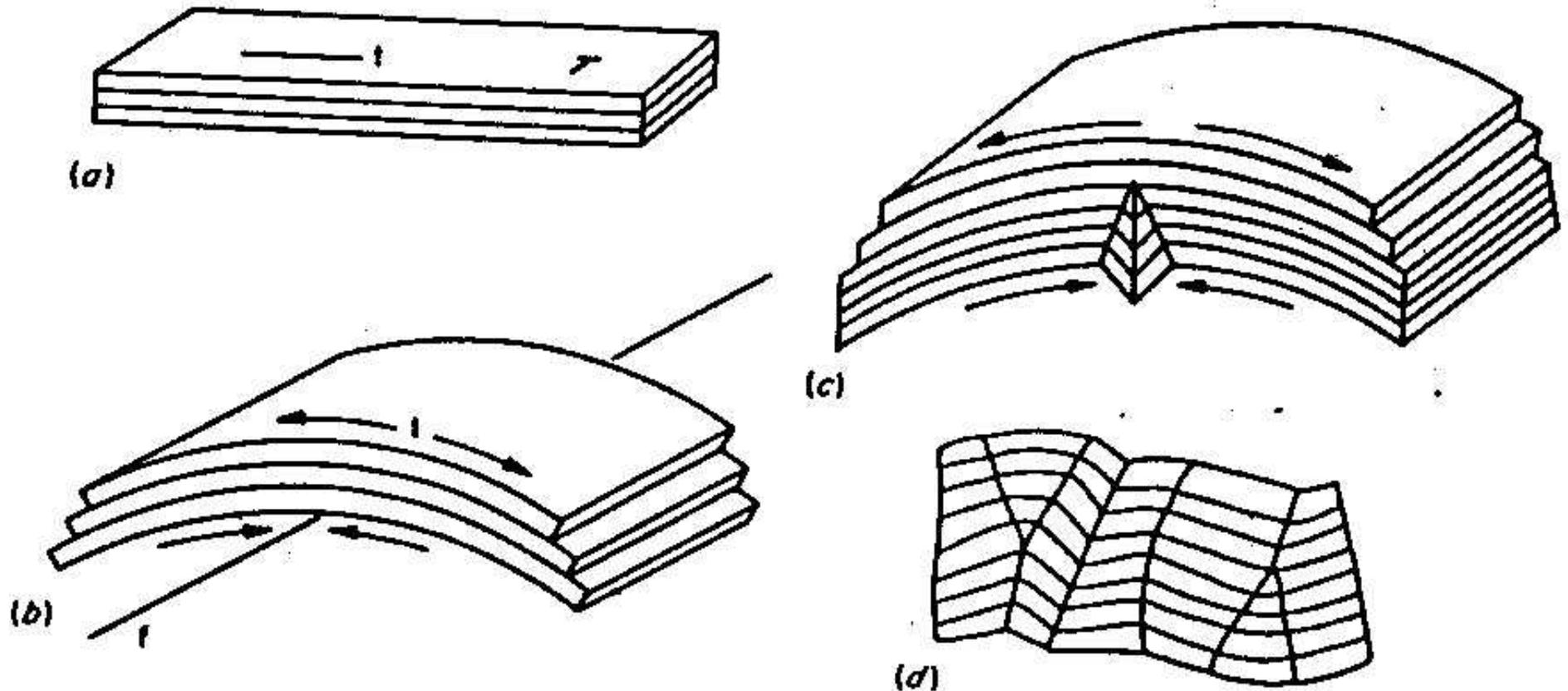


Figure 7-7 Sketch showing the development of kink bands by the mechanism of bend gliding. (a) Undistorted crystal; (b) crystal bent by "two-sided" gliding parallel to the layer of atoms; (c) initial stage kinking leading to a chevron-shaped kink; (d) complex kinking as seen in a section normal to f . τ = gliding plane, f = gliding line, f = axis of rotation or bending. (After Mugge, 1898.)

Development of kink bands

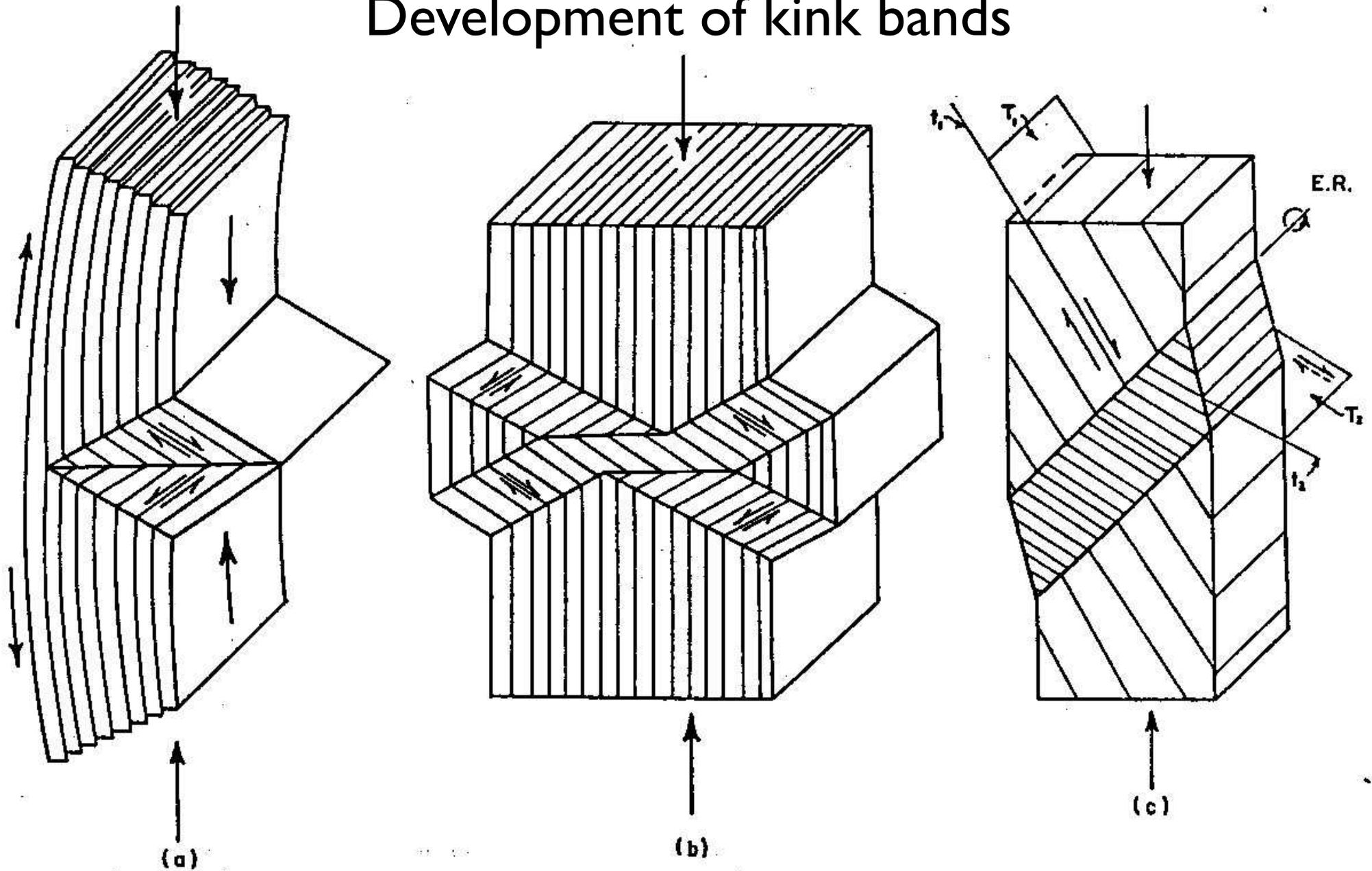
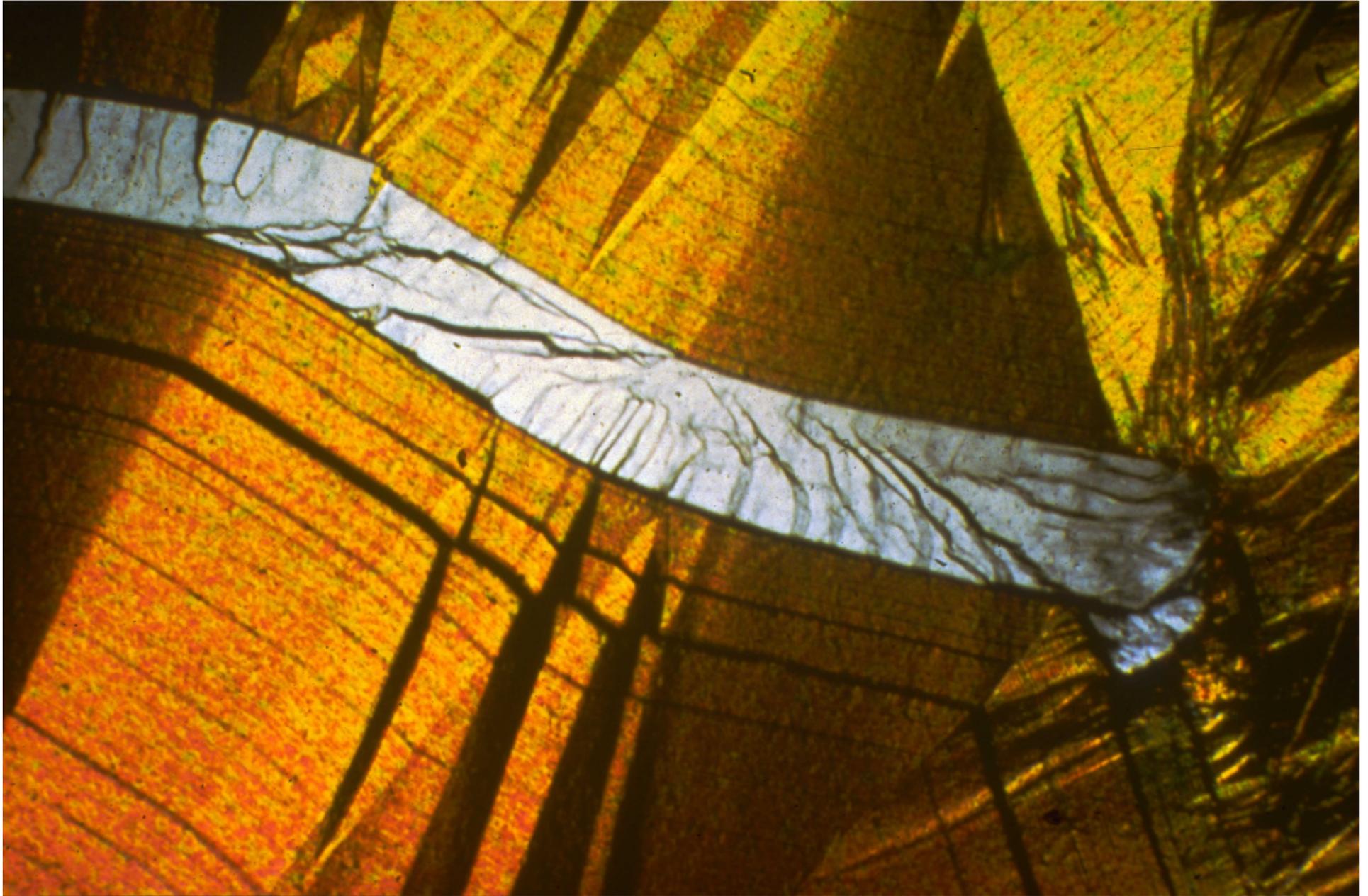


Figure 7-8 Schematic drawings of three types of kink bands in crystals. (a) Kink bands in crystals loaded parallel to strong planar anisotropy. (b) Intersecting conjugate kinks loaded parallel to a strong planar anisotropy. (c) Symmetrical kink in crystal whose slip plane T_1 is in an orientation of high shearing stress. (From Carter and Raleigh, 1969.)

Kinked biotite, brittle deformation in folded feldspar



Kink fold in Santa Monica slate

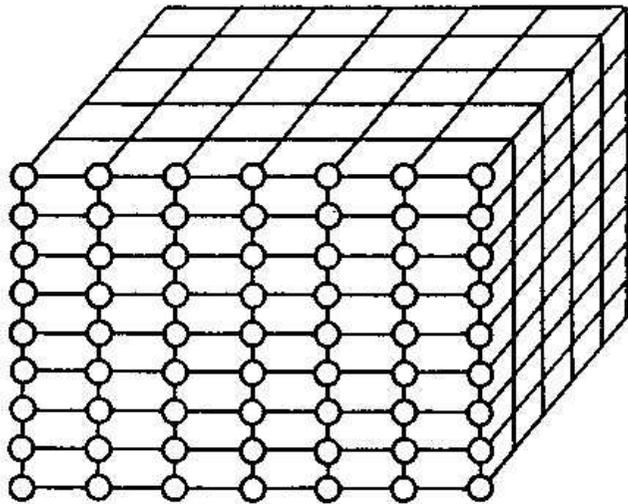


Low-Temperature Crystal Plasticity

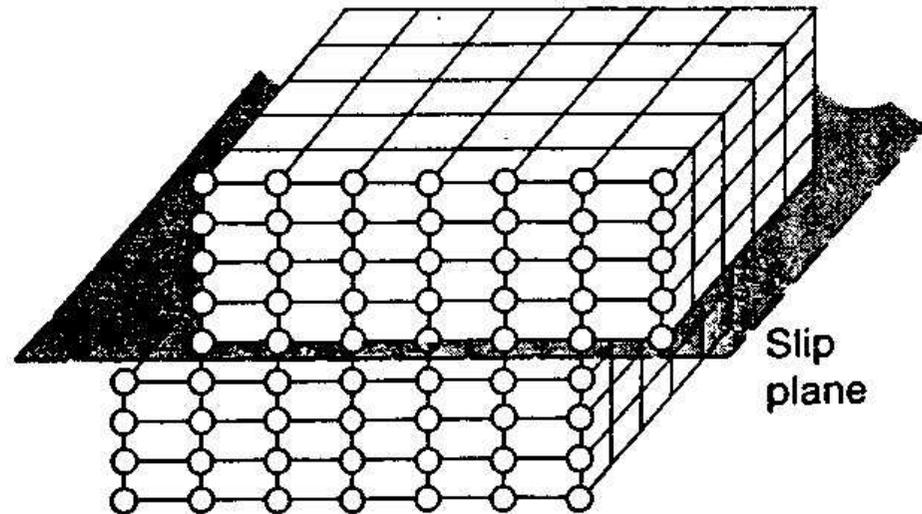
Processes that depend more on differential stress than on temperature, and that change a mineral's shape without melting, fracturing or faulting.

- Pressure solution
- Kinking
- Dislocation glide

Undeformed lattice



Dislocation glide

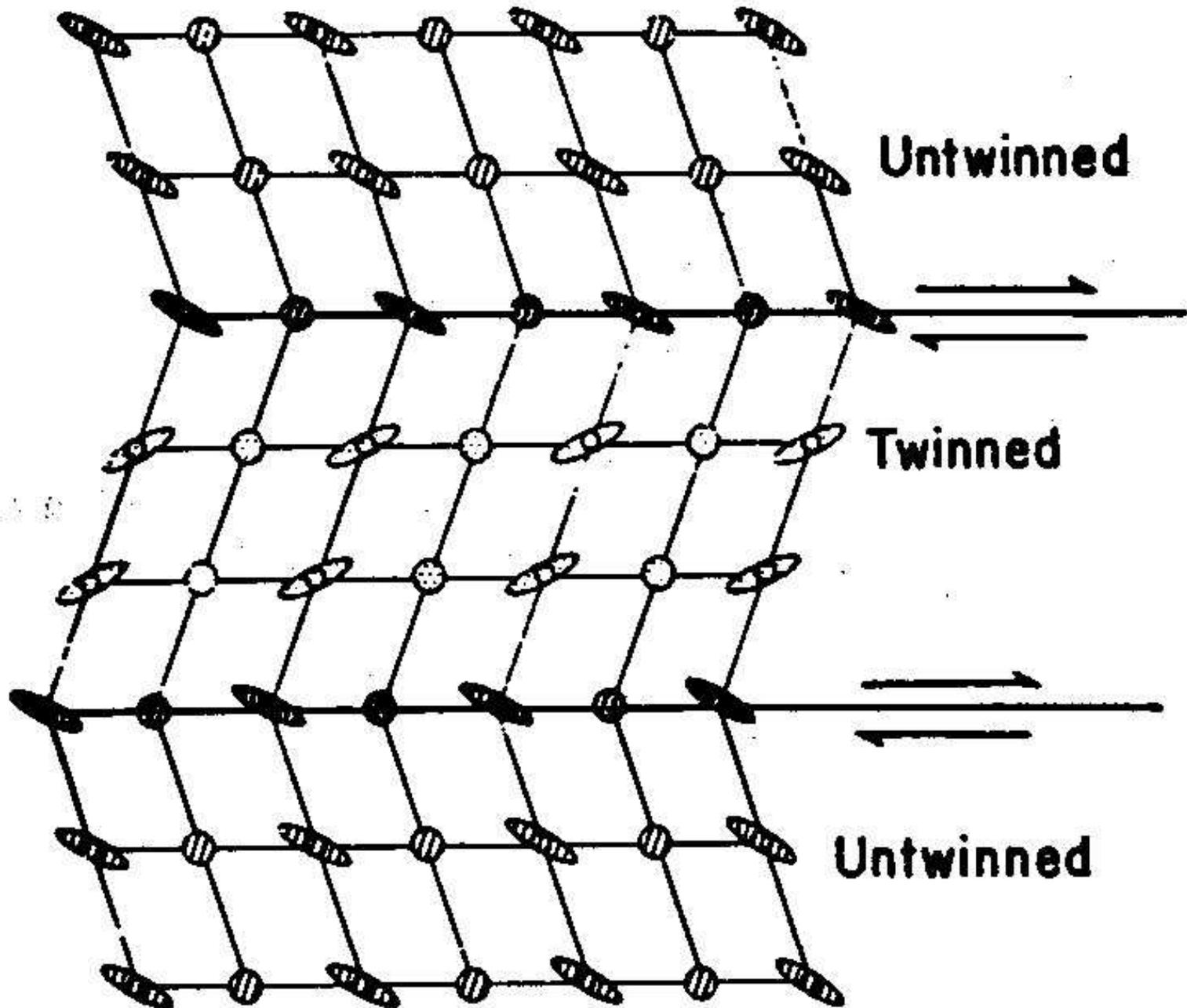


Low-Temperature Crystal Plasticity

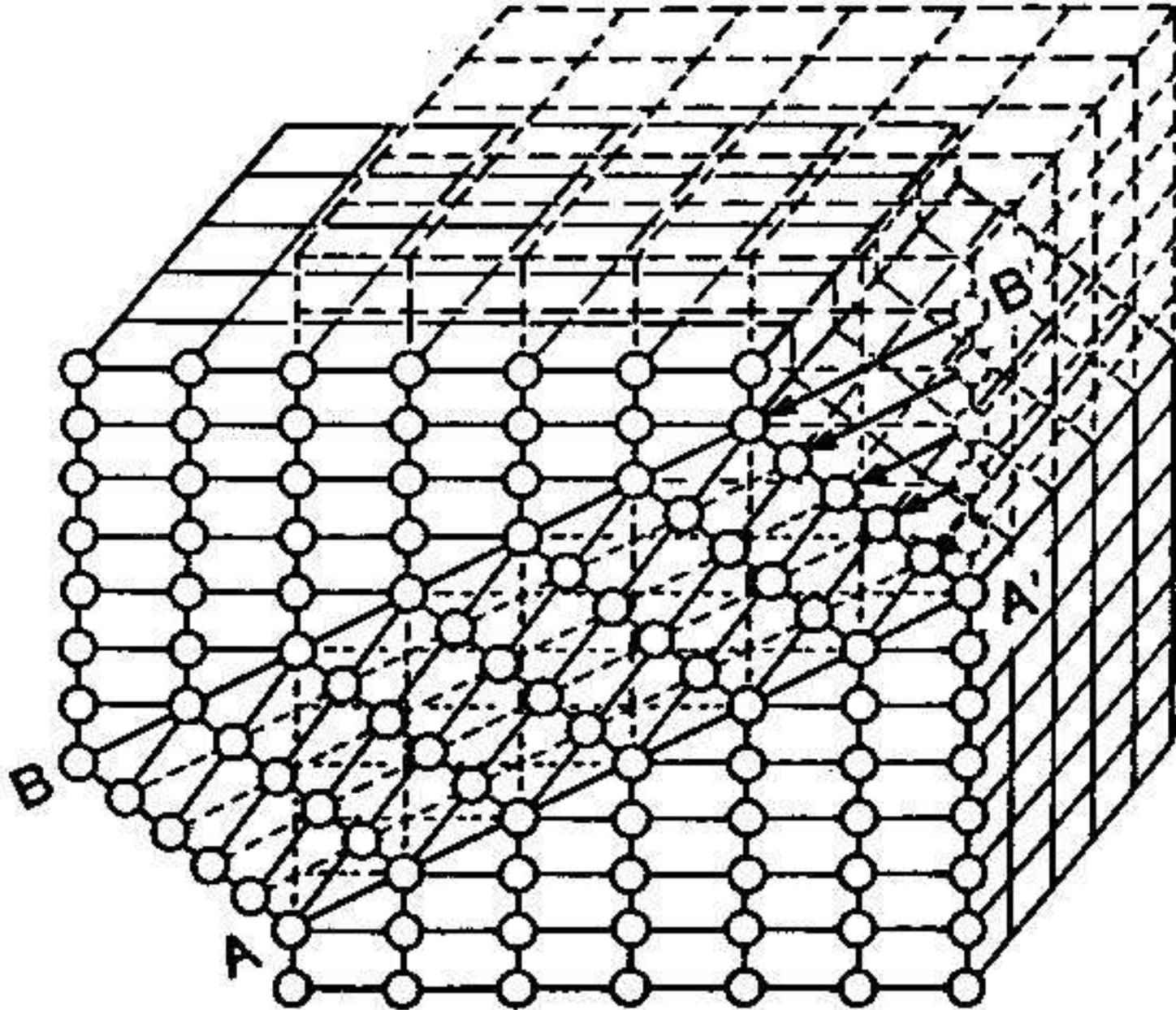
Processes that depend more on differential stress than on temperature, and that change a mineral's shape without melting, fracturing or faulting.

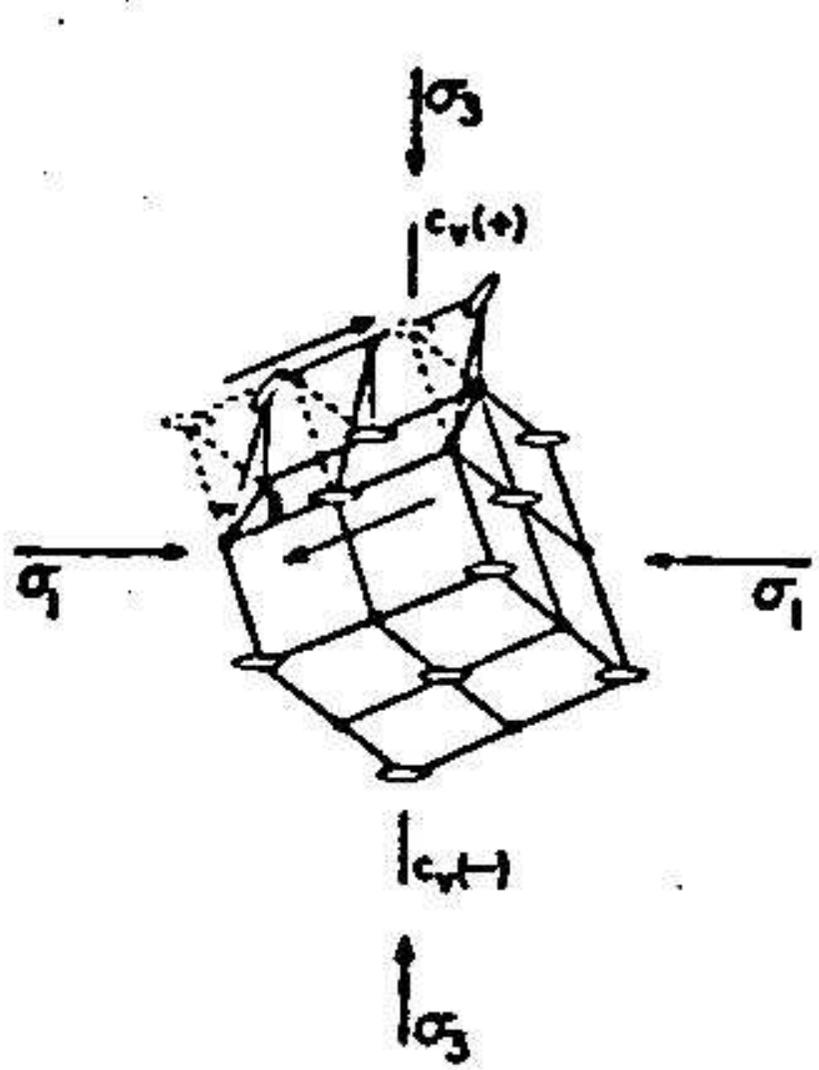
- Pressure solution
- Kinking
- Dislocation glide
- Mechanical twinning

Mechanically twinned calcite lattice



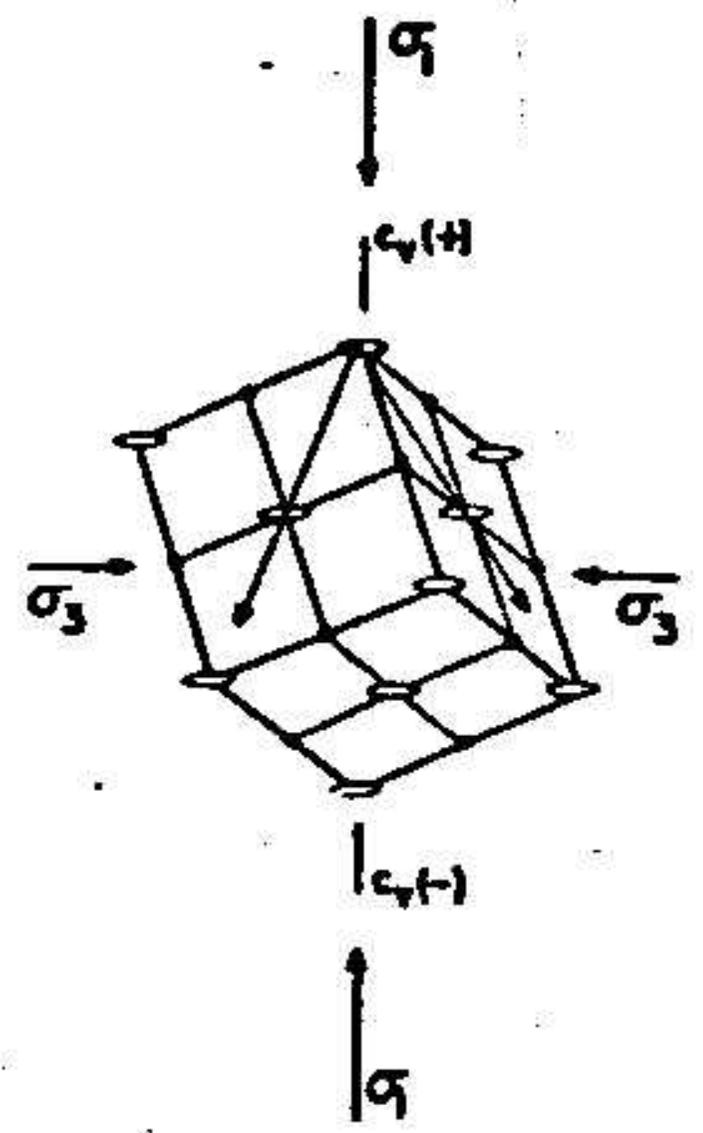
Mechanically twinned lattice



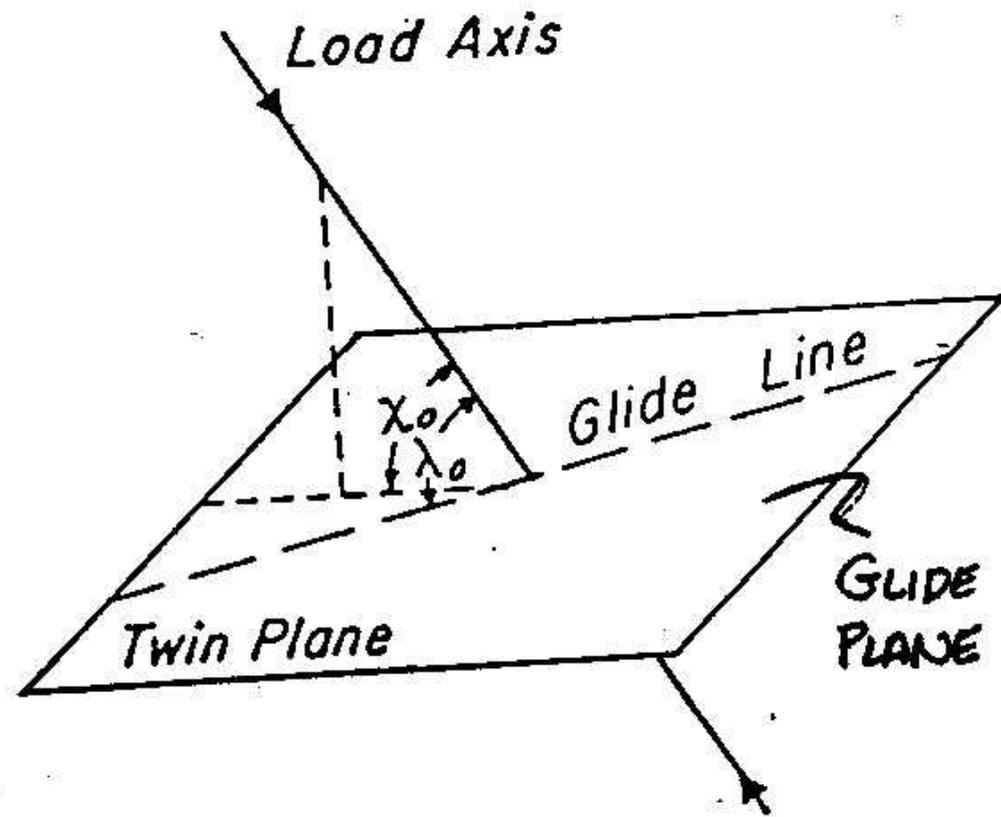


• Calcium ion
 ○ Carbonate group

LOAD FAVORABLE FOR TWINNING



LOAD UNFAVORABLE FOR TWINNING
 (FAVORABLE FOR TRANSLATION ON r AND t)



RESOLVED SHEAR STRESS COEFFICIENT S_0 IS A FUNCTION OF THE ANGLES BETWEEN THE GLIDE PLANE AND THE LOAD AXES (χ_0) AND THE GLIDE LINE AND THE LOAD AXIS (λ_0).

$$S_0 = \sin \chi_0 \cos \lambda_0$$

$$\tau = S_0 (\sigma_1 - \sigma_3) = \frac{\sigma_1 - \sigma_3}{2} \sin 2\theta$$

MAX τ OCCURS WHEN $\theta = 45^\circ$

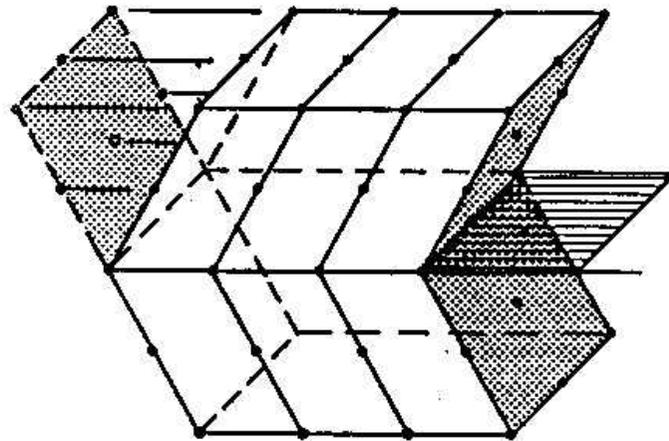
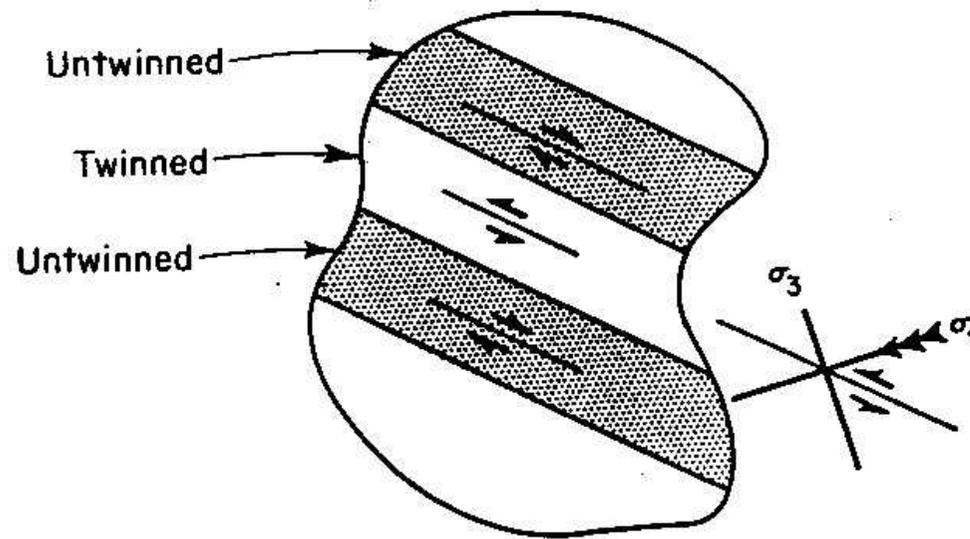
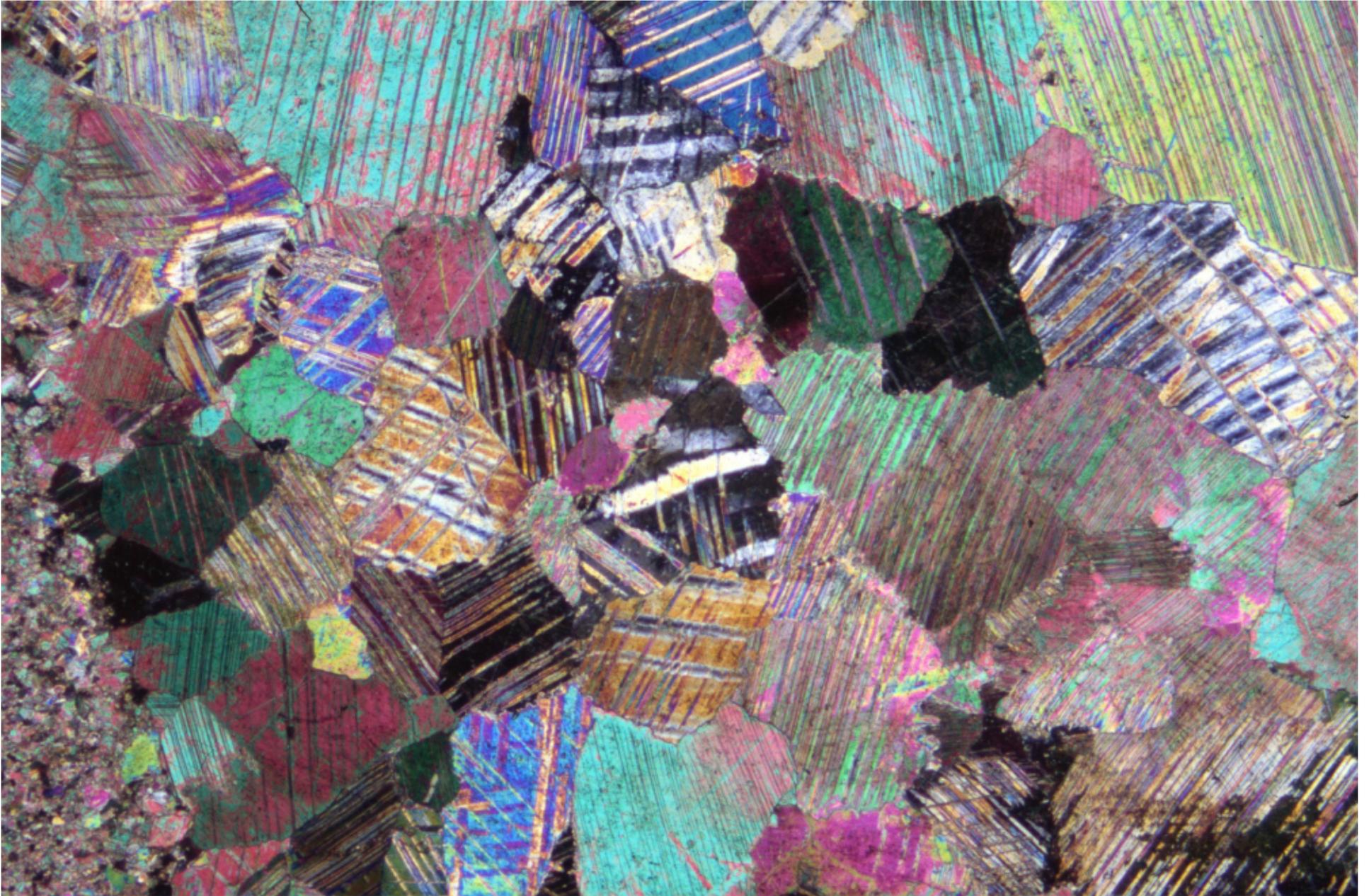


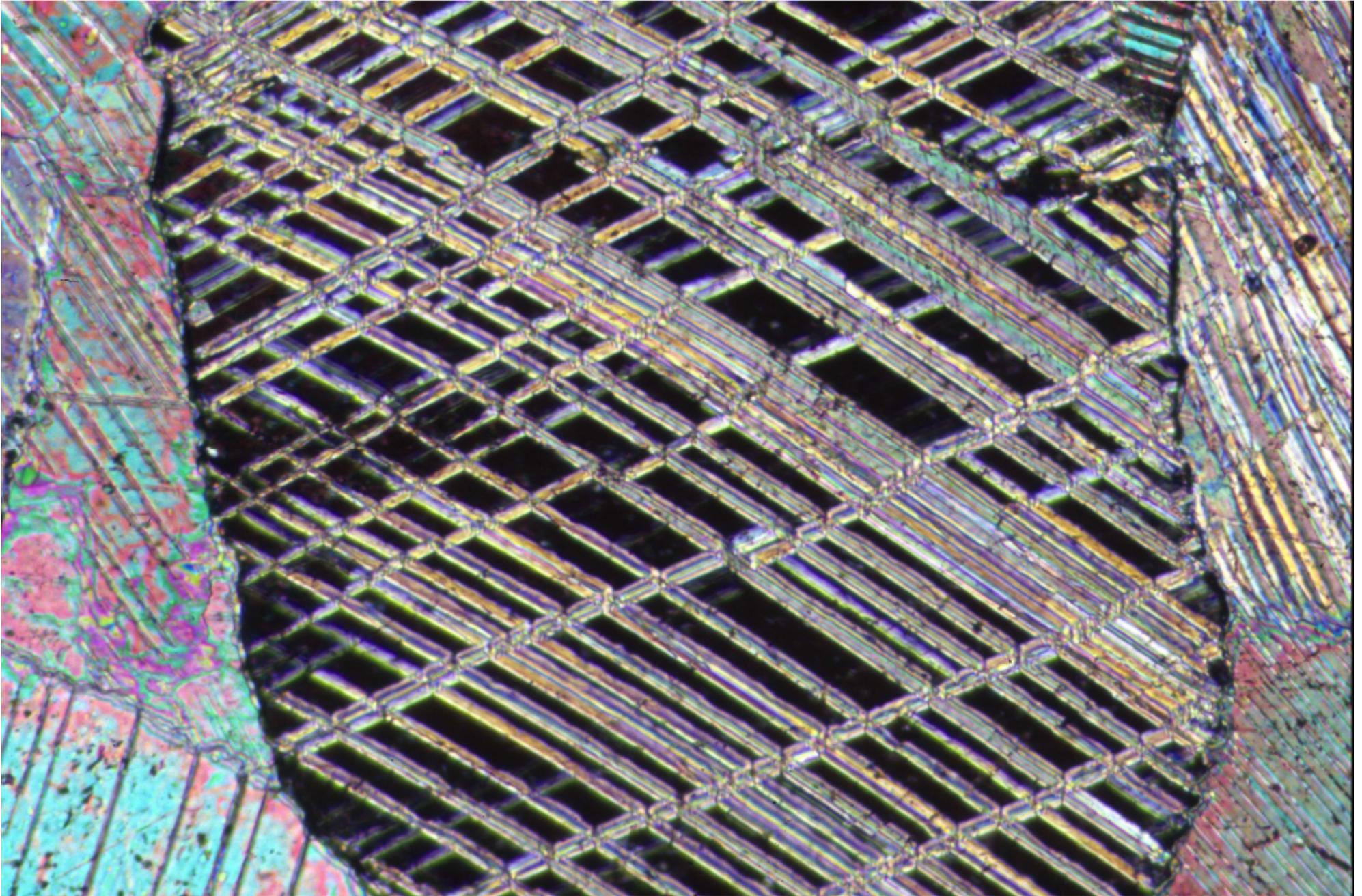
Figure 7-6 (Top) Twin gliding is most likely to occur when the principal stress direction is oriented at an angle that will produce high shear stress on the potential glide surface. (Center) A section through a twinned calcite crystal. (After Friedman, 1963, *Jour. of Geology*, by permission of Univ. of Chicago.) (Bottom) A block diagram showing displacements across a horizontal twin plane. (After Carter and Raleigh, 1969.)

Twinned calcite grains



Photomicrograph by Tina Gammill

Mechanical twins in calcite



Photomicrograph by Tina Gammill

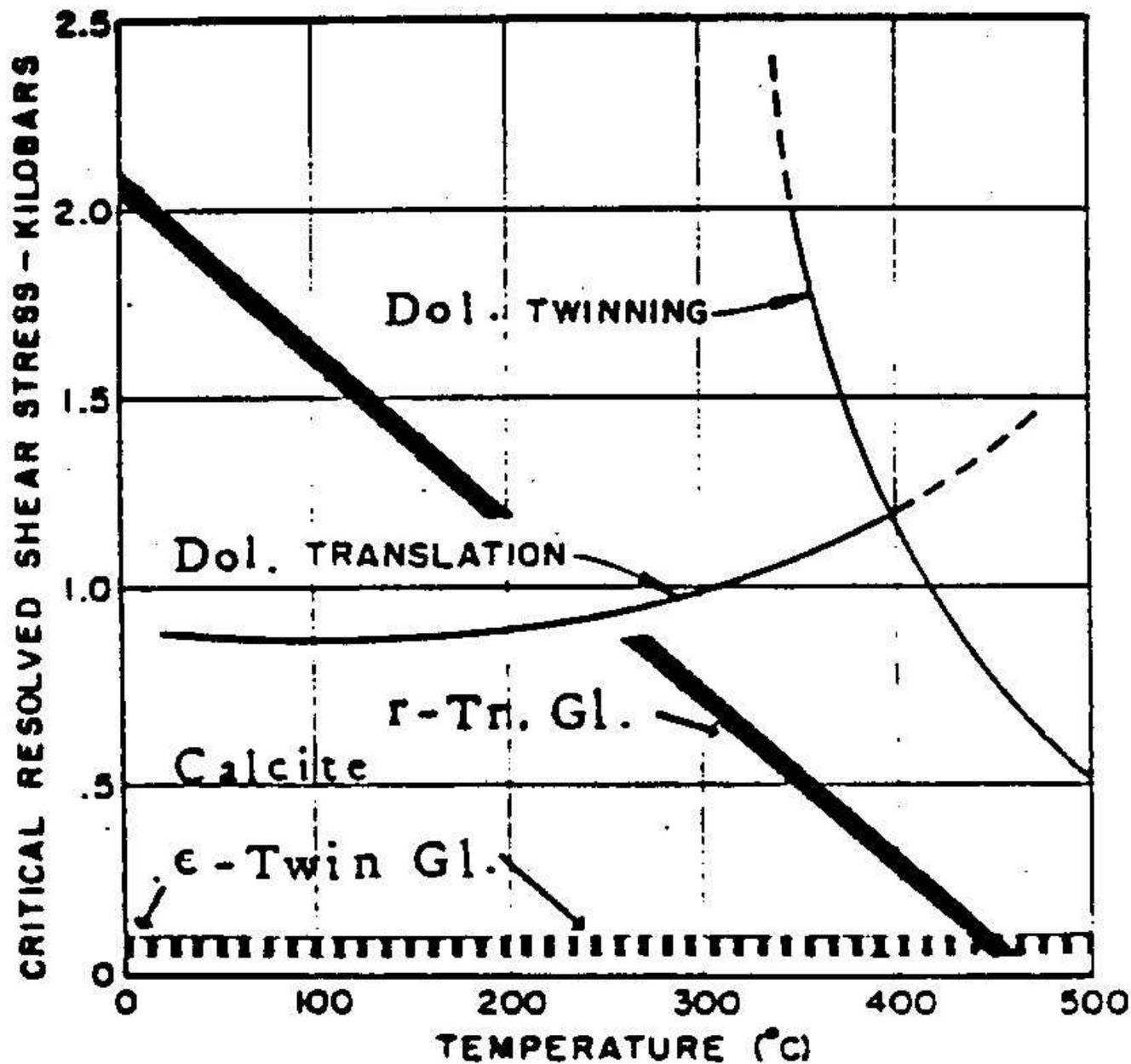


Figure 60. Critical resolved shear stress for dolomite (Dol.) and calcite (e and r) versus temperature.

High-Temperature Crystal Plasticity

Diffusion-assisted and hence
temperature-dependant
processes that change a
mineral's shape without melting,
fracturing or faulting

**Point defects:
vacancies,
interstitials,
substitutions**

Vacancies

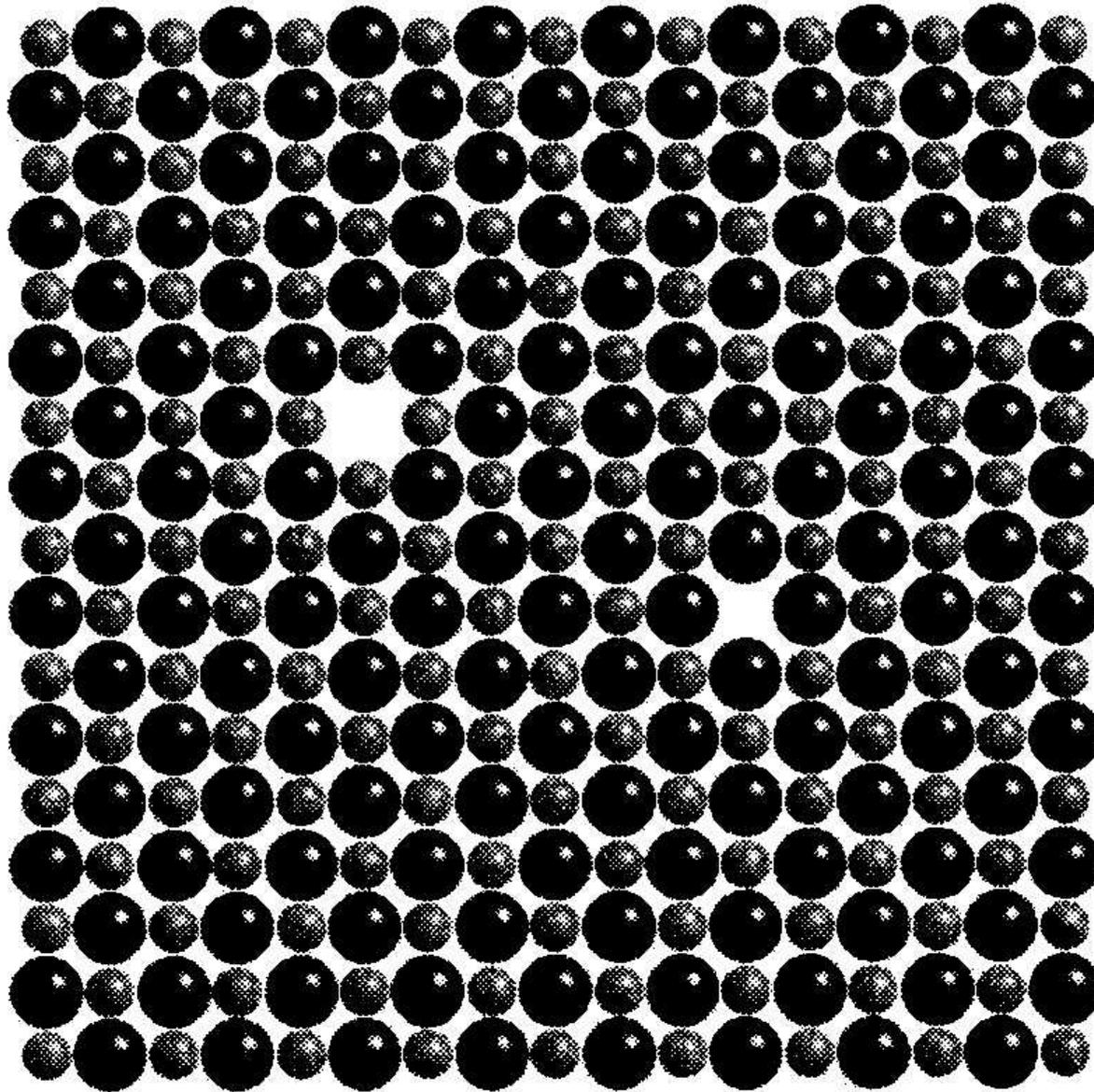


Fig. A.1 Cation and anion charge-balanced Shottky defects in NaCl.

Interstitial atoms

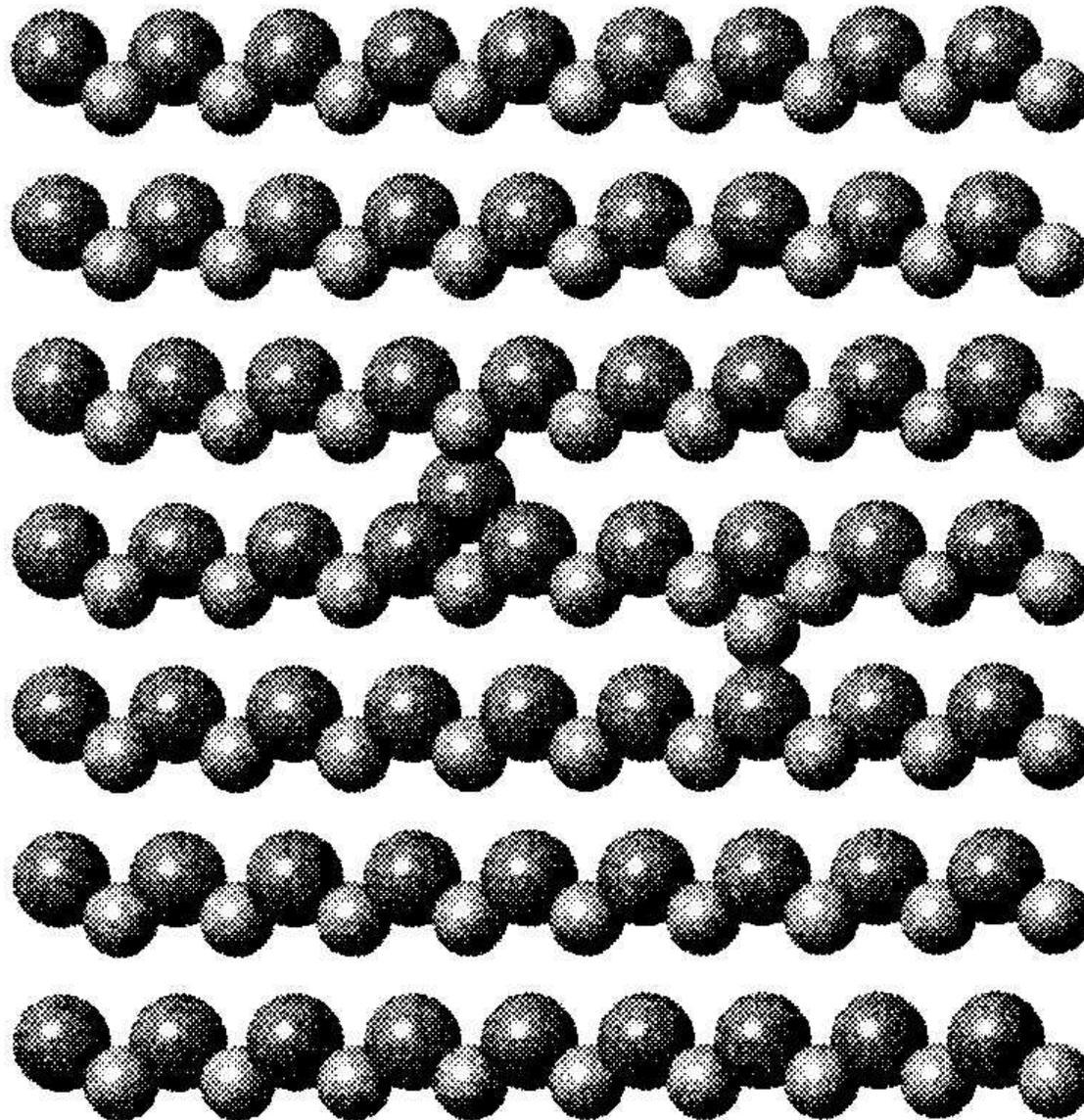


Fig. A.2 Pair of charge-balanced Frenkel defects in AgI.

Substitution errors

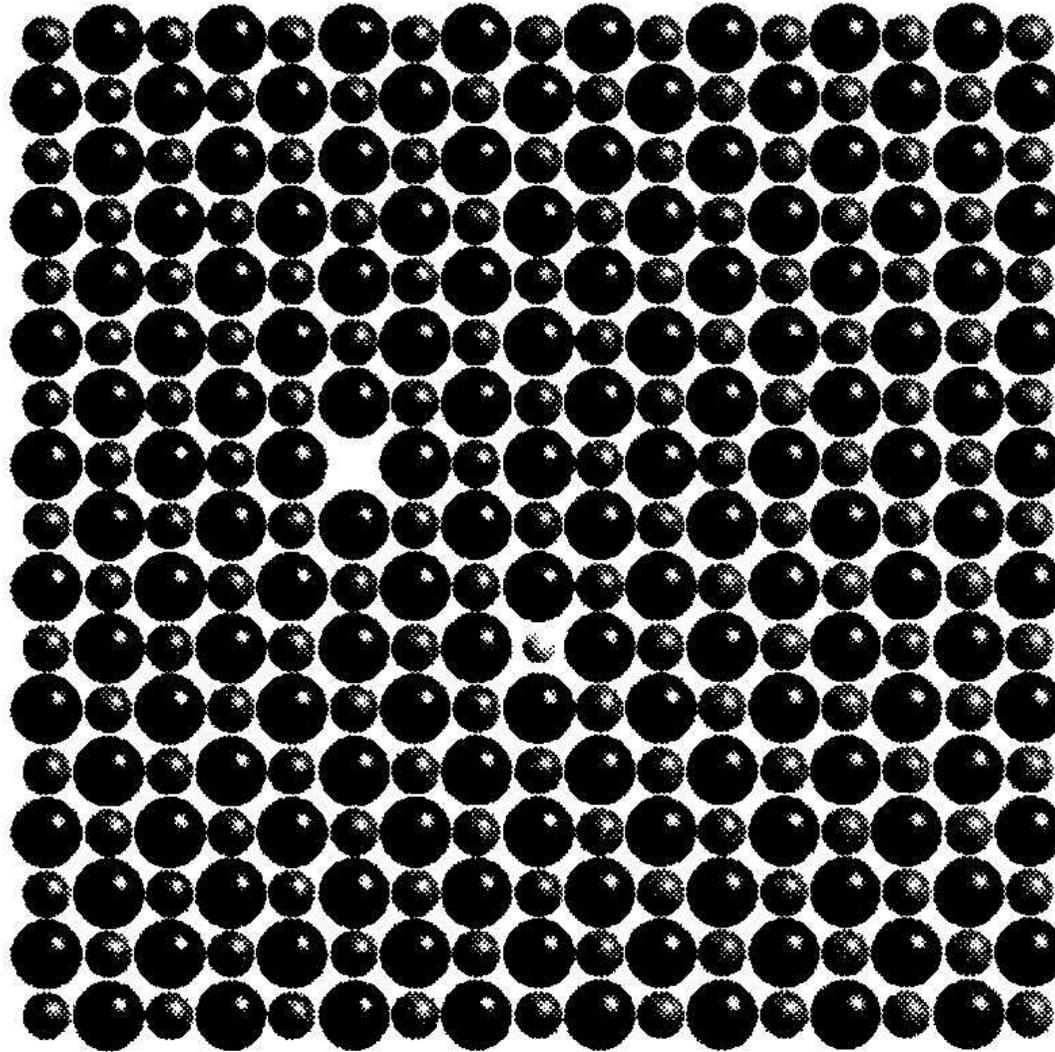


Fig. A.3 Substitution of a Ca^{2+} cation for a Na^{+} cation in NaCl, accompanied by the formation of a vacant cation site in order to maintain charge neutrality.

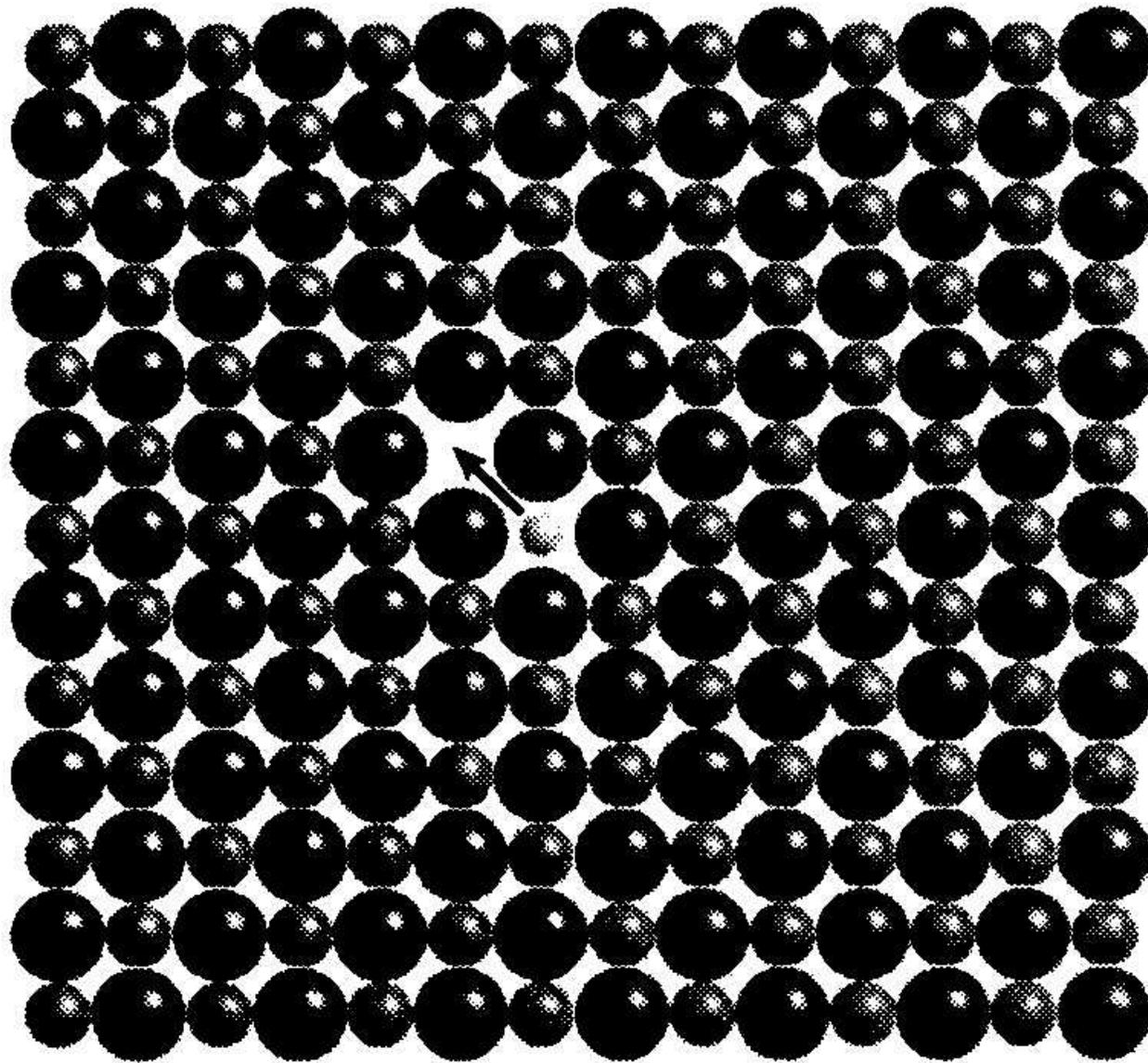
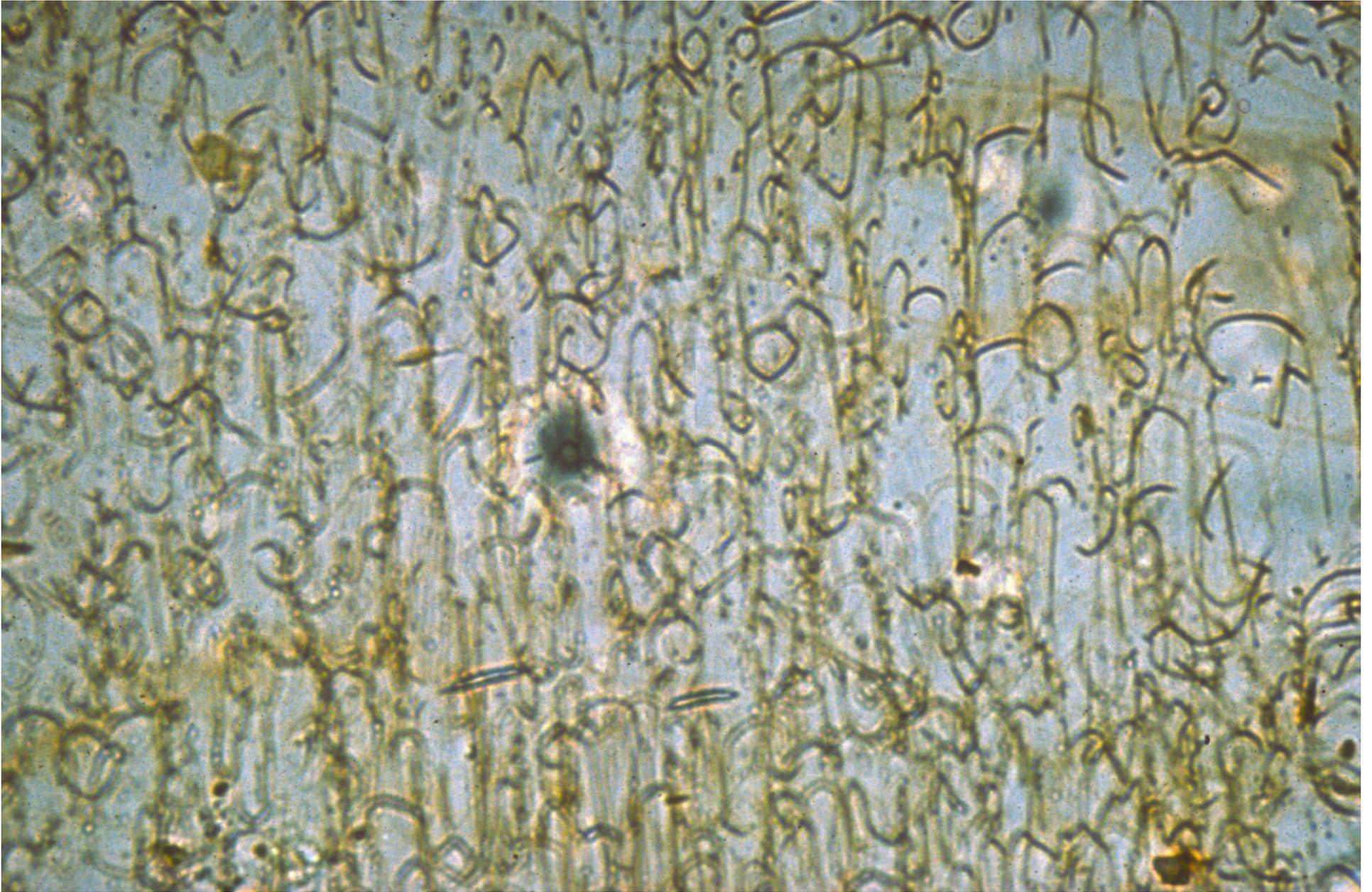


Fig. A.4 Diffusion of a cation in NaCl assisted through the presence of Shottky defects.

Line defects

- Twins
- Dislocations
 - Edge
 - Screw
 - Mixed

Oxidation etched dislocations in olivine



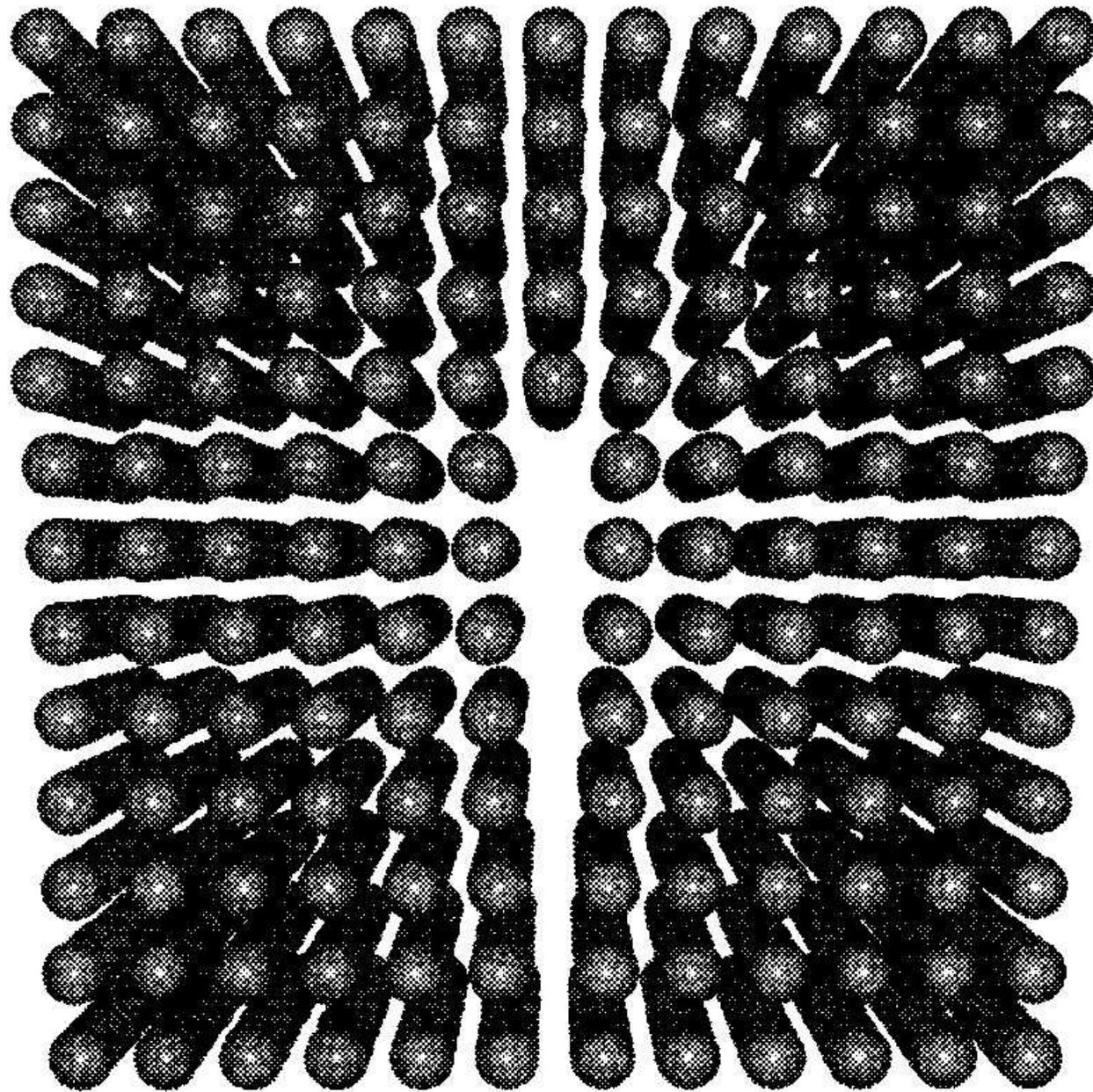
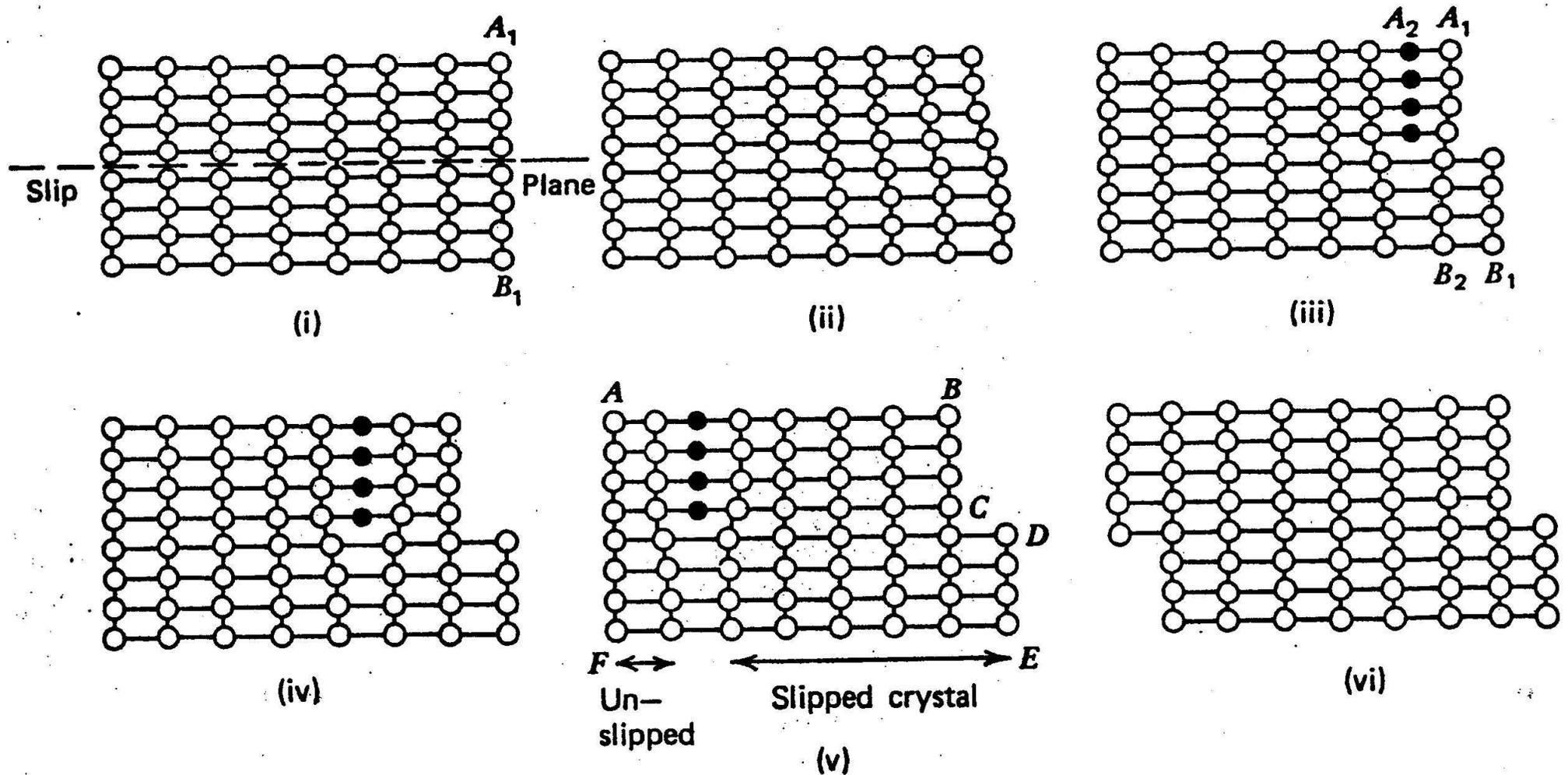
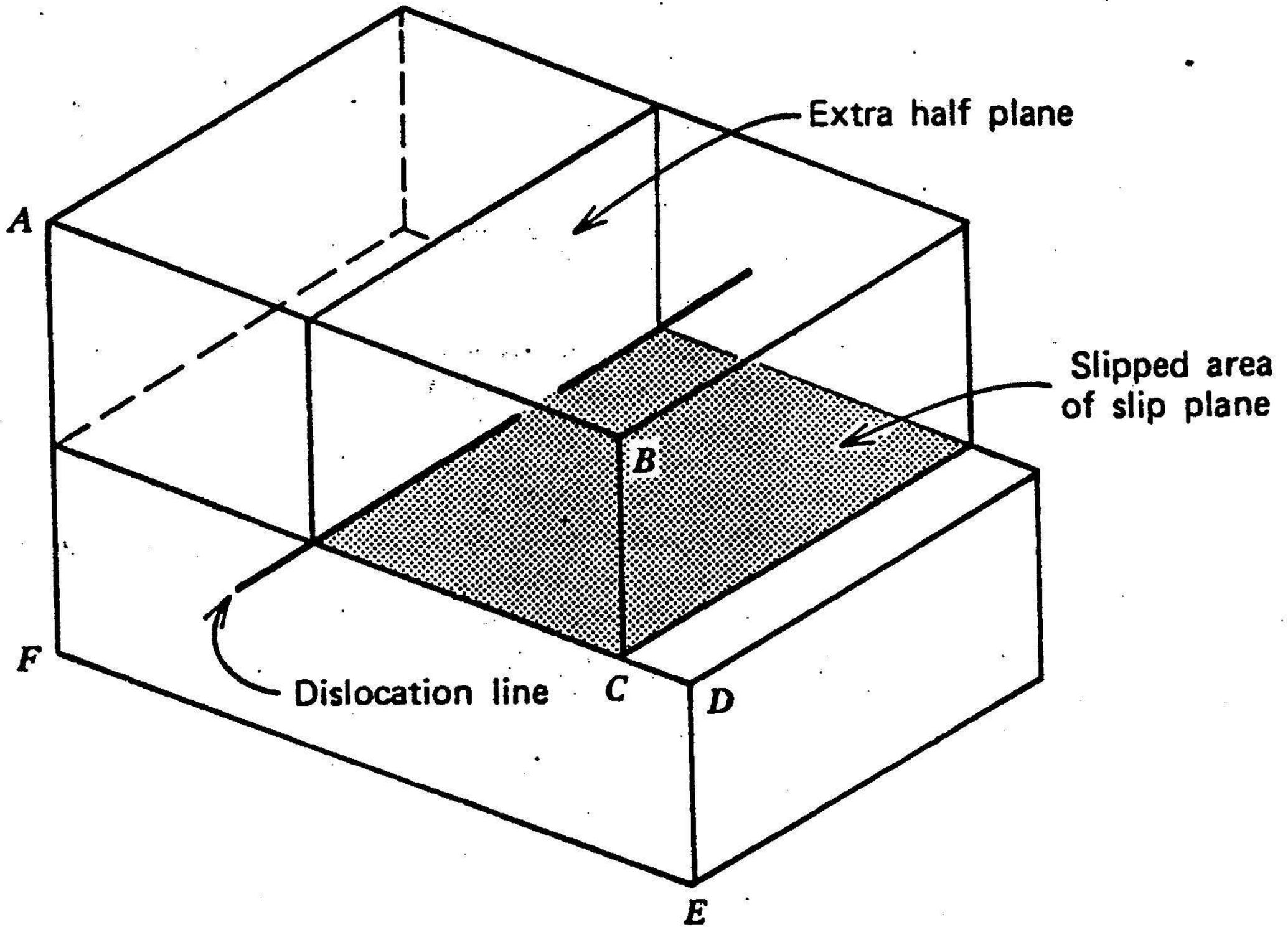


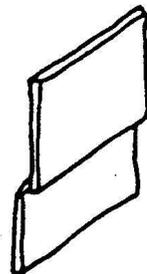
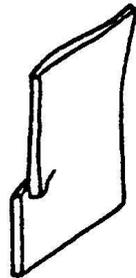
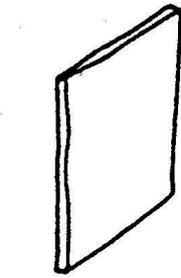
Fig. A.6 Schematic representation of an edge dislocation.

Motion of edge dislocation through a lattice

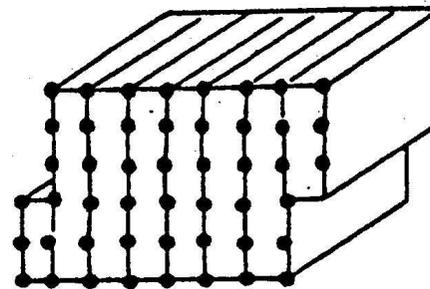
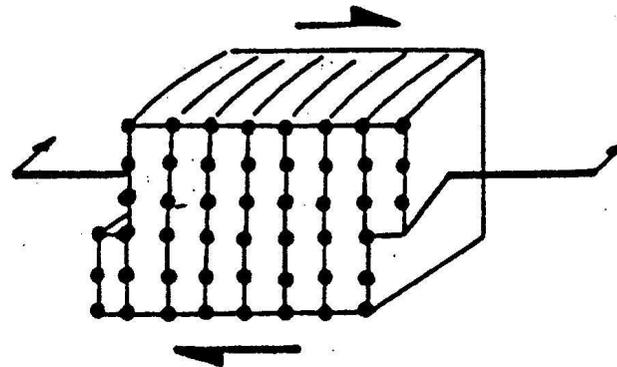
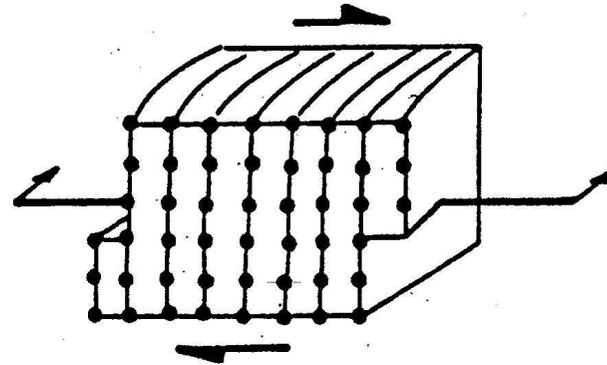
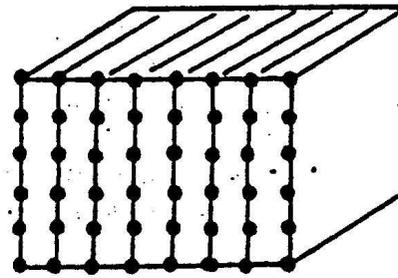




Propagation of a screw dislocation

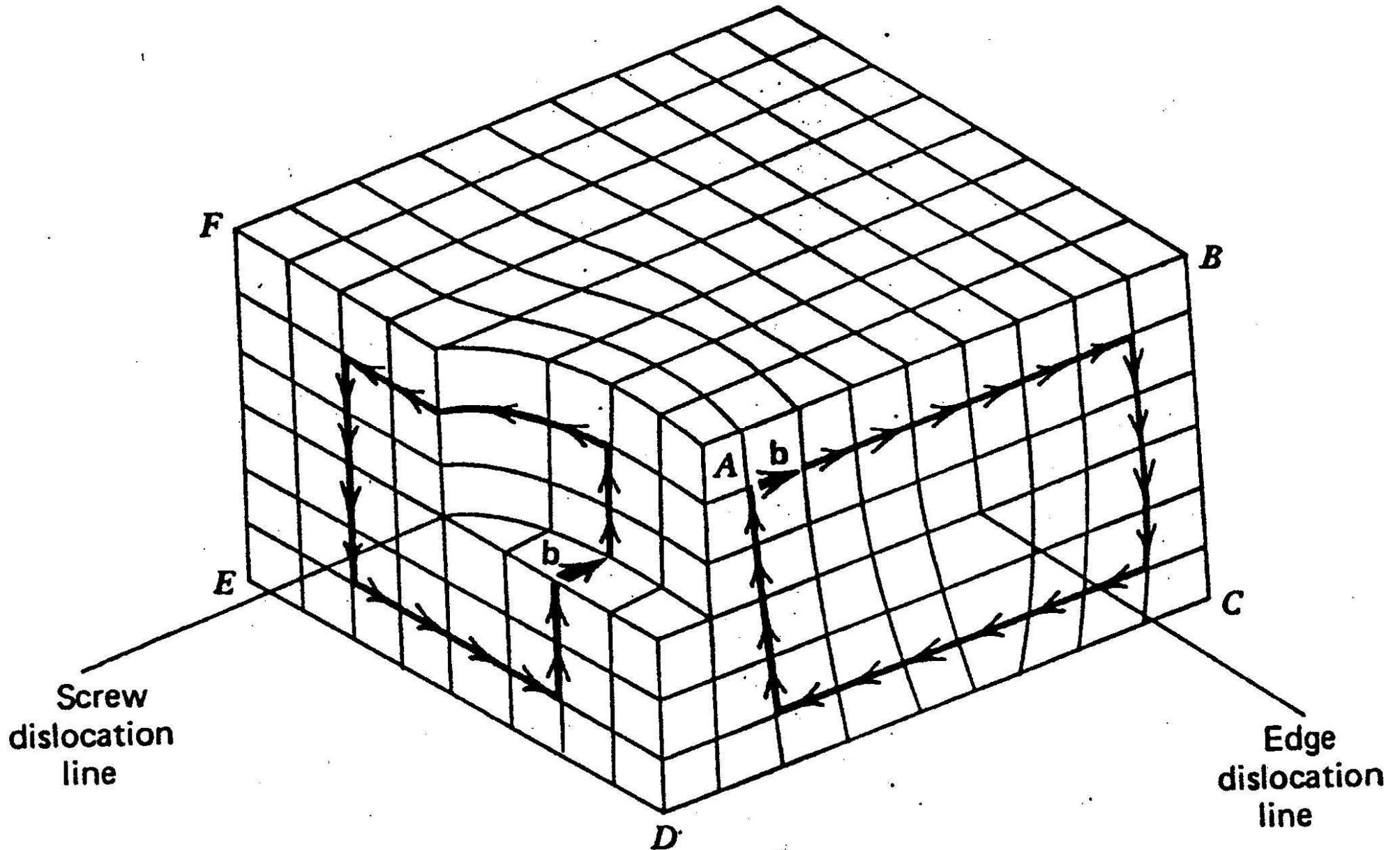


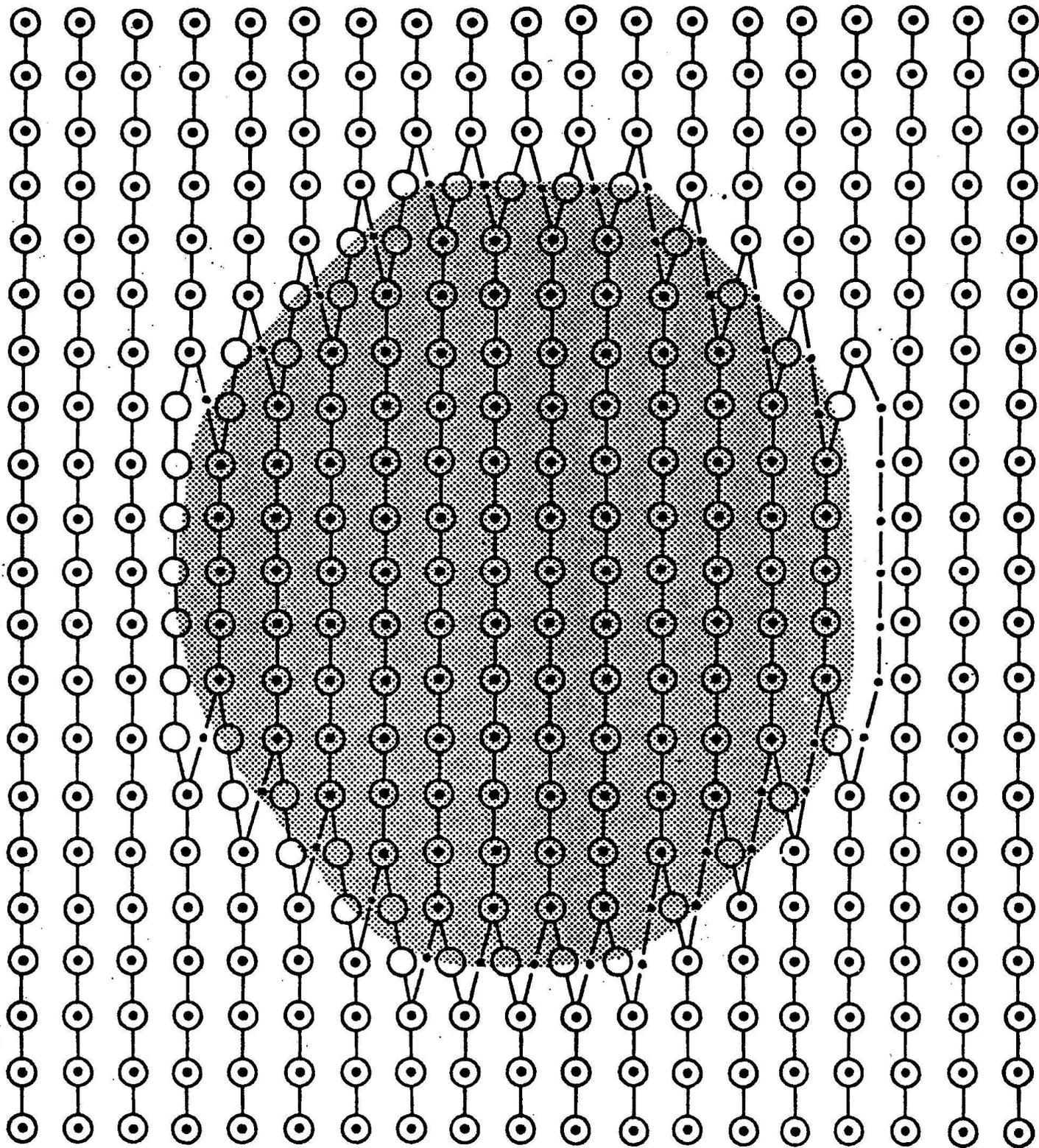
(a)

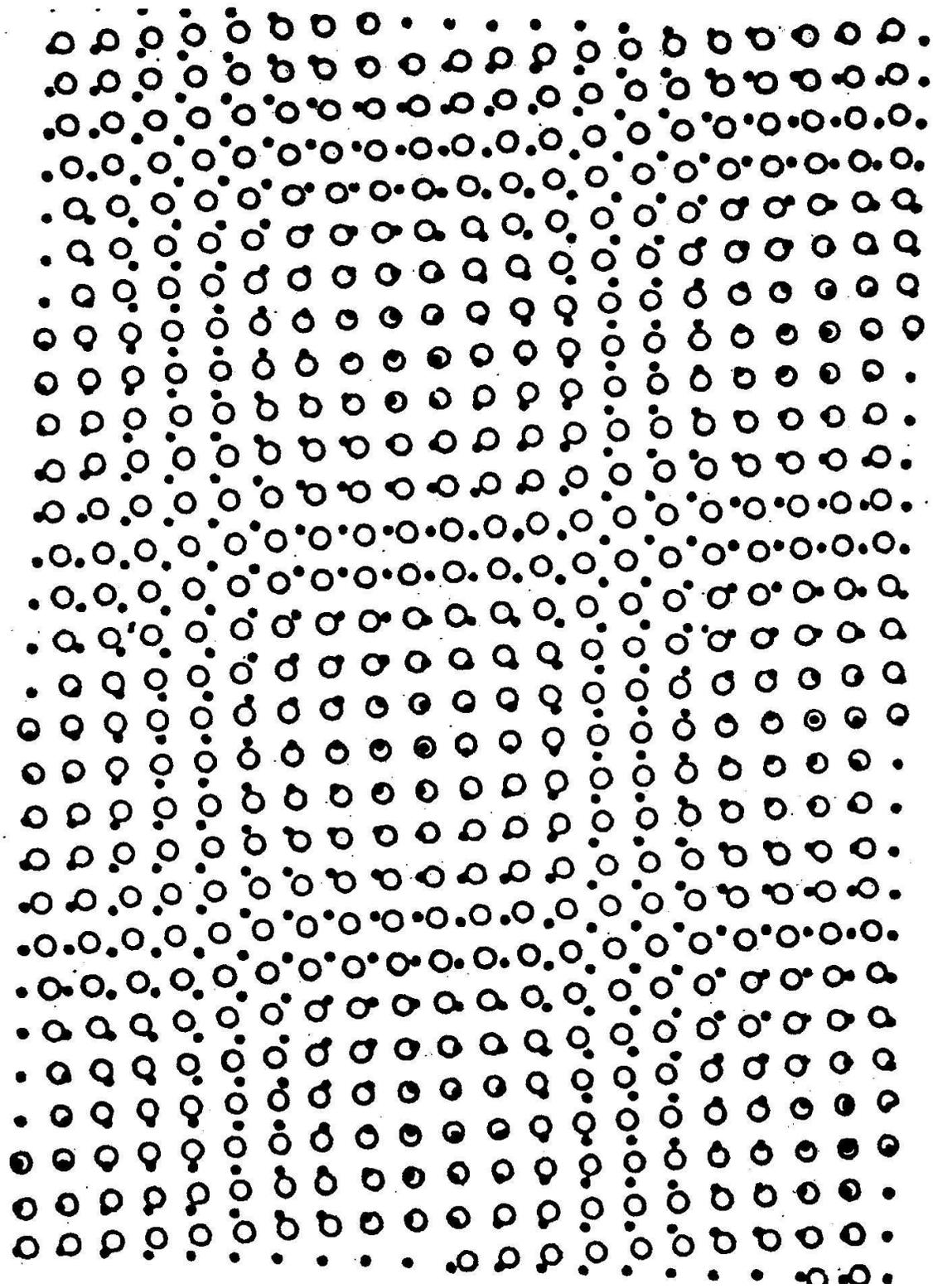


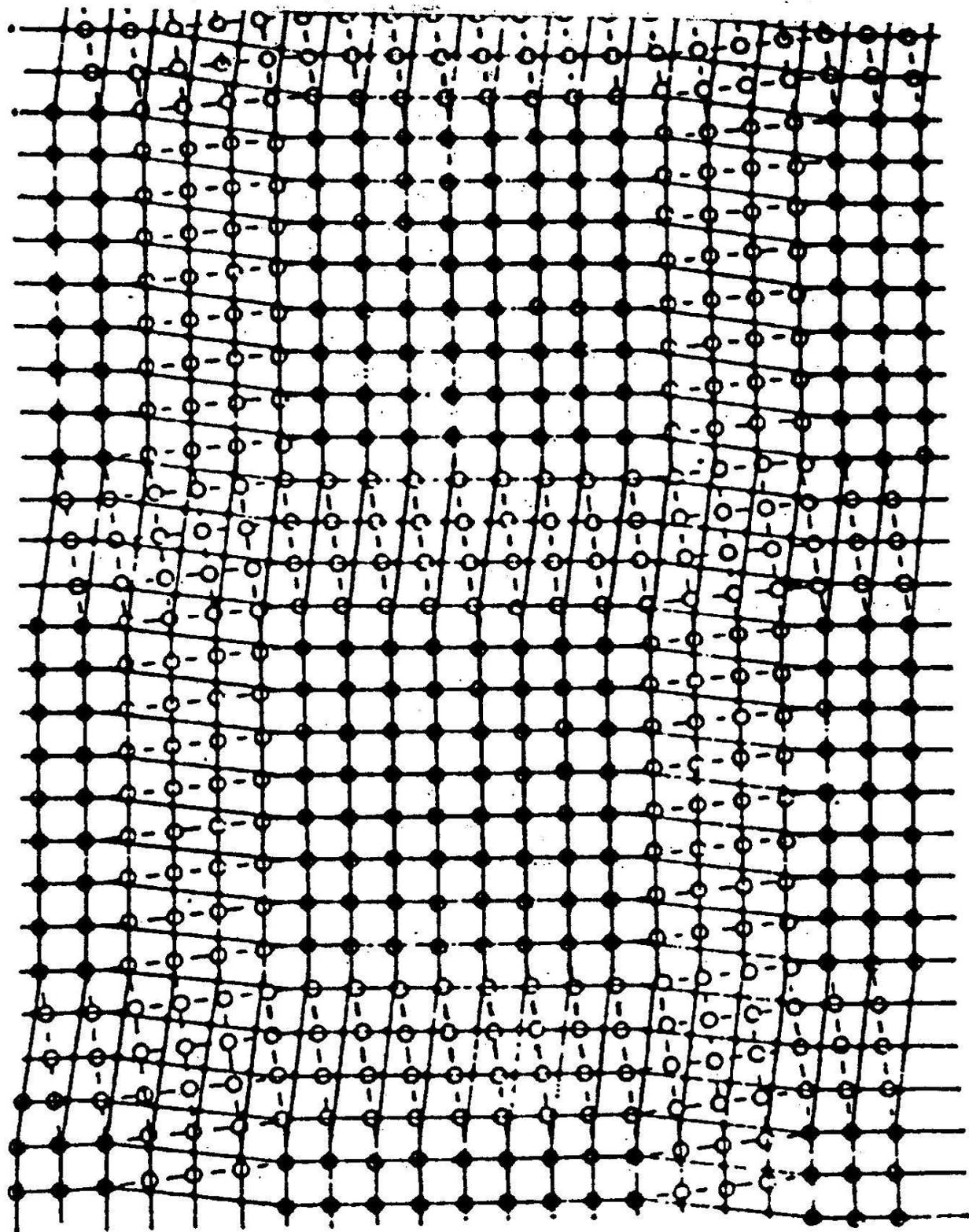
(b)

Edge and screw dislocations on the same slipped patch





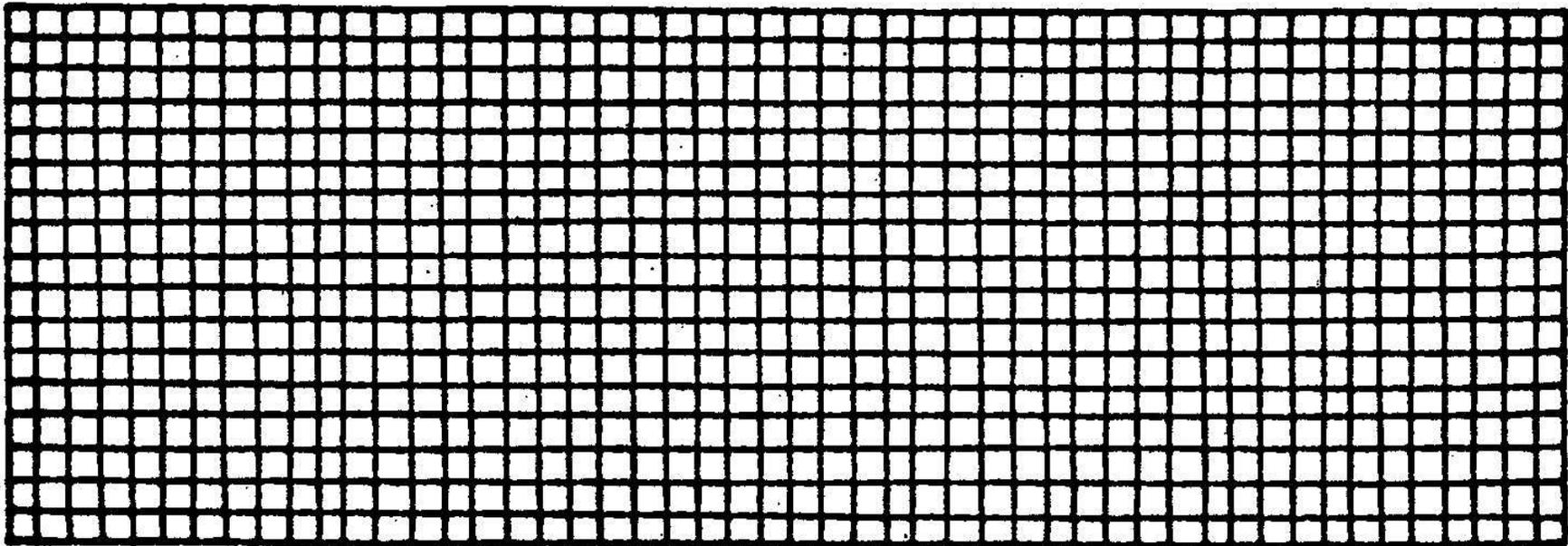




Planar defects

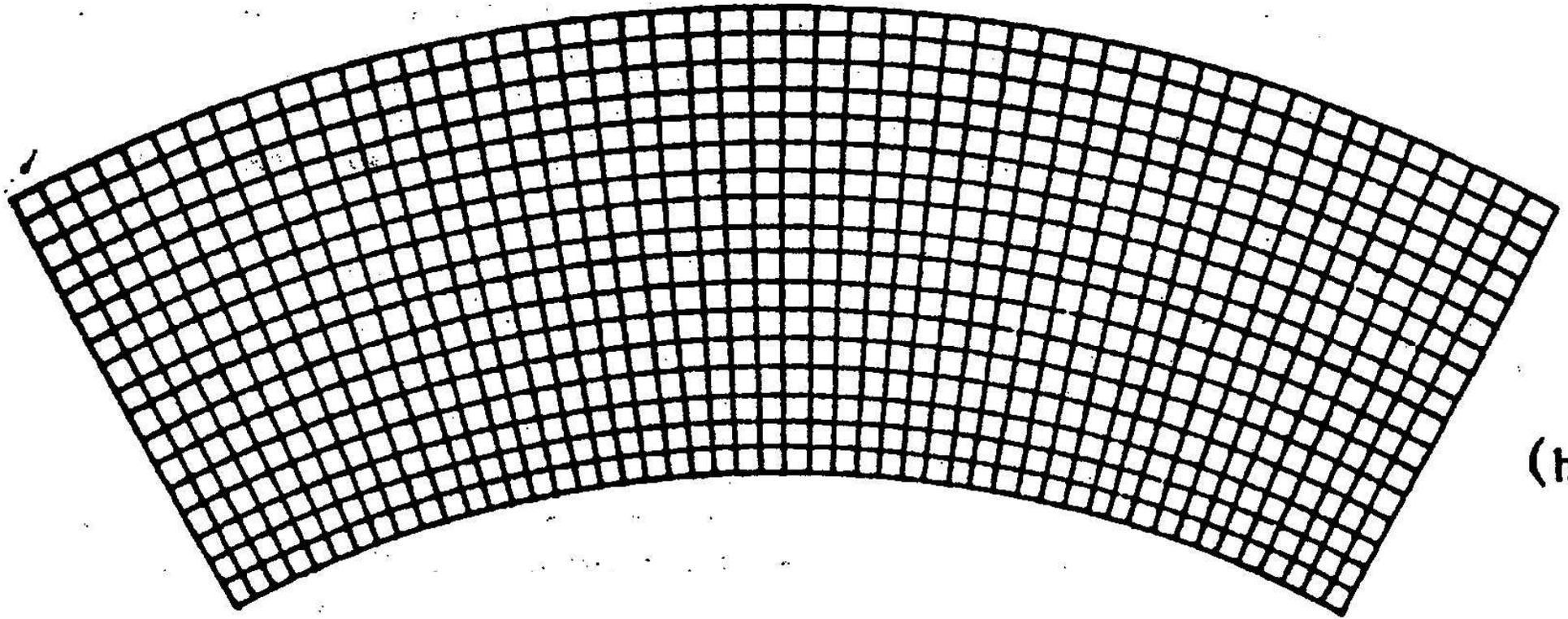
- Grain boundaries
- Twin planes
- Subgrain boundaries
- Deformation bands/lamellae
- Bohm lamellae
- Stacking faults

Unstrained lattice



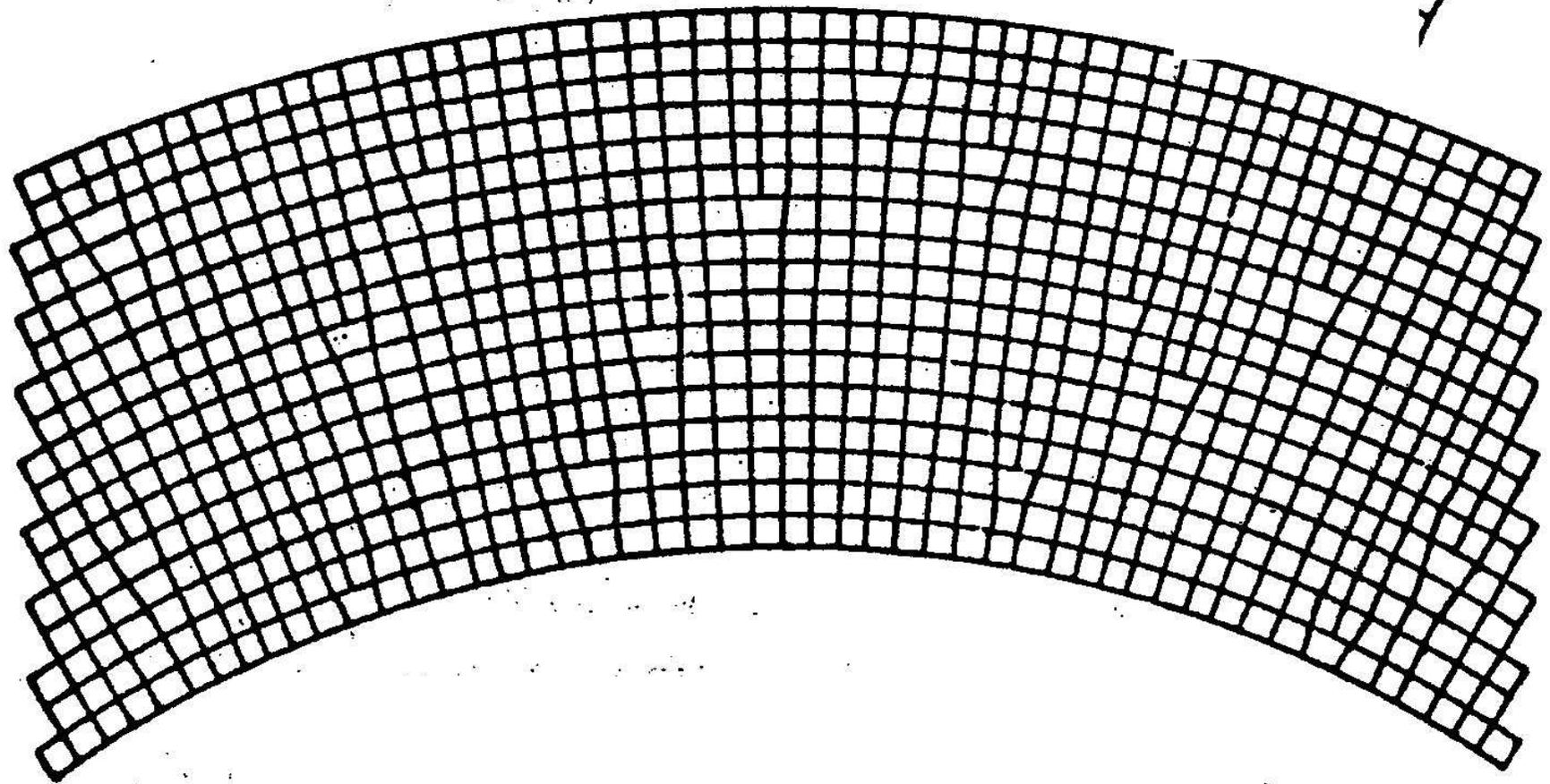
(a)

Elastically strained lattice



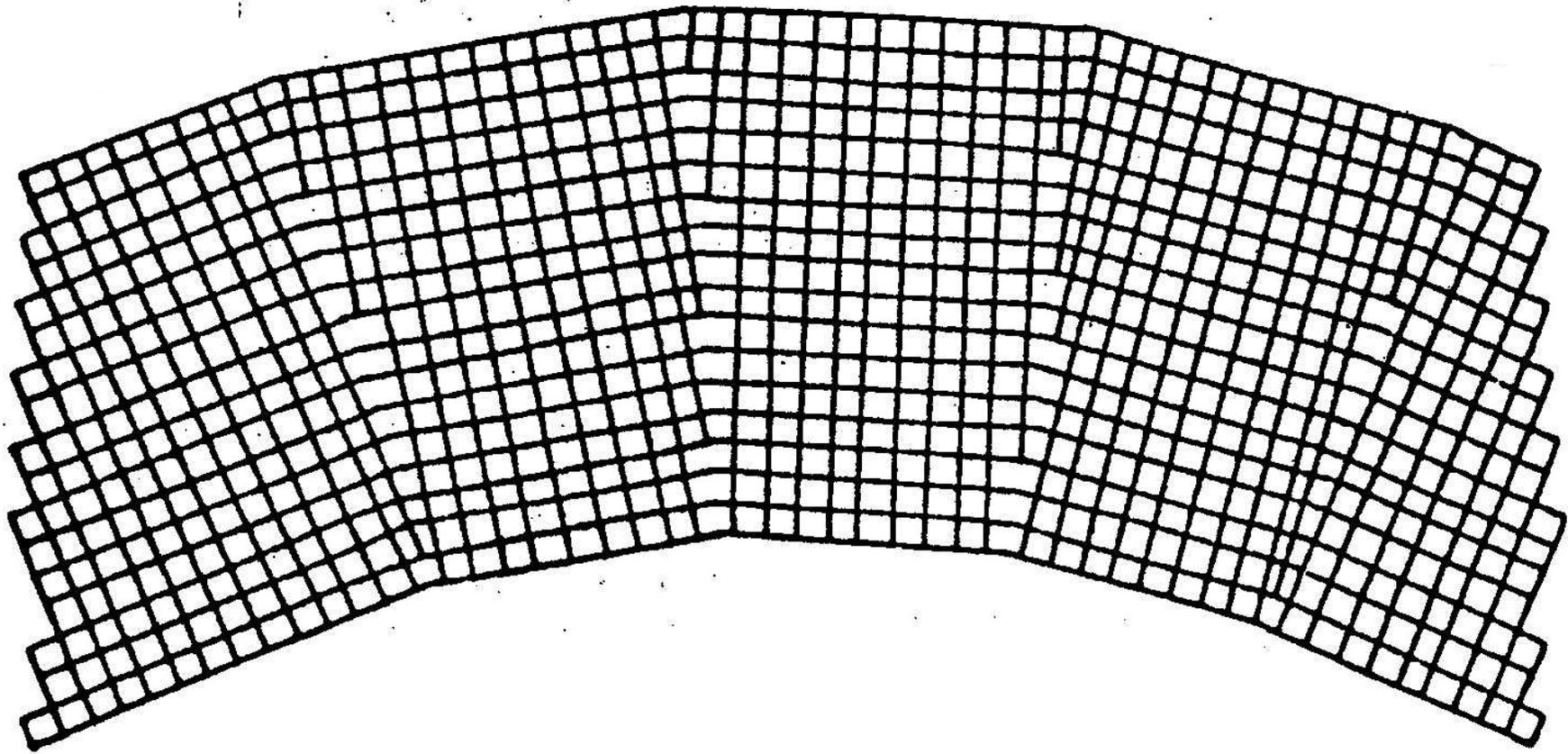
(b)

Plastically strained lattice



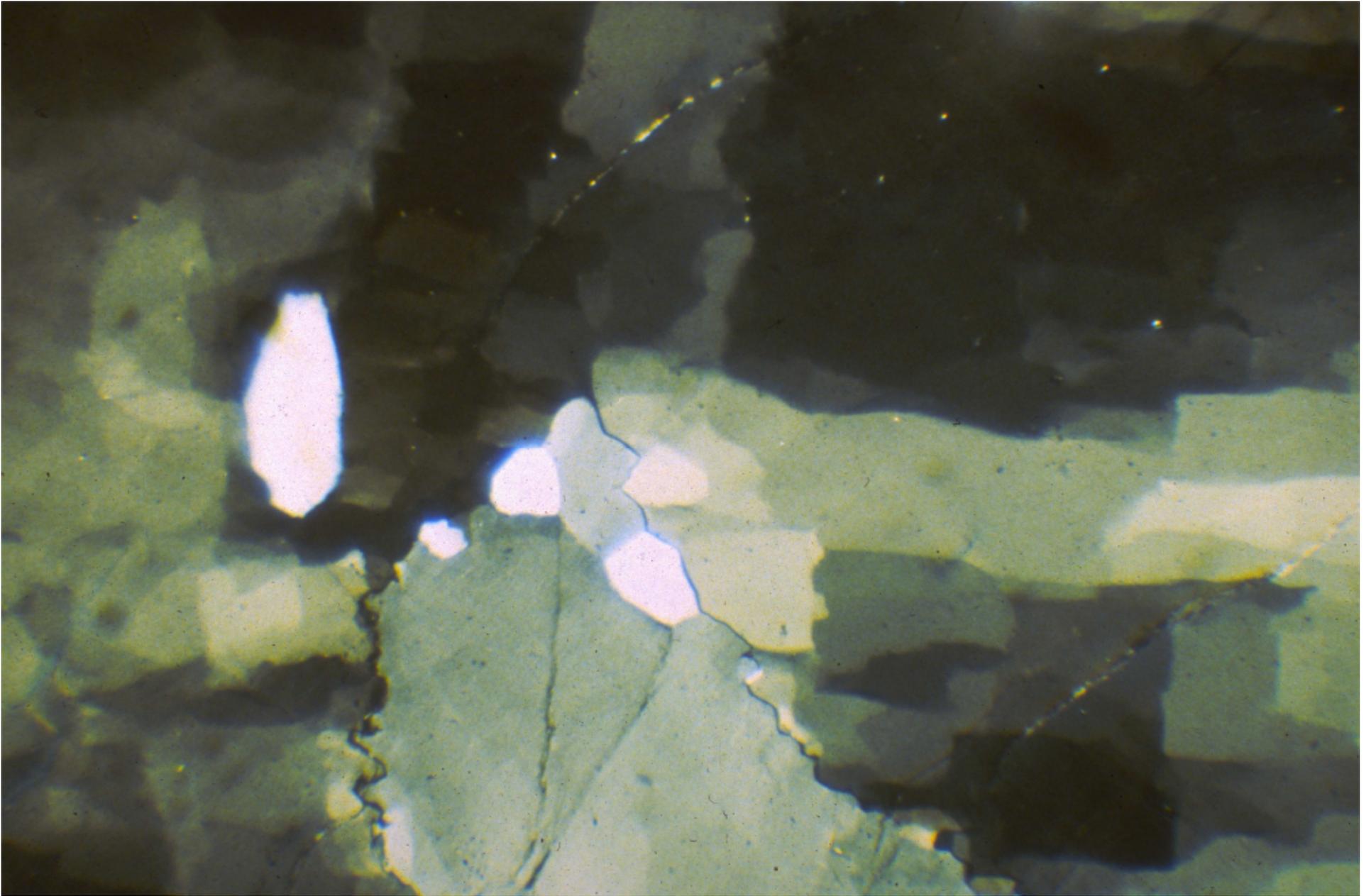
(c)

Poligonized lattice



(d)

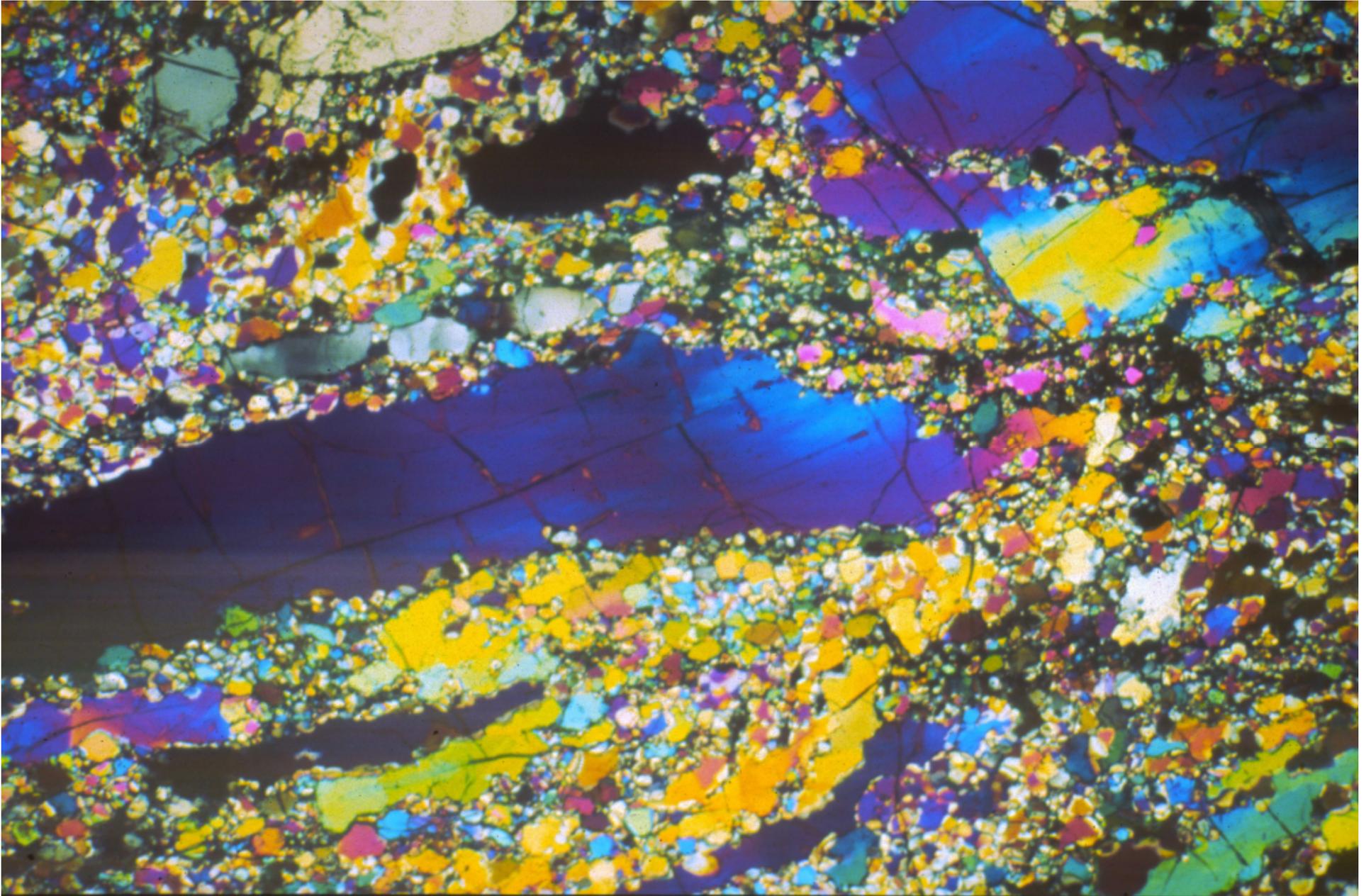
Naturally deformed quartzite



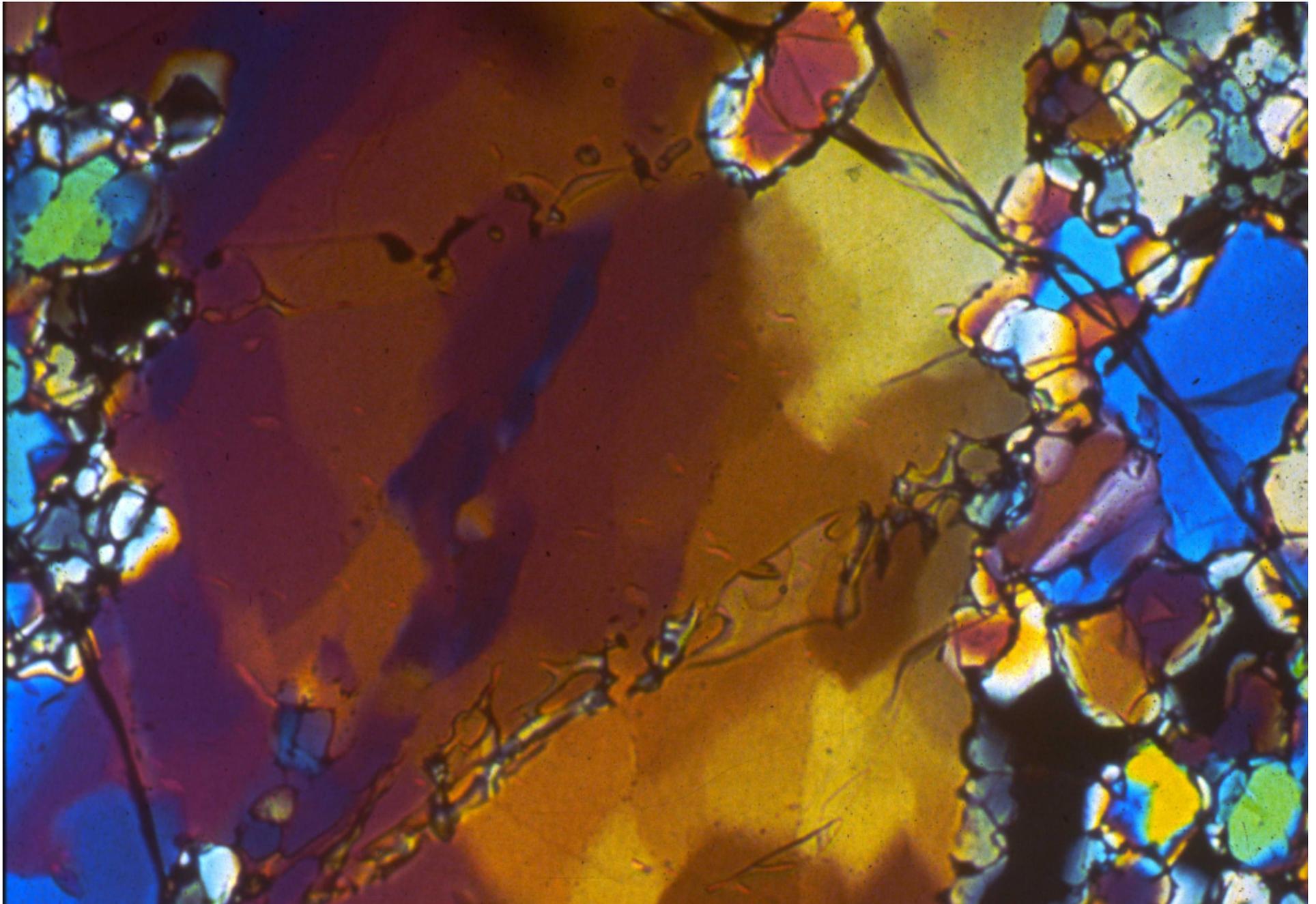
Experimental deformation of dunite, with flattened grains, subgrains and recrystallization



Naturally deformed peridotite, Hualali, Hawaii

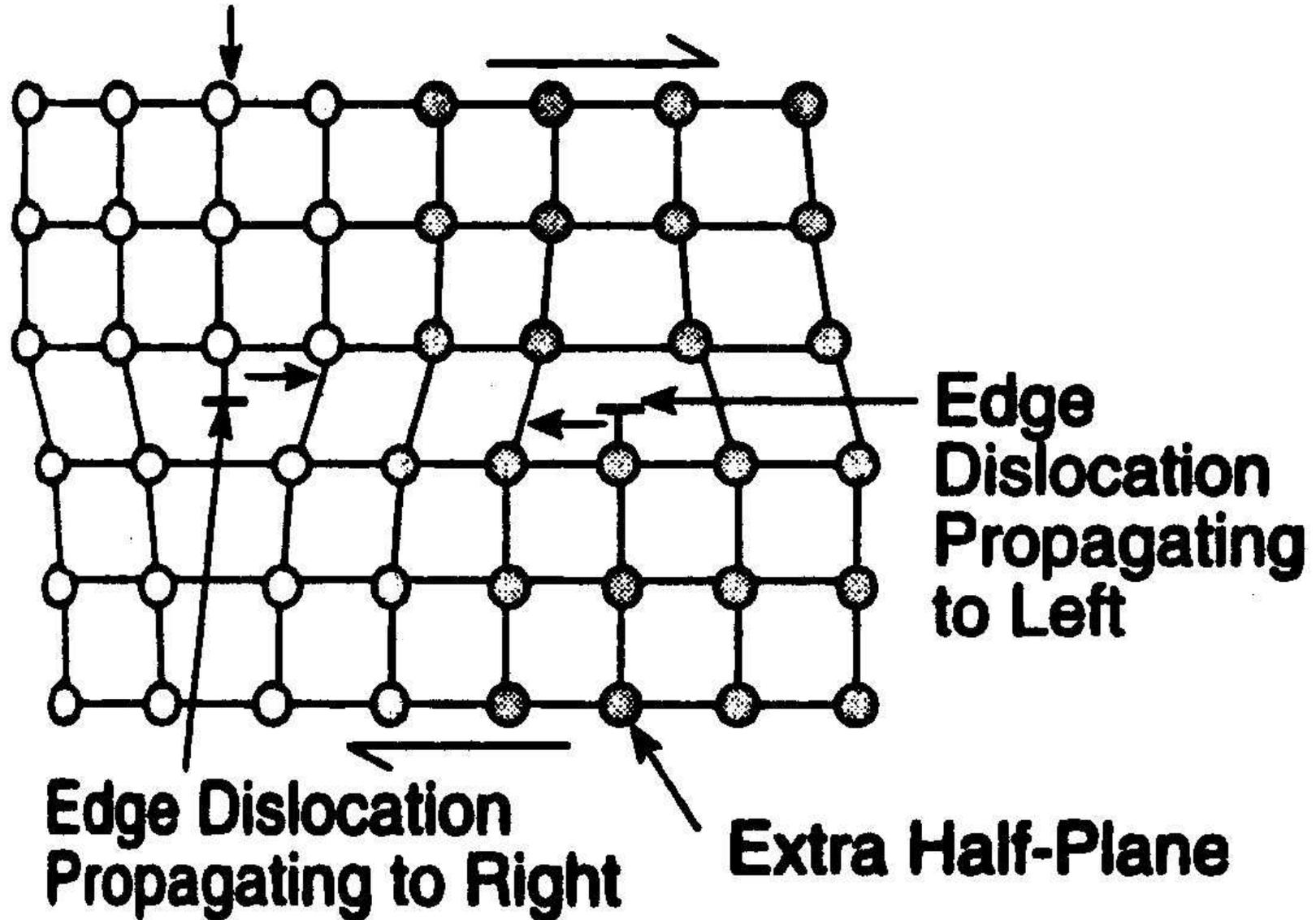


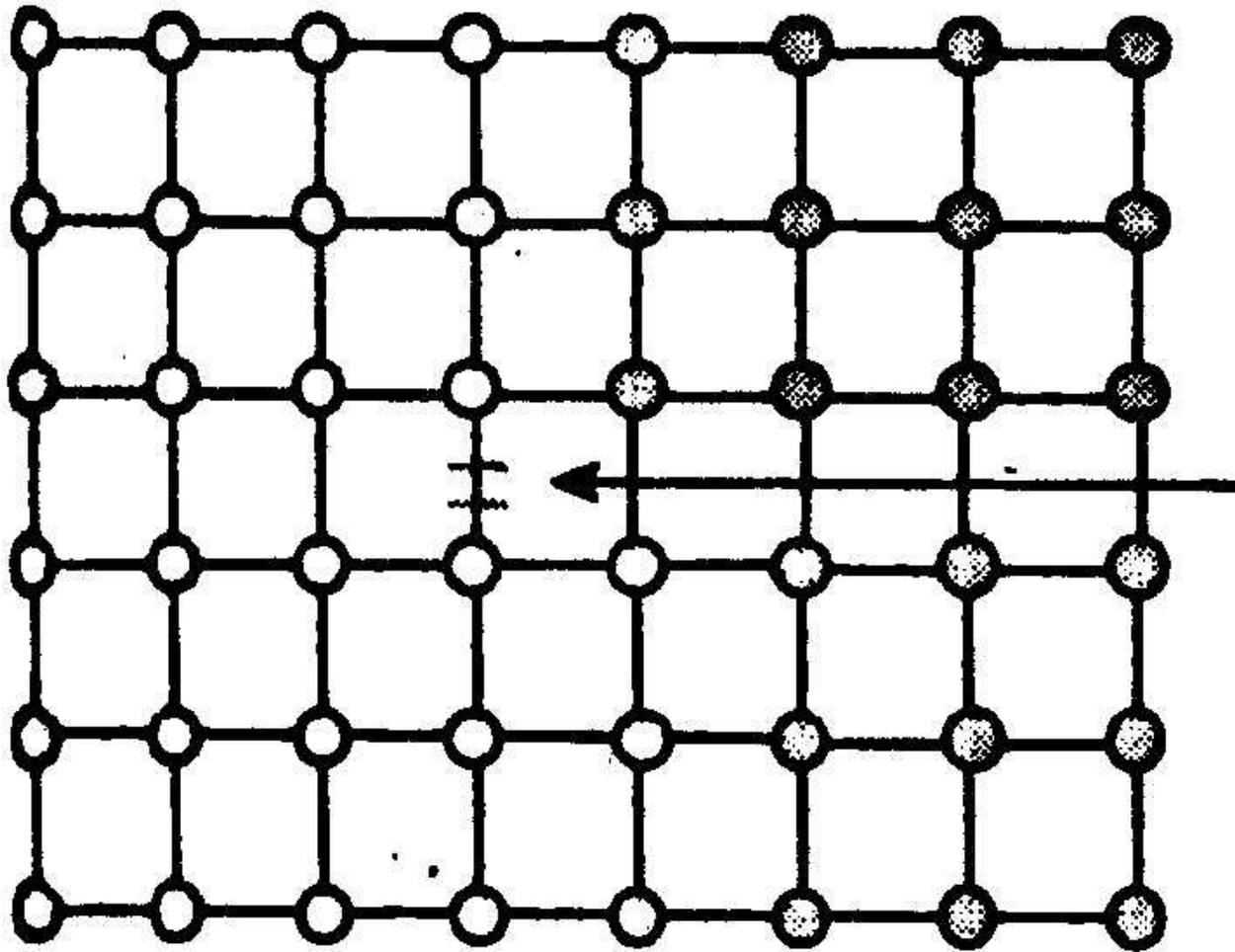
Naturally deformed peridotite; recrystallized grains in olivine subgrains



Edge Dislocations of Opposite Sign Within Same Slip Planes

Extra Half-Plane



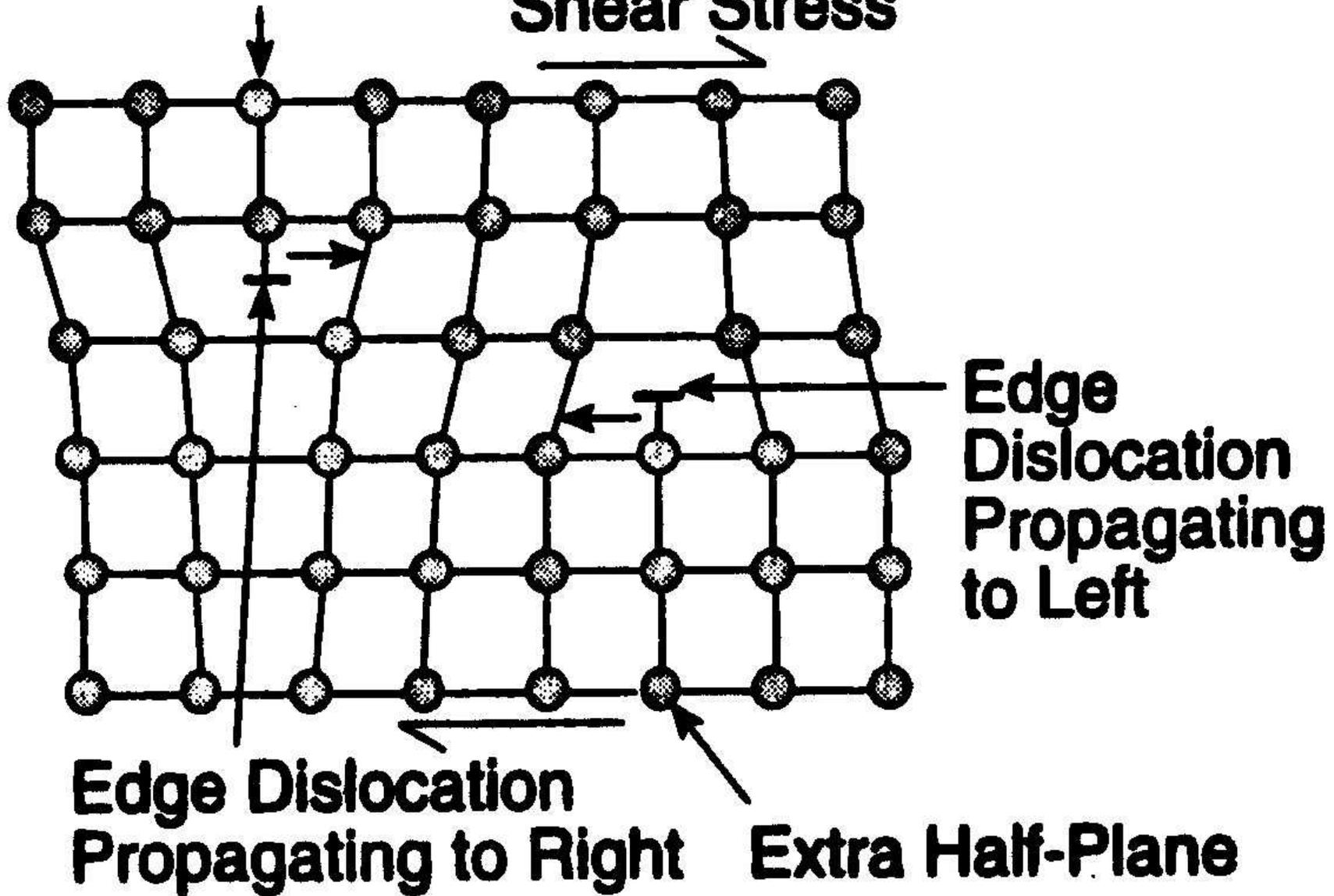


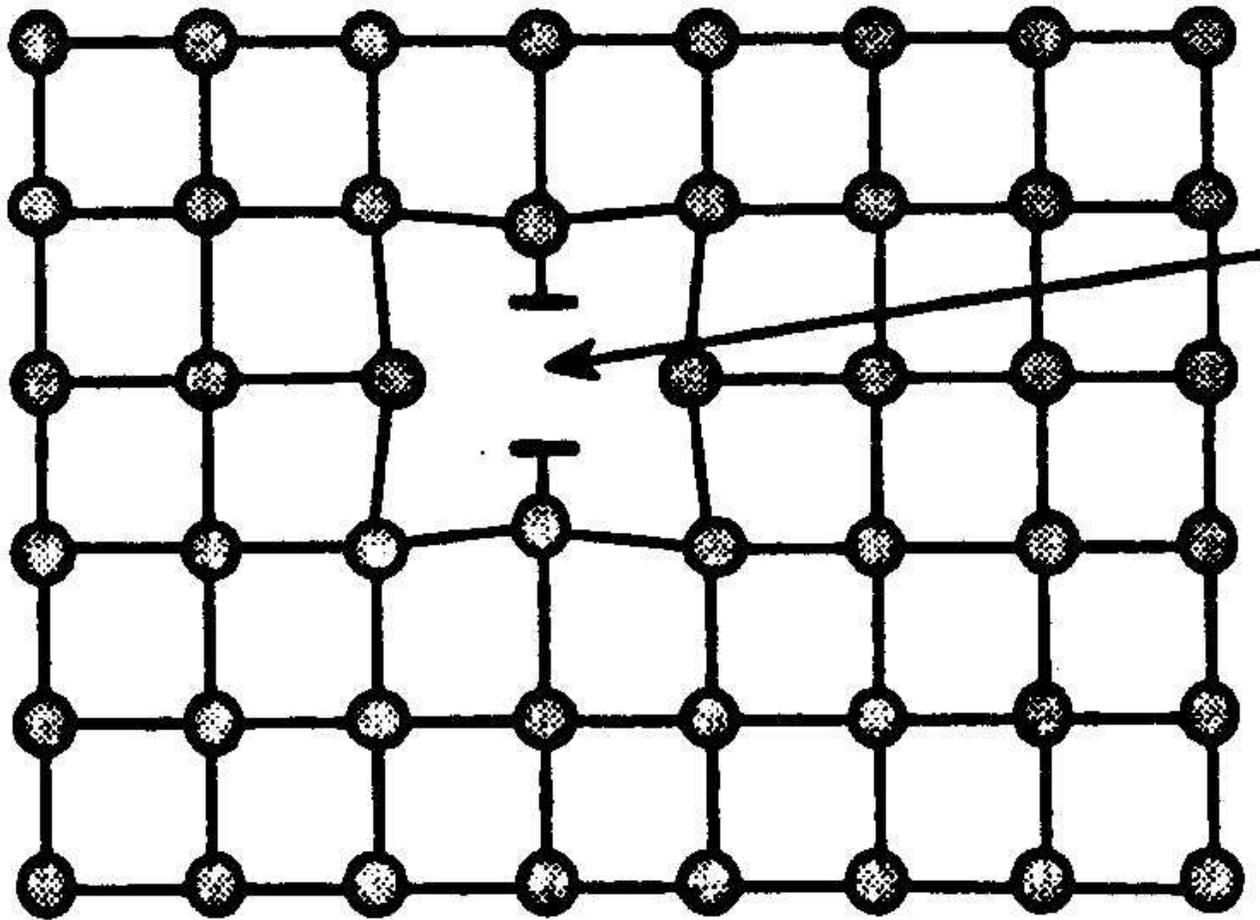
**Dislocations
Cancel Each
Other and
Lattice is
Healed**

Edge Dislocations of Opposite Sign Within Different Slip Planes

Extra Half-Plane

Shear Stress



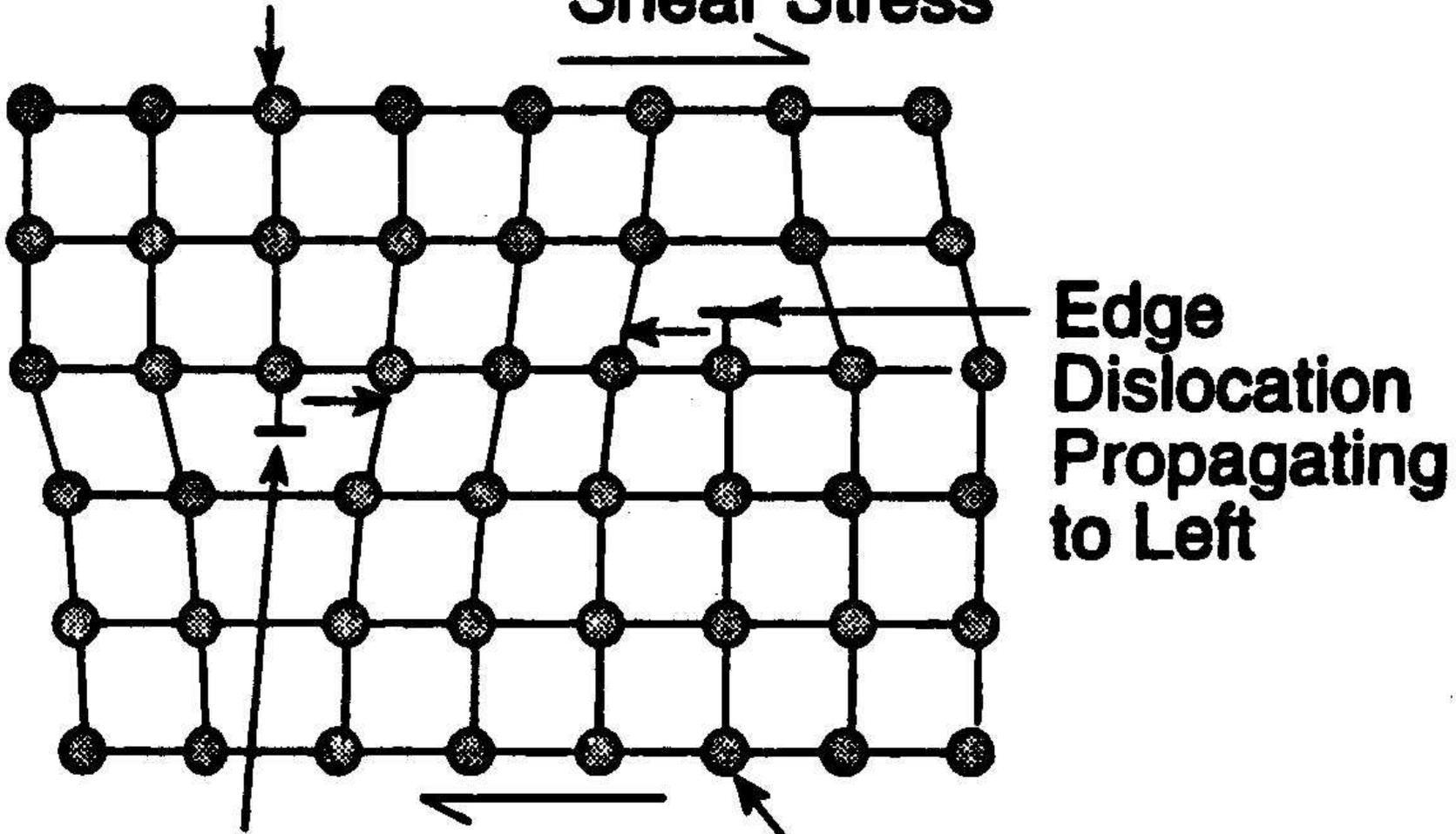


**Dislocations
Meet and
Produce a Line
of Vacancies**

Edge Dislocations of Opposite Sign with "Overlapping" Half-Planes

Extra Half-Plane

Shear Stress

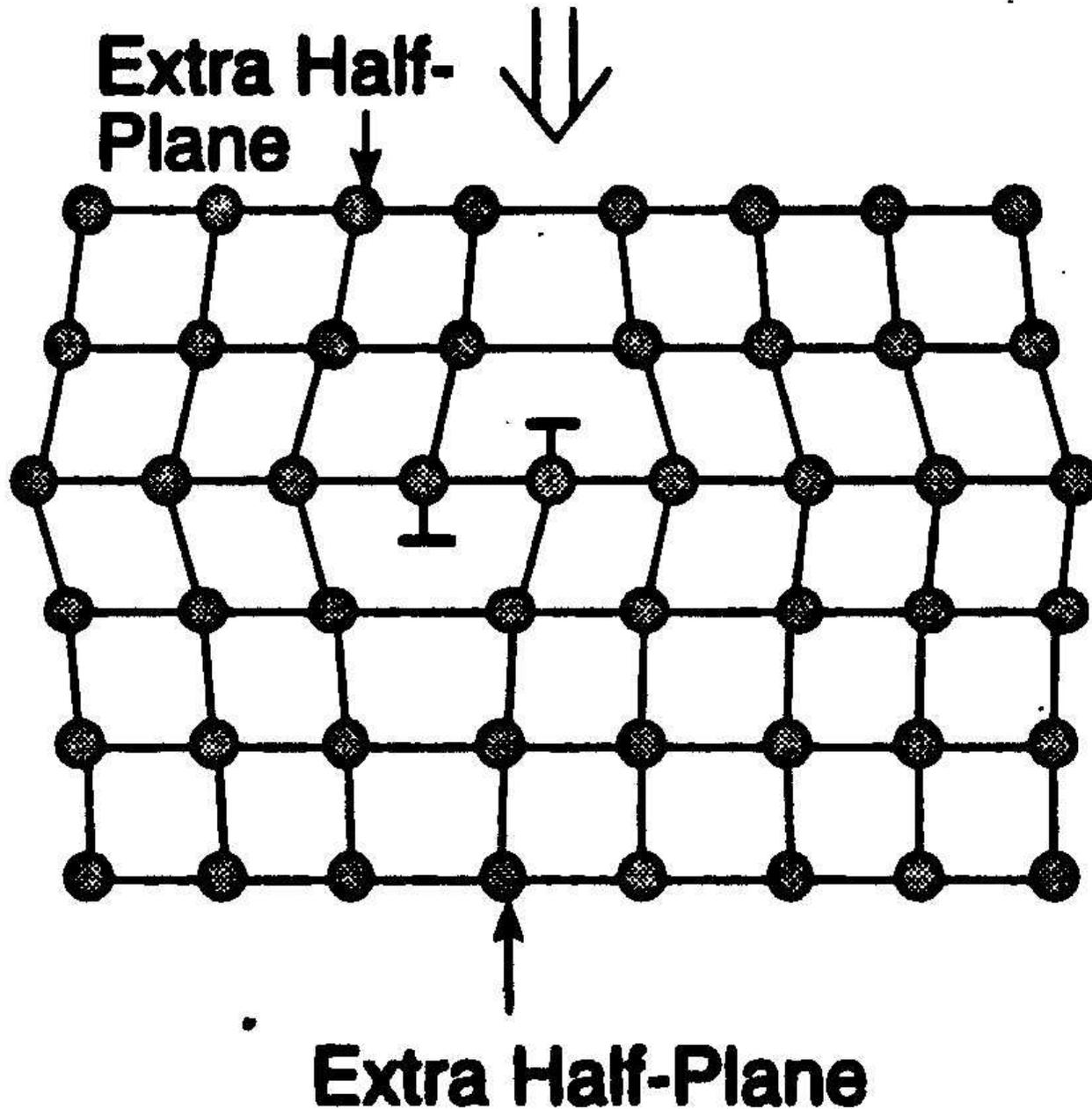


Edge Dislocation Propagating to Left

Edge Dislocation Propagating to Right

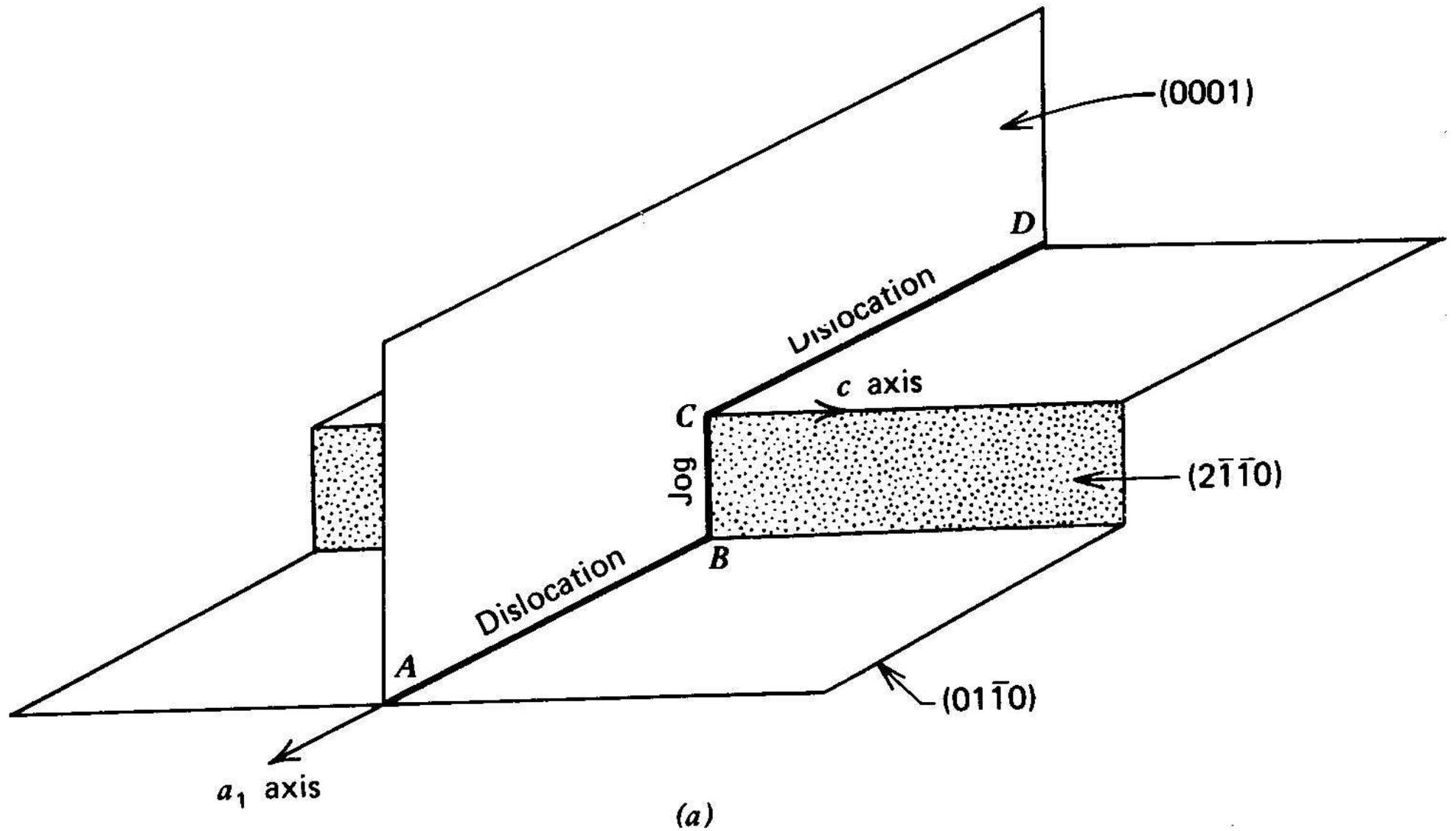
Extra Half-Plane

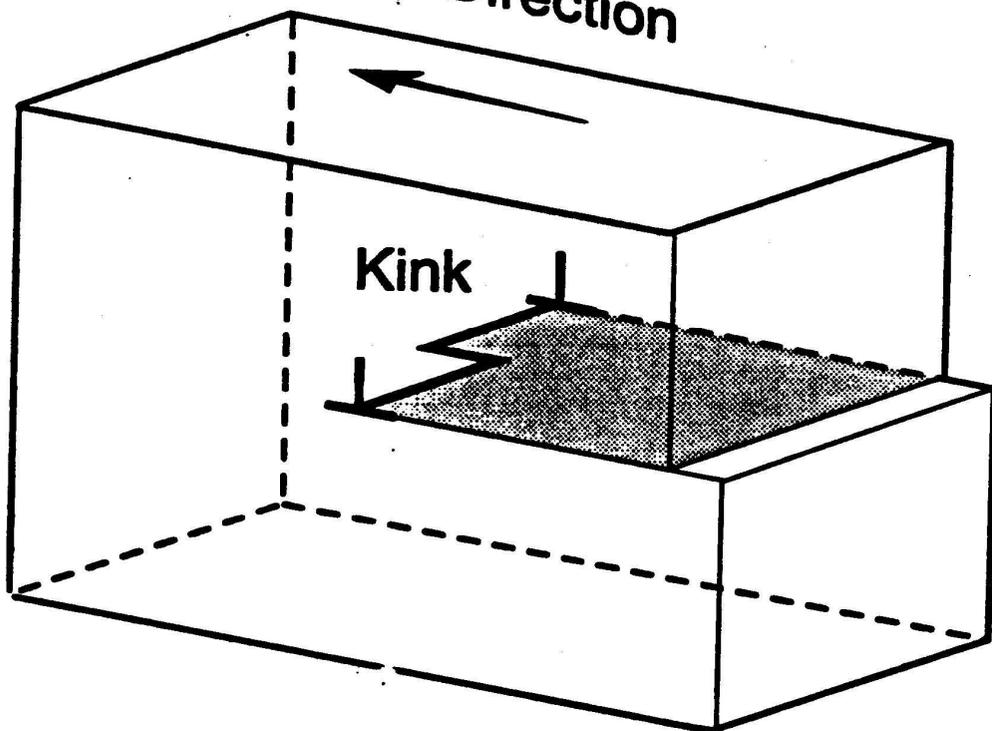
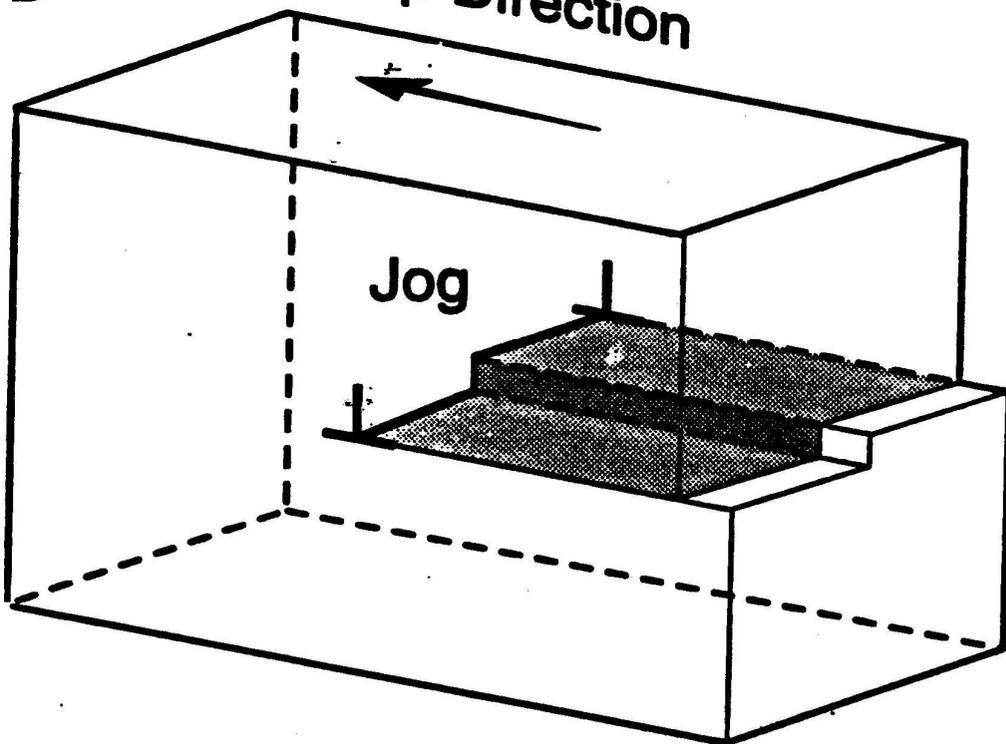
Dislocations Become Locked and Remain in Lattice, Resulting in Strain Hardening



**Note: If
Either Half-
Plane can
Shorten via
Climb, then
the Lattice
is Healed**

Jog in an edge dislocation



A**Slip Direction****B****Slip Direction**

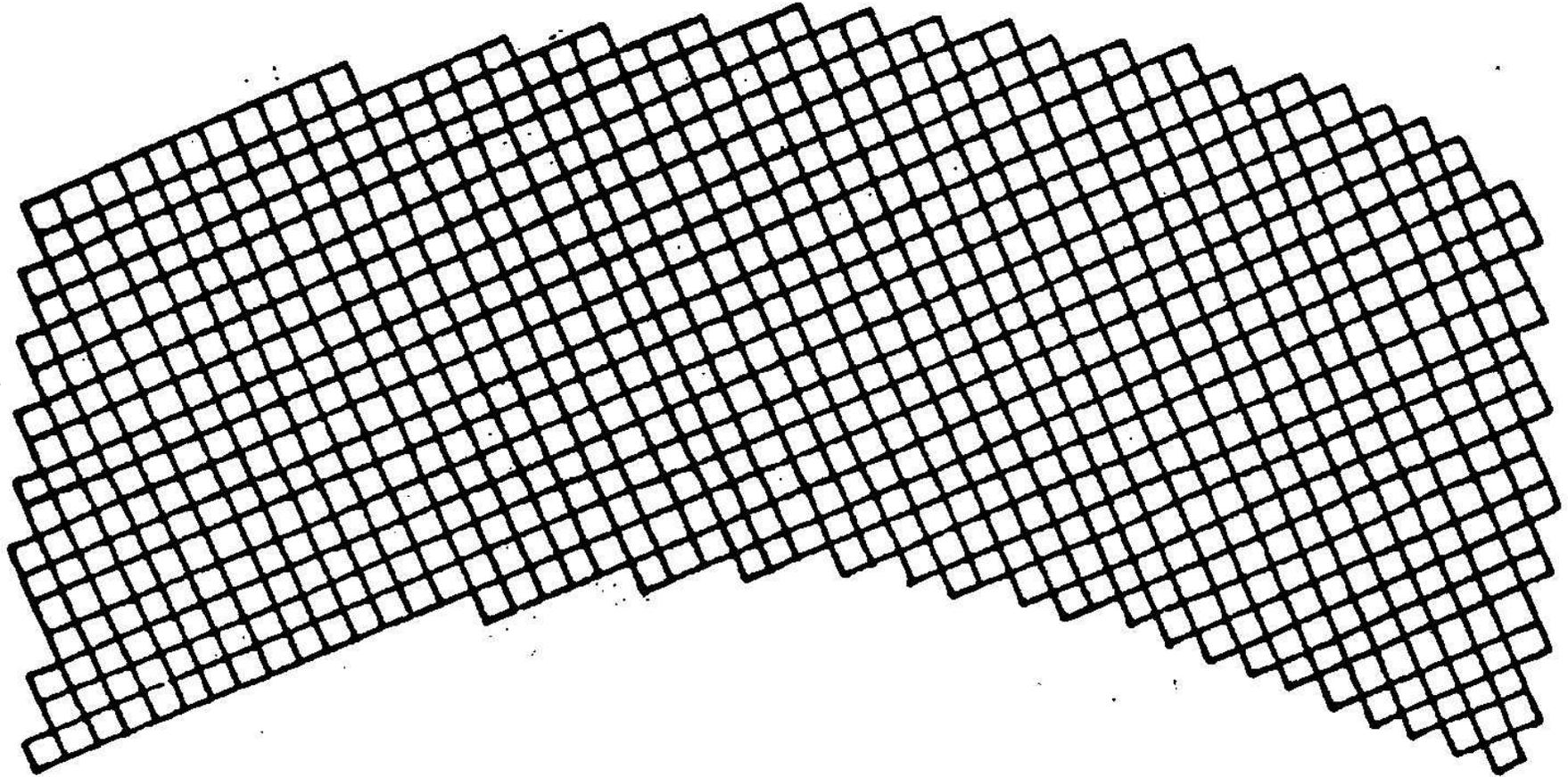
Recovery

Processes occurring between 0.3-0.5 T_m that reduce dislocation density (and hence reduce the elastic strain energy inside of a crystal).

Work hardening (tangling of dislocations) competes with recovery.

- ***Vacancy diffusion*** helps untangle dislocations
- ***Climb*** to straighten and untangle dislocations
- Dislocation annihilation
- Ordering of dislocations into walls

Unstrained, recovered lattice



(e)

**Dislocation creep =
dislocation glide +
dislocation climb**

The motion of dislocations and vacancies through a crystal occurs at all temperatures, but it is much faster at high temperatures than at low temperatures.

**Dislocation creep =
dislocation glide +
dislocation climb**

At high temperatures, it takes less energy for vacancies to diffuse through or around a crystal.

The amount of strain energy needed to break chemical bonds is reduced at high T.

Competing Processes

Work Hardening:

dislocations tangle and obstruct each others' motion. Strain leads to an increase in dislocations, inhibiting further strain.

Competing Processes

Work Softening:

dislocations are annihilated or organized into subgrain boundaries (tilt walls), resulting in lattices that contain fewer dislocations.

Recovery and recrystallization

are involved; enhanced at higher temperatures.

Homologous Temperature (T_m)

This is the melting temperature of a mineral expressed in the Kelvin temperature scale:

$$0 \text{ K} = -273.16^\circ\text{C}$$

Zero Kelvin is called ***absolute zero***, because it is the temperature at which the volume of any ideal gas would reach zero and at which all thermal vibration of an atom ceases.

Primary Recrystallization

Occurs at temperatures above half the homologous temperature (T_m) for a mineral.

- Grain boundary area reduction (GBAR)
 - Grain boundaries are straightened and flattened
 - Ratio of volume to surface area is maximized for given physical and chemical conditions
- Equilibrium is approached, given enough time at high temperature

Static recrystallization

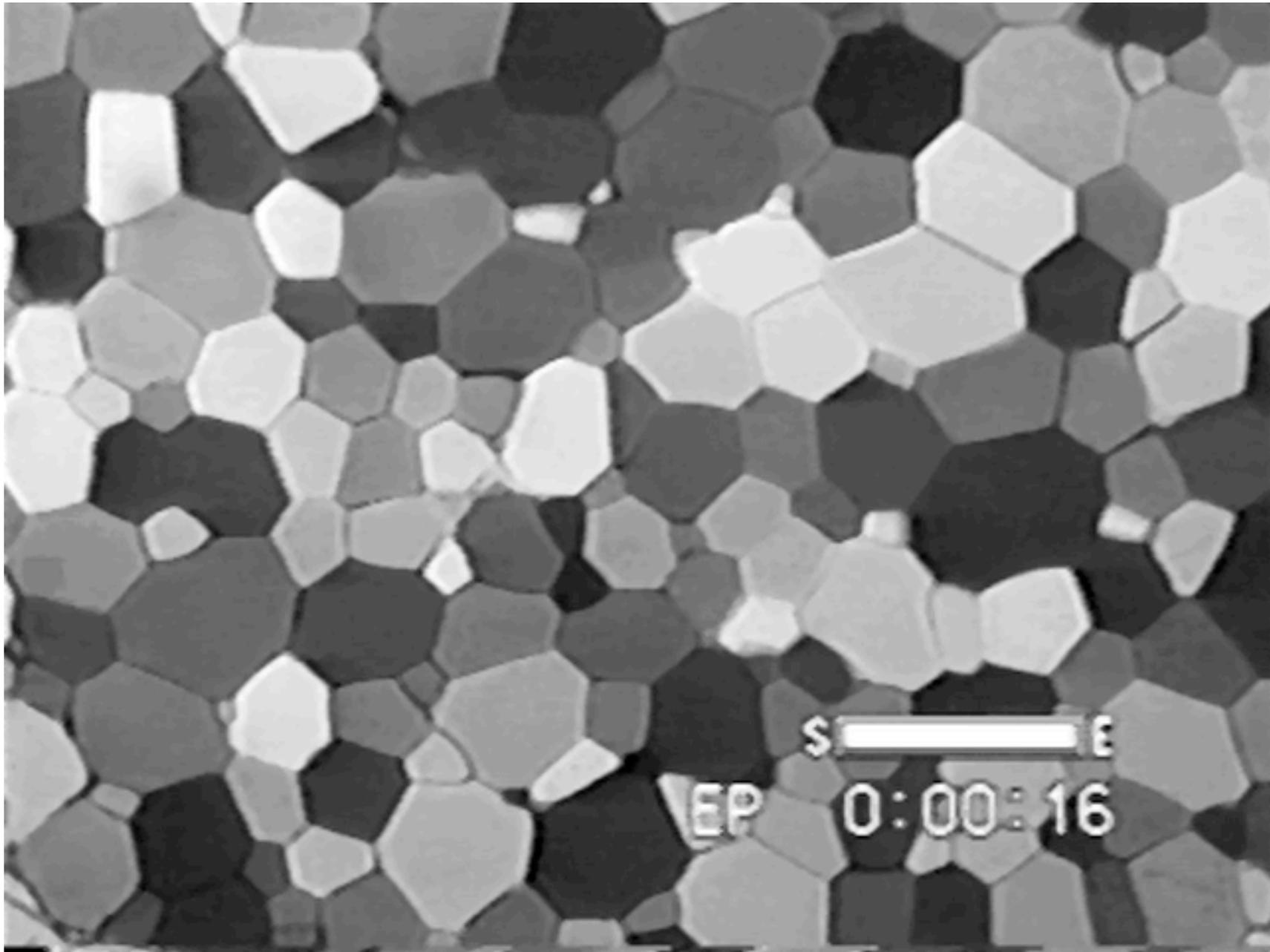


Dynamic Recrystallization

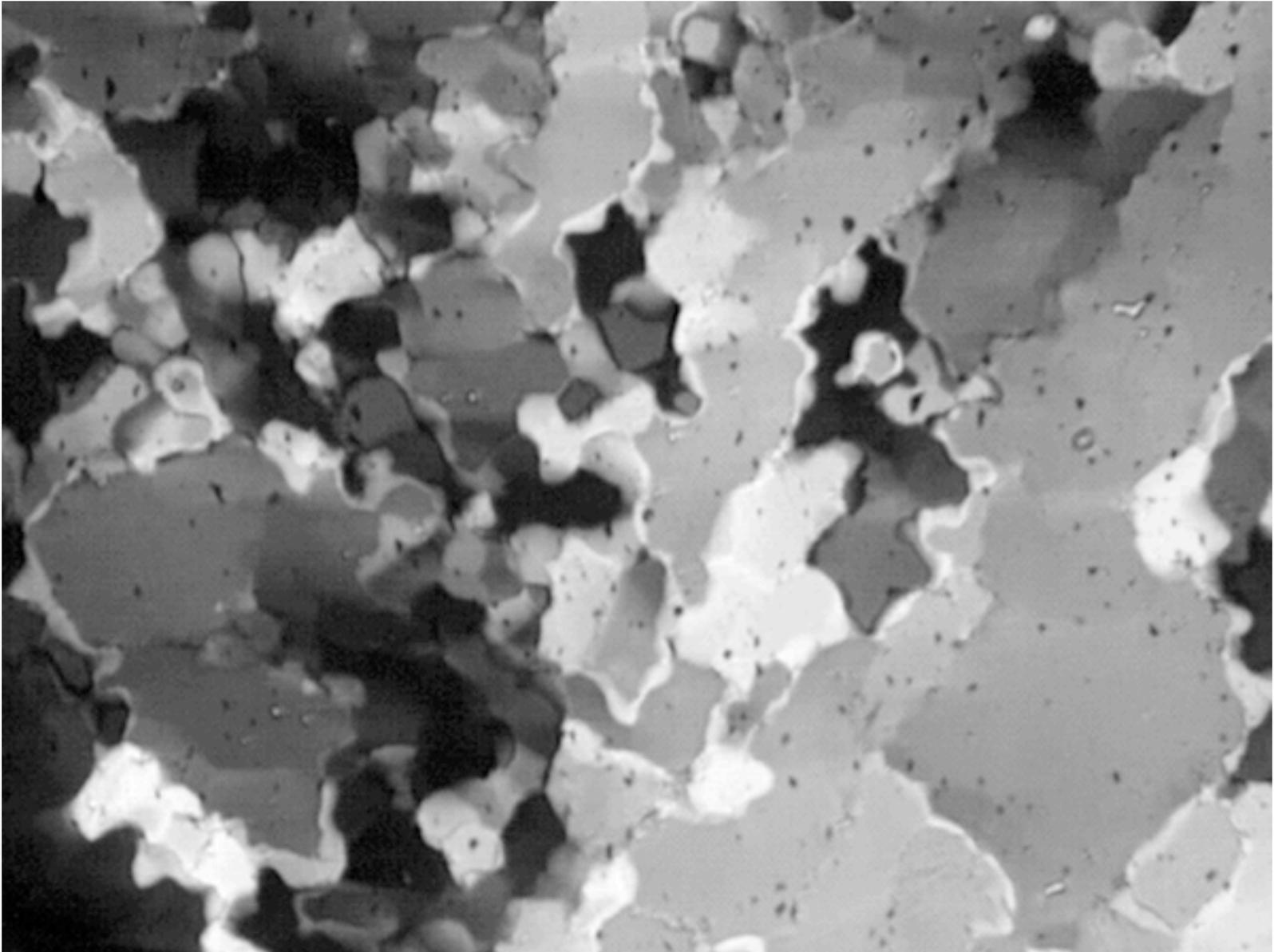
Processes that reduce the internal strain energy of a crystal and reduce the surface energy along grain boundaries.

- Grain boundary migration recrystallization (GBM)
- Subgrain rotation recrystallization (SR)

Grain boundary migration



Dynamic recrystalization

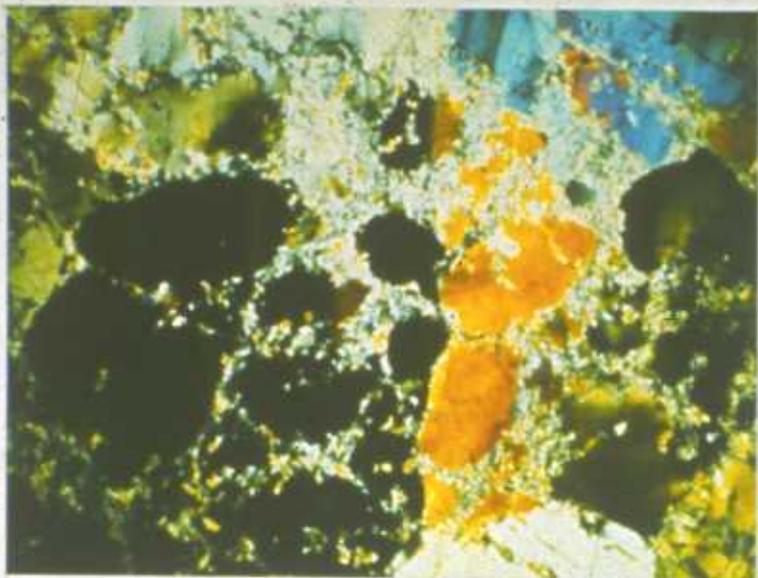


Dynamic Recrystallization

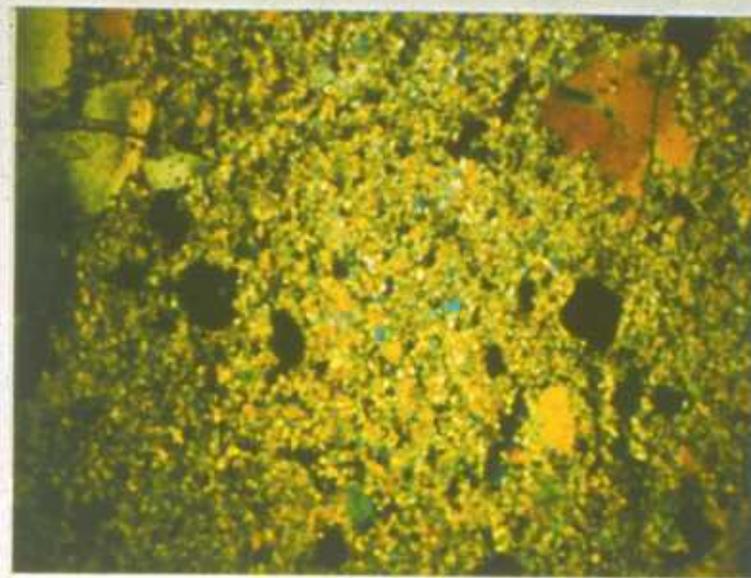
...under *high* flow stress results in ***smaller*** crystals

Dynamically recrystallized rocks with smaller crystals are typically stronger and denser than they were before deformation.

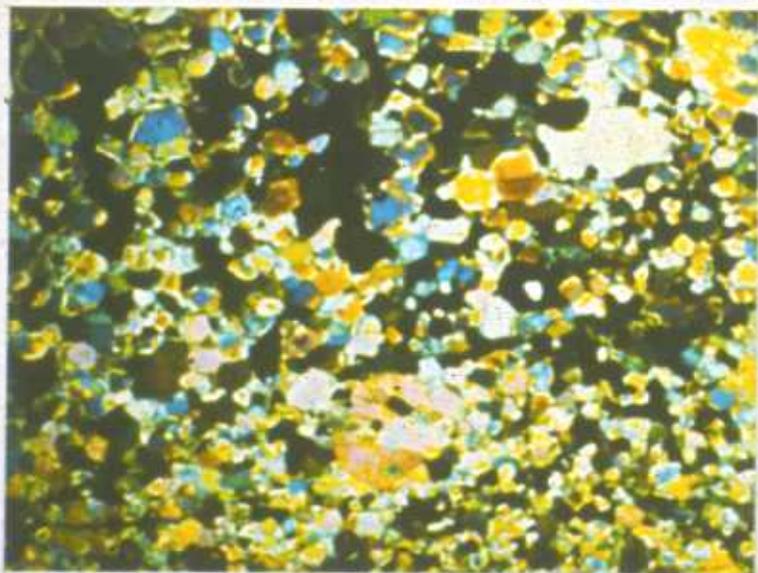
MOUNT BURNET DUNITE ("dry")



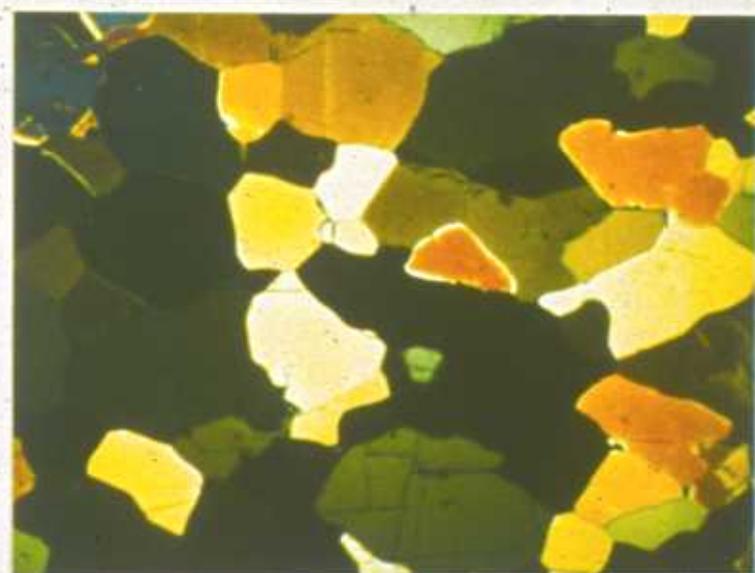
$\sigma = 9.0 \text{ kbar}$, $D = 10 \mu\text{m}$ 500 μm



$\sigma = 5.4 \text{ kbar}$, $D = 25 \mu\text{m}$ 500 μm



$\sigma = 2.3 \text{ kbar}$, $D = 80 \mu\text{m}$ 500 μm



$\sigma = 0.7 \text{ kbar}$, $D = 400 \mu\text{m}$ 500 μm

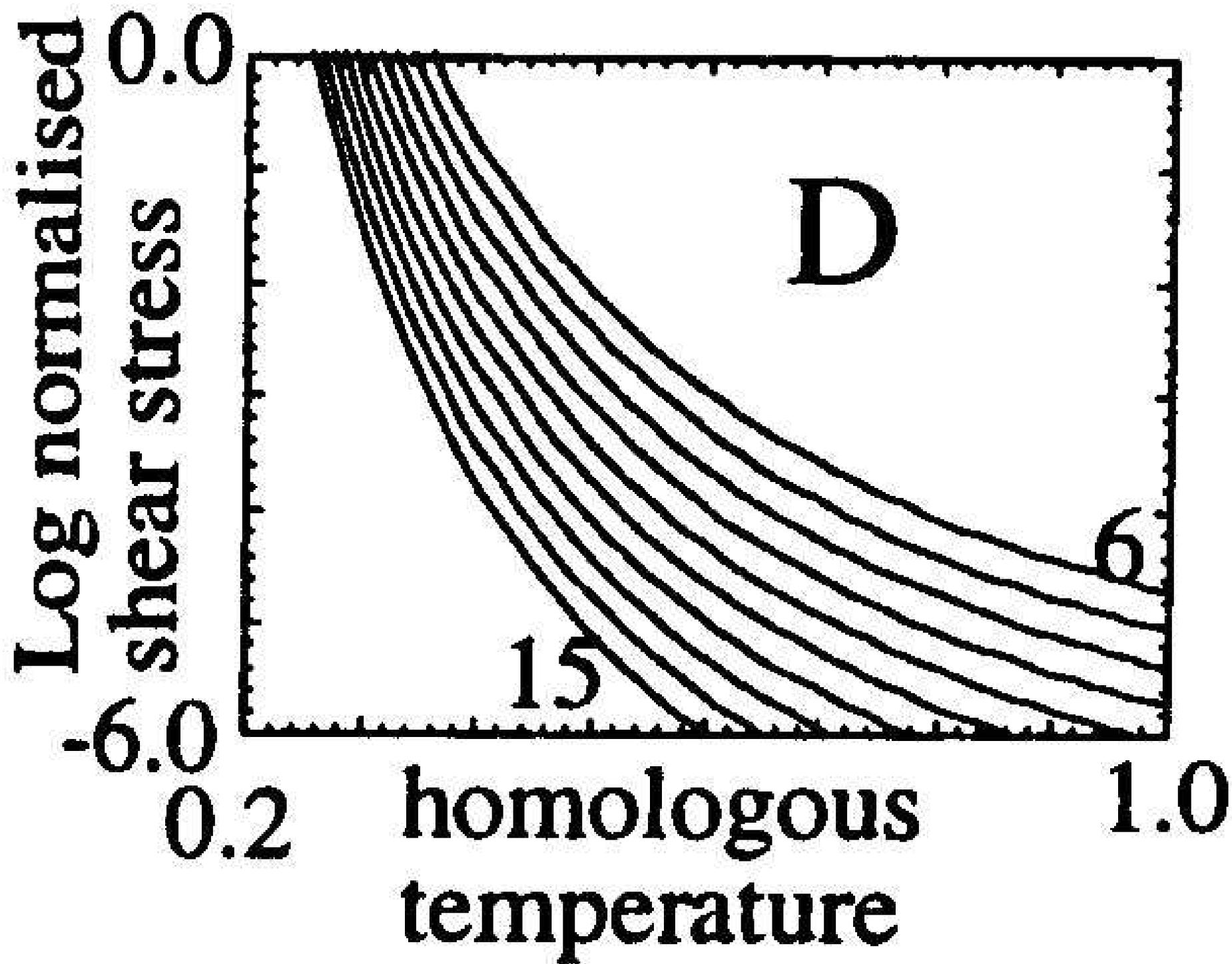
Flow Laws

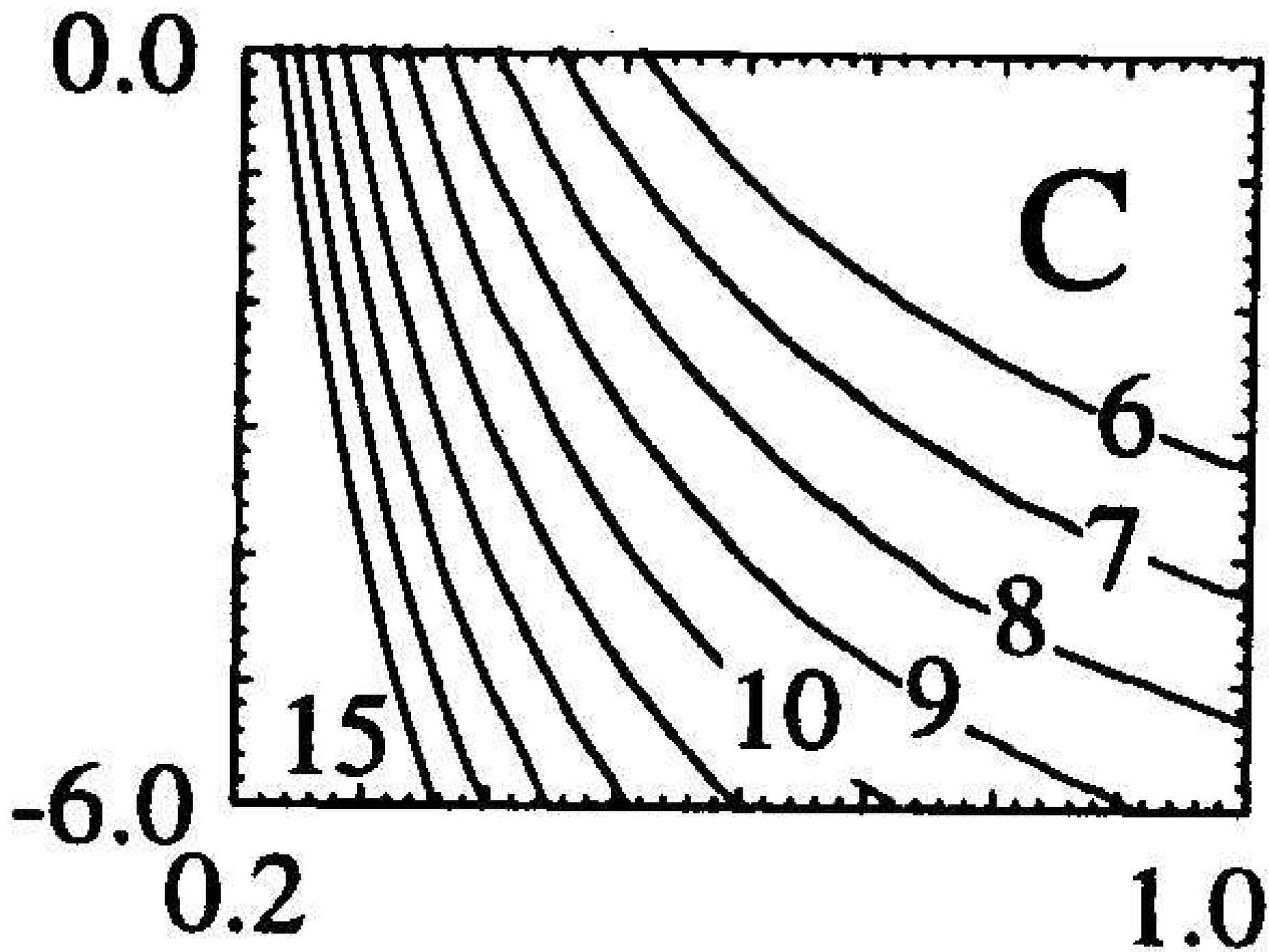
Dislocation (or power-law)
creep modeled with a form of the
Dorn equation

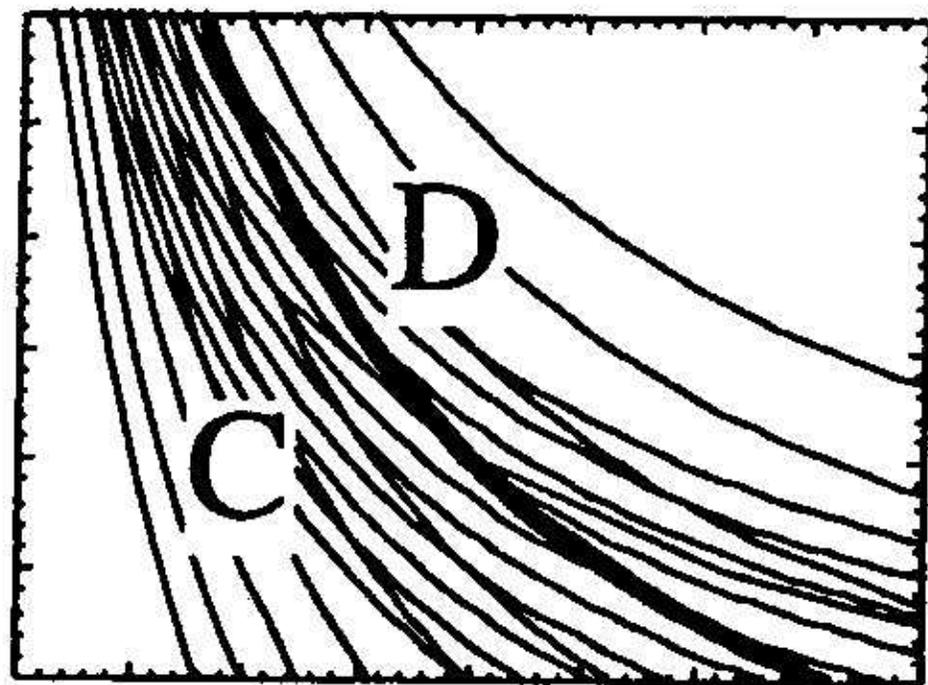
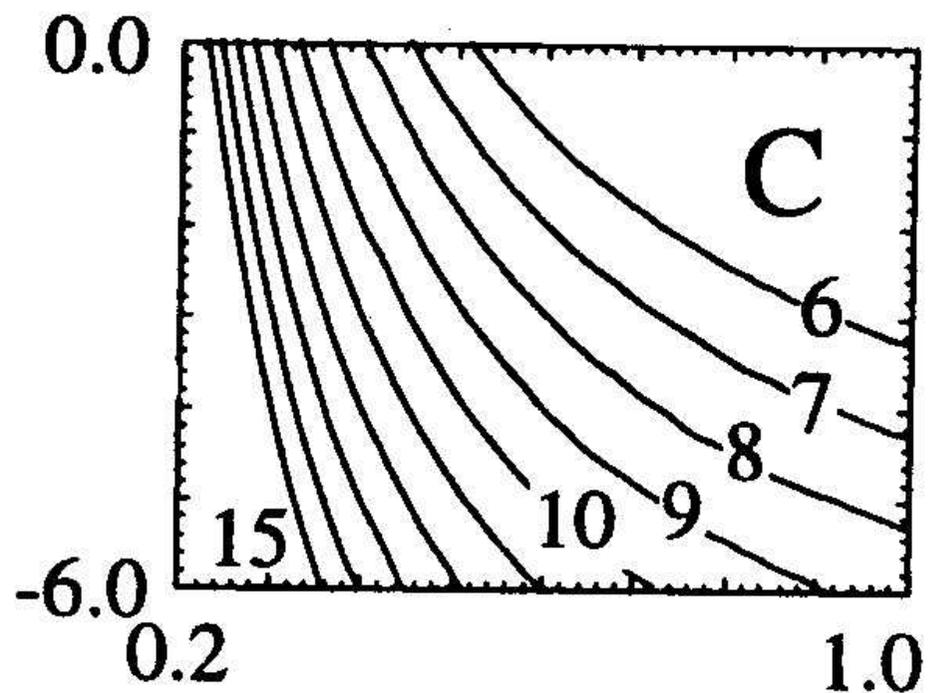
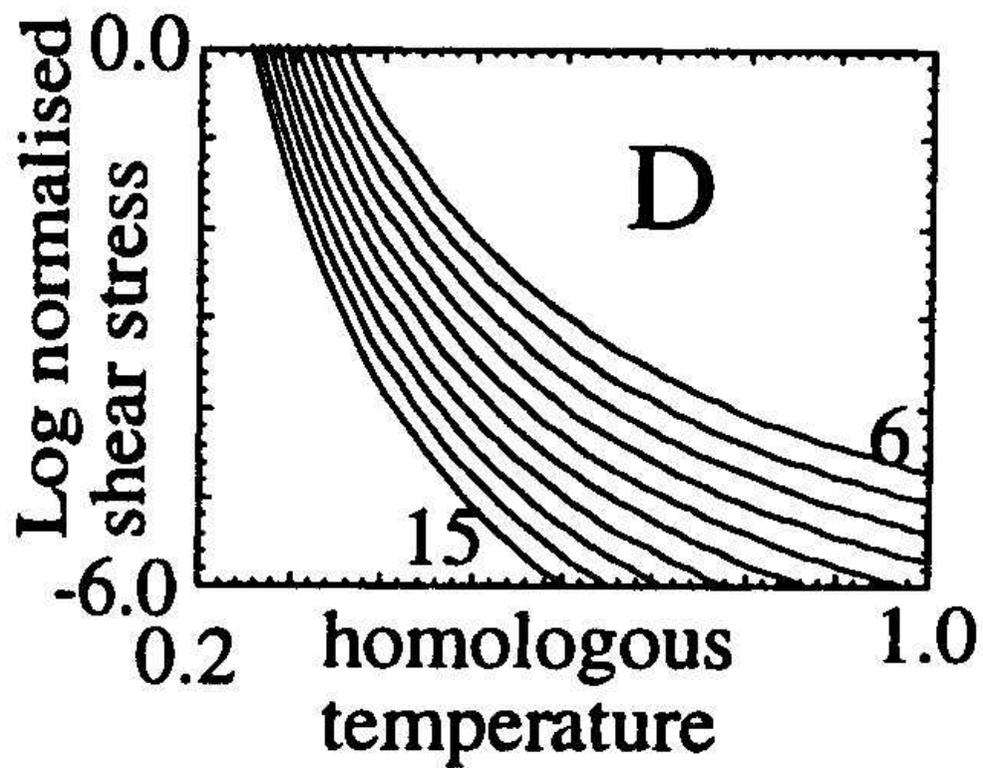
$$\dot{\epsilon} = A\sigma^n e^{(-Q/RT)}$$

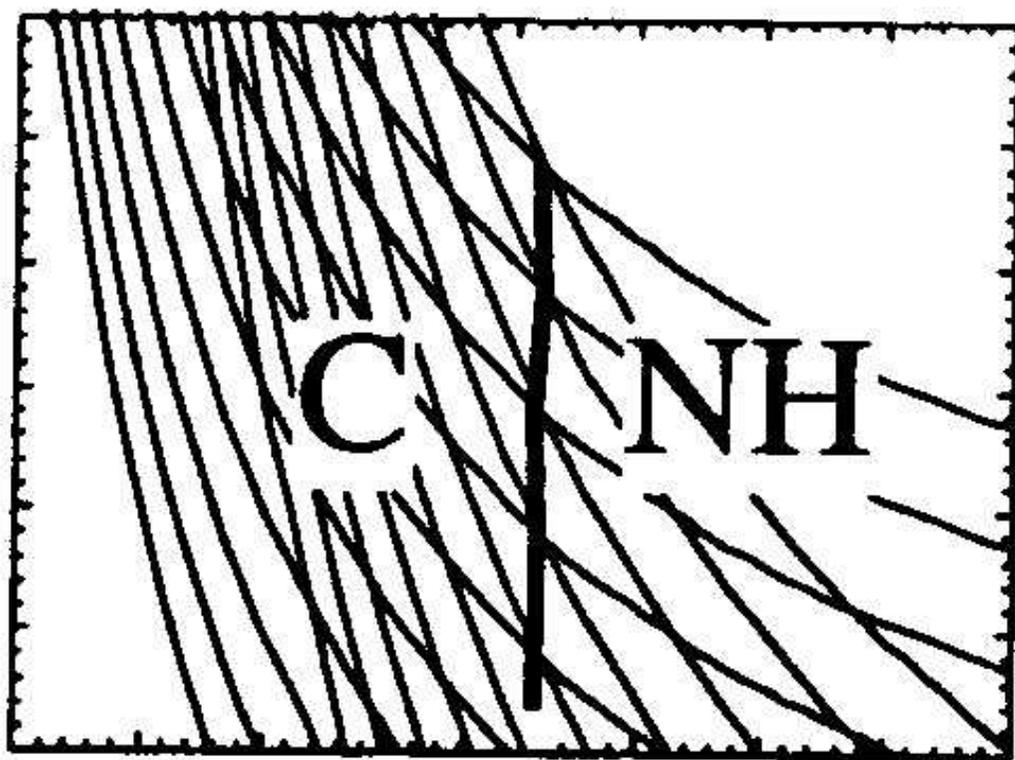
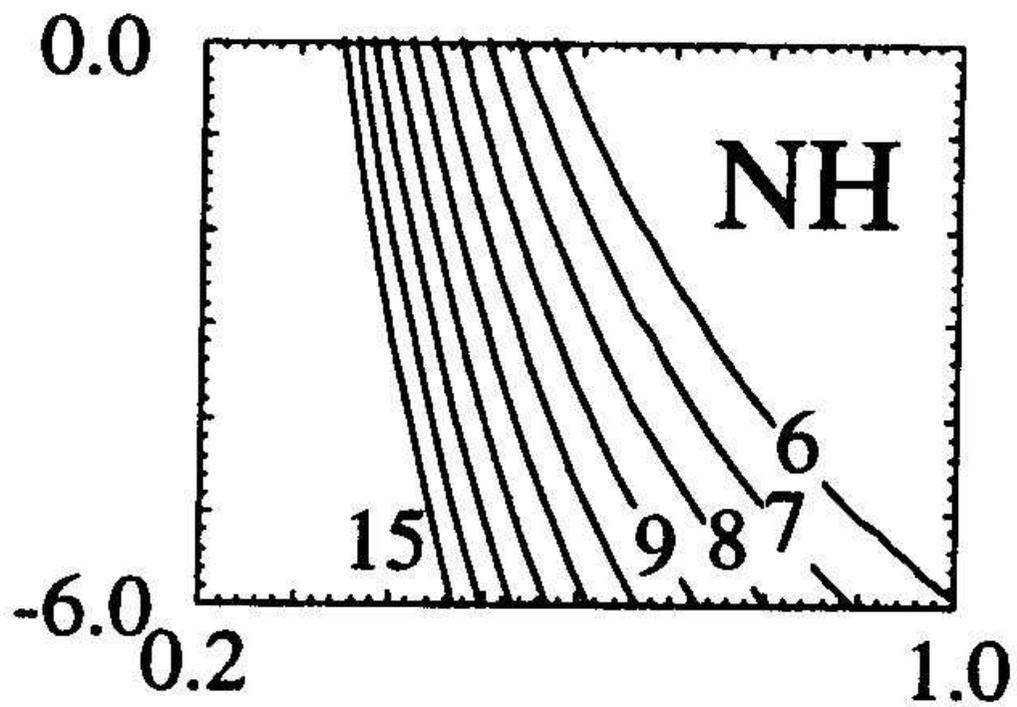
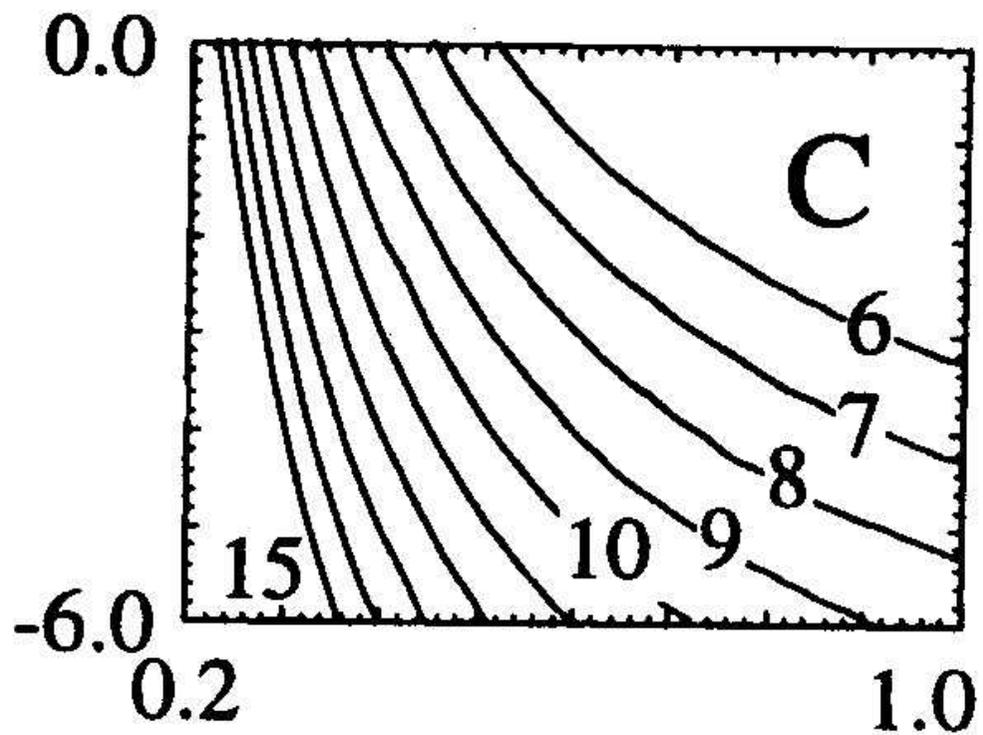
Diffusion creep

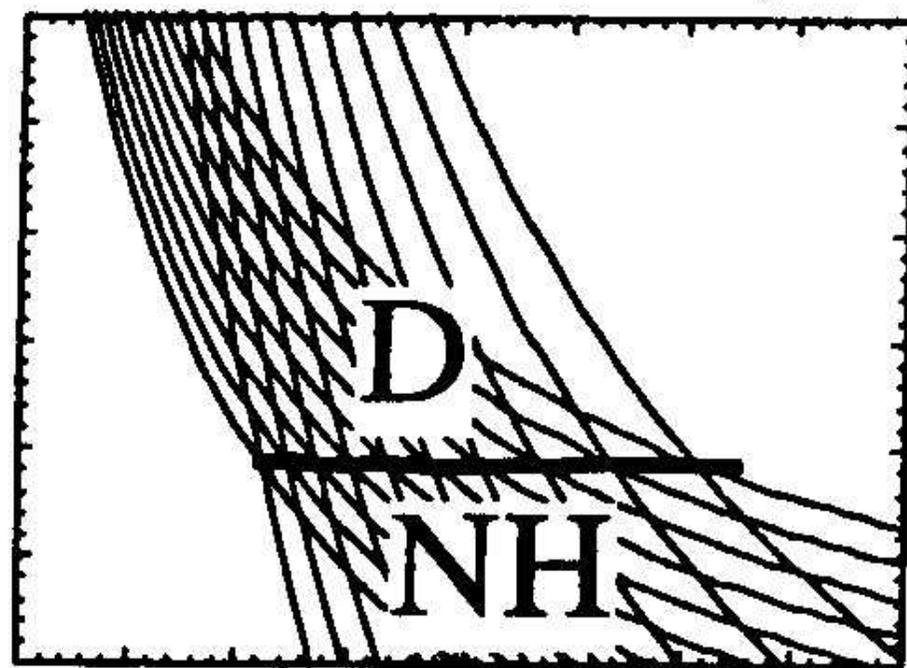
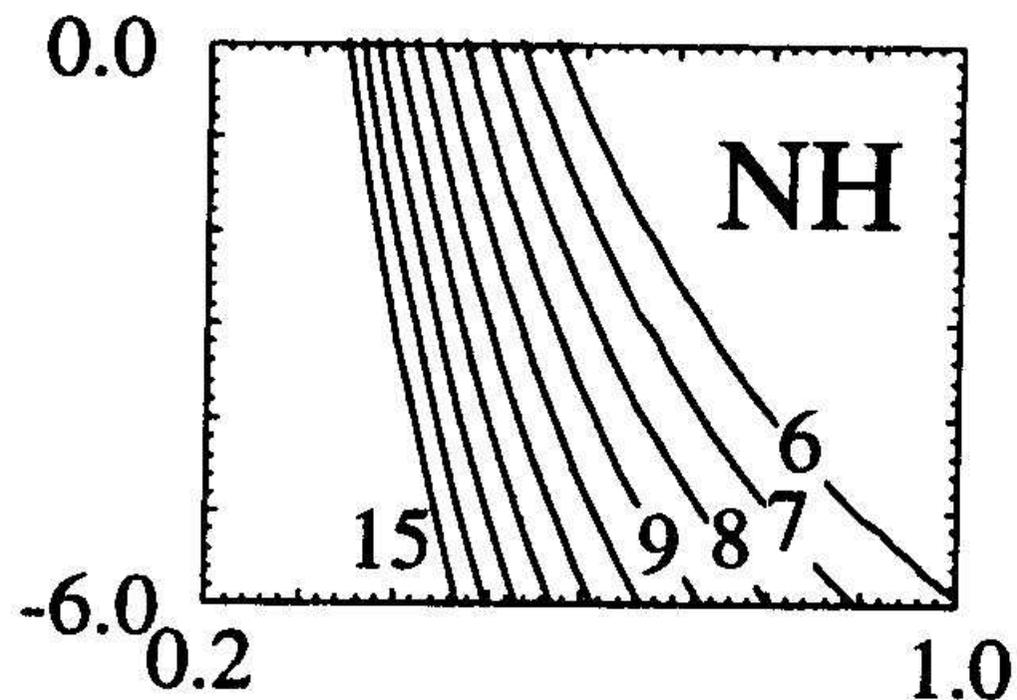
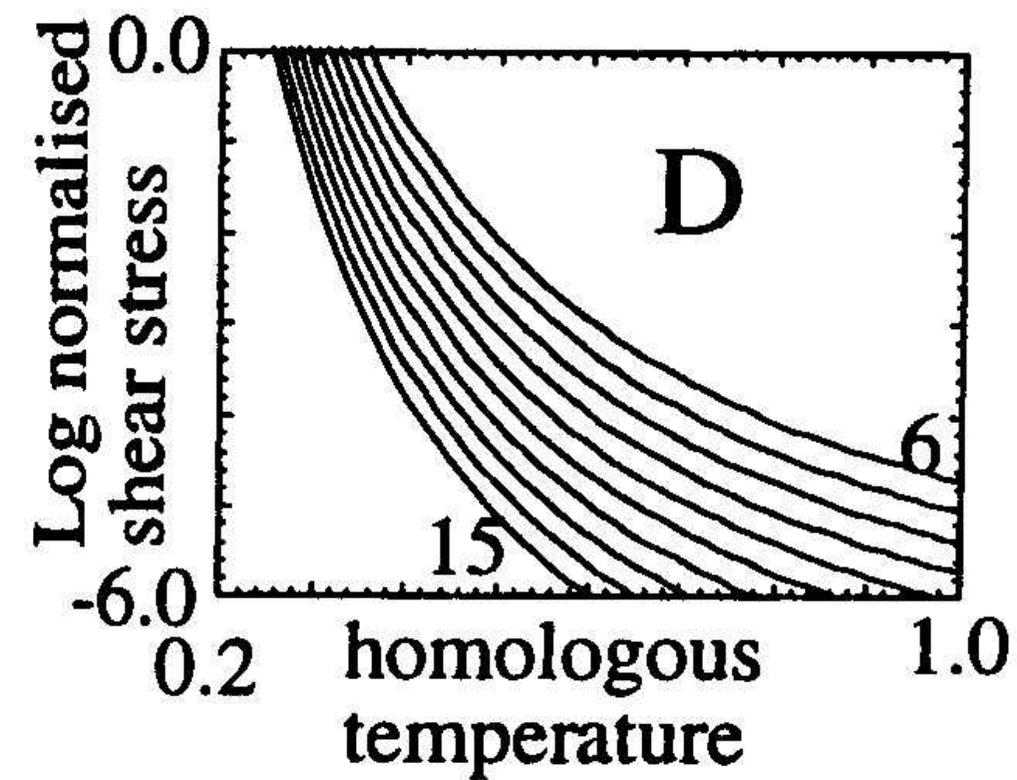
- Coble creep (grain-boundary diffusion)
- Nabarro-Herring creep (volume/
vacancy diffusion)



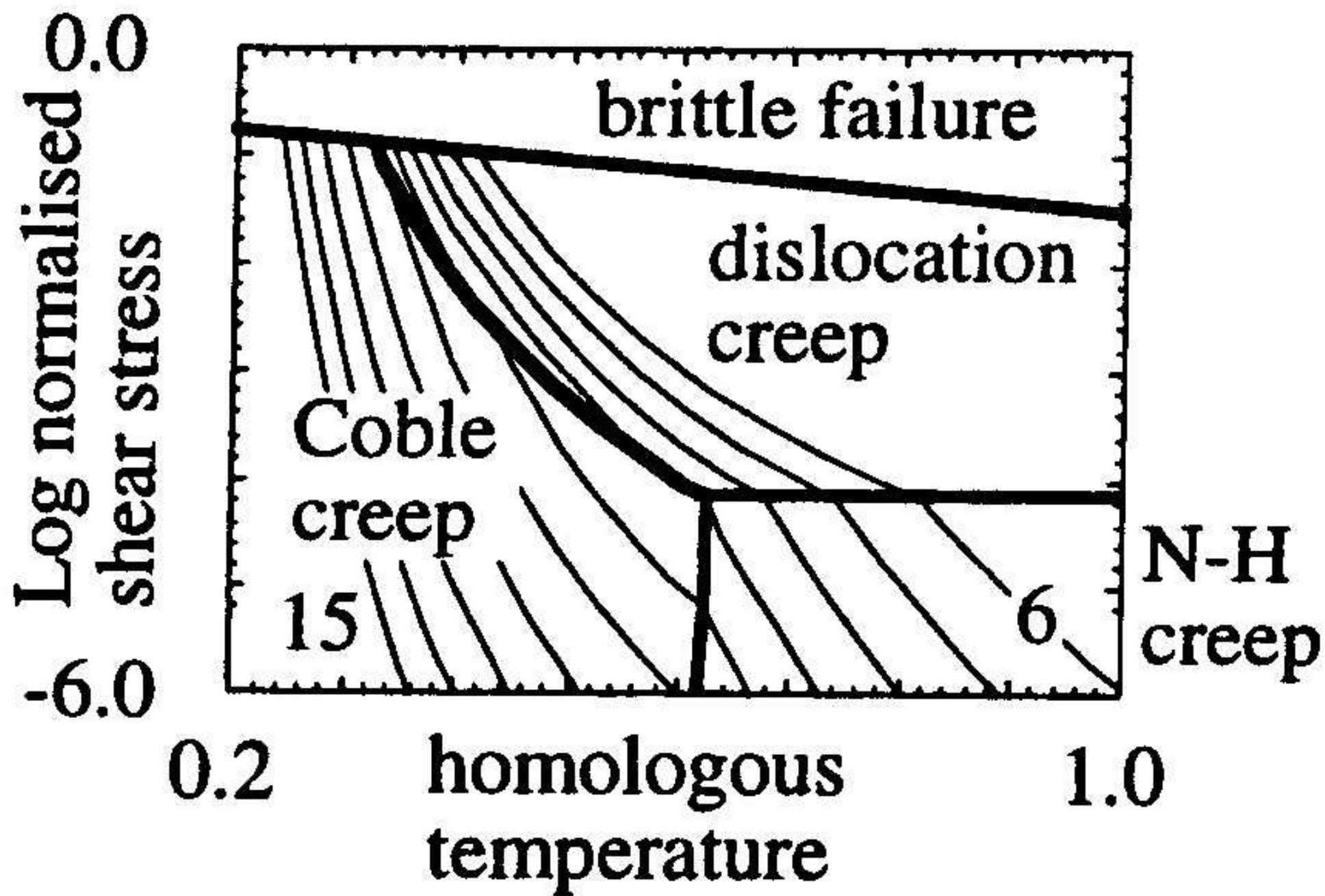




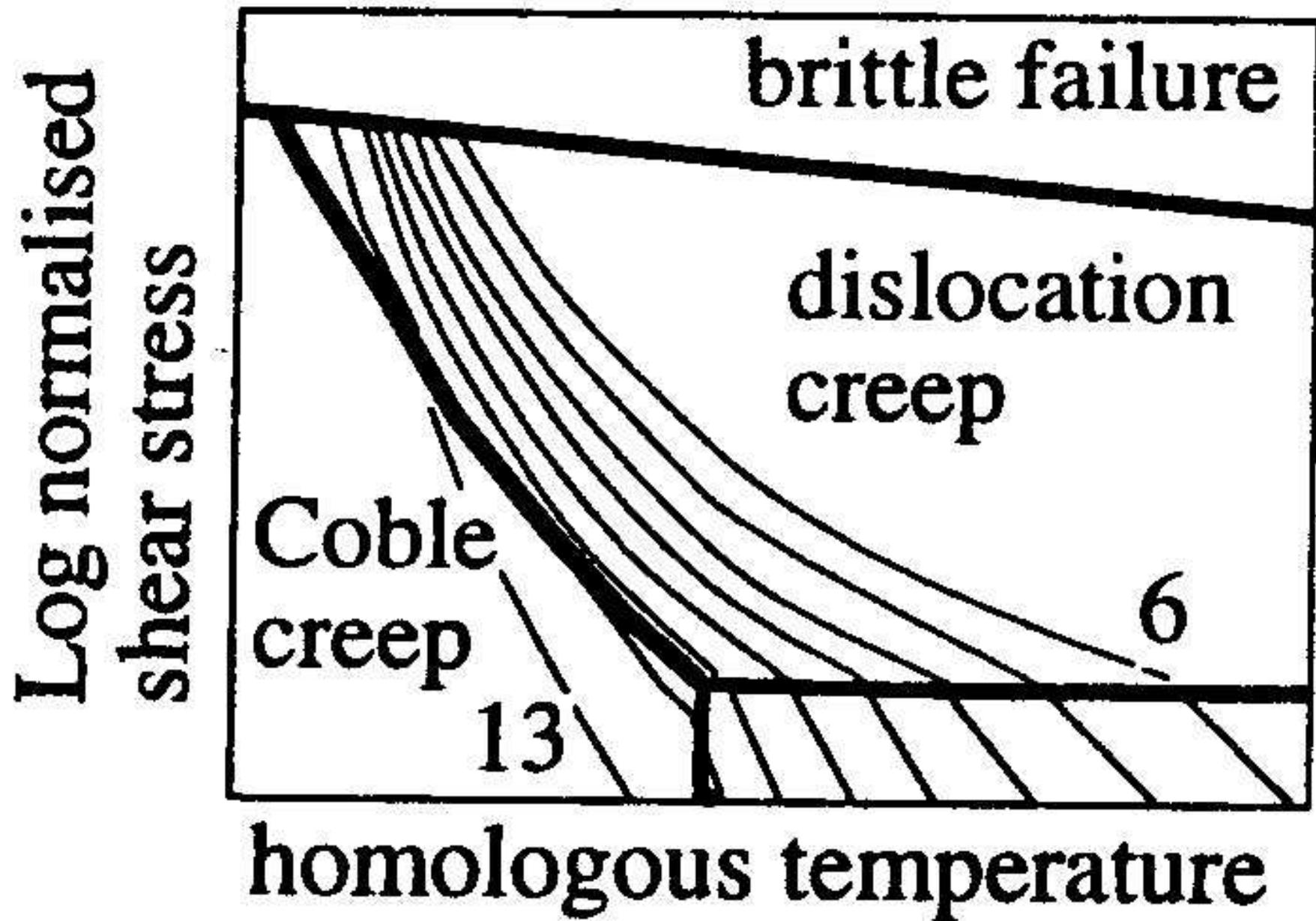


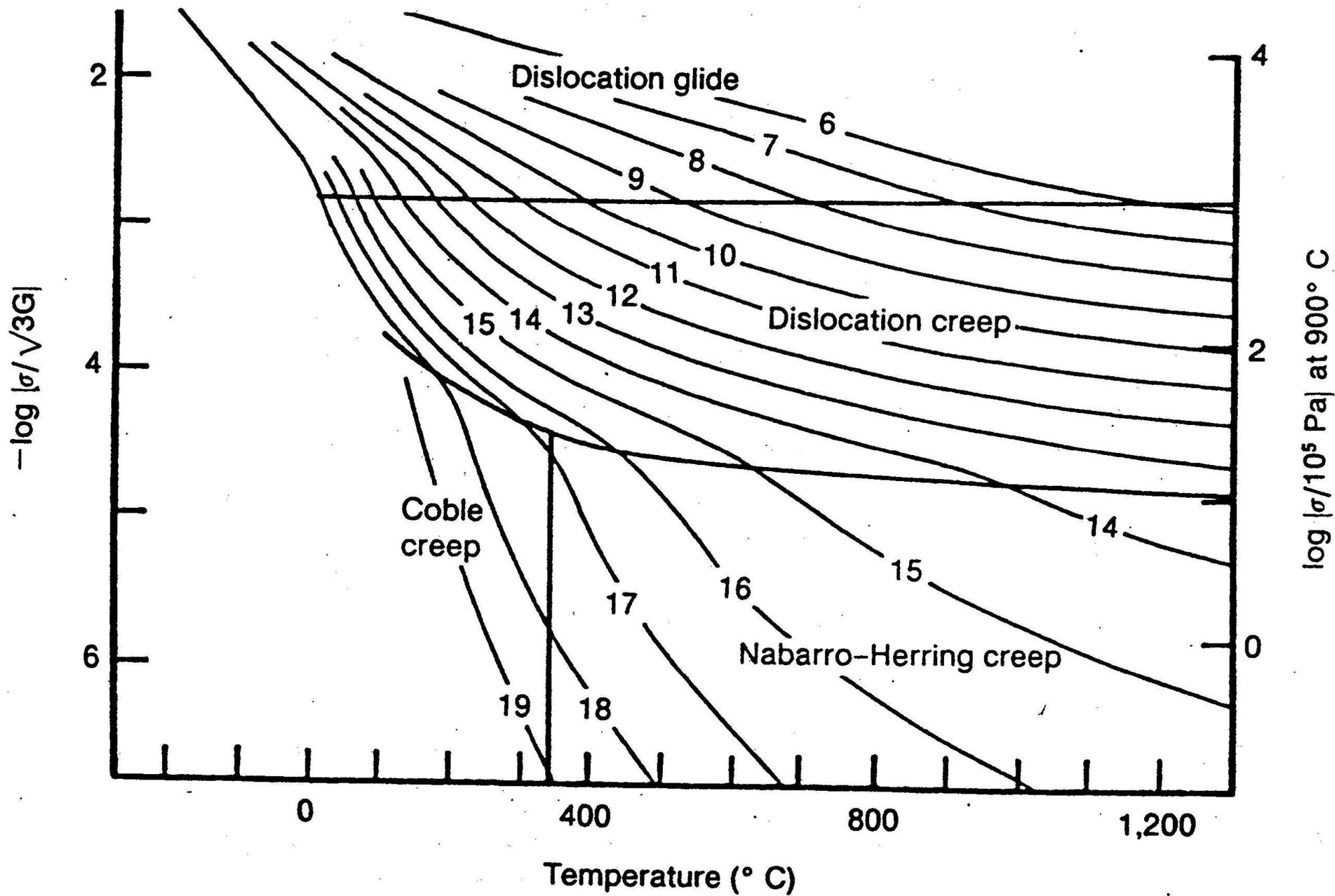


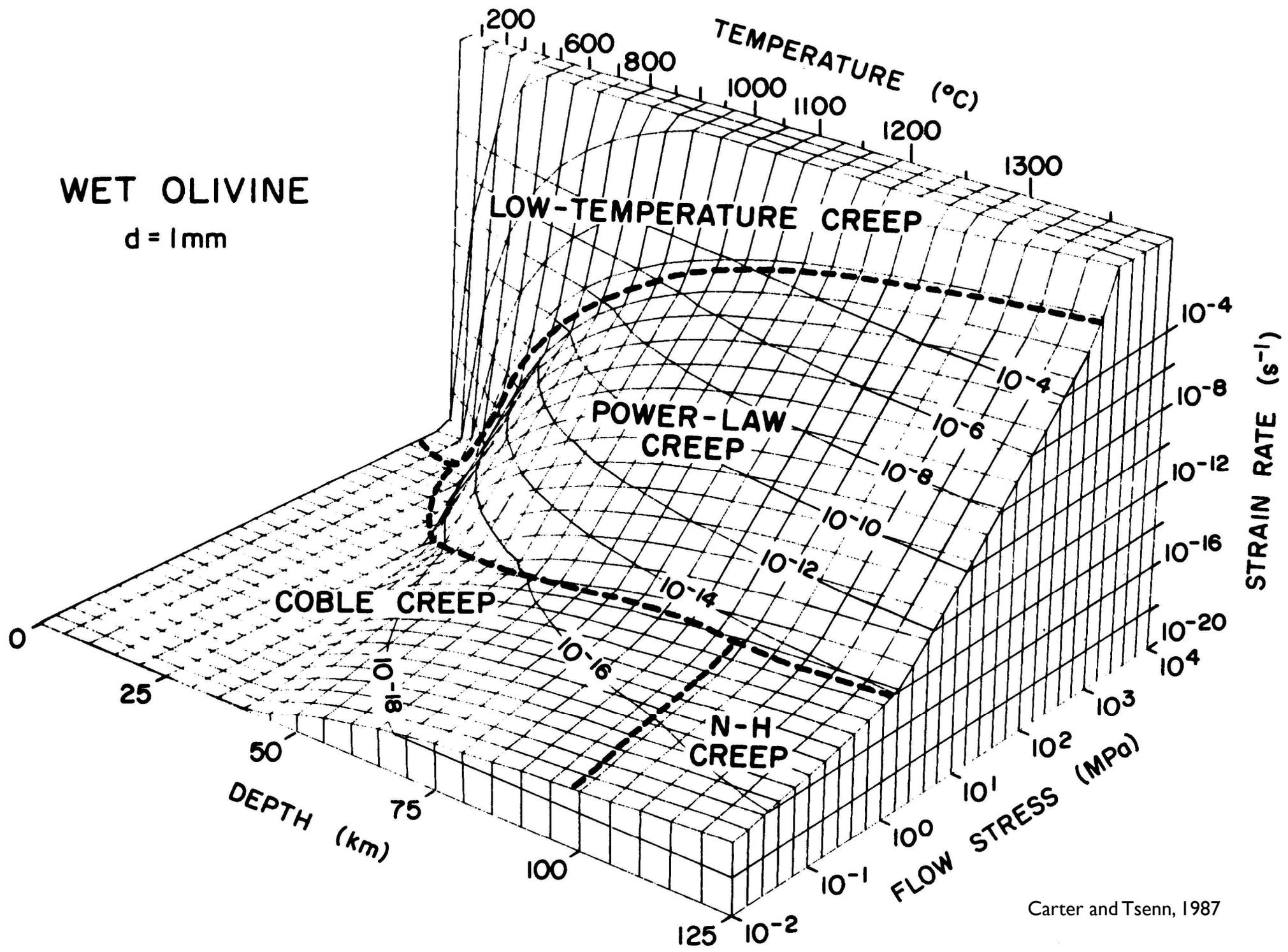
grain size $10\ \mu\text{m}$; $P=100\ \text{MPa}$



grain size $100\ \mu\text{m}$; $P=100\ \text{MPa}$

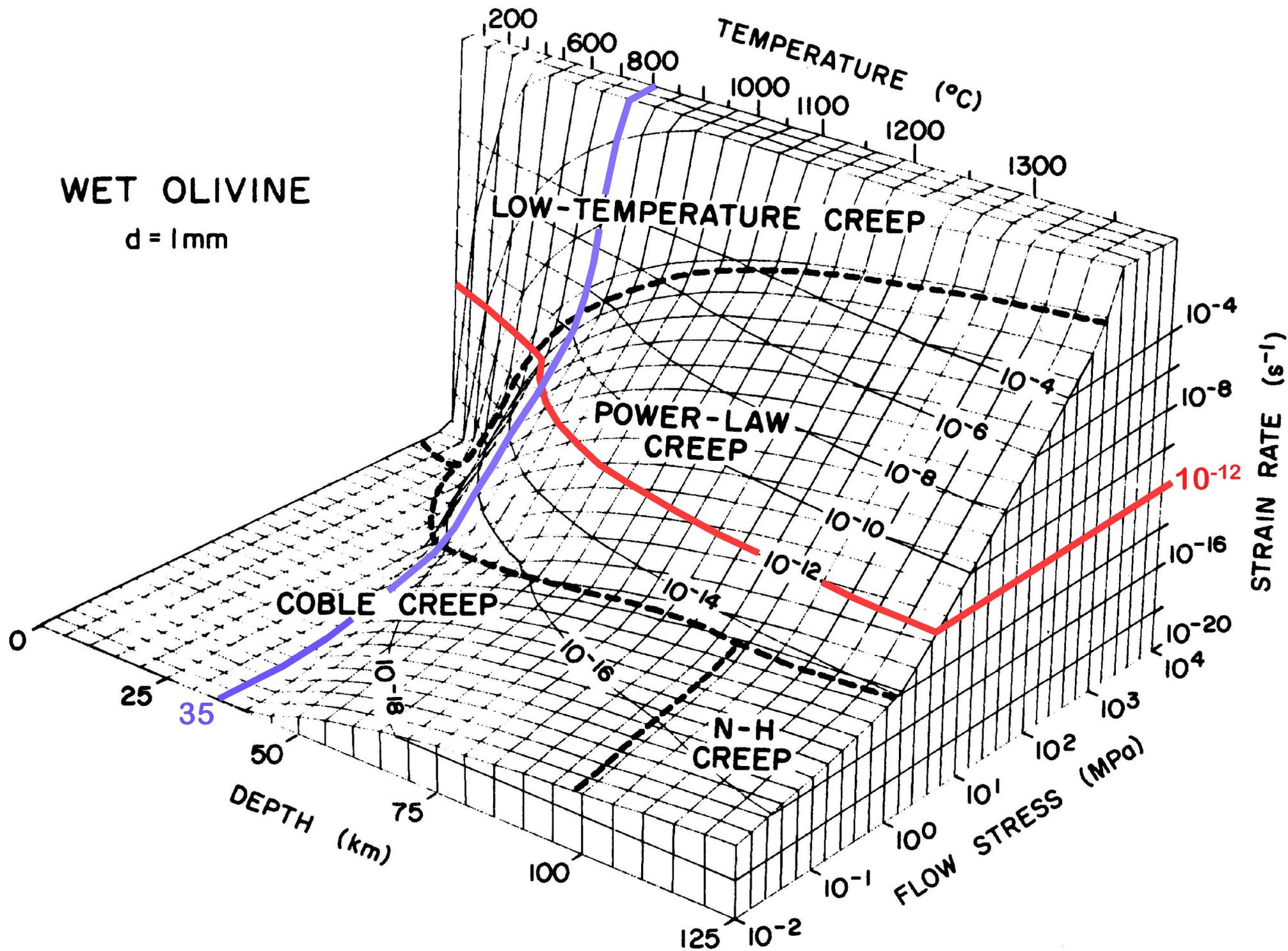




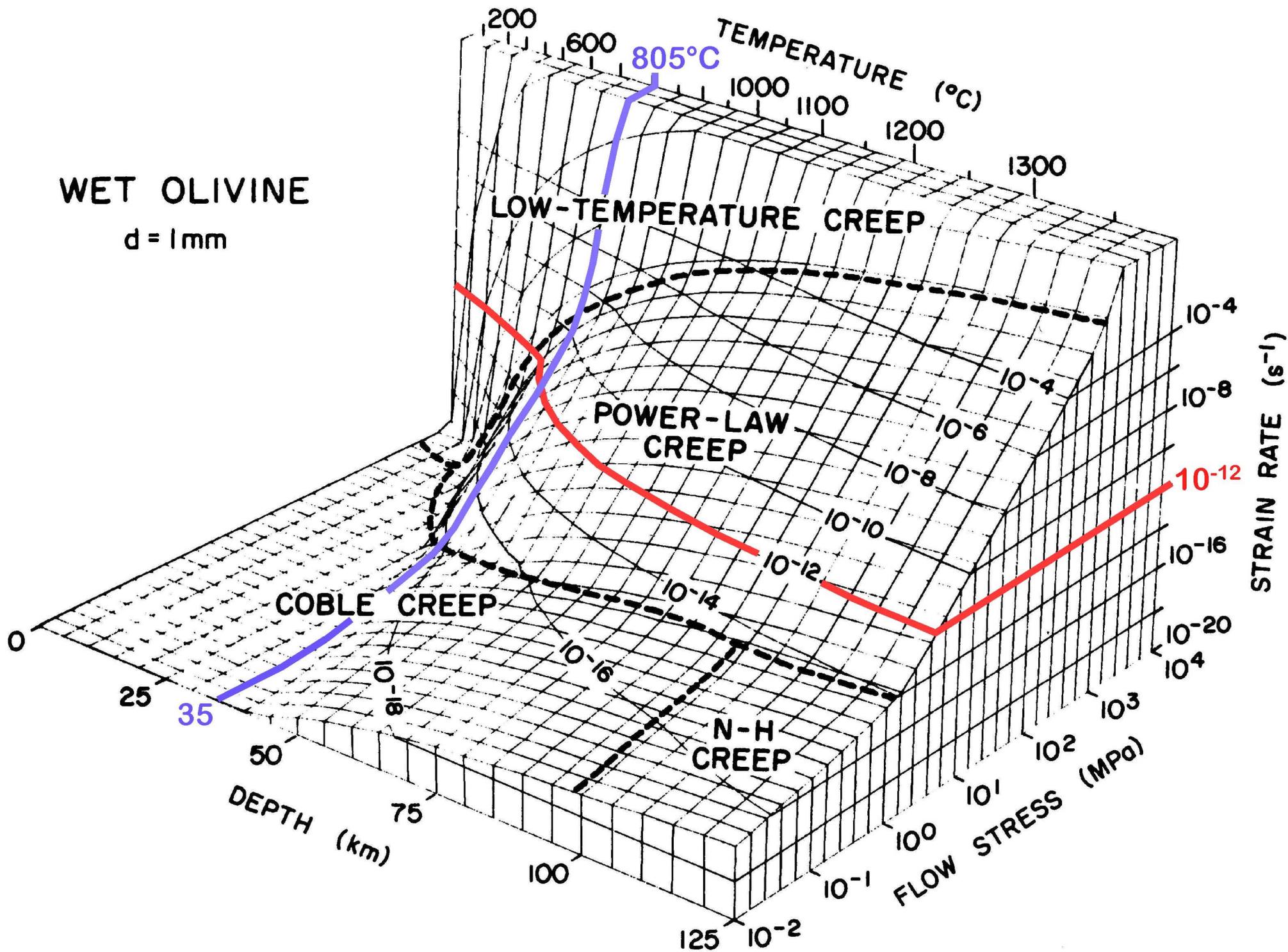


Carter and Tsenn, 1987

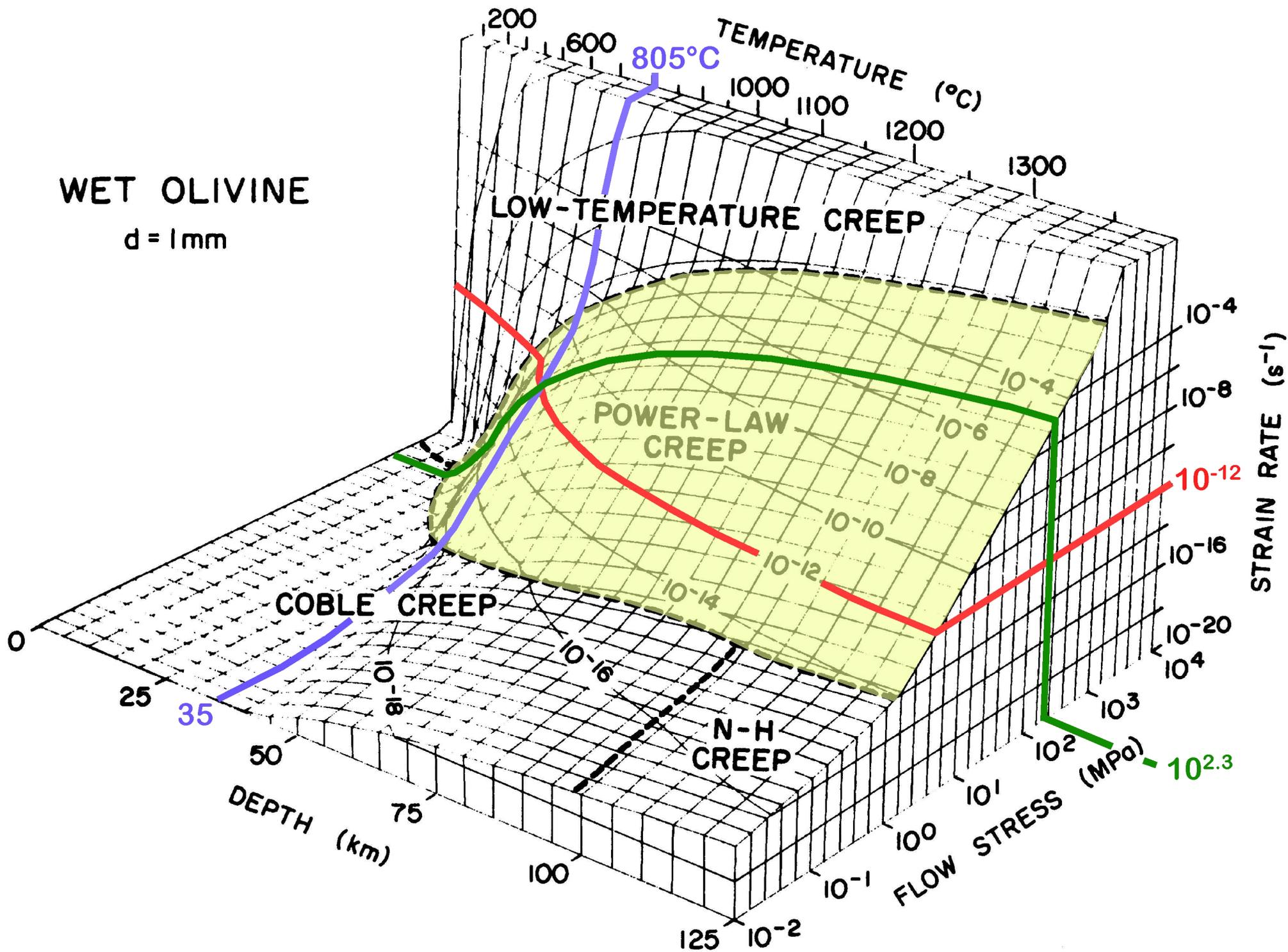
WET OLIVINE
d = 1mm



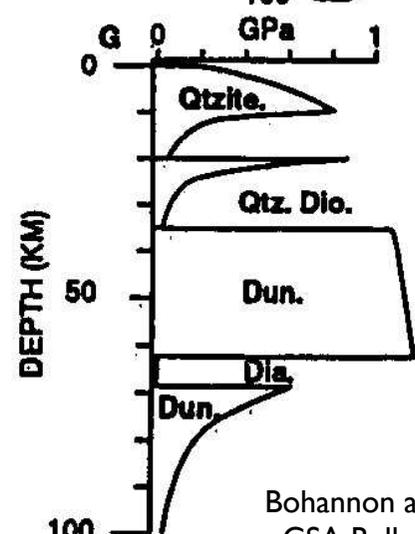
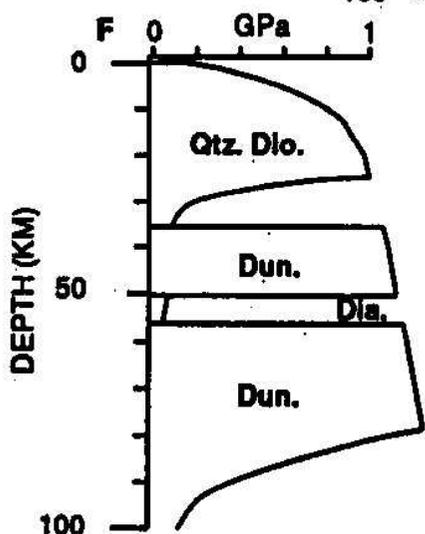
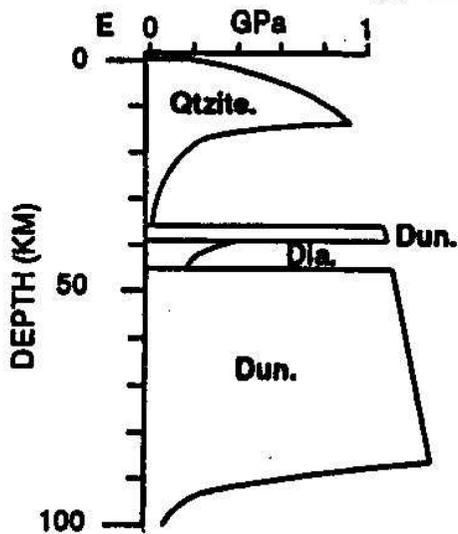
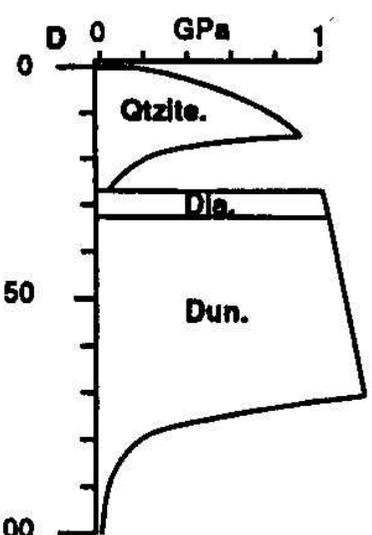
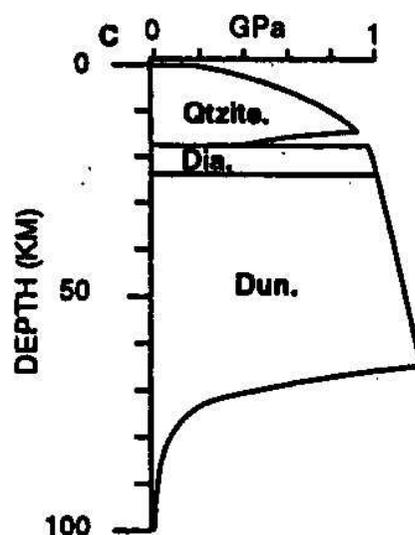
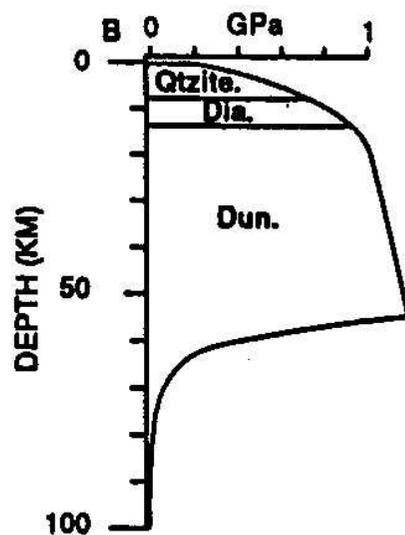
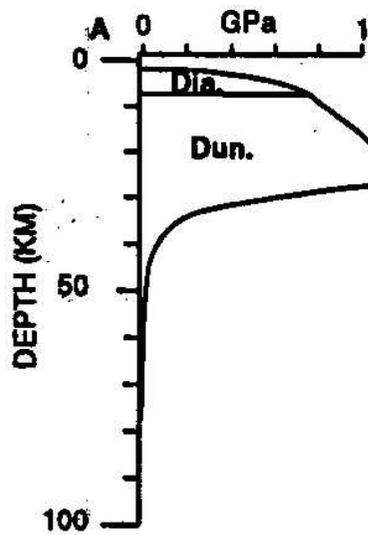
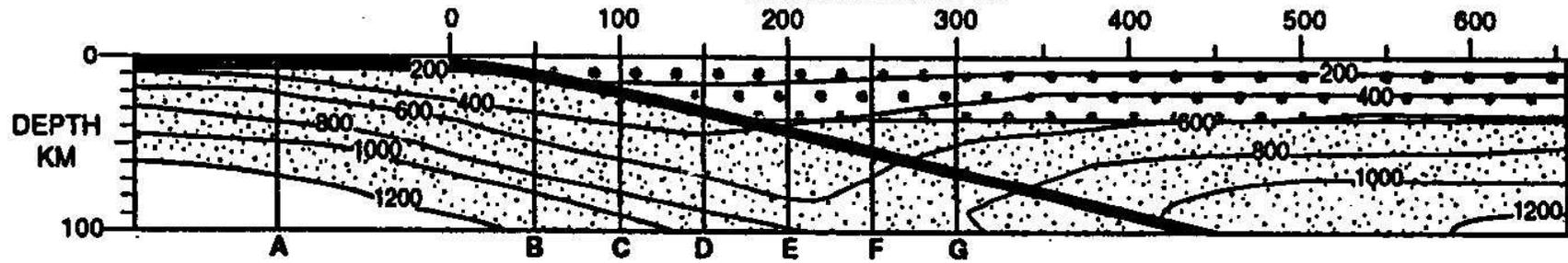
WET OLIVINE
d = 1mm



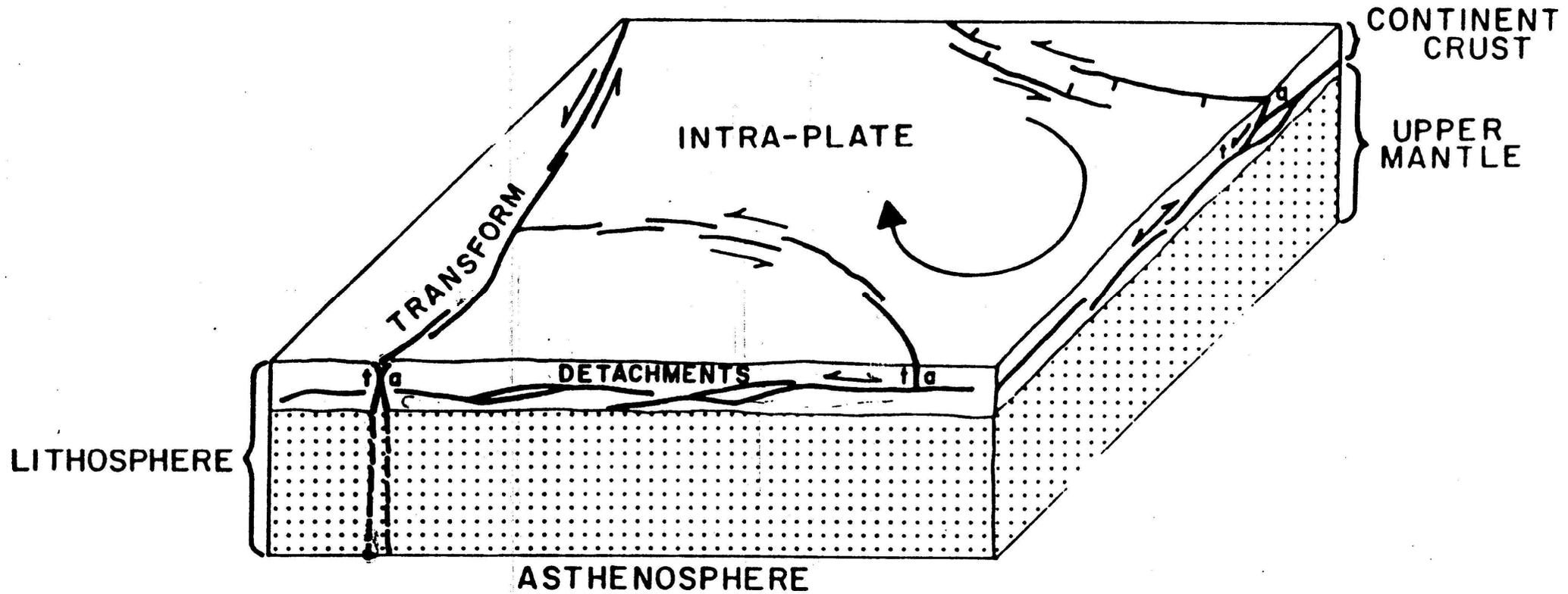
WET OLIVINE
d = 1mm



KILOMETERS INLAND OF
CONTINENTAL EDGE

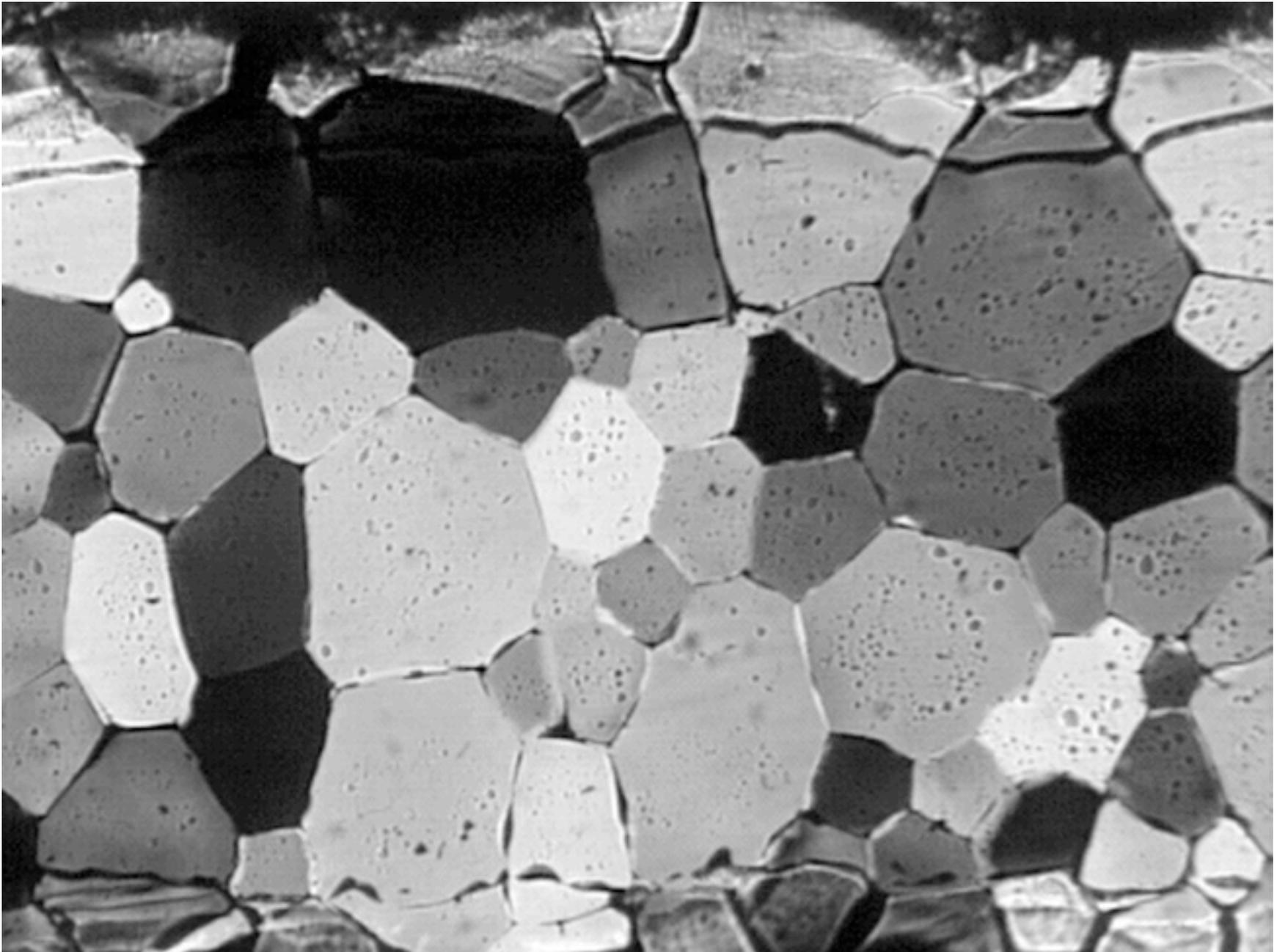


“Flake” tectonics involving strong upper continental crust moving over a weaker lower continental crust (crustal asthenosphere)

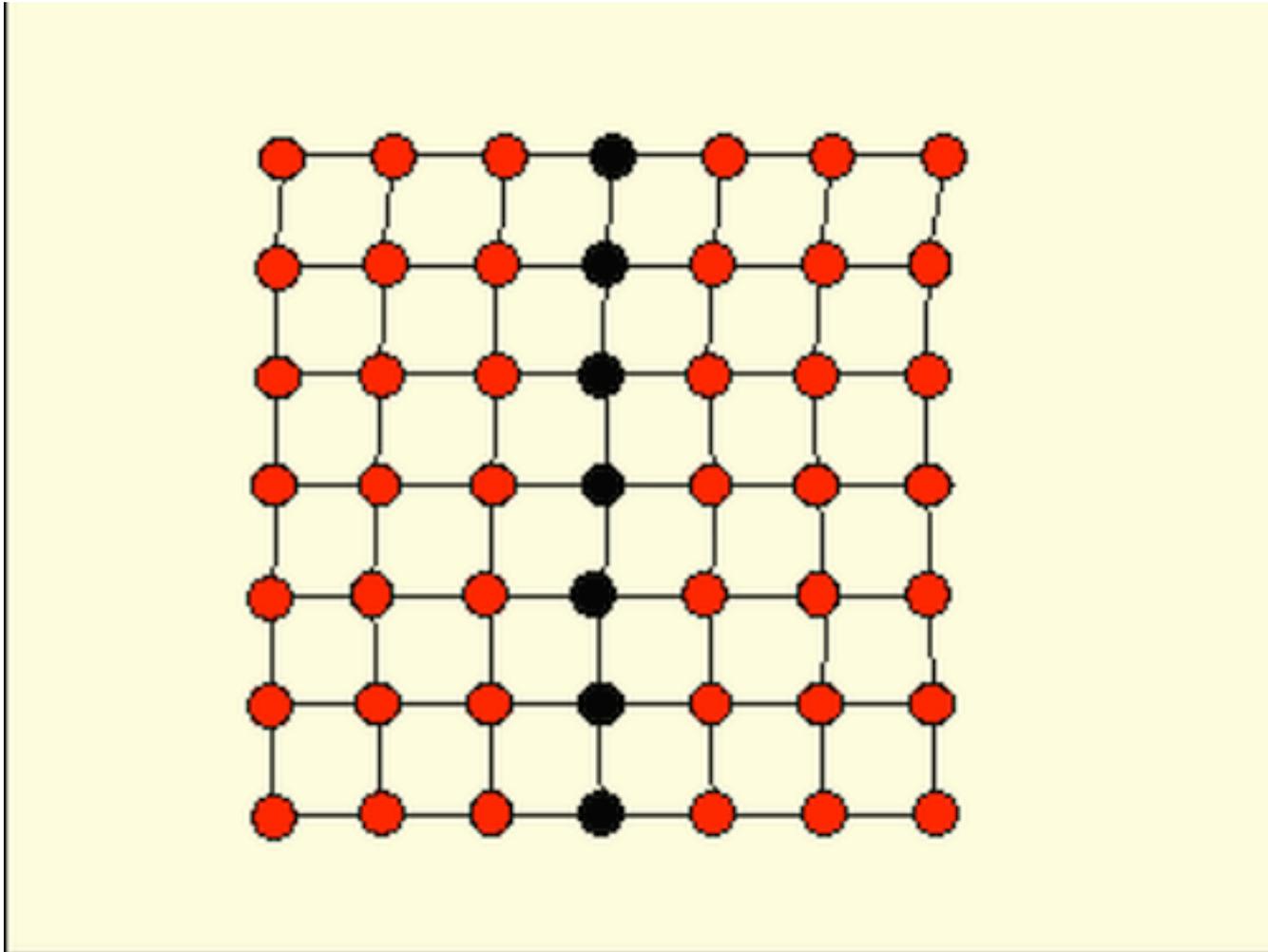


from Lemiszki and Brown

Plastic shear

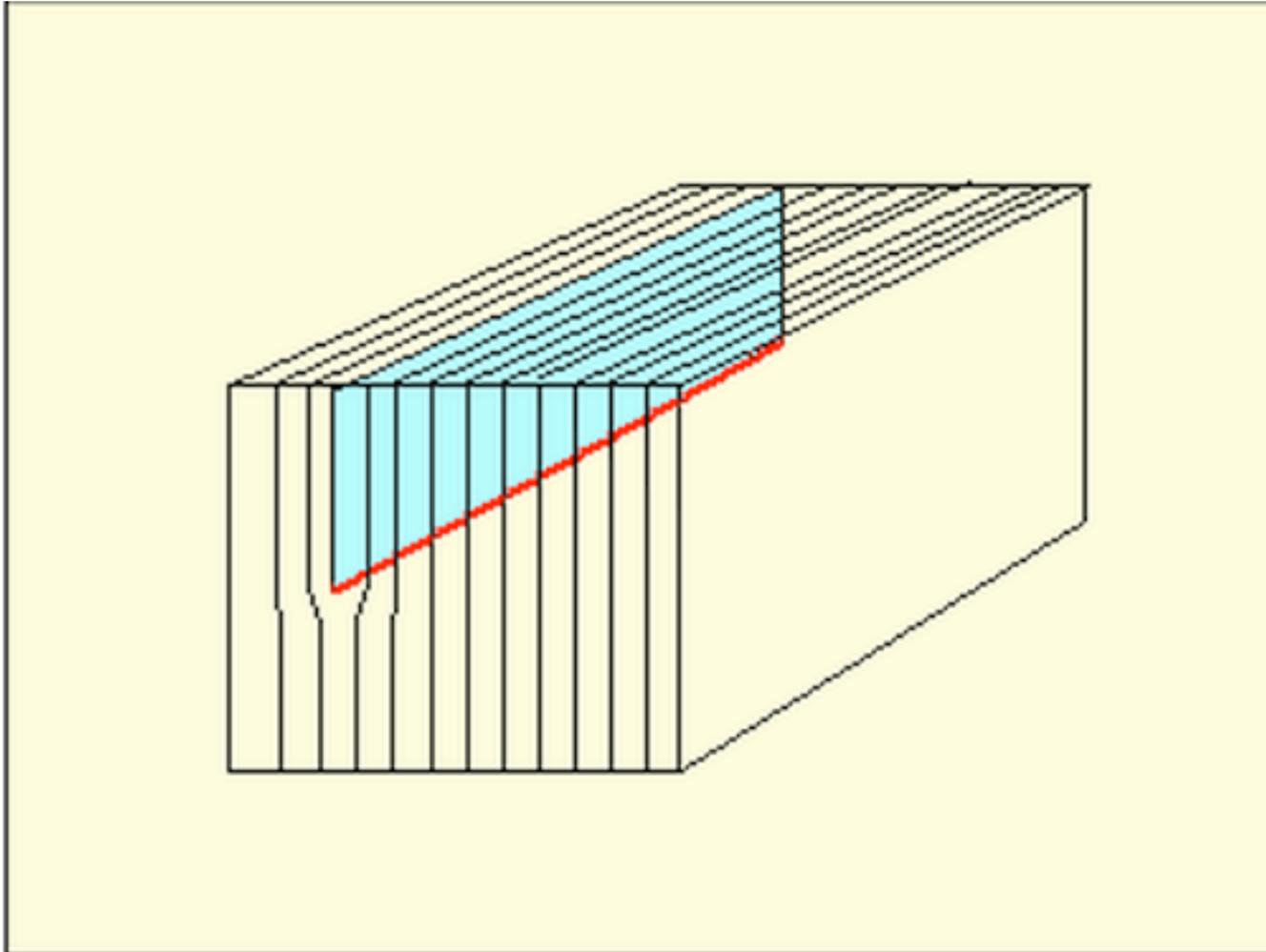


edge dislocation

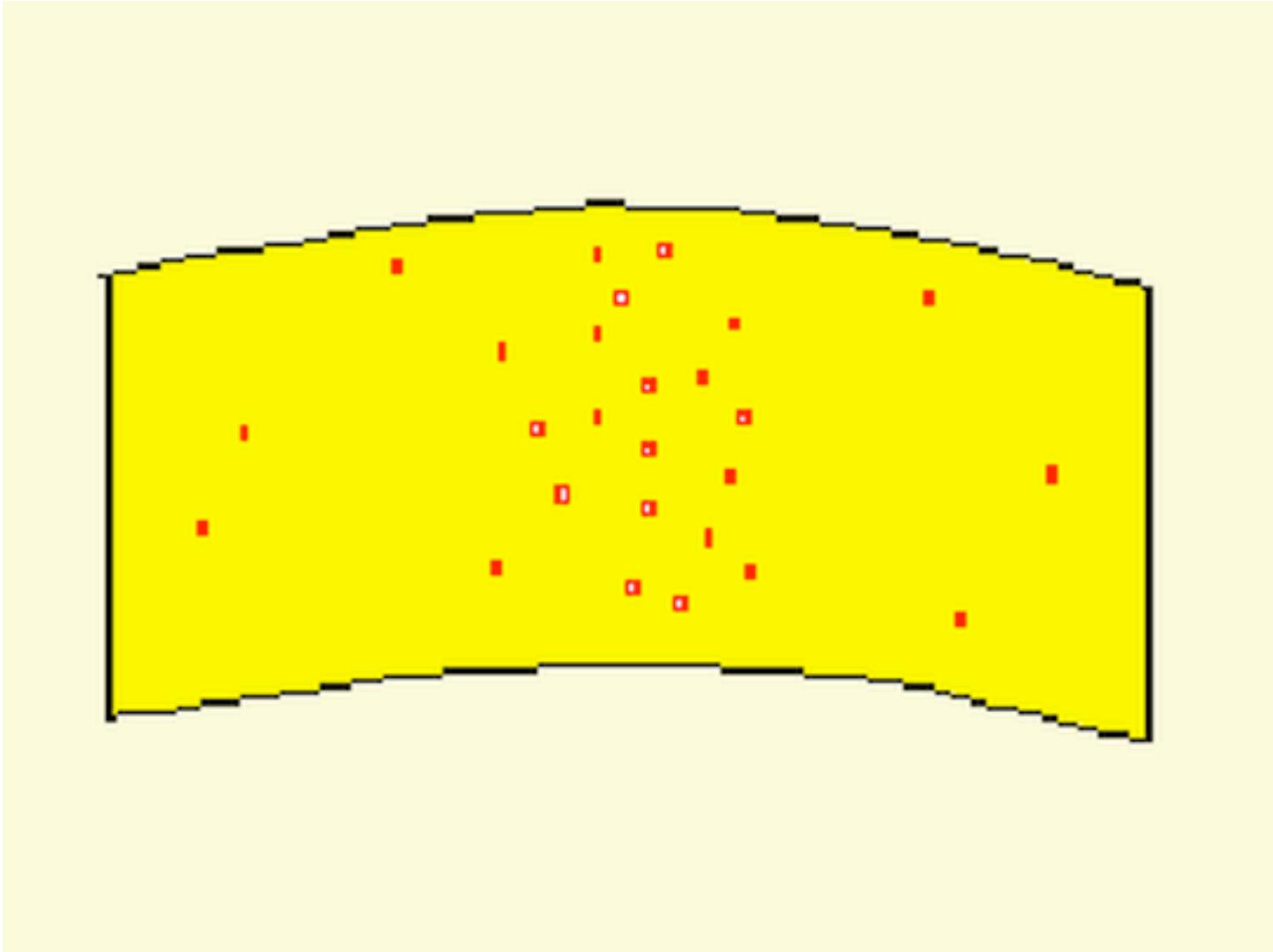


from Passchier and Trouw, 1998

edge dislocation

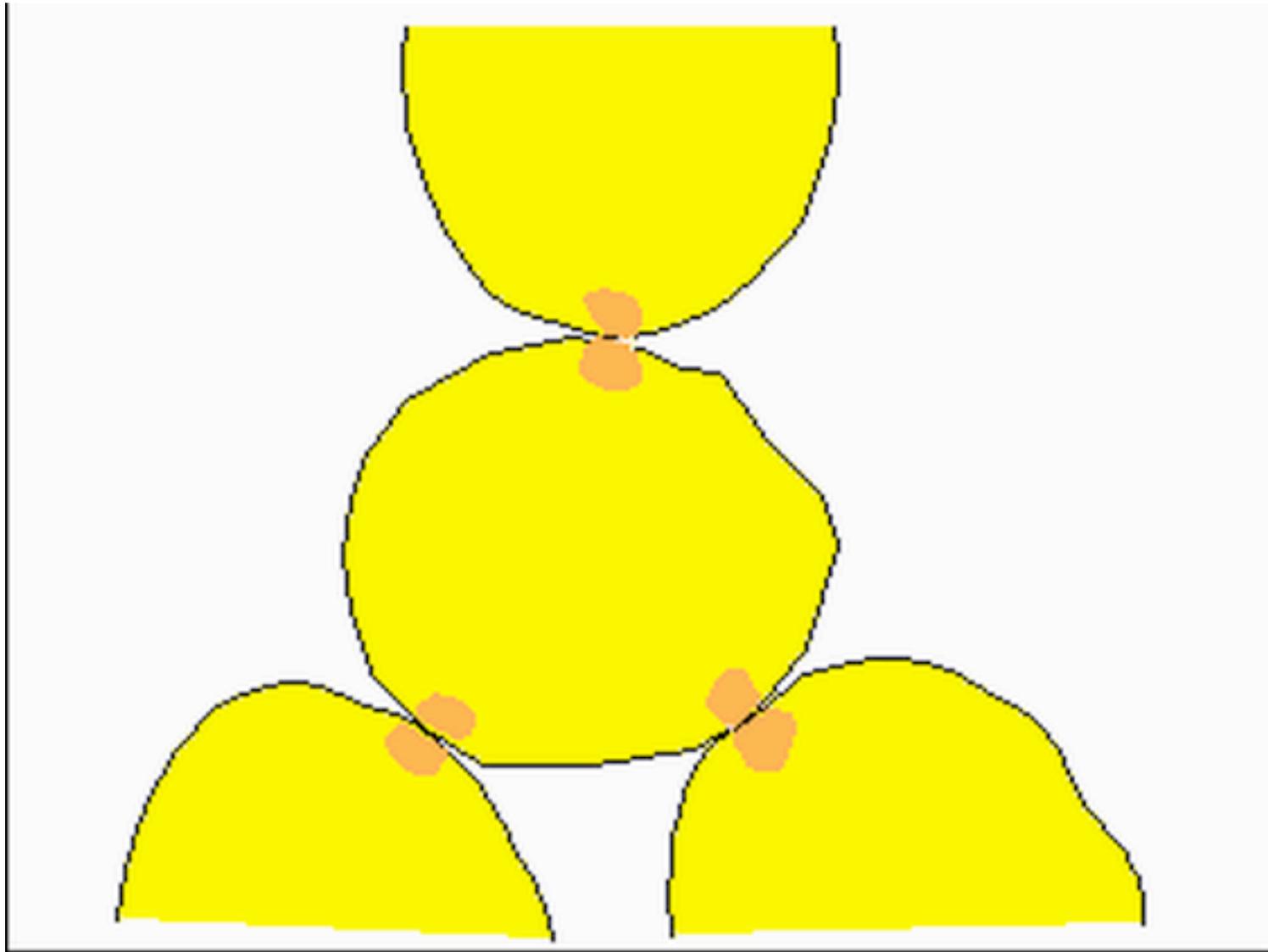


from Passchier and Trouw, 1998



from Passchier and Trouw, 1998

Pressure Solution



from Passchier and Trouw, 1998

Static recrystallization

