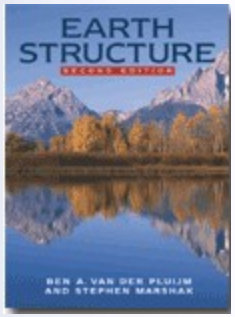
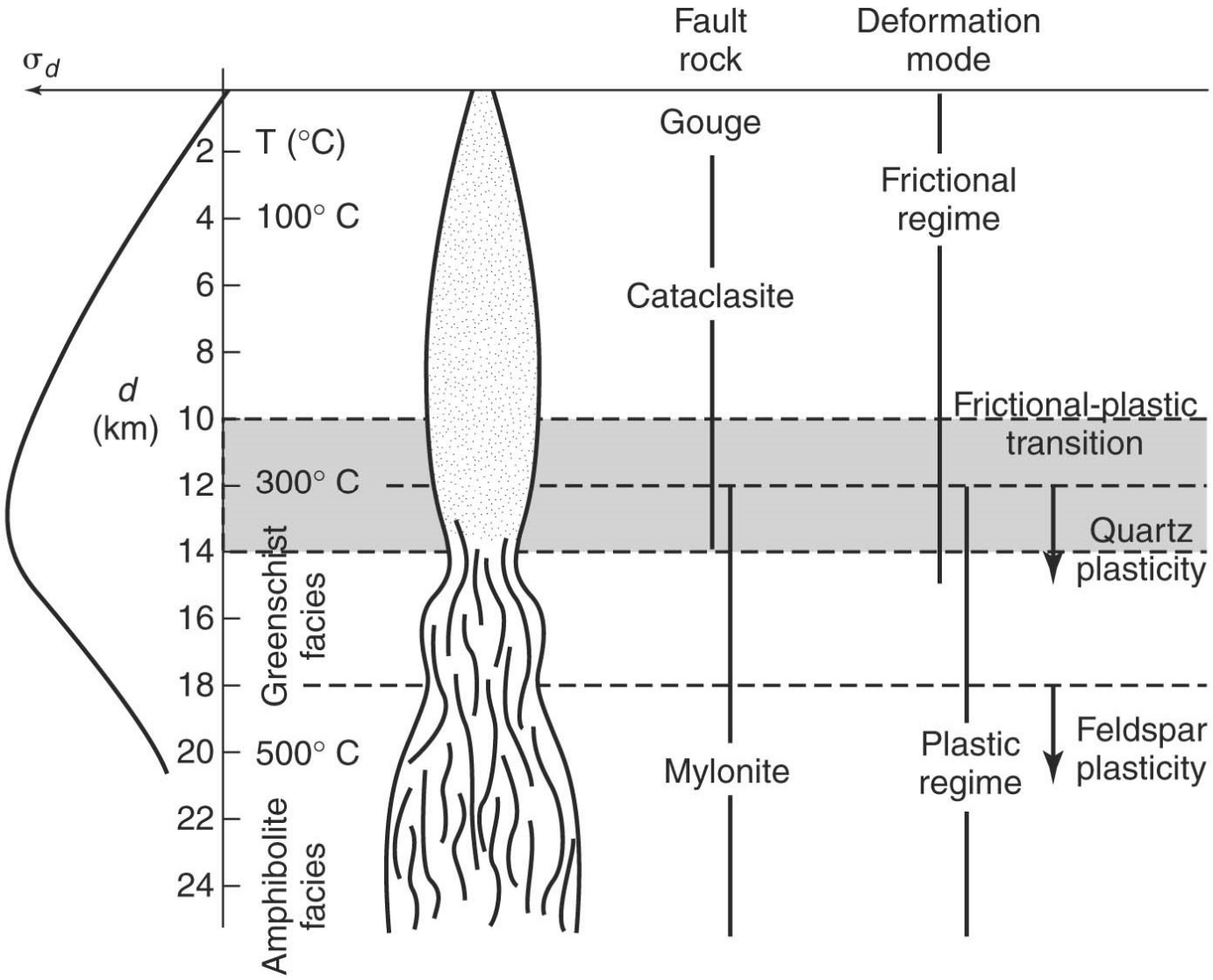
Lecture 11

Ductile Deformation and Microstructures



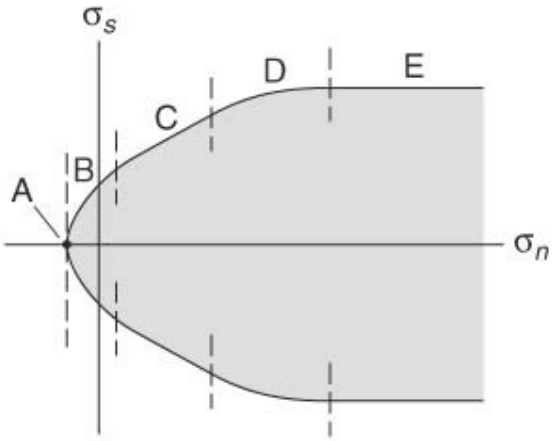
Earth Structure (2nd Edition), 2004
W.W. Norton & Co, New York
Slide show by Ben van der Pluijm

Crustal Fault Model



Brittle and Ductile Behavior

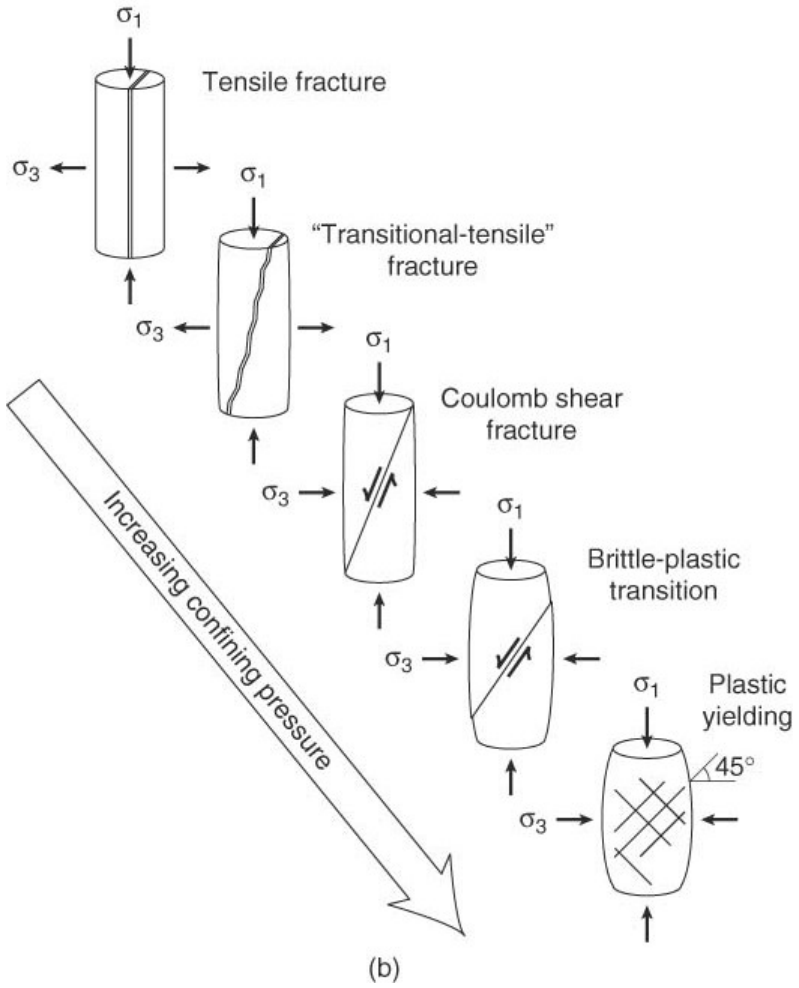
Brittle behavior describes deformation that localizes on mesoscopic scale and involves formation of fractures.



Composite failure envelope

A: Tensile failure criterion
B: Mohr (parabolic) failure criterion
C: Coulomb (straight-line) failure criterion
D: Brittle-plastic transition
E: von Mises plastic yield criterion

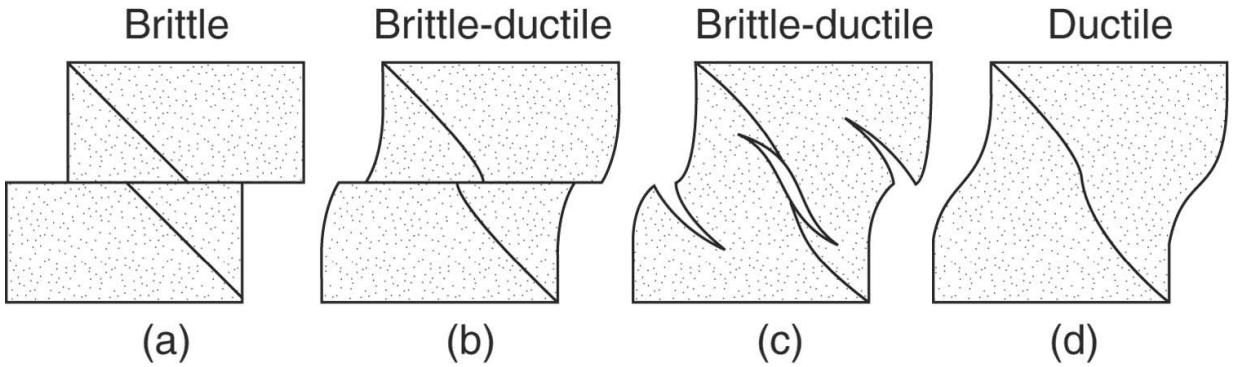
(a)



(b)

Ductile behavior describes ability of rocks to accumulate significant permanent strain that is distributed on mesoscopic scale.

Brittle vs. Ductile failure



Brittle behavior

normal stress and P_f dependent (effective stress

temperature and strain insensitive

shear stress is function of normal stress

Ductile behavior

normal stress and P_f insensitive

temperature and strain rate dependent

shear stress is function of temperature and strain rate

Ductile strain mechanisms

We distinguish three fundamental mechanisms that produce ductile behavior in rocks and minerals:

(1) **cataclastic flow** – analgous to a bean bag

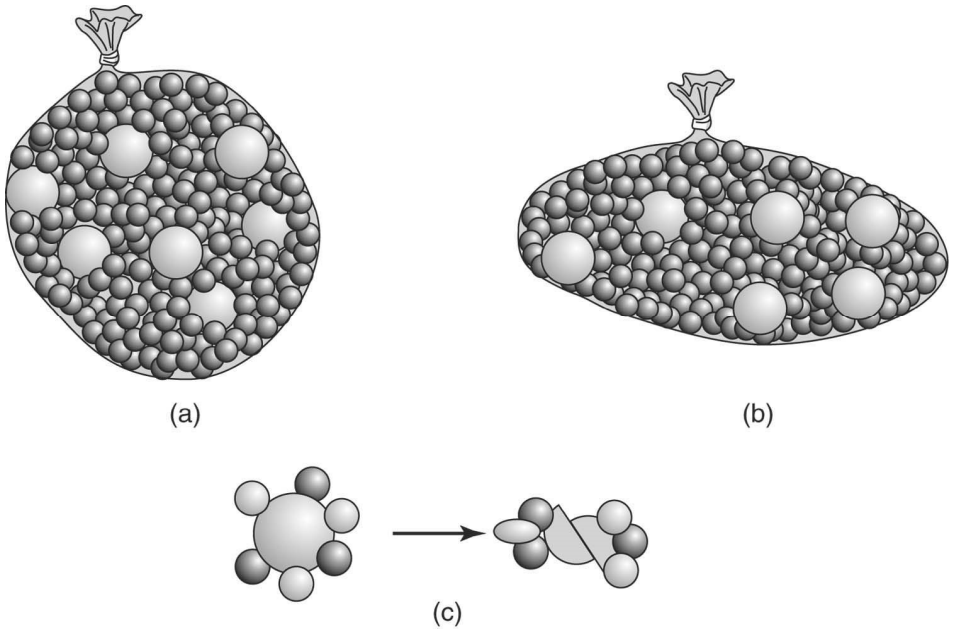
(2) **diffusional mass transfer** – transport of material by diffusion through a lattice – like water through a sponge

(3) **crystal plasticity** – solid dislocation like ice flowing

- Which processes dominate at a given time in a rock's history is primarily a function of temperature, stress, strain rate, grain size, composition, and fluid content.

- Temperature, in particular, is an important parameter, but different minerals behave ductilely at different temperatures.

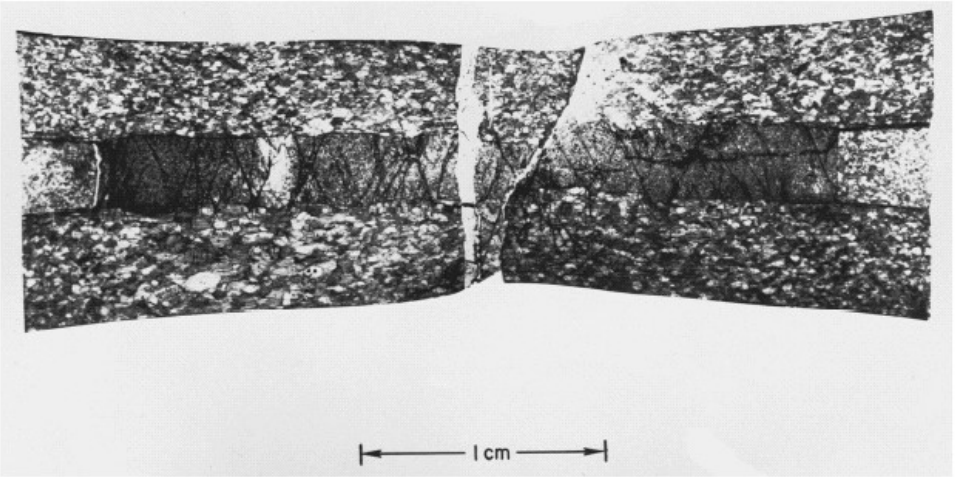
Cataclastic flow Figs. 9.2 and 9.3

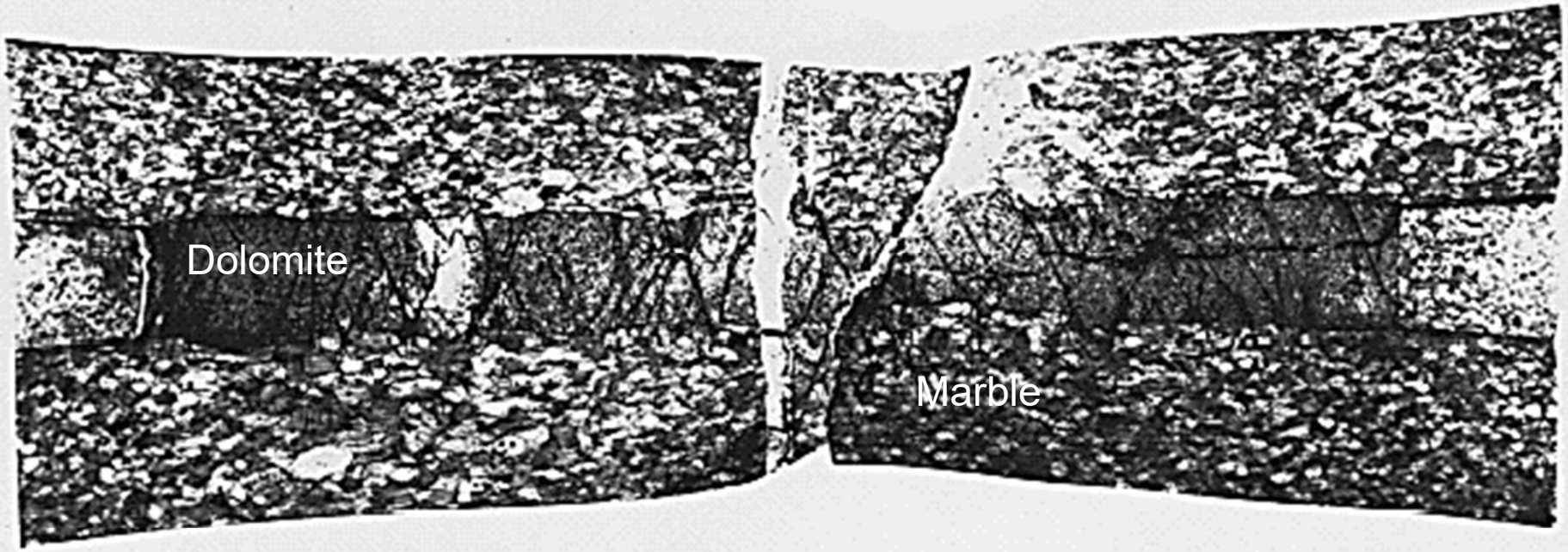


Changing shape of bag is accomplished by grains sliding past one another.

Large grains may fracture and slide on the fracture surface.

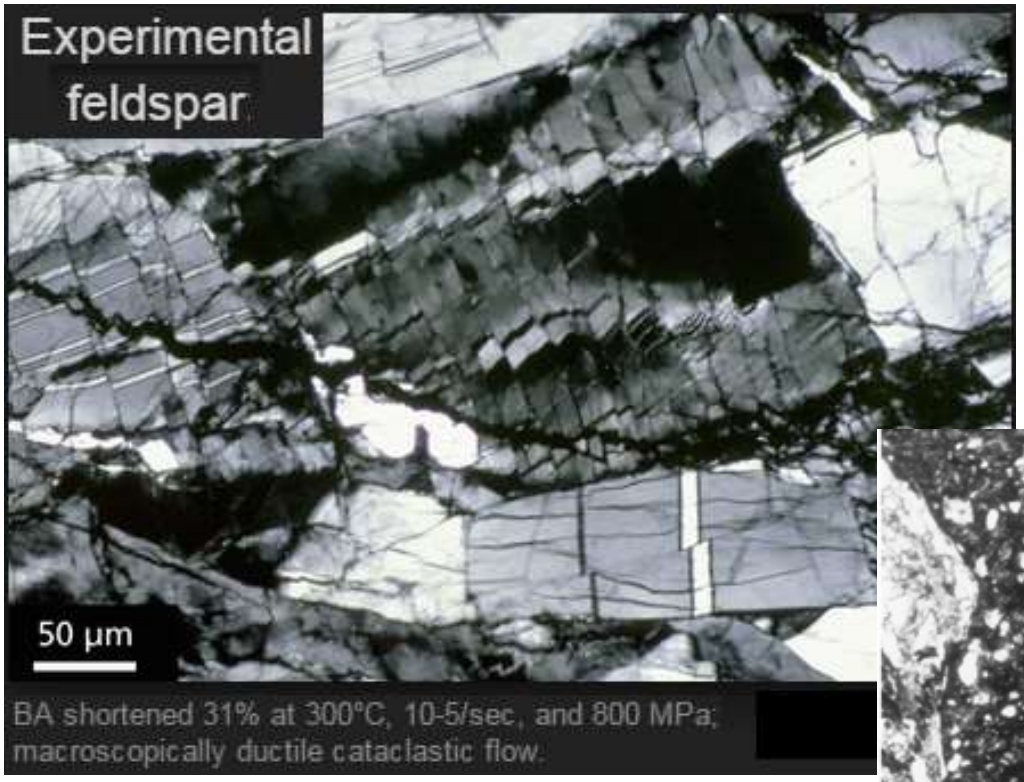
- Extension experiment showing cataclastic flow in Luning dolomite (Italy) that issurrounded by marble that deformed by crystal plastic processes.



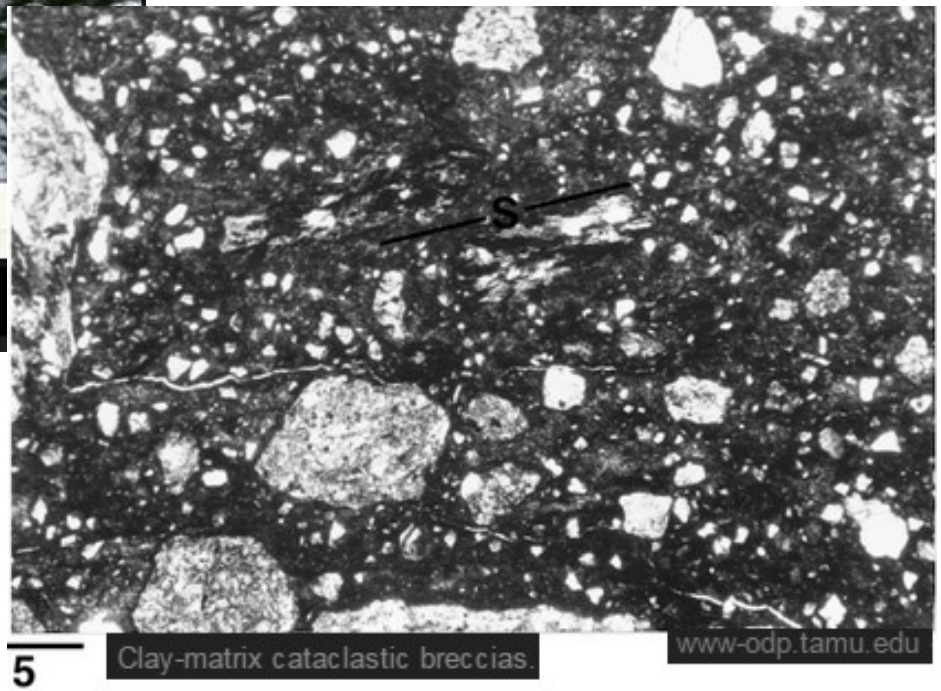


This contrasting behavior reflects the relative strength of the materials.

Cataclastic flow

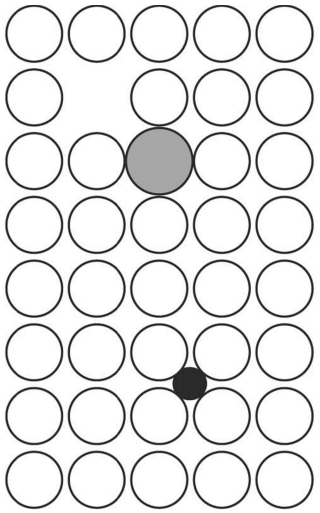


BA shortened 31% at 300°C, 10-5/sec, and 800 MPa; macroscopically ductile cataclastic flow.



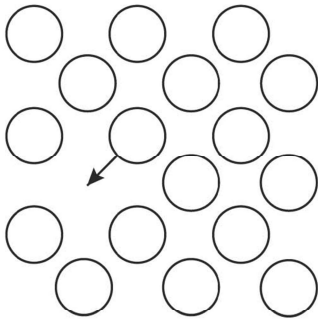
Clay-matrix cataclastic breccias.

Diffusional Mass Transfer Sec. 9.5



- Flow of rocks also occurs by the transfer of material through a process called **diffusion;** when an atom (or a point defect) migrates through a crystal.

- Three diffusion-related deformation mechanisms that are important for natural rocks: (1) **pressure solution,** (2) **grain-boundary diffusion,** and (3) **volume diffusion** *in order of increasing temperature*

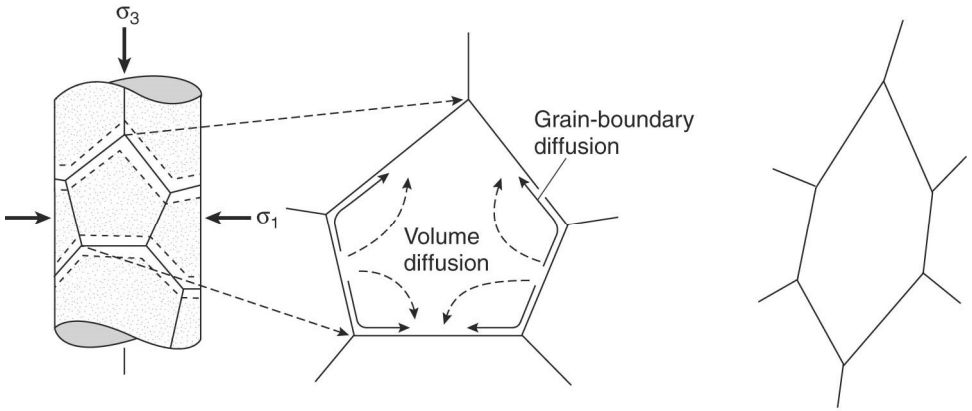


- "Wet" diffusion (or pressure solution) - fluid at grain boundary is transporting agent (static or moving fluid) and occurs at lower temperatures

- "Dry" diffusion – Process is strongly dependent on thermal energy for particle to jump into crystalline vacancies by breaking and reattaching atomic bonds

Diffusional Mass Transfer Fig. 9.20

Material transport occurs through grains by diffusional flow (Nabarro-Herring creep) or around grains (Coble creep) from *differential stress* that produces shape change



Nabarro-Herring creep or *volume diffusion*: $e^o \sim D_v/d^3$

D is diffusion coefficient and d is grain size

Coble creep or *grain-boundary diffusion*: $e^o \sim D_b/d^2$

Note: *pressure solution is fluid-assisted grain-boundary diffusion*

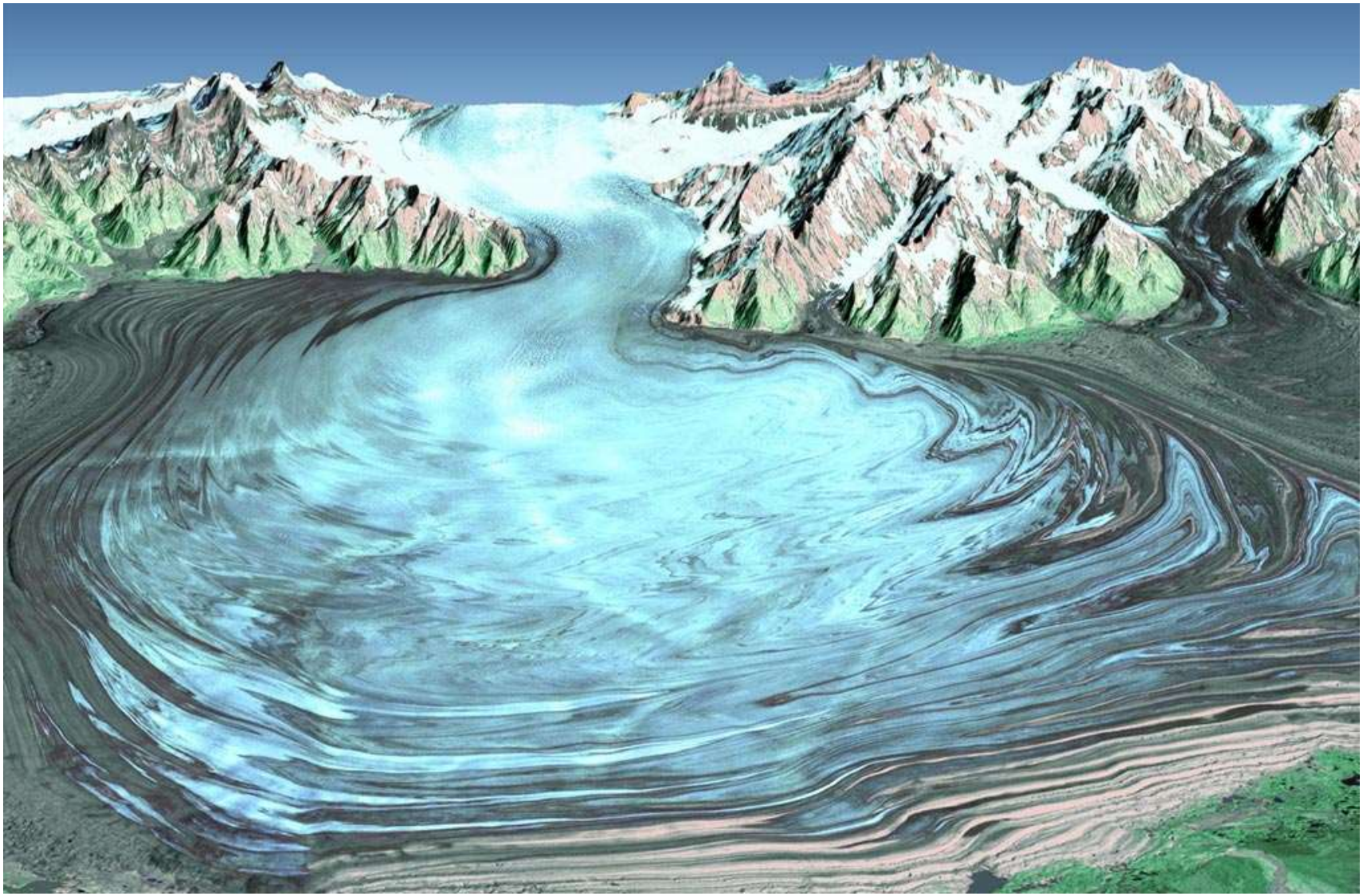
Plastic Flow - Ice

Oblique aerial view of folds in Malaspina Glacier; Mt. St. Elias and St. Elias Mountains in background.

Scale of folding in glacier is in miles. Yakutat district, Alaska Gulf region, Alaska. USGS, August 25, 1969

Plastic Flow - Ice

Malaspina Glacier, combining Landsat and Shuttle Radar Topography Mission data. NASA/JPL



Crystal Plasticity *Sec. 9.3* Various distortion of Earthen solid phases

- Dislocations in a crystal lattice are able to migrate through the crystal lattice if the activation energy for movement is achieved.
- *Applying a differential stress is a driving mechanism for dislocation motion.*
- The distortion of the crystal lattice around dislocations is another source of driving energy, as the system tries to achieve a lower internal strain energy.
- **Mechanical twinning** is a low-temperature plastic behavior of crystals that is common is some minerals
- **Glide** and **Creep** are high-temperature types of behaviors that involve d*islocation movement;* a combination of glide and climb

Mechanical twinning

Growth twins develop during the growth of a crystal

Mechanical twinning is a type of crystal plastic process that involves partial dislocations or kinks in the crystal lattice

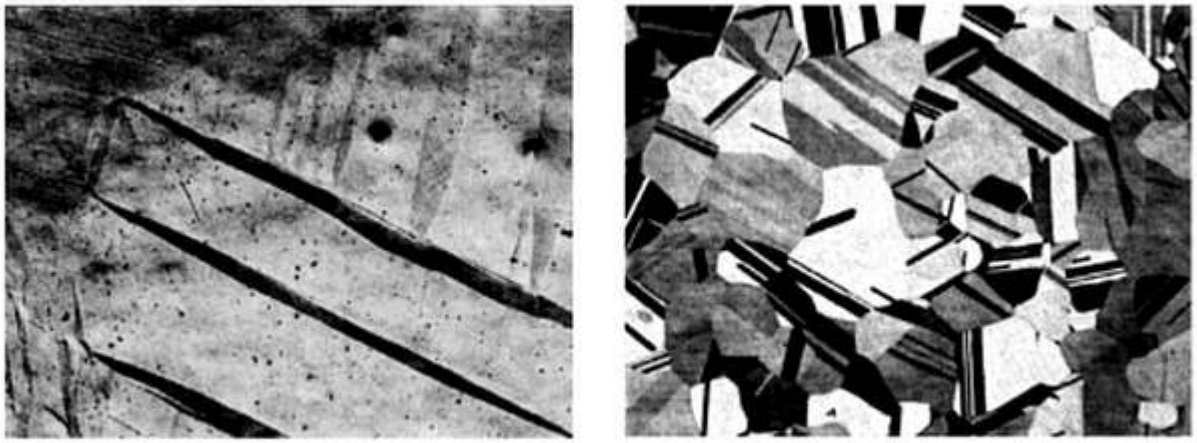


Figure 10.14. Different appearance of deformation twins and annealing twins. (a) Deformation twins in magnesium. (b) Annealing twins in brass. From W. F. Hosford, *Ibid.*

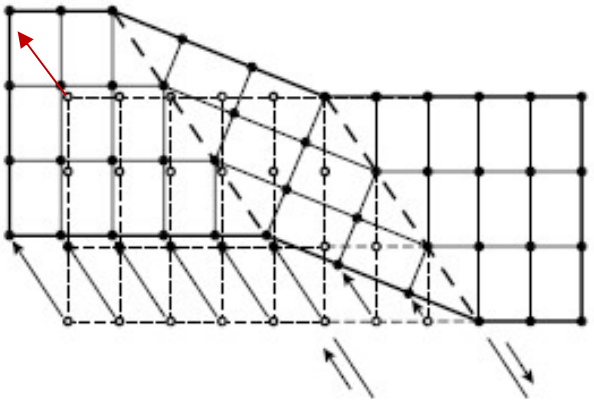
Twin boundary separates two regions of a twinned crystal.

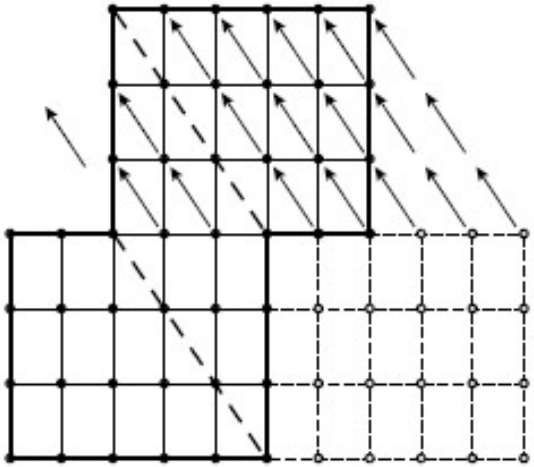
The lattices in the twinned two portions are mirror images of each other; in other words, a twin boundary is a mirror plane with a specific crystallographic orientation.

Schematic illustration of mechanical twinning.

Closed circles are atoms in final structure and open circles give the original positions of displaced atoms.

The heavy outline marks a twinned grain, in which the twin boundaries (heavy dashes) are mirror planes.





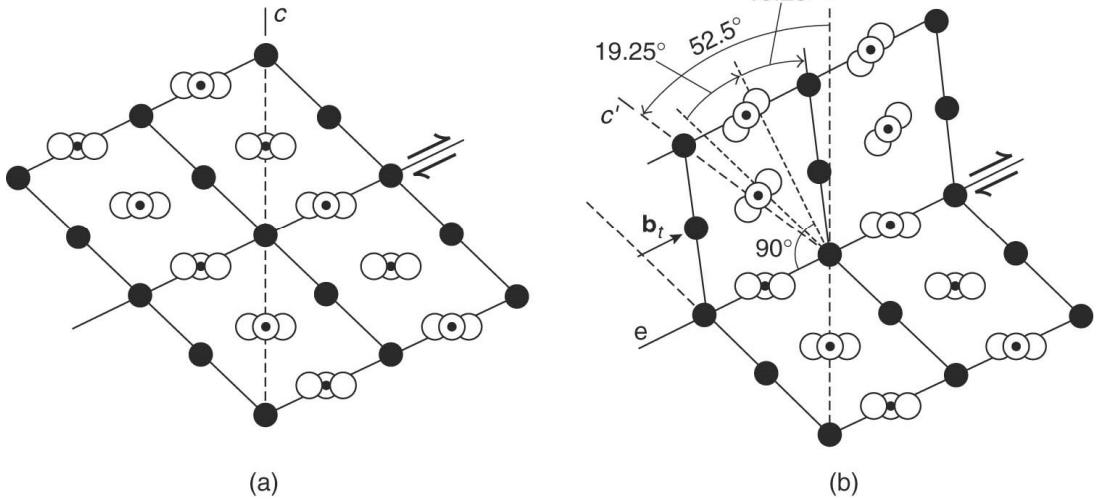
The atomic displacements are of unequal length and generally do not coincide with one atomic distance.

Twinning contrasts with dislocation glide (b), in which atoms move one or more atomic distances in the glide plane (heavy dashed line).

Mechanical twinning in Calcite Fig. 9.17

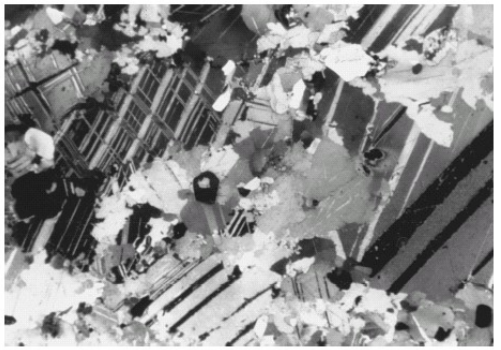
An example of low-temperature plasticity

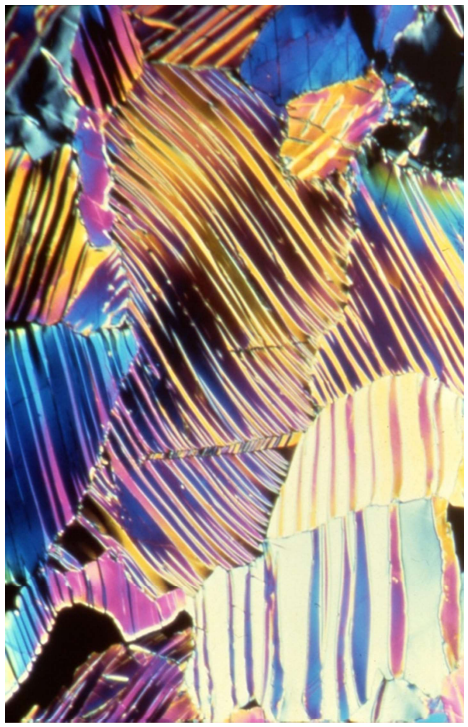
Calcite crystal lattice showing layers of Ca (large black dot) and CO_3 groups (C is small dot, O is large open circle);



The twinned calcite lattice in (b) shows the partial dislocation (**b***t*) and angular rotations of the *c*-axis and the crystal face.

natural

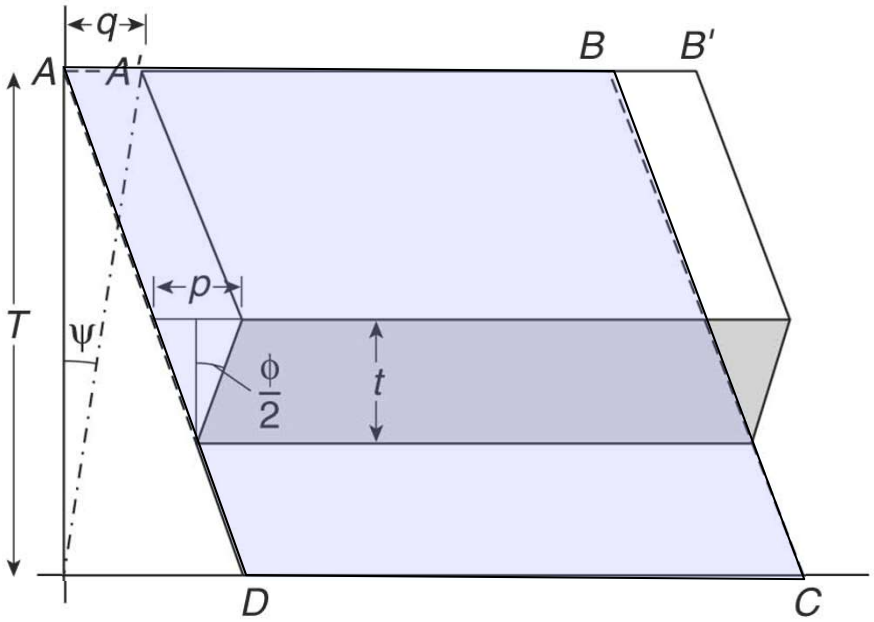




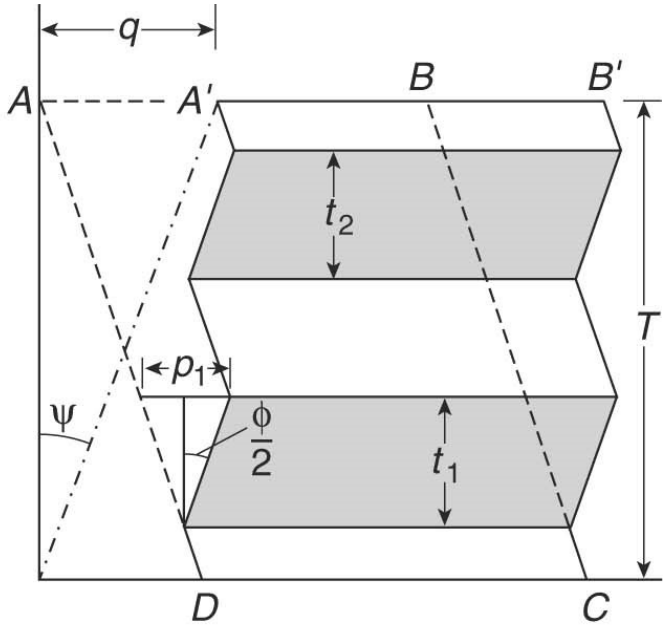
experimental

Calcite strain-gauge technique Fig. 9.18

Because Calcite twins in a fixed manner under certain P&T conditions, the strain that a twinned calcite grain accumulates provides a gauge for deterring differential stress magnitudes for naturally deformed carbonate rocks.



An original grain *ABCD* with a single twin of thickness, *t* (shaded region)



Calcite grain with multiple twins

Calcite strain gauge: $\gamma = \frac{0.7}{T}\pi\sum_{i=1}^{n} t_i$

Dominant Slip System in Minerals

TABLE 9.1 DOMINANT SLIP SYSTEMS IN COMMON ROCK-FORMING MINERALS

Mineral	Glide plane and slip direction[a]	Comments
Calcite	$\{\bar{1}018\}\langle 40\bar{4}1\rangle$	e-twinning
	$\{10\bar{1}4\}\langle\bar{2}021\rangle$	r-twinning
	$\{10\bar{1}4\}\langle\bar{2}021\rangle$	r-glide
	$\{01\bar{1}2\}\langle 2\bar{2}01\rangle$ or $\langle\bar{2}021\rangle$	f-glide
Dolomite	$\{\bar{1}012\}\langle 10\bar{1}1\rangle$	f-twinning
	$[0001]\langle 2\bar{1}\bar{1}0\rangle$	c-glide
	$\{01\bar{1}2\}\langle 2\bar{2}01\rangle$ or $\langle\bar{2}021\rangle$	f-glide
Mica	$[001]\langle 110\rangle$	basal (c) slip
Olivine	$[001][100]$	
	$\{110\}[001]$	
Quartz	$[0001]\langle 11\bar{2}0\rangle$	basal (c) slip
	$\{10\bar{1}0\}[0001]$	prism (m) slip, along c
	$\{10\bar{1}0\}\langle 11\bar{2}0\rangle$	prism (m) slip, along a
	$\{10\bar{1}1\}\langle 11\bar{2}0\rangle$	rhomb (z) slip

[a]Miller indices for equivalent glide planes from crystal symmetry are indicated by { }; specific glide planes are indicated by [ ]; equivalent slip directions from crystal symmetry are indicated by < >; individual slip directions are indicated by [ ].
From: Wenk, 1985

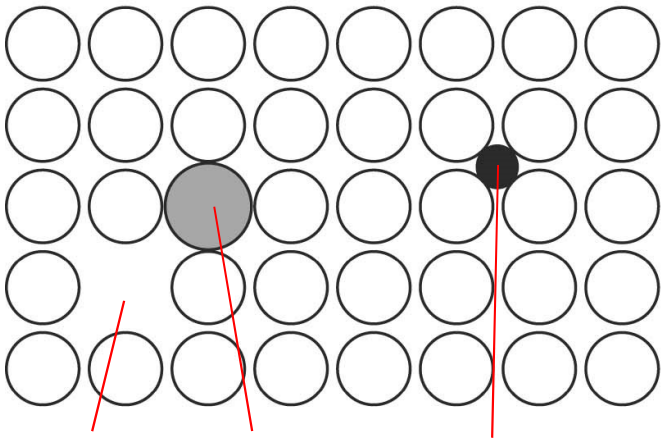
Crystal Plasticity *Sec. 9.3*

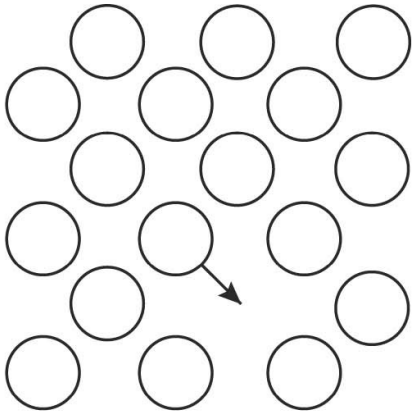
Ductile behavior of materials at elevated temperatures is achieved by the motion of crystal defects

3 types of defects in a crystal lattice:

***1) Point** defects*

vacancies and impurities





vacancy migration (diffusion)

Crystal Plasticity

Low-temperature (0>Th>.3)

- mechanical twinning
- dislocation glide

Medium (.3>Th>.7) and high-temperature (.7>Th>1)

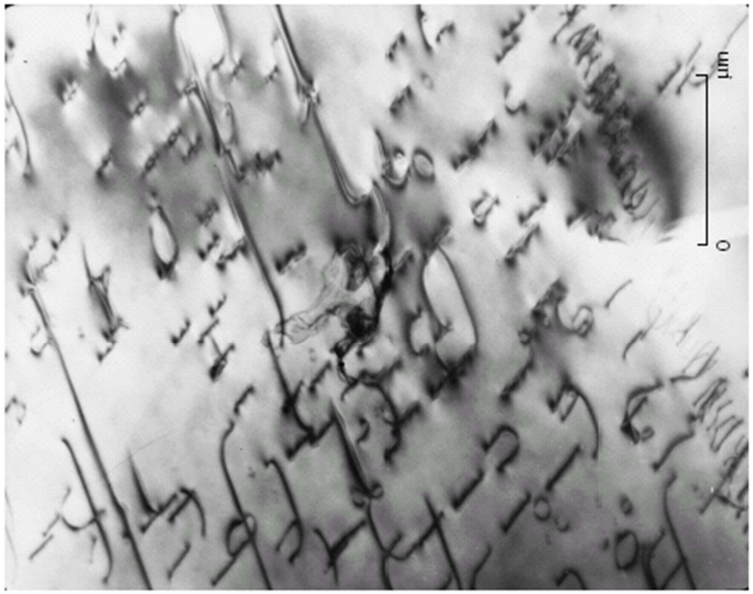
- Dislocation creep (glide + climb)
- Recovery
- Recrystallization
- Grain boundary sliding or superplasticity (GBSS)

Th is homologous temperature: T/Tmelting (in K)

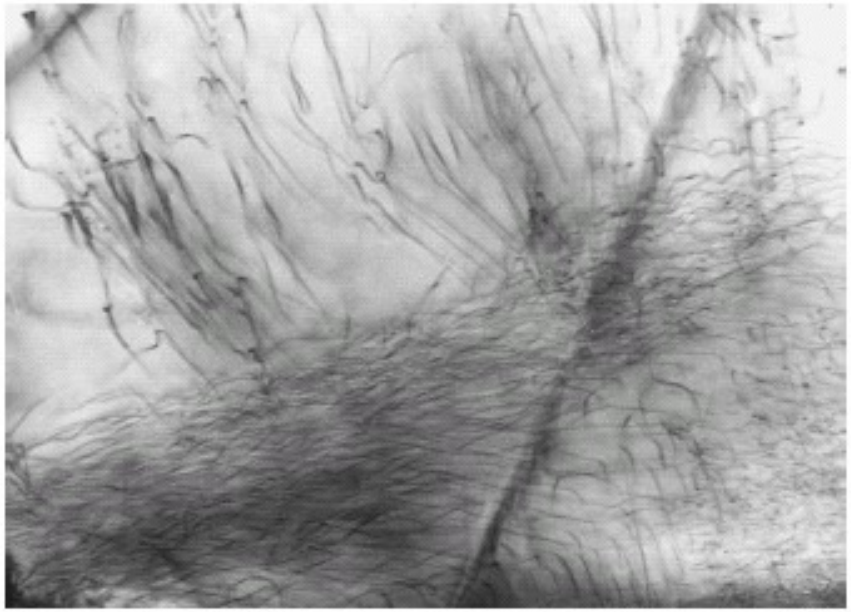
Line and plane defects: Dislocations Figs. 9.5 and 9.6

2) Line defects (dislocations) – linear arrays of lattice imperfection

3) Plane defects (stacking faults) - planar arrays of lattice imperfection



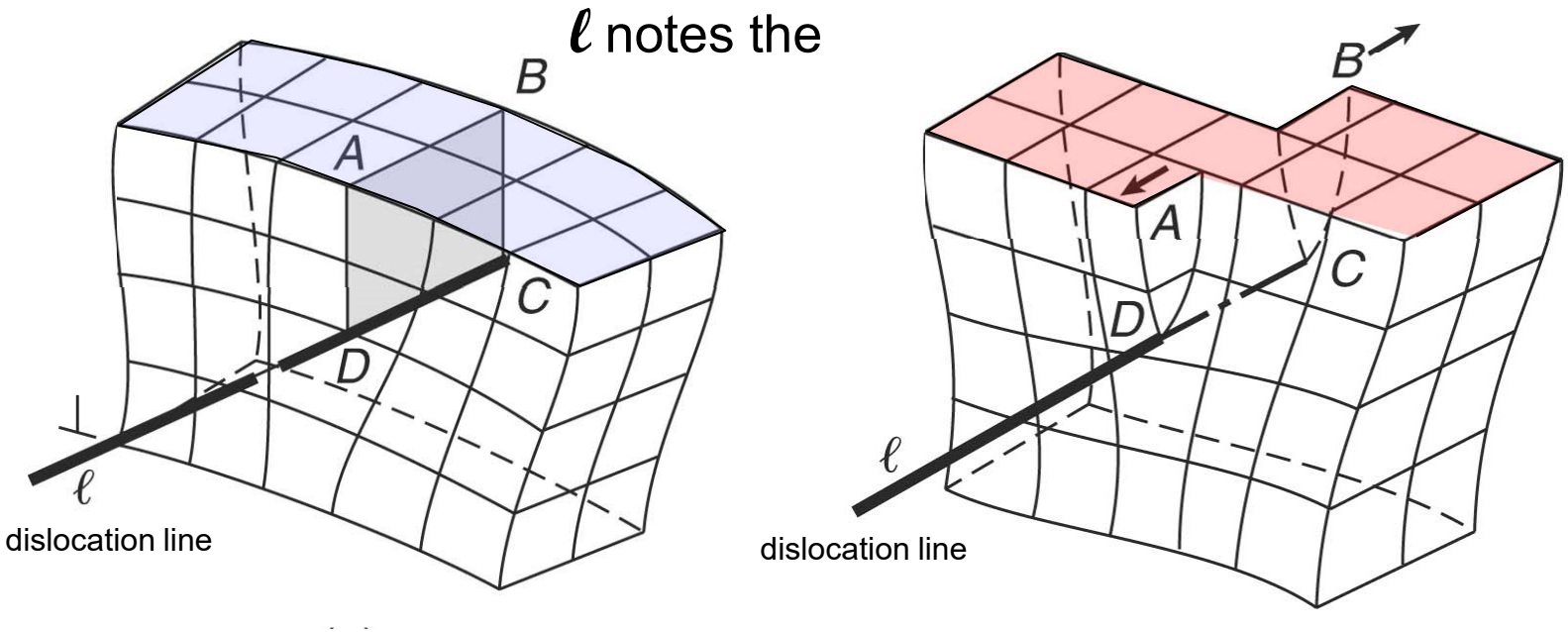
- Transmission (TEM) electron micrograph showing dislocation lines, loops, and arrays in experimentally deformed olivine.



- TEM and etching imaging of dislocations in olivine from a Hawaiian mantle nodule.
- The dislocations appear by a decoration technique that allows for optical inspection. Width of view is ~200 μm.

Dislocation Geometry and End-member types Fig. 9.7

- The ***critical resolved shear stress (CRSS)*** is the minimum stress needed to for a glide plane to produce an edge dislocation from the successive breaking of bonds.



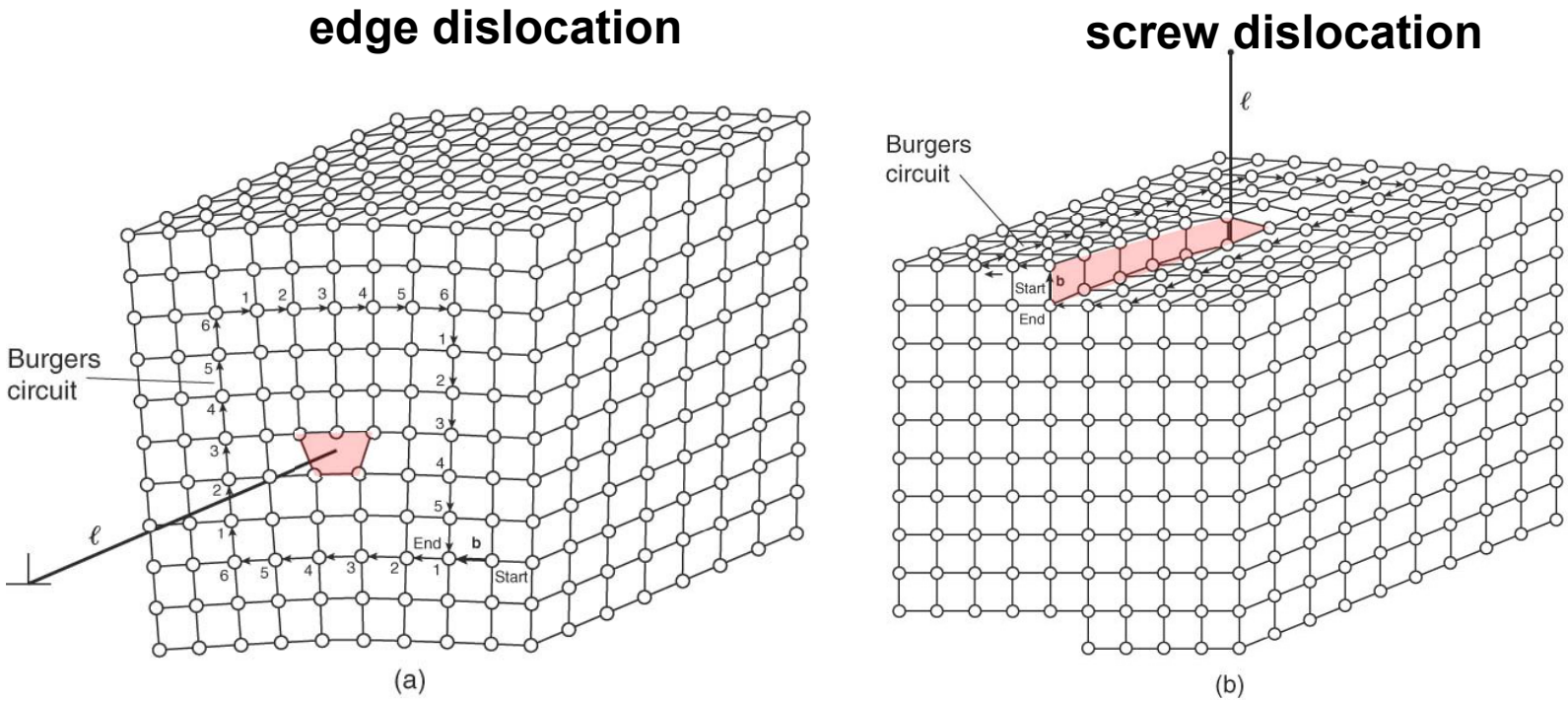
Edge dislocation has an extra half-plane of atoms.

Screw dislocation results in a lattice twist and offset (in a corkscrew manner)

- Crystal-lattice dislocations are characterized using two end-member types that commonly occur together producing **mixed dislocations.**

Dislocation Line and Burgers vector Fig. 9.8

In a deformed crystal, an atom-by-atom circuit around the dislocation fails to close by one or more atomic distances whereas a similar circuit in a perfect crystal would be complete.

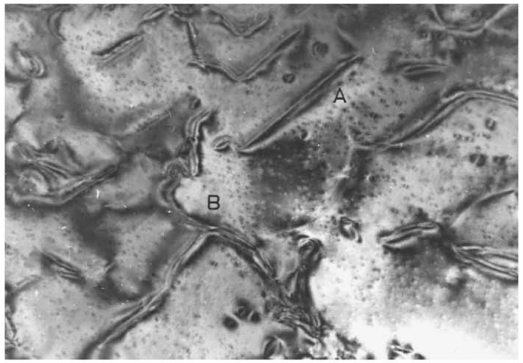


- The arrow connecting the two ends of the incomplete circuit is called the **Burgers vector**, **b**, with a length commonly on the order of nanometers (1×10^{-9} m).

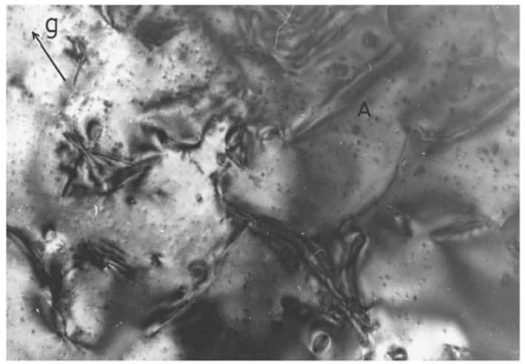
- The Burgers circuit remains in the same plane for an edge dislocation but steps up or down to another plane for a screw dislocation.

Imaging Dislocations Sec. 9.8 and Fig. 9.23

Electron Microbeam Analysis Laboratory (**EMAL**)

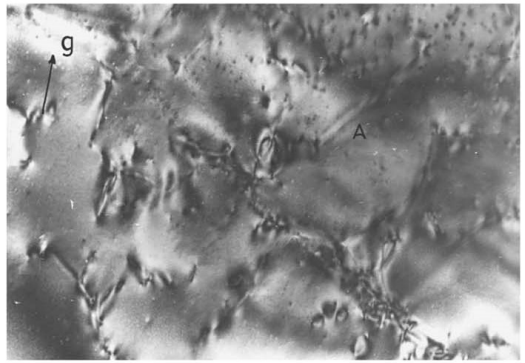


(a)



(b)

(c)



(d)

Dislocations in calcite viewed for different diffracting lattice planes

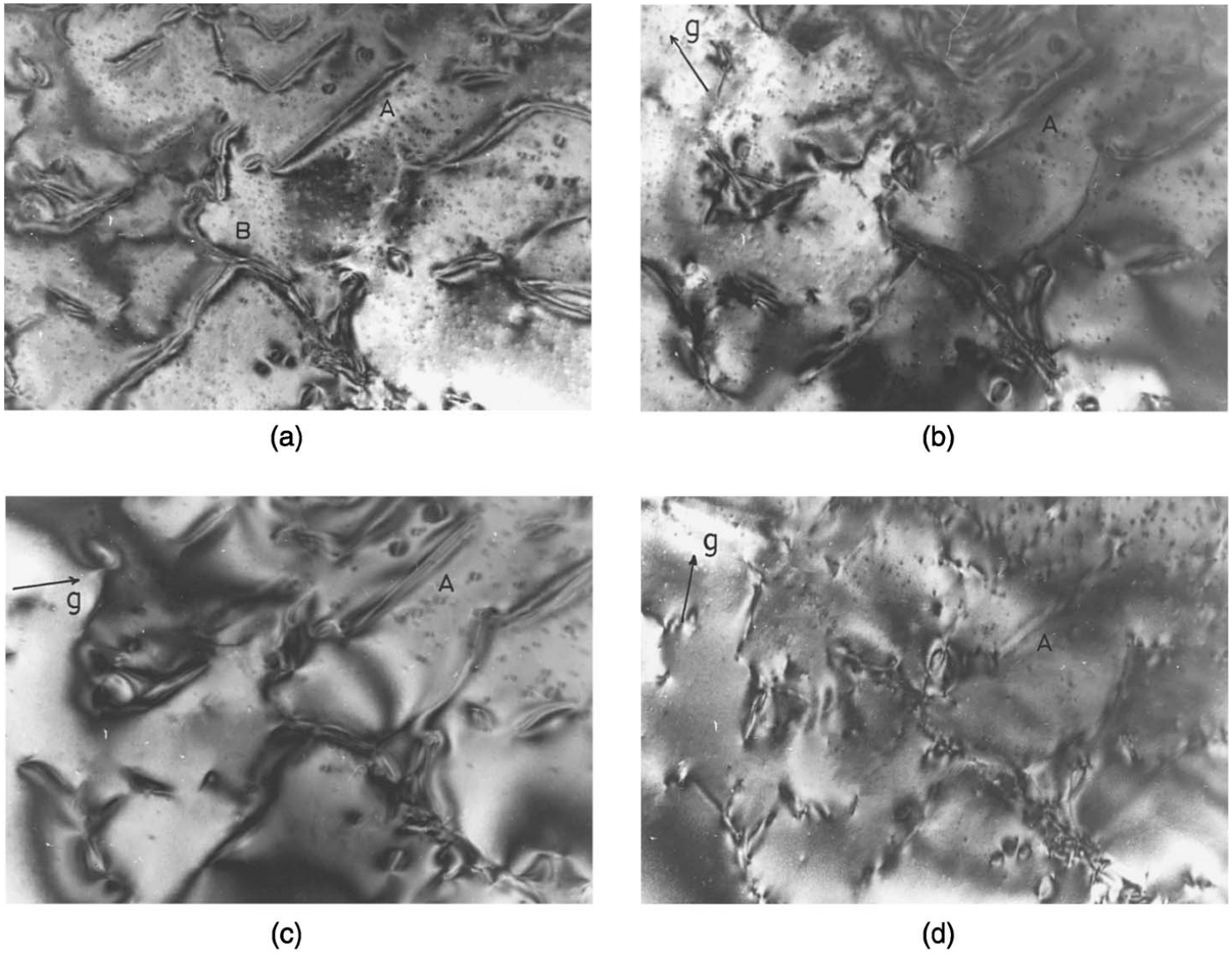
Imaging Dislocations Sec. 9.8 and Fig. 9.23

Dislocations in calcite

View of the same area for different diffracting lattice planes

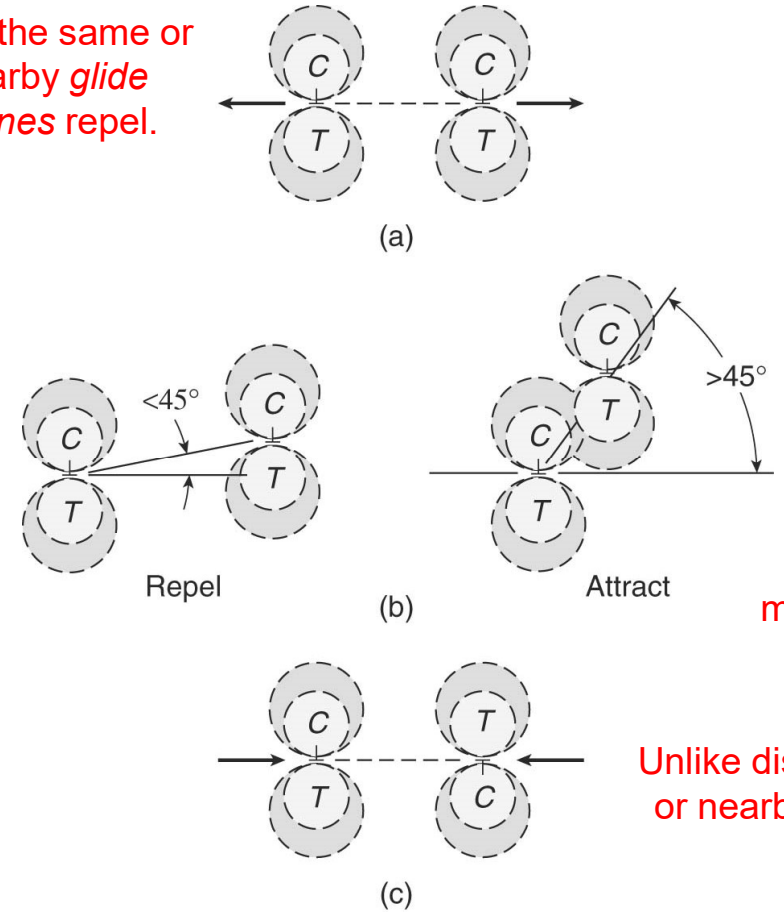
'A' marks a mixed dislocation

Width of view of each TEM image is ~1.7 μm



Interactions between neighboring edge dislocations Fig. 9.11

Like dislocations on the same or nearby *glide planes* repel.



- Deformation and temperature introduce energy into the crystal, which allows dislocations to move.
- At low temperatures dislocations move on preferred crystallographic **glide planes** (or **slip planes**) resulting from the mineral lattice structure.

Like dislocations on widely separated glide planes may attract or repel depending on the angle between the lines joining the dislocations.

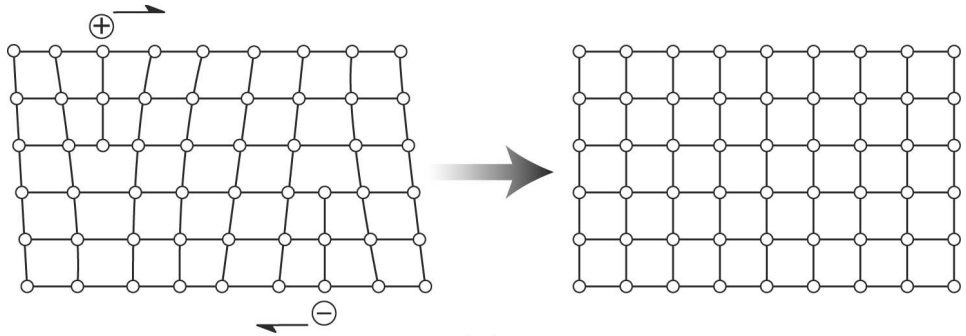
Unlike dislocations on the same or nearby glide planes attract.

Regions labeled C and T are areas of compression and tension, respectively, associated with each dislocation

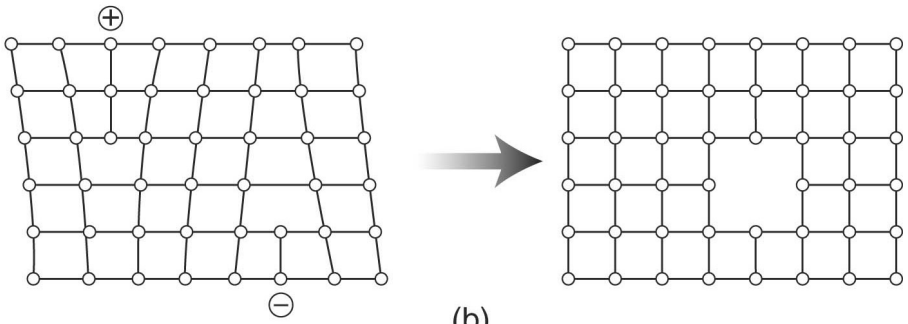
Stress field are shaded regions around edge dislocations of compressive or tensile nature

Dislocation Glide Fig. 9.14

Two edge dislocations with opposing extra half-planes that share a glide plane move in opposite direction to meet and form a perfect crystal.



(a)



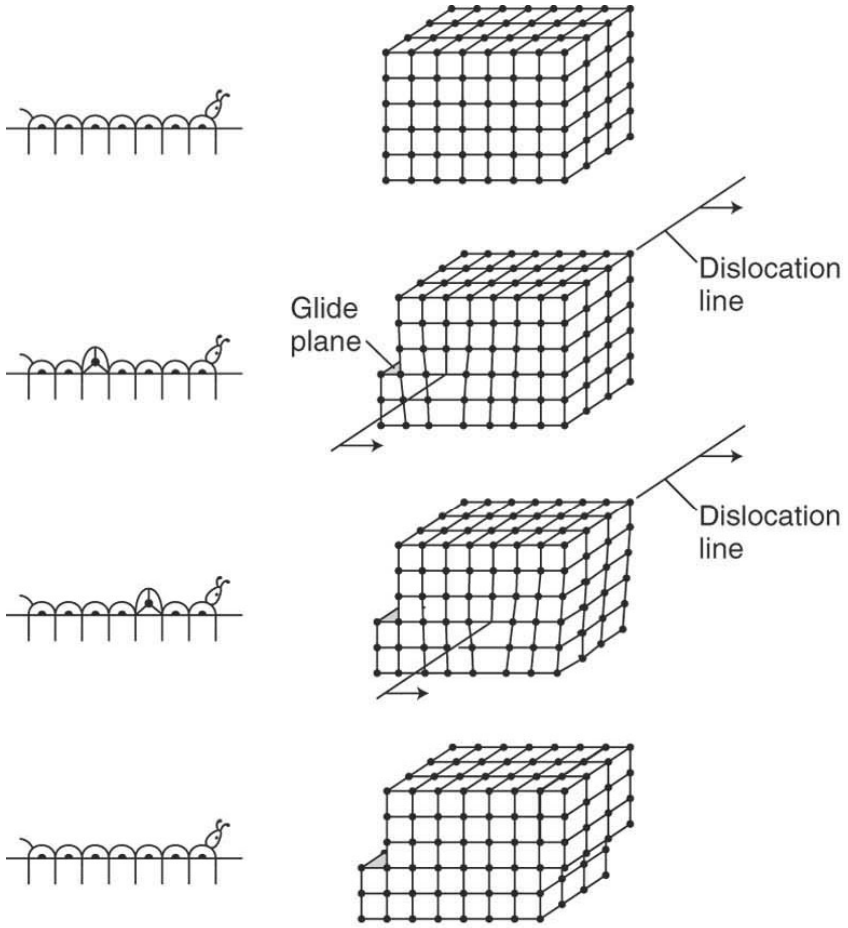
(b)

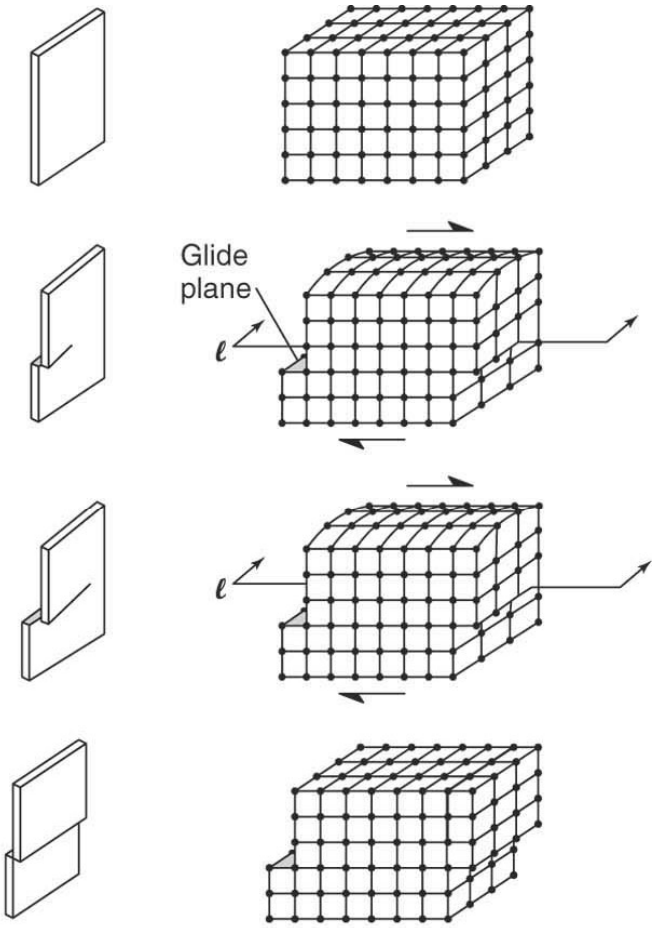
When they move in different glide planes, a vacancy may be formed when they meet.

- Glide lowers distortional energy, but may not produce a perfect lattice
- Dislocation annihilation
- *Dislocation glide is the process that produces a change in the shape of grains; it is therefore the main **strain-producing mechanism** of crystal plasticity.*

Dislocation Glide Fig. 9.12

Showing dislocation lines, **l,** and shaded glide planes

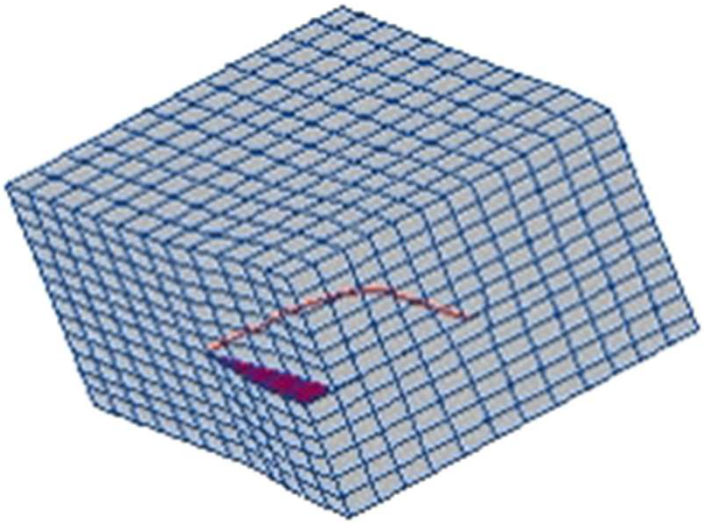




Edge dislocation *movement is analogous to the segmental motion of a caterpillar.*

Screw dislocation movement *is analogous to tearing a sheet of paper, with the screw dislocation at the tip of the tear.*

Dislocation Glide Fig. 9.12



Russ, 1997

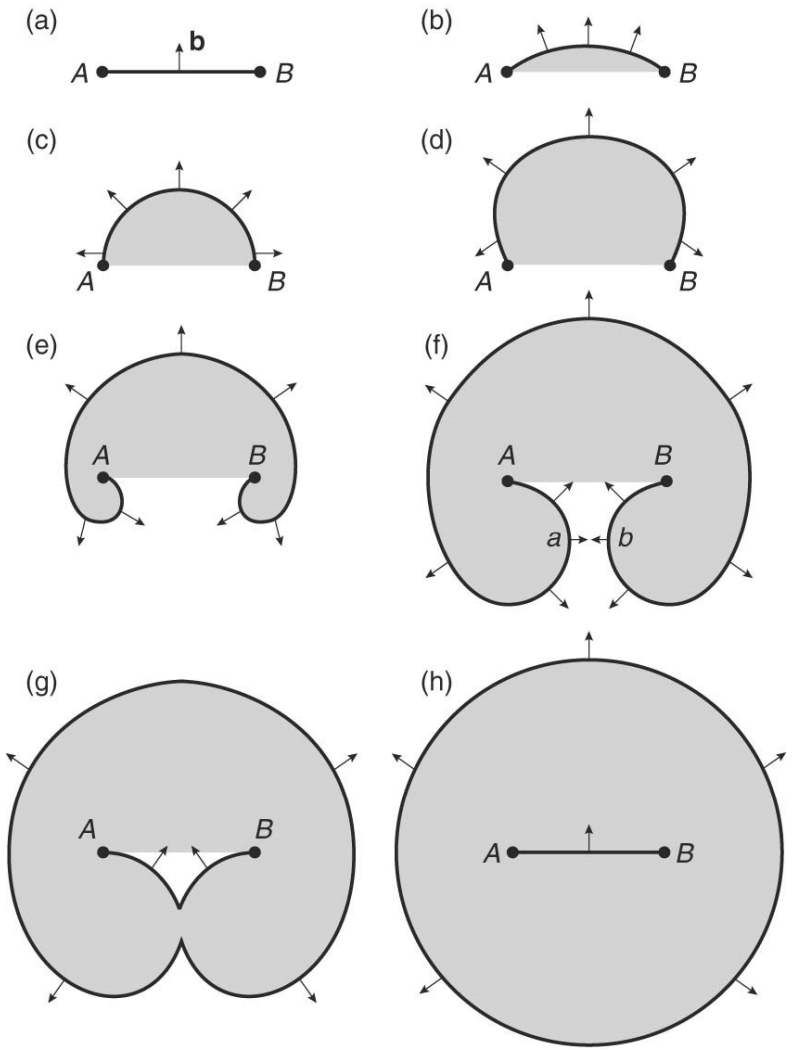
- When a dislocation reaches the edge of the grain there are no more atoms below to attach to and the crystal becomes offset.
- This offset of the crystal edge produces stair-step structures on the surface of the crystal known as **slip bands,** which are sometimes visible on large crystal surfaces.
- Thus, the process of dislocation movement produces permanent strain without the material ever losing coherency.

After the dislocation glides through the lattice, it leaves behind a strained crystal with a potentially perfect crystal lattice structure

Origin of Dislocations Fig. 9.19

Dislocation multiplication in a Frank-Read source.

- A pinned dislocation with Burgers vector, b, bows out during glide (b–g) to form a new dislocation (h).
- The slipped portion of the grain is shaded.
- During glide (b-g), the *A*–*B* dislocation will bow out because it is pinned at its edges and eventually this produces the kidney-shaped loop
- As *a* and *b* come together they annihilate (g), forming a new *A*–*B* dislocation line, while leaving the old loop present (h)
- The process starts again for the new *A*–*B* dislocation line while the first loop continues to glide

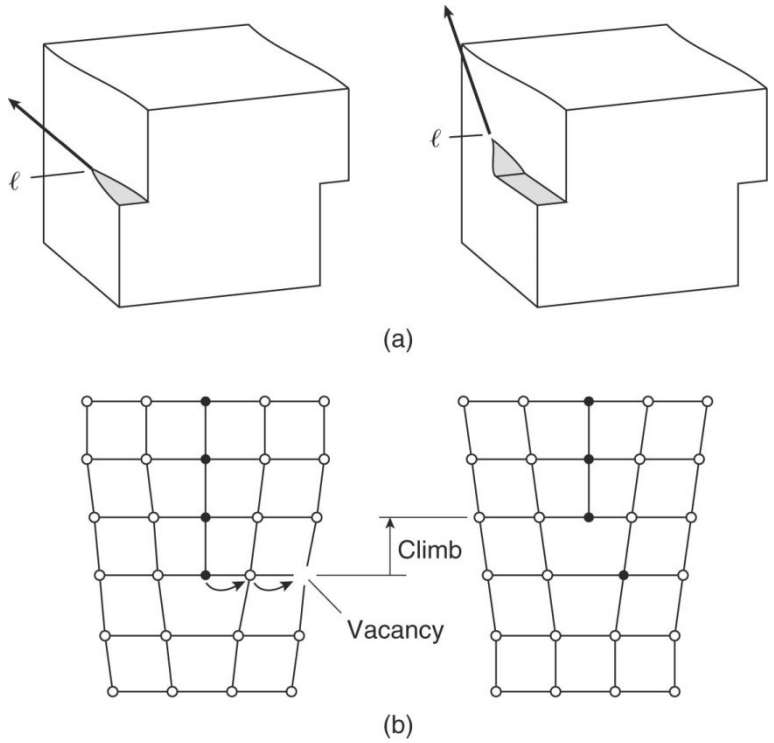


There is no restriction on the number of cycles

Cross-slip and Climb Fig. 9.13

Medium to high temperature plasticity.

- Obstacles that result from the presence of many immobile dislocations are called **pile-ups.**
- In order to overcome these obstacles, edge and screw dislocations must move out of their current glide plane, which they do by the processes of **climb** and **cross-slip**, respectively.
- **Climb** *is when diffusion accompanies the transfer* of glide to a parallel but different plane in the lattice
- **Cross-slip** is when glide leaves one slip plane for another, less favored one with favorable CRSS for slip



- *It is likely that, for a given applied stress, the CRSS is exceeded on at least one and sometimes more than one glide planes.*

Cross-slip and Climb Fig. 9.13

Medium to high temperature plasticity.

- Both cross-slip and climb are activated at temperature conditions that exceed those for dislocation glide in a mineral given the same stress conditions
- The therefore typically occur at deeper and hotter depths

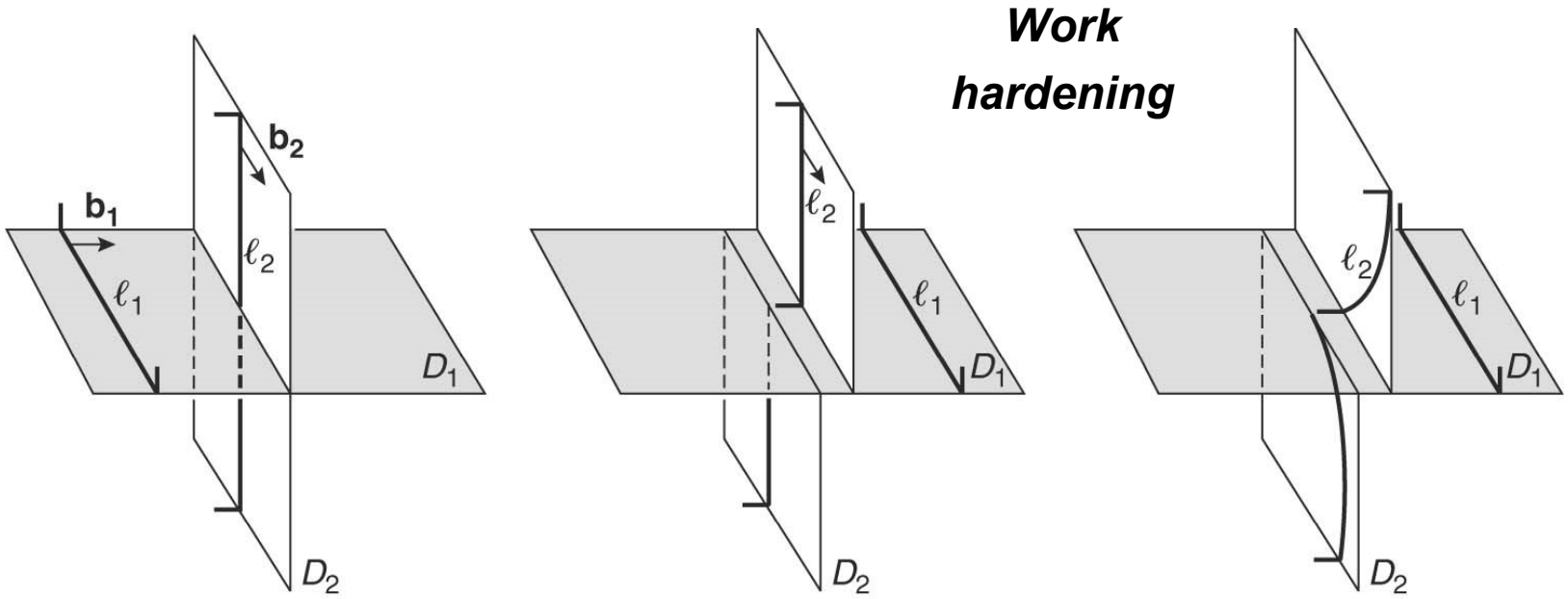
  >300°C for quartz–rich and limestone

  >500°C for mafics, feldspars, and dolomite
- Cross-slip and climb facilitate dislocation glide, *but by themselves produce little finite strain*; they allow a dislocation to leave its original glide plane, to bypass an impurity, for example.
- Cross-slip and climb are therefore the **rate-controlling mechanisms** of crystal plasticity (limit the resulting strain rate).
- Sometimes the terms **low-temperature creep** are used for dislocation glide (and twinning) and **high-temperature creep** for dislocation glide plus climb.

Jogs and Interacting dislocations Fig. 9.22

The formation of a jog from the interaction of two mobile edge dislocations.

For simplicity, dislocation *D*2 is initially kept stationary while dislocation *D*1 moves; the glide planes (shaded and unshaded), Burgers vectors (b), and dislocation lines (**l**) for each edge dislocation are shown



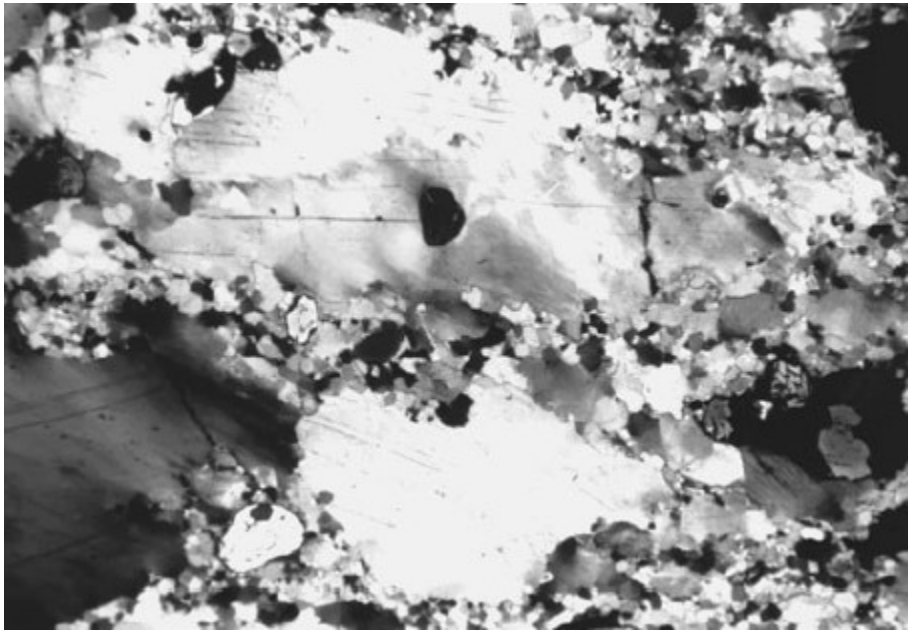
- Upon *D*1 passes through dislocation line **l**2, a small step of one Burgers vector (b1) length is created; this small step is a jog, with a differently oriented dislocation line segment but the same b2
- Assuming that the CRSS for glide differs in different directions, the ability of *D*2 to move is no longer the same along **l**2, and the jog pins the dislocation by anchoring a segment of **l**2 (c).

Recovery (low-medium T plasticity) Fig. 9.26

- The atomic bonds are bent by deformation and the crystal lattice is elevated from its lowest energy state with additional **stored strain energy.**

- One way to lower the internal strain energy of a grain is to reduce localized crystal defects through climb, cross-slip, and glide

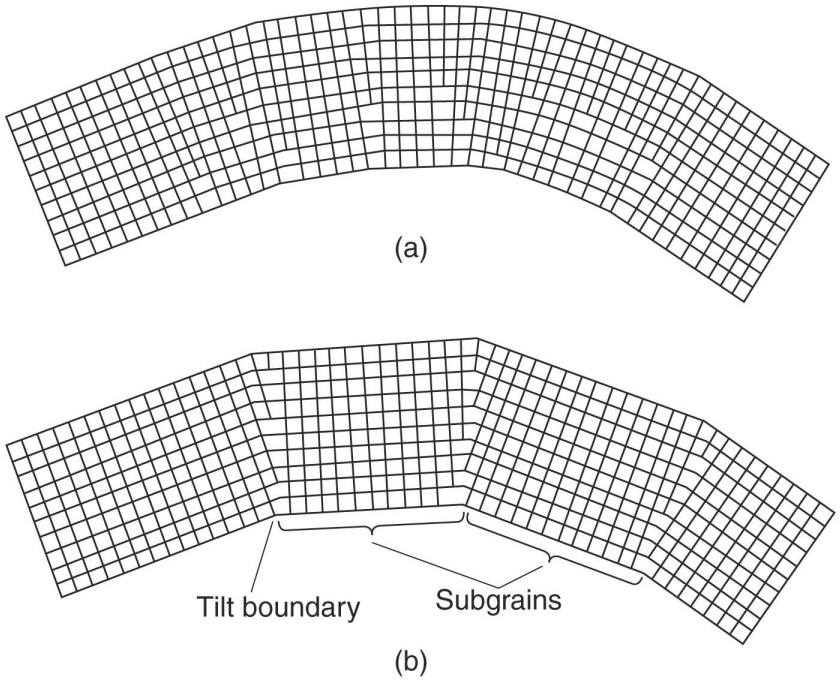
- **Recovery** occurs from temperature-activated rearrangement of lattice dislocation, producing the characteristic
- Sub-grain deformation microstructure with low-angle grain boundaries



Subgrain microstructure and undulose extinction in a marble mylonite from southern Ontario (Canada). Width of view is ~4 mm.

Recovery (low-medium T plasticity) Fig. 9.24

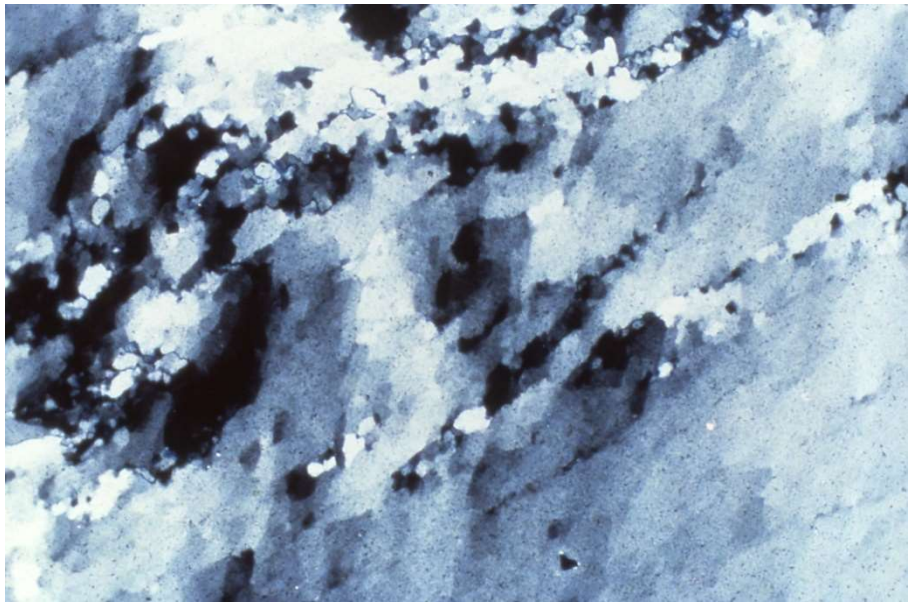
- Dislocations in a crystal lattice become arranged into a zone of low-angle dislocations, called a **dislocation wall** or **tilt boundary**
- *Recovery through dislocation creep can also* lower internal strain energy through annihilation and/or moving dislocations to the edge of crystals, so that the internal strain is minimized.



Irregularly distributed dislocations are rearranged by glide and climb to form a dislocation wall (or tilt boundary) that separates subgrains (b).

Subgrain (tilt) walls from plastic recovery

Subgrain - the region of a large crystal that is enclosed by a tilt boundary with an angular difference across the boundary that is less than 10° (low angle)



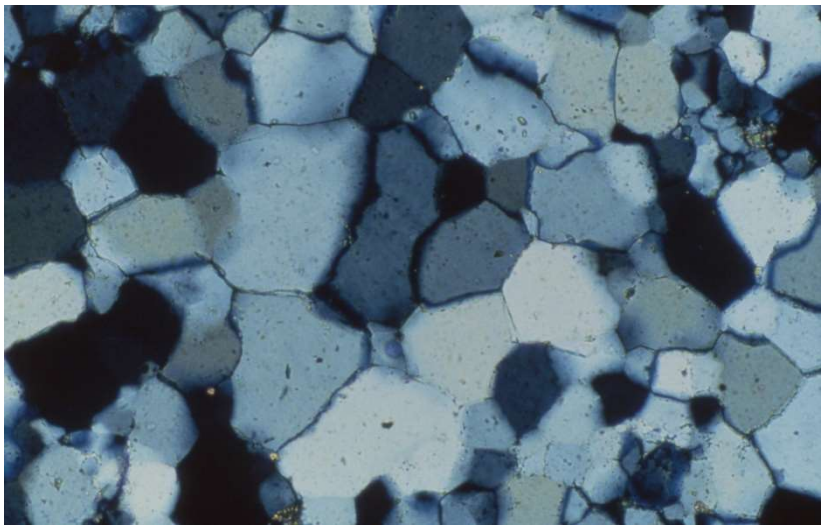
Number of dislocations in tilt wall 500μm long, 2nm wide, Burgers vector of 0.5nm and angular mismatch θ of 10°. Dislocation spacing of ~2.9nm and thus more than 170,000 (!) dislocations, representing a dislocation density in low-angle tilt wall (1×10^{-8} cm2) of 1.7×10^{13} cm–2.

- *This resulting internal strains are not recoverable (as in elastic strain), because permanent distortions are produced around dislocations in the crystal*

Recrystallization (medium T plasticity)

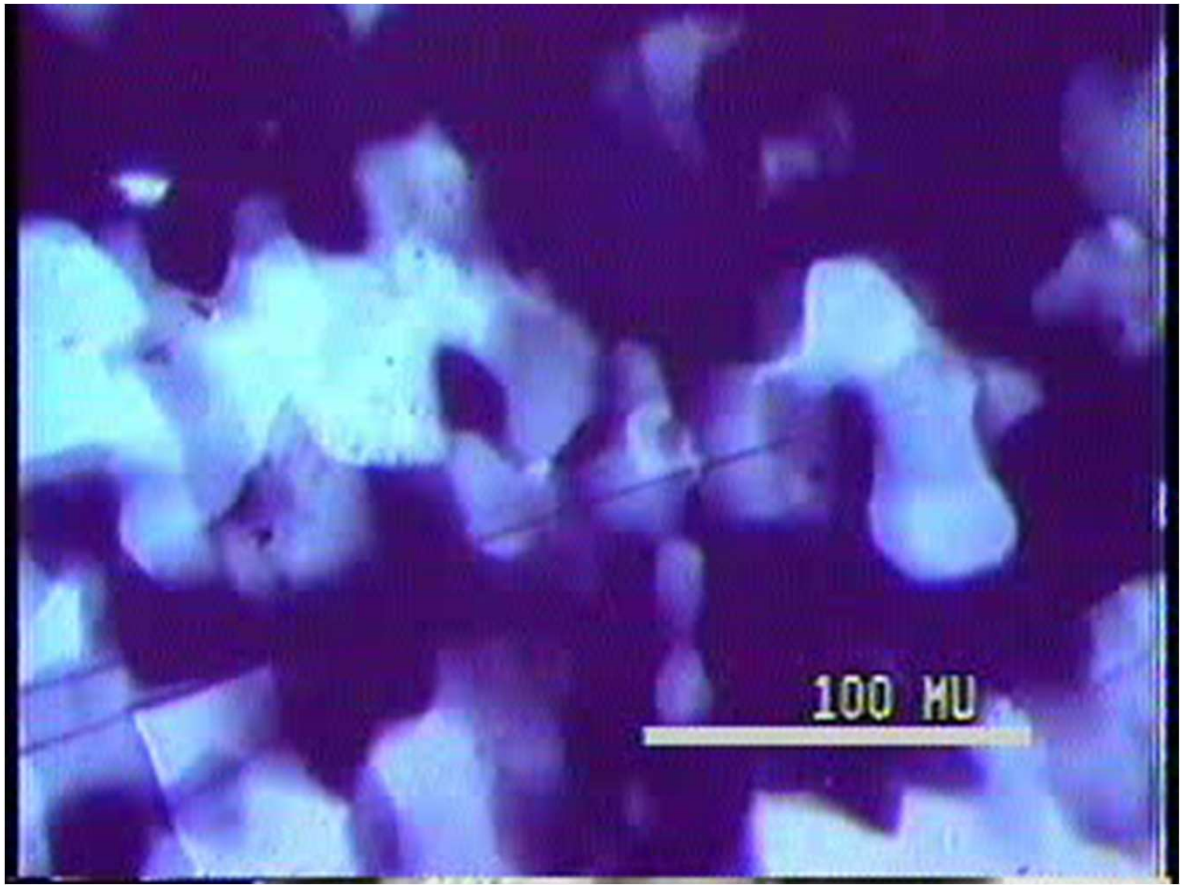
- Recrystallization forms **high-angle grain boundaries** that separate relatively strain-free grains from each other.
- In rocks, a recrystallized microstructure is characterized by grains ***without undulatory extinction*** and with relatively straight grain boundaries (high angle) that meet at about 120° triple junctions with ***foam structure***
- Recrystallization occurring under isotropic stress conditions or when the differential stress is removed is called **static recrystallization;** otherwise know as **annealing.**

Recrystallized quartz showing foam structure



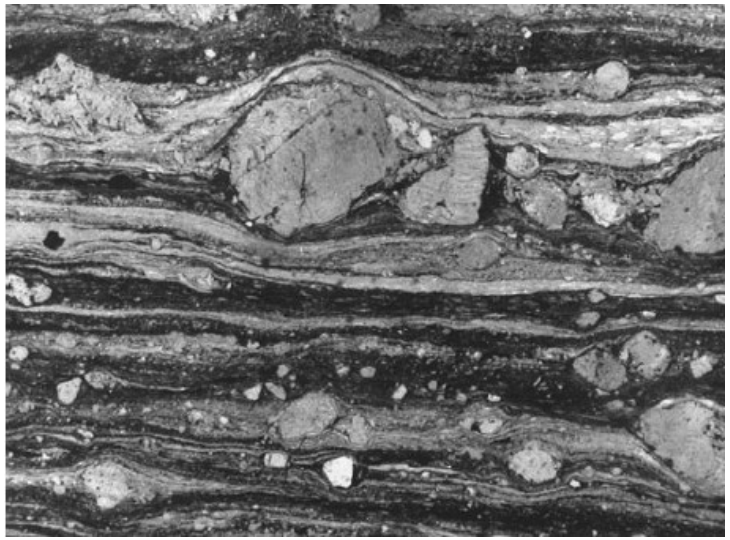
Note: recrystallization in petrology is dominated by changes in chemical potential among phases, whereas recrystallization in materials science involves changes in strain energy within the same phase

Annealing

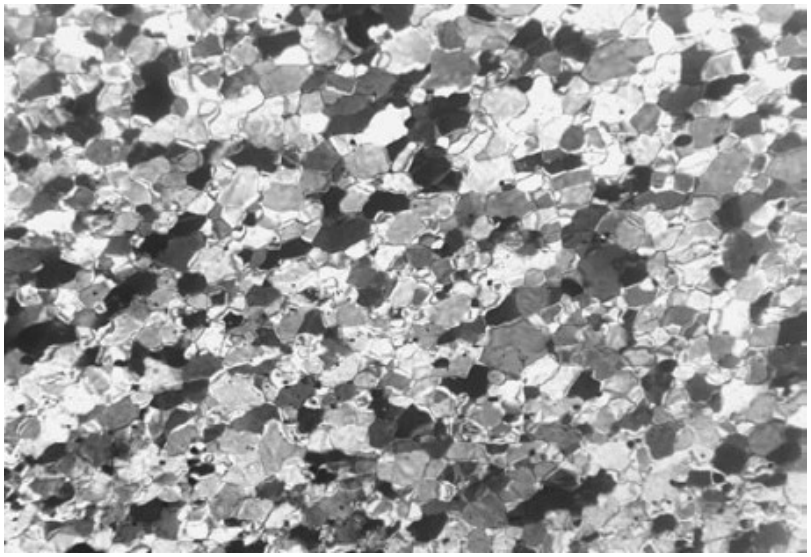


Recrystallization (medium T plasticity)

- Recrystallization within an anisotropic stress field (i.e., a differential stress) is called **dynamic recrystallization.**



- Dynamic recrystallization results in grain-size reduction, which is well known from sheared rocks (such as the mylonite above)



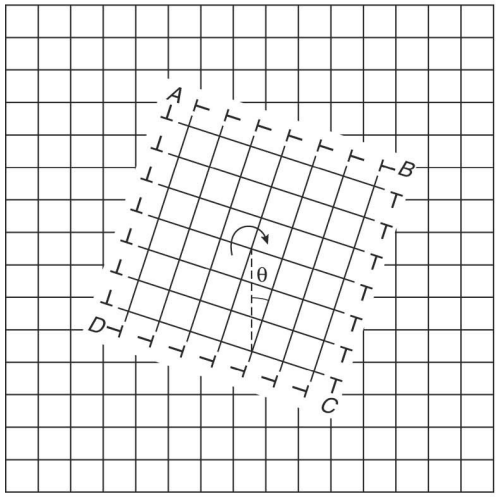
Recrystallization microstructure, showing relatively strain-free grains with straight grain boundaries and representing the most deformed stage in a marble mylonite

- From a microstructural perspective the only thing that distinguishes static recrystallization from dynamic recrystallization is a relatively larger recrystallized grain size.

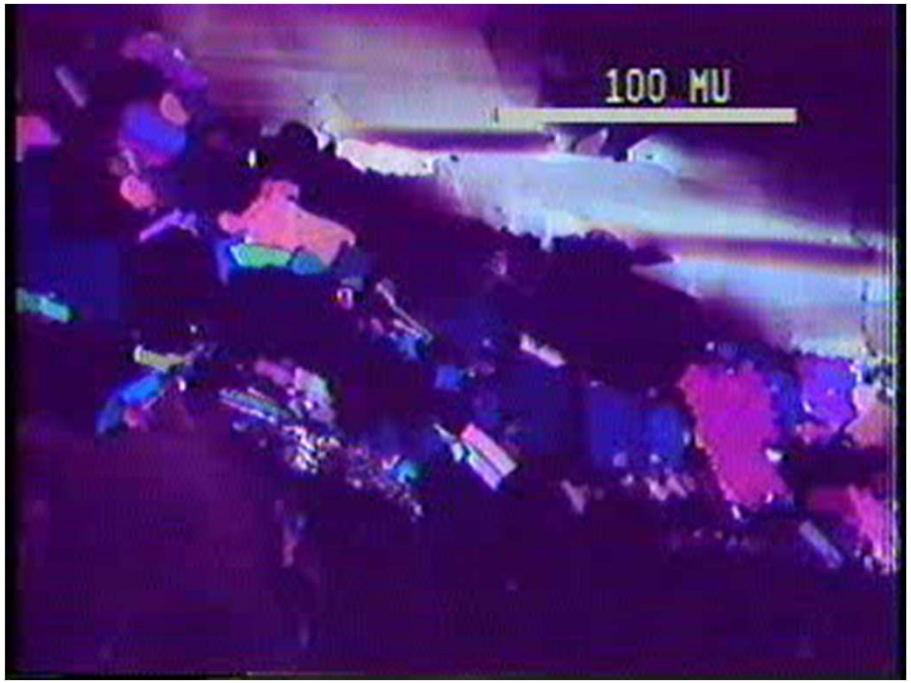
Recrystallization mechanisms Sec. 9.9.3

There are two main mechanisms for recrystallization

1) **Rotation recrystallization** describes the progressive misorientation of a subgrain as more dislocations move into the tilt boundary, thereby increasing the crystallographic mismatch across this boundary.



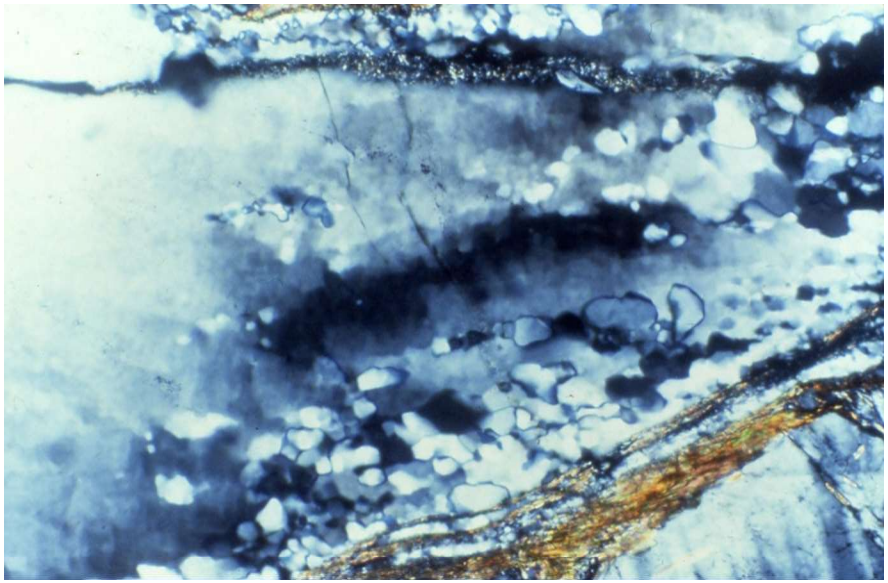
(a)



Schedl and van der Pluijm, 1990

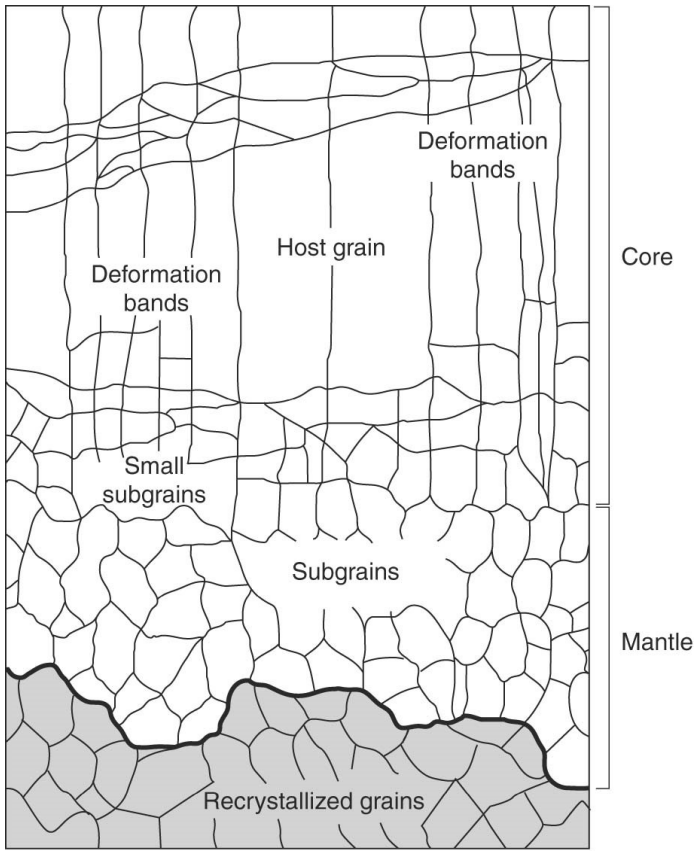
Recrystallization mechanisms Sec. 9.9.3

The common microstructure in which relatively deformation-free grain interiors progress to subgrains and then to recrystallized grains toward grain boundaries (Figure 9.30) is called a **core-mantle structure** or **mortar structure.**



core-mantle structure (qtz)

Recrystallized grains occur at the edge of the mantle by progressive misorientation of subgrains.

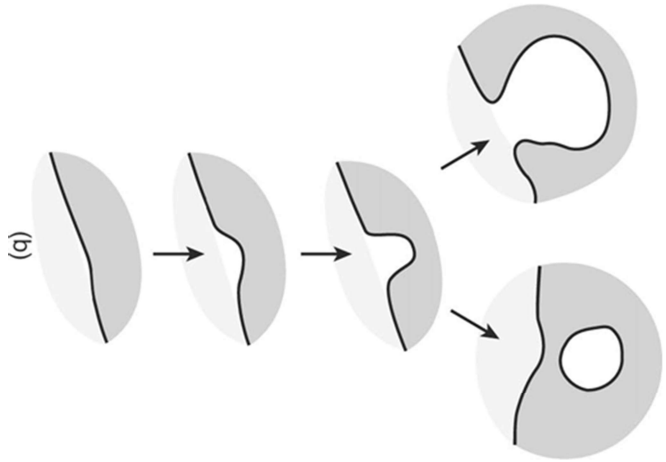


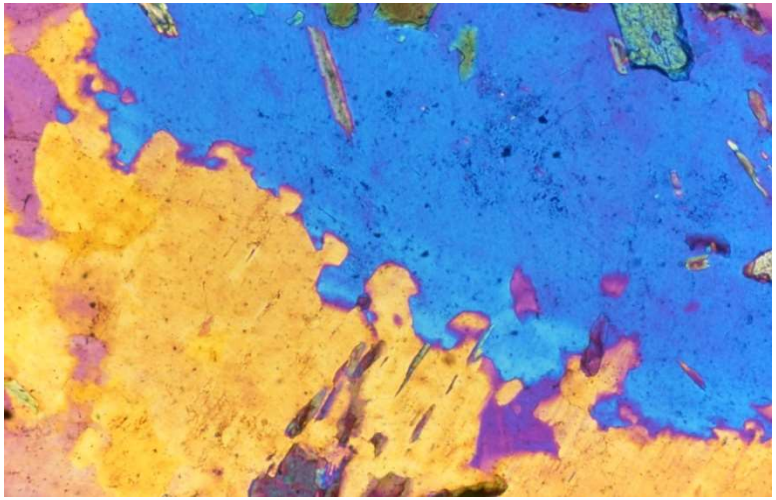
The internal portion of the host grain (core) shows weak deformation features such as undulose extinction and deformation bands, or may even be strain-free.

Recrystallization mechanisms Sec. 9.9 ³

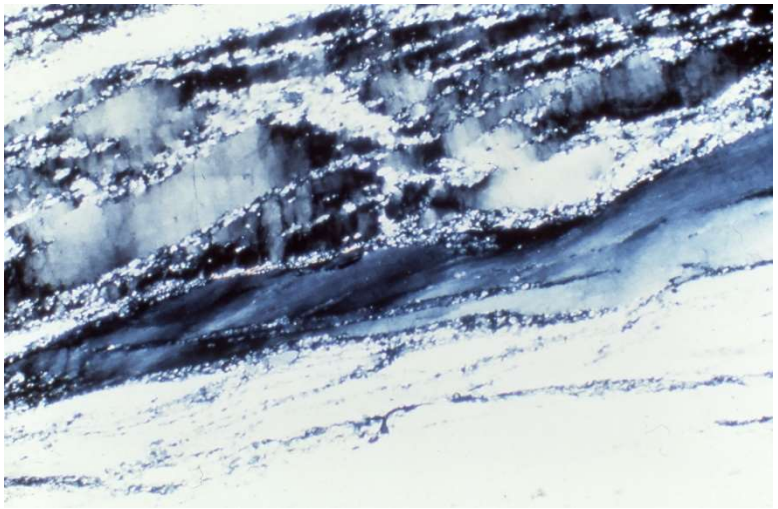
2) **Migration recrystallization** is a process by which grains grow at the expense of their neighbor(s)

Grain boundaries effectively sweep through neighbors; the grain that grows has a lower dislocation density than the grain(s) consumed.





feldspar grain boundary bulging



quartz-grain boundary migration recrystallization

Recrystallization mechanisms Sec. 9.9.3

- The dominance of rotation recrystallization (subgrain rotation) and migration recrystallization (bulge nucleation) is largely a function of strain rate.
- Bulge nucleation is generally favored at higher strain rates and high temperatures.
- Experiments have shown that a characteristic range of grain sizes occur for a specific condition of stress and mechanism of recrystallization.
- Therefore, recrystallized grain size can be used as a **paleopiezometer** (derived from the Greek “piezo,” meaning to press) to calculate differential stress

Paleopiezometry

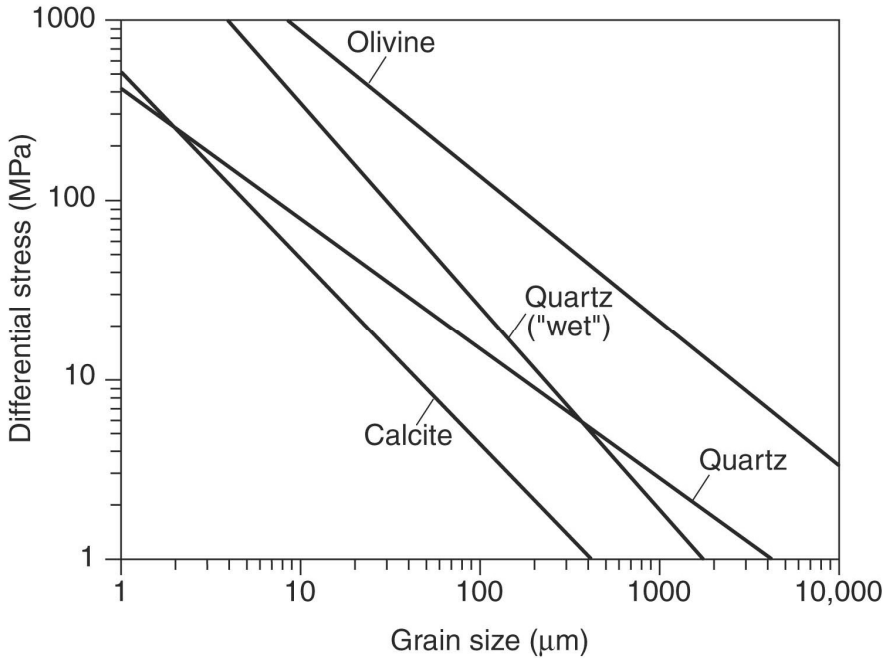


TABLE 9.4	EMPIRICALLY DERIVED PARAMETERS FOR RECRYSTALLIZED GRAIN SIZE–DIFFERENTIAL STRESS RELATIONSHIPS	
Mineral	*A* (in MPa)	*i* (with *d* in μm)
Calcite	467	1.01
Quartz	381	0.71
Quartz ("wet")	4090	1.11
Olivine	4808	0.79

Sources: Mercier et al. (1977), Ross et al. (1980), Schmid et al. (1980), Ord and Christie (1984).

Recrystallized grain size is inversely proportional to differential stress: $\sigma_d = Ad^{-i}$

A and *i* are empirically derived parameters for a mineral

d is grain size in micrometers (μm).

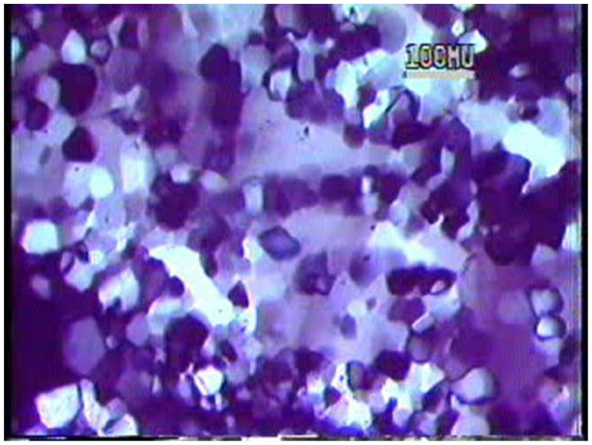
Grain Boundary Sliding Superplasticity (high T plasticity)

Grain size sensitive creep that does not produce permanent shape change of individual grain (stable microstructure).

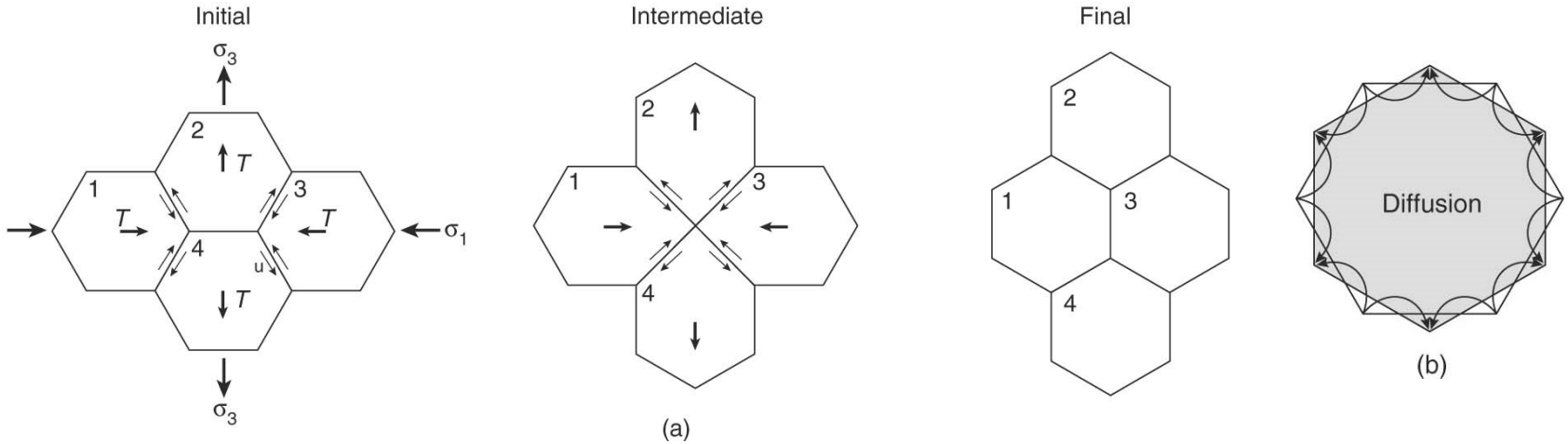
Deformation occurs by diffusion-assisted grain switching

Characteristics:

- small grain size
- no dimensional (or shape) fabric
- no crystallographic fabric



Schedl and van der Pluijm, 1990



Flow laws

$$e^o = A\, f(\sigma_d)\, \exp(-E^*/RT)\, f(d)$$

A is material constant, E* is activation energy, R is gas constant, T is temperature (in K), $f(\sigma_d)$ is differential stress function, f(d) is grainsize function

- For **dislocation glide** (low to medium temperature creep) the function of stress is *exponential*: $e^o = A \exp(\sigma_d) \exp(-E^*/RT)$ and it's therefore sometimes called *exponential creep*

- For **dislocation glide and climb** (medium to high temperature creep) the stress is raised to the *power* n: $e^o = A\, \sigma_d^n \exp(-E^*/RT)$ and it's therefore called *power law creep*, with n the *stress exponent* (2<n<5)

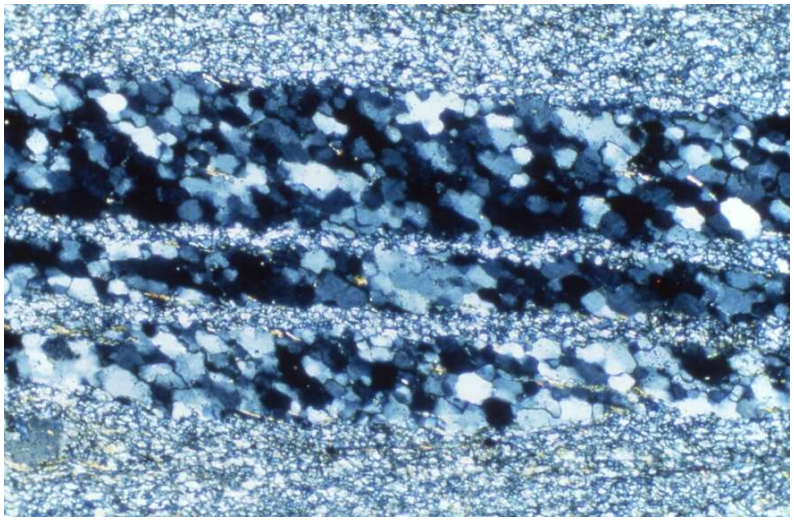
- For **diffusional creep** (high T plasticity): $e^o = D_o\, d \exp(-E^*/RT)\, d^{-r}$

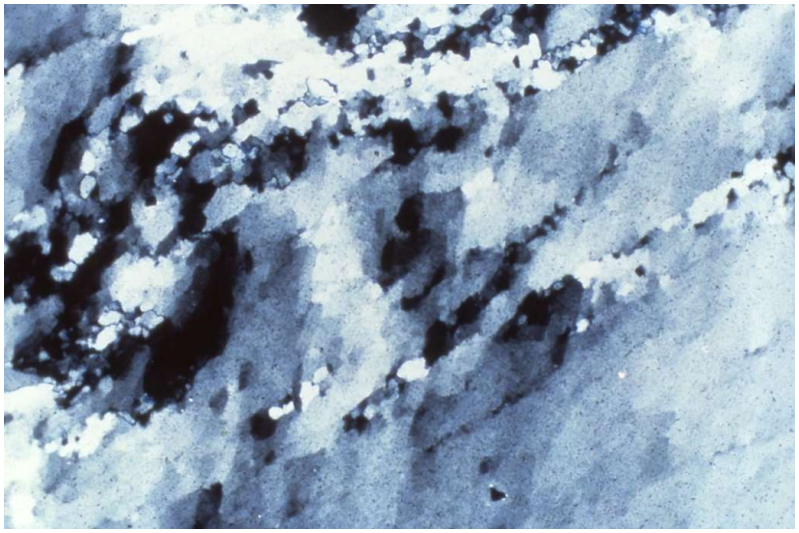
  This is also called *grain-size sensitive creep,* with r=2-3
  (note: r=1 is viscous creep)

Highest strain rate dominates behavior

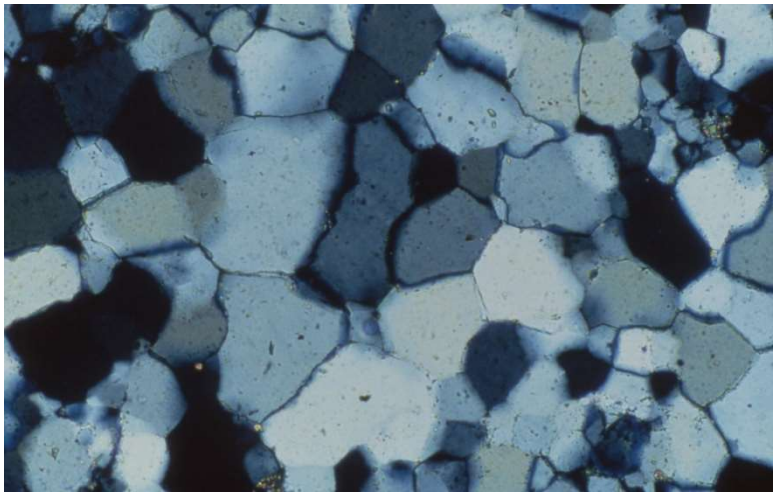
Quartz Microstructures

shape fabric





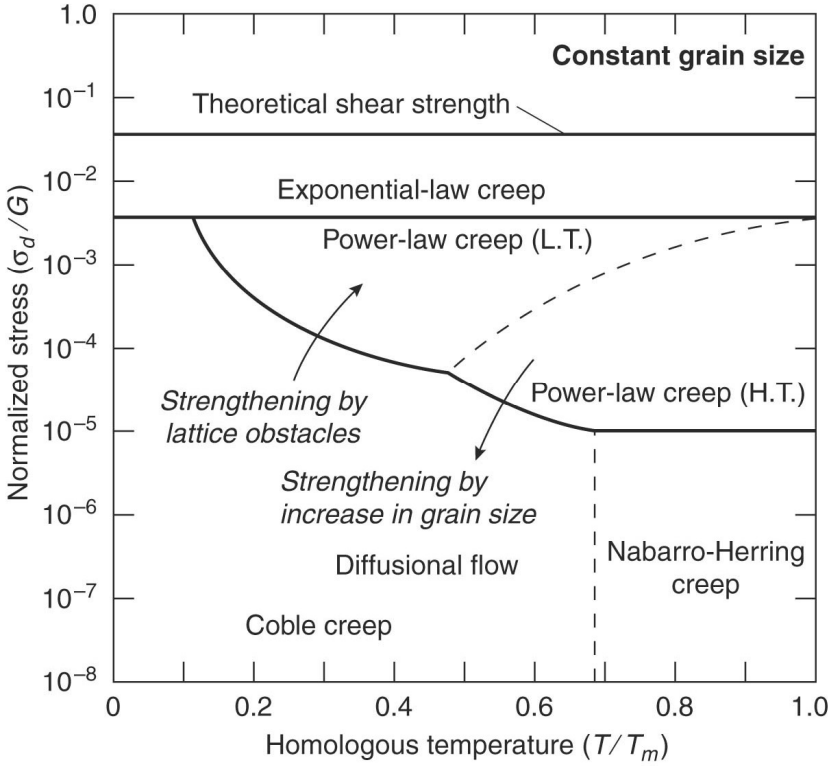
deformation bands + subgrains



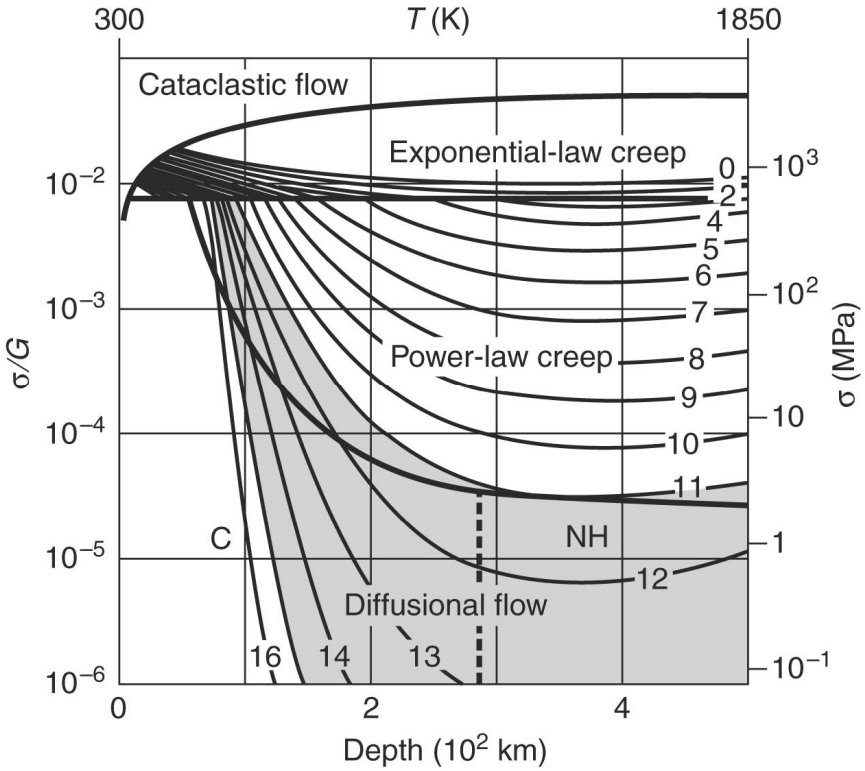
annealing

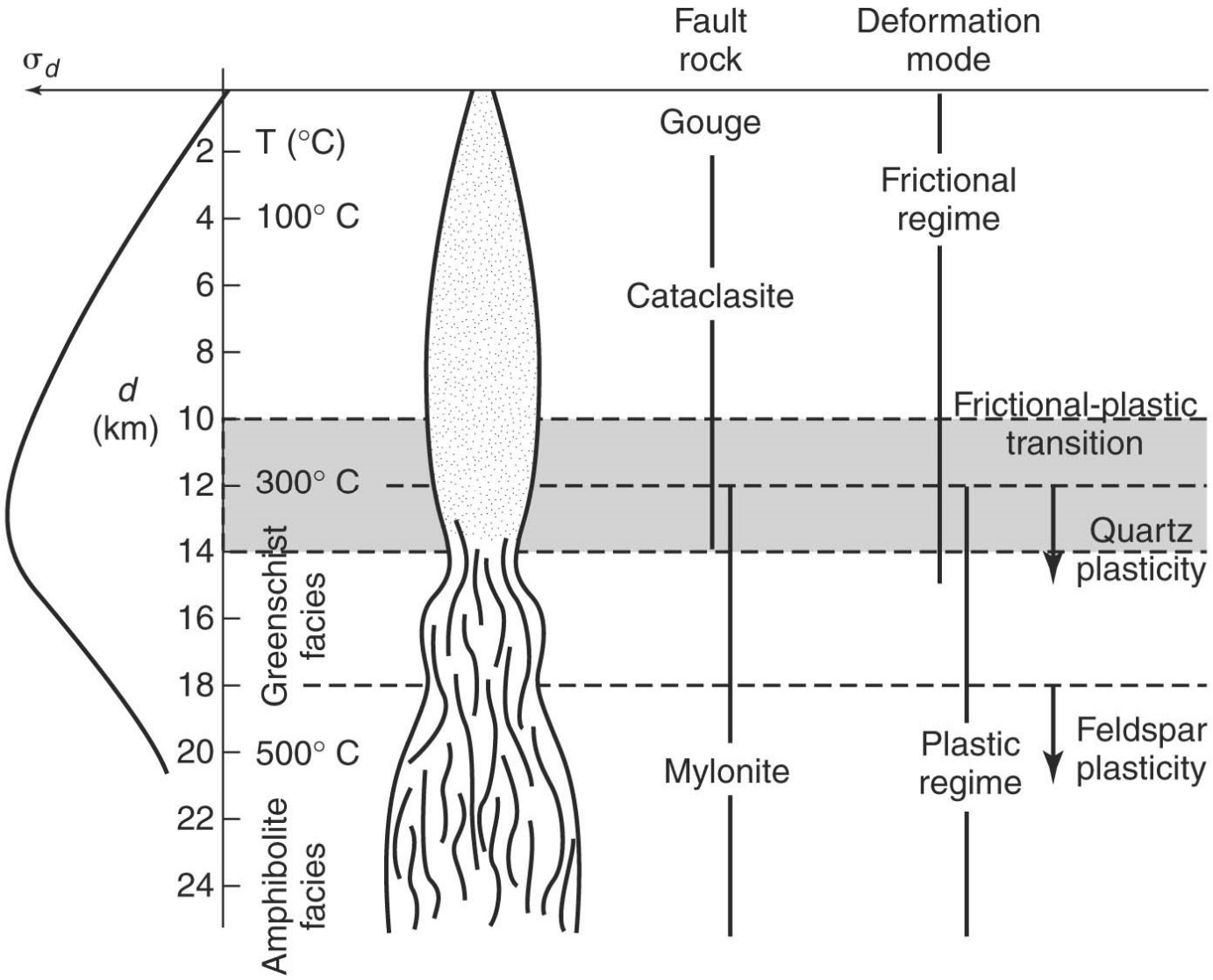
Deformation Regime map Figs. 9.33 and 9.36

Schematic of a deformation mechanism map, showing normalized stress versus homologous temperature at a constant grain size.



Deformation mechanism map for olivine with a grain size of 100 μm



Process (P) or Mechanism (M)	Atomic-Scale Process	Diagnostic Microstructures	Rheological Implications	Common Minerals
Bulk rotation (M or P)	Physical rotation of whole or part of mineral grains	Helical inclusion trails, bending of crystals, delta and sigma porphyroclasts		Any
Climb (M)	Diffusional addition or removal of atoms at dislocation line			Any; more at high *T*
Diffusive mass transfer (M or P)	"Long range" diffusion of atoms	Veins, pressure shadows, porphyroblasts		Any, especially quartz and calcite
Dislocation glide (M)	Rearrangement of interatomic bonds	Deformation lamellae, deformation bands, undulose extinction	$\dot{e} \propto \sigma^3$, also a hardening with finer grain size	Any; more at low stress and high *T*
Fracturing (M)	Breaking of inter-atomic bonds	Gouge, breccias, boudinaged grains		Any; more at high stress and low *T*
Frictional sliding (M)	Frictional sliding on surfaces	Gouges, breccias, pseudotachylytes, domino grains	$\tau \propto \sigma^n$	Any; more at high stress and low *T*
Grain boundary migration (P or M)	Local diffusion and reorientation of atoms or atomic clusters	Irregular grain boundaries, pinning microstructures, orientation families; lattice-preferred orientations with strong point maxima, non-120° triple junctions	Produces low dislocation density; material softer	Any; more at high *T*; especially quartz, olivine, feldpar
Grain boundary sliding (M)	Dislocation movement on "clean" grain boundaries, shearing on "dirty" ones			Any

Crustal Fault Model