Deformation at the Microscale

Deformation processes occur at the microscale and lead to changes in the internal structure, shape or volume of a rock.

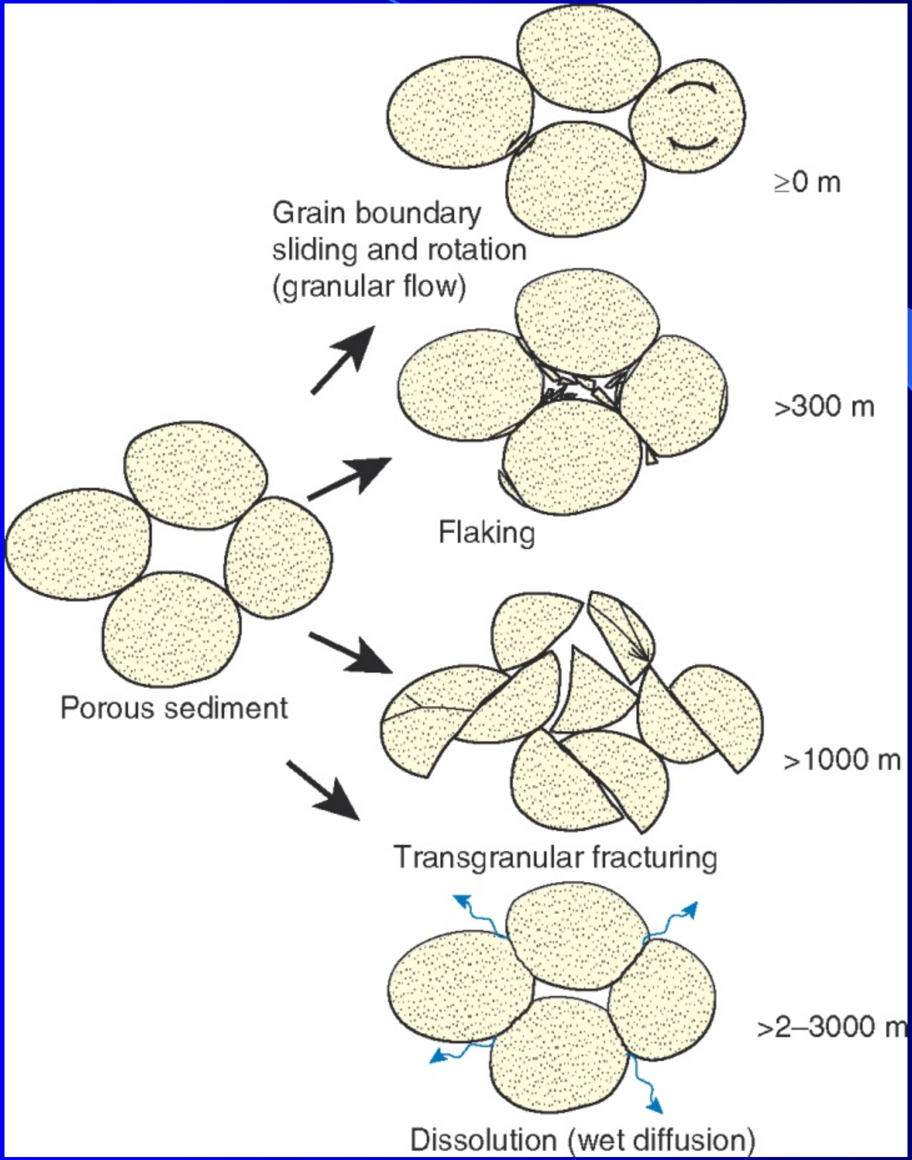
BRITTLE DEFORMATION	Fracturing	
	Frictional sliding	
BRITTLE FLOW	Granular flow	Frictional sliding Rolling
	Cataclastic flow	Grain fracturing
PLASTIC FLOW	Diffusion	Wet diffusion Grain-boundary diffusion Volume diffusion
	Crystal plasticity	Twinning Dislocation creep

Brittle versus Plastic deformation mechanisms is a function of:

- Pressure – increasing pressure favors plastic deformation
- Temperature – increasing temperature favors plastic deformation
- Rheology of the deforming minerals (for example quartz vs feldspar)
- Availability of fluids – favors brittle deformation
- Strain rate – lower strain rate favors plastic deformation

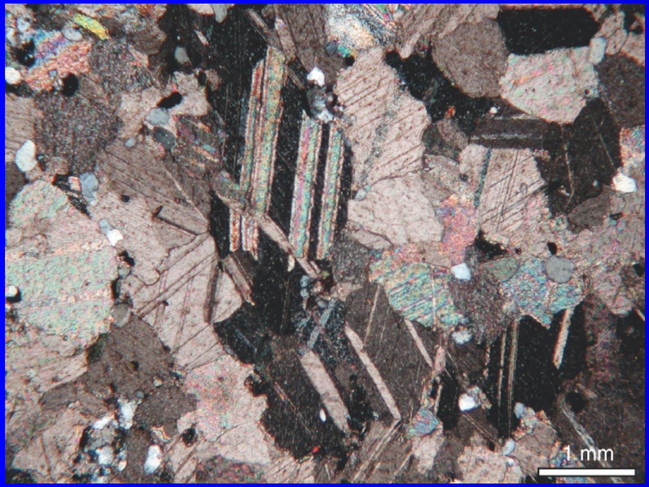
Given the different rheology of different minerals, brittle and plastic deformation mechanisms can occur in the same sample under the same conditions. The controlling deformation mechanism determines whether the deformation belongs to the brittle or plastic regime.

Brittle deformation mechanisms operative at shallow depths.



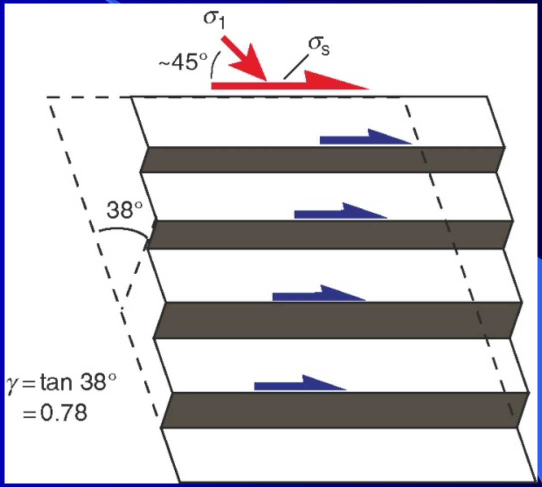
Crystal-plastic Deformation Mechanisms

Mechanical twining – mechanical bending or kinking of the crystal structure.



Mechanical twins in calcite

In the case of calcite, the 38º angle turns the twin plane into a mirror plane. The amount of strain associated with a single kink is fixed by this angle.

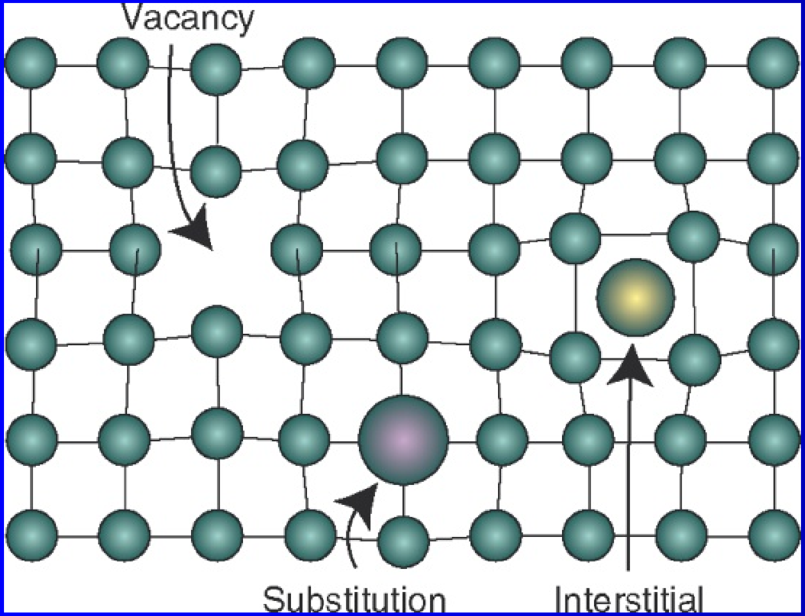


Deformation (glide) twins in a calcite crystal. Stress is ideally at 45º to the shear (glide plane). Dark lamellae have been sheared (simple shear).

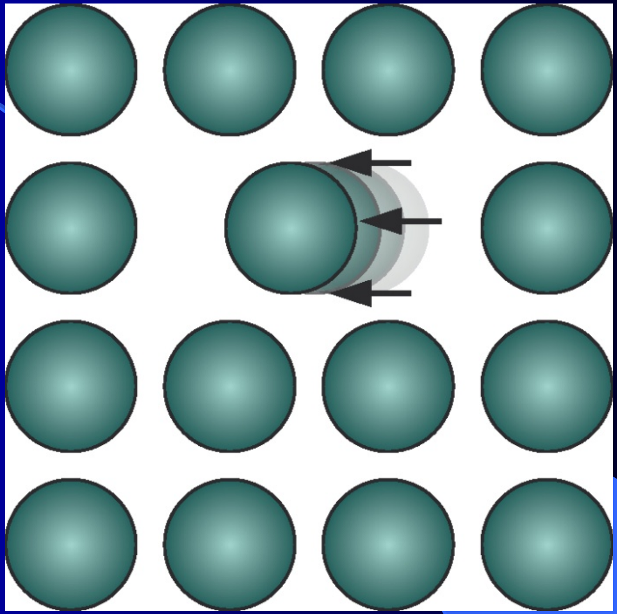
Crystal Defects

- Point defects – due to vacancies or impurities in the crystal structure.
- Line defects (dislocations) – a mobile line defect that causes intracrystalline deformation via slip. The slip plane is usually the place in a crystal that has the highest density of atoms.
- Plane defects – grain boundaries, subgrain boundaries, and twin planes.

Types of defects – vacancy, substitution, interstitial



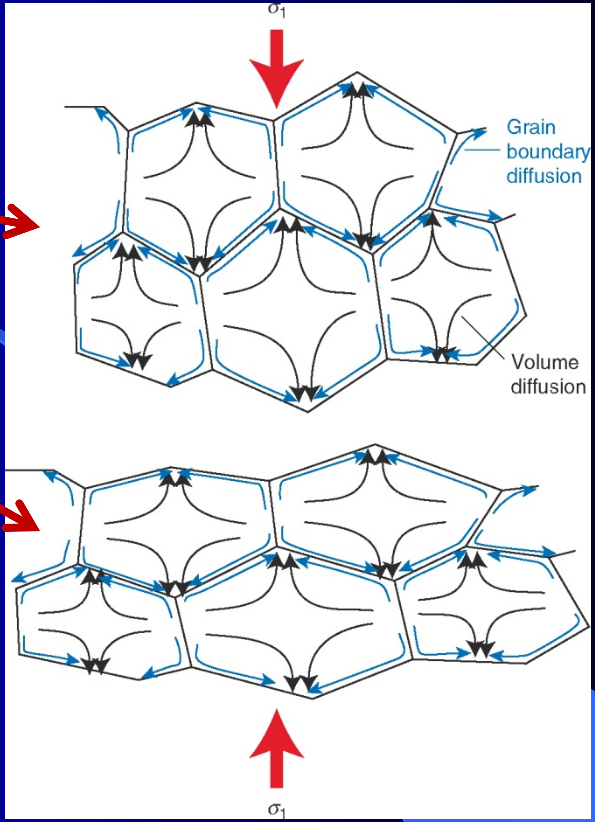
Migration of vacancies through a crystal structure by diffusion.

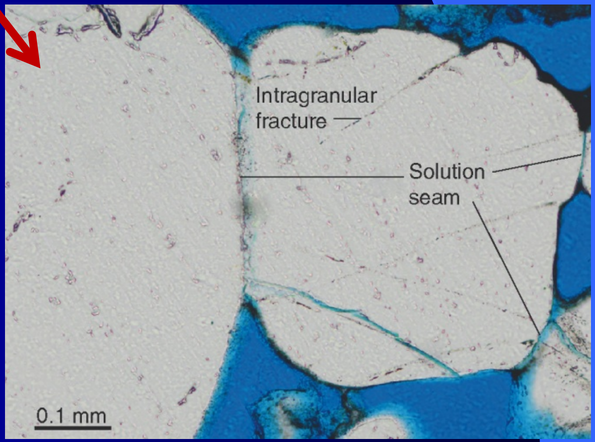


The movement of dislocations occurs in the plane or direction which requires the least energy. When a crystal is deformed by plastic deformation the dislocation density increases. Deformation adds energy to the crystal and a high density of defects implies a high-energy state. A low-energy state is thermodynamically favored, so the spontaneous direction is one of decreasing dislocation density, but this involves activation energy.

Diffusion creep

- Volume diffusion ((Nabarro-Herring creep) – vacancies move through crystals (temperature and stress controlled.
- Grain boundary diffusion (Coble creep) - vacancies move along grain boundaries (temperature and stress controlled).
- Pressure solution (wet diffusion) - ions move in fluid films and pore fluid (chemically and stress controlled.
- Grain boundary sliding (superplastic creep) – relatively rapid strain rates at low differential stress occurs in fine-grained rocks in the mantle and lower crust. The sliding along grain boundaries is frictionless and no voids open during the deformation. The small grain sizes favor this process because of the short distances to grain boundaries (short diffusion paths).





Dislocations and Dislocation Creep

- Slip plane – plane along which dislocation moves. Weak crystallographic directions are usually the planes in a crystal that have the highest density of atoms. Mica has one slip plane, quartz has 4 potential planes. The basal plane for quartz (normal to the crystallographic c-axis) is activated at low metamorphic grade. Orientation of c-axis reflects the deformation mechanism and kinematic framework.

- Edge dislocation – the edge of an extra half-plane in the crystal structure.

- Screw dislocation – dislocation line is oriented parallel to the slip direction.

- Dislocation creep – motion and destruction of dislocations in a crystal. Dislocation movements do not damage or weaken the mineral.

- Dislocation pile-ups – multiple dislocations entangle and accumulate. By-passing this pileup requires energy. At low T's not enough energy so we leave plastic deformation and re-enter the brittle regime.

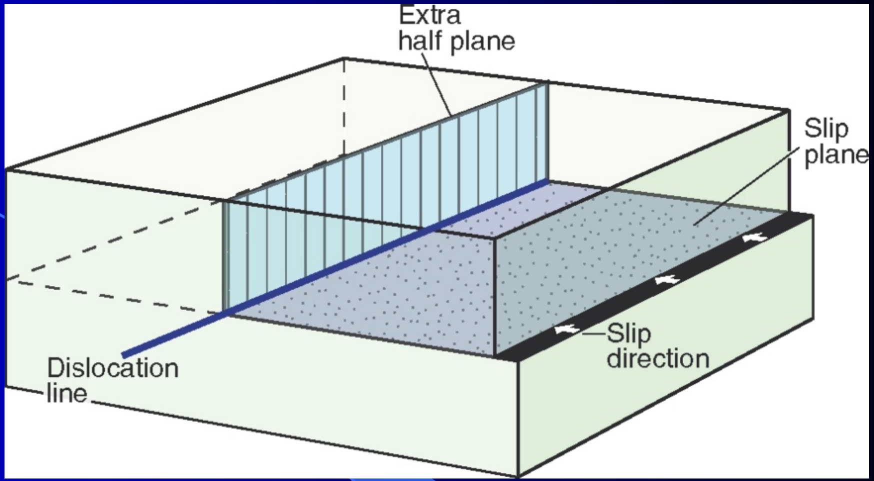
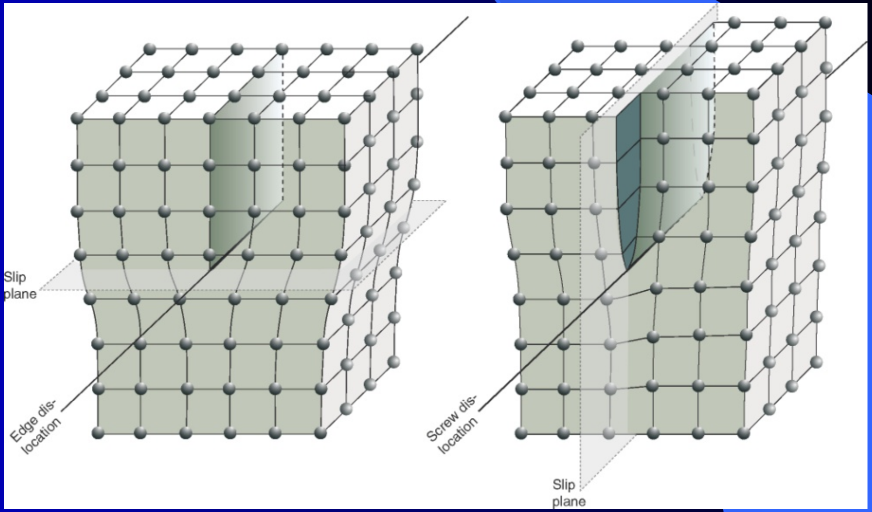
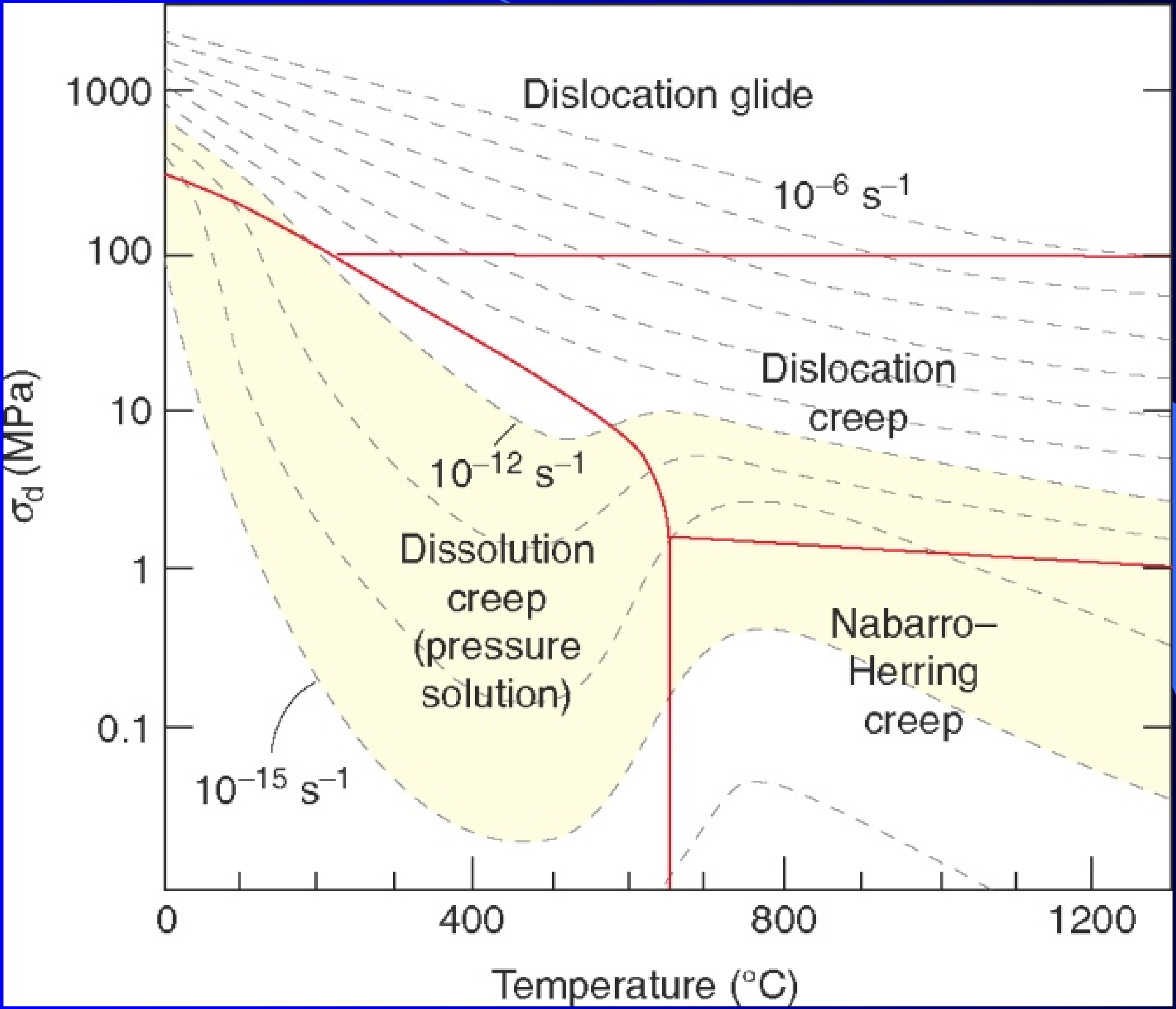


Illustration of dislocation line, slip plane, extra half-plane, and slip direction

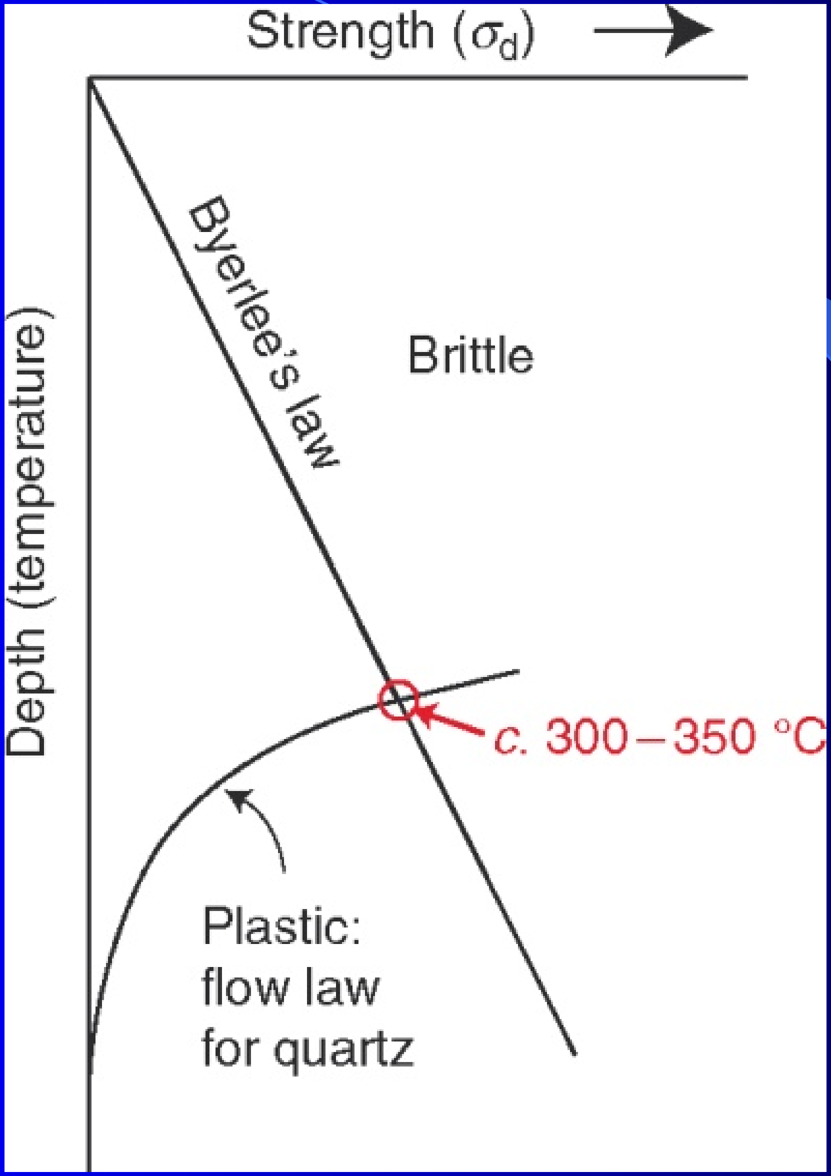


Edge dislocation (l) and screw dislocation (r).

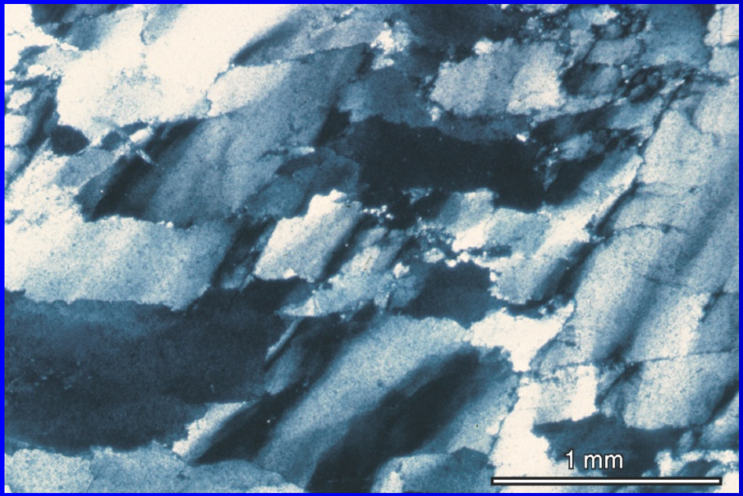
Stress, temperature and strain rate (contoured) control type of deformation mechanism



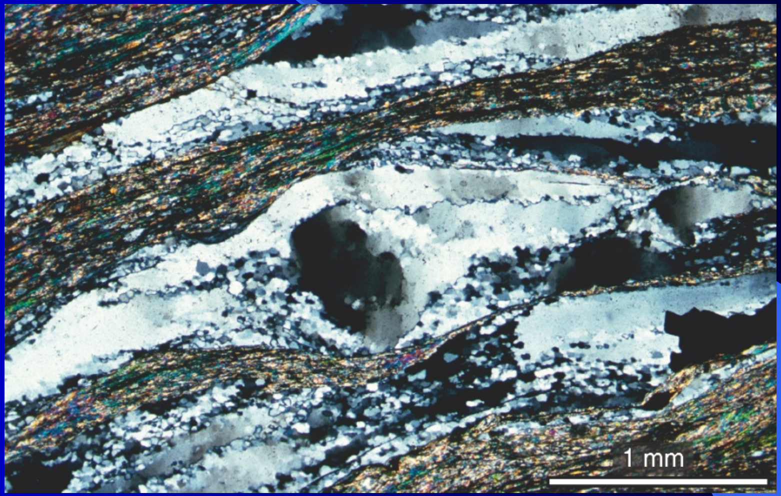
Transition from brittle to plastic behavior redux.



Recovery – all processes that move, cancel out and order dislocations into walls that separate portions of the original grain with slightly different crystallographic orientations.

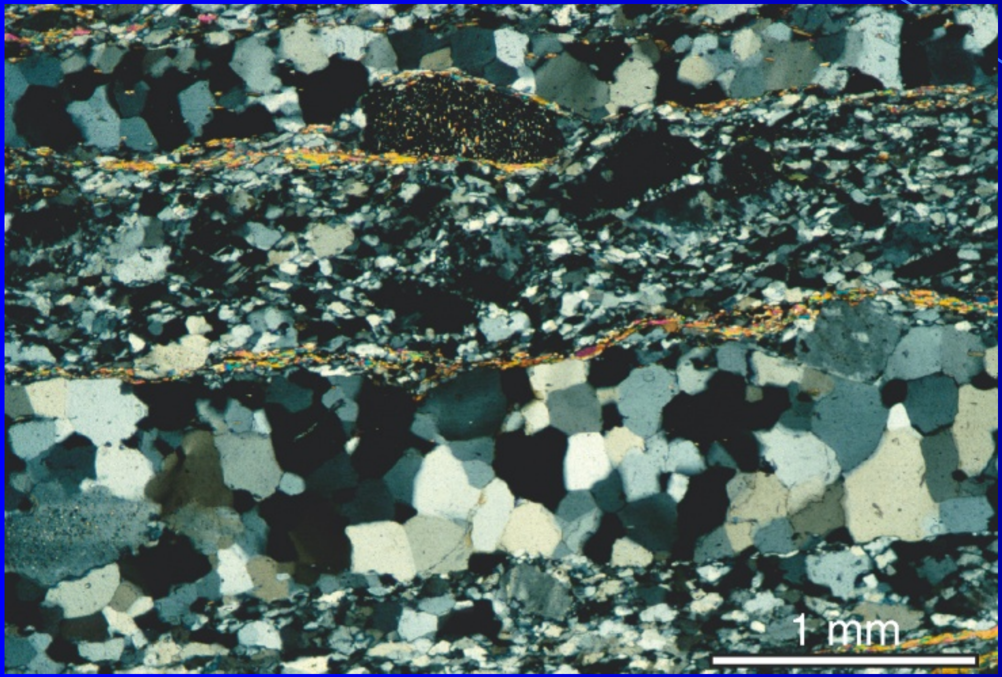


Deformation bands in quartz crystals characterized by undulose extinction.



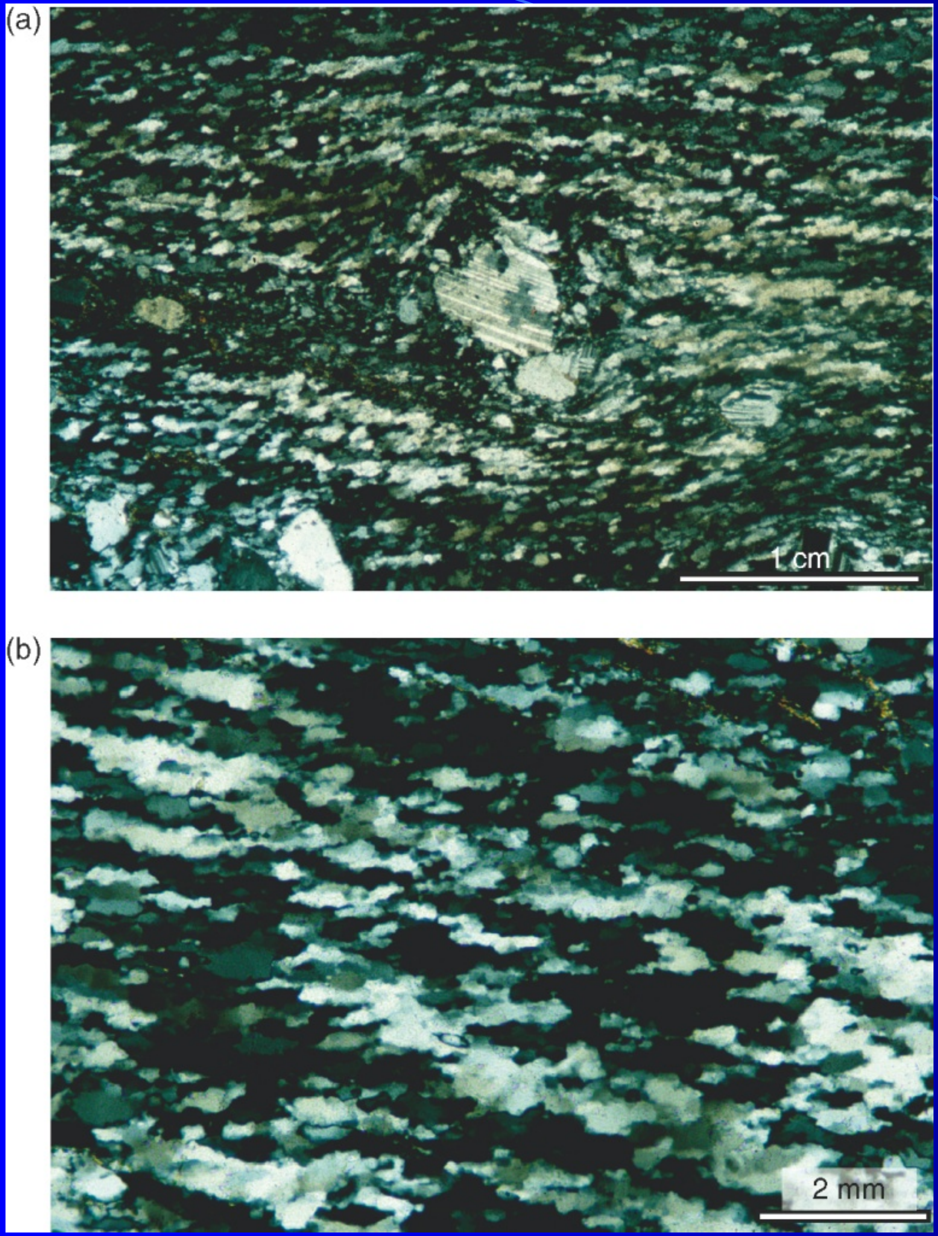
Subgrains and deformation bands in quartz. A large grain is breaking down forming a core of relict quartz with a mantle of subgrains and new grains.

Recrystallization – the process whereby strained and dislocation-rich grains are replaced by unstrained grains with few or no dislocations.



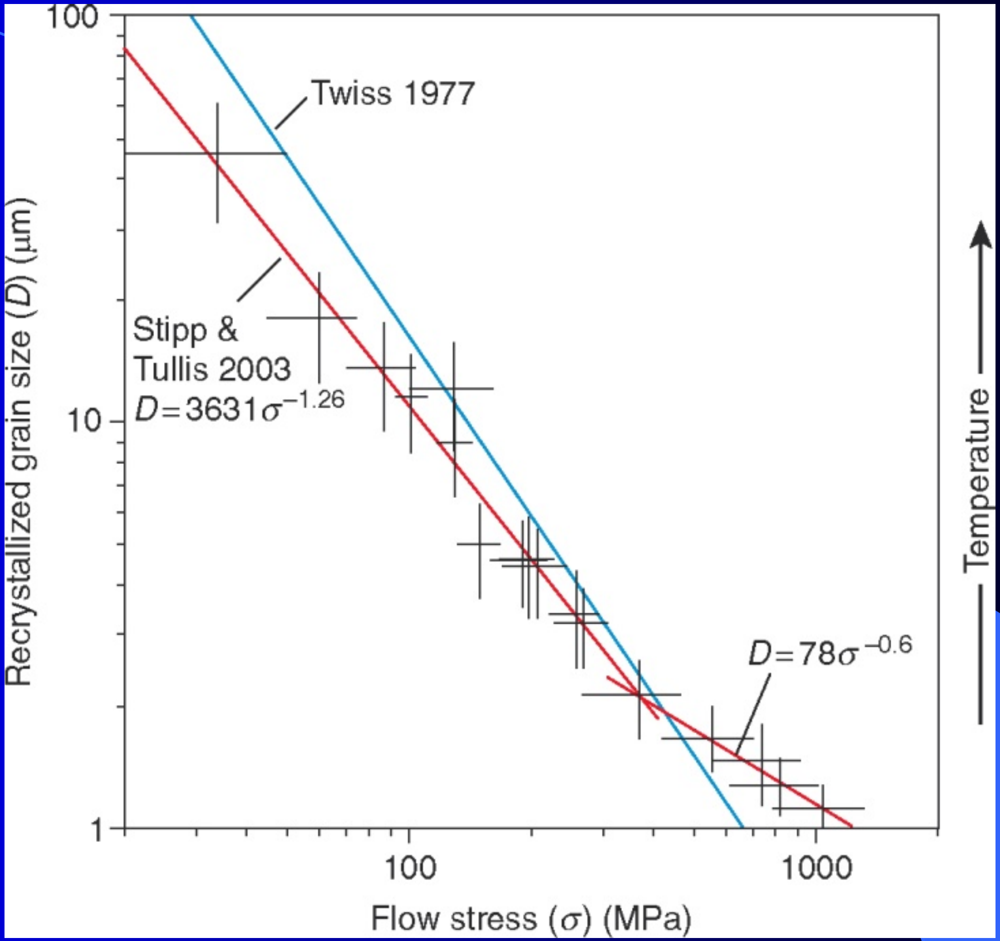
Recrystallized quartz bands in meta-rhyolite. Note the even size and strain-free nature of the recrystallized grains. Grain boundaries are more irregular than would be expected for static recrystallization and are therefore interpreted as dynamic.

Dislocation accumulation is counteracted by recrystallization which involves formation or migration of grain boundaries. A battle between stress and tranquility.



Dynamic recrystallization in a greenschist-facies shear zone. The new grains are oblique to the main foliation because they have only experienced the last part of the non-coaxial deformation. The middle grain in (a) is a feldspar porphyroblast. (b) is a close-up view of part of (a).

The size of subgrains and dynamically recrystallized grains is related to differential stress. In general the average grain size goes down with increasing differential stress and strain rate. A secondary relationship is that there is an inverse relationship between temperature and stress, i.e. at lower temperatures greater stress is required to produce the same amount of deformation.



Grain size plotted against differential stress for quartz. Two red lines are best fit curves to the data. The blue line is a theoretically estimated curve.