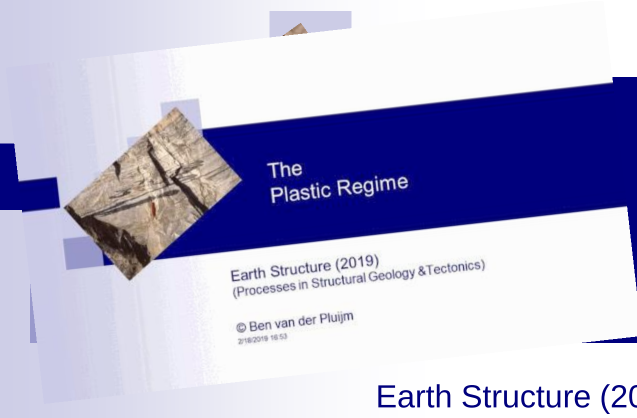


The Plastic Regime

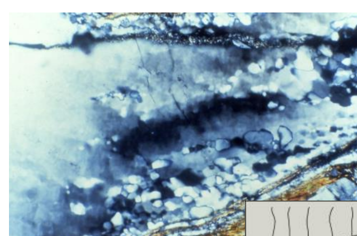
Earth Structure (2019)
(Processes in Structural Geology &Tectonics)

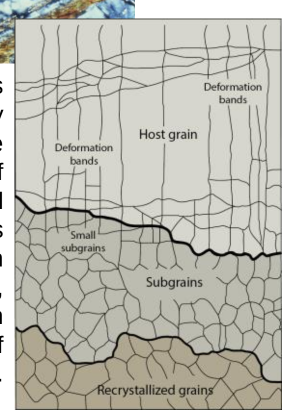
2/28/2019 09:30

Rock Stories: Mineral Deformation

Deformed rocks are aggregates of deformed minerals. As temperature increases with depth in Earth, minerals progressively deform by crystal plastic processes, like dislocation creep and solid diffusion, instead of by fracturing.

Crystal plasticity produces characteristic microstructures in minerals that reflect the temperature and stress conditions of deformation. Often, deformed minerals are replaced by new, finer-grained ("recrystallized") grains in solid-solid processes. For example, quartz and feldspar in deformed deeper crustal rocks or olivine in deformed mantle rock.



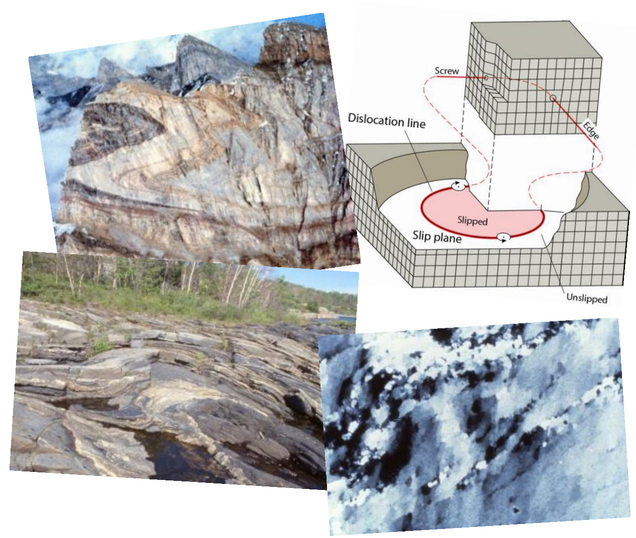


Recrystallized grains at a grain boundary form by progressive misorientation of subgrains. Internal host grain shows weakest deformation (undulose extinction), illustrated in quartzite. Width of view is ~4mm.

We Discuss …

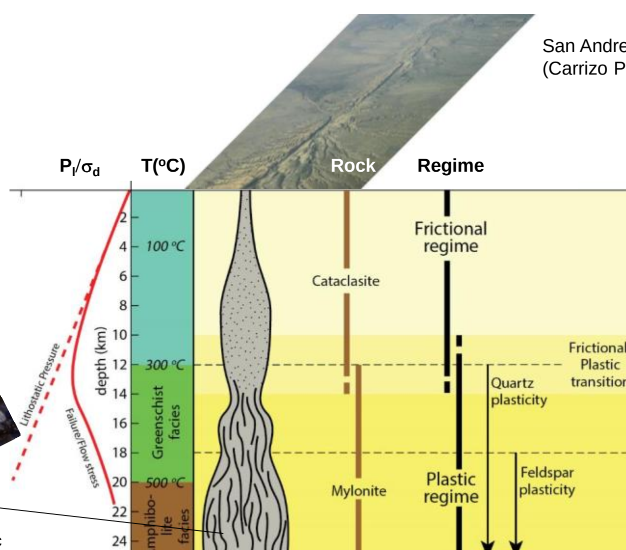
The Plastic Regime

- Strain rate
- Viscosity
- Crystal defects
  - Point defects
  - Line defects (dislocations)
- Crystal plasticity
- Dislocation creep
  - Glide (=> strain)
  - Climb (=> strain rate)
- Microstructures
  - Twinning (~low T_h)
  - Recovery (~mid T_h)
  - Recrystallization (~med-high T_h)
- Diffusional processes and microstructures (~high T_h)
- Deformation mechanism maps
- Frictional/Plastic v Brittle/Ductile: Confusing terminology?



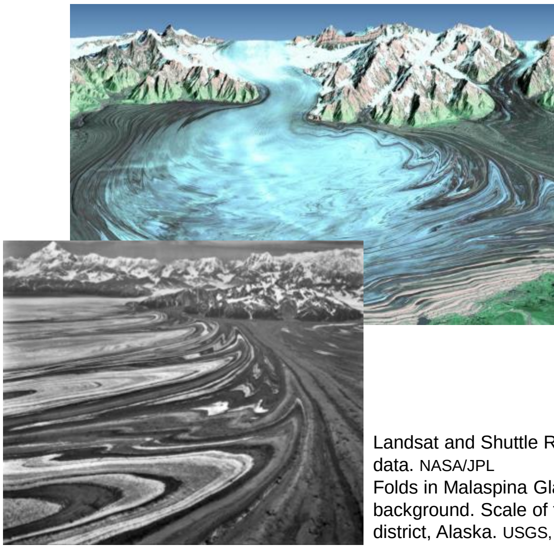
Generalized Fault Model, Conditions and Deformation Regimes

San Andreas Fault (Carrizo Plain, CA)



Parry Sound mylonitic shear zone (Grenville; On. Canada)

Plastic Deformation or Flow - Ice



Landsat and Shuttle Radar Topography Mission data. NASA/JPL
Folds in Malaspina Glacier; St. Elias Mountains in background. Scale of folding is in miles. Yakutat district, Alaska. USGS, August 25, 1969

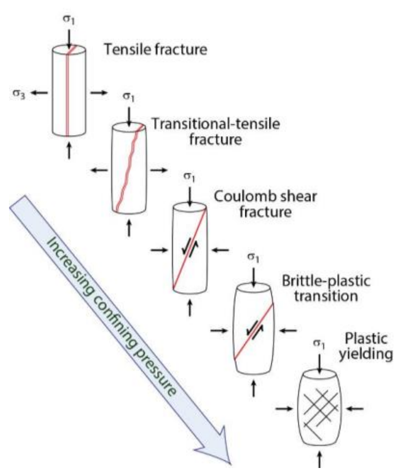
Frictional Regime vs. Plastic Regime

Frictional regime where deformation is localized and involves fractures.

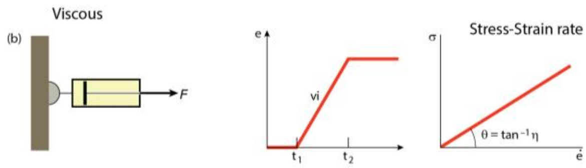
- normal stress and pressure dependent
- temperature and strain insensitive
- shear stress is function of normal stress

Plastic regime where deformation is distributed and involves crystal flow.

- normal stress and pressure insensitive
- temperature and strain dependent
- shear stress is function of temperature and strain rate



Strain with Time: Strain Rate



Strain rate (ė): time interval it takes to accumulate a certain amount of elongation: $\dot{e}$ = **e**/t = $\delta l/l_o$. 1/t; unit is 1/time (s^{-1})

Shear strain rate: $\dot{\gamma} = 2\dot{e}$

Time interval for 30% strain	$\dot{e}$
1 day (86.4 × 10^3 s)	3.5 × 10^{-6}/s
1 year (3.15 × 10^7 s)	9.5 × 10^{-9}/s
1 m.y. (3.15 × 10^{13} s)	9.5 × 10^{-15}/s

Example (SAF):
810km strike-slip fault moving 350 km in 10 m.y. (~35 mm/y):

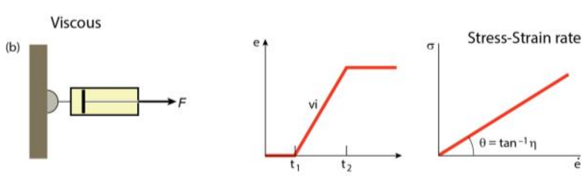
ė = (350/810)/(31.5x10^{13}) = 1.3x10^{-15}/s (1.3E-15/s)

(this assumes continues fault displacement, not movement pulses)

Note: Fingernail 1cm *growth* rate is not strain rate:

1/1.5/3.15E7 = 2E^{-8}/s

Viscosity



Viscous property ("stickiness"): permanent strain (e.g., flowing water, ice, rocks):

σ = η . ė

η (eta) is viscosity; unit is Pa.s

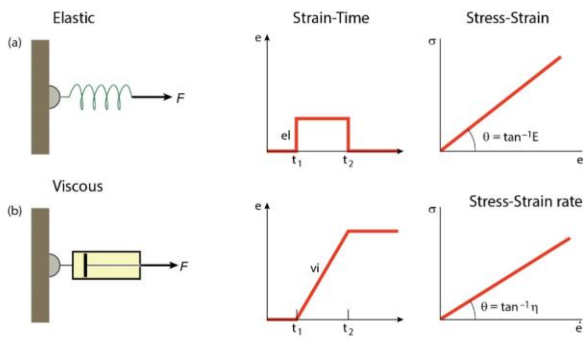
ė is strain rate (= **e**/t); unit is 1/sec

So, viscosity is time-dependent and permanent (unlike elasticity, which is instantaneous and recoverable)

TABLE 5.5	REPRESENTATIVE VISCOSITIES (IN Pa · s)
Air	10^{-5}
Water	10^{-3}
Olive oil	10^{-1}
Honey	4
Glycerin	83
Lava	10–10^4
Asphalt	10^5
Pitch	10^9
Ice	10^{12}
Glass	10^{14}
Rock salt	10^{17}
Sandstone slab	10^{18}
Asthenosphere (upper mantle)	10^{20}–10^{21}
Lower mantle	10^{21}–10^{22}

From several sources, including Turcotte and Schubert (1982).

Linear Rheologic Models



Elastic behavior
rubber band
$\sigma = E \,.\, e$ ($\sigma_s = G.\, \gamma$)

Viscous behavior
Water, ice
$\sigma = \eta \,.\, \dot{e}$; $\int \sigma \, dt = \sigma.t$

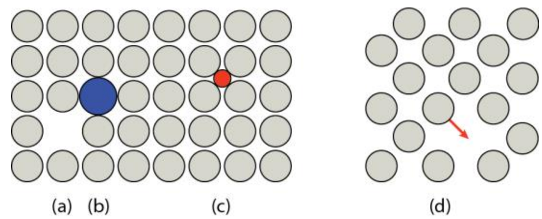
Mechanisms of Plastic Deformation

a - Dislocation creep
(e.g., ice, middle and lower crust, upper mantle)

b - Diffusional mass transfer
(e.g., melts, lower crust, mantle)

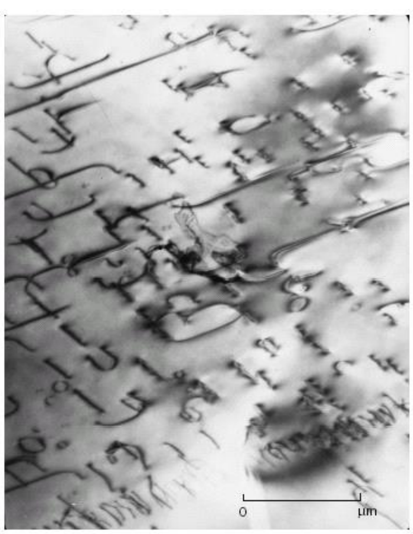
Nature's Imperfections: Crystal defects

Types of Defects:
- Point defects
- Line defects (dislocations)
- Planar defects (stacking faults)



Point defects:
a) vacancy,
b) substitutional impurity,
c) interstitial impurity,
d) vacancy migration.

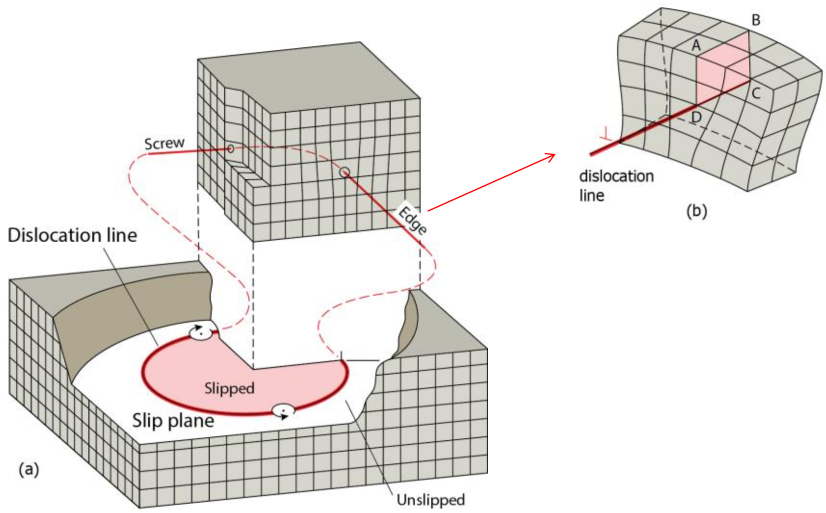
Line defects: Dislocations



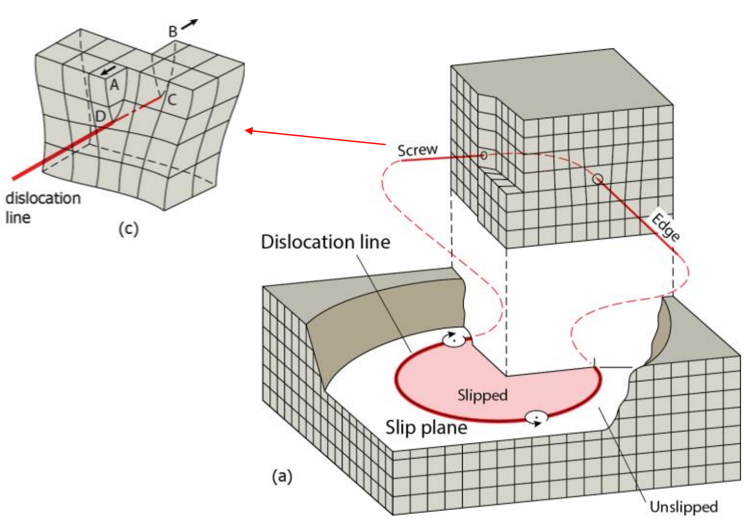
Width of view is ~200 μm

TEM (left) and imaging of dislocations by etching (above) in olivine.

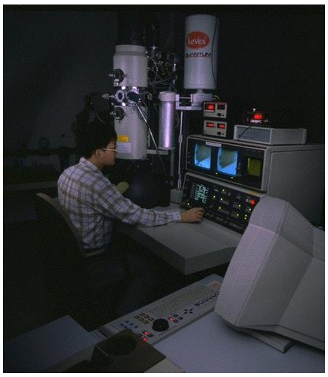
Dislocation end-member geometries: Edge dislocation



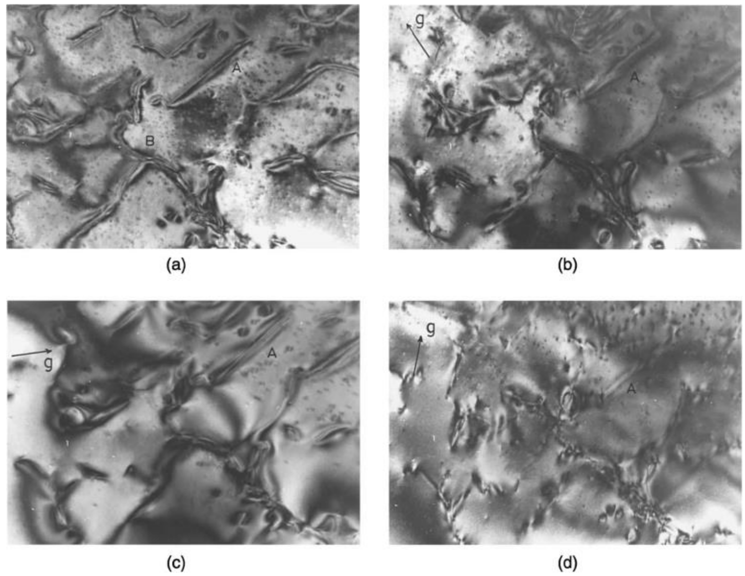
Dislocation end-member geometries: Screw dislocation



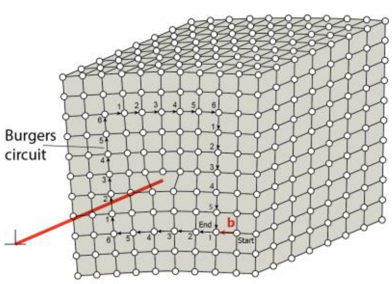
Imaging Dislocations

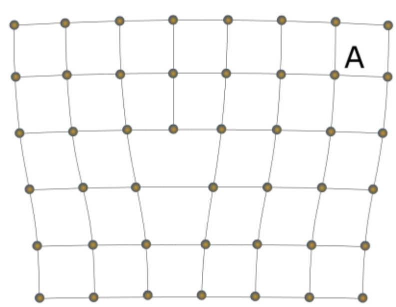


EMAL-STEM



Dislocation Line (**l**) and Burgers Vector (**b**)

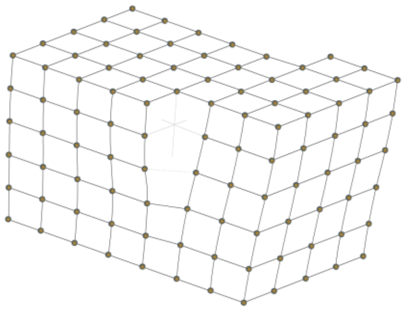


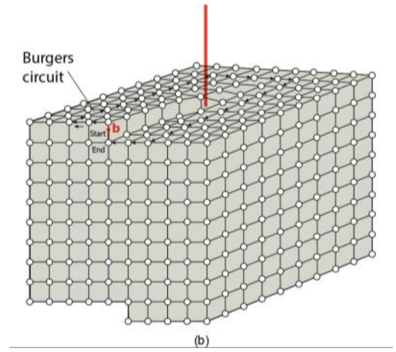


Fossen, 2016

The Burgers circuit around an edge dislocation (marked by **l**).
The closure mismatch for dislocations is Burgers vector, **b**.
In edge dislocation: **b**⊥**l**; in screw dislocation: **b**//**l**.

Dislocation Line (**l**) and Burgers Vector (**b**)

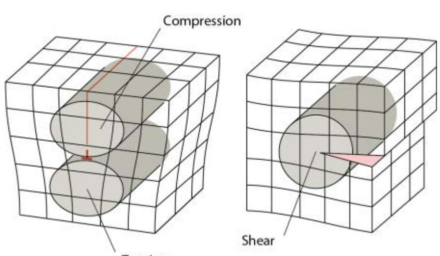


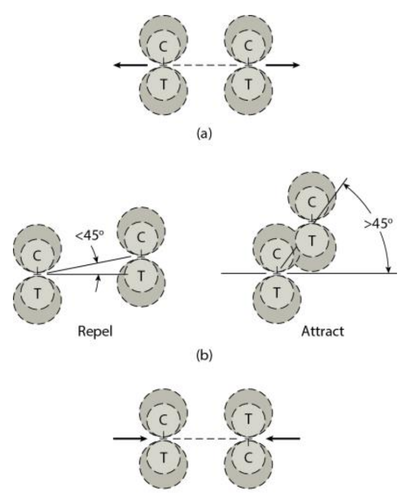


Fossen, 2016

The Burgers circuit in a screw dislocation.
The closure mismatch for dislocations is Burgers vector, **b**.
In edge dislocation: **b**⊥**l**; in screw dislocation: **b**//**l**.

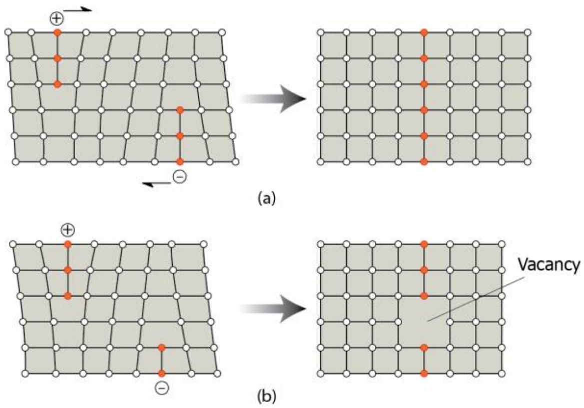
Stress Field and Interactions among Dislocations

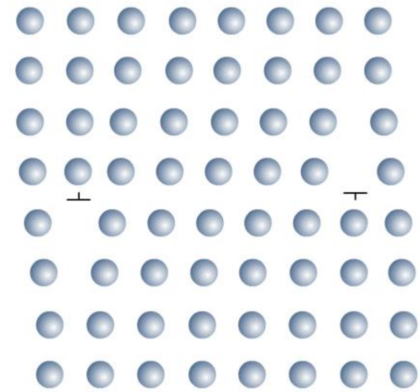




Elastic stress ≈ G . b/r
G = shear modulus = σ_s/γ
b = Burgers vector
r = distance

Dislocation Glide (cnt.)

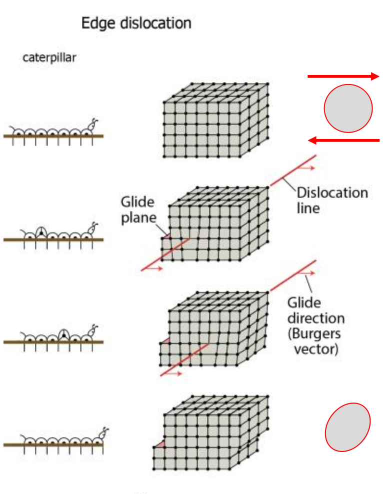


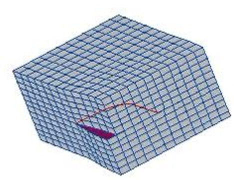


Fossen, 2016

Glide lowers distortional energy, but not necessarily toward perfect lattice.

Dislocation Glide

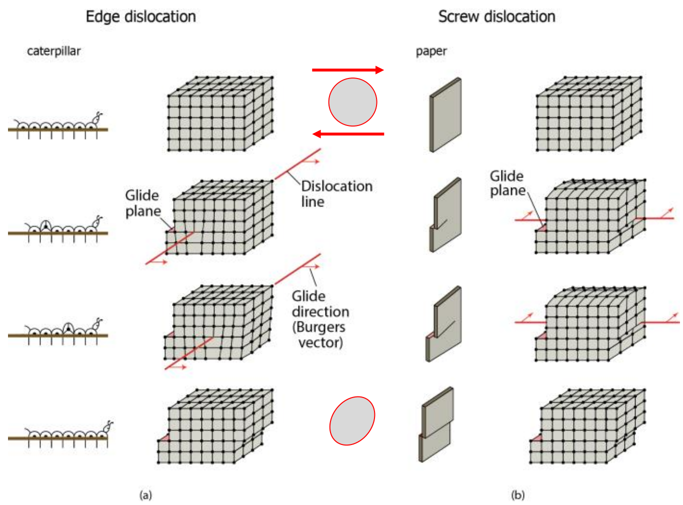


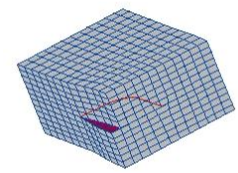


Russ, 1997

- Driving energy for movement is lattice distortion.
- Low-T plasticity, as it requires breaking a few bonds.
- Dislocation glide is *strain producing* mechanism.

Dislocation Glide





Russ, 1997

- Driving energy for movement is lattice distortion.
- Low-T plasticity, as it requires breaking a few bonds.
- Dislocation glide is *strain producing* mechanism.

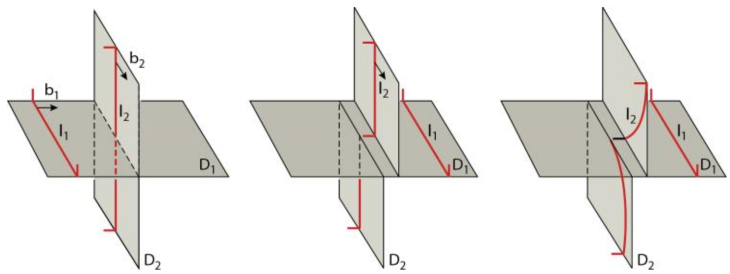
FYI: Dominant Slip System in Common Minerals

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

Jogs and Interacting Dislocations

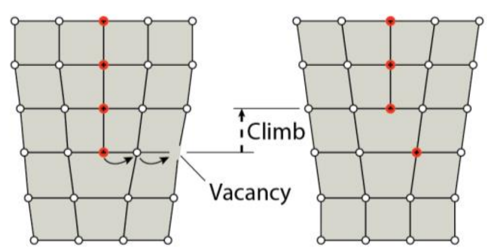


Locking (or tangled) dislocations explain property of "work hardening" or strengthening of materials (e.g., metal swords)

Dislocation Climb

Climb is medium to high temperature plasticity, as it requires breaking more atomic bonds than glide.

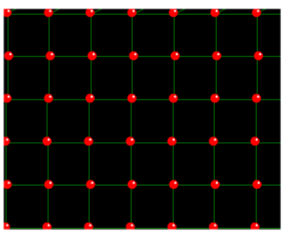
Glide is *strain producing*,
Climb (enabling glide) is *strain rate controlling*.



Origin of Dislocations

- Crystal growth
- Strain
  (Frank-Read source)

Edge dislocations | Screw dislocations | Frank Read sources | Defect tangles

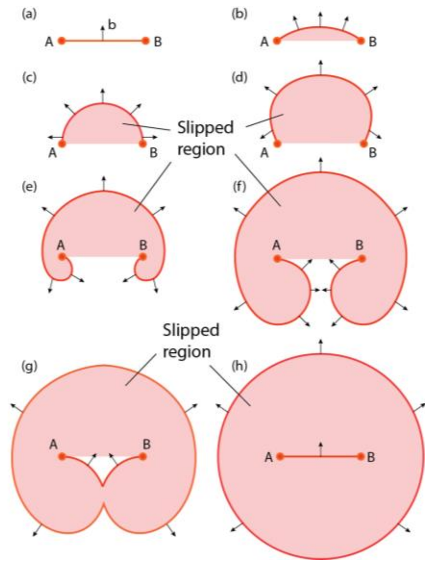


An edge dislocation bounds an extra half plane of atoms.

Edge dislocation glide is a Mode II mechanism with no loss of cohesion. Glide requires very high normalized stresses but is independent of temperature.

The vector required to close the lattice defect is called the Burger's vector. The slip vector is // to it in this case. The combination of slip vector and glide plane is called a slip system. For example, basal slip in <a> is common in quartz

DePoar, 2002



Crystal Plasticity and Microstructures

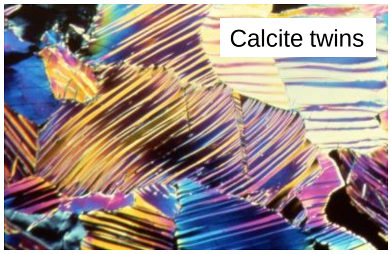
Low-temperature plasticity ($0<T_h<.3$)
- Twinning
- dislocation glide

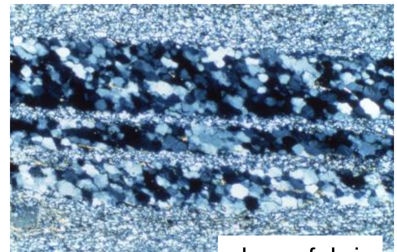
Medium-temperature plasticity ($.3<T_h<.7$)
- dislocation creep (= glide+climb)
  - recovery
  - recrystallization (dynamic and static)

High-temperature plasticity ($.7<T_h<1$)
  - superplasticity (GBSS)

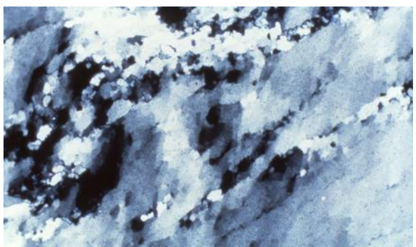
T_h is homologous temperature: $T/T_{melting}$ (in K).
For example, quartz: $T_{melting}$ is ~1975 K (~1700°C)
Qz plasticity starts at: 1975*0.3 ≈ 590K (≈ 315°C; greenschist metamorphic facies)

Crystal Plastic Deformation Microstructures

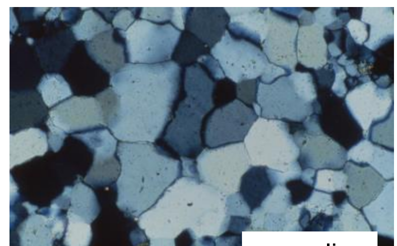




shape fabric

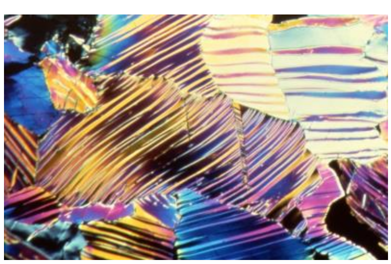


deformation bands+subgrains

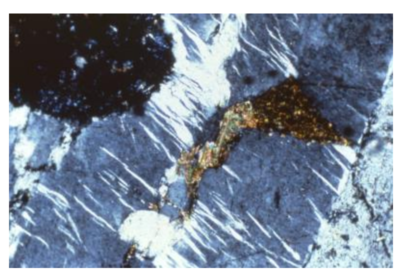


annealing

Mechanical Twinning (Low T plasticity)



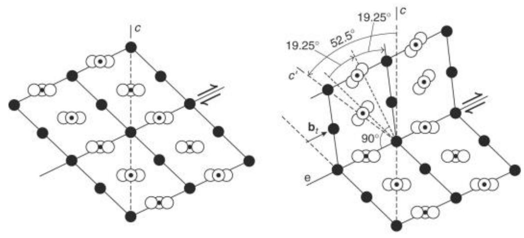
Calcite twins; experiments



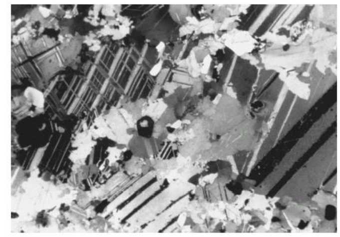
Feldspar twins (vs. unmixing lamellae)

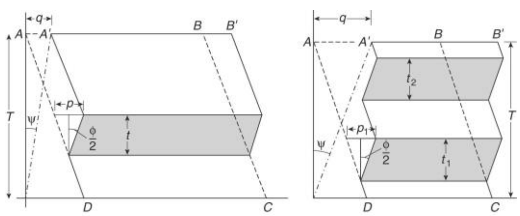
Extra: calcite twinning analysis for differential stress and strain

Extra: Mechanical Twinning in Calcite and Strain



(a) (b)





(a) (b)

Calcite strain gauge:

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

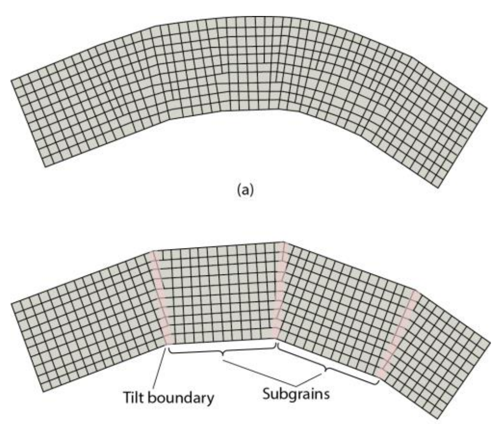
Recovery (low-medium T plasticity)

Temperature activated rearrangement of dislocations (by glide and climb) forms low-angle grain boundaries (or tilt walls), resulting in **subgrains.**

Glide is strain-producing mechanism
Climb is rate-controlling mechanisms

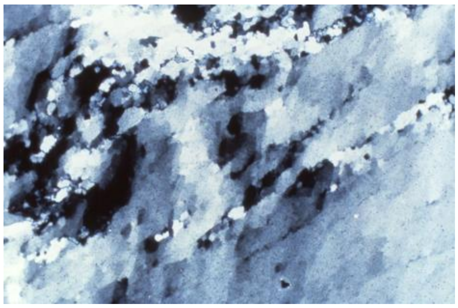
Dynamic (stressed material) vs. static (no stress) recovery.

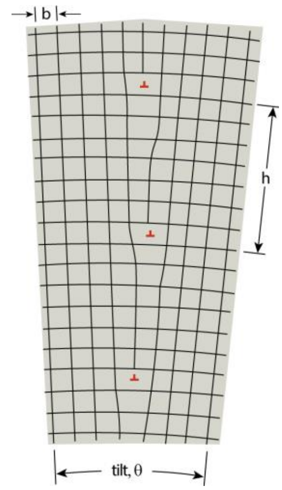
Also called Exponential Creep:
$\dot{e}$ (strain rate) ∞ exp(σ)



(a)
(b)

Subgrain (or Tilt) walls





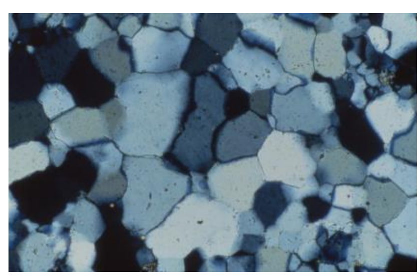
Number of dislocations in tilt wall 0.5mm long, 2nm wide (area is 1×10^{-6} mm²)

Burgers vector (**b**) of 0.5nm and angular mismatch θ of 10°

Dislocation spacing (**h**) of ~2.9nm and, thus, >170,000 (!) dislocations, representing a dislocation density in this low-angle tilt wall of 1.7×10^{11}/mm².

Recrystallization (medium T plasticity)

Dislocation creep (glide and climb) that removes internal strain energy remaining after recovery, to form high-angle grain boundaries (>10º angular mismatch)



Characteristics:

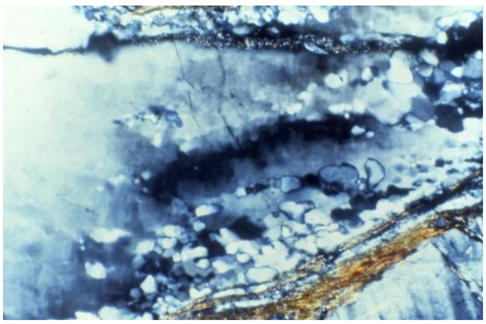
- strain-free grains (low internal strain energy)
- straight grain boundaries (low grain-boundary energy)
- 120º triple points ("foam texture")

Dynamic (stressed material) vs. static (no stress) recrystallization

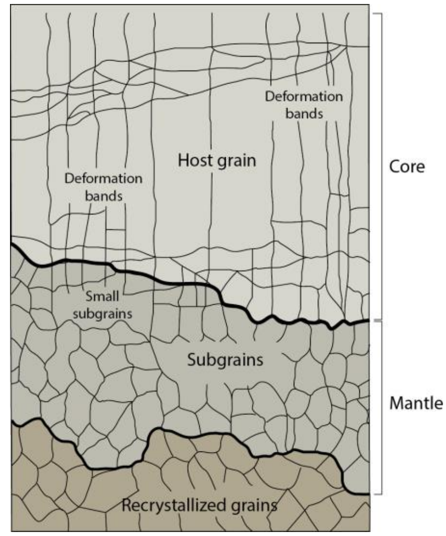
Power law creep: $\dot{e}$ (strain rate) $\propto \sigma^n$

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

Core-Mantle Microstructure



Core-mantle structure in Qtz



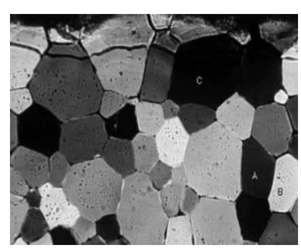
Dynamic Recrystallization vs. Static Recrystallization

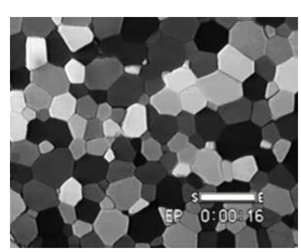
Dynamic recrystallization:

- Relatively small grain size (see mylonites)
- Straight grain boundaries
- Fine "foam" texture
- Strain (or work) softening (cf. dislocation tangles and strain hardening)

Static recrystallization ("annealing"):

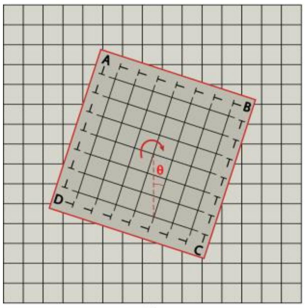
- Relatively large grain size
- Straight grain boundaries
- Coarse "foam" texture





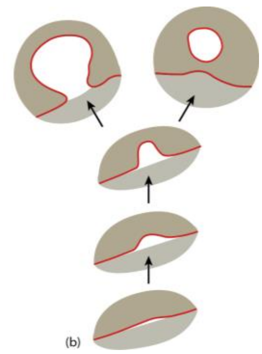
OCP experiments; W. Means

Recrystallization Mechanisms



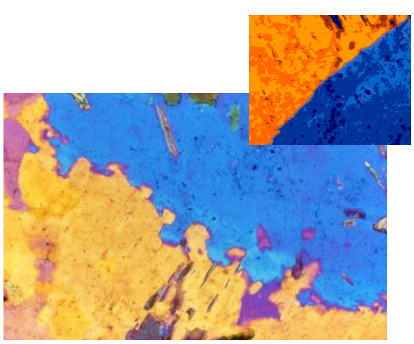
(a)

- Progressive subgrain misorientation (or subgrain rotation): **Rotation recrystallization** (a)

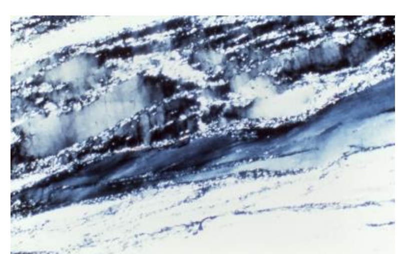

(b)

- Grain boundary bulging: lower energy grain moving into higher energy grain because of high dislocation density in high-energy grain: **Migration recrystallization** (b)
- Subgrain coalescense

Migration Recrystallization



grain boundary bulging in Feldspar



Grain boundary migration recrystallization in Quartz

OCP video

Stress Analysis: Paleopiezometry

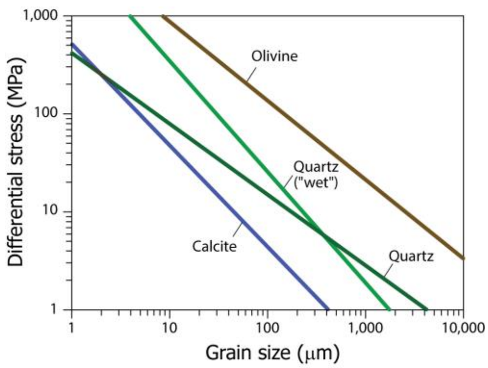


TABLE 9.4 EMPIRICALLY DERIVED PARAMETERS FOR RECRYSTALLIZED GRAIN SIZE–DIFFERENTIAL STRESS RELATIONSHIPS

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: $\boldsymbol{\sigma_d = A.d^{-i}}$

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

d is grain size in micrometers (μm).

E.g., mantle olivine grain size mm-cm, meaning differential stress is 3-20 MPa. Low σ_D!

Mechanisms of Plastic Deformation

a - Dislocation creep

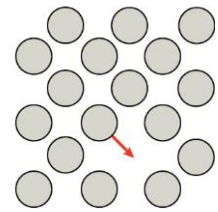
(e,g., ice, middle and lower crust, upper mantle)

b - Diffusional mass transfer

(e.g., melts, lower crust, mantle)

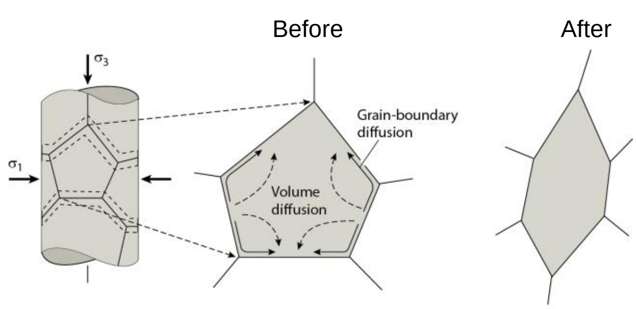
Diffusional Mass Transfer

"Dry" diffusion
- atomic vibration is function of temperature
- random jumps to vacancies in crystal
- Requires high homologous temperature
- Types:
  - Grain-boundary diffusion (Coble creep)
  - Volume diffusion (Nabarro-Herring creep)


(d)

"Wet" diffusion (or pressure solution)
- fluid at grain boundaries is dissolution and transporting agent (static or moving fluid)
- low homologous temperature

Types of Diffusional Mass Transfer



(a) (b)

Grain-boundary diffusion (or Coble creep): $\dot{e} \sim D_b/d^2$

Volume diffusion (or Nabarro-Herring creep): $\dot{e} \sim D_v/d^3$

$\dot{e}$ is strain rate; D is diffusion coefficient; d is grain size

Note: pressure solution is fluid-assisted grain-boundary diffusion ("wet" diffusion) that occurs at low T (upper crust).

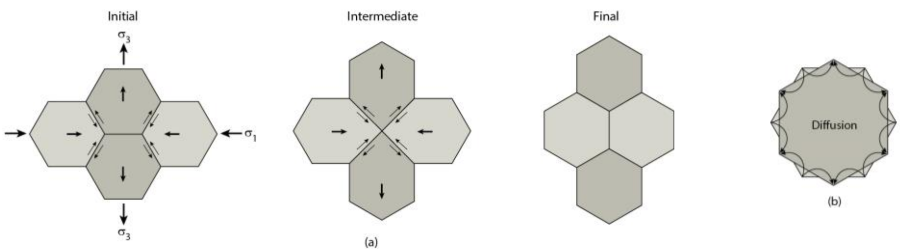
Superplasticity (high-T plasticity)

Grain-size sensitive creep that produces continuous 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

GBS in octachloropropane
Schedl and van der Pluijm, 1990



Governing Equations (Flow Laws) of Plasticity

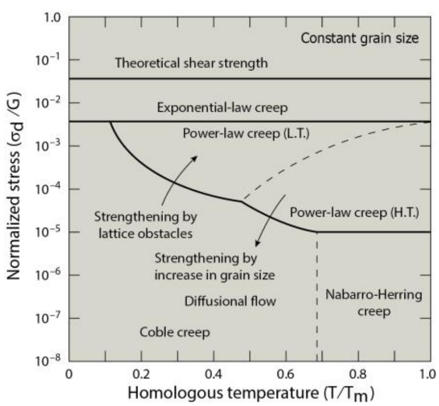
$$\dot{e} = A\ f(\sigma_d)\ .\ \exp(-E^*/RT)\ .\ f(d)$$

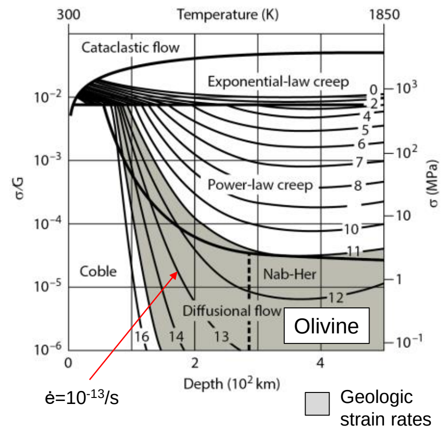
A is material constant, E* is activation energy, R is (... T is temperature (in K), $f(\sigma_d)$ is differential stress function, f(d) is grain-size functio(

The deformation mechanism that produces the highest strain rate dominates in rocks and minerals.

- **Dislocation glide** (low- to medium-T creep):
  function of stress is *exponential*: $\dot{e} = A \exp(\sigma_d) \exp(-E^*/RT)$
  Also called *exponential creep*
- **Dislocation creep (glide+climb;** medium-T creep):
  fion stress is raised to power n: $\dot{e} = A\ \sigma_d^{\ n} \exp(-E^*/RT)$
  Also called *power law creep*, with n the *stress exponent* (2<n<5)
- **Diffusional creep** (high-T plasticity):
  $\dot{e} = D_o\ d \exp(-E^*/RT)\ d^{-r}$
  Also called *grain-size sensitive creep,* with r=2-3 (note: r=1 is linear viscous creep)

Synthesis: Deformation Mechanism Maps





$\dot{e} = A\ f(\sigma_d)\ .\ exp(-E^*/RT)\ .\ f(d)$

A deformation regime map solves the various flow equations (glide, creep, diffusion) for key parameters: strain rate **$\dot{e}$**, stress **σ_d**, temperature **T**, grain size **d**.

Confusing Terminology ?: Frictional v Plastic Mechanisms

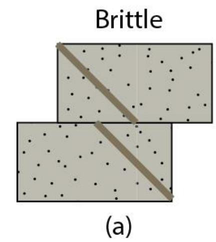
Mechanism - What processes dominate? Is material moving along a fault, representing *frictional sliding*, or, flowing, like ice glacier, by *plasticity*.

Behavior - How a material responds to stress? Does it localize deformation, like breaking of a plate, or distributed deformation, like shaping of soft clay. The terms *brittle* and *ductile* describe these behaviors, respectively.

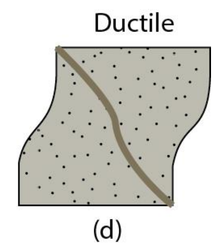
Regime - What are ambient conditions during deformation? Is pressure dominant environmental parameter, resulting in frictional processes, like upper crustal faulting and sliding. Or, is temperature dominant, promoting crystal plastic and diffusional processes, like salt in upper crust, formation of mylonites in deeper crust, flow of mantle rocks.

Confusing Terminology ?: Brittle v Ductile Behavior

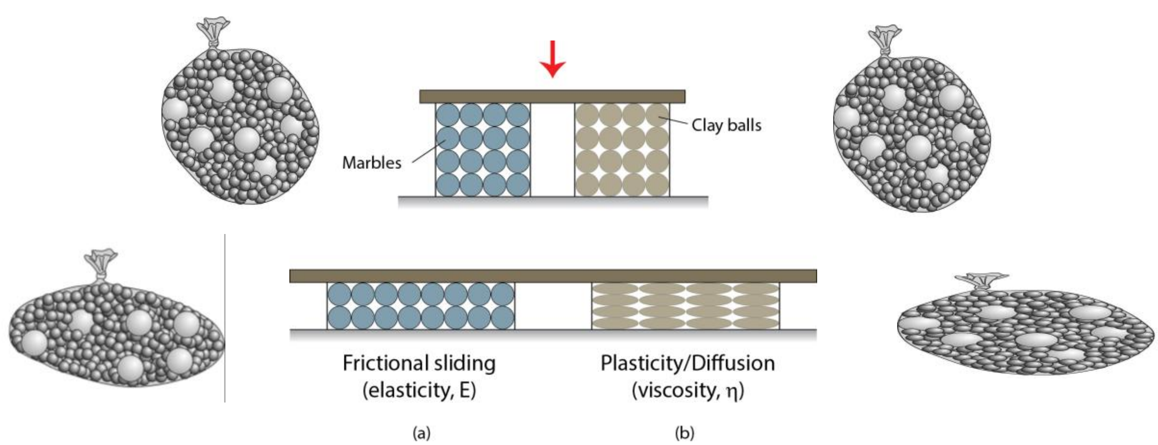
Brittle structures: response of a solid material to stress during which it loses continuity (cohesion). Brittle behavior reflects role of fracture mechanisms where **strain is localized**. It occurs when stresses exceed a critical value, after a body has undergone elastic (+/- minor viscous) strain.



Ductile structures: response of a solid material to stress such that it flows like a fluid. In a material that deformed ductilely, **strain is distributed**, meaning that strain accumulates without formation of (mesoscopic) discontinuities.
Note: Ductile behavior can involve both brittle (cataclastic flow) and plastic deformation.



Ductile Strain: Behavior v Mechanism



The word ductile is variably used, as equivalent to plasticity in geophysics, and as distributed strain, *regardless of mechanism*, in structural geology.

We use deformation *behavior* for ductility and plasticity for deformation *mechanism*.