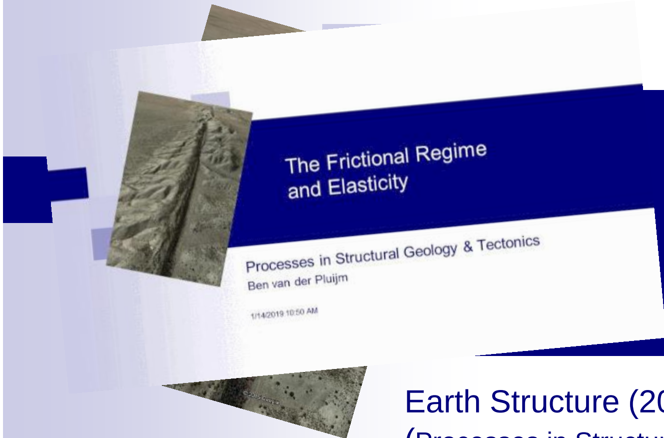

The Frictional Regime and Elasticity

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

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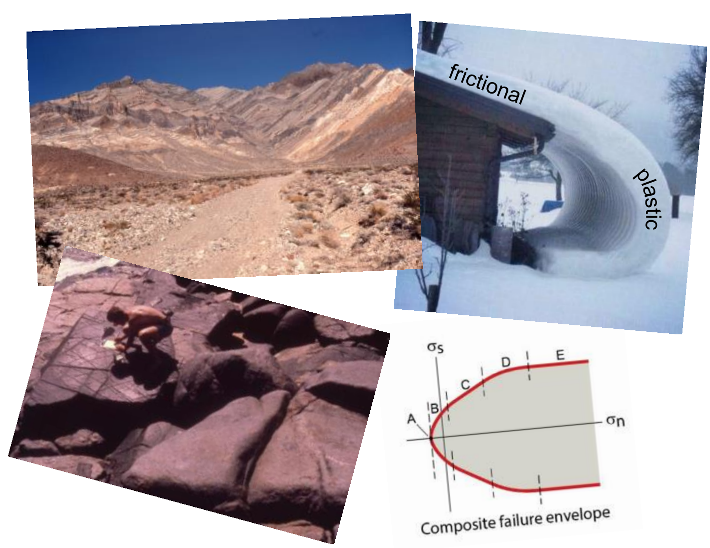
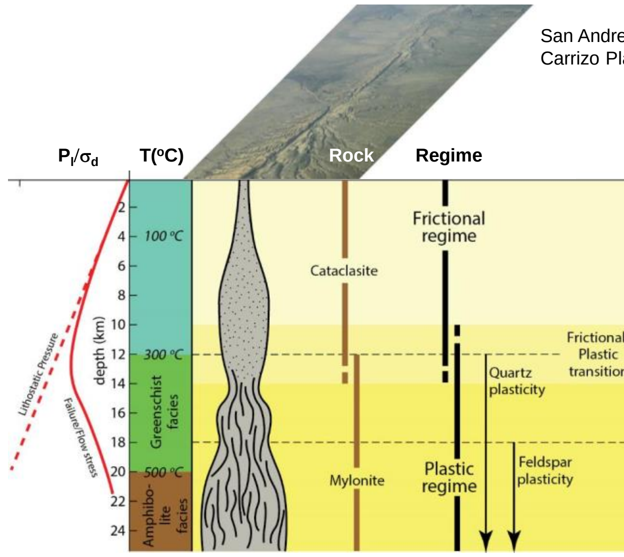
We Discuss …

The Frictional Regime and Elasticity

- Processes of Brittle Deformation
- Tensile Cracking
- Axial Experiments
- Formation of Shear Fractures
- Failure Criteria
- Faults and Stress
  - Andersonian Theory
- Frictional Sliding
  - Byerlee's Law
- Stress and Sliding
- Role of Fluids
  - Fracking
- Structure and Society
  - Earthquakes, Landslides, Fracking



Generalized Fault Model, Conditions and Deformation Regimes



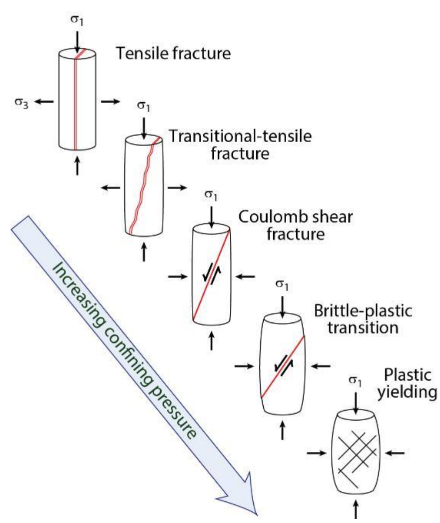
Summary: Frictional and Plastic Deformation Regimes

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

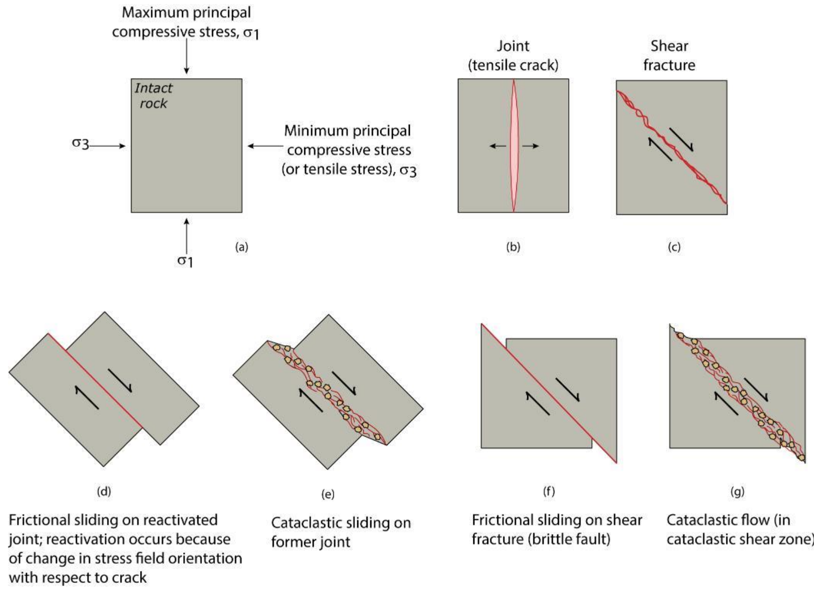
Plastic regime where deformation is distributed and involves crystal flow.

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



Brittle Deformation and Structures

Brittle deformation is permanent change in a solid material due to formation of cracks and fractures and/or due to sliding on preexisting fractures.



Categories of brittle deformation:

- Tensile cracking
- Shear failure (fault)
- Frictional sliding
- Cataclastic flow

(see next)

Categories of Brittle Deformation

- **Tensile cracking**. This type of brittle deformation involves propagation of cracks into previously unfractured material when a rock is subjected to a tensile stress. If the stress field is homogeneous, tensile cracks propagate in their own plane and are perpendicular to the least principal stress (σ_3).

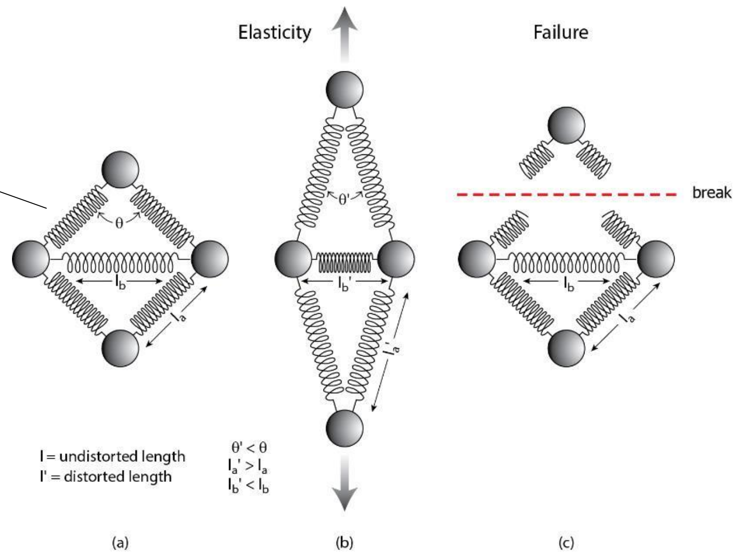
- **Shear failure**. This type of brittle deformation results in the initiation of a macroscopic shear fracture (fault) at an acute angle to the maximum principal stress when a rock is subjected to a triaxial compressive stress. Shear failure involves growth and linkage of microcracks.

- **Frictional sliding**. This process refers to the occurrence of sliding on a preexisting fracture surface, without the significant involvement of plastic deformation mechanisms.

- **Cataclastic flow**. This type of brittle deformation refers to macroscopic *ductile* (=distributed) flow as a result of grain-scale fracturing and frictional sliding distributed over a band of some width.

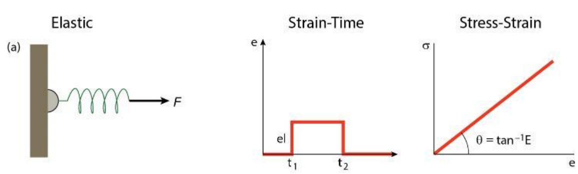
Elasticity and Failure: Atomistic View

Atomic bonds are elastic, like springs



Bonds:
a) Equilibrium
b) Stretched
c) Broken

Elasticity



Medium	E (GPa)	ν (Poisson's ratio)
Iron	196	0.29
Rubber	0.01–0.1	almost 0.5
Quartz	72	0.16
Salt	40	~0.38
Diamond	1050–1200	0.2
Limestone	80	0.15–0.3
Sandstone	10–20	0.21–0.38
Shale	5–70	0.03–0.4
Gabbro	50–100	0.2–0.4
Granite	~50	0.1–0.25
Amphibolite	50–110	0.1–0.33
Marble	50–70	0.06–0.25

Elastic Behavior:

$\sigma = E \cdot \mathbf{e}$

E = Young's Modulus

e = strain = $(l-l_o)/l_o$

(rubber band)

$\sigma_s = G \cdot \gamma$

G=shear modulus (rigidity)

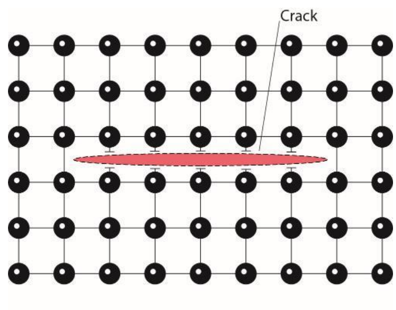
γ = shear strain

Other elastic parameters:

Bulk Modulus (K): $K = \sigma/\Delta V$;

Poisson's ratio: $\nu = e_{\text{perpendicular to } \sigma}/e_{\text{parallel to } \sigma}$

Rock Strength Paradox



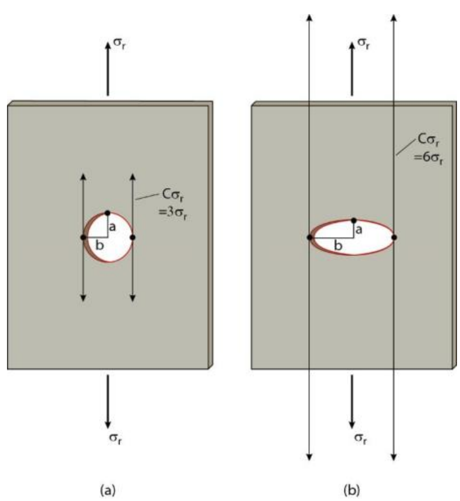
Strength Paradox:
Rocks allow only few % elastic strain (**e**) before permanent deformation (failure), which occurs at low stresses.

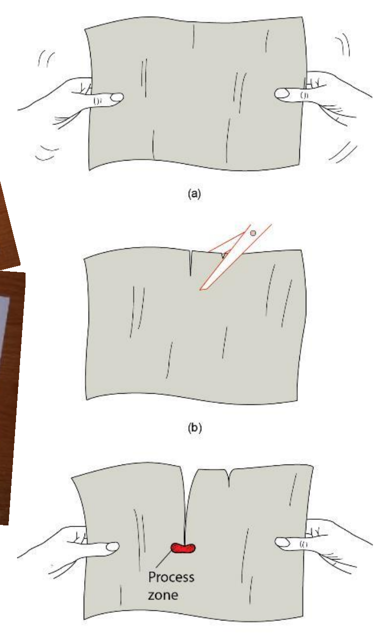
σ = E . **e**
(say, granite and **e** = 10%)

= $5x10^{10}$. 0.1 = $5x10^{9}$ Pa
= $5x10^{3}$ MPa

Thus, theoretical strength of rock is 1000's MPa, but observed tensile strength of rocks is only 10's MPa.

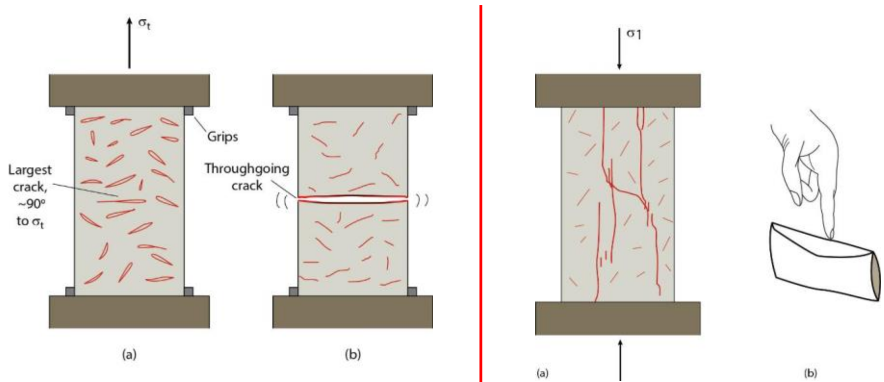
Tensile Failure and Stress Concentration





Remote v. local stress: stress concentration, C, is: (2b/a) +1
Crack 1 x .02 μm: C = 100 !
C greater as crack grows longer.

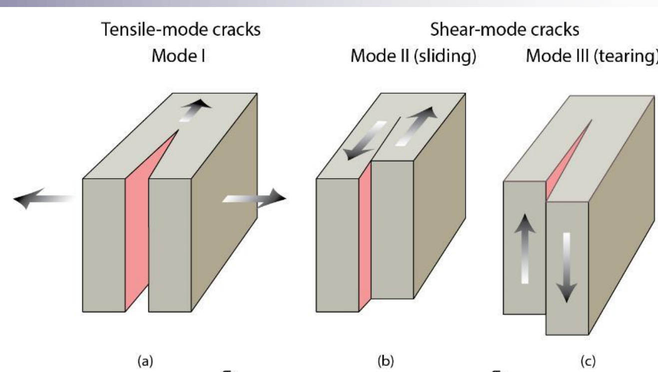
Axial Experiments: Griffith Cracks



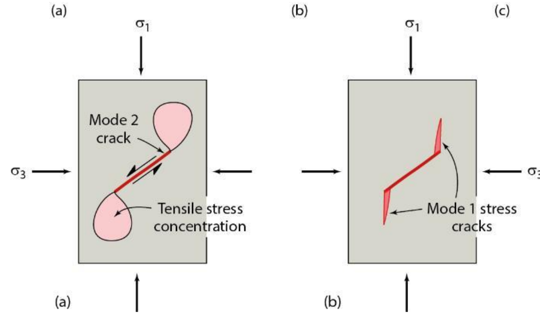
Extension **Compression**

Effect of preexisting (or Griffith) cracks: preferred activation, then longest cracks grow because of stress concentration.

Crack Modes



Tensile cracks (Mode I)
Shear cracks (Mode II and III)



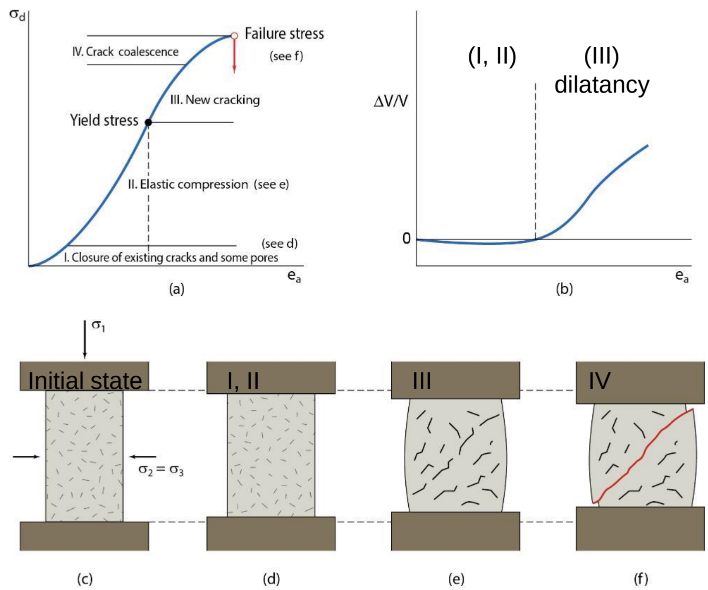
Shear-mode cracks are **not** faults. When they propagate, they rotate into Mode I orientation ("wing cracks")

Formation of Shear Fractures

Shear fracture (or fault) is surface across which rock loses continuity when shear stress parallel to surface is sufficiently large.

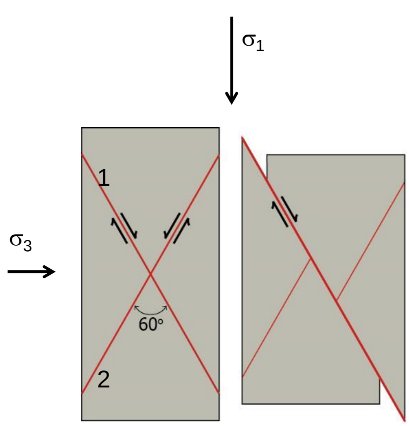
Faults are *not* same as large tensile cracks, as their eventual orientation shows.

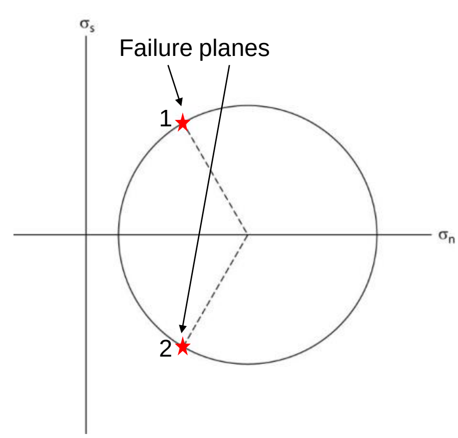
Differential stress at failure is called **failure stress** (σ_f).



Shear Failure Criteria 1 – Coulomb Criterion

Two failure surfaces at ~30º to σ_1
(= ~60º to σ_3).





Shear Failure Criteria 1 – Coulomb Criterion

Coulomb failure criterion:

$\sigma_s = C + \mu\sigma_n$

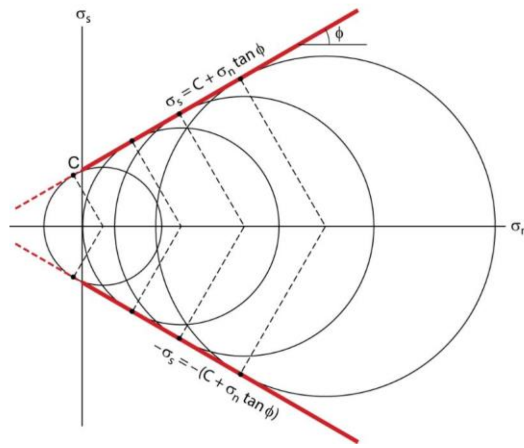
σ_s is shear stress parallel to fracture surface at failure

C is **cohesion**, a constant that specifies shear stress necessary to cause failure if normal stress across potential fracture plane equals zero

σ_n is normal stress across shear fracture at instant of failure

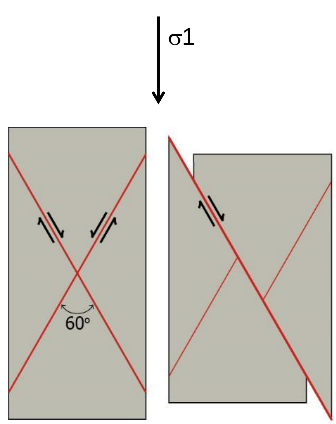
μ is a constant: **coefficient of internal friction**

Failure surfaces (two!) at ~30º to σ_1 (= ~60º to σ_3. Yet, σ_s is maximum at 45º. Why?

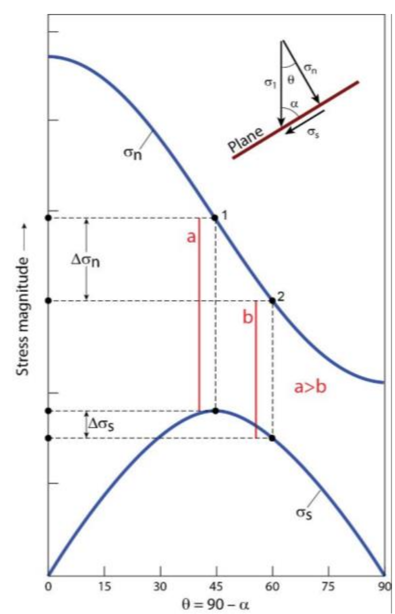


Why 30º instead of 45º Fracture Angle with σ_1?

Fracture surfaces at ~30º to σ1 and ~60º to σ_3. Yet, σ_s is maximum at 45º.



(a) (b)



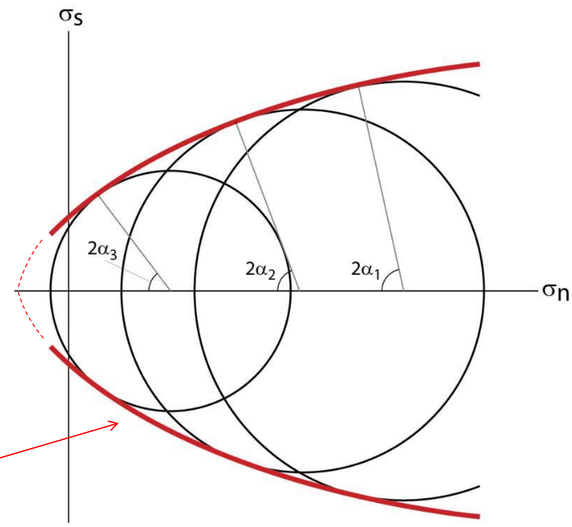
Shear Failure Criteria 2 – Tensile Stress

Parabolic failure envelope: steeper near tensile field and shallower at high σ_n (Mohr criterion)

Fractures toward 90º in tension, fractures around 30º in compression, relative to σ_1

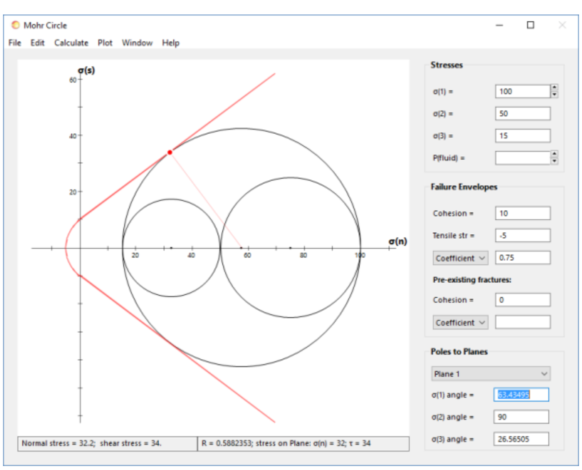
Combined:

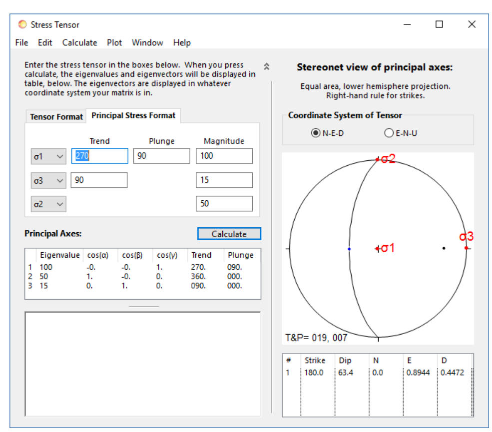
Mohr-Coulomb failure criterion



failure envelope

MohrPlotter





R Allmendinger

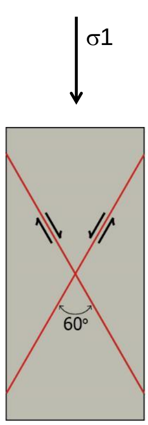
Fault Types

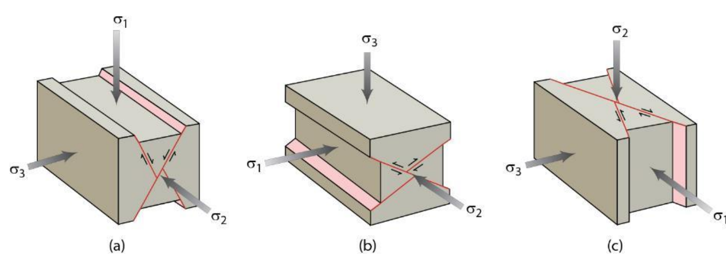
Normal Fault

Lateral-slip Fault
(Strike-slip Fault)

Reverse Fault

Predictions from Anderson's Theory of Faulting





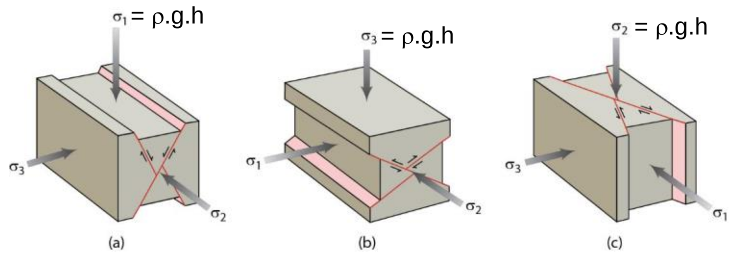
Earth solid-air contact is free surface, meaning no shear stresses, so orthogonal principal stresses predict:

- High-angle normal faults
- Low-angle reverse faults
- Lateral-slip faults

But, unexplained:

- Low-angle normal faults
- Non-conjugate fault systems

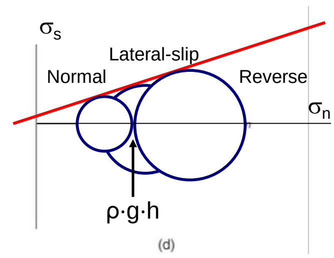
Principal Stresses and Fault Types



Normal Fault Reverse Fault Lateral-Slip Fault

Vertical ρ·g·h is σ_1, σ_2 or σ_3, so differential stress (σ_1-σ_3 = $2\sigma_s$) for faulting is increasingly greater from normal, to lateral slip to reverse faulting.

Predicts earthquake magnitude by fault type, with thrust quakes largest.



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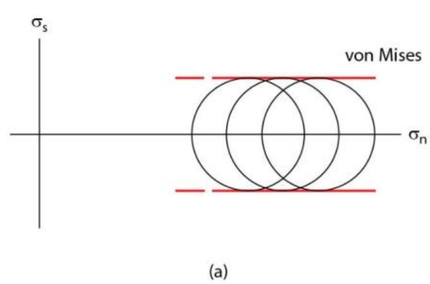
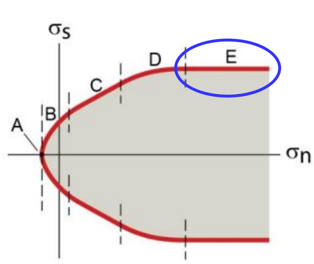
Shear Failure Criteria 3 – High Stress

At high confining stresses:
 Von Mises criterion

Plastic deformation occurs at high (normal) stress, which is shear stress independent





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

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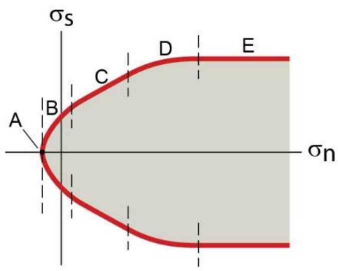
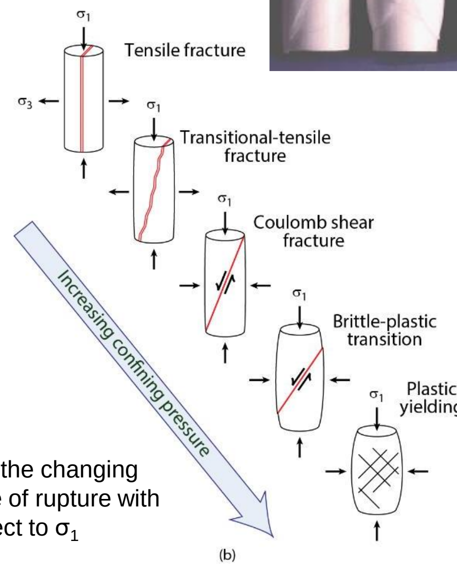
Composite failure envelope



Composite failure envelope

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

(a)



Note the changing angle of rupture with respect to σ_1

(b)

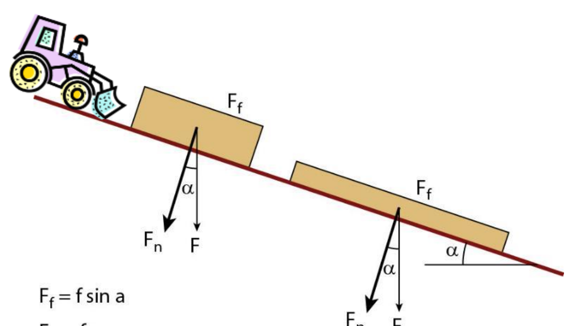
Friction: Sliding on a Surface

Frictional sliding refers to movement on a pre-existing surface when shear parallel to surface exceeds sliding resistance.

Amonton's Laws of Friction:

- Frictional force is function of normal force.
- Frictional force is independent of (apparent) area of contact.
- Frictional force is (mostly) independent of material used.

(17th C)



$F_f = f \sin a$

$F_n = f \cos a$

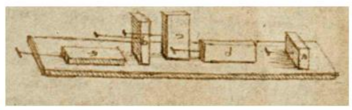
$F_f/F_n = \sin \alpha / \cos \alpha = \mu$

(15th C da Vinci experiments)

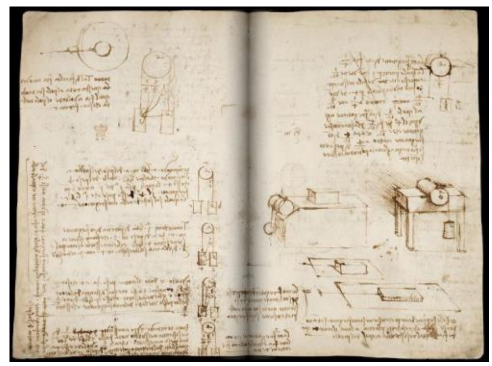
Extra: Leonardo Da Vinci and Friction

(a)

a), b) Codex Atlanticus, Biblioteca Ambrosiana, Milan (CA folio 532r ca. 1506-8)
c), d) Codex Arundel, British Library, London (Arundel folio 41r ca. 1500-05)



(b)



(d)

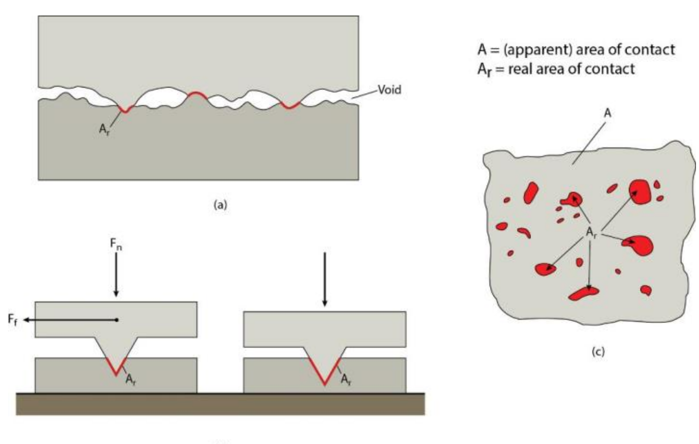
(c)

Surface Roughness (Asperities)

The bumps and irregularities (roughness) that protrude on natural surfaces are called **asperities**, which “anchor” surfaces.

Real v. Apparent
Area of Contact

Larger mass (larger F), deeper penetration

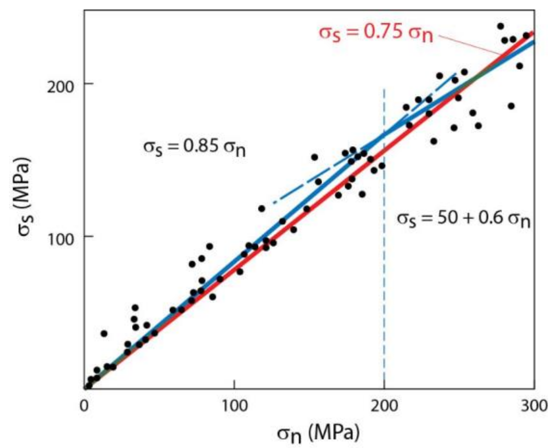


Frictional Sliding Criterion (Byerlee's Law)

σ_s / σ_n = constant = μ
= coefficient of friction

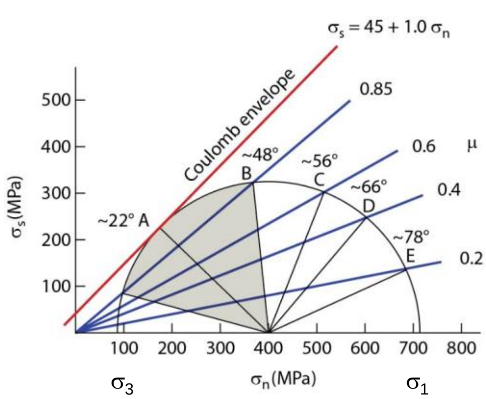
Byerlee's Law depends on σ_n.
For σ_n < 200 MPa,
best-fitting criterion is
$\sigma_s = 0.85.\sigma_n$

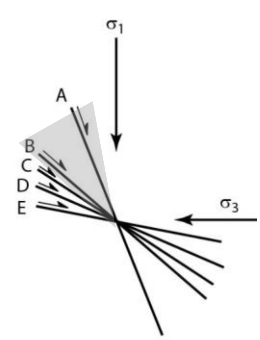
For 200 MPa < σ_n < 2000 MPa,
best-fitting criterion is
σ_s = 50 MPa + $0.6.\sigma_n$



μ = 0.6-0.85, or **~0.75** (static friction; vs. dynamic friction)

Sliding on Existing Fractures or Create New Fractures ?





Instead of new failure surface (A), sliding on existing surfaces (gray area).
Preexisting surfaces from B to E will slide with decreasing friction coefficients.
(Blair Dolomite experiment)

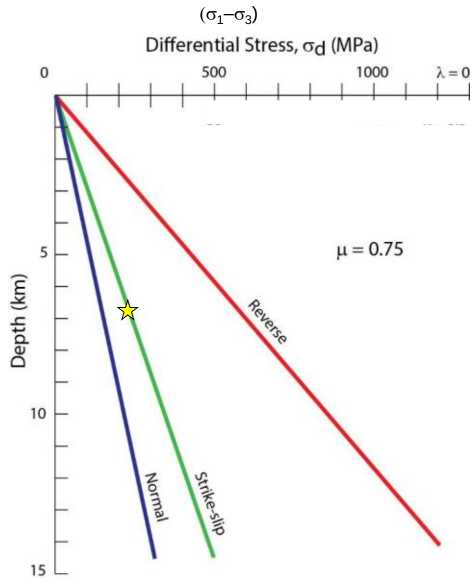
Optional: Stress Conditions for Sliding

$\mu = 0.75$

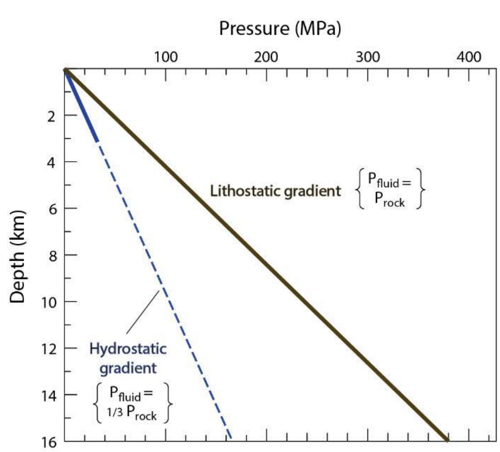
$\sigma_d \geq \beta\ (\rho \cdot g \cdot h)$

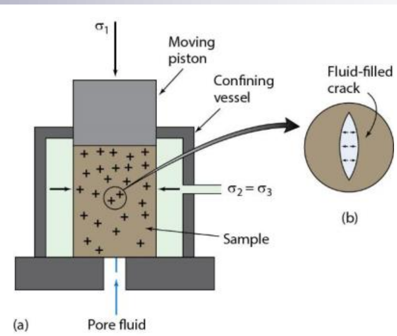
β is 3, 1.2, and 0.75 for reverse, strike-slip, and normal faulting

☆ borehole measurement, sliding on strike-slip fault, but stable on reverse fault



Fluids and Failure





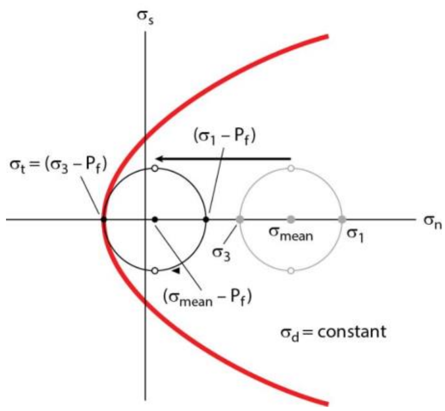
Hydrostatic (fluid) pressure

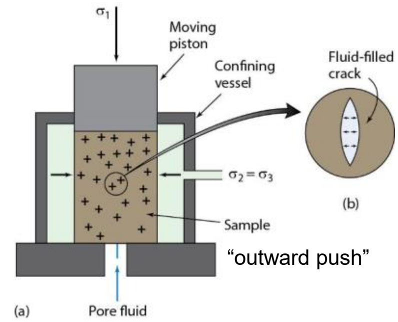
$P_f = \rho \cdot g \cdot h$, where ρ is density of water (1000 kg/m^3), g is gravitational constant (9.8 m/s^2), and h is depth.

Lithostatic (load) pressure

$P_l = \rho \cdot g \cdot h$, weight of overlying column of rock (ρ = 2500–3000 kg/m^3).

Fluid Pressure and Effective Stress





"outward push"

(e.g., hydraulic fracturing or "fracking")

$\sigma_s = C + \mu.(\sigma_n - P_f)$ [fracturing]

$\sigma_s = \mu.(\sigma_n - P_f)$ [sliding]

$(\sigma_n - P_f)$ is commonly labeled σ_n*, the effective stress.

So, $\mu_{effective} = \mu\ (1 - P_f/\sigma_n)$

$\mu_{effective} \leq \mu$

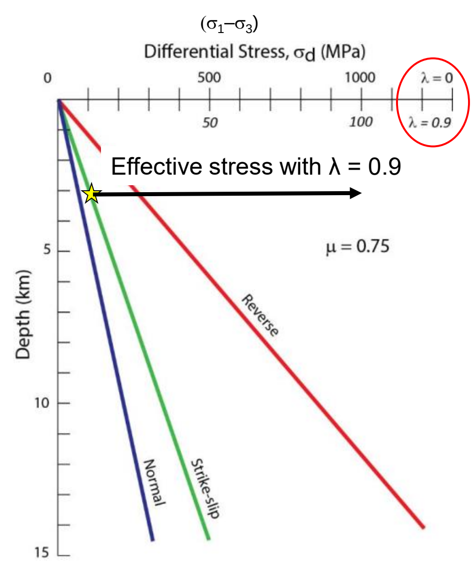
Optional: Limiting Stress Conditions for Sliding, with Pore-fluid Pressure

$\sigma_d \geq \beta\ (\rho{\cdot}g{\cdot}h)\ .\ (1 - \lambda)$
$\lambda = 0.9$ (90% of lithostatic pressure)

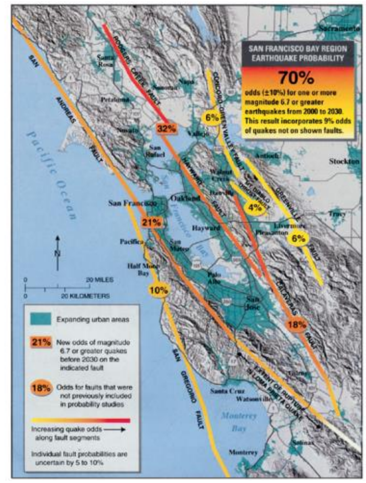
β is 3, 1.2, and 0.75 for reverse, strike-slip, and normal faulting (with $\mu = 0.75$)

$\lambda = P_f/P_l$, ratio of pore-fluid pressure and lithostatic pressure

Ranges from ~0.36 (1000/2750) for hydrostatic fluid pressure to 1 for lithostatic fluid pressure



Structure and Society: Earthquakes

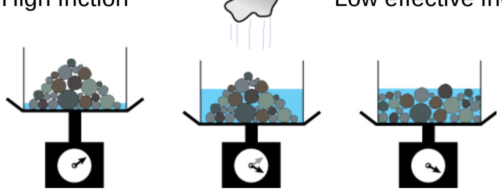


Forthcoming lecture ….

Structure and Society: Fluid-induced Landslides and Fracking

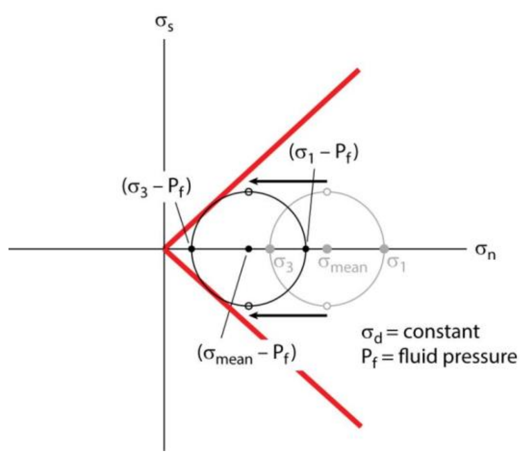
Dry and Stable
High friction

Wet and Unstable
Low effective friction



$\mu = \sigma_s / \sigma_n$

$\mu_{effective} = \mu\,(1 - P_f/\sigma_n)$

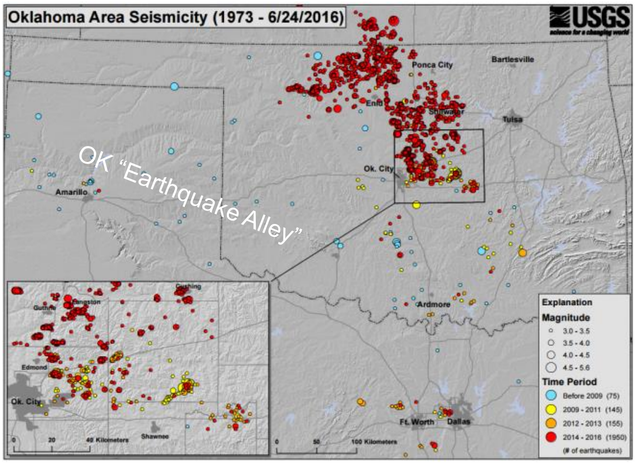


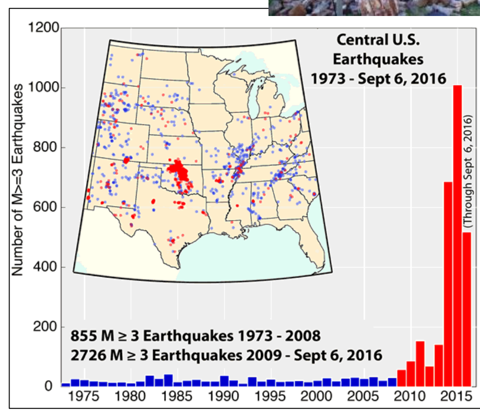
Increasing λ (= P_f/P_l) increases failure potential

1994 landslide, Mesa County, Colorado (CGS).

Structure and Society: Hydraulic Fracturing (Fracking)

Prague, OK;
M5.7, 2011 (USGS)





Biggest so far: M5.8 on 9/9/2016
(~surface atom bomb)

https://goo.gl/FIm01i