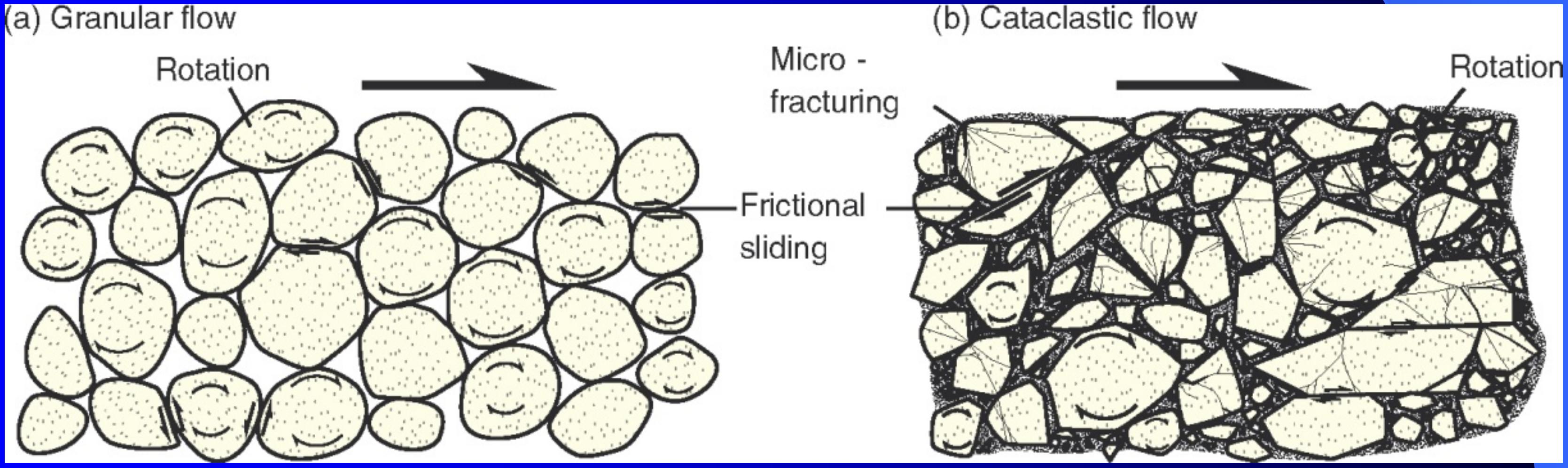
Fracture and Brittle Deformation

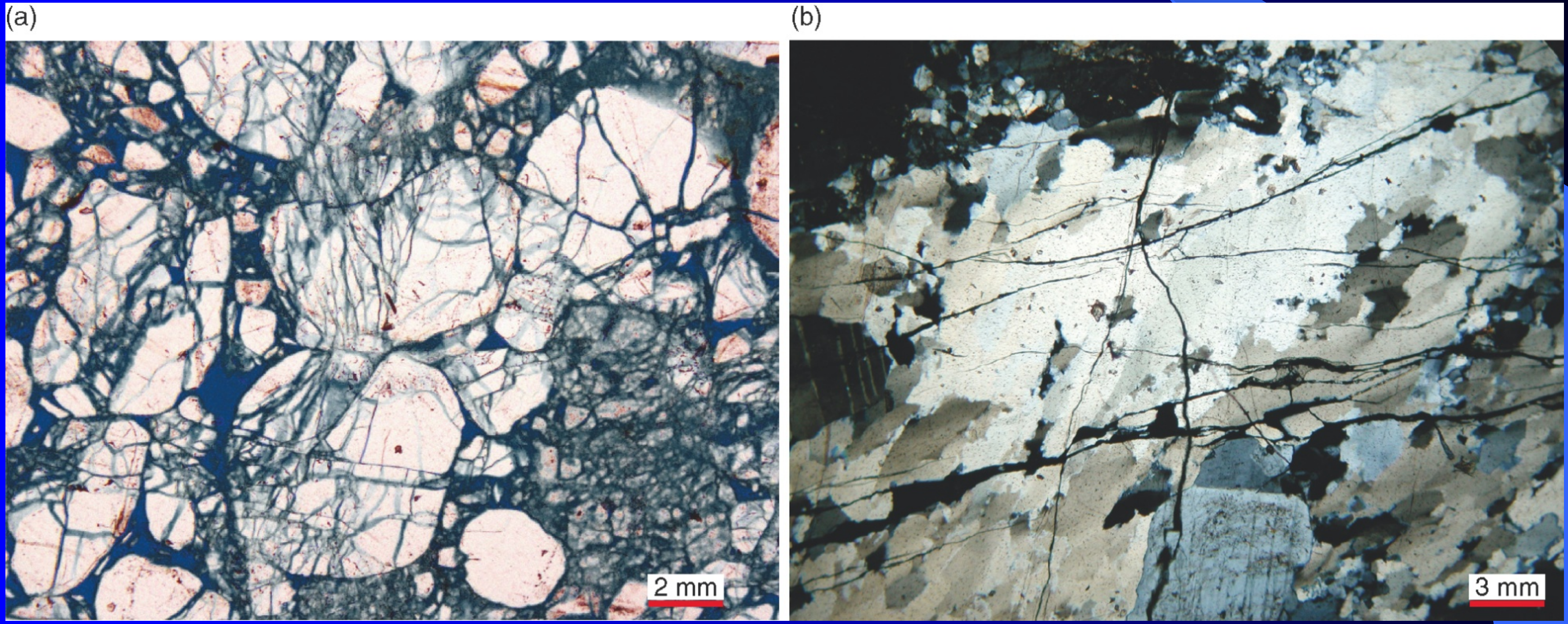
The brittle regime is where the physical conditions promote brittle deformation mechanisms such as frictional sliding along grain contacts, grain rotation and grain fracture.

Particulate flow involves grain rotation and frictional sliding between grains, while cataclastic flow also involves grain fracturing or cataclasis. Both can give rise to structures that appear ductile at the mesoscopic scale.



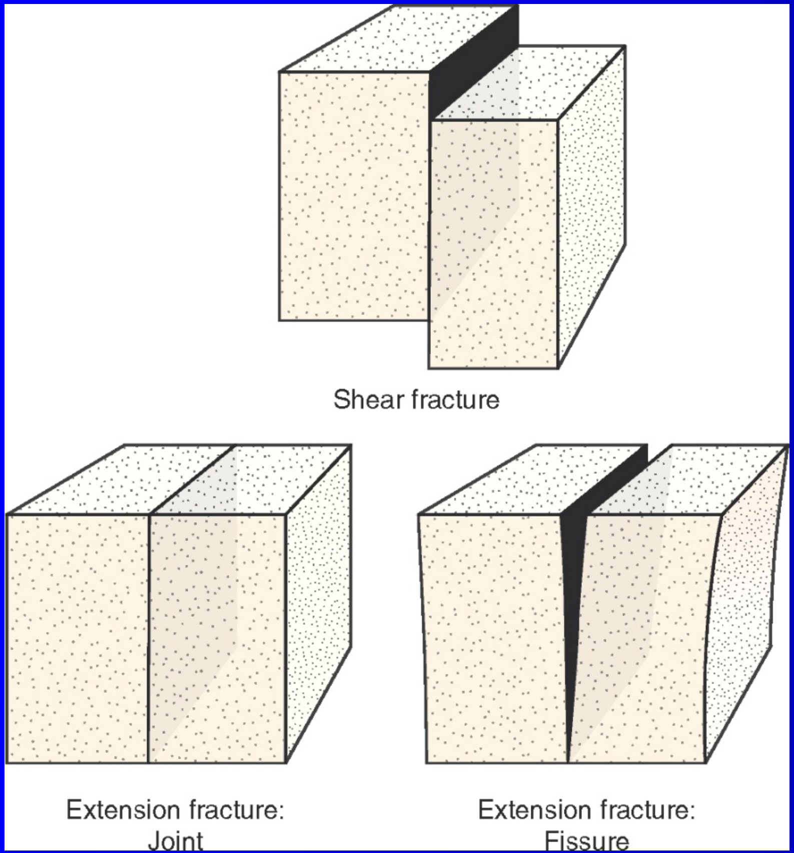
a) Intragranular fractures in cataclastically deformed porous sandstone. Fractures are restricted to single grains.

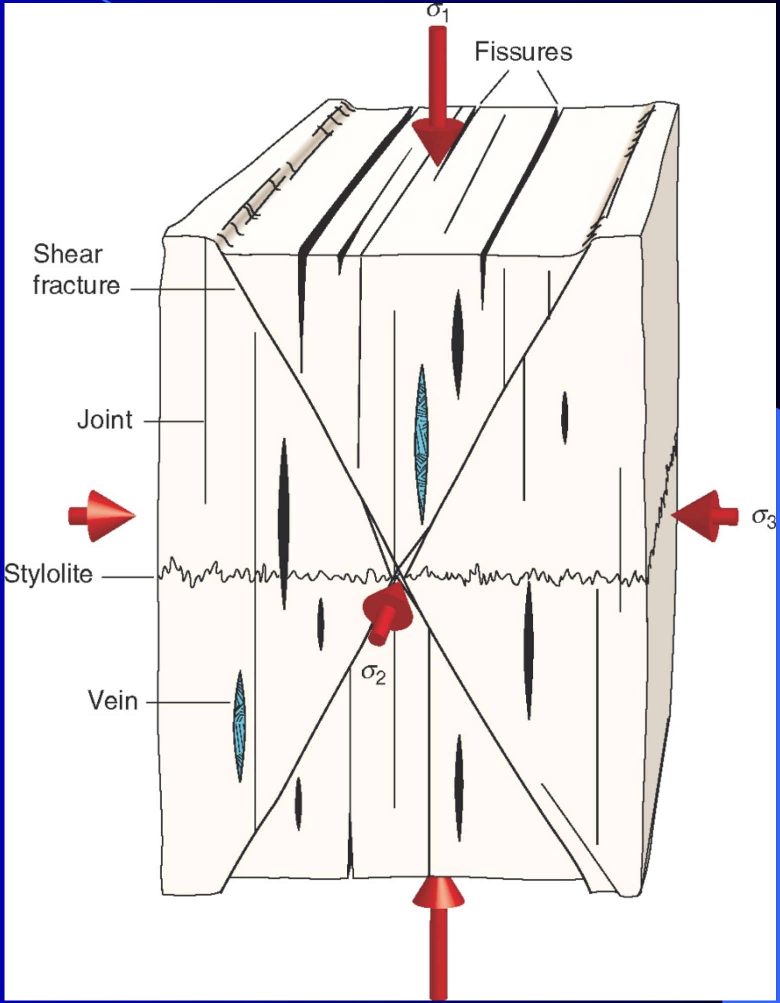
b) Intergranular fractures in a metamorphic rock. Fractures extend across a number of grains.



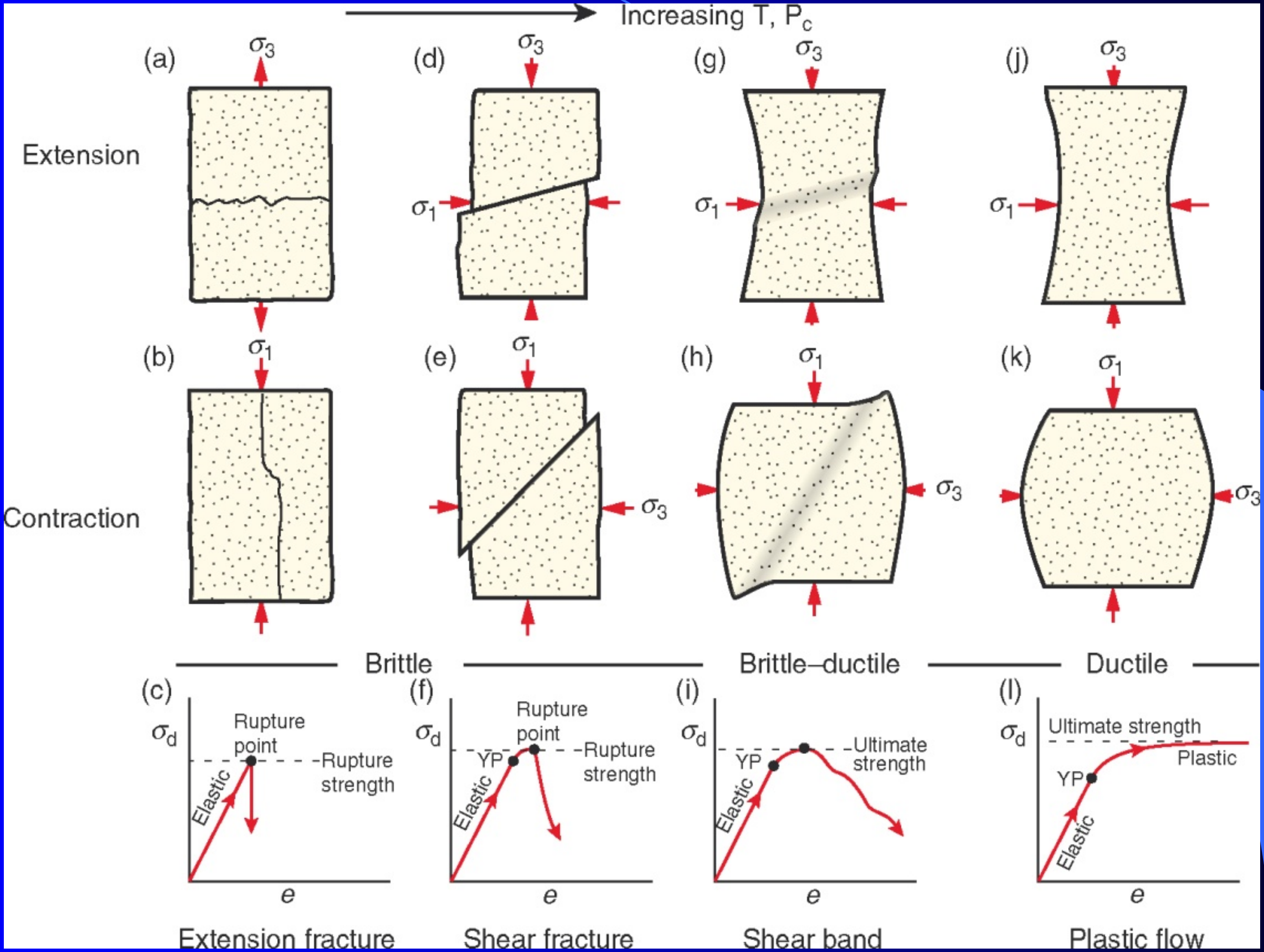
A fracture is any planar or subplanar discontinuity that is very narrow in one dimension compared to the other two and forms as a result of external (e.g. tectonic) or internal (thermal or residual) stress.

Types of fractures





Relationship between temperature, confining pressure, and behavior of materials.



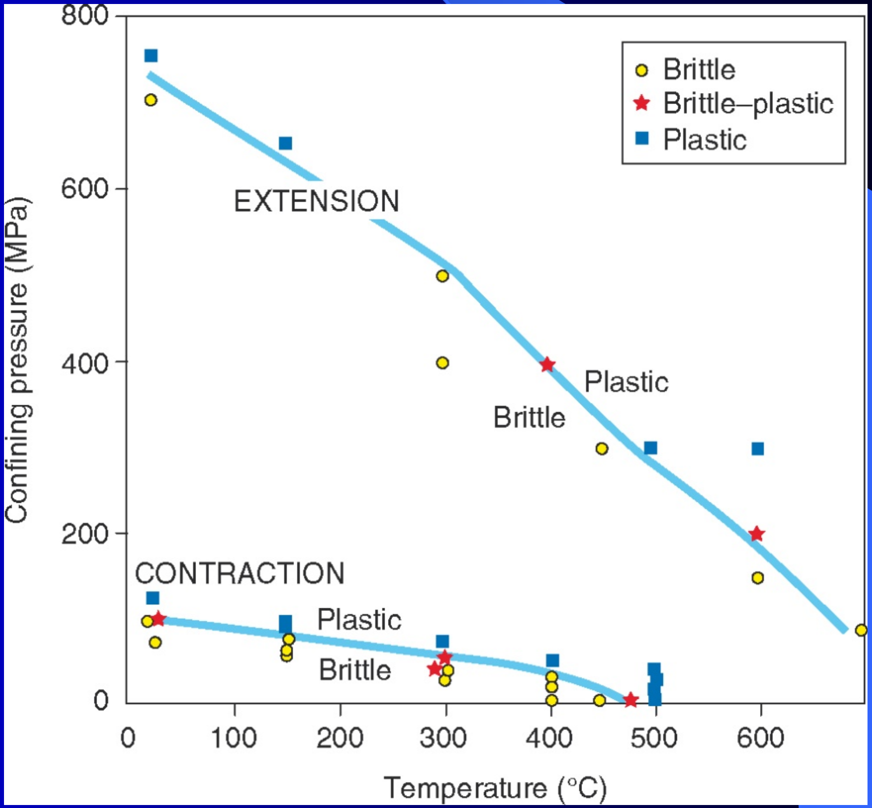
Extension and tensile fractures:

- Ideally develop perpendicular to σ_3
- In terms of strain, they develop perpendicular to the stretching direction
- Fissures are extension fractures that are more open than joints (see image)
- Extension fractures are typical for deformation under low or no confining pressures
- They form at low differential stress

Shear fractures:

- Are oblique to σ_3 by an angle that depends most on rock properties and the state of stress
- They commonly develop in conjugate pairs bisected by σ_1
- They form in the upper part of the crust and near the brittle-plastic transition

The brittle-plastic transition occurs at higher confining pressure under extension than under contraction.



Failure and fracture criteria:

- Fracture initiation requires a differential stress that exceeds the strength of the rock
- Increasing the confining pressure makes it necessary to increase the differential stress in order to fracture a rock

The Coulomb fracture criterion:

- At the instant of failure the rock is critically stressed

  $\sigma_s = \sigma_n \tan \varphi$ where φ is the angle of internal friction

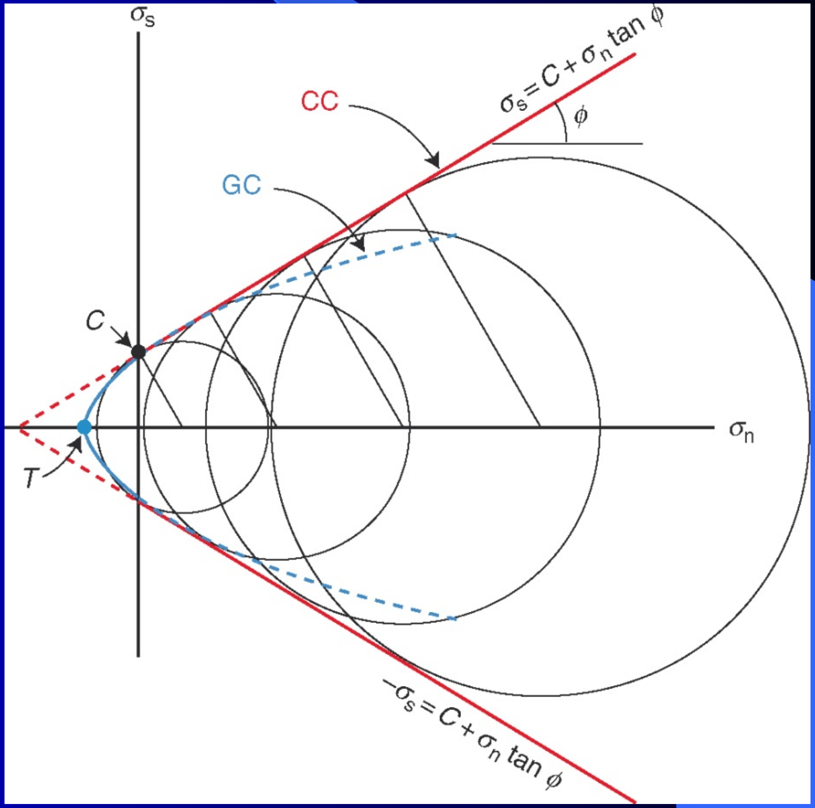
  $\mu = \tan \varphi$ = coefficient of internal friction

- Mohr-Coulomb fracture criterion

  $\sigma_s = C + \sigma_n \tan \varphi = C + \sigma_n \mu$

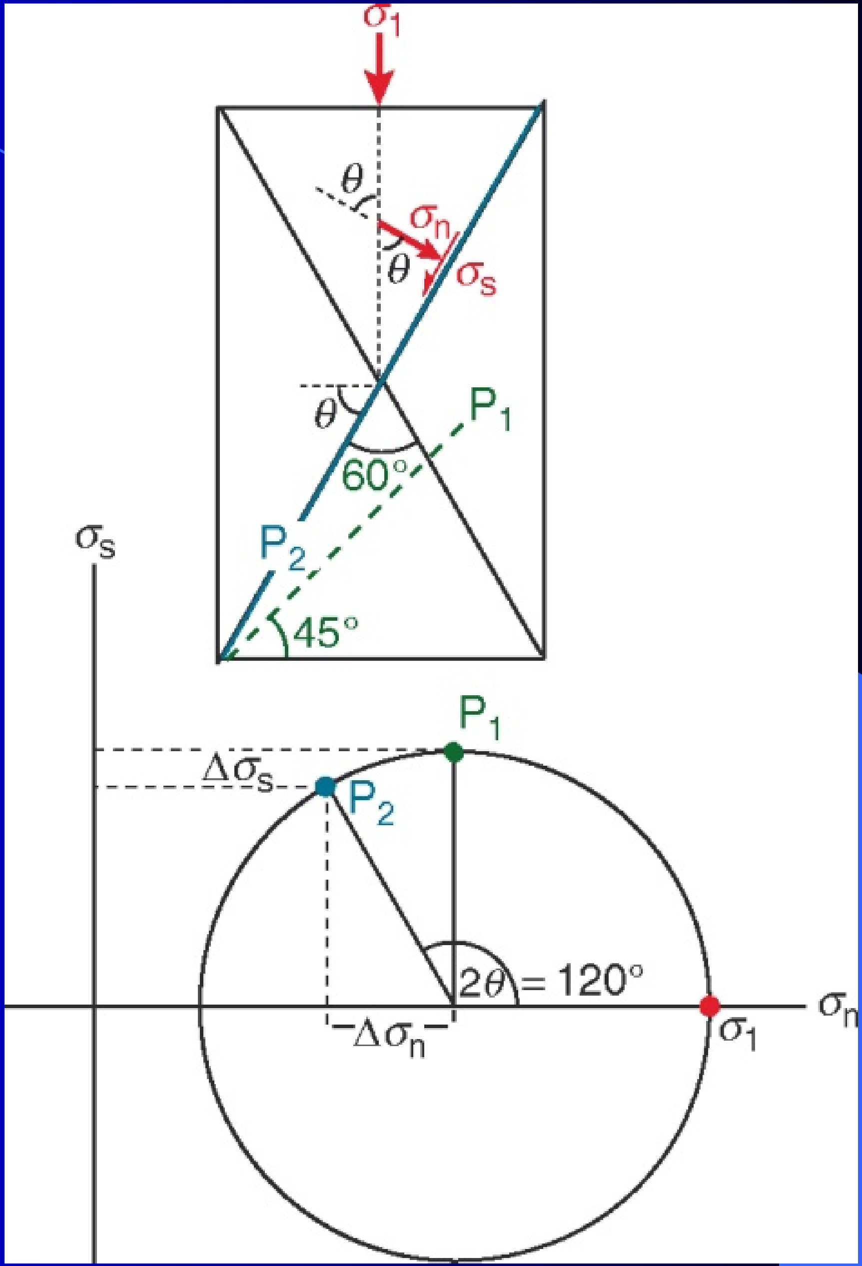
  C = critical shear stress along a surface across which $\sigma_n = 0$ = cohesive strength

  T = critical tensile strength



The answer to Mr. Barry's – why don't fractures form at 45º.

When the shear stress is at a maximum the normal stress is also very high. As the angle decreases, the normal stress decreases more rapidly than the shear stress. The optimal balance between normal stress and shear stress depends on the angle of internal friction. The Coulomb criterion predicts that this angle is around 60º for many rock types. The angle also depends on the confining pressure, temperature and pore fluid.



Griffith's theory of fracture:

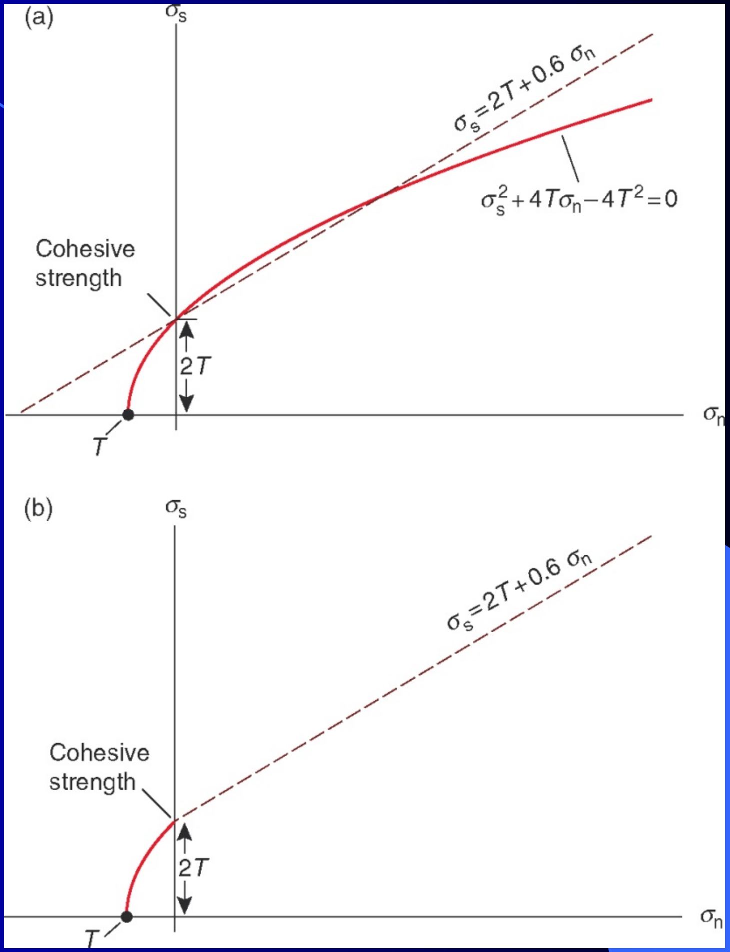
- Microscopic cracks, pores and other flaws weaken rocks
- Griffith fracture criteria – non-linear relationship between the principal stresses for a critically stressed rock

$$\sigma^2_s + 4T\sigma_n - 4T^2 = 0$$

T = critical tensile stress

- When $\sigma_n = 0$, $\sigma_s = 2T$
- Therefore C = 2T
- Combining Griffith and Coulomb fracture criterion gives

$$\sigma_s = 2T + \sigma_n\mu$$



Combining all criterion yields the drawing below showing the relationship between the styles of fracturing and the confining pressure

The ductile regime can be approximated by a constant shear stress criterion – von Mises criterion

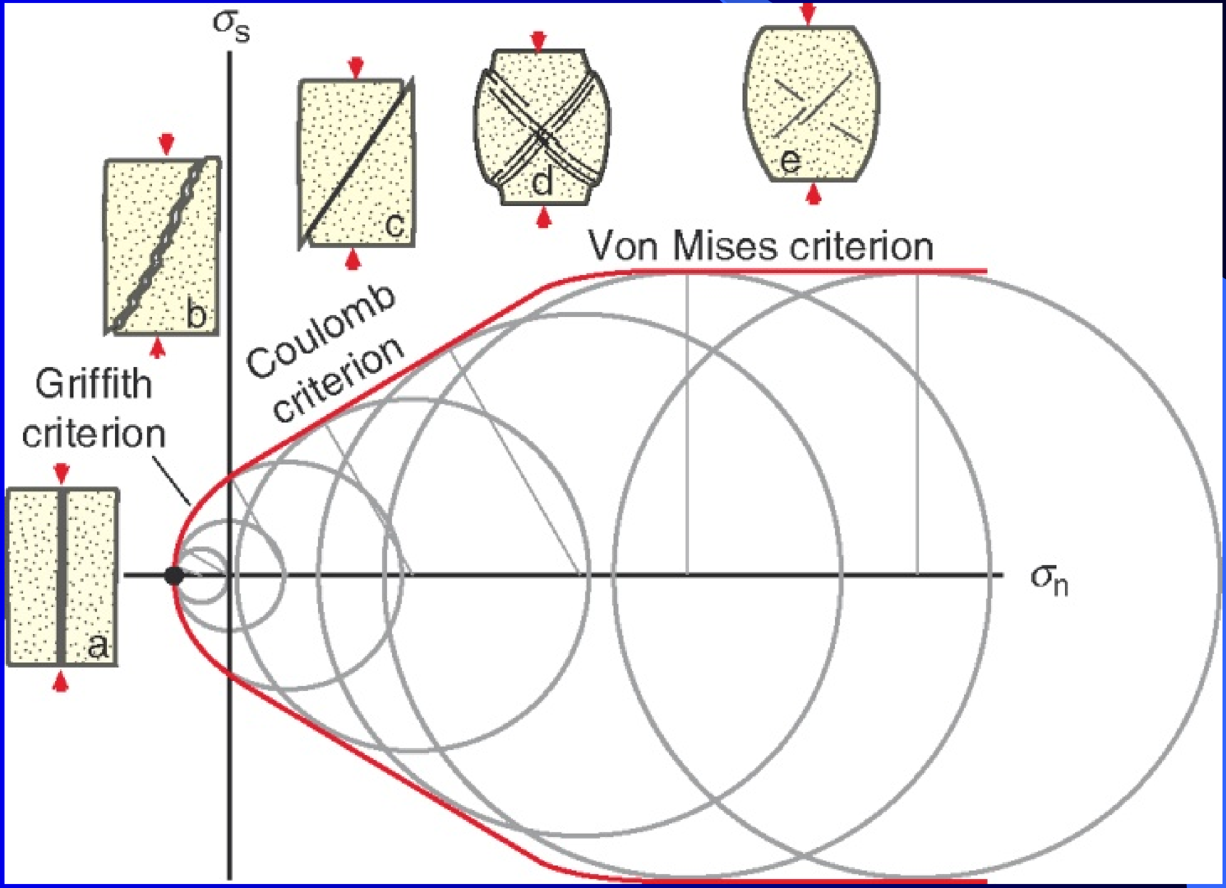
a) Tensile fracture

b) Hybrid or mixed-mode fracture

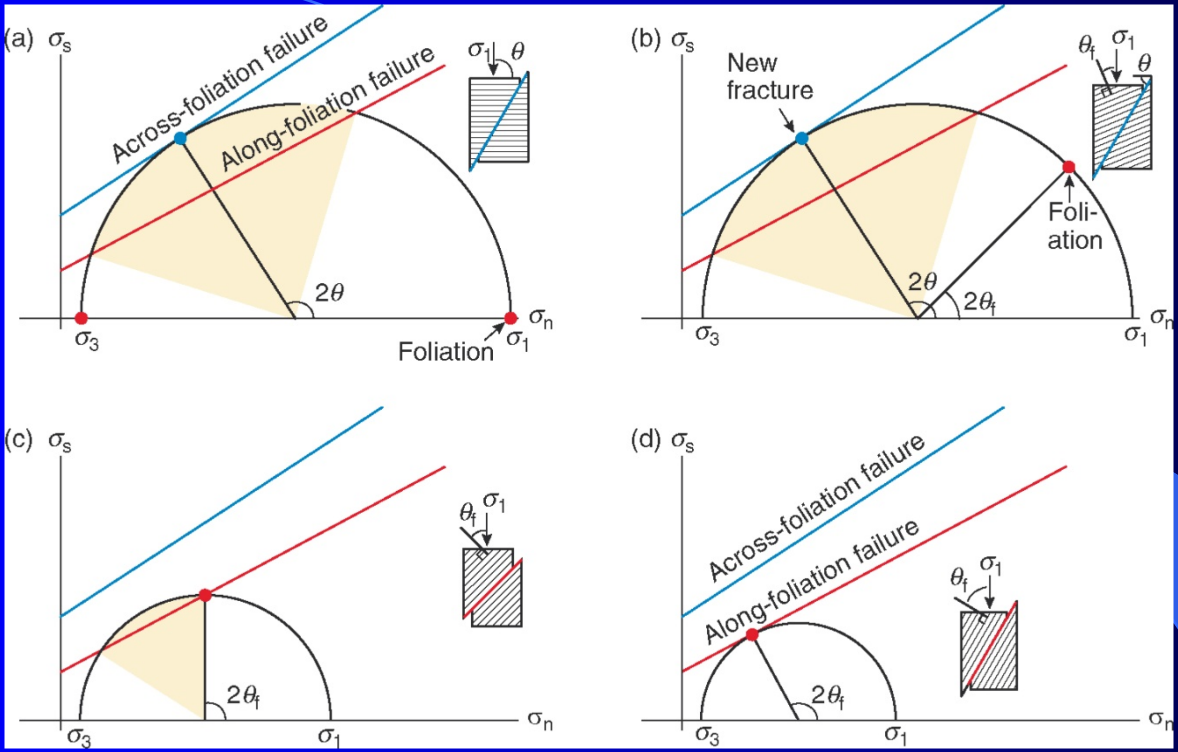
c) Shear fracture

d) Semi-ductile shear bands

e) Plastic deformation



Failure of rocks with pre-existing fabric



a) σ_1 perpendicular to foliation and across-foliation failure occurs

b) σ_1 at high angle to foliation (foliation still outside colored area) and across-foliation failure occurs

c) σ_1 at 45^o to the foliation and foliation-parallel failure occurs. Colored sector is region in which foliation-parallel failure would occur

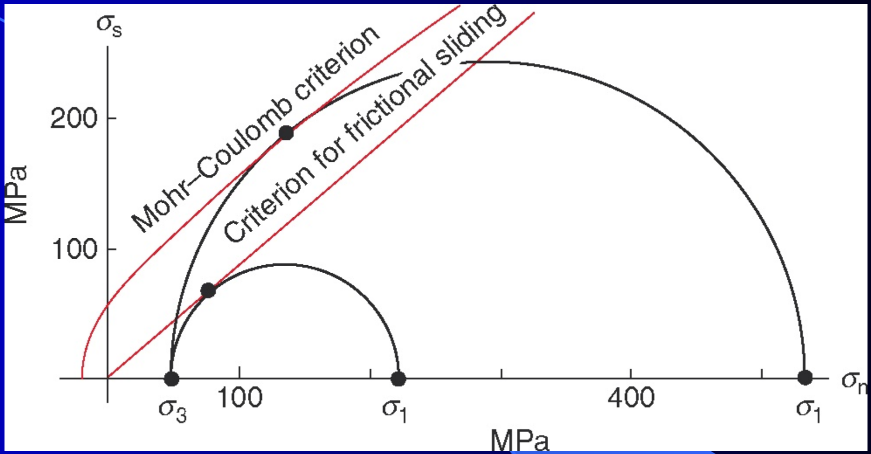
d) The angle between σ_1 and the foliation that gives the lowest possible differential stress that leads to failure

Reactivation and frictional sliding

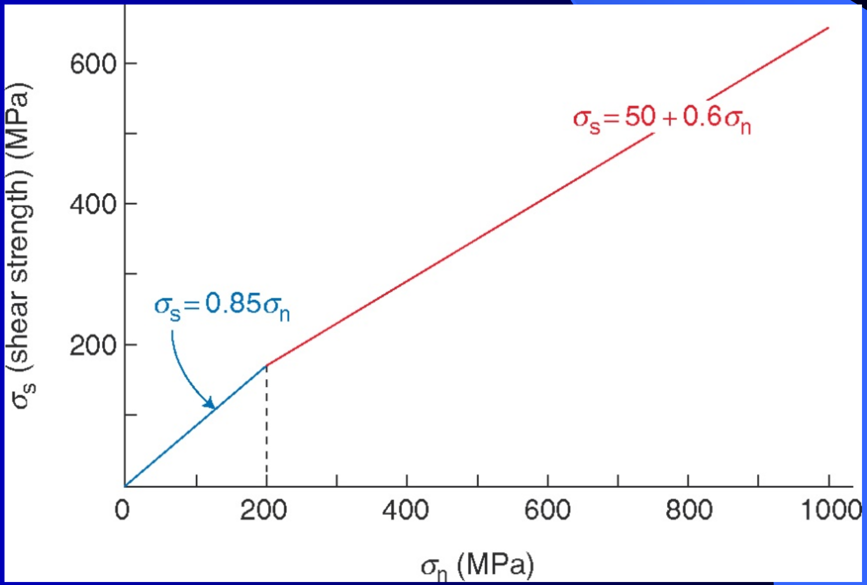
Coefficient of sliding friction (μ_f) = $\frac{\sigma_s}{\sigma_n}$

If the fracture has cohesive strength: $\mu_f = \frac{\sigma_s - Cf}{\sigma_n}$

At low confining pressures surface roughness is important and fault asperities resist fault slippage. This is important because it inhibits the release of strain energy.



Byerlee's law describes the vertical increase in critical shear stress required for faulting through the frictional upper crust.



Fluid Pressure and Effective Stress

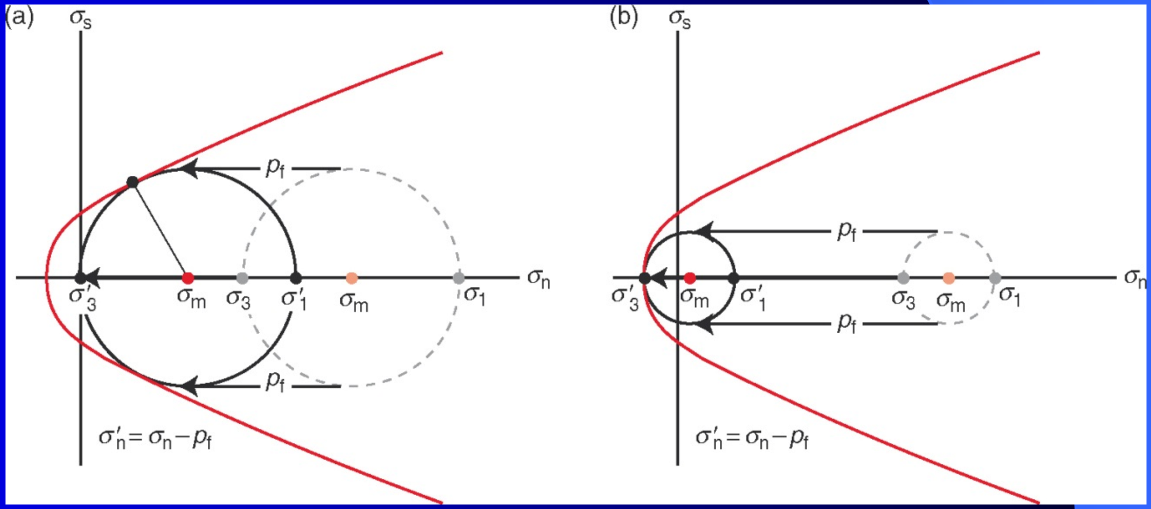
Causes of fluid overpressures:

- In sedimentary sequences pore water confined between impermeable layers. Fluid pressure builds up because of pressure increases during burial
- Heating of water because of increase T with depth leads to overpressures
- Metamorphic reactions release water and carbon dioxide
- Injection of magma
- The fluid pressure counteracts the normal stress on a fracture, so that the shear stress may be sufficient for reactivation.

$$\sigma_s = C - \mu(\sigma_n - p_f)$$

The effective stress is tensile if

$$\sigma_3 = \sigma_3 - p_f < 0$$

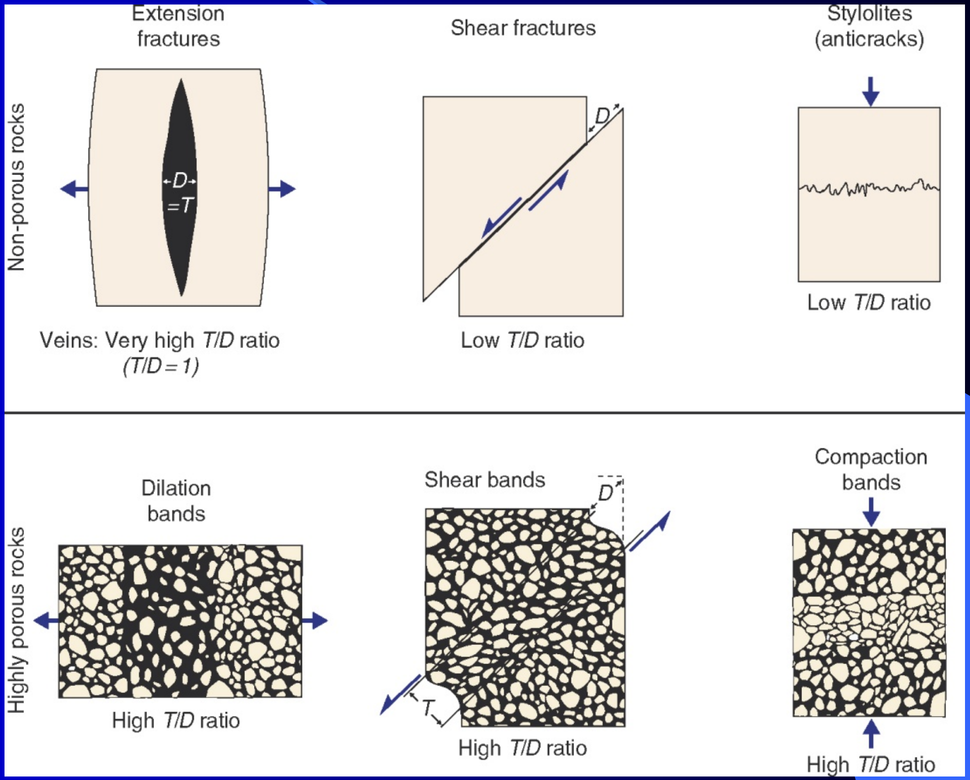


Deformation bands and fractures in porous rocks

Deformation bands are mm-thick zones of localized compaction, shear and/or dilation in deformed porous rocks.

Differences between deformation bands and ordinary fractures:

- Thicker and exhibit smaller shear displacements.
- Deformation bands maintain or show increased cohesion.
- Form low-permeability tabular objects. Regular fractures increase permeability.
- Strain hardening occurs during the formation of deformation bands. Strain softening during fracturing.

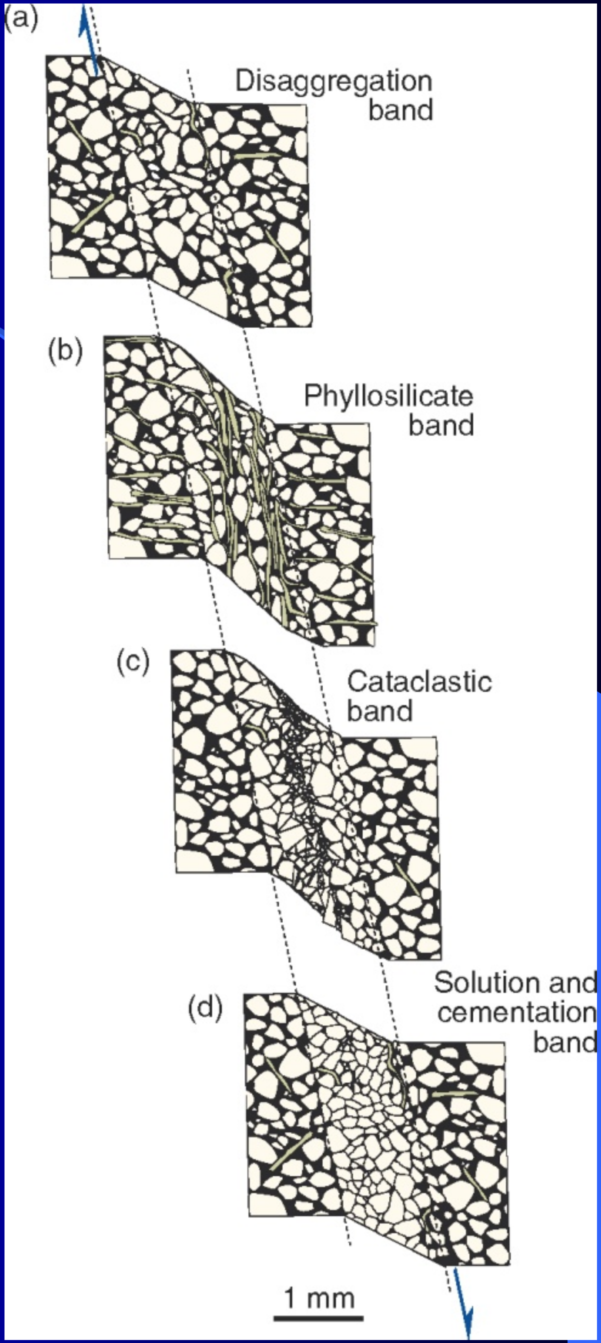


T = thickness, D = displacement

Types of deformation bands distinguished by dominant deformation mechanism:

- Disaggregation band – shear-related disaggregation of grains by grain rolling, grain boundary sliding and breaking of grain bonding cements.
- Phyllosilicate bands – platy minerals promote grain sliding.
- Cataclastic bands – mechanical grain breaking is significant.
- Solution and cementation bands – preferential dissolution of minerals in the rock and precipitation of material as cement.

The influence of deformation bands on petroleum or groundwater production depends on the permeability contrast, cumulative thickness, orientations, continuity and connectivity.



Different types of deformation bands form at different stages during burial. Extension fractures are most likely to form during uplift.