

Fracture Mechanics or Modes of fracturing

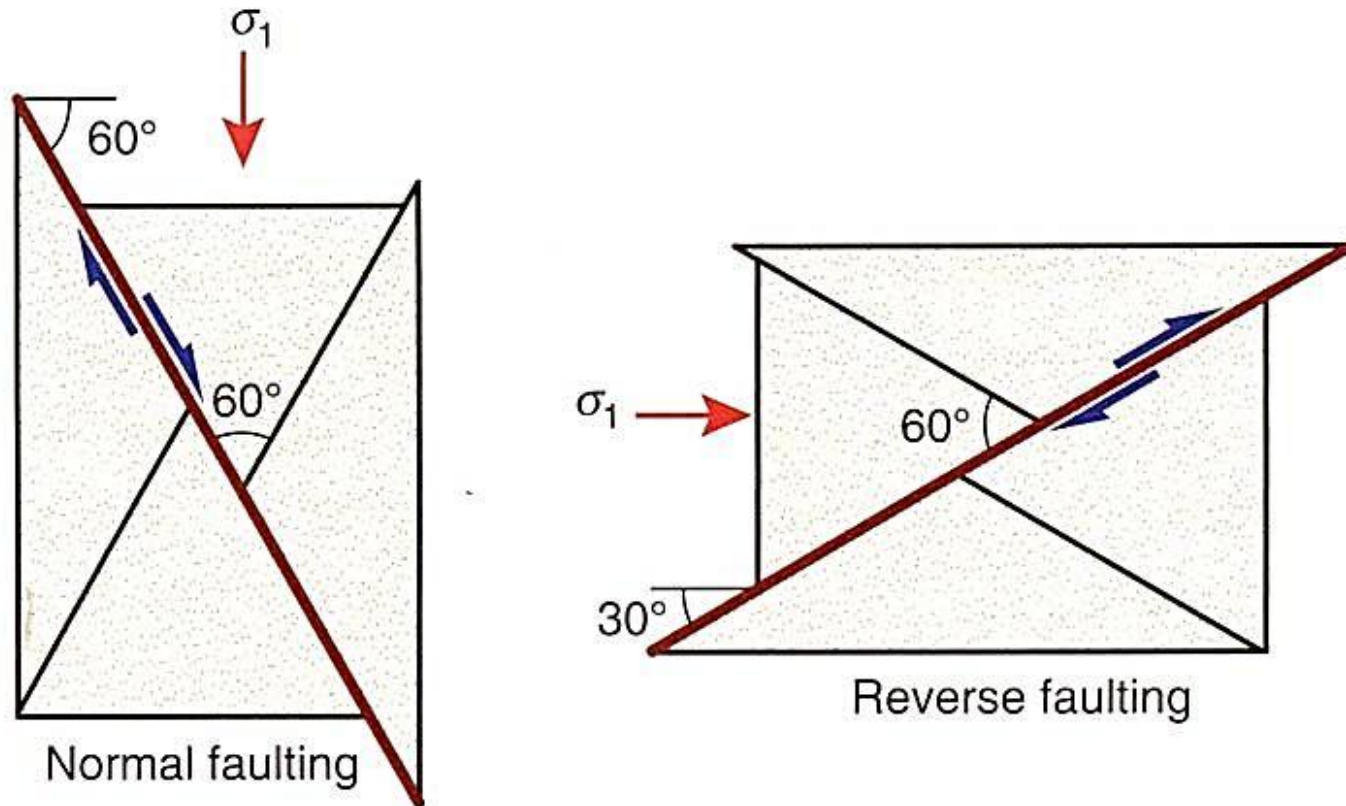
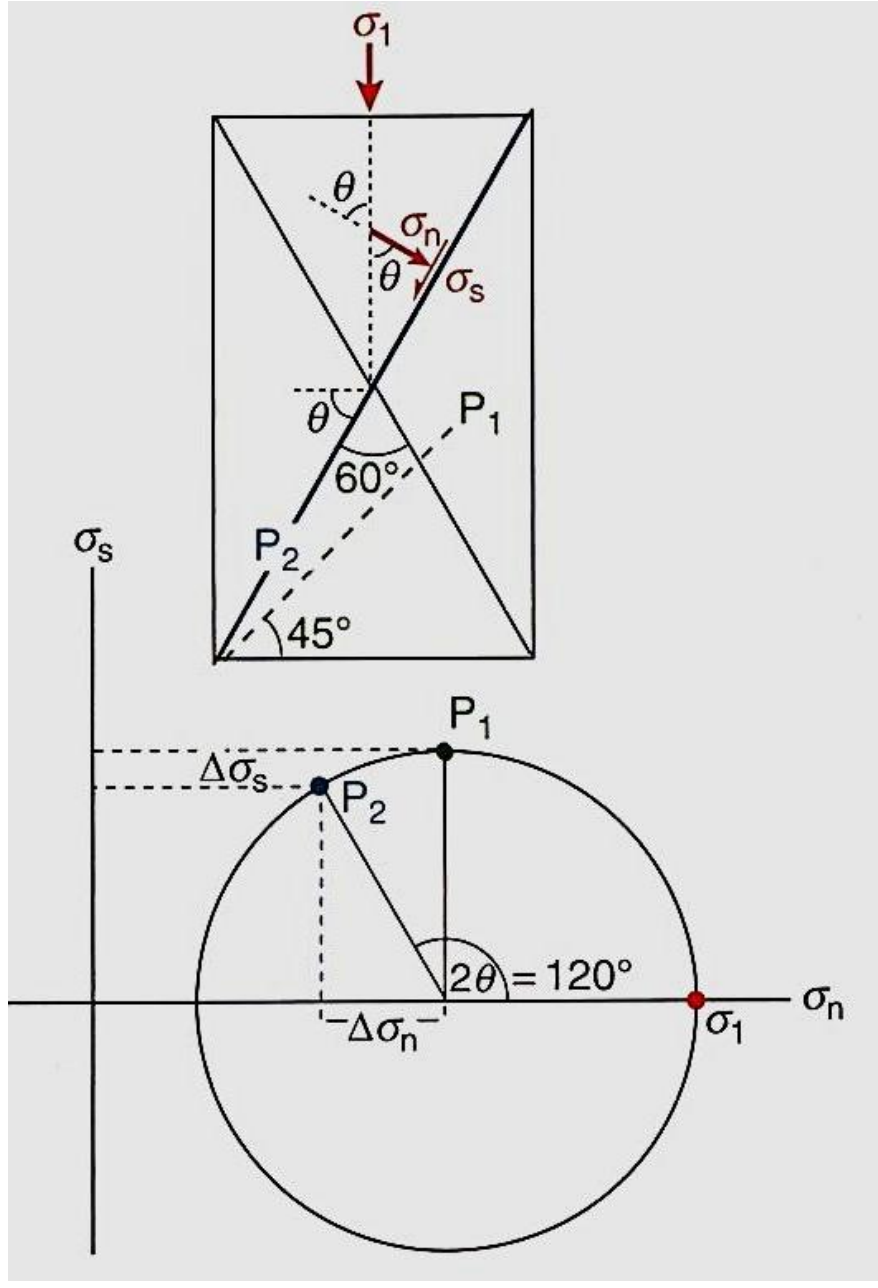


Figure 7.13 The angle between the maximum principal stress and the shear plane is commonly found to lie close to 30° . This implies that normal faults dip steeper (60°) than reverse faults (30°).



P_1 is the plane of maximum resolved shear stress ($2\theta = 90^\circ$) and forms at 45° to σ_1 . The plane P_2 oriented at 30° to σ_1 has a slightly lower shear stress (the difference is $\Delta\sigma_s$), but a much lower normal stress (by $\Delta\sigma_n$). It is therefore easier for a shear fracture to form along P_2 than along P_1 .

The Coulomb law of Failure

The Coulomb's law of failure is based on dynamic/mechanical models developed by Coulomb (1773) and Mohr (1900). The law is an equation that describes the height and slope of the linear envelope of failure for rocks in compression (Fig. 5.41):

$$\sigma_c = \sigma_0 + \tan \phi (\sigma_N)$$

Where

- σ_c = **critical shear stress required for faulting**
- σ_0 = **Cohesive strength**
- $\tan \phi$ = **Coefficient of internal friction**
- σ_N = **Normal stress**

Insight regarding the conditions under which joints and shear fractures are formed in rocks can be derived from experimental deformation in the laboratory.

The fracture strengths of rocks can be measured, and the orientations of fractures with respect to principal stress directions can be observed.

Experimental testing of rock strength and empirical observation of the conditions under which rocks fracture form the fundamental basis for exploring the actual mechanics of fracturing.

It provides a necessary complement to theoretical analysis of the mechanics of fracturing.

Basic Approach in Experimental Testing

For each experimental test the basic procedure is to hold one principal stress constant, and then progressively increase or decrease the other to create an ever-increasing differential stress.

For tensile strength tests, an increasing tensile stress (σ_3) is applied to the ends of the specimen while compressive confining pressure ($\sigma_1 = \sigma_2$) perpendicular to the flank of the cylindrical specimen is held constant (Figure 5.33A).

When the tensile strength of the rock is overcome, the specimen breaks in a mode I tension fracture.

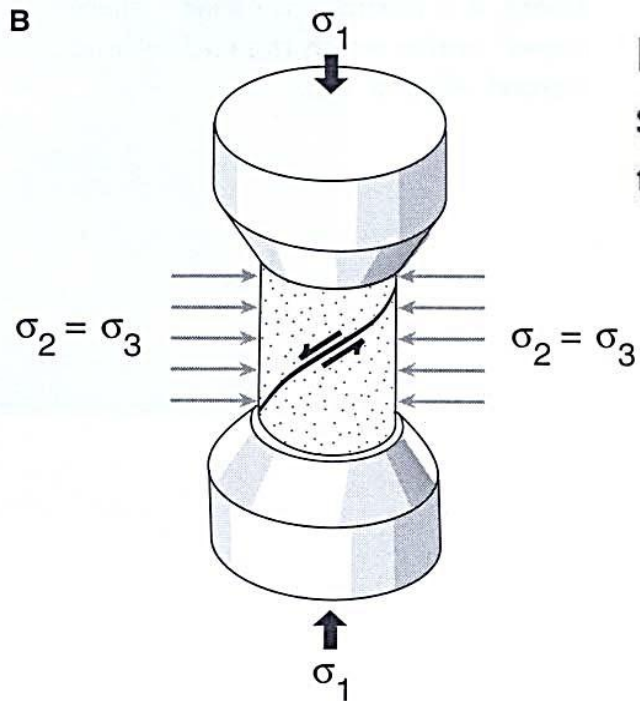
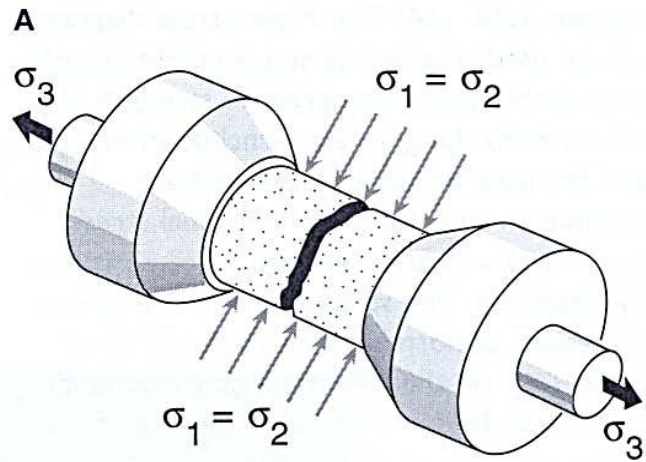
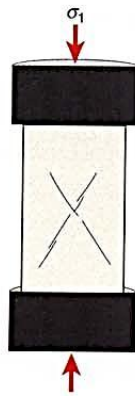


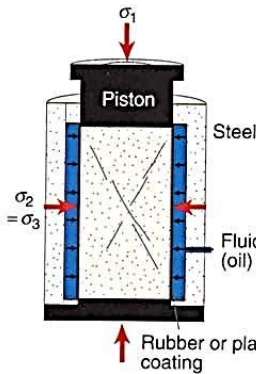
Figure 5.33 The basic setup for (A) tensile strength tests and (B) compressive strength tests.

BOX 7.1

DEFORMING ROCKS IN THE LABORATORY

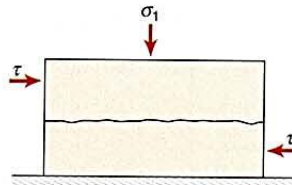


Uniaxial deformation rig, used to find the uniaxial strength of rocks. Experiments show that, in general, fine-grained rocks are stronger than coarse-grained ones, and the presence of phyllosilicates lowers the strength.



Triaxial rig. Oil pressure is pumped up in a chamber around the sample to increase the confining pressure.

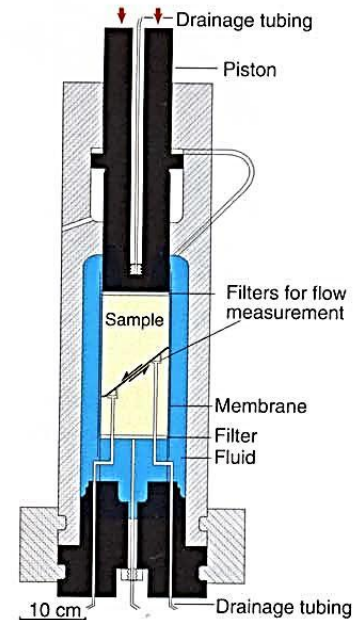
The mechanical properties of rocks are explored in rock mechanics laboratories, where samples are exposed to various stress fields that relate to different depths and stress regimes in the crust. Uniaxial rigs can be used to test the uniaxial compressive or tensile strength of rocks. Triaxial tests, where $\sigma_1 > \sigma_2 = \sigma_3$, are more common, where rock cylinders are loaded in the axial direction while the sample is confined in fluid that can be pumped up to a certain confining pressure. A typical triaxial rig can build up an axial stress of 2–300 MPa and a confining pressure of up to 50–100 MPa or more. Sample and fluid are commonly separated by a membrane to avoid the fluid entering the sample and changing its mechanical properties. For porous rocks or sediments it may be possible to control the pore pressure (e.g. up to 50 MPa). The distance between the pistons is monitored together with axial loading and confining pressure. The ringshear apparatus is used to explore the effect of large shear strain under vertical compression of up to about 25 MPa.



Shearbox experiment where the resistance against shear is explored. The higher the normal stress, the higher the shear stress necessary to activate the fracture. The roughness of the fracture is also important.



Ringshear apparatus, where the amount of shear strain that can be imposed on the sample is unlimited. Loose sediment is added and processes such as clay smear and cataclasis can be studied.



A triaxial rig where fluid (oil or water) can be pumped in and influence the behavior of an existing fracture.

For compressive strength tests, increasing compressive stress (σ_1) is applied to the ends of the test specimen while compressive confining pressure ($\sigma_3 = \sigma_2$) perpendicular to the flank of the cylindrical specimen is held constant (Figure 5.33B).

When the compressive strength of the rock is overcome, the specimen breaks by shear failure.

For both tensile and compressive strength tests the magnitudes of σ_1 and σ_3 , at failure are calculated and recorded. The specimen is then removed from the pressure vessel, whereupon the orientation of the fracture can be measured relative to the stress field that caused the failure.

From this information, we can determine the values of normal stress and shear stress on the fracture at the instant of failure.

The Mohr circle diagram provides a graphical means to describe the values of shear stress and normal stress on any plane within a body subjected to known values of greatest and least principal stress.

We can now use the Mohr diagram to "map" the failure values of normal stress and shear stress for each experiment, as well as the conditions of greatest and least principal stress that prevailed at the instant of failure (Figure 5.34A).

After a series of tests has been carried out on the same lithology under different conditions of confining pressure, a whole family of failure values (or points of failure) can be identified.

Collectively these define an envelope of failure (Figure 5.34B), which separates the differential stress conditions under which the rock will remain unfractured and stable, versus the differential stress conditions under which the rock will fail by fracturing.

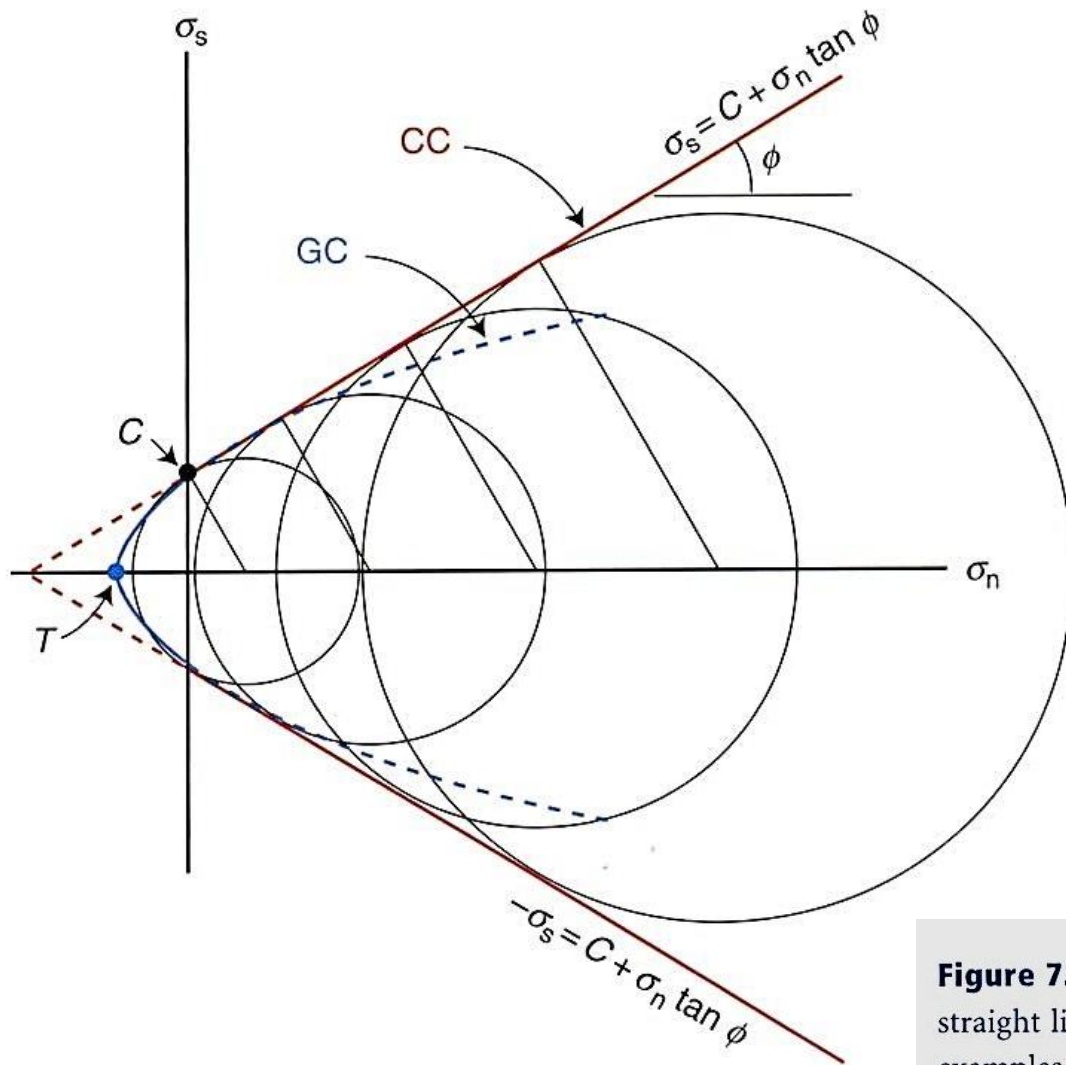


Figure 7.10 The Coulomb fracture criterion occurs as two straight lines (red) in the Mohr diagram. The circles represent examples of critical states of stress. The blue line represents the Griffith criterion for comparison. The combination of the two is sometimes used (GC in the tensile regime and CC in the compressional regime). CC, Coulomb criterion; GC, Griffith criterion; C , the cohesive strength of the rock; T , the tensile strength of the rock.

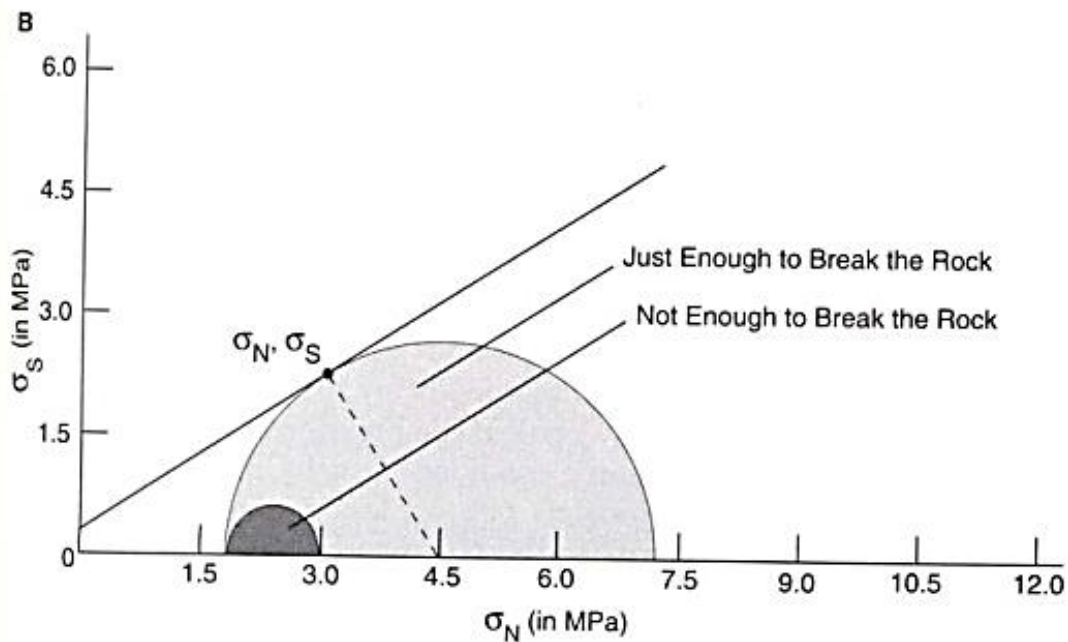
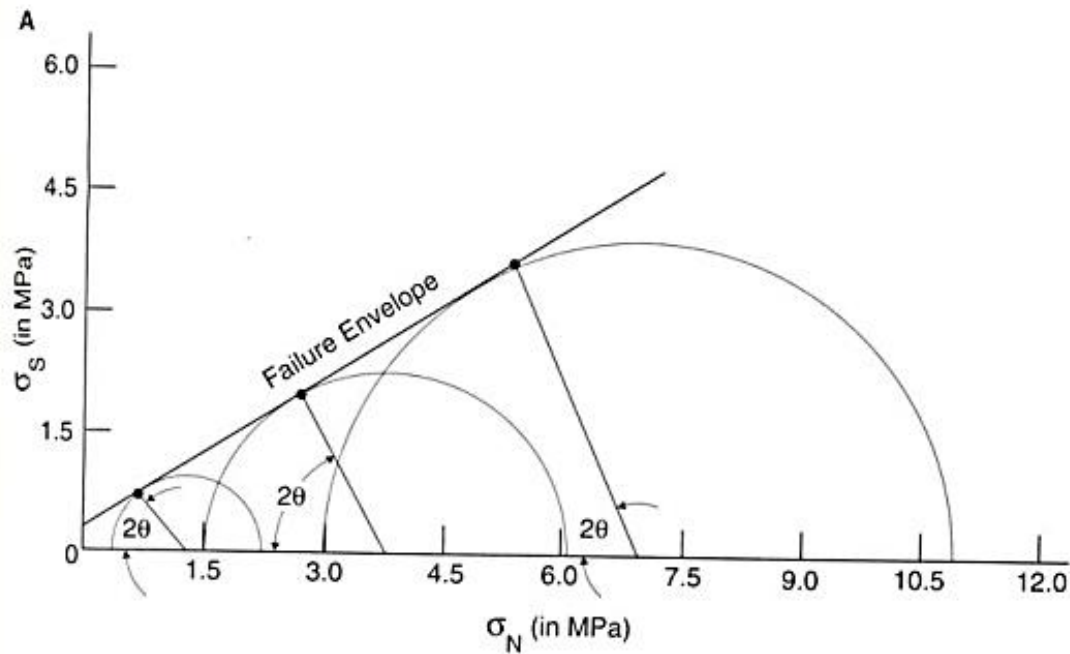
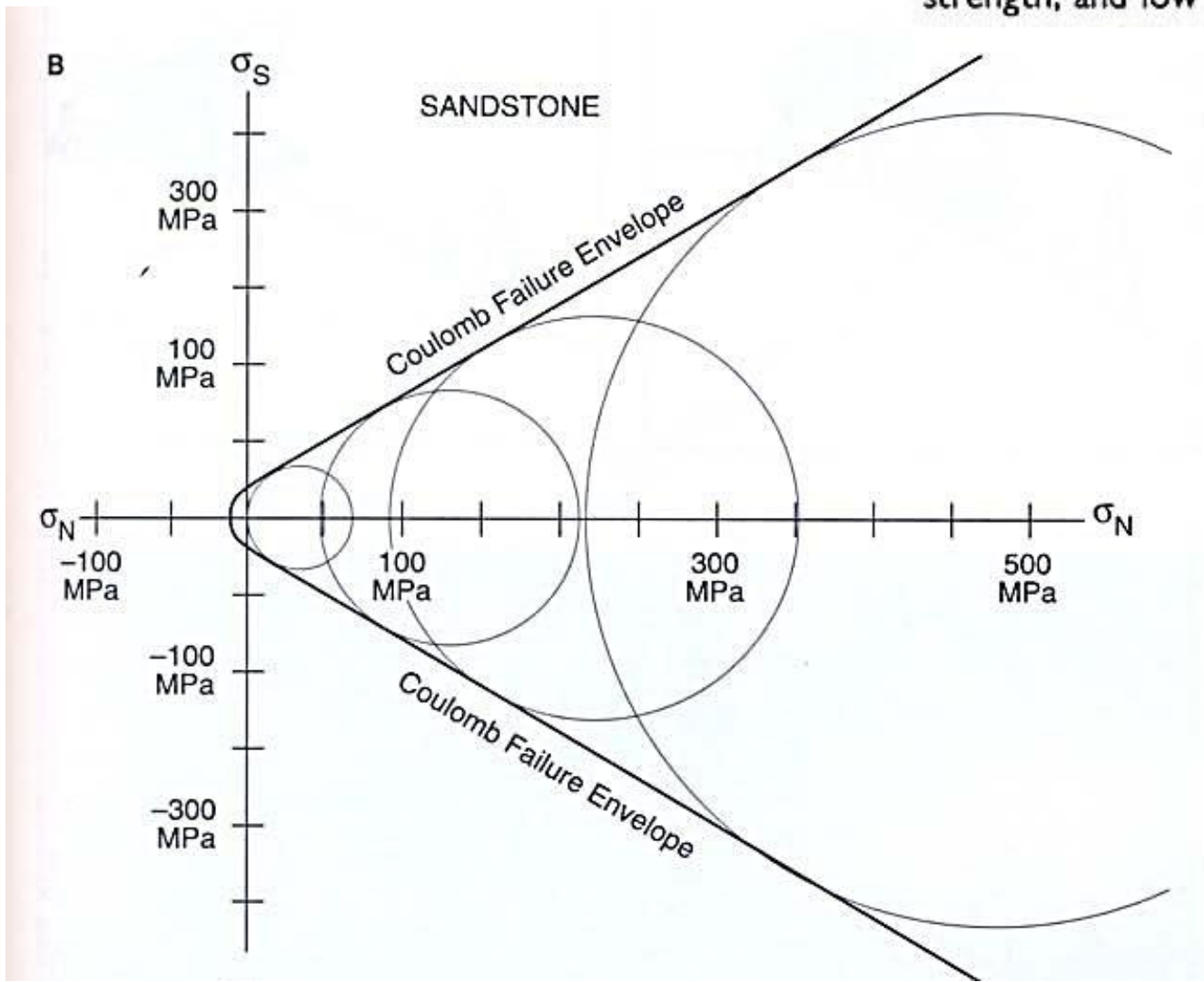


Figure 6.61 Construction of a Mohr envelope of failure. (A) The plotting of the principal stress values (σ_1 and σ_3) for each of three experiments. Also shown, for each experiment, is the angular relationship of faulting to the direction σ_1 . The envelope of failure passes through the "failure points" representing each of three experiments. (B) Use of the failure envelope as a guide to determining the stress level at which the rock will fault under confining pressure of 1.85 MPa. (C) Equation for the Coulomb law of failure in relation to the properties of the Mohr diagram.

Figure 5.44 (continued) (B) Schematic portrayal of failure envelope for a rock marked by low tensile strength, low cohesive strength, and low internal friction. (C)



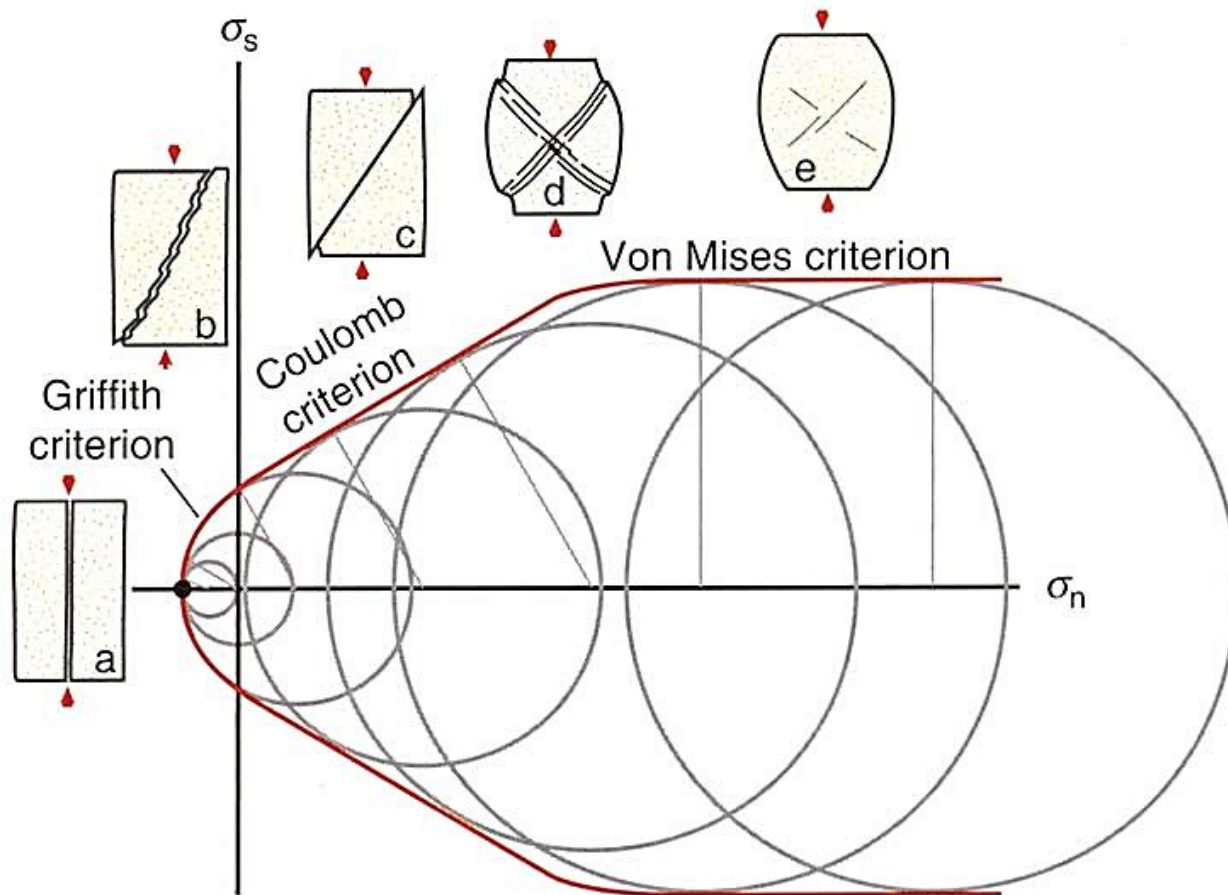
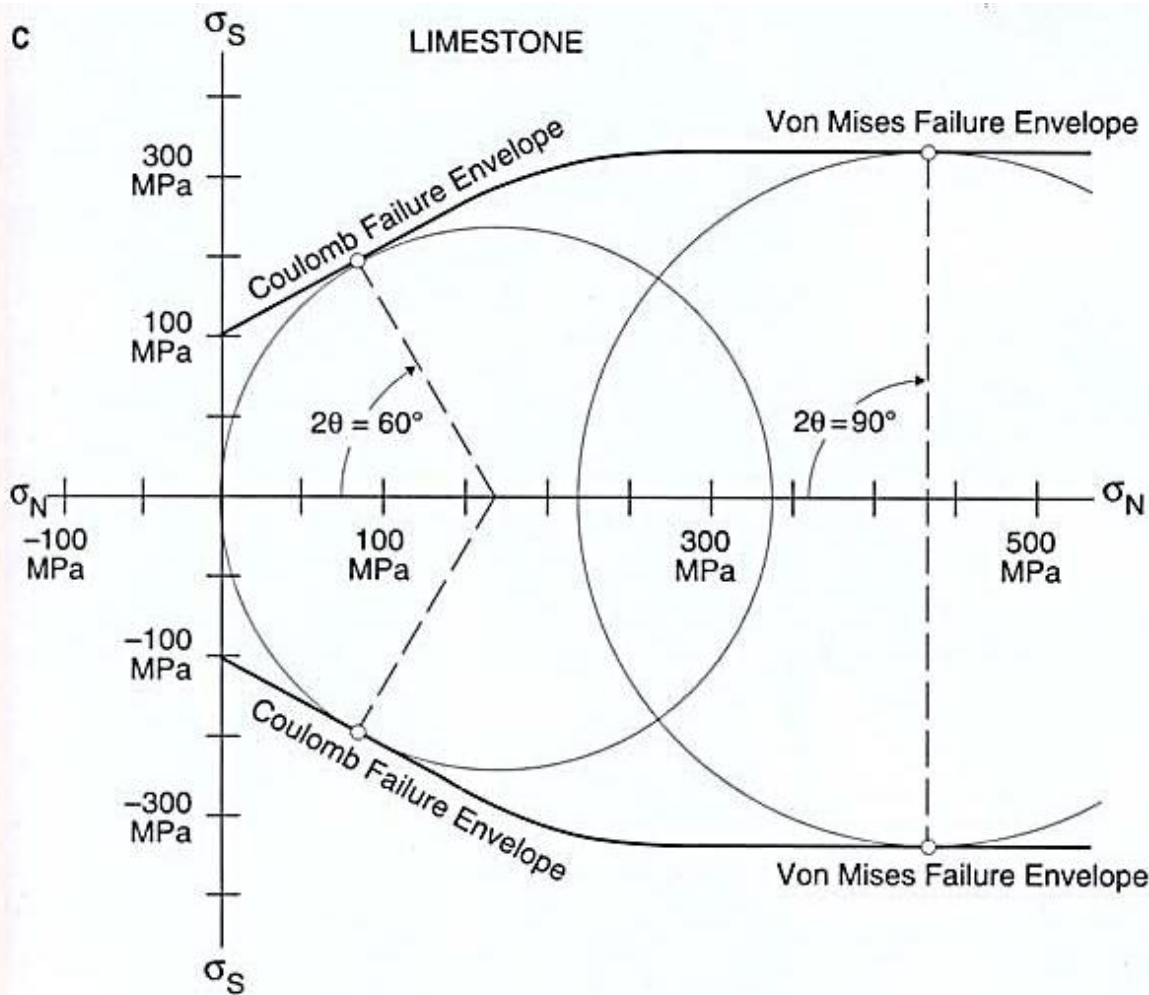


Figure 7.15 Three different fracture criteria combined in Mohr space. Different styles of fracturing are related to confining pressure: (a) Tensile fracture, (b) hybrid or mixed-mode fracture, (c) shear fracture, (d) semi-ductile shear bands, (e) plastic deformation.



5. 44C Schematic portrayal of failure envelope for a rock marked by high tensile strength, high cohesive strength, and high internal friction.

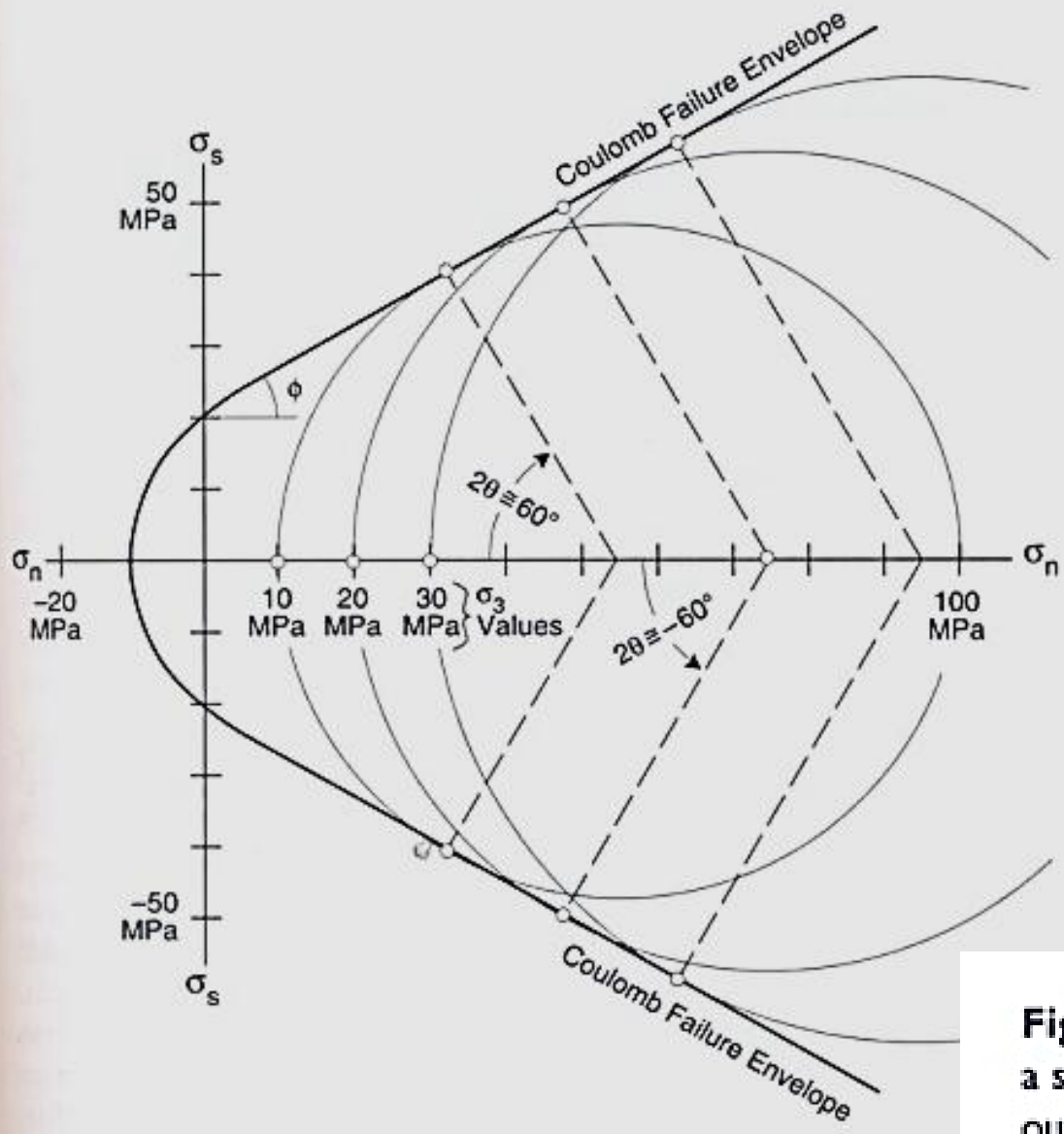


Figure 5.40 Mohr circle representation of a series of compressive strength tests carried out under different conditions of confining pressure (10, 20, 30 MPa). Points of failure lie on a straight line, the Coulomb envelope of failure.

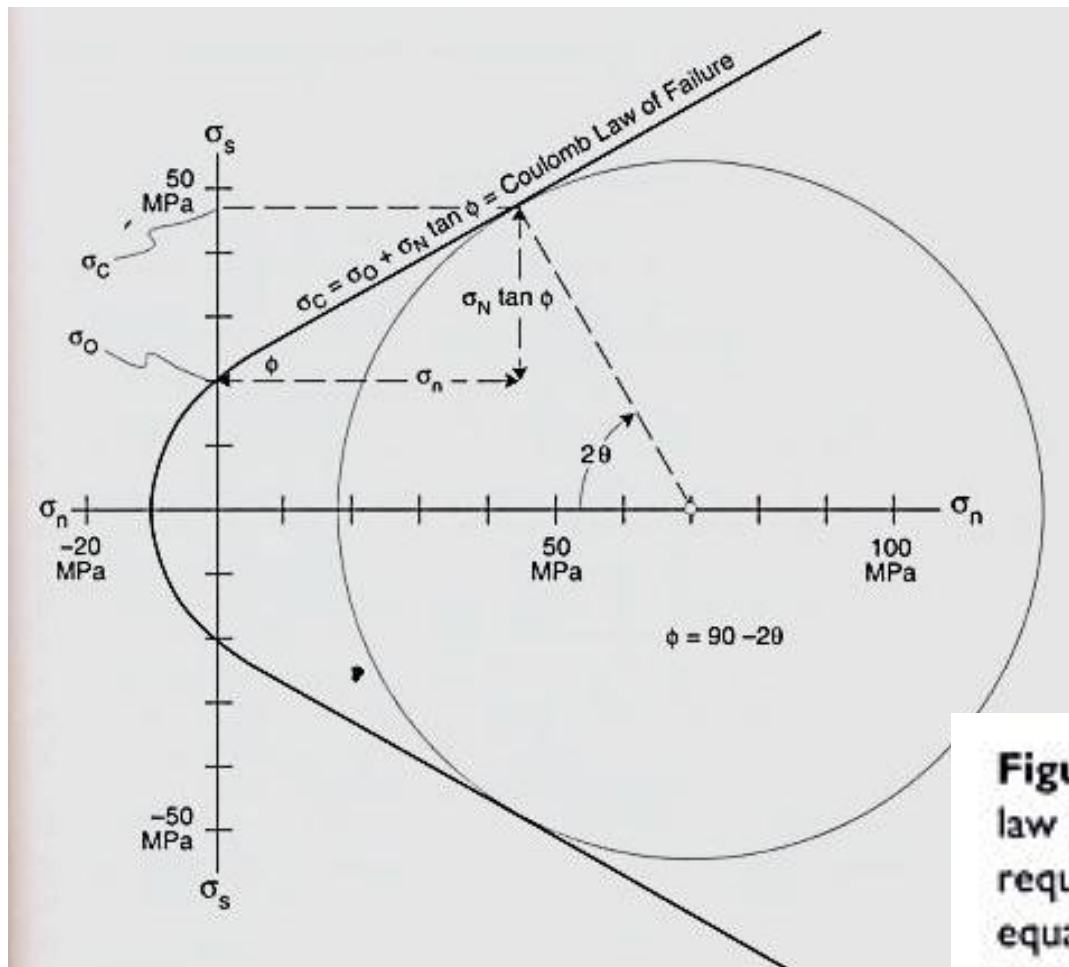


Figure 5.41 According to the Coulomb law of failure, the critical shear stress (σ_c) required to break a rock by shear failure is equal to the cohesive strength of the rock (σ_0) plus another increment of shear equal to the product of normal stress (σ_n) and the coefficient of friction of the rock ($\tan \phi$). Graphically, the angle of internal friction (ϕ) is simply the slope angle of the Coulomb envelope.

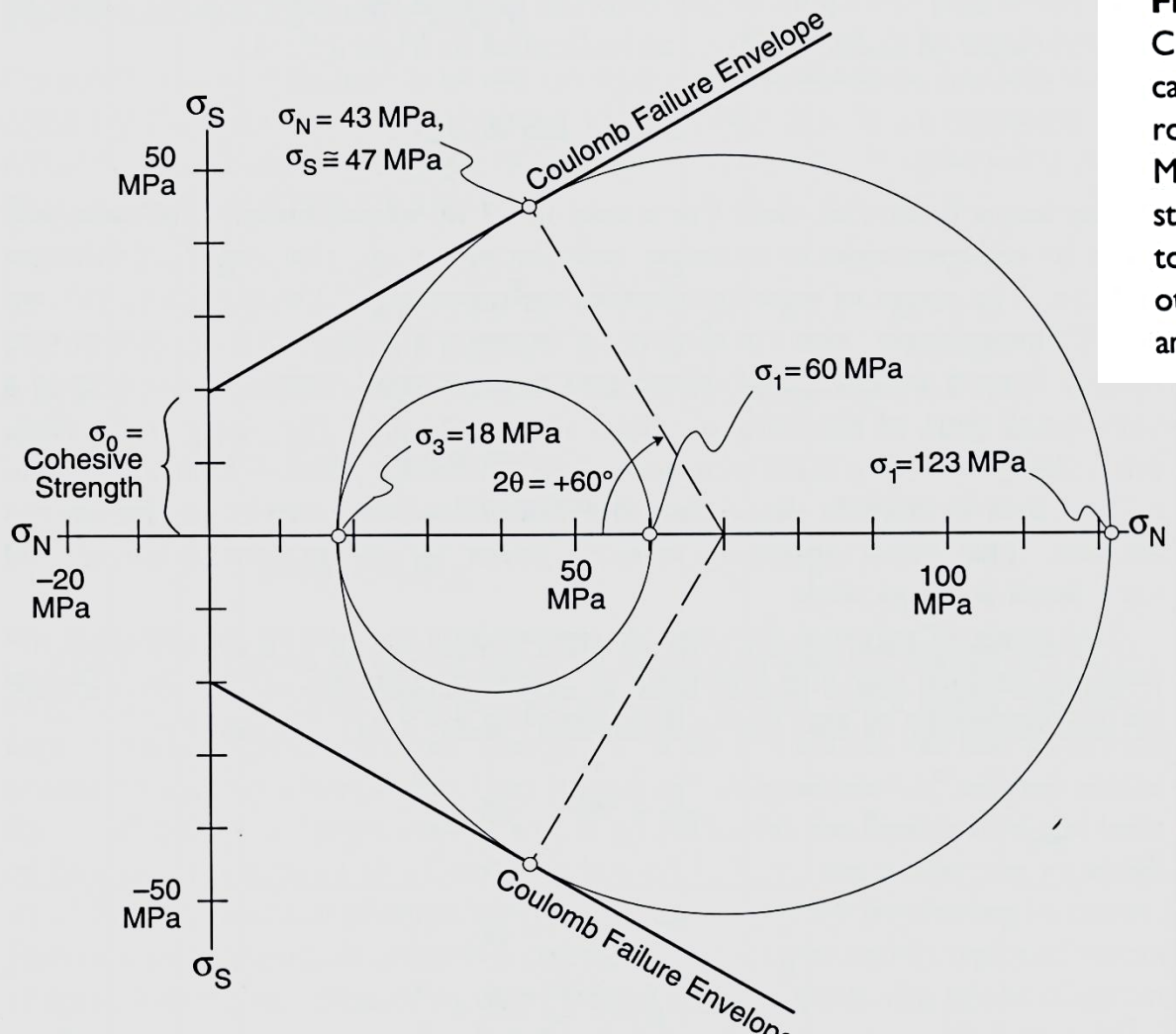


Figure 5.42 Having established the Coulomb failure envelope for this rock, we can predict the conditions under which the rock will fail. If confining pressure is set at 18 MPa, will the raising of greatest principal stress (σ_1) to a level of 60 MPa be enough to cause shear failure? Not a chance! On the other hand, 123 MPa would be just the right amount.

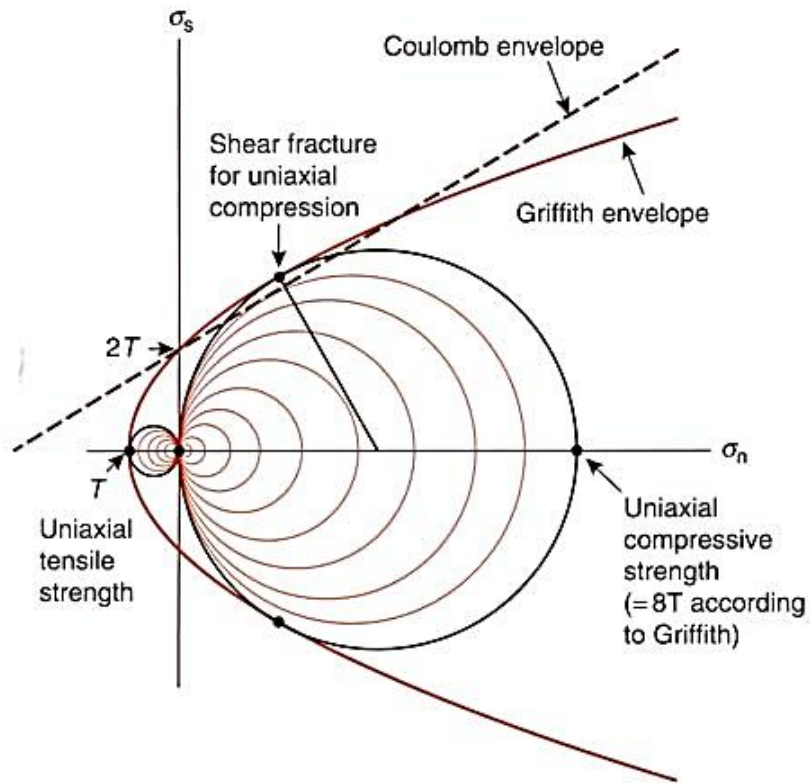


Figure 7.16 Illustration of the meaning of the terms uniaxial tensile and compressive strength in the Mohr diagram. Uniaxial means that only $\sigma_1 \neq 0$, which is obtained in a uniaxial deformation rig where the confining pressure is zero. By gradually compressing the rock sample, the uniaxial compressive strength is reached when a shear fracture first forms. By pulling the sample until a tensile fracture forms, the uniaxial tensile strength is found. Note that the uniaxial compressive strength is much larger than the tensile strength for the same rock and conditions.

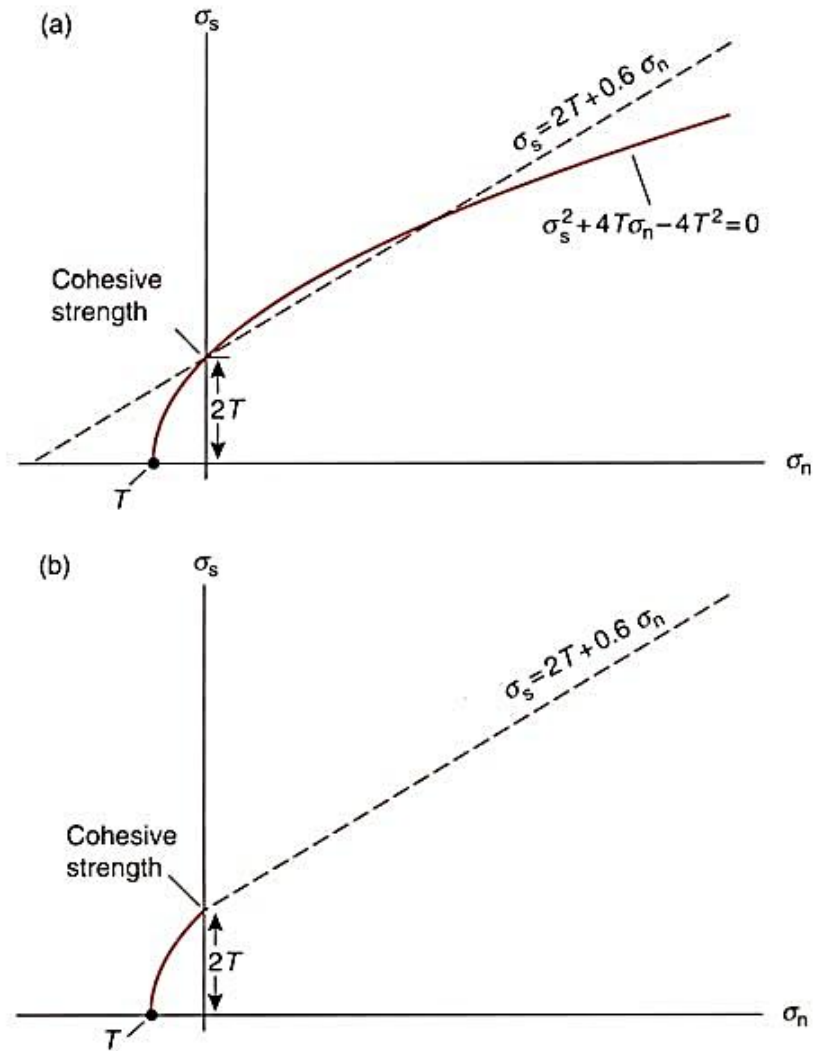


Figure 7.17 (a) Comparison of the Griffith and Coulomb fracture criteria (the coefficient of internal friction is chosen to be 0.6). (b) The combined Griffith-Coulomb criterion.

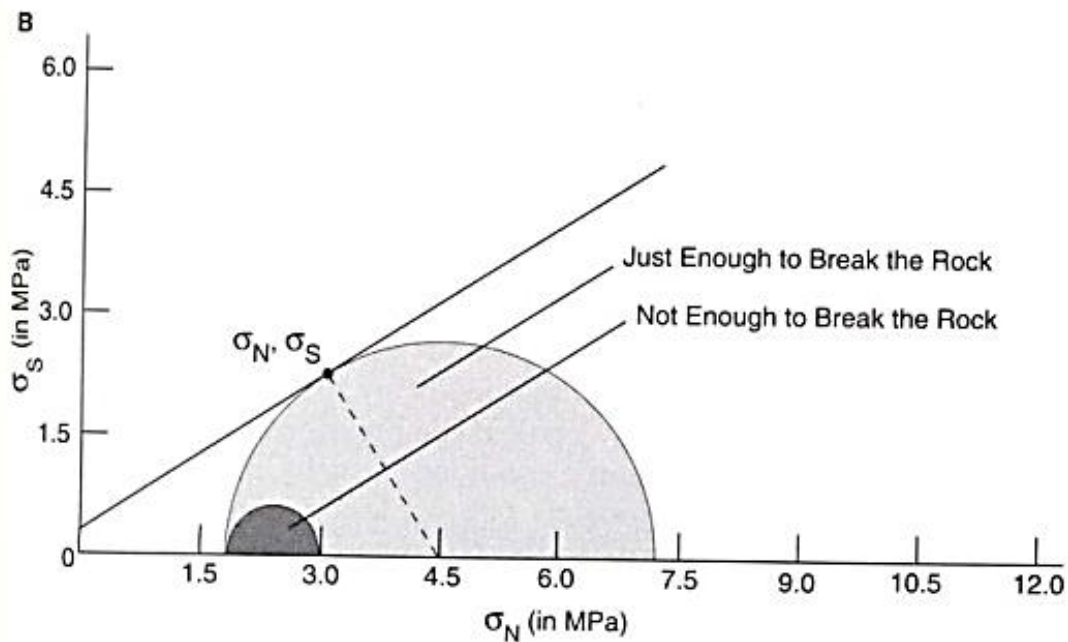
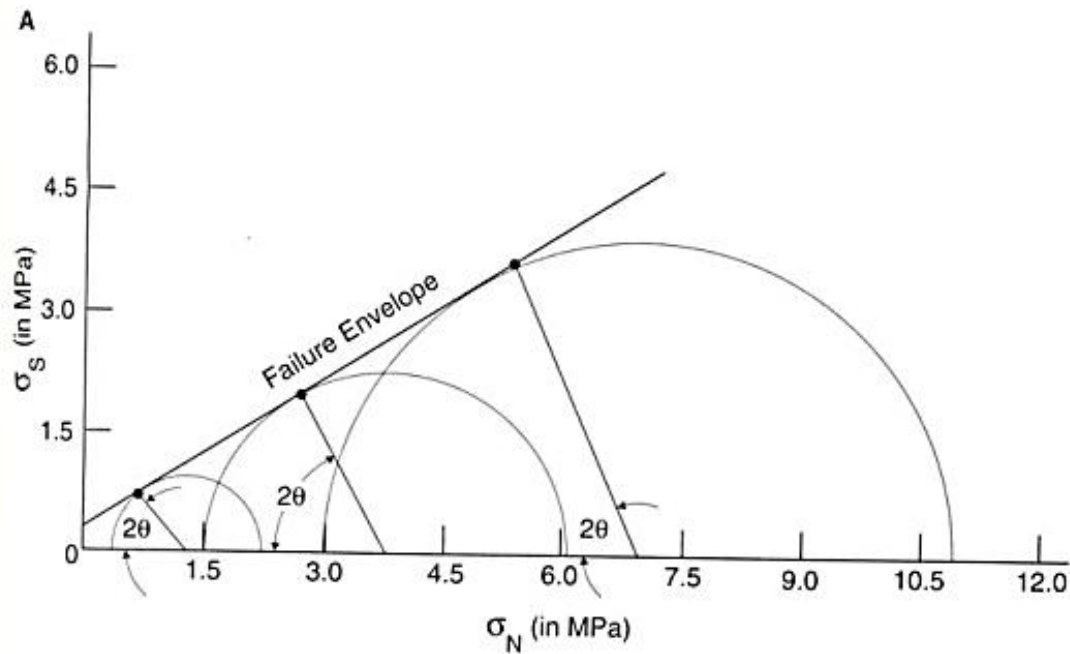


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Thank you

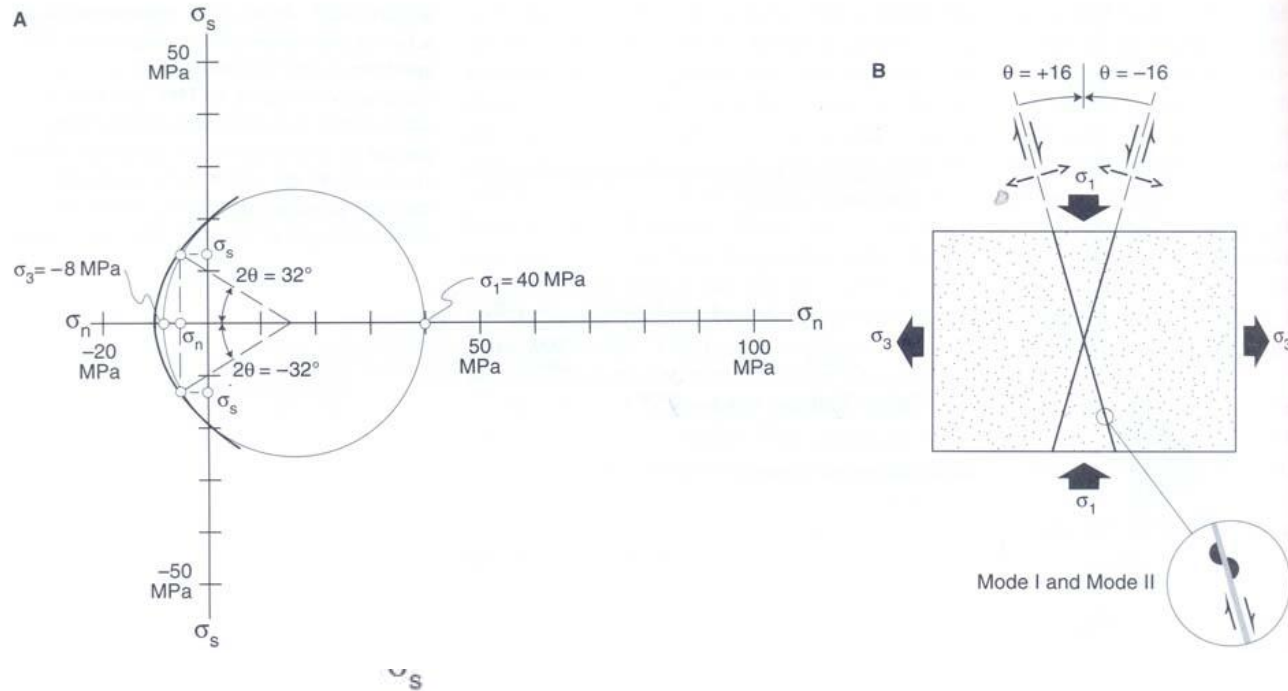


Figure 5.38 (A) Mohr circle representation of a tensile and compressive strength test under the special condition where confining pressure has a value greater than $3 \times$ tensile strength (T_0) but less than $5 \times$ tensile strength (T_0). The failure envelope for these conditions is parabolic (see darkened curve). (B) These conjugate fractures formed under conditions of transitional tensile behavior. Note that they are partly tensile (mode I) and partly shear. They intersect at an unusually small angle (in this case, 32°), which is bisected by the direction of greatest principal stress (σ_1).

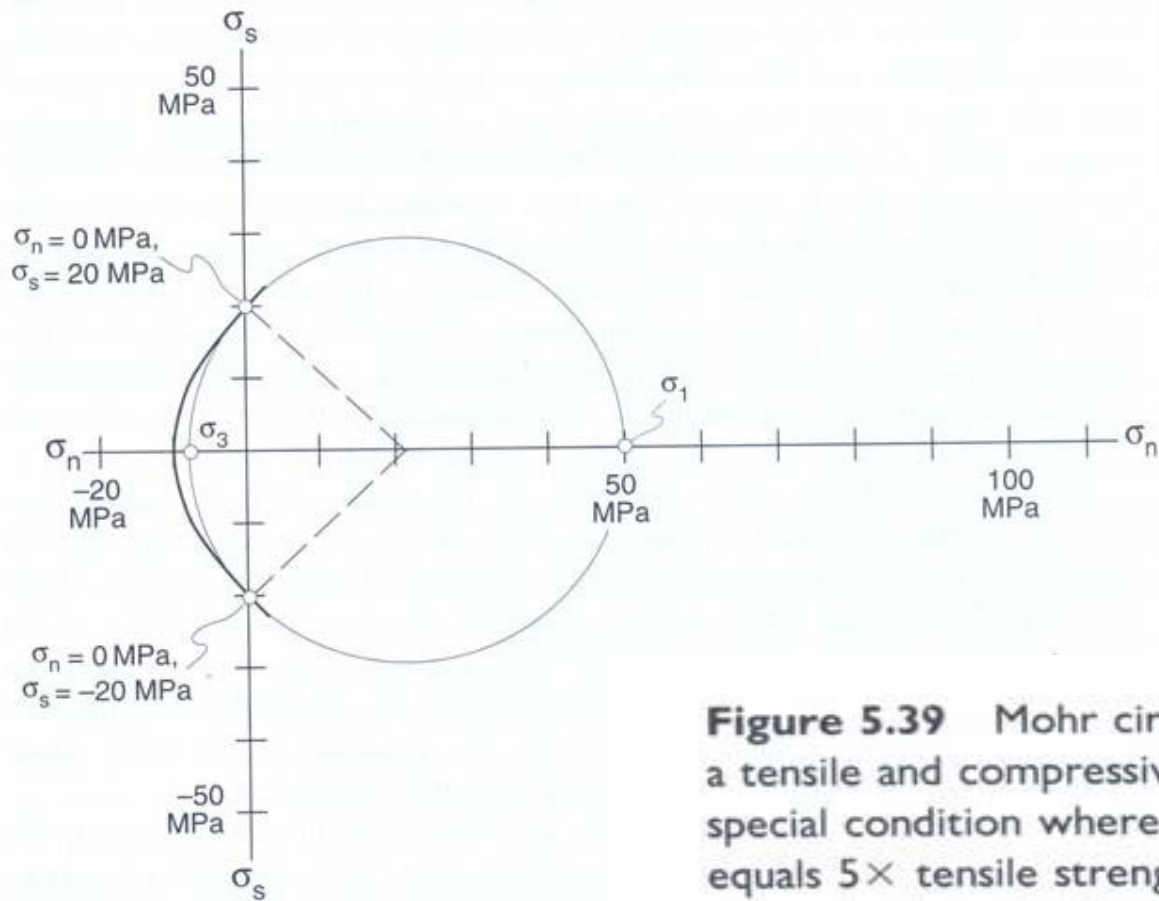


Figure 5.39 Mohr circle representation of a tensile and compressive test under the special condition where confining pressure equals $5 \times$ tensile strength (T_0). The normal stress (σ_N) on the fracture at failure is zero. The shear stress (σ_S) is equal approximately to twice the tensile strength (T_0).

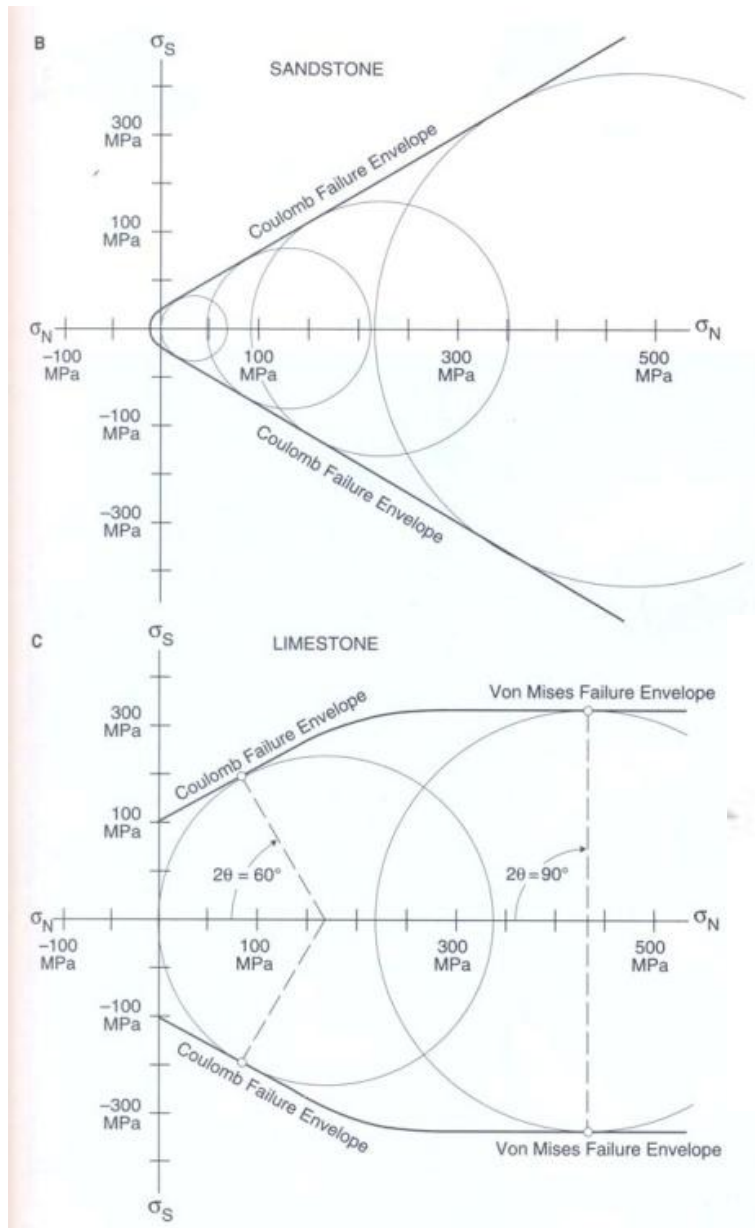


Figure 5.44 (continued) (B) Schematic portrayal of failure envelope for a rock marked by low tensile strength, low cohesive strength, and low internal friction. (C) Schematic portrayal of failure envelope for a rock marked by high tensile strength, high cohesive strength, and high internal friction.

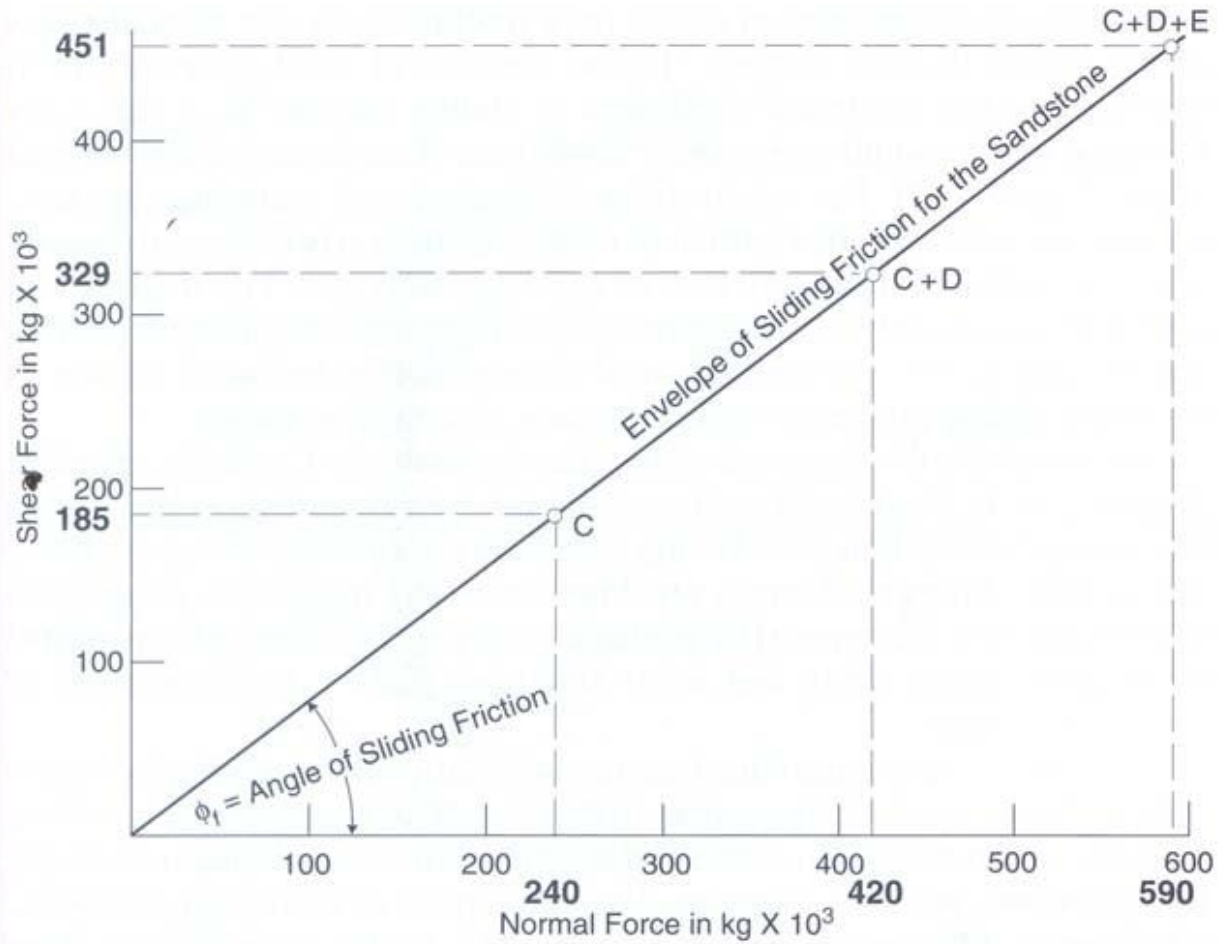


Figure 5.46 (continued) (C) Mohr-diagram plot shows the results—a straight-line relationship!!

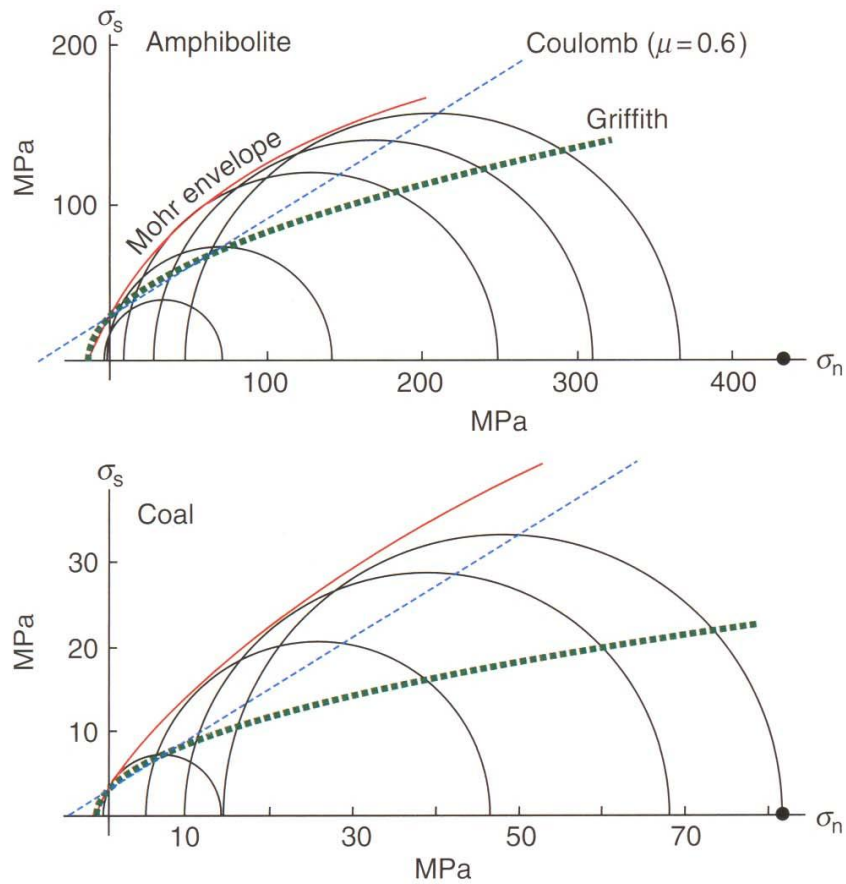


Figure 7.14 The Griffith and Coulomb fracture criteria superimposed on the experimental data presented in Figure 7.11. The criteria are placed so that they intersect the vertical axis together with the Mohr envelope. Neither of the criteria fit the data very well. The Griffith criterion works well for tensile stress (left of origin), but shows a too low slope in the entire compressional regime. The Coulomb criterion approaches the envelope for high confining pressure (right side of the diagram).

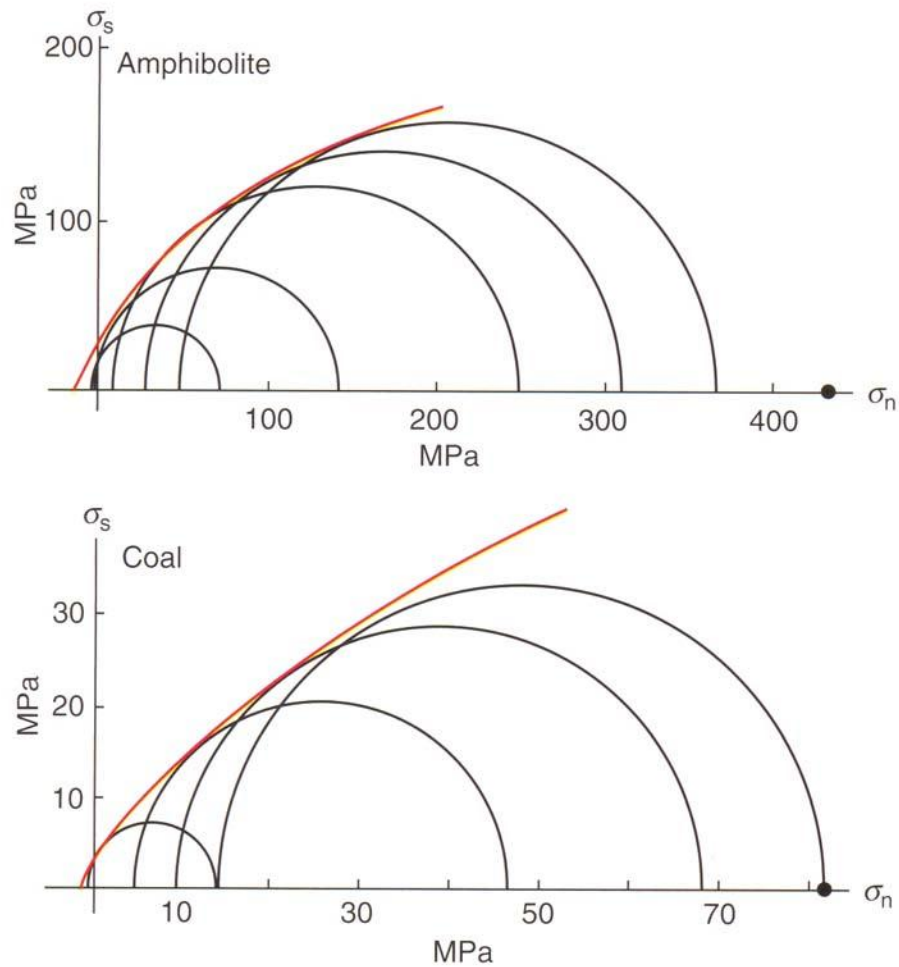


Figure 7.11 The Mohr envelope for amphibolite and coal based on triaxial tests. When the confining pressure is increased, the strength of the rock increases, and a new circle can be drawn in the figure. Note that the envelope diverges from the linear trend defined by the Coulomb criterion. From Myrvang (2001).

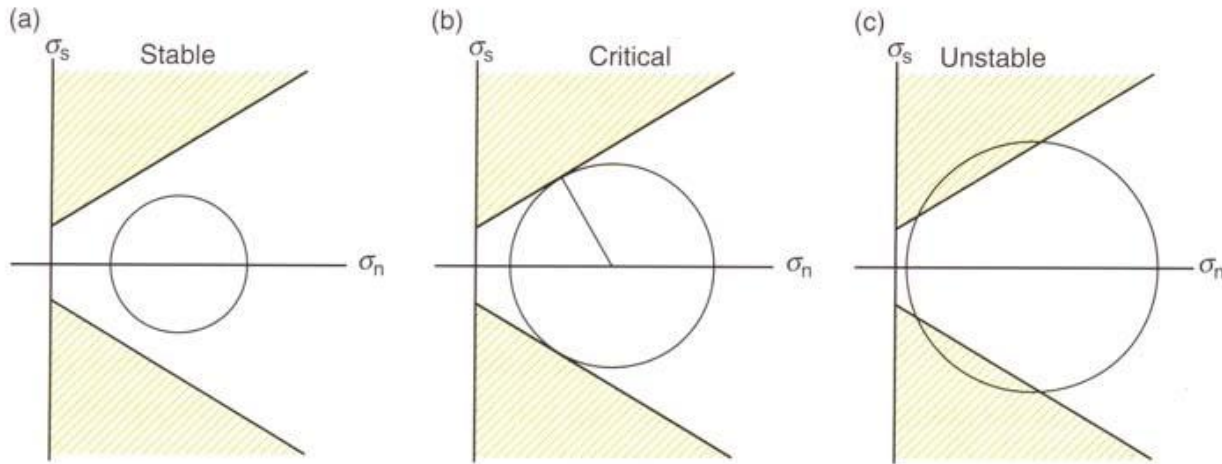


Figure 7.12 (a) Stable state of stress. (b) Critical situation, where the circle touches the envelope. This is when the rock is at the verge of failure, also called critically stressed. (c) Unstable situation where the state of stress is higher than that required for failure.

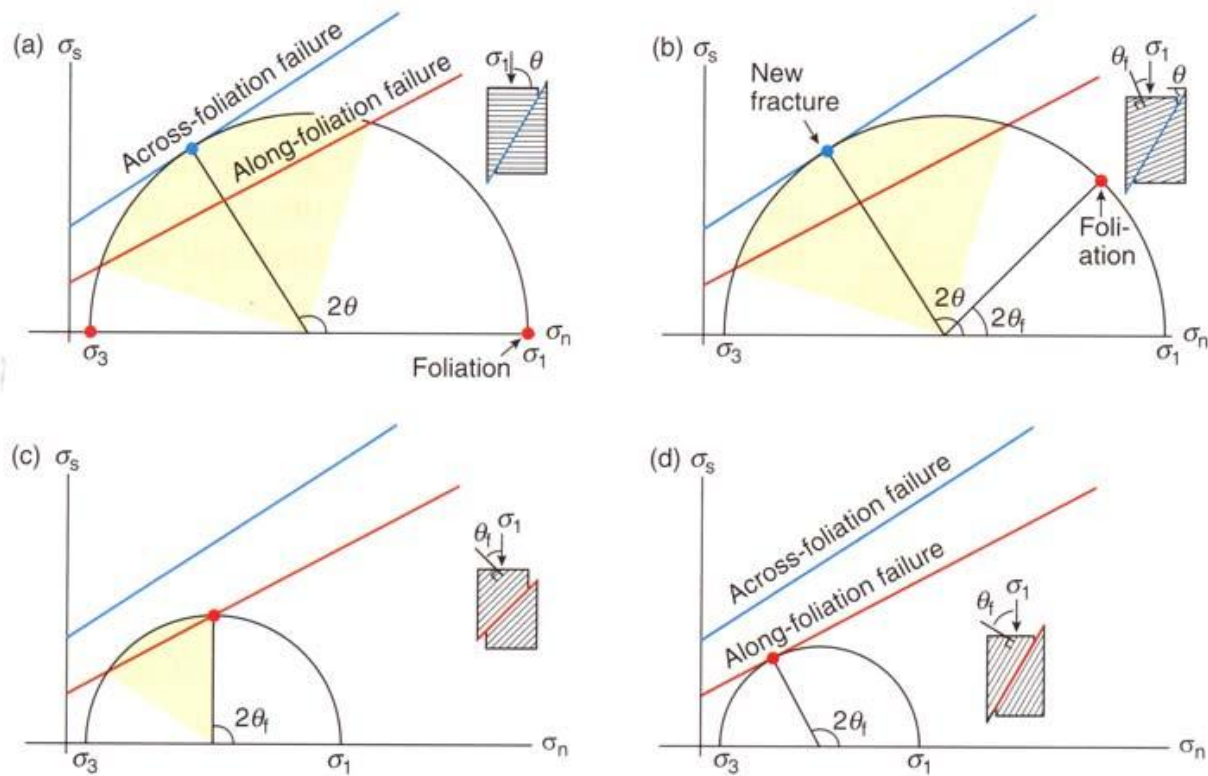


Figure 7.22 Illustration of the role of a preexisting foliation, for constant σ_3 . (a) σ_1 acting perpendicular to the foliation, in which case differential stress builds up until the Mohr circle touches the upper envelope and across-foliation failure occurs. Colored sector indicates the range of orientations for along-foliation failure. (b) σ_1 at a high angle to the foliation, still too high for foliation-parallel failure (foliation still outside of the colored sector). (c) σ_1 at 45° to the foliation, causing foliation-parallel failure. Sector indicates the range of foliation orientations where along-foliation failure would occur for this particular state of stress. (d) The angle between σ_1 and the foliation that gives failure at the lowest possible differential stress. This is the weakest direction of a foliated rock.

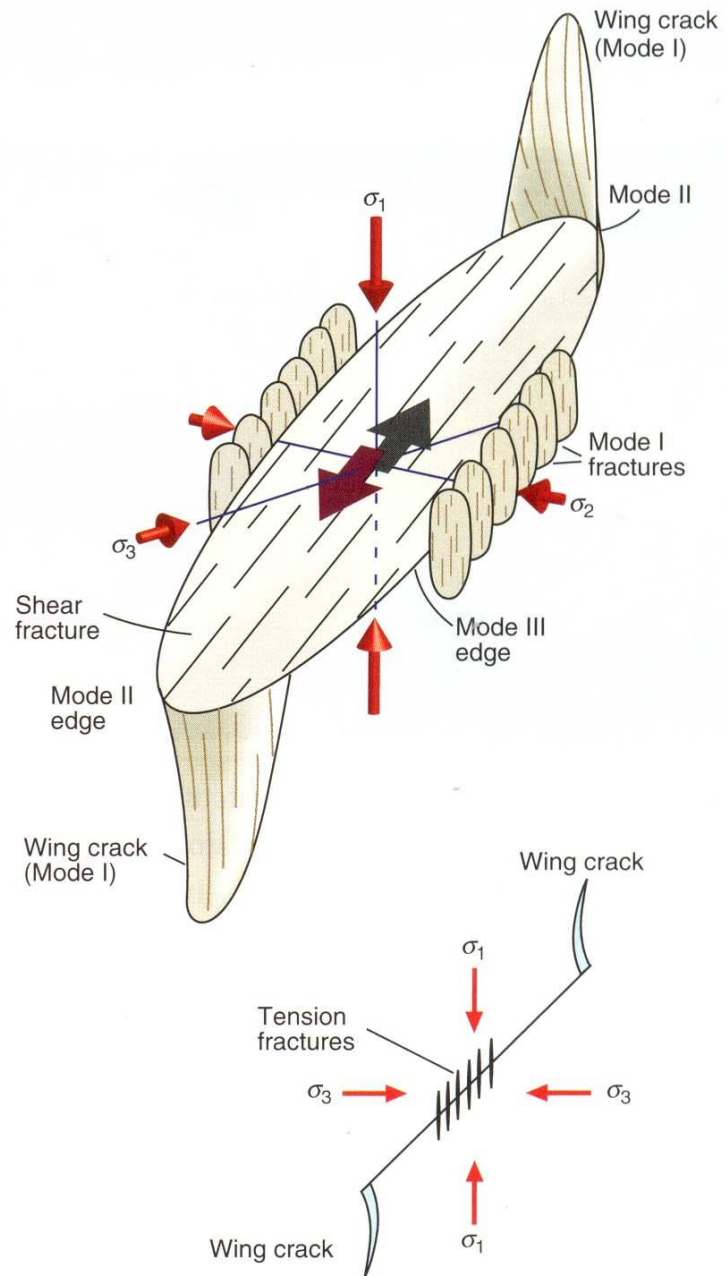


Illustration based on Scholtz (1990).

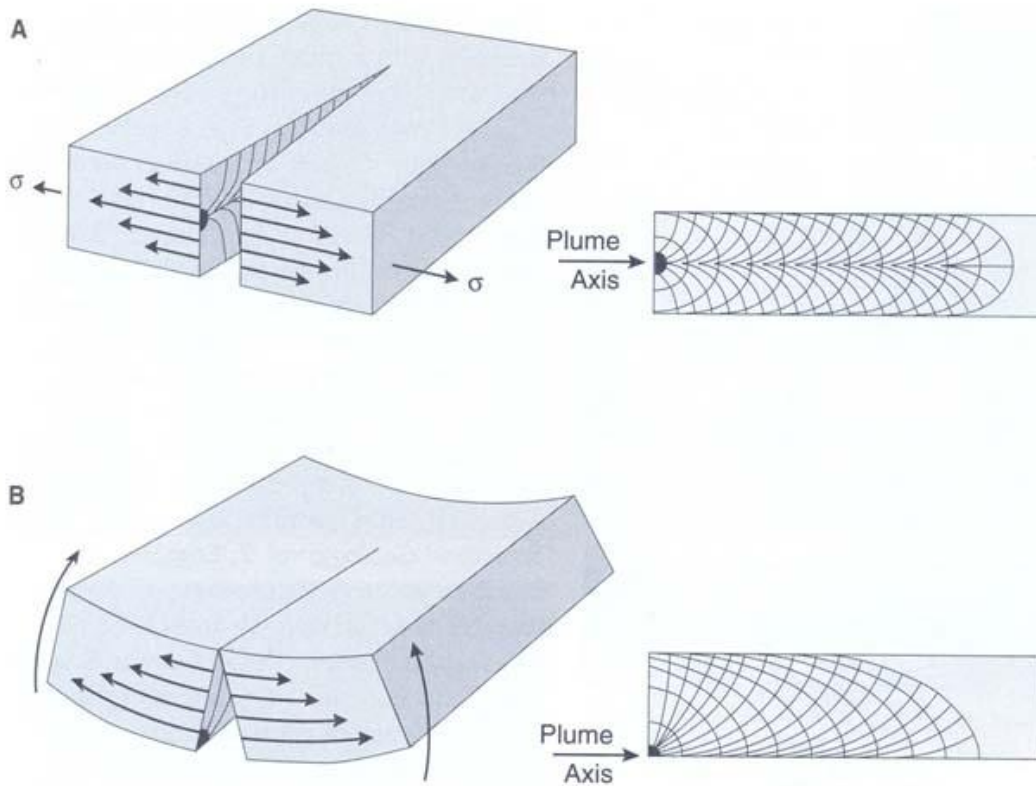


Figure 5.16 (A) Hackles produced on joint surface in rock layer broken in tension. Solid black dot is origin. Hackles radiate from origin. Parabolic curves in insert describe propagating joint front, sometimes preserved as ribs. (B) Hackles produced on joint surface produced through bending of a rock layer. Solid black dot is origin. Hackles radiate from origin. Solid curves represent propagating joint front. [From DeGraff and Aydin (1987). Published with permission of Geological Society of America.]

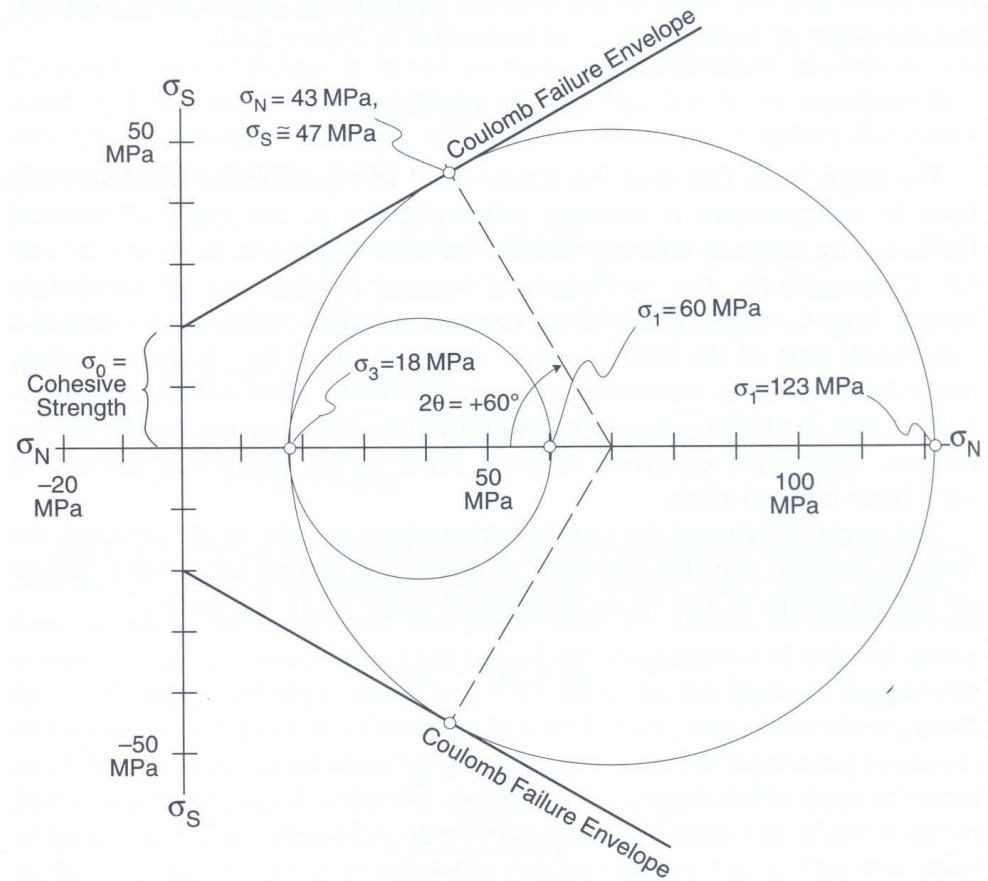


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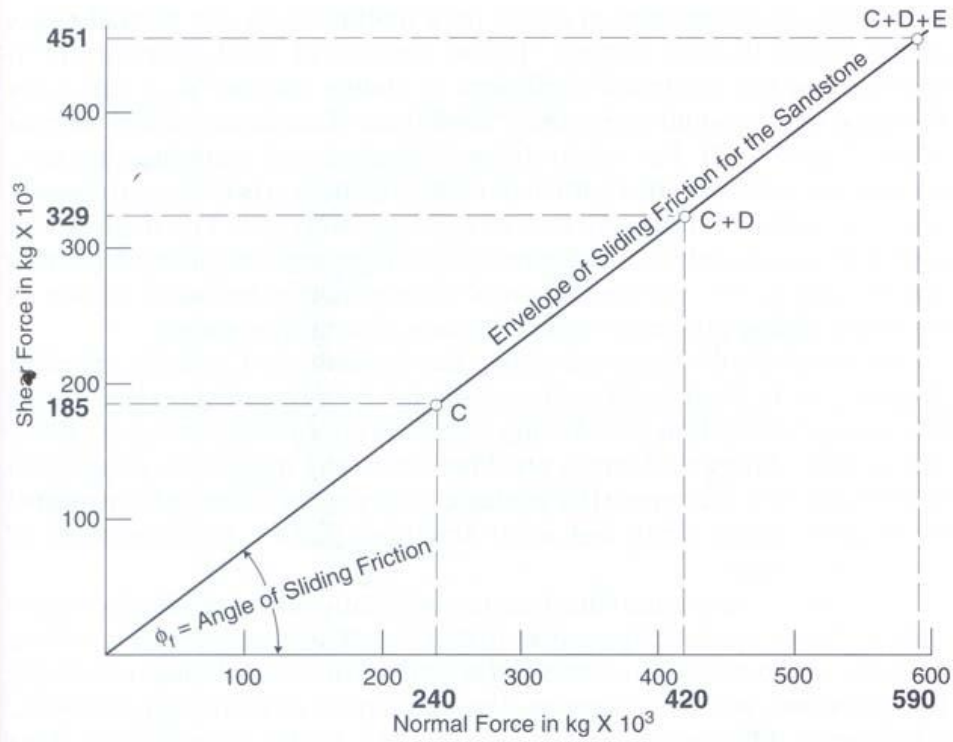


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