University of Anbar

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Department of Applied Geology

Advanced Structural Geology

Title of the lecture

Formation of Shear Fractures

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Formation of shear fractures

Shear fractures differ markedly from tensile cracks. A shear fracture is a surface across which a rock loses continuity when the shear stress parallel to the surface is sufficiently large. Shear fractures are initiated in laboratory rock cylinders at a typical angle of about 30° to σ_1 under conditions of confining pressure ($\sigma_1 > \sigma_2 = \sigma_3$). Because there is a component of normal stress acting on the fracture in addition to shear stress, friction resists sliding on the fracture during its formation. If the shear stress acting on the fracture continues to exceed the frictional resistance to sliding, the fracture grows and displacement accumulates. Shear fractures (or faults) are therefore not simply large shear-mode cracks, because, as we have seen, shear-mode cracks cannot grow in their own plane. This conceptual difference is very important. So how do shear fractures form? We can gain insight into the process of shear-fracture formation by generating shear ruptures during a laboratory triaxial loading experiment, using a rock cylinder under confining pressure. So, to begin our search for an answer to this question, we first describe such an experiment. In a confined-compression triaxial-loading experiment, we take a cylinder of rock, jacket it in copper or rubber, surround it with a confining fluid in a pressure chamber, and squeeze it between two hydraulic pistons. In the experiment shown in Figure 1, the rock itself stays dry. During the experiment, we apply a confining pressure ($\sigma_2 = \sigma_3$) to the sides of the cylinder by increasing the pressure in the surrounding fluid, and an axial load (σ_1) to the ends of the cylinder by moving the pistons together at a constant rate. By keeping the value of σ_3 constant while σ_1 gradually increases, we increase the differential stress ($\sigma d = \sigma_1 - \sigma_3$). In this experiment we measure the magnitude of σ_d, the change in length of the cylinder (which is the axial strain, e_a), and the change in volume (Δ) of the cylinder. A graph of σ_d versus e_a (Figure 1a) shows that the experiment has four stages. In Stage I, we find that as σ_d increases, e_a also increases and that the relationship between these two quantities is a concave-up curve. In Stage II of the experiment, the relationship between σ_d and e_a is a straight line with a positive slope. During Stage I and most of Stage II, the volume of the sample decreases slightly. In Stage III of the experiment, the slope of the line showing the relation between σ_d and e_a decreases. The stress at which the curve changes slope is called the **yield strength**. During the latter part of Stage II and all of Stage III, we observe a slight increase in volume, a phenomenon known as dilatancy, and if we had a very sensitive microphone attached to the sample during this time, we would hear lots of popping sounds that reflect the formation and growth of microcracks. Suddenly, when σ_d equals the failure stress (σ_f), a shear rupture surface develops at an angle of about 30° to the cylinder axis, and there is a stress drop. A stress drop in this context means that the axial stress supported by the specimen suddenly decreases and large strain accumulates at a lower stress. The value of σ_d at the instant that the shear rupture forms and the stress drops is called the **failure strength for shear rupture**. Once failure has occurred, the sample is no longer intact and frictional resistance to sliding on the fracture surface determines its further behavior. What physically happened during this experiment? During Stage I, preexisting open microcracks underwent closure. During Stage II, the sample underwent elastic shortening parallel to the axis, and because of the Poisson effect expanded slightly in the direction perpendicular to the axis (Figure 1d). The Poisson effect refers to the phenomenon in which a rock that is undergoing elastic shortening in one direction extends in the direction at right angles to the shortening direction. The ratio between the amount of shortening and the amount of extension is called Poisson's ratio, ν. At the start of Stage III, tensile microcracks begin to grow throughout the sample, and wing cracks grow at the tips of shear-mode cracks.

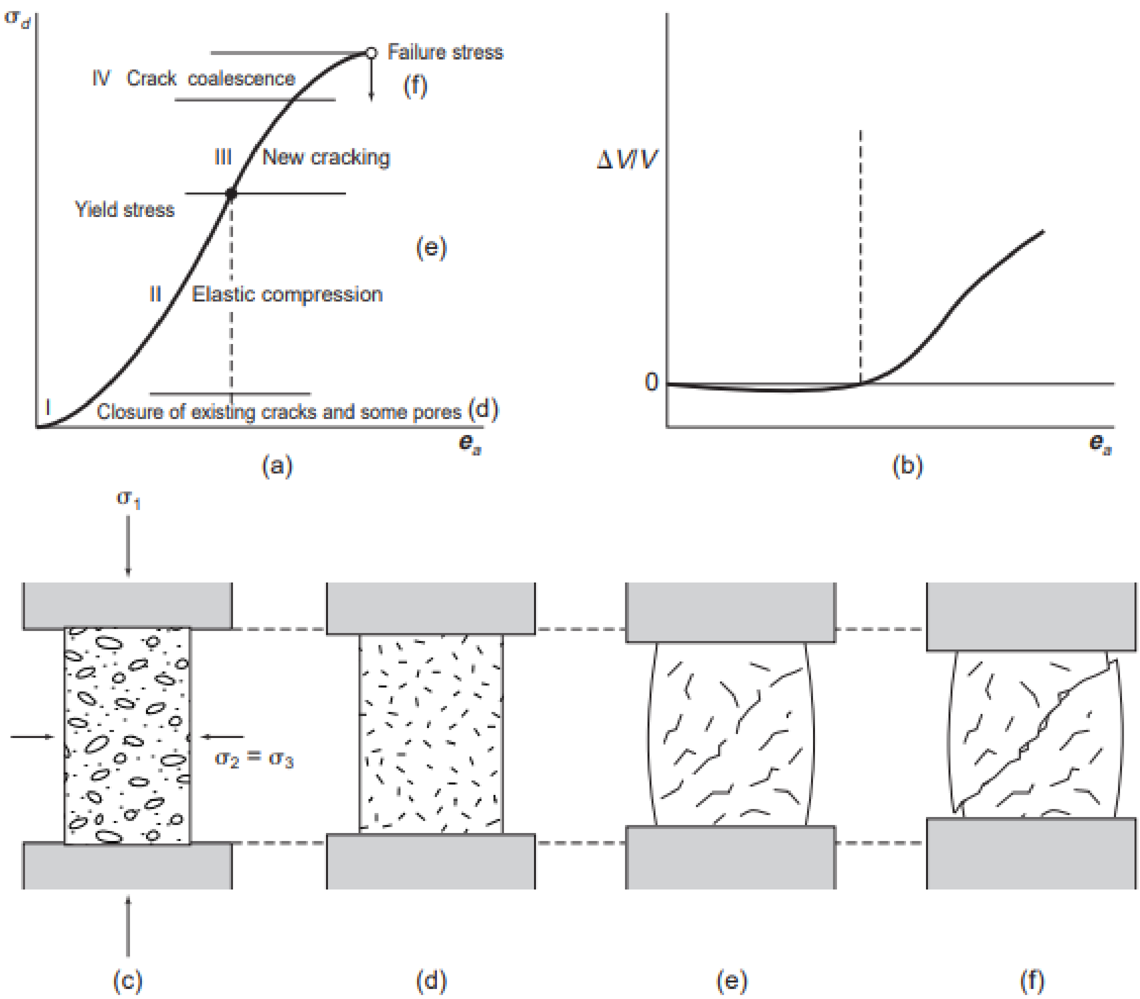

Figure 1 Fracture formation. (a) Stress–strain plot (differential stress versus axial shortening) showing the stages (I–IV) in a confined compression experiment. The labels indicate the process that accounts for the slope of the curve. (b) The changes in volume accompanying the axial shortening illustrate the phenomenon of dilatancy; left of the dashed line, the sample volume decreases, whereas to the right of the dashed line the sample volume increases. (c–f) Schematic cross sections showing the behavior of rock cylinders during the successive stages of a confined compression experiment and accompanying stress–strain plot, emphasizing the behavior of Griffith cracks (cracks shown are much larger than real dimensions). (c) Pre-deformation state, showing open Griffith cracks. (d) Compression begins and volume decreases due to crack closure. (e) Crack propagation and dilatancy (volume increase). (f) Merging of cracks along the future throughgoing shear fracture, followed by loss of cohesion of the sample (mesoscopic failure).

The initiation and growth of these cracks causes the observed slight increase in volume, and accounts for the popping noises (Figure 1e). During Stage III, the tensile cracking intensifies along a narrow band that cuts across the sample at an angle of about 30° to the axial stress. Failure occurs in Stage IV when the cracks self-organize to form a throughgoing surface along which the sample loses continuity, so that the rock on one side can frictionally slide relative to the rock on the other side (Figure 1f). As a consequence, the cylinders move together more easily and stress abruptly drops. The fracture development scenario described above shows that the failure strength for shear fracture is not a definition of the stress state at which a single crack propagates, but rather it is the stress state at which a multitude of small cracks coalesce to form a throughgoing rupture. Also note that two ruptures form in some experiments, both at ∼30° to the axial stress. The angle between these conjugate fractures is ∼60°, and the acute bisector is parallel to the maximum principal stress. With continued displacement, however, it is impossible for both fractures to remain active, because displacement on one fracture will offset the other. Thus, typically only one fracture will evolve into a throughgoing fault.

Shear-Fracture Criteria and Failure Envelopes

A **shear-fracture criterion** is an expression that describes the stress state at which a shear rupture forms and separates a sample into two pieces. Because shear-fracture initiation in a laboratory sample inevitably leads to failure of the sample, meaning that after rupture the sample can no longer support a load that exceeds the frictional resistance to sliding on the fracture surface, shear-rupture criteria are also commonly known as shear-failure criteria. Charles Coulomb was one of the first to propose a **shear-fracture criterion**.

He suggested that if all the principal stresses are compressive, as is the case in a confined compression experiment, a material fails by the formation of a shear fracture, and that the shear stress parallel to the fracture surface, at the instant of failure, is related to the normal stress by the equation

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

where σ_s is the shear stress parallel to the fracture surface at failure; C is the cohesion of the rock, a constant that specifies the shear stress necessary to cause failure if the normal stress across the potential fracture plane equals zero; σ_n is the normal stress across the shear fracture at the instant of failure; and μ is a constant traditionally known as the **coefficient of internal friction**. The name for μ originally came from studies of friction between grains in unconsolidated sand and of the control that such friction has on slope angles of sand piles, so the name is essentially meaningless in the context of shear failure of a solid rock; μ should be viewed simply as a constant of proportionality. The equation, also known as **Coulomb's failure criterion**, basically states that the shear stress necessary to initiate a shear fracture is proportional to the normal stress across the fracture surface. The Coulomb criterion plots as a straight line on a Mohr diagram (Figure 2). To see this, let's plot the results of four triaxial loading experiments in which we increase the axial load on a confined granite cylinder until it ruptures. In the first experiment, we set the confining pressure ($\sigma_2 = \sigma_3$) at a relatively low value, increase the axial load (σ_1) until the sample fails, and then plot the Mohr circle representing this **critical stress state**, meaning the stress state at the instant of failure, on the Mohr diagram. When we repeat the experiment, using a new cylinder, and starting at a higher confining pressure, we find that as σ_3 increases, the differential stress ($\sigma_1 - \sigma_3$) at the instant of failure also increases. Thus, the Mohr circle representing the second experiment has a larger diameter and lies to the right of the first circle. When we repeat the experiment two more times and plot the four circles on the diagram, we find that they are all tangent to a straight line with a slope of μ (i.e., tan φ) and a y-intercept of C, and this straight line is the Coulomb criterion. Note that we can also draw a straight line representing the criterion in the region of the Mohr diagram below the σn-axis.

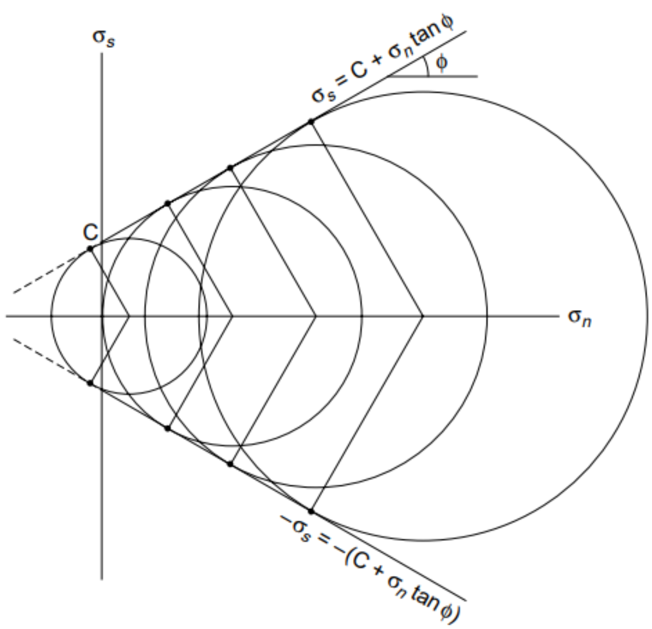

Figure 2Mohr diagram showing a Coulomb failure envelope based on a set of experiments with increasing differential stress. The circles represent differential stress states at the instant of shear failure. The envelope is represented by two straight lines, on which the dots represent failure planes

A line drawn from the center of a Mohr circle to the point of its tangency with the Coulomb criterion defines 2θ, where θ is the angle between the σ_3 direction and the plane of shear fracture (typically about 30°). Because the Coulomb criterion is a straight line, this angle is constant for the range of confining pressures for which the criterion is valid. The reason for the 30° angle becomes evident in a graph plotting normal stress magnitude and shear stress magnitude as a function of the angle between the plane and the σ_1 direction (Figure 3). Notice that the minimum normal stress does not occur in the same plane as the maximum shear stress. Shear stress is at its highest on a potential failure plane oriented at 45° to σ_1, but the normal stress across this potential plane is still too large to permit shear fracturing in planes of this orientation. The shear stress is a bit lower across a plane oriented at 30° to σ_1, but is still fairly high. However, the normal stress across the 30° plane is substantially lower, favoring shear-fracture formation.. This failure criterion does not relate the stress state at failure to physical parameters, as does the Griffith criterion, nor does it define the state of stress in which the microcracks, which eventually coalesce to form the shear rupture, begin to propagate. The Coulomb criterion does not predict whether the fractures that form will dip to the right or to the left with respect to the axis of the rock cylinder in a triaxial loading experiment. In fact, as mentioned earlier, **conjugate shear fractures**, one with a right-lateral shear sense and one with a left lateral shear sense, may develop (Figure 4). The two fractures, typically separated by an angle of ~60°, correspond to the tangency points of the circle representing the stress state at failure with the Coulomb failure envelope. The German engineer Otto Mohr conducted further studies of shear-fracture criteria and found that Coulomb's straight-line relationship only works for a limited range of confining pressures.

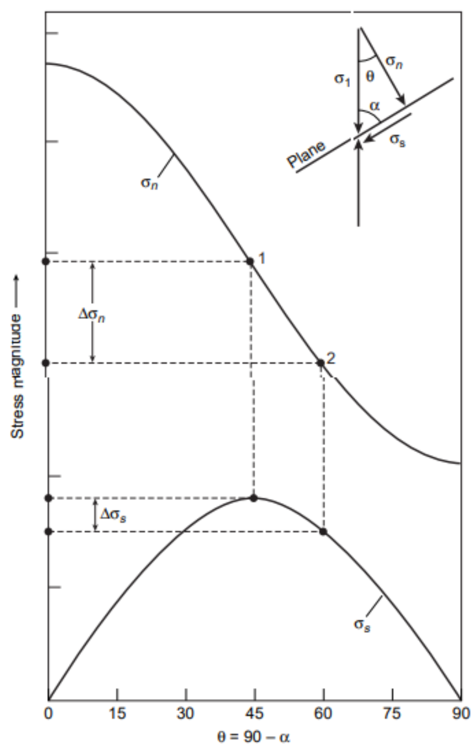

Figure 3 The change in magnitudes of the normal and shear components of stress acting on a plane as a function of the angle α between the plane and the σ1 direction; the angle θ = 90 – α is plotted for comparison with other diagrams. At point 1 (α=θ= 45°), shear stress is a maximum, but the normal stress across the plane is quite large. At point 2 (θ = 60°, α = 30°), the shear stress is still quite high, but the normal stress is much lower.

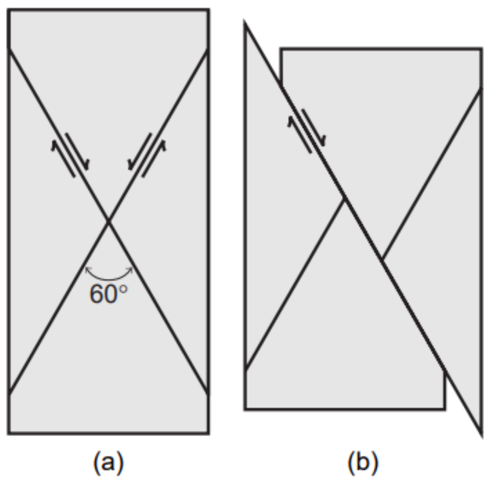

Figure 4 Cross-sectional sketch showing how only one of a pair of conjugate shear fractures (a) evolves into a fault with measurable displacement (b).

He noted that at lower confining pressure, the line representing the stress state at failure curved with a steeper slope, and that at higher confining pressure, the line curved with a shallower slope (Figure 5). Mohr concluded that over a range of confining pressure, the failure criteria for shear rupture resembles a portion of a parabola lying on its side, and this curve represents the **Mohr-Coulomb criterion** for shear fracturing. Notice that this criterion is also empirical. Unlike Coulomb's straight-line relation, the change in slope of the Mohr-Coulomb failure envelope indicates that the angle between the shear fracture plane and σ_1 actually does depend on the stress state.

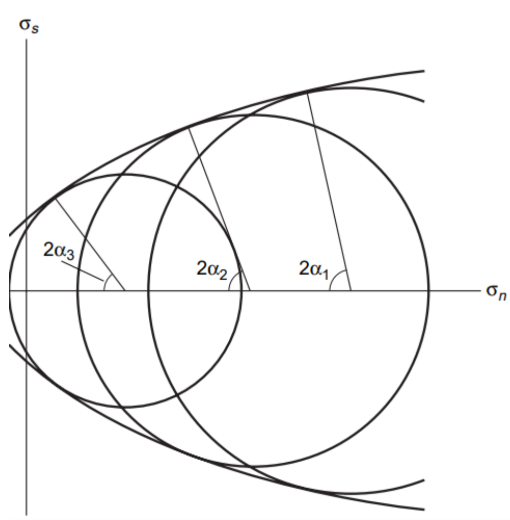

Figure 5 Mohr failure envelope. Note that the slope of the envelope steepens toward the σ_s-axis. Therefore, the value of α (the angle between fault and σ_1) is not constant (compare $2\alpha_1$, $2\alpha_2$, and $2\alpha_3$).

At lower confining pressures, the angle is smaller, and at high confining pressures, the angle is steeper. The Mohr-Coulomb criterion (both for positive and negative values of σ_s) defines a failure envelope on the Mohr diagram. A **failure envelope** separates the field on the diagram in which stress states are "stable" from the field in which stress states are "unstable" (Figure 6). By this definition, a **stable stress state** is one that a sample can withstand without undergoing brittle failure. An **unstable stress state** is an impossible condition to achieve, for the sample will have failed by fracturing before such a stress state is reached (Figure 6). In other words, a stress state represented by a Mohr circle that lies entirely within the envelope is stable, and will not cause the sample to develop a shear rupture. A circle that is tangent to the envelope specifies the stress state at which brittle failure occurs. Stress states defined by circles that extend beyond the envelope are unstable, and are therefore impossible within the particular rock being studied. Can we define a failure envelope representing the critical stress at failure for very high confining pressures, very low confining pressures, or for conditions where one of the principal stresses is tensile? The answer to this question is controversial. We'll look at each of these conditions separately. At high confining pressures, samples may begin to deform plastically. Under such conditions, we are no longer really talking about brittle deformation, so the concept of a "failure" envelope no longer really applies. However, we can approximately represent the "yield" envelope, meaning the stress state at which the sample begins to yield plastically, on a Mohr diagram by a pair of lines that parallel the σ_n-axis (Figure 7a). This yield criterion, known as **Von Mises criterion**, indicates that plastic yielding is effectively independent of the differential stress, once the yield stress has been achieved. If the tensile stress is large enough, the sample fails by developing a throughgoing tensile crack. The tensile stress necessary to induce tensile failure may be represented by a point, T_0, the **tensile strength**, along the σ_n-axis to the left of the σ_s-axis (Figure 7b). As we have seen, however, the position of this point depends on the size of the flaws in the sample.

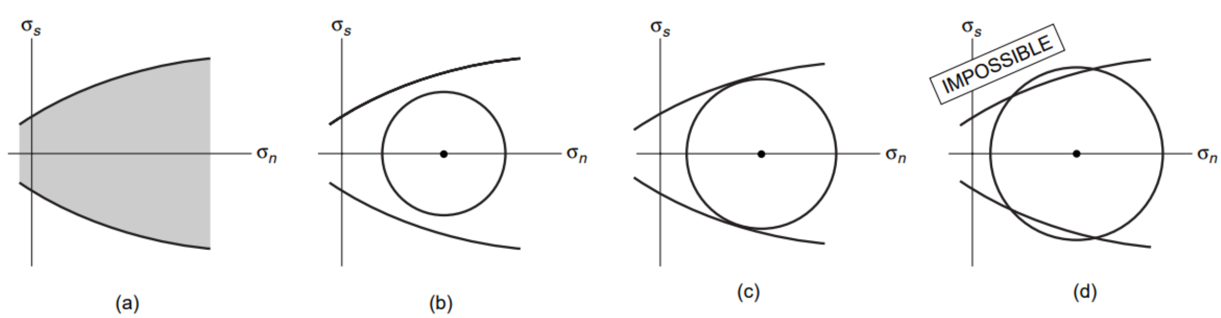

Figure 6(a) A brittle failure envelope as depicted on a Mohr diagram. Within the envelope (shaded area), stress states are stable, but outside the envelope, stress states are unstable. (b) A stress state that is stable, because the Mohr circle, which passes through values for σ1 and σ3 and defines the stress state, falls entirely inside the envelope. (c) A stress state at the instant of failure. The Mohr circle touches the envelope. (d) A stress state that is impossible.

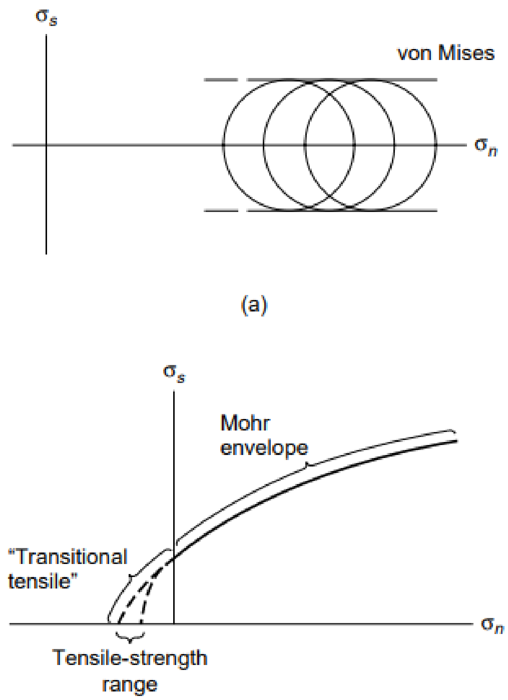

Figure 7 (a) Mohr diagram illustrating the Von Mises yield criterion. Note that the criterion is represented by two lines that parallel the σn-axis. (b) The extrapolation of a Mohr envelope to its intercept with the σn-axis, illustrating the "transitional-tensile" regime, and the tensile strength (T0). Note that the tensile strength has a range of values, because it depends on the dimensions of preexisting flaws in the deforming sample

Thus, even for the same rock type, experiments show that the tensile strength is very variable and that it is best represented by a range of points along the σ_n-axis. There are competing views as to the nature of failure for rocks subjected to tensile stresses that are less than the tensile strength. Some geologists have suggested that failure occurs under such conditions by the formation of fractures that are a hybrid between tensile cracks and shear ruptures, and have called these fractures **transitional-tensile fractures** or **hybrid shear fractures**. The failure envelope representing the conditions for initiating transitional-tensile fractures is the steeply sloping portion of the parabolic failure envelope (Figure 7b). Most fracture specialists, however, claim that transitional-tensile fractures do not occur in nature, and point out that no experiments have yet clearly produced transitional-tensile fractures in the lab. Taking all of the above empirical criteria into account, we can construct a composite failure envelope that represents the boundary between stable and unstable stress states for a wide range of confining pressures and for conditions for which one of the principal stresses is tensile (Figure 8). The envelope roughly resembles a cross section of a cup lying on its side. The various parts of the curve are labeled. Starting at the right side of the diagram, we have Von Mises criteria, represented by horizontal lines. (Remember that the Von Mises portion of the envelope is really a plastic yield criterion, not a brittle failure criterion).

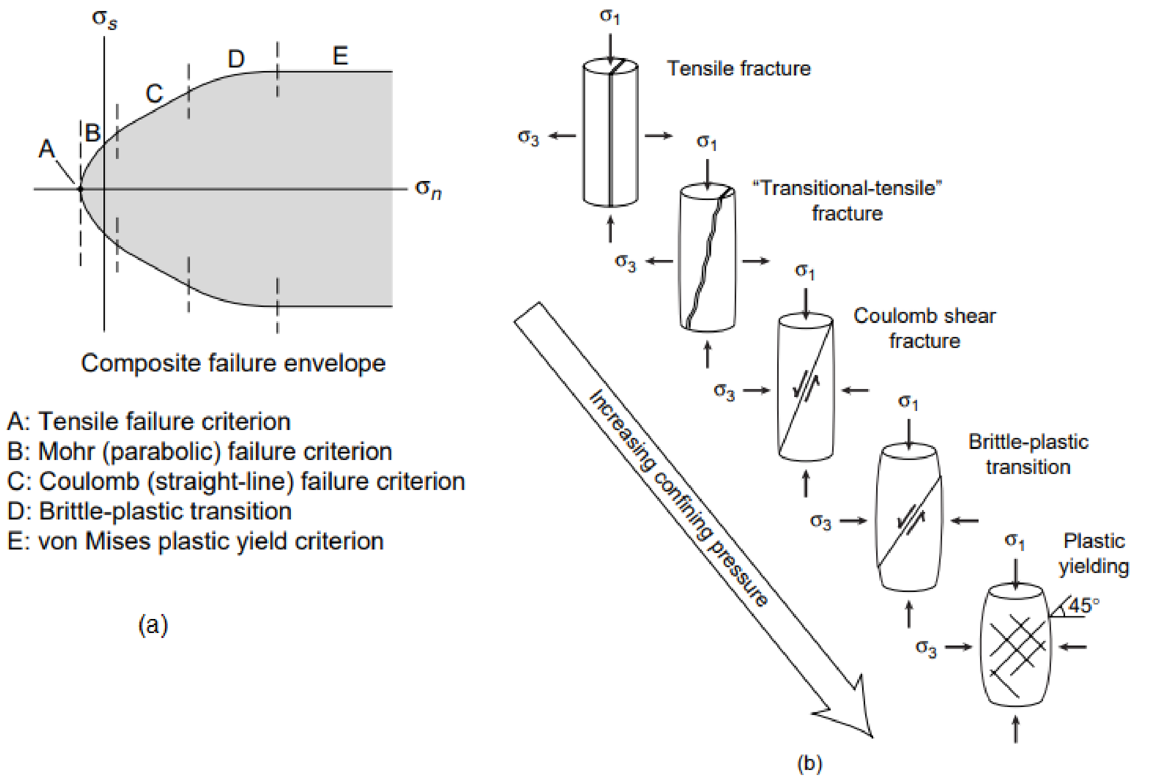

Figure 8 (a) A representative composite failure envelope on a Mohr diagram. The different parts of the envelope are labeled, and are discussed in the text. (b) Sketches of the fracture geometries that form during failure. Note that the geometry depends on the part of the failure envelope that represents failure conditions, because the slope of the envelope is not constant.

The portion of the curve where the lines begin to slope effectively represents the brittle–plastic transition. To the left of the brittle–plastic transition, the envelope consists of two straight sloping lines, representing Coulomb's criterion for shear rupturing. For failure associated with the Coulomb criterion, remember that the angle between the shear rupture and the σ1 direction is independent of the confining pressure. Closer to the σ_s-axis, the slope of the envelope steepens, and the envelope resembles a portion of a parabola. This parabolic part of the curve represents Mohr's criterion, and for failure in this region, the decrease in the angle between the fracture and the σ1 direction depends on how far to the left the Mohr circle touches the failure curve. The part of the parabolic envelope with steep slopes specifies failure criteria for supposed transitional tensile fractures formed at a very small angle to σ_1, but as we discussed, the existence of such fractures remains controversial. The point where the envelope crosses the σ_n-axis represents the failure criterion for tensile cracking, but as we have discussed, this criterion really shouldn't be specified by a point, for the tensile strength of a material depends on the dimensions of the flaws it contains. Note that for a circle tangent to the composite envelope at T_0, $2\theta = 180$ (or, $\alpha = 0$), so the fracture that forms is parallel to σ_1! Also, note that there is no unique value of differential stress needed to cause tensile failure, as long as the magnitude of the differential stress (the diameter of the Mohr circle) is less than about $4T_0$, for this is the circle whose curvature is the same as that of the apex of the parabola.

Effect of environmental factors in failure

The occurrence and character of brittle deformation at a given location in the earth depends on environmental conditions (confining pressure, temperature, and fluid pressure) present at that location, and on the strain rate. Conditions conducive to the occurrence of brittle deformation are more common in the upper 10–15 km of the Earth's crust. However, at slow strain rates or in particularly weak rocks, ductile deformation mechanisms can also occur in this region, as evident by the development of folds at shallow depths in the crust. Below 10–15 km, plastic deformation mechanisms dominate. However, at particularly high fluid pressures or at very rapid strain rates, brittle deformation can still occur at these depths. We have described brittle deformation without considering how it is affected by environmental factors. Not surprisingly, temperature, fluid pressure, strain rate, and rock anisotropy play significant roles in the stress state at failure and/or in the orientation of the fractures that form when failure occurs. Most of these factors have already been discussed, so we close on brittle deformation by focusing on the effect of fluids.

Effect of Fluids on Tensile Crack Growth

All rocks contain pores and cracks—we've already seen how important these are in the process of brittle failure. In the upper crust of the earth below the water table, these spaces, which constitute the porosity of rock, are filled with fluid. This fluid is most commonly water, though in some places it is oil or gas. If there is a high degree of **permeability** in the rock, meaning that water can flow relatively easily from pore to pore and/or in and out of the rock layer, then the pressure in a volume of pore water at a location in the crust is roughly hydrostatic, meaning that the pressure reflects the weight of the overlying water column (Figure 9).

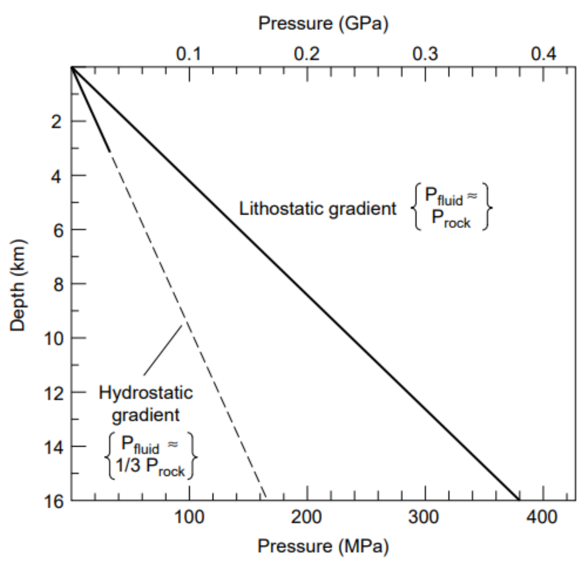

Figure 9 Graph of lithostatic versus hydrostatic pressure as a function of depth in the Earth's crust.

Hydrostatic (fluid) **pressure** is defined by the relationship $P_f = \rho \cdot g \cdot h$, where ρ is the density of water (1000 kg/m3), g is the gravitational constant (9.8 m/s2), and h is the depth. **Pore pressure**, which is the fluid pressure exerted by fluid within the pores of a rock, may exceed the hydrostatic pressure if permeability is restricted. For example, the fluid trapped in a sandstone lens surrounded by impermeable shale cannot escape, so the pore pressure in the sandstone can approach or even equal **lithostatic pressure** (P_l), meaning that the pressure approaches the weight of the overlying column of rock (i.e., $P_f = P_l = \rho \cdot g \cdot h$, where ρ = 2000–3000 kg/m3). Note that rock, on average, is two to three times denser than water. When the fluid pressure in pore water exceeds hydrostatic pressure, we say that the fluid is **overpressured**.

How does pore pressure affect the tensile failure strength of rock? The pore pressure is an outward push that opposes inward compression from the rock, so the fluid supports part of the applied load. If pore pressure exceeds the least compressive stress (σ_3) in the rock, tensile stresses at the tips of cracks oriented perpendicularly to the σ_3 direction become sufficient for the crack to propagate. In other words, pore pressure in a rock can cause tensile cracks to propagate, even if none of the remote stresses are tensile, because pore pressure can induce a crack-tip tensile stress that exceeds the magnitude of σ_3. This process is called **hydraulic fracturing**. On a Mohr diagram, it can be represented by movement of Mohr's circle to the left (Figure 10). Note that rocks do not have to be over-pressured in order for natural hydraulic fracturing to occur, but P_f must equal or exceed the magnitude of σ_3.

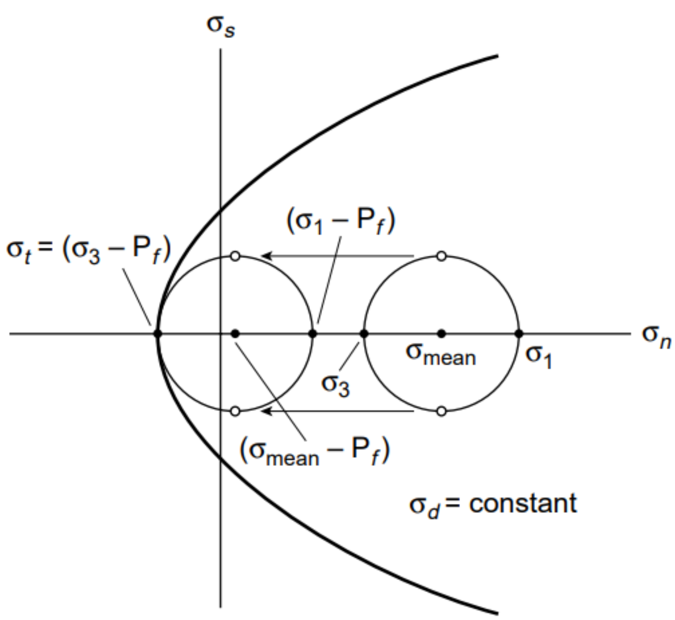

Figure 10 A Mohr diagram showing how an increase in pore pressure moves the Mohr circle toward the origin. The increase in pore pressure decreases the mean stress (σ_{mean}), but does not change the magnitude of differential stress ($\sigma_1 - \sigma_3$). In other words, the diameter of the Mohr circle remains constant, but its center moves to the left.

Another effect of fluids comes from the chemical reaction of the fluids with the minerals comprising a rock. Reaction with fluids may lower the tensile stress needed to cause a crack to propagate, even if the pore-fluid pressure is low. Water, for example, reacts with quartz to bring about substitution of OH molecules for O atoms in quartz lattice at a crack tip. Since the bond between adjacent OH groups is not as strong as the bond between oxygen atoms, it breaks more easily, so it takes less remote tensile stress to cause the crack to propagate. This phenomenon is called **subcritical crack growth**, because crack propagation occurs at stresses less than the critical stress necessary to cause a crack to propagate in dry rock.

Effect of Pore Pressure on Shear Failure and Frictional Sliding

We can observe the effects of pore pressure on shear fracturing by running a confined compression experiment in which we pump fluid into the sample through a hole in one of the pistons, thereby creating a fluid pressure, P_f, in pores of the sample. The fluid creating the confining pressure acting on the sample is different from and is not connected to the fluid inside the sample. The magnitude of P_f decreases the confining pressure (σ_3) and σ_1 by the same amount. So, if the pore pressure increases in the sample, the mean stress decreases but the differential stress remains the same. This effect can be represented by the Coulomb failure criterion equation; P_f decreases the magnitude of σ_n on the right side of the equation

$$\sigma_s = C + \mu(\sigma_n - P_f)$$

The term ($\sigma_n - P_f$) is commonly labeled σ_n*, and is called the **effective stress**. From a Mohr diagram, we can easily see the effect of increasing the P_f in this experiment. When P_f is increased, the whole Mohr circle moves to the left but its diameter remains unchanged (Figure 10), and when the circle touches the failure envelope, shear failure occurs, even if the relative values of σ_1 and σ_3 are unchanged. In other words, a differential stress that is insufficient to break a dry rock, may break a wet rock, if the fluid in the wet rock is under sufficient pressure. Thus, an increase in pore pressure effectively weakens a rock. In the case of forming a shear fracture in intact rock, pore pressure plays a role by pushing open microcracks, which coalesce to form a rupture at smaller remote stresses. Similarly, an increase in pore pressure decreases the shear stress necessary to initiate frictional sliding on a preexisting fracture, for the pore pressure effectively decreases the normal stress across the fracture surface. Thus, fluids play an important role in controlling the conditions under which faulting occurs.

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