Lab 5: Brittle faults

Fall 2005

1 Review of brittle behavior/Mohr-Coulomb failure

A material is said to exhibit Coulomb behavior when its strength increases linearly with increasing confining pressure. The strength of the material, called the Coulomb fracture criteria, is given by:

$$|\sigma_\tau| = s_0 + \sigma_n \tan\phi$$

σ_τ is the shear stress

σ_n is the normal stress

s_0 is called the *cohesive shear strength*

ϕ is called the *angle of internal friction*

In $\sigma - \tau$ space, the Coulomb fracture criterion plots as a line with slope $\tan\phi$ and τ intercept $= s_0$ (see below). When shear stresses in the material equal or exceed the Coulomb fracture criterion, the material fractures. Thus, when the state of stress of a body is represented by a Mohr circle (in $\sigma - \tau$ space), fracture will occur when the Mohr circle becomes tangent to the Coulomb fracture criterion. Moreover, the tangent point is related to the orientation of the fracture that develops via the angle 2α read off the Mohr diagram.
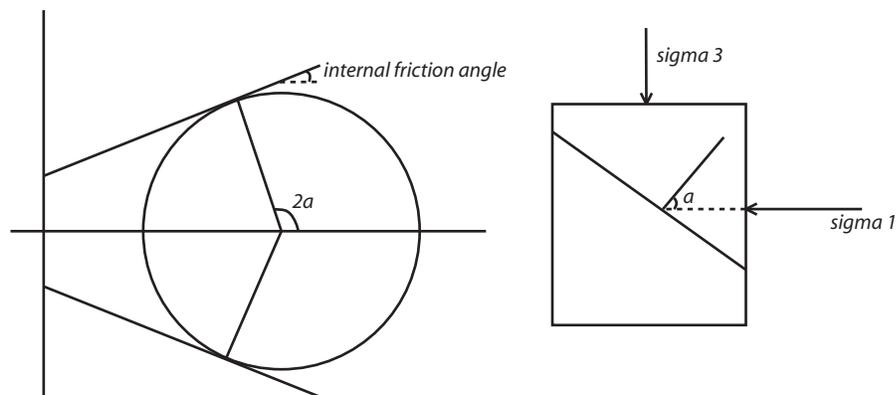

Figure 1:

In many geologic problems, we would like to be able to infer the stresses which formed the structures that we can observe. By making some simplifying assumptions, we can use observed fault geometry (orientation of fault planes or joint surfaces and sense of slip) to get a good first order approximation of the orientations and relative magnitudes of the stresses which acted to produce the faults or joints.

Coulomb failure (fracture) occurs along two planes that are oriented symmetrically about the $\sigma 1$ and $\sigma 3$ directions where the shear stress equals the shear strength of the rock. Since the three principal stresses are mutually orthogonal, the intersection of a conjugate pair of Coulomb fracture planes will always be parallel to $\sigma 2$; the $\sigma 1$ and $\sigma 3$ directions will bisect the angles between the planes ($\sigma 1$ always bisects the acute angle between the failure planes, see below). If we make the assumption that the faults in the shallow crust are produced by Coulomb fracture, then we can use the preceding relationships to determine the orientations of $\sigma 1$, $\sigma 2$ and $\sigma 3$. In addition, we can determine the internal angle of friction for the rock from the relationship $\theta = 45° + \phi/2$.

If we know only one fault plane, but also know the slip direction, it is still possible to estimate the orientations of the principal stress directions. Given a fault plane and a direction of motion (inferred from slickensides, for example), $\sigma 1$, $\sigma 2$, and $\sigma 3$ can be estimated. Knowing the slip direction, $\sigma 2$ is contained within the plane of the fault and oriented perpendicular to the slip direction in the fault plane (see below). $\sigma 1$ and $\sigma 3$ must then be in a plane perpendicular to the $\sigma 2$ axis. Then, one can assume an angle of internal friction, ϕ, (usually taken to be 30°) and $\sigma 1$ and $\sigma 3$ can be found (see below). A stereonet is well suited to solve this sort of problem.
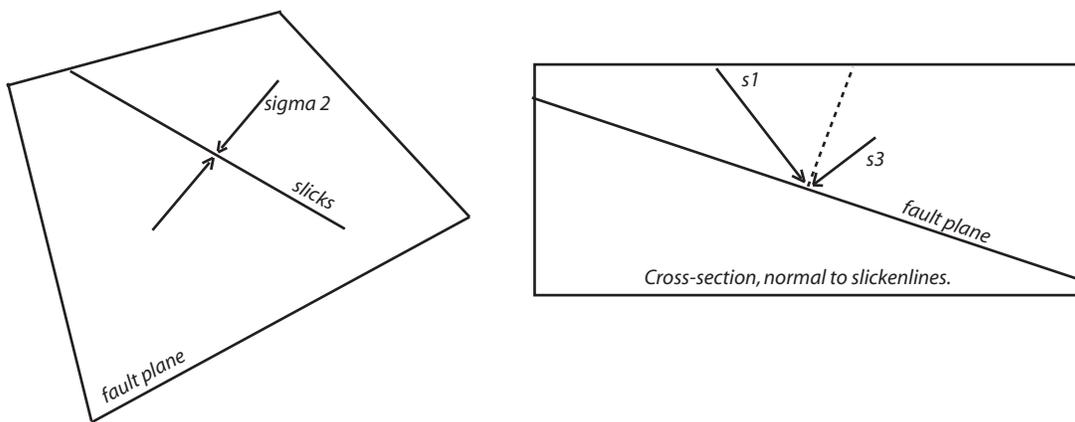

Figure 2:

Note, there are two possible orientations of $\sigma 1$ at 60° from the normal to the fault plane. It is important to consider the direction of motion on the fault as evidenced by separate information. Using this knowledge, choose the right orientation of $\sigma 1$ and $\sigma 3$ which would give the apparent offset.

2   Fault terminology

You've probably seen many of the below definitions before, but its good to have them all in one place. These are the fundamentals for describing faults.

Slip vector is the displacement of originally adjacent points, called piercing points, on opposite sides of the fault.

Strike-slip fault is a fault in which movement is parallel to the strike of the fault plane. Strike-slip faults are also called *wrench faults, tear faults* or *transcurrent faults.* A right lateral (dextral) fault is one in which the rocks on one fault block appear to have moved to the right when viewed from the other fault block. A left lateral (sinistral) fault displays the opposite sense of displacement.

Dip-slip fault is a fault in which movement is parallel to the dip of the fault plane.

Oblique-slip fault is a fault in which movement is parallel to neither the dip nor strike of the fault plane.

Hanging wall block is the fault block that overlies a non-vertical fault (usually high angle).

Footwall block is the block that underlies a non-vertical fault.

Normal fault is a dip-slip fault in which the hanging wall has moved down relative to the footwall.

Reverse fault is a dip-slip fault in which the hangingwall has moved up relative to the footwall.

Thrust fault is a low angle reverse fault.

Detachment fault is a low angle normal fault.

Listric fault is a fault shaped like a snow shovel blade, steeply dipping in its upper portions, becoming progressively less steep with depth.

Translational fault is a fault in which no rotation occurs during movement, so that originally parallel planes on opposite sides of the fault remain parallel.

Rotational fault is a fault in which one fault block rotates relative to the other.

Scissor fault is a fault whose sense of displacement is reversed across a point of zero slip and whose amount of displacement increases away from this point.

Slickensides are a thin film of polished mineralized material that develops on some fault planes. They contain striations parallel to the direction of latest movement. Often it is not possible to tell from slickensides alone in which of two possible directions movement actually occurred.

Fault trace is the exposure of the fault plane on the earth's surface.

Separation is the perpendicular distance between the two traces of a displacement marker bed or plane measured in the fault plane. Separation may be measured in a number of directions along the fault plane.

Strike separation is measured parallel to the strike of the fault (horizontally)

Dip separation is measured parallel to the dip of the fault.

3   Determining net slip on a fault: Non-rotational faulting

The following is an example of determining the displacement of a fault, assuming a planar and non-rotational fault. In this example there is no topographic relief, but this does not have to be the case.

The problem: The fault plane is oriented N90E/80S and planes 1 & 2 represent two dikes with attitudes N25E/60NW and N35W/40NE respectively. You know that this fault in non-rotational and therefore displacement is uniform along the fault because the offset dikes have the same attitude on either side of the fault. In order to find the displacement across the fault, we need to find the position of a line that has been broken by it. One plane will not work, unless you independently know the slip direction on the fault. A linear feature, however, is enough by itself to determine true separation. Its usually called a *piercing point*. Alas, piercing points are rare in geology: some geological examples that have been used include fold hinges, and some geomorphic features such as stream beds. Here we will use the line formed by the intersection of the two dikes as a piercing point.

The method:

1. Construct a cross section of the fault surface. In this example there is no topography so the cross section is a horizontal line.

2. Mark the location of the dikes along the fault. Label the points on the cross section to indicate on which side of the fault the dike lies.

3. To find where the line of dike intersection occurs in the fault plane on both sides of the fault, we use a stereonet to find the pitch of both planes in the fault plane.

   (a) Plot the plane of the fault

   (b) Plot the planes of the dikes

   (c) Determine the angle of pitch/rake on the fault plane along a great circle

4. Draw the pitch angles on the cross section and extend the resulting lines to find the intersections of the pair on one side of the fault and on the other side. The intersections represent the position of the line of intersection of the dikes in the fault plane. The line connecting them defines the *net slip* in the plane of the fault The dip slip component is measured in the plane of the fault along the true dip direction. The strike slip component is measured in the plane of the fault along the strike direction. In this example the north side is downthrown with respect to the south and displaced to the east.

5. To find horizontal slip in the vertical plane measure (dip slip component)*cos(dip of fault). For vertical slip, use (dip slip component)*sin(dip of fault)

4   Rotational Faulting

More rarely, rotational motion occurs on faults. You can recognize this because the same unit will have a different strike and dip across the fault. In the following example the hanging wall has been rotated counterclockwise relative to the footwall. There are two methods for determining the amount of rotation. Refer to the figures below.

Method 1   1. Plot the pole of the fault (F) and the poles of the bedding in the footwall block (A) and the hanging wall block (B) on the stereonet.

2. Orient the fault so it is vertical, so move point F 30˚ to F' to the outer circle. Points A and B move 30˚ to points A' and B'.

3. During rotational faulting the axis of rotation is perpendicular to the fault plane. Look at the map and imagine rotating the fault from its 60S dip into a vertical position. Use your left hand to represent the fault and your right hand to represent the bedding in the footwall. Stick a pencil through the fingers of your right hand to represent the pole to bedding. Now, keeping your left hand vertical, rotate your hands 180˚ and observe the relationship between the vertical fault plane and the pole to bedding. This relationship can be plotted on the stereonet by turning the tracing paper to put the pole of the fault (F) at the north pole. The small circle on which A' now lies, together with its mirror image across the equator, defines the locus of all possible pole to bedding orientations if the footwall block is rotated about an axis perpendicular to the fault. *The amount of rotation therefore is equal to the angle between A' and B',* which is 50˚.

Method 2:   Determine the pitch of each apparent dip in the fault plane. Because the pitch in the footwall and hanging wall were identical prior to rotation, *the difference in pitch equals the amount of rotation.* In this problem the apparent dips are in opposite directions so the pitches are added together. The pitch on the hanging wall in the fault plane is 42˚ and the pitch on the footwall is 8˚, indicating 50˚ rotation.

5 Lab 5 Exercises

5.1 Faults of the world

Draw a geological map and cross-section or block diagram to illustrate: (i) a right-lateral strike-slip fault; (ii) a normal fault; (iii) a thrust fault; (iv) a klippe; (v) a scissor fault. Feel free to scan or trace a real geological map. The cross-section can be schematic, but should be clear illustrations of the definitions. Label hangingwall and footwall, and name an area of active tectonic deformation where one might observe faults (i), (ii) and (iii).

5.2 Mohr-Coulomb failure and the effects of fluid pressure

Downie Slide in southeast British Colombia is a huge (1.6 billion cubic metres) bedrock landslide which developed when the Colombia River valley was deglaciated about 7000 years ago. The bedrock consists predominantly of biotite schist, and the base of the slide is a thick zone of crushed, micaceous gouge parallel to the dominant fabric in the (intact) bedrock. This slip plane strikes parallel to the river and dips 22°. Geotechnical work has determined the following:

Slope	22°
ρ_{avg}	2850 kg-m^{-3}
Thickness of slide	250 m
Avg. water column height	10 m
1000yr. max water column	50 m
Internal friction angle (ϕ)	28°

1. Assuming that the weight of the rock is the only source of stress at the base, what is the value of the vertical stress?

2. What are the normal and shear stresses at the base under (i) dry conditions; (ii) average conditions; (iii) maximum (1000yr.) conditions?

3. Assuming that the cohesion along the slide base is zero, plot the Mohr-Coulomb failure envelope

4. Draw Mohr circles for each of the three conditions cited above. What is the stability of the slide in each case?

5. How much fluid pressure, in terms of meters of water column height is required to initiate failure?

5.3 Joints

While they should have been doing better things with their time, a group of geologists at field camp became highly interested in joints. In particular, they noticed that after hundreds of measurements and many deep, deep conversations, that the joints in their field area mostly clustered around two orientations: the first set was oriented 350/60, the second 210/70. More deep, mystical conversations punctuated by weird junk food cravings led to the determination that these were, in fact, shear fractures. Assuming that these constitute a conjugate set

(that is, they formed in response to the same, homogenous stress field), determine the directions of the principal stresses, the angle of internal friction in the rock, and the sense and direction of slip on the joint surfaces. Be cool, use a stereonet.

5.4   Piercing points

Of the faults shown in figure **??**, which ones have piercing points which allow you to determine the net slip on the fault? Identify these. For the other faults, determine the possible sense of strike-slip and dip-slip separation.

5.5   Piercing points II

While mapping along the Colorado river, Alexis mapped an unrecognized fault, which among other things, appeared to cut off a trend of old gold mines found along a particularly rich vein. All the land north of the fault was staked, but if she could find the continuation of the vein across the vein, Alexis realized that she could pay off her student loans, buy an advanced degree, and keep her daschund in stupid little sweaters for the rest of its life. The fault strikes due East and dips 60°N. The relevant data are as follows:

Feature	Attitude	Distance along N. wall	Distance along S. wall
Limestone bed	010/45	0 m	160 m
Dyke	135/65	205 m	260 m
Gold vein	145/70	360 m	???

Determine the rake, trend and plunge of the slip direction, the amount of net slip and classify the fault. Locate the vein on the south side of the fault.

5.6   The faulted dyke at Beavertail

Calculate the net slip direction (the trend and plunge) and magnitude of slip on the fault that cut the mafic dyke we saw at the first stop at Beavertail point. Use the following (averaged) orientations:
Dyke: 155/28
Fault: 244/61
Fault straie: 60->346
Strike offset: 4m
Try starting with a map-view sketch or a block diagram. What is the sense of offset?