GY 111 Lecture Notes

Rock Deformation

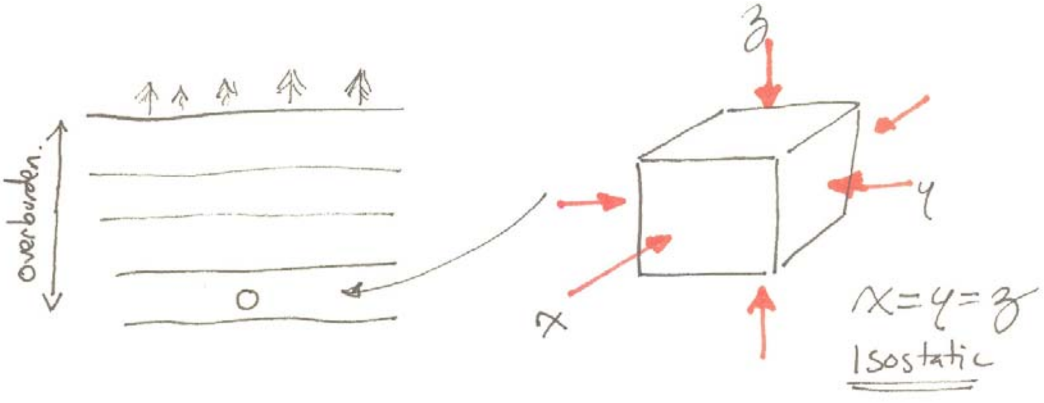
Lecture Goals:
A) Confining pressure and rock deformation
B) Elastic versus permanent deformation
C) Types of deformation

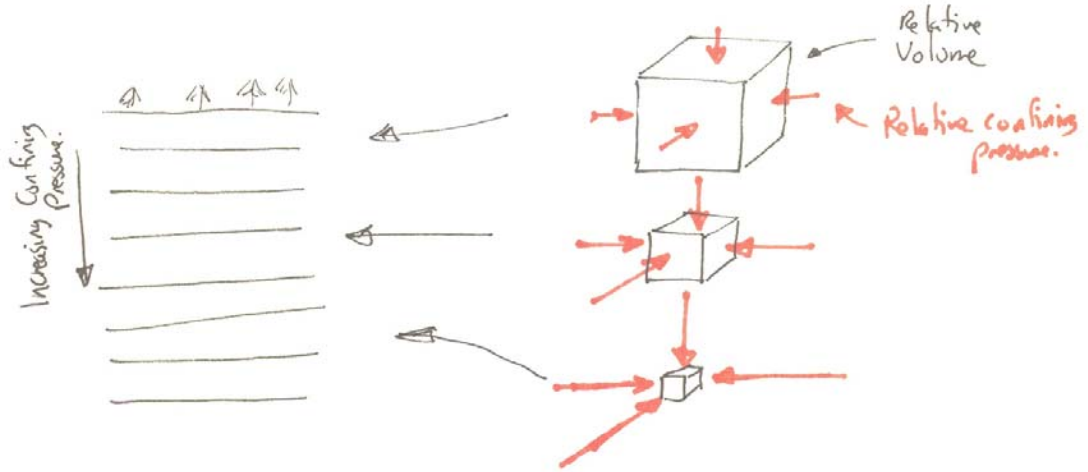
Reference: Press et al., 2004, Chapter 11; Grotzinger et al., 2007, Chapter 7 (p 154-163)

A) Confining pressure and rock deformation

In an earlier lecture dealing with metamorphism, we discussed the role of **pressure** in changing the orientation of minerals. That type of directed pressure is usually associated with compression at or near convergent plate boundaries. It is more properly called **stress** and in particular, **compressive stress** since that is the type of force that operates at that type of boundary.

There are other types of stress at other plate boundaries. For example, divergent plate boundaries are sites of **tension** or **tensile stress** and transform plate boundaries are sites of **shear** or **shear stress**. There is, however, another type of pressure that we need to discuss. It isn’t so much “directed” as it is uniform. It is the pressure associate with rocks as they get buried by successive layers of sediment and sedimentary rock. This overlying material is usually called **overburden** and if you recall, we previously discussed it when we were discussing how **compaction** produces shale from fine-grained sediment. The pressure that squeezes the water out of the sediment and compacts it into shale is said to be **isostatic** as it is equal in all directions. Some geologists (yours truly included) call this type of isostatic force the **confining pressure**. The best way to visualize confining pressure is to imagine a cube of sedimentary rock that is being subjected to equal compression from 3 different directions.
It stands to reason that the deeper the rocks are buried, the more intense the confining pressure. The volume of rock pictured above will decrease the deeper the rocks are buried (see cartoon at the top of the next page). However, the volume will always remain cubical because confining pressure is isostatic.





At this point, we need to introduce an important term; **rock deformation**. It is defined as *any change in the **volume, shape** or **attitude**[1] of a rock body*. So the volume change that occurs when confining pressure increases is an example of rock deformation. But I have to tell you, identifying volume changes in rocks is really tricky. You can really only do it if there is some means by which to gauge the original volume of the rock. If you started off with a oolitic limestone or a quartz arenite sandstone which both consist of evenly sized and spaced sedimentary particles, volume loss could be recognized by squashed grains[2]. But what if the starting rock was a granite or a shale? Volume loss in these rocks is very difficult to recognize. Recognizing change in shape or attitude can be a much easier means by which to recognize rock deformation, but once again, you need to know the starting shape/attitude of the rock body. Once again, the best rocks to use to illustrate these aspects of deformation are sedimentary[3]. Sedimentary rocks are always initially deposited in nearly horizontal layers. In fact, this characteristic comprises one of the few laws or principles in geology[4]. The **Principle of Original Horizontality** states that *all sedimentary beds are initially deposited in horizontal layers* (see next figure at the top of the next page). A second equally obvious geological "law" is the **Principle of Superposition**. It states that *in any succession of sedimentary rocks, the oldest layers are on the bottom of the stack, unless they have been overturned.* I will explain the item in red shortly, but first, let's consider why these two principles are very useful when discussing the deformation of rock bodies.

Since we know that sedimentary rocks were originally deposited in horizontal layers, we can safely conclude that tilted sedimentary layers (those no longer horizontal) have been

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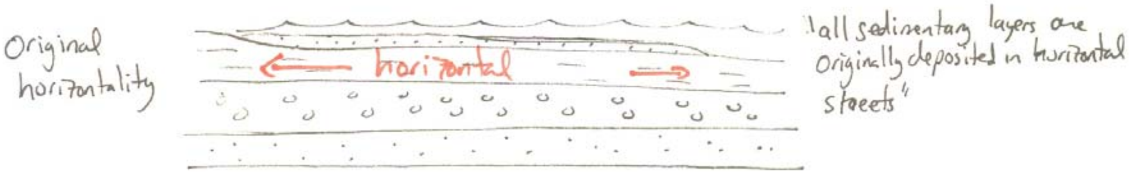
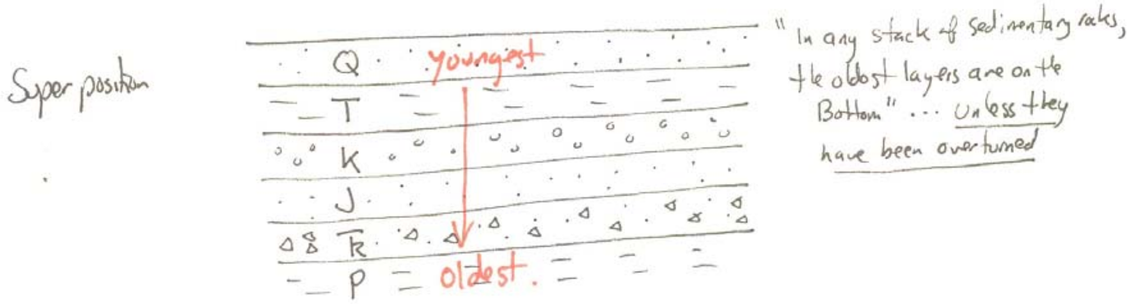
[1] Or if you prefer, the orientation.

[2] Please don't confuse the squashed grains being discussed here with fused crystals that occur during metamorphism (e.g., in marble or quartzite). The pressures involved with metamorphism are far greater than what we are considering here.

[3] I know what you are thinking. "Haywick's biased. He's a sedimentologist, so it stands to reason that he would be pushing sedimentary rocks over igneous and metamorphic rocks when discussing rock deformation." Not true! Sedimentary rocks offer an easily recognized starting orientation. Read on.

[4] As I have previously stated, geology is a non-exact science. Most of our knowledge is derived from clever interpretations rather than mathematical calculations. If you prefer a whole bunch of "laws", I recommend that you check out one of the "exact sciences" like physics or chemistry. Bring your calculator.





deformed. It is far harder to recognize deformation in igneous bodies like a batholith as their original shape and orientation is not easy to determine[5]. In GY 111, I will make your lives a bit easier by limiting all of our discussion in the lectures and all of the exercises on rock deformation in the lab to sedimentary rocks. Just remember those two really, really important principles.

Let's conclude this section with a short discussion on bed attitude. **Horizontal bedding** as the name implies is bedding that in horizontally orientated (i.e., non-deformed). A bed that is tilted is said the be **inclined. Inclined bedding** can be tilted any amount in any direction. In our next lecture, we will discuss the method that geologists use to describe bedding orientation. Beds that are tilted perpendicular to the horizon (AKA straight up) are said to be **vertical. Vertical bedding** and steeply inclined bedding (see image of Mt Rundle to left from http://www.pbase.com/turnstyle/image/32550221) is actually quite common in mountain belts and forms impressive spires that just beg to be ascended by aspiring rock climbers. It is also possible for beds to be tilted more than 90˚ from their original horizontal disposition. These beds are said to be **overturned**. Once, as a student, I led a field trip to Banff National Park in Canada to show my colleagues some beautiful Cretaceous ripple

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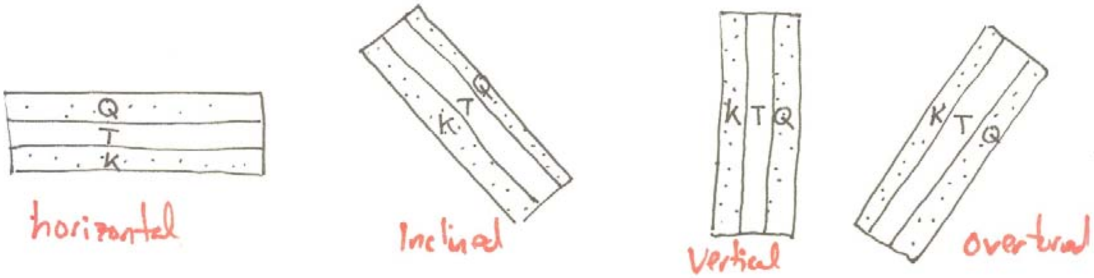
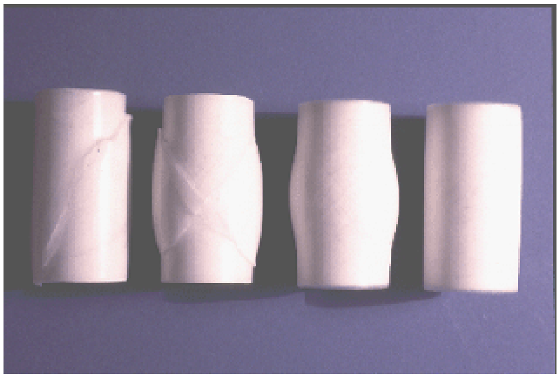
[5] The exception would be an igneous dike.



marks on some "horizontal" sandstone beds near Mt Rundle (again refer to the previous image). The thing was that the ripples were upside down. The entire sedimentary succession had been rotated 180˚ from its starting orientation. It is the fact that sedimentary layers can be tilted past 90˚ that explains the red text in the Principle of Superposition on the previous page of these notes. If the sedimentary succession has been overturned, then the oldest rocks are no longer on the "bottom" of the succession. In the field, the only way to recognize overturned bedding is by upside down features (e.g., ripples) or by fossils. If you find an older fossil in rocks that overly younger sedimentary rocks, the succession must be overturned. In GY 111 labs, you will be provided with data that will allow you to determine the age relationships of the rock layers.

B) Elastic versus Permanent Deformation



We've discussed changes in volume and attitude. Now let's consider changes in the shape of rock bodies. In order to do this, we need to go back to the effects of stress on rocks. Believe it or not, there has been a considerable amount of work done on this topic, specifically the way rocks change shape when subjected to compression, tension or shear. This topic hasn't really be driven by purely academic research, but more by economic necessity, legislation and a constant fear of being sued. Whenever any structure is built, its weight pushes down on the substrate that it is laying on. If the rock or soil is too weak, it deforms and the structure may collapse. Obviously this would be a bad thing, so engineers and architects put a lot of effort into making sure that the substrate that they are building on is capable of supporting the structure that they are designing/erecting[6]. Consider the new RSA tower in downtown Mobile. It is the tallest building in Alabama and it was built on Quaternary sediment and sedimentary rocks. Fine grained, pretty wet stuff that is prone to compaction. But fear not! Long before building

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[6] Sometimes they don't always get it right. Notable "mistakes" include the "leaning" Tower of Pisa in Italy and the stretch of Interstate 10 from Slidell to New Orleans which I refer to as the Vomit Expressway due to it irregular surface.

construction began, engineers or engineering geologists[7] took samples of the soil and the rock and tested them to determine their compressive strength. This is a cool analysis. You take these materials to a testing facility (here in Mobile it's at Thompson Engineering) and they put the material in a very precise hydraulic press that is hooked up to a computer (see image to left from http://www.bgu.ac.il/geol/rockmech/lab/fig2.1.jpg). For soil, they place the sample in a cylinder before they place it in the press. For rock, they extract a cylindrical core from the bed rock and place it directly in the press. Once everything is set up, the press is started and the soil/rock is squeezed until it "fails". The pressure required to make the soil or rock fail ultimately determines the strength of the material. As long as the strength is higher that the weight (AKA compressive stress) of the building[8], the substrate can support it. Many buildings have had to be redesigned when they have been declared "too heavy" for the substrate. Alternatively, there are ways to increase the compressive strength of soil if the contractor is willing to pay to do it.

Thompson Engineering also tests the strength of concrete. This is a good idea when you consider how much our society depends upon this material. Every time that you travel across the Bay Way to the Eastern Shore, you are traveling over a concrete surface that is supported above Mobile Bay by concrete columns. Fortunately, all this concrete and the sediment that it is resting on was tested during construction to ensure that the road surface would not fail or sink into the bay.

Geologists also are involved in planning the location of dams. Here it is important to ensure that the weight of the concrete and the weight of the water in the reservoirs are factored into the strength calculations. Dams, when they fail, tend to kill people.

At the smaller scale of things, geologists in universities test the behavior of rock when subjected to stress. Years of study have shown that rocks go through a specific set of responses when subjected to stress. For this part of the lecture, we have to set some starting circumstances in order to understand deformation. Consider a cylinder of granite, at room temperature and atmospheric pressure (this corresponds to low confining pressure), subjected to compressive stress (see top part of the diagram on the next page as well as the image start of this section from http://pasadena.wr.usgs.gov/office).

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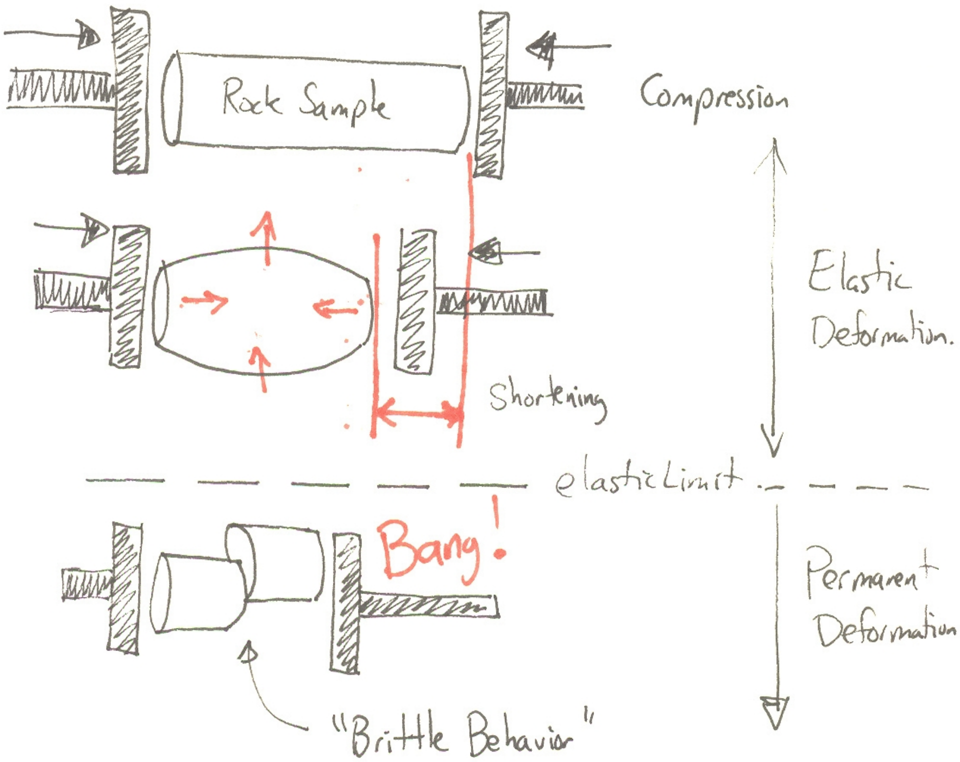
[7] Engineers and geologists generally have a relationship that is best described as "cautious". We work together, but neither particularly trusts the abilities of the other. Geologists tend to think that the engineers are "too up themselves" and narrow-minded whereas the engineers think that the geologists are "too irrational" and that they aren't focused enough. By the way, when geologists and engineers get together at company picnics, geologists always win the post-meal football game. It isn't because they are better at the sport. Engineers spend a lot of time designing a winning game plan, but while they are sitting around with their calculators, the geologists are drinking all the beer and quietly moving the ball up the sideline when no one is looking. Irrational, maybe; stupid, no.

[8] the weight of the building not only consists of the concrete and steel of the frame, but the furniture and people as well.



As you increase the compression, the cylinder starts to deform. Notice that the cylinder shortens in the direction of stress (this is a natural consequence of compression) and that it spreads out in a direction perpendicular to the direction of stress. In other words, it begins to change into a barrel shape rather than a cylinder[9]. If the compressive stress should let up at this point, the granite will return to its normal shape. All materials have a certain amount of **elasticity,** but if you exceed this (the maximum elasticity is called the **elastic limit**), you pass into the realm of **permanent deformation.** For our granite example, the permanent deformation involves breakage. The cylinder of rock breaks along one or more planes. When a rock breaks, it is said to be **brittle deformation**. I once experienced an experiment involving brittle deformation. When I was an undergraduate student, I was wandering around the sacred halls of the General Science building at McMaster University[10] when I heard a "bang". I swear, I though someone had been shot. What I actually heard was a cylinder of rock that "failed". A graduate student was conducting a strength test on a piece of basalt from Iceland. When it broke, it broke

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[9] The distortion in the cartoon is exaggerated. The actual amount of deformation isn't all that great.

[10] I did my undergraduate degree at McMaster in the 1980's. The geology program was one of the best in the <u>world</u>, but at the time I didn't realize this. Like most students, my goal was to survive to graduation. "Mac" is located in Hamilton, Ontario, Canada. To get there from Mobile, tale I65 to Louisville. Then Switch to I75 to Cincinnati. Then take I 71 to Cleveland. At Cleveland, take I 90 E to Buffalo, NY. Once you are in Buffalo, follow the signs to "Canada". Cross at the Buffalo-Fort Eire, ON bridge. Once in Canada, be sure to stop at the first Tim Horton's Donut shop. Canadians are lucky because they have the best donuts on the planet (Krispy Cream and Dunkin do not compare). McMaster is located about 40 miles from the US border. There are 3 donut shops within walking distance of the General Science Building. They still remember me at 2 of these.

with a bang. What that graduate student did was to cross from elastic deformation to permanent deformation. The rock broke because it had to.

Is **brittle behavior** the only response to stress? No. If the conditions are right, a rock may bend rather than break. This type of deformation is called **ductile behavior** and it results in rocks that "flow" rather than break. Some rocks naturally tend to behave ductily when subjected to stress. Shale, halite and gypsum bend rather than break. In contrast, quartz arenite sandstone and limestone tends to break rather then bend. At least near the surface of the Earth where the confining pressure is low. If instead, the confining pressure is high (this would occur if the rocks were buried deep in the Earth), even the most "brittle" rocks bend rather than break. The confining pressure is a important variable in the rock deformation equation and the moral of the story is that the deeper a rock is buried, the more likely it is to behave ductily.

Remember that experiment that I told you of earlier at McMaster University? Well I talked to the graduate student that was doing the research and she told me that it was possible to vary the lab set up to imitate high confining pressure situations. She said "that if you increase the confining pressure and repeat the experiment, the rocks simply bend." No breakage occurs. No big "bang" is heard in the sacred hallways of the General Science Building. Kind of boring I said. She agreed. But the thing is, rocks behave according to the conditions that they are experiencing. From a geological point of view, we can determine the conditions that a rock experienced based upon the deformation that occurred. In other words, If a geologist identifies the deformation history of a rock, he/she can determine <u>all</u> of the conditions that affected that rock. This is an incredible thing to be able to do. It's kind of like geo-CSI except that there wasn't a crime and we aren't looking for a murderer. We are only seeking a part of the history of the planet[11].

I mentioned earlier that there are several types of stress; compression, tension and shear. You might be interested to hear that rock deformation experiments have been done for each type of stress. The press that I told you of earlier can pull instead of push in order to do tensile stress experiments. Were you to do this, you would find that rocks have tensile elasticity (and a tensile elastic limit) and that when stretched paste this point, that they will break or bend depending upon the confining pressure. The cartoon on the next page summarizes tensile (brittle) behavior of a cylinder of rock. Note that instead of shortening, the rock stretches. This should not come as a surprise to anyone.

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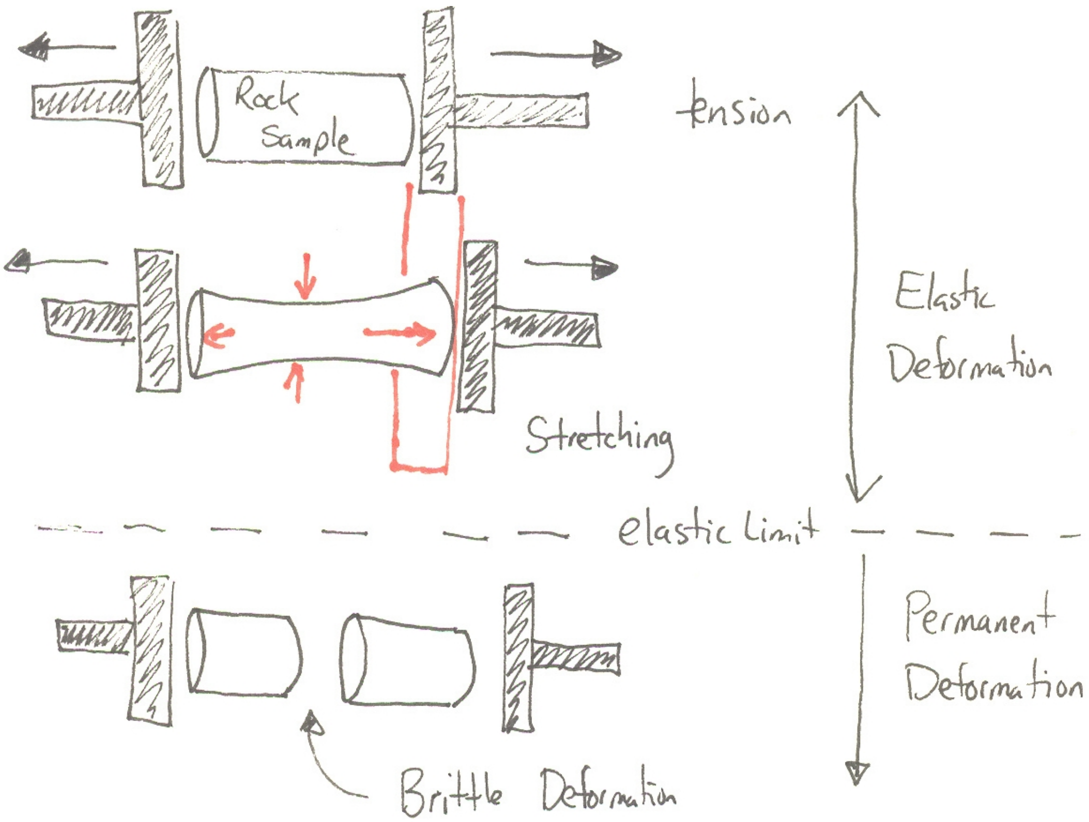
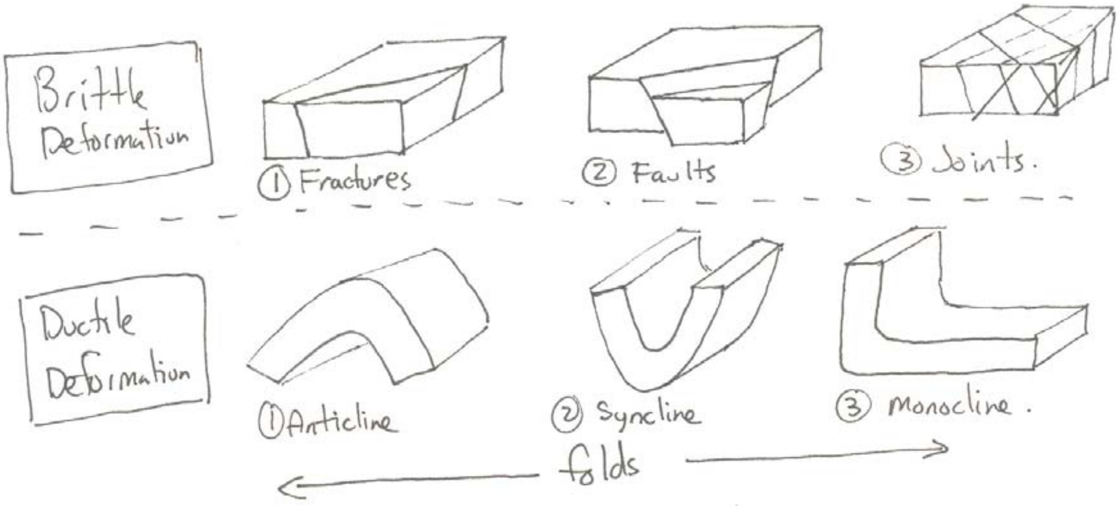
[11] This aspect of geology is called Earth history. The University of South Alabama offers an introductory class in Earth History (GY 112) which is, in the opinion of the your humble instructor, the Most Important Class that you will EVER take. Trust me. If you take GY 112, it will change your life.

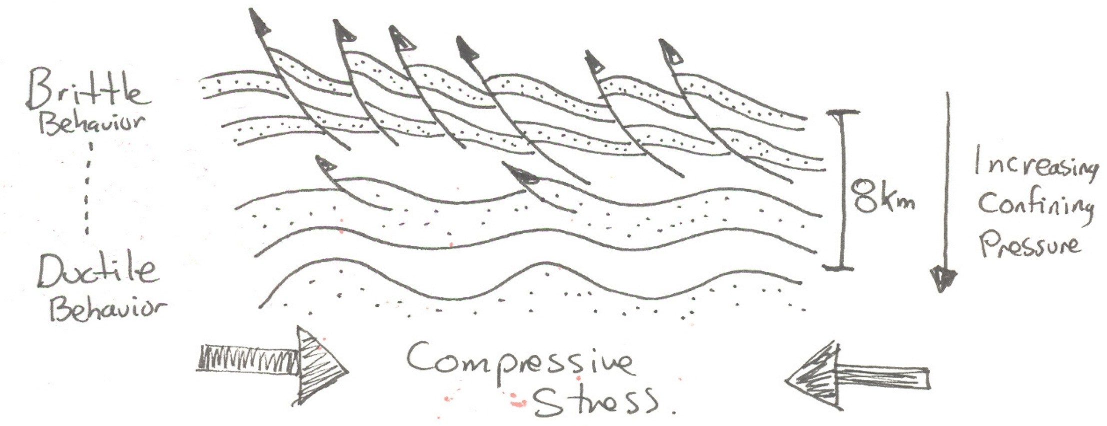


C) Types of Deformation

Okay. So we have talked about deformation. Here is the summary information about today's lecture. Rocks can deform in two fundamentally different ways. They can break, or they can bend. Rocks that break will produce either **fractures** (cracks), **joints** or **faults**. Each of these will be discussed in a future lecture.



Rocks that bend, will result in **folds**. This too will be he subject of a future lecture. And let's not forget that deformation behavior is ultimately dependent on confining pressure. The deeper you go, the more likely that rock will behave ductily. In fact, at any one place on the surface of the Earth, faulting (brittle deformation) can occur near the surface while folding (ductile deformation) occurs at depth (see figure below).



No one has ever said that understanding geological processes is "easy", but those individuals capable of doing this experience a sense of satisfaction that is rarely duplicated in any other area of science. Just think about it…. geologists are resolving the history of the planet. Pity the poor chemist whose sole purpose in life is too make aspirin or the lowly biologist that just counts the number of fish caught in a net. Geologists rule because they deal with the BIG Picture. The Earth itself. Nobody else doe this. Nobody else is capable of doing it.

Important terms/concepts from today's lecture

(Google any terms that you are not familiar with)

pressure
stress
compaction, compression (compressive stress)
tension (tensile stress)
shear (shear stress)
overburden
confining pressure
isostatic
(rock) deformation (shape, volume, attitude)
Principle of original Horizontality
Principle of Super Position
horizontal bedding
inclined bedding
vertical bedding
overturned bedding
elasticity
elastic deformation
elastic limit
permanent deformation
brittle behavior
elastic behavior
fracture
joints
faults
folds