LAB Exercise #10
What controls rheology?

Based on lab exercise developed by Dyanna Czeck

Exercises are in two parts. The Lab exercise is to be completed and submitted today.
The Homework Problems are **Due Friday, 6 May 2016 at 11:00am.**

Objective: Rheology is the way in which rocks respond to stress. One of the ultimate goals of structural geology is to predict how any rock will deform due to an applied stress. We will explore many of the different parameters (lithology, stress, temperature, confining pressure, preexisting weaknesses, strain rate, accumulated strain) that result in the deformation or strain that we see in rocks. Since we can't watch rocks deform in nature, we must use analogue materials to understand the parameters that control rheology and compare these deformed analogue materials to information we have on real rocks. We will explore a number of analogue materials to explore the factors that control rheology.

LAB EXERCISE (35 pts)

Work through the following modules in groups of four. Spend an average of 20 minutes on each module and turn in one set of answers for the whole group.

Module 1: Lithology (10 pts)
Part A: *Analogue*

Materials: play-doh, modeling clay, textbook, ruler, watch

Procedure:
1. Make two identical-sized blocks out of play-doh and modeling clay. (The blocks should be at least 5 cm x 5 cm x 5 cm.) Record the dimensions of your two blocks.
2. Deform the two blocks by placing a weight or your textbook on top of each block and allowing the weight to deform the blocks.
3. Take time, so you can establish a strain rate.
4. Remove the textbook and measure the dimensions of each of the blocks after deformation.

Questions:
1. What are the new dimensions of each block and how much strain was accommodated?
2. Which material is "stronger" (play-doh or modeling clay)? Explain your answer.
3. Which material shows signs of brittle deformation? You will probably see little fractures in one of the materials.

Part B: *Rocks*

Figure 1: Deformed granitoid dikes within greenschist facies metasedimentary rock from Rainy Lake region, Ontario. The metasedimentary rock has a strong ductile fabric (foliation and lineation).

Questions:

1. Figure 1 shows a competent rock and an incompetent rock. Which is which? How can you tell? (Hint: think about which shows evidence for brittle deformation and compare this to the analogue experiment above.)
2. In Figure 1, the granitoid dikes are both boudinaged and folded. How could both occur within the same deformation?
3. There are several fractures within the boudinaged portion of the dike. In general, how are these fractures oriented? Do the fractures indicate the orientation of stress or strain?

Module 2: Temperature & Moisture Content (10 pts)

Part A: *Analogue*

Materials: candles and lots of cheese!

Procedure:

1. Make observations of the rheological properties of the cheese at different temperatures. See the table (pg. 3) for interesting rheological properties of various cheese types and compare with your observations.
2. Note the different moisture content of the cheeses and how they deform.

Questions:

1. Based on your observations, is an increase in temperature more likely to cause materials to strain viscously or elastically?
2. Based on your observations, is an increase in temperature more likely to cause materials to have brittle or ductile deformation?
3. How does moisture content affect the rheological behavior of the cheeses and would you expect the same effect for rocks?

Rheological property	*Definition*	*Cheese type displaying property*
Elasticity (rubberiness)	Tendency of cheese to recover its original shape and dimensions upon removal of an applied stress	Swiss-type cheese, low-moisture Mozzarella
Springiness	Tendency to recover from large deformation (strain) after removal of deforming stress	Swiss-type cheese, low-moisture Mozzarella
Elastic fracturability	Tendency of hard cheese to crack, with very limited flow (confined to vicinity of crack); after fracture, the broken surfaces can be fitted to each other	Parmesan, Romano, Gruyere
Brittleness	Tendency of hard cheese to fracture at a relatively low permanent deformation	Romano, Parmesan
Firmness (hardness)	High resistance to deformation by applied stress	Cheddar, Swiss-type cheese, Romano, Parmesan, Gouda
Longness	The resistance of cheese to fracture until a relatively large deformation is attained	Mozzarella, Swiss
Toughness (chewiness)	A high resistance to breakdown upon mastication	Mozzarella, String cheese, Halloumi
Softness	Low resistance to deformation by applied force	Blue cheese, Brie, Cream cheese
Plastic fracturability	The tendency of cheese to flow on fracture	Mature Cheddar, Blue cheese, Chaumes, Raclette
Shortness	The tendency to plastic fracture at a small deformation; low resistance to breakdown upon mastication	Camembert, Brie
Adhesiveness (stickiness)	The tendency to resist separation from another material with which it makes contact (e.g., another ingredient or a surface such as a knife blade or palate)	Mature Camembert
Crumbliness	The tendency to break down easily into small, irregularly shaped particles (e.g., by rubbing)	Cheshire, Wensyledale, Blue cheese, Stilton, Feta
Shear thickening	The tendency to increase in apparent viscosity when subjected to an increasing shear rate (especially upon heating)	Cream cheese (when heated), 'creaming' of processed cheese products
Shear thinning	The tendency to exhibit a decrease in apparent viscosity when subjected to an increasing shear rate	Quarg (especially at low temperatures, i.e., <4 °C)

Table 1 from O'Callaghan & Guinee, "Rheology and Texture of Cheese"

Part B: *Griggs et al. deformation experiment for basalt under various temperatures*

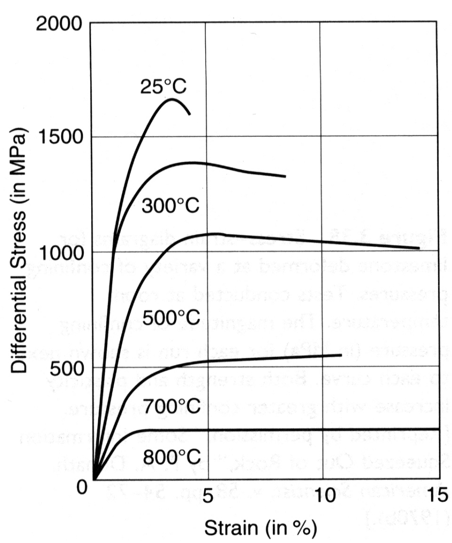


Figure 2: Stress-strain diagram for basalt deformed at 5 kbar confining pressure under a variety of temperature conditions. From Griggs, Turner, and Heard (1960). Graph copied from Davis and Reynolds (1996).

Questions:

1. Examine Figure 2. At what temperature is the basalt "strongest?"
2. Make a rough plot of temperature (absolute temperature in Kelvin) vs. differential stress (in MPa) at yield. What kind of functional form has been found to explain the observed relationship?
3. Discuss limitations of this relationship.

Module 3: Confining Pressure (5 pts)

Donath's experiments for rocks under various confining pressures

Figure 3 (below) is from a famous experiment by Fred Donath (1970, American Scientist). It shows specimens of limestone that were deformed to approximately the same total strain (15%) at different confining pressures.

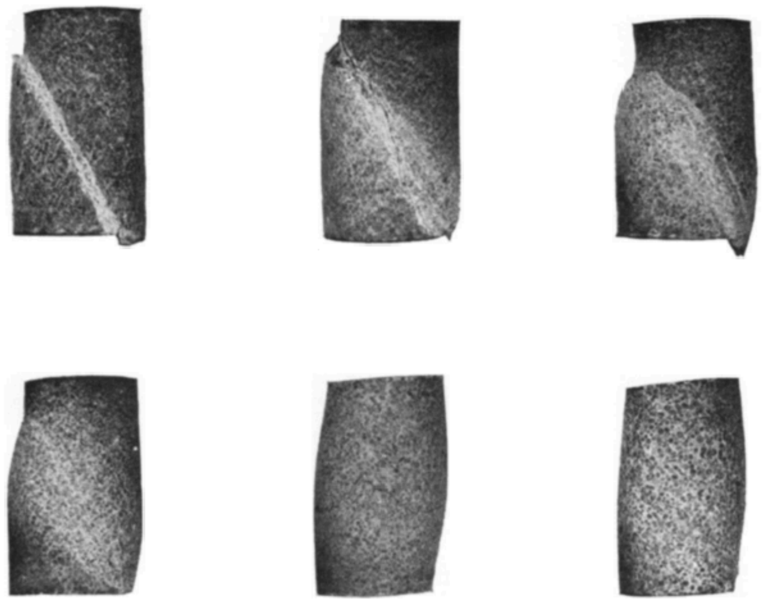


Figure 3: Specimens of Crown Point limestone deformed to approximately the same total strain (~15%) at different confining pressures. Increased confining pressure causes a transition in deformation mode from shear fracture at 200 bars (top left) to a well-defined ductile fault at 700 bars (top right) and at 900 bars (bottom left) to incipient ductile faults at 1400 and 1800 bars (bottom center and right). A shear zone developed in the specimen deformed at 600 bars (top center). Specimens were initially ½" diameter by 1" length. From Figure 7 in Donath (1970).

Figure 4 is also from Donath's experiment. It shows a graph between the differential stress and strain for the limestone deformation experiment (specimens shown above).

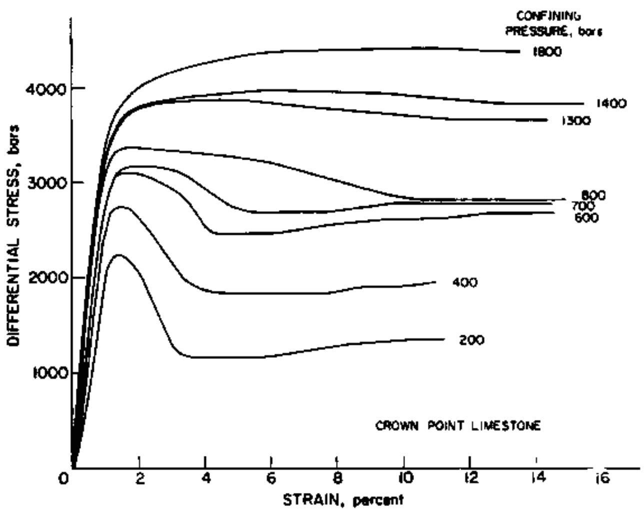


Figure 4: Stress-strain diagrams for limestone deformed at a variety of confining pressures. Tests conducted at room temperature. The magnitude of confining pressure (in MPa) for each run is shown next to each curve. Both strength and plasticity increase with greater confining pressure. From Figure 6 in Donath (1970).

Questions:

1. At what confining pressure is the rock "strongest?"
2. At what confining pressure is there more ductile deformation?
3. How do you interpret this result? Is this truly ductile deformation?

Module 4: Strain Rate (5 pts)

***Part A**: Analogue*

Materials: silly putty, string cheese

Procedure

1. Roll the silly putty into a small sausage shape.
2. Pull QUICKLY on the silly putty and watch it deform.
3. Pull SLOWLY on the silly putty and watch it deform.
4. Compare the behavior of the silly putty with the string cheese.
5. Develop an experiment that allows you to explore the strain-rate dependence of strength of silly putty.

***Part B:** Yule Marble deformation experiments*

Review Figure 5.

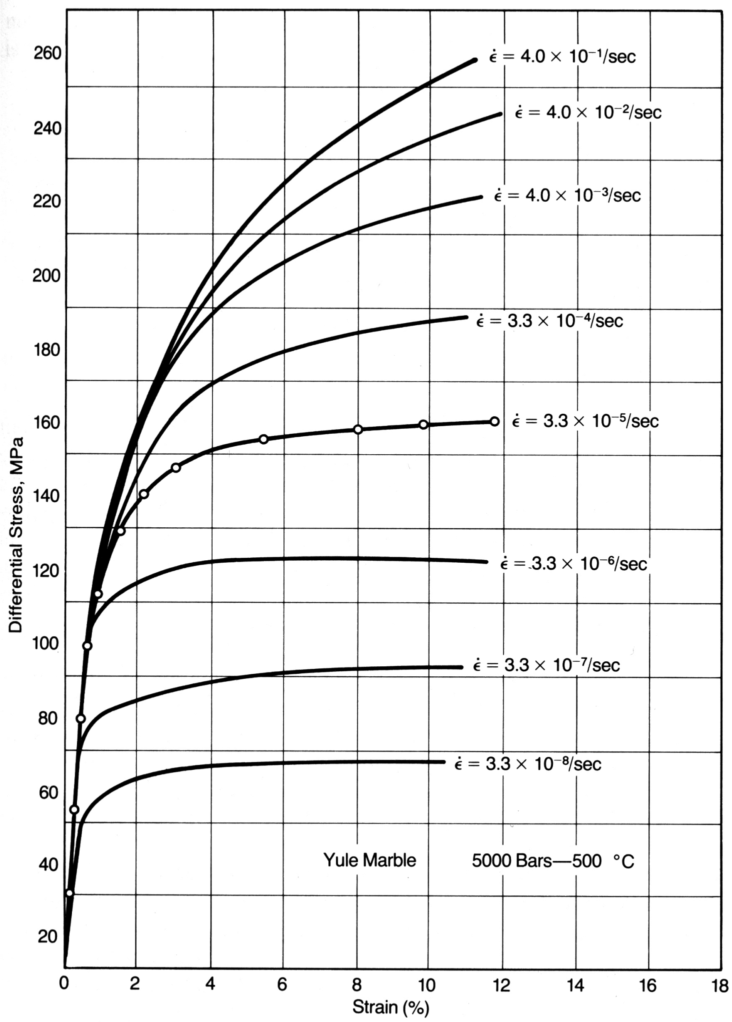


Figure 5: Stress-strain diagram for Yule marble deformed in extension at different strain rate conditions. After Heard (1963). Figure copied from Davis and Reynolds (1996).

Questions:

1. Are rocks "stronger" or "weaker" at faster strain rates? Explain your answer.
2. What rheological flow law properly reflects the strain rate dependence of the observed strength? Do we have to be selective in which data to include?

Module 5: Stress-Strain Relationships (5 pts)
Design Your Own Experiment

Materials: springs, syringes, weights (plastic slider), sliding table, fishing wire, watch

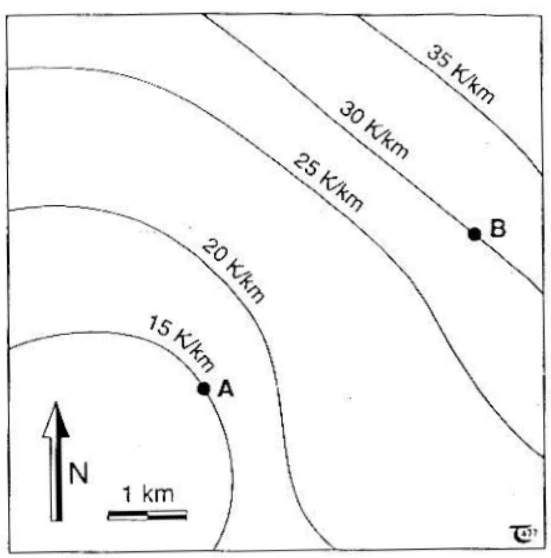
Utilize the above materials in an experiment that tests simple elastic, viscous, plastic, and/or viscoelastic models. Focus on proving one deformation law, such as Hooke's Law, linear Newtonian flow or that of a visco-elastic Maxwell or Kelvin body. **Write a short paragraph explaining your experimental setup and results.**

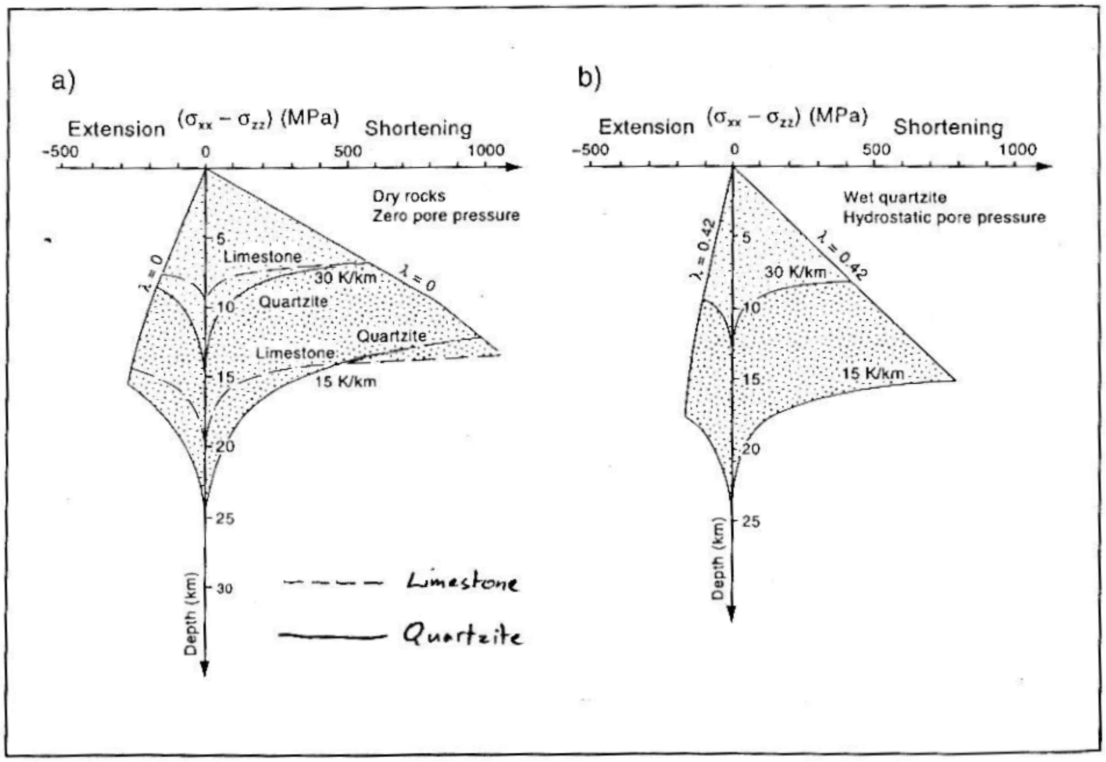
Upon completion of the 5 modules, submit one set of answers for the whole group.

References:
Davis, G. H., and Reynolds, S. J. 1996. Structural Geology of Rocks and Regions, 2nd edition. New York: John Wiley & Sons, p. 132-137.
Donath, F. A., 1970. Some information squeezed out of rock. American Scientist 58, 54-72.
Griggs, D. T., Turner, F. J., and Heard, H. C., 1960. Deformation of rocks at 500° to 800° C, in Griggs, D. T., and Handin, J. (eds.), Rock deformation: Geological Society of America Memoir 79, 39-104.
Heard, H. C., 1963. Effect of large changes in strain rate in the experimental deformation of Yule marble. Journal of Geology 71, 162-195.

HOMEWORK PROBLEMS (65 pts)

Using the insight that you developed from working on the various lab modules, and the figures below, answer the following questions on a separate sheet of paper about the strength of the crust. The first figure below shows geothermal contours for a sedimentary basin located in the Ganges Plain of India adjacent to the Himalaya. The second two figures show crustal strength profiles for both dry and wet rocks assuming a deformation rate of 1e-14/s. Initially, assume that the subsurface is made up *solely* of wet quartzite with hydrostatic pore pressure.





Crustal strength profiles for: (a) dry rocks, and (b) rocks with hydrostatic pore pressure.

1. Write out the brittle (Byerlee) and ductile (power-law) equations that were used to calculate these strength envelopes. What do these crustal strength profiles attempt to show? **10 pts**
2. Why does the brittle strength of the crust increase with depth? **5 pts**
3. Why does the ductile strength decrease with depth? **5 pts**
4. What is the significance of the intersection of the two deformation laws? **5 pts**
5. How deep does one need to drill before the first ductile deformation structures can be expected in locations A and B, respectively? Explain how you found these values. **5 pts**
6. What would be the depths if the rocks turn out to be dry at all depths? **5 pts**
7. What is the effect of water on brittle and ductile deformation laws? **10 pts**
8. Schematically, draw a second strength profile on the right diagram for deformation at 10 times the strain rate shown. Explain how you tried to determine this profile. **10 pts**
9. Schematically, with a different color/pattern modify the right diagram for a case in which the crust consists of olivine dominated mafic rocks below 15 km. Explain. **10 pts**