Viscosity experiments: physical controls and implications for volcanic hazards
INSTRUCTORS NOTES

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OVERVIEW

Teaching students about viscosity is easy, effective and fun. It is a topic that is conducive to a range of teaching and learning styles, and allows for the integration of theory, experiments, and calculations. During the course of this exercise, students are required to make predictions about the outcomes of experiments, quantitatively document the results of their experiments, calculate viscosities using the Jeffreys equation (Jeffreys 1925; Nichols 1939; Cas and Wright 1987), and extrapolate the concepts learned from their laboratory results to natural conditions appropriate for silicate magmas and lavas. Students are also introduced to Ken Wohletz's freeware program MAGMA (http://www.ees1.lanl.gov/Wohletz/Magma.htm), which allows them to determine viscosities for magma and lava compositions, and are required to do some simple graphical analysis of the effects of composition, dissolved H_2O, and % solids on magma and lava viscosity using the MAGMA calculations. Viscosity is important for students at all levels of earth science to understand because it is a critical control on morphologies of volcanoes, velocities of lava flows, eruptive styles (effusive versus explosive), and ascent velocities of magmas within the earth.

The objectives of the lab are for students to:

- learn about the rheological property called viscosity and some of the factors that affect it;
- think about and discuss ways in which viscosity controls styles of eruptions and relates to volcanic hazards; and
- practice quantitative skills.

I have used the viscosity experiments as a classroom demonstration in introductory geology courses, as one part of a more extensive lab on volcanoes in introductory geology courses, and as a more intensive viscosity lab for introductory petrology courses. Generally the students do this exercise after they have had at least one introductory lecture on volcanoes, so that they are familiar with several basic terms, including viscosity, lava, magma, as well as some basic igneous rock terms (basalt, andesite, rhyolite). Over the fives years that I have been using the experiments, students at all levels have commented that the experiments are some of the most memorable, interesting and fun parts of my courses. I would welcome any direct student or instructor feedback for improvements or additions to the exercises (edwardsb@dickinson.edu).

NOTES FOR PART 1

This first part of the lab gives a brief overview of viscosity and some of the terms used to describe different types of viscous behavior. The important and sometimes confusing concept presented here is that HIGH viscosity means that liquids will move slowly or have a LOW velocity. I recently had students chant out loud the following phrases to help ingrain this relationship in their memories:

"High viscosity, low velocity. Low viscosity, high velocity".

The students, in an introductory geology class, thought that the chanting was "fun" and was enough of a out-of-the-ordinary teaching style that it seemed to make a favorable impact on their learning. Some of the explanation is a heavy on terminology, and probably the details of different types of viscous behavior only need to be discussed in a petrology level class. I usually do not introduce equations for predicting viscosity (e.g., Bottinga and Weill 1972; Shaw 1972), but this would be an appropriate place to do so; the program MAGMA calculates viscosities using both methods. Barb Nash has formulated two real world applications of Jeffreys equation that also demonstrate Shaw's method for calculating viscosities for different magma compositions and conditions (available on the Teaching Petrology website).

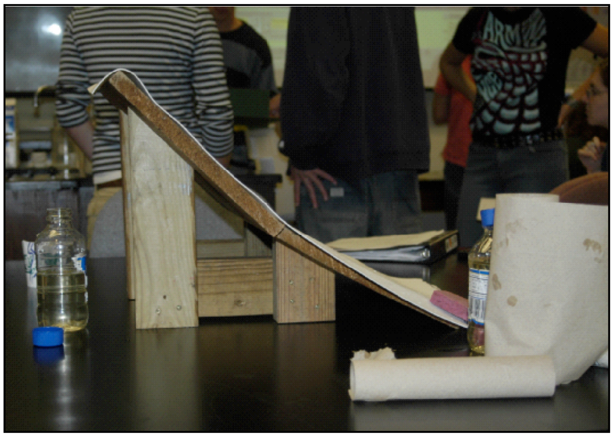
Notes for Part 2

The syrup viscosity experiments are the heart of the lab exercise and the most time-consuming and important part. Many of the experiments re-enforce students' native intuitions about viscosity: most students can accurately predict that hotter liquids have lower viscosities than colder liquids. However, few students have strong intuitions about how the addition of solids or bubbles will affect liquid viscosities. The syrup flow experiments can be completed relatively quickly, requiring about 20-30 minutes for each set, if the students are not compelled to do significant quantification of starting materials. For example, the standard lab setup does not require students to measure the temperatures of the starting materials, or quantitatively estimate the percentages of bubbles or solids or dissolved water added to the syrups. However, for a more advanced class, students could easily quantify all of those parameters and even use their results to make predictive equations for the effects of any of the four variables, then conduct more experiments to test their predictions. For introductory geology classes, the students are only asked to complete one or two of the groups of experiments. In upper level classes, each group of students can be required to do all four sets of experiments, depending on the time available.

Materials

A variety of equipment and materials need to be assembled for the syrup experiments. These include:

- a board or flat object that can be inclined and easily cleaned (a board covered with wax paper or shelf paper; see Figures 1A and B below);

	
Figure 1A. Oblique frontal view of a viscosity ramp. Lines are for reference so that students can calculate syrup flow velocities. The material covering the surface is padded vinyl shelf paper.	Figure 1B. Profile view of viscosity ramp. This ramp was constructed with two different angles: a 45˚ upper slope and a 30˚ lower slope.

- clear corn syrup (approximately 3 16 oz bottles for one lab of twenty students);

- a bucket of ice or nearby refrigerator to maintain temperature for cold syrup;
- a microwave (CAREFUL!) or a hot plate to maintain temperature for hot syrup;
- solid particles to mix into the syrup (sand, rice, cake sprinkles);
- a bowl and a whisk or hand mixer to make syrups with different bubble contents;
- beakers or plastic cups to hold the syrups;
- stop watches for timing the syrup flows;
- rulers for measuring distances;
- protractors for measuring the angle of the sloped surface;
- thermometers (if students will be required to quantify syrup temperatures);
- enough drinking straws for at least one per group;
- sponges and small buckets of water for cleanup; and
- calculators or a computer for computing viscosities using Jeffreys equation.

General experiment instructions

The syrup experiments are easy to conduct with a small amount of practice. Generally groups of 2-4 students for each set of experiments works well. Students begin by preparing the different varieties of syrup for their specific group. Preparation of the syrups can be totally qualitative or extremely qualitative: if the equipment is available students can measure precise volumes of syrup and add precise quantities of water, so that they know quantitatively how different the syrups in their group of experiments are different. Ideally the students will pour the same amount of syrup in each individual experiment, so the comparisons between experiments are reliable; however this can be challenging! Once the different types of syrup are prepared for a given group of experiments, generally it is useful have the students organize themselves, so that one person pours, another person uses the stopwatch to time, and the other students make observations about the syrup flows as they move down the inclined surface.

It is also important to note and to point out to the students that each set of experiments contains one syrup that is essentially identical: room temperature syrup with no added water, solids or bubbles. At the end of the experiments students can compare their results for this one “replicate” experiment and discuss how much and why their answers differ. The reported viscosity for Karo corn syrup at room temperature is 20-30 poise.

Set 1: Effect of temperature

This set of experiments is relatively self-explanatory and the results are intuitively obvious to the students. Be sure to warn students that the hot syrup can be dangerous, especially if using a microwave to heat the syrup. Students must also be ready to time! The hot syrup has a low viscosity and a high velocity! Have students carefully observe the cooled surface of the hot syrup flow to observe pahoehoe textures.

Set 2: Effect of water

This set of experiments is also self-explanatory and the results are intuitively obvious to the students. It is important that the water is well-mixed with the syrup to form a liquid with uniform viscosity. Because of the ease of measuring the amounts of water added to the syrup, this group of experiments would be idea for more quantitative measurements.

Set 3: Effect of solids

This set of experiments is not as intuitive to the students, but is important because many lava flows contain appreciable abundances of phenocrysts, which should cause in increase in lava viscosity (Murase and McBirney 1973; McBirney and Murase 1984; Spera 2001). However, commonly students expect the syrup with added solids to have a lower viscosity because it has a higher density; however, Jeffreys equation shows that viscosity is directly proportional to density, so an increase in density should produce an increase in viscosity! Students should find that the syrups with added solids have slower viscosities than that without solids. During this set of experiments students should also carefully observe the flow path of individual particles and make sketches. Careful observers will see that solid particles are carried to the end of the flow, move over the end and often become stuck in the boundary layer between the surface of the incline and the syrup.

Set 4: Effect of bubbles

This set of experiments is the most difficult to run, and produces complex results. However, it is worth the effort because bubble growth and formation is a critical aspect of volcanic eruptions (Spera 2000; Wallace and Anderson 2000; Manga and Loewenburg 2001). Ideally, bubbles can be created within the syrup by gentle-to-vigorous stirring with a kitchen whisk; alternatively a hand mixer can be used. However, three competing affects will influence student results. First, if bubbles are created by stirring with a handmixer, often the syrup mixture is heated in the process. So after mixing the syrup needs to be allowed to return to room temperature; alternatively, students can use the results from Set 1 experiments to predict the viscosity of bubble-free syrup at the temperature of the bubbly syrup. Second, adding bubbles to the syrup will decrease the density of the syrup, leading to a decrease in viscosity according to Jeffreys equation. Third, while bubbles remain spherical and in an undeformed state, they act in a similar manner to solid particles and should produce an increase in viscosity. However, if the bubbles start to deform due to high rates of shear stress, their presence can act to decrease viscosity (see Manga and Loewenburg 2001 for a detailed discussion).

Calculating viscosities using Jeffreys equation

Jeffreys equation is straight forward to use, although for introductory level courses I tend to have the equation programmed into a spreadsheet before lab so the students only need to enter their velocity data into the equation.

$$\eta = \frac{g \cdot \rho \cdot \sin \theta \cdot d^2}{n \cdot V} \qquad \textbf{\textit{Jeffreys equation}}$$

where η = viscosity in poise (dyne s cm^{-1} = g cm^{-1} s^{-1})*[note that 10 poise = 1 Pascal seconds (Pa s)]*, ***g*** is the gravitational constant (980 cm/s^2), ρ is density (assume this is 1.4 g cm^{-3} for the corn syrup), θ is the angular measurement of the slope (no units), ***d*** is the thickness of the flow (in cm), ***n*** is a constant (3 for broad flows and 4 for narrow, channelized flows), and ***V*** is the measured velocity (in cm s^{-1}). With the exception of the gravitational constant, all or some subset of the information needed for Jeffreys equation can be provided to the students. In the lab handout the equation is arranged so that the students can plug in their measured syrup flow velocities and directly calculate viscosities. The velocities are determined by the students measuring the amount of time it takes the syrup flow to travel a fixed distance. If graduated cylinders and a balance are available, it is simple to have students determine densities for themselves. The angle of the inclined surface can also be measured if a protractor is available. The thickness of the flows is also an important variable in the equation, so students need to measure or estimate the thickness of the flow while it is moving down the inclined surface. ACH Foods Inc. reports that the density for Karo corn syrup is about 1.38 g/cm^3 at 77˚F. I include the two common units of viscosity, poise and Pascal-seconds (Pa-s), because they are the most common units students are likely to encounter when seeing viscosities in the literature; also, the viscosities calculated by MAGMA are in units of Pa-s.

NOTES FOR PART 3

The answers to most of the questions are pretty self-explanatory for this part of the exercise, if the students make careful observations about the syrup flows. For example, when the syrups reach the bottom of the incline, the less viscous syrups will spread faster and will form a wider but thinner flow front. Make sure students are aware that they need to sketch the final morphologies of the syrup flows BEFORE they clean up the experiments! At the completion of this part of the exercise, students should formulate a hypothesis about how the viscosity parameters they measured affect viscosity of liquids. These hypotheses can be tested in Part 5 using MAGMA. If enough space is available to have each group run their experiments simultaneously, it will be useful to have all of the students circulate and observe the end results of the syrup flows for each set of experiments and discuss differences and similarities.

NOTES FOR PART 4

This next part of the lab allows students to apply their newfound knowledge and skills with Jeffreys equation to extrapolate from the lab to the real world. For *Part A* they need to rearrange Jeffreys equation to solve for velocity instead of viscosity; this only requires switching the viscosity and the velocity terms in the equation.

$$V = \frac{g \cdot \rho \cdot \sin\alpha \cdot d^2}{n \cdot \eta}$$

Then, using the data from Murase and McBirney (1973), students can calculate the velocities for lava flows of different compositions and see how differences in viscosities drastically influence volcanic hazard assessments from lava flow hazards.

Part B is a qualitative exercise that guides students, through a series of questions, to the idea that higher viscosities prevent gas bubbles from easily escaping and allow for a buildup of gas pressures, which can lead to more explosive eruptions.

NOTES FOR PART 5

In the final part of the exercise, students are asked to use MAGMA to reproduce some of their syrup experiments using equations for predicting viscosities of real magma compositions. The program is easy to install on computers and easy to use, with only one screen interface. Data for "magma" chemical compositions can be entered manually or a variety of common rock compositions can be accessed via a pull-down menu. Magma viscosities can be calculated as a function of temperature, pressure (a small effect), dissolved water content, and percent solids present. Ideally the students can use MAGMA calculations to reconfirm their intuitions from the syrup experiments and test their hypotheses on "real" magmas/lavas.

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