Portable Rock-Analog Deformation Apparatus (PRADA)

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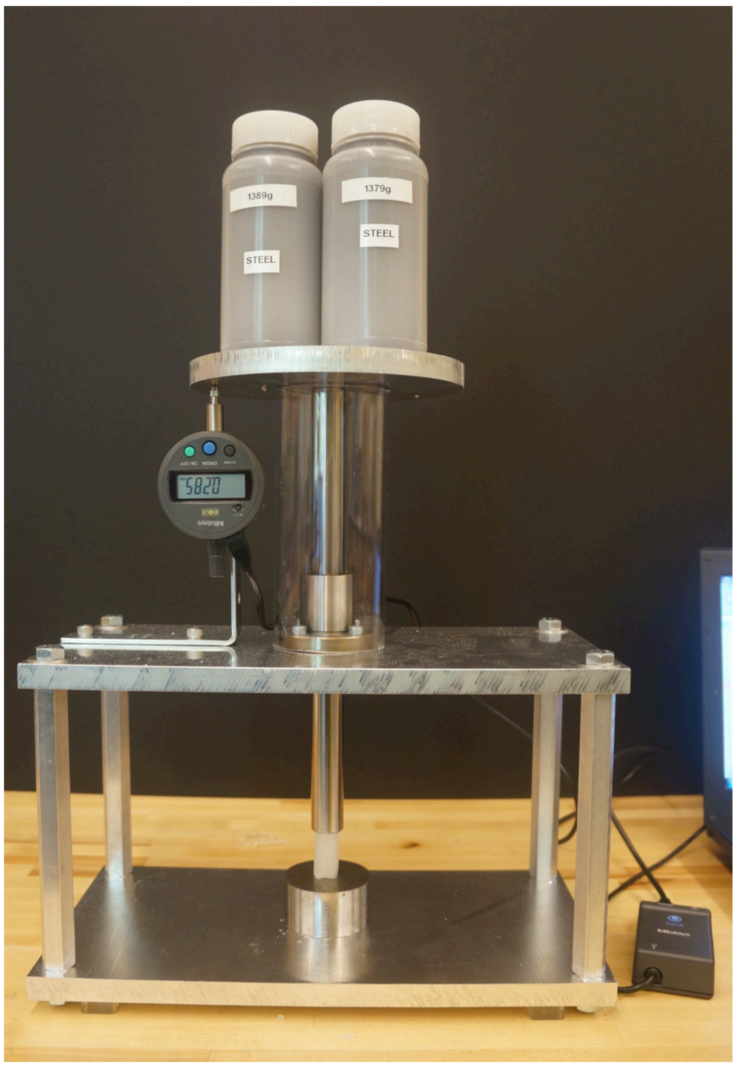

espm.wustl.edu/PRADA

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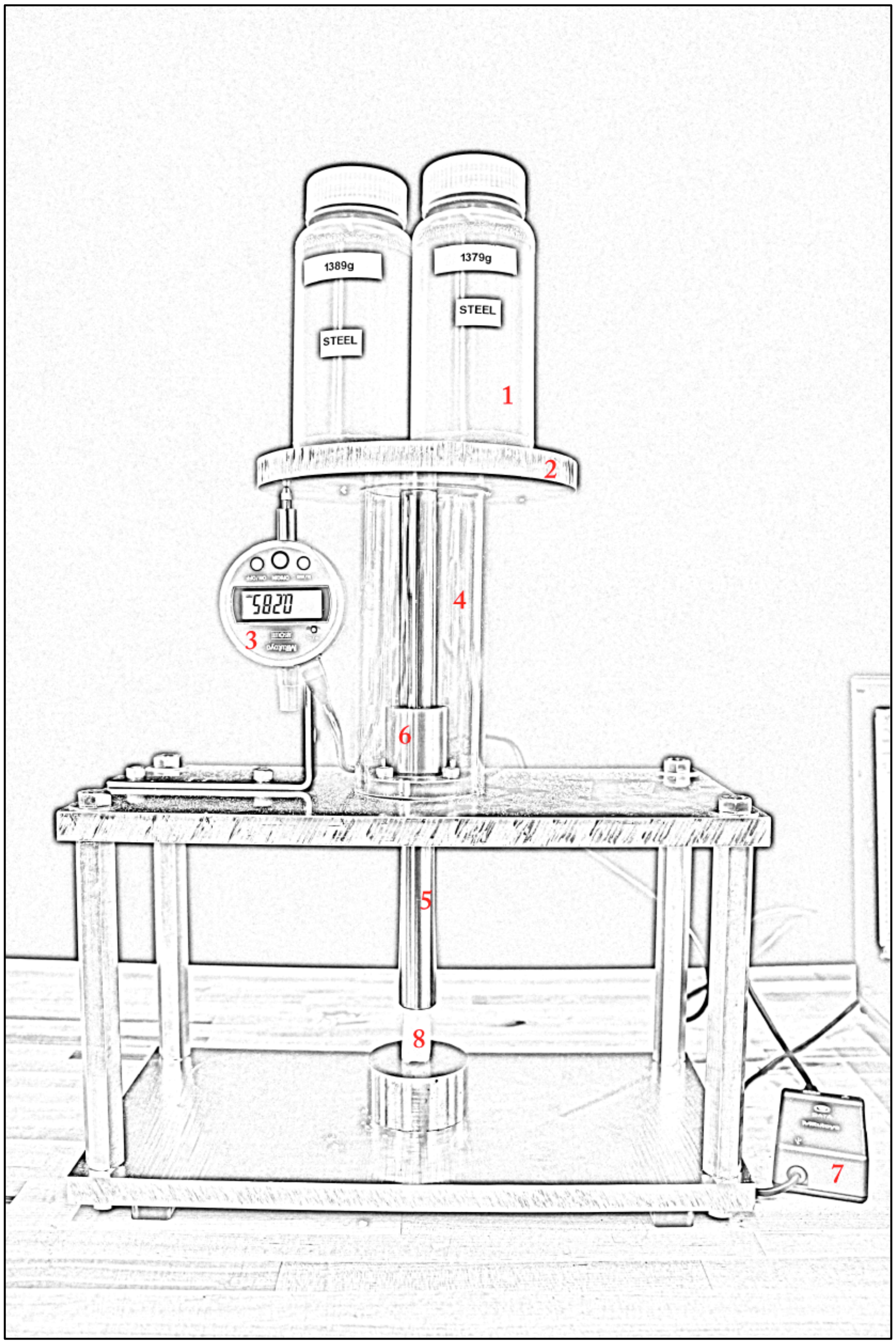

Figure 1: Schematic cartoon of PRADA
1 – Calibrated weights for applying load
2 – Circular aluminum plate for holding calibrated weights
3 – Digital indicator for measuring relative displacement
4 – Polycarbonate sleeve for protecting digital indicator from catastrophic impact
5 – Loading shaft
6 – Linear bearing for aligning loading shaft
7 – Input device for interfacing between digital indicator and laptop
8 – Sample for deformation

1. Introduction

The Portable Rock-Analog Deformation Apparatus (PRADA) is a simple device designed for making precise rheological measurements of relatively soft materials such as waxes or clays. Many of these materials exhibit non-linear rheologies, and are thus suitable analogs for rocks deforming at high pressure and temperature. A prototype of this apparatus was built in 2009, and has been incorporated successfully into Washington University's undergraduate curriculum through structural geology and introductory geophysics classes.

An award from NSF (EAR-1352306) has supported the design and construction of 12 of these apparatuses (Figure 1). These apparatuses will be distributed free of charge to liberals arts colleges and other institutions to help build an infrastructure for teaching experimental rock mechanics at the undergraduate level.

The PRADA is an example of what is known as a "dead-weight creep apparatus," which means that near-constant stresses are applied using calibrated weights. Differential stresses, which drive deformation, are calculated easily from the forces being applied and the dimensions of the test specimen. Displacement (and thus strain) is calculated using a precise digital indicator. The apparatus is designed so that it can be constructed and maintained with minimal equipment. All parts are obtainable from the supply catalog McMaster-Carr (www.mcmaster.com) and a complete parts list and schematic drawing is available on the PRADA website (espm.wustl.edu/prada). All PRADAs come with a lifetime service contract.

2. Scientific Background

The following is just a brief introduction to the basic principles of experimental rock mechanics. There are many excellent textbooks that discuss the scientific background in greater detail (e.g. Poirier, 1985, Chapter 1)[1]. Rocks at high pressure and temperature deform by one of several mechanisms, including diffusion creep and dislocation creep.

During diffusion creep, stress and strain are related by the following equation:

$$\dot{\varepsilon}_{dif} = A\sigma d^{-m} \exp\left(-\frac{H_{dif}}{RT}\right) \quad (1)$$

where $\dot{\varepsilon}$ is strain-rate, which has units of inverse seconds; σ is the differential stress; A and m are material specific constants; H is the activation enthalpy for diffusion creep, R is the gas constant, and T is temperature. Note that strain-rate and stress are linear with respect to one another, however the diffusion creep law has an inverse power-law

[1] Poirier, J-P, (1985) *Creep of Crystals*, Cambridge University Press, 260pp

dependence on grain-size (m is nominally 2 for Nabarro-Herring creep and 3 for Coble creep).

During dislocation creep, stress and strain are related by a similar expression:

$$\dot{\varepsilon}_{dis} = A\sigma^{n}\exp\left(-\frac{H_{dis}}{RT}\right) \tag{2}$$

In this case, however, stress and strain-rate exhibit a power law relation where n is typically 3-5. Also there is no grain-size sensitivity to dislocation creep.

There are two basic categories of rock deformation experiments: constant strain-rate and constant stress tests (the latter is also known as a "creep" test). In principle both methods should yield the same rheological information. In a constant strain-rate test, deformation of a sample is imposed by an actuator that moves at a constant displacement rate. Stress, which may vary throughout the experiment, is measured using some type of calibrated transducer or load-cell. In a creep test a constant stress is applied and displacement (strain) is continuously monitored. A plot of strain versus time is called a creep curve (Figure 2). The slope of this line is the strain-rate. During a creep test, the experiment is run until it is determined that the strain-rate has reached steady state.

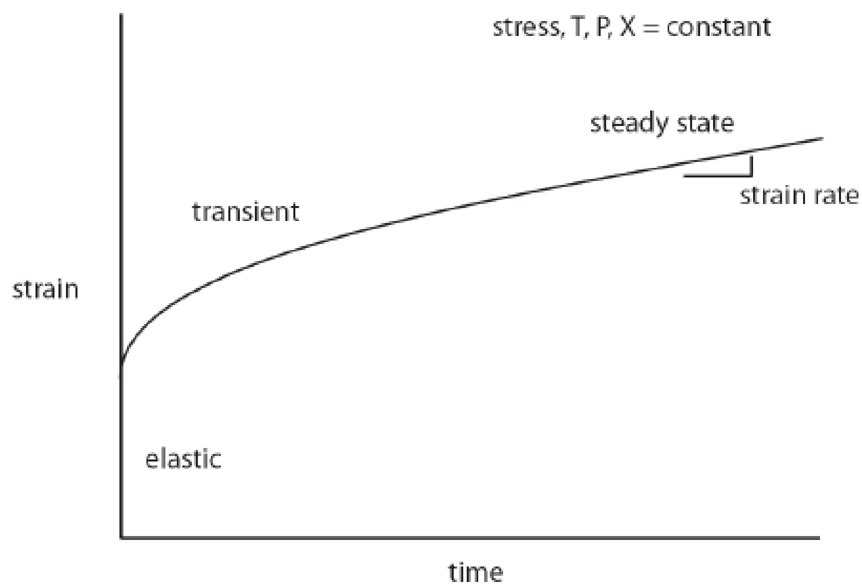

Figure 2: Schematic creep curve for a test at a constant temperature (T), hydrostatic pressure (P), chemical composition (X), and load. The initial strain is entirely elastic, followed by an interval of transient creep in which strain-rate decreases monotonically, followed by a period of steady-state creep where strain accumulates linearly.

To fully parameterize a constitutive relationship, such as equation 2, it is necessary to conduct experiments over a range of stresses and a range of temperatures. For example, to determine the stress exponent n, one would conduct experiments at constant temperature and a range of stresses. The slope of a log-log plot of stress versus steady-state strain-rate is used to determine n. Flow laws parameterized in this manner are widely used in geophysics to model the deformation of the crust and mantle, especially in deep Earth or planetary settings that are inaccessible to traditional geologic study.

3. Preparing samples for deformation

PRADA is designed to deform cylindrical samples that are less than 0.75 inches in diameter. The length of the cylinder should be at least two times the diameter; short samples may be compromised by friction along the faces of the cylinder. For normal use, I recommend samples that are 0.50 inches in diameter and approximately 2 inches long. With your apparatus I have provided a cylindrical die in which to prepare a sample (Figure 3).

Figure 3: Materials for preparing a sample for deformation. Left: 1 lb bag of paraffin wax beads. Right: aluminum die with steel push rod (long) and bottom plug (short).

The following instructions refer to paraffin wax as the test sample, however there are many other interesting materials that could be studied.

Materials needed: Die set with hex key, paraffin beads, hot plate, aluminum foil, heat resistant container (e.g.: old can), and hammer or mallet

1. In a heat resistant container, melt a small quantity of paraffin beads (130°C works well).

2. Place the die set on the aluminum foil to protect the work space

3. Tighten the 4 screws holding the two halves of the aluminum die around the bottom plug and the push rod. The push rod should still be able to move freely.

4. Take the push rod out and make sure the bottom plug is all the way at the bottom of the die set

5. Pour the hot molten paraffin until it forms a dome at the top of the die.

6. As the paraffin cool down, the top part of the cylinder will shrink and form a hole. As soon as the paraffin turns all white (about 1 min), hammer the top of the cylinder to flatten the surface using the push rod and a mallet. You might need to do that a couple of times as the cylinder keeps cooling and shrinking.

7. Wait 5 min for the whole cylinder to be entirely cool, then loosen the 4 screws a bit and hammer the cylinder out of the die using the push rod.

8. The bottom plug might stick to the paraffin cylinder. It can easily be unstuck. You can put a thin layer of WD-40 before pouring the hot paraffin if it is difficult to remove the bottom plug .

9. For the creep test to give good results the sample should be fully dense. You can confirm that the sample is free of open spaces by calculating its density and comparing it to its theoretical value. You can also look at the specimen under a binocular microscope.

10. Measure the initial diameter and the length of your cylinder using a micrometer or ruler.

11. Before casting the next cylinder, make sure to hand tight the screws around the bottom plug and the push rod (return to step 3)

12. The die set needs to be fully cleaned every 25-30 cylinders (use acetone or nail polish remover)

5. Measuring displacement

PRADA measures displacement using a Mitutoyo digital indicator. This indicator has a range of 13 mm and a precision of 0.001 mm (one micron). These indicators can communicate with a laptop using the included USB input device. The input device treats the digital indicator like a keyboard. When you plug it into a USB slot for the first time it should load the necessary drivers automatically. Once it is configured, pressing the blue "data" button will write the value on the face of the digital indicator. I have provided an Excel file that will allow you to input displacements, and adds a time stamp so you can calculate strain-rates. You are, of course, welcome to write a more sophisticated program in Matlab or another language.

6. Applying a load

Loads are applied using calibrated weights. For my lab I took 12 one-pint Nalgene bottles and filled them with steel shot. Each bottle was weighed and labeled with the mass (about 1.4 kg each). With your PRADA I have provided a sealable bucket that can be filled with water. We have pre-calibrated the weight according to the table below, but you may want to double-check this calibration for accuracy.

Liters	Weight (kg)	Weight (lbs)
0	1.2	2.6
2	3.05	6.7
4	4.92	10.8
6	6.72	14.8
8	8.59	18.9
10	10.47	23.1
12	12.34	27.2
14	14.23	31.4

Other easy solutions would be to go to your local sporting goods store and pick up some 5 and 10 lb barbell plates, or to fill stackable Tupperware with sand. Keep in mind that for the paraffin exercise (assuming a sample with an initial diameter of 0.5 inches) you will need to apply upwards of 30 lbs of force in several well-spaced increments. Also, note that the moving part of the PRADA, which includes the steel shaft and the circular aluminum plate, has finite mass as well. These are labeled, and must be included in your calculations.

7. Running an experiment

1. Position your sample such that the micrometer is at the low end of its range. Depending on the length of your sample, this may require you to shim up the sample using a small flat object. A metal or polycarbonate shims (included) will work well.

2. Insert the steel shaft into the linear bearing. The mass of the shaft is small enough that you won't deform the sample much until you add more load.

3. Zero the digital indicator.

4. Position your mass on top of the circular aluminum disk. For the half-inch diameter paraffin sample, ~10 lbs of force is a good place to start. Although the sample will not appear to be deforming, a quick glance at the digital indicator will confirm that it is indeed changing length. So you should start logging data immediately.

5. If you are using the provided spreadsheet put the cursor in cell C3 (or F3 / I3 in subsequent runs). Pressing the blue button will log the displacement and the cumulative elapsed time. Displacement can be readily converted to strain by normalizing by the initial length.

6. Continue logging data at regular intervals until you are convinced that the strain-rate has reached steady state. At this point you can unload the specimen. I always recommend measuring the dimensions after the experiment to see how much of the deformation you have imposed is permanent.

7. For typical lab exercises I will have students (i) run three experiments at three different loads, (ii) plot the stress versus strain-rate to calculate a stress exponent, and (iii) to compare their results with published flow laws for paraffin.

8. Maintaining your apparatus

The PRADA should require almost no maintenance. Keep it clean and dry in between uses. Most of the body is aluminum. The shaft and linear bearing are tool steel. A spot of oil or WD-40 on the steel parts will keep things in good shape.

The digital indicator is the most sensitive (and expensive) piece of the apparatus. Make sure that the weights never slam down such that the indicator is pushed to its maximum range. The polycarbonate sleeve around the shaft and bearing will keep this from happening.

9. Acknowledgements

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