Rheology
or
How to Squish a Rock
or
What is $\eta$ and how do we know?

Phil Skemer
Washington University in St Louis

CIDER
June 29th, 2017
EXPERIMENTAL DEFORMATION AND FAULTING IN WOMBEYAN MARBLE

By M. S. Paterson
AN EXPERIMENTAL INVESTIGATION INTO THE ACTION OF DIFFERENTIAL PRESSURE ON CERTAIN MINERALS AND ROCKS, EMPLOYING THE PROCESS SUGGESTED BY PROFESSOR KICK

FRANK D. ADAMS
McGill University, Montreal

(6) Column of Carrara marble before and after deformation, using alum as an embedding material
The upper mantle:

- Bread in the jelly sandwich?
- Crème in the crème brûlée?
- Banana in the banana split?
Abers et al. 2006

Diagram: Non-Newtonian with cold forearc mantle

Depth (km)

Distance from Trench (km)

Legend:
- 200
- 400
- 600
- 800
- 1000
- 1200
- 1400
Rheology (n): describes the ability of stressed materials to deform, or flow, using fundamental parameters including as strain rate, elasticity and viscosity (from Greek, *rheos*, to stream or flow)

*van der Pluijm and Marshak (2017)*
\[ \sigma = \frac{F}{A} \text{ [Pa]} \]

\[ \sigma_{ij} = \begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{bmatrix} \]

\[ \sigma_1 > \sigma_2 > \sigma_3 \]
Longitudinal Strain (-rate)

\[ \varepsilon = -\frac{l_{\text{final}} - l_{\text{initial}}}{l_{\text{initial}}} \]

Longitudinal Strain

Before

\[ l_o \]

After

\[ l_f \]

\[ \varepsilon = 0.23 \]
Shear Strain (-rate)

\[ \gamma = \frac{a}{b} \]

\( \gamma = 0 \)

\( \gamma = 1 \)

\( \gamma = 5 \)

\( \gamma = 10 \)

\( \gamma = 50 \)
Shear Strain(-rate)

\[
\gamma = 0
\]

\[
\gamma = 1
\]

\[
\gamma = 5
\]

\[
\gamma = 10
\]

\[
\gamma = 50
\]

Linckens et al. (2011, 2015)
## Silly Putty

<table>
<thead>
<tr>
<th>Item</th>
<th>Approved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>No</td>
</tr>
<tr>
<td>Prosthetics</td>
<td>Yes</td>
</tr>
<tr>
<td>Protein Powder</td>
<td>Yes</td>
</tr>
<tr>
<td>Putty Balls</td>
<td>Yes</td>
</tr>
<tr>
<td>Radio</td>
<td>Yes</td>
</tr>
</tbody>
</table>

You may transport this item in carry-on or checked bags. For items you wish to carry on, you should check with the airline to ensure that the item will fit in the overhead bin or underneath the seat of the airplane.

**Razor-Type Blades**

Box cutters, razor blades not in a cartridge are prohibited in carry-on.

Any sharp objects in checked bags should be sheathed or securely wrapped to prevent injury to baggage handlers and inspectors.
What controls the style of deformation?

- Forces applied (stress)
- Rate at which it is deformed (strain-rate)
- Magnitude of deformation (strain)
- Temperature
- Pressure
- Composition
Ideal Models of Rheology

Spring, representing elastic behavior

Dashpot, representing viscous behavior

Sliding block, representing plastic behavior
Elastic

\[ \sigma \quad E \quad \varepsilon \]
Elastic

t_0 = apply a constant stress

\( t_0 = \) apply a constant stress

\( t_1 = \) remove stress
Viscous

\[ \sigma \sim \dot{\varepsilon} \]

\( \eta \)
Viscous

t₀ = apply a constant stress
t₁ = remove stress
Plastic

critical yield stress

\[ \sigma \]

\[ \dot{\varepsilon} \]
Maxwell (Elastico-viscous) Solid

$t_0 = \text{apply a constant stress}$  
$t_1 = \text{remove stress}$
Kelvin (Visco-elastic) Solid
Burgers (General Linear) Solid

\[ E_2 \]

\[ \eta_2 \]

\[ E_1 \]

\[ \eta_1 \]

\[ \varepsilon \]

\[ t_0 \]

\[ t_1 \]

Time
Micro-Creep Curves in Geologic Materials

\[ \gamma = \text{high} \] for 1300°C

\[ \gamma = \text{low} \] for 1200°C

Shear strain (\(\times 10^6\))

\(\sigma = 93\) kPa

Sundberg and Cooper (2010)
Experimental Rock Deformation

- Prepare & characterize starting material
  - Composition
  - Microstructure

- Establish deformation conditions
  - Temperature
  - Pressure

Option #1:
- Hold stress constant and monitor changes in strain-rate (creep test)

Option #2:
- Hold strain-rate constant and monitor changes in stress

Characterize deformed material

Fit data to relevant flow law
Influence of water on plastic deformation of olivine aggregates
2. Dislocation creep regime

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Rheology of the Upper Mantle and the Mantle Wedge: A View from the Experimentalists

Greg Hirth

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

David Kohlstedt

Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota
Experimental Rock Deformation

Prepare & characterize starting material
  - Composition
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Establish deformation conditions
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Option #1
Hold stress constant and monitor changes in strain-rate (creep test)

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Characterize deformed material

Fit data to relevant flow law
Xenoliths or other natural rocks

Gem-quality olivine crystals

Ground to fine-grained powder
Hot-pressed to make a dense, homogeneous, fine-grained polycrystal

Demouchy et al (2011)
Experimental Rock Deformation

1. Prepare & characterize starting material
   - Composition
   - Microstructure

2. Establish deformation conditions
   - Temperature
   - Pressure

Option #1: Hold stress constant and monitor changes in strain-rate (creep test)

Option #2: Hold strain-rate constant and monitor changes in stress

Characterize deformed material

Fit data to relevant flow law
Paterson Apparatus

- Iron jacket
- Deformation specimen
- Alumina spacers
- Yttria-stabilized zirconia

Kohlstedt Lab, University of Minnesota

- Low pressure ($P<300$ Mpa)
- Excellent stress resolution
- Low or high strain (depends on instrument)
- Large sample volume

Photo credit: SERC
Griggs Apparatus

• Moderate pressure / temperature
• Poor stress resolution
• Moderate strain
• Moderate sample volume
D-DIA Apparatus

- High pressure and temperature
- Good stress resolution
- Low strain
- Small sample volume
Large Volume Torsion Apparatus (LVT)

Washington University in St. Louis

- Moderate pressure / temperature
- Poor stress resolution
- Large strains
- “large” sample volume

2-phase mixtures of calcite and anhydrite

Cross & Skemer (2017) JGR
Nano-indentation / Micropillar Compression Testing

- High ‘pressure’ and moderate temperature
- Excellent stress resolution
- Low strain
- Sub-micron sample volume
Experimental Rock Deformation

Prepare & characterize starting material
- Composition
- Microstructure

Establish deformation conditions
- Temperature
- Pressure

Hold stress constant and monitor changes in strain-rate (creep test)

Option #1

Option #2

Hold strain-rate constant and monitor changes in stress

Characterize deformed material

Fit data to relevant flow law
Raw data recorded by deformation apparatus

Mei and Kohlstedt (2000)
Experimental Rock Deformation

Prepare & characterize starting material
- Composition
- Microstructure

Establish deformation conditions
- Temperature
- Pressure

Option #1
Hold stress constant and monitor changes in strain-rate (creep test)

Option #2
Hold strain-rate constant and monitor changes in stress

Characterize deformed material

Fit data to relevant flow law
Microstructural Analysis

Grain-size

Mei and Kohlstedt, 2000

Dislocations

Wallis et al 2016

Grain Scale Microstructures (EBSD)

Hansen et al 2011

Lattice Preferred Orientation

Hansen et al 2014
Experimental Rock Deformation

Prepare & characterize starting material
- Composition
- Microstructure

Establish deformation conditions
- Temperature
- Pressure

Option #1: Hold stress constant and monitor changes in strain-rate (creep test)

Option #2: Hold strain-rate constant and monitor changes in stress

Characterize deformed material

Fit data to relevant flow law
Dislocation Creep

Microstructural Effects:

1. Changes grain size and shape
2. Produces LPO

\[ \dot{\varepsilon} \propto \frac{\sigma^n}{d^m} \]

- \( n = 3-5 \)
- \( m = 0 \)
Diffusion Creep

\[ \dot{\varepsilon} \propto \frac{\sigma^n}{d^m} \]

- \( n = 1 \)
- \( m = 2-3 \)

Microstructural Effects:
1. Changes grain shape, not size
2. Does not produce LPO
Constitutive Expressions for High PT Deformation

\[ \dot{\varepsilon} = A \sigma^n F(y) d^{-m} C_{OH}^r \exp(\alpha \phi) \exp \left( -\frac{E + PV}{RT} \right) \]
Stress Dependence

\[ \dot{\varepsilon} = A \sigma^n F(\gamma) d^{-m} C_{OH}^r \exp(\alpha \varphi) \exp\left(-\frac{E + PV}{RT}\right) \]

Temperature Dependence

\[ T (^\circ\text{C}) \]

1350 1300 1250 1200

\[ P = 100 \text{ MPa} \]

\[ \sigma = 155 \text{ MPa} \]

\[ a_{\text{H}_2\text{O}} \approx 1 \]

\[ Q = 470 \text{ kJ/mol} \]

\[ P = 300 \text{ MPa} \]

\[ \sigma = 175 \text{ MPa} \]

\[ a_{\text{H}_2\text{O}} \approx 0 \]

\[ Q = 510 \text{ kJ/mol} \]
Olivine Deformation Mechanism Map

- T = 1200°C
- P = 300 MPa
- Mg # ~ 90
- COH = dry
- Melt $\phi = 0$

Hansen et al. (2011)
Kranjc et al. (2016)
Portable Rock Analog Deformation Apparatus (PRADA)

Dead weight creep apparatus
Room pressure
Room temperature
• 10 apparatus available

• Samples of paraffin are already prepared

• Each group will complete and analyze 2-3 creep tests

• We will compile our data to see if the rheology of paraffin wax at room T is linear or non-linear