Deformation mechanisms in crystalline magma

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Why do we care?

Effusive

Explosive

Mount Etna, Jan 2011
(dailymail)
DUCTILE to BRITTLE

Modified from Tuffen et al. 2008

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The glass transition: pure silicate melt

Relaxed, equilibrium

Unrelaxed, disequilibrium
In nature: pure silicate melt is rare

- Addition of pores and *crystals*

COMPLEX RHEOLOGY
The stress effect

Increasing applied stress
- Instantaneous
  - Decreases viscosity

Constant stress
- Gradual
  - Decreases viscosity

Cordonnier et al. 2009

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The ductile-brittle transition

Cordonnier et al. 2009

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Experimental procedure

Uniaxial press:
• Constant stress
• 940-950 °C

➢ To study in situ the rheology of multi-phase melts.
Material Properties

MAKE-UP (excluding porosity)

Glass ~ 40 %
Crystals ~ 35 %
Microlites ~ 20 %
Temperature effect

\[ \sigma = \frac{48155}{(T-885)} \dot{\gamma}^{0.5} \]

Lavallee et al. (2011)
Strain Effects

Time Dependent

Constant Stress

7 %  14 %  21 %  28 %  35 %

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Strain Effects

- Time Dependent
- Strain Dependent

- Constant Stress
- Strain Dependent

7 %  14 %  21 %  28 %  35 %

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Strain Effects

Constant Stress

Time Dependent

Strain Dependent

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Stress Effects

Lavallee et al. (in prep.)

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Stress Effects

Seismic b-values decrease

Localised macroscopic crack growth across ductile-brittle transition
**Stress Effects**

Strain at failure:
- 28.5 MPa: 20%
- 46 MPa: 12%
- 76 MPa: 5.5%

Stress Effects - inc. Stress dec. Strain to failure
Strain-rate Effects

\[ \log \eta_b = -0.993 + \frac{8974}{T} - 0.543 \log \gamma \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Log viscosity (Pa s) vs. Strain rate (s^{-1}).}
\end{figure}

Validity: 50-80% crystals <25% vesicles

Lavallee et al. (2007)
Measuring deformation

- Porosity
- Ultrasonic velocity waves for dynamic:
  - Young’s modulus and
  - Poisson’s ratio

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<tr>
<th>Sample</th>
<th>Porosity (%)</th>
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<td>12 MPa</td>
<td>24 MPa</td>
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<tr>
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<td>20% strain</td>
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<tr>
<td>B2</td>
<td>9.5</td>
<td>10.9</td>
<td>11.9</td>
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<td>LAH4</td>
<td>27.2</td>
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<th>Young’s Modulus (GPa)</th>
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<tr>
<td>LAH4</td>
<td>0.34</td>
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</tbody>
</table>
Neutron Computed Tomography

Low-load deformation

High-load deformation
Summary

- Dense magmas are more susceptible to dilation.
- Dilation is initiated at lower strain with higher stresses.
- Higher temperature results in higher strain rates.
- Higher stress results in higher strain rates.
- We observe a strain-dependent decrease in viscosity at constant stress and instantaneous decrease with increasing stress.
- Higher applied stresses form more AE, lower b-values and decrease the total strain required for failure.
- Dynamic elastic properties show a complex evolution of initial strengthening and subsequent weakening of the material with increasing strain.
- Strain has a larger effect on crystallographic alignment.
- Stress has a larger effect on crystal size reduction.
Outcomes

- Chemically similar lava types have different mechanical properties, displaying a significant range of measured strain rates at a given temperature and applied stress.
- Crystallinity increases the range of the ductile-brittle transition and failure of magma becomes dependent upon total strain.
- Dynamic Young’s modulus and Poisson’s ratio do not change significantly, thus (for magma) do not represent the true characteristics of the samples and should not be used as a proxy to strain (or damage).
- Thus crystallinity has a significant effect on magma rheology with the implication that viscous models may not encompass the full complexity of crystal-bearing magma.

➢ We need a better mechanical understanding to improve our models!!
Reading


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