New insight into mantle rheology from laboratory experiments: Grain-boundary sliding and viscous anisotropy

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Plate boundaries require localization.
Plate boundaries require localization.

Many plate boundaries appear anisotropic.
I have three questions to answer…

• Is there a mechanism that allows localization and anisotropy?
  • Dislocation-accommodated grain-boundary sliding (disGBS)

• Are there mechanical consequences of that anisotropy?
  • Viscous anisotropy

• Can we demonstrate these mechanisms lead to localization?
  • Even in monophase materials
Dislocation Creep

high strain rate

med strain rate

low strain rate

Diffusion Creep

Steady-state grain size

after Karato and Wu (Nature, 1993)
strong anisotropy

Dislocation Creep

high strain rate

med strain rate

low strain rate

no anisotropy

after Karato and Wu (Nature, 1993)
strong anisotropy

after Karato and Wu (*Nature*, 1993)
Dislocation model of GBS

see Ashby (Surf. Sci., 1972)
Dislocation model of GBS

Migration and sliding are coupled!
Dislocation model of GBS

Ashby (Surf. Sci., 1972)
Grain-boundary viscosity

Olivine

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

Viscosity (Pa s) vs Temperature (°C)

- Xu et al. (2004)
- Sunberg and Cooper (2008)

Ice

\[ \sigma = 1 \text{ MPa} \]

Viscosity (Pa s) vs Temperature (°C)

- Tatibouet et al. (1987)
- Cole and Durrell (1995)
Grain-boundary viscosity

Olivine

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

- Single crystal
- [110]_c
- [011]_c

Grain boundary

Xu et al. (2004)
Sunberg and Cooper (2008)

Ice

\[ \sigma = 1 \text{ MPa} \]

- Single crystal
- Basal glide

Grain boundary

Tatibouet et al. (1987)
Cole and Durrell (1995)
Accommodation of GBS

- Cavitation
- Elastic deformation
- Diffusional flow
- Dislocation motion
Accommodation of GBS

Cavitation

Elastic deformation

Diffusional flow

Dislocation motion

Diffusion creep

Dislocation-accommodated GBS
Accommodation of GBS

\[ \dot{\varepsilon} = A \frac{\sigma^n}{d^p} \exp\left(\frac{-Q}{RT}\right) \]

\( n = 2 \) and \( p = 2 \)

or

\( n = 3 \) and \( p = 1 \)

Dislocation motion

Dislocation-accommodated GBS
Textures in polycrystals

Zhang et al. (JSG, 1994)
Textures in polycrystals
Textures in polycrystals

Leads to anisotropy in...
- Elasticity
- Electrical conductivity
- Thermal conductivity
- Viscosity?
disGBS in olivine in compression

\[ \dot{\varepsilon} \propto \frac{\sigma^{2.9}}{d^{0.73}} \]

Hansen et al. (J. Geophys. Res., 2011)
disGBS in olivine in compression

\[ \dot{\varepsilon} \propto \frac{\sigma^{2.9}}{d^{0.73}} \]

\( T = 1473 \text{ K} \)
\( d = 10 \mu\text{m} \)

Hansen et al. (J. Geophys. Res., 2011)
disGBS in olivine in torsion

Hansen et al. (J. Geophys. Res., 2012)
disGBS in olivine

1200°C
Fo$_{50}$ stress = 100 MPa

$\dot{\varepsilon} \propto \frac{\sigma^{4.0}}{d^{0.73}}$

Hansen et al. (J. Geophys. Res., 2012)
disGBS in olivine

Hansen et al. (J. Geophys. Res., 2012)
Extrapolation to Earth

$T = 1473 \text{ K}$

- Dislocation creep
  - $\dot{\varepsilon} = 10^{-6} \text{s}^{-1}$
- Diffusion creep
  - $\dot{\varepsilon} = 10^{-10} \text{s}^{-1}$
Extrapolation to Earth

$T = 1473 \text{ K}$

![Diagram showing the relationship between stress, grain size, and creep mechanisms for synthetic and natural olivine lab data.](image)

- **Dislocation creep**
  - $\dot{\varepsilon} = 10^{-6} \text{ s}^{-1}$
  - $\dot{\varepsilon} = 10^{-10} \text{ s}^{-1}$

- **Diffusion creep**

- **Synthetic olivine lab data**

- **Natural olivine lab data**

- **Upper mantle**
A simple extrapolation predicts disGBS is the dominant mechanism in the lithosphere.

Kohlstedt and Hansen
Treatise on Geophysics
in press
Extrapolation to other rocky planets

Higher temperatures promote dislocation creep.
Some consequences of viscous anisotropy

Convection cells


Density instabilities

Lev and Hager, *GJI*, 2008
Outstanding problems for olivine…

How do you deal with the lack of slip systems?

Table 2. Slip System Data Used to Simulate High-Temperature Deformation

<table>
<thead>
<tr>
<th>Slip System</th>
<th>Critical Resolved Shear Stress $\tau_0^*$</th>
<th>Stress Exponent $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(010)[100]</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>(001)[100]</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>(010)[001]</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>(100)[001]</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>{011}[100]</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>{031}[100]</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>{110}[001]</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>{111}[110]</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>{111}[011]†</td>
<td>500</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Outstanding problems for olivine…

How do you deal with the lack of slip systems?
How do you deal with the role of grain boundaries?

Hansen et al., *in prep.*

Outstanding problems for olivine…

How do you deal with the lack of slip systems?
How do you deal with the role of grain boundaries?
How do we go to high strain?

Outstanding problems for olivine…

How do you deal with the lack of slip systems?
How do you deal with the role of grain boundaries?
How do we go to high strain?
What about pre-existing textures?

How much weakening from texture vs. grain size?

\[ \dot{\varepsilon} = 4.5 \times 10^{-5} \text{s}^{-1} \]

Hansen et al., *J. Geophys. Res.*., 2012
Predicted stress based on change in grain size

\[ \varepsilon = 4.5 \times 10^{-5} \text{s}^{-1} \]

How much weakening from texture vs. grain size?

How much weakening from texture vs. grain size?

\[ \dot{\varepsilon} = 4.5 \times 10^{-5} \, \text{s}^{-1} \]

Predicted stress based on change in grain size

About 30% reduction in stress from texture

\[ \delta = \frac{\text{viscosity in tension}}{\text{viscosity in torsion}} \]
Can these data lead to a general model?

numerical
(Knoll et al., JGR, 2009)
Comparison to laboratory data

Experiment

\[
\begin{align*}
\text{Max:} & \quad 2.9 \\
\text{Min:} & \quad 0.21
\end{align*}
\]

\[
\begin{align*}
\text{Max:} & \quad 2.8 \\
\text{Min:} & \quad 0.25
\end{align*}
\]

\[
\begin{align*}
\text{Max:} & \quad 1.8 \\
\text{Min:} & \quad 0.48
\end{align*}
\]

Model

\[
\begin{align*}
\text{Max:} & \quad 2 \\
\text{Min:} & \quad 0.35
\end{align*}
\]

\[
\begin{align*}
\text{Max:} & \quad 2.2 \\
\text{Min:} & \quad 0.12
\end{align*}
\]

\[
\begin{align*}
\text{Max:} & \quad 2 \\
\text{Min:} & \quad 0.26
\end{align*}
\]

\[\gamma = 0.0\]
An anisotropic mechanical model

\[ \varepsilon_{ij} = \Phi_0 \Phi_{ijkl} \sigma_{kl} \sigma_e^{(n-1)} \]

Constant stress
\[ \Phi_{ijkl} = \sum_{g} F_{ijkl}^g \]

Constant strain rate
\[ \Phi_{ijkl} = \left( \sum_{g} \frac{1}{F_{ijkl}^g} \right)^{-1} \]

Average of two bounds
\[ \Phi_{ijkl} = \frac{1}{2} \left[ \left( \sum_{g} \frac{1}{F_{ijkl}^g} \right)^{-1} + \sum_{g} F_{ijkl}^g \right] \]

\[ F_{ij} = \begin{bmatrix} F_{11} & F_{12} & F_{13} \\ F_{12} & F_{22} & F_{23} \\ F_{13} & F_{23} & F_{33} \end{bmatrix} \]

Anisotropy of one crystal
An anisotropic mechanical model

Tension

Strain rate, $\varepsilon_{11}$ (s$^{-1}$)

\[
-10^{-6} \quad -10^{-5} \quad -10^{-4} \quad -10^{-3}
\]

Stress, $\sigma_{11}$ (MPa)

-10$^2$

Torsion

Strain rate, $\varepsilon_{12}$ (s$^{-1}$)

\[
10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^{-0}
\]

Stress, $\sigma_{12}$ (MPa)

10$^2$

[1 0 0] [0 1 0] [0 0 1]
An anisotropic mechanical model

Tension

Strain rate, $\varepsilon_{11}$ (s$^{-1}$)

Stress, $\sigma_{11}$ (MPa)

Torsion

Strain rate, $\varepsilon_{12}$ (s$^{-1}$)

Stress, $\sigma_{12}$ (MPa)

[1 0 0] [0 1 0] [0 0 1]
An anisotropic mechanical model
An anisotropic mechanical model

\[ \dot{\varepsilon}_{ij} = \Phi_0 \Phi_{ijkl} \sigma_{kl} \sigma_e^{(n-1)} \]

Anisotropy of the aggregate

\[ \Phi_{ijkl} = \left( \sum_g \frac{1}{F_{ijkl}^g} \right)^{-1} \]

Anisotropy of one crystal
An anisotropic mechanical model

\[ \dot{\varepsilon}_{ij} = \Phi_0 \Phi_{ijkl} \sigma_{kl} \sigma_e^{(n-1)} \]

Anisotropy of the aggregate

\[ \Phi_{ijkl} = \left( \sum_g \frac{1}{F_{ijkl}^g} \right)^{-1} \]

Anisotropy of one crystal
Localization is observed...

Hansen et al., *EPSL*, 2012

200 µm
That’s great, but is it scalable?
Application to natural shear zones

Josephine Peridotite
Pyroxene layering
Application to natural shear zones

Shear strain measured from orientation of pyroxene layering

Warren et al., *EPSL*, 2008
<table>
<thead>
<tr>
<th>Shear Strain</th>
<th>[100]</th>
<th>[010]</th>
<th>[001]</th>
<th>Shear Strain</th>
<th>[100]</th>
<th>[010]</th>
<th>[001]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td>168%</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
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<tr>
<td>65%</td>
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<td><img src="image3.png" alt="Image" /></td>
<td>258%</td>
<td><img src="image4.png" alt="Image" /></td>
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<td>386%</td>
<td><img src="image4.png" alt="Image" /></td>
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<td><img src="image6.png" alt="Image" /></td>
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<tr>
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<td><img src="image3.png" alt="Image" /></td>
<td>525%</td>
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<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Warren et al., *EPSL*, 2008
Warren et al., *EPSL*, 2008
Evolution of fabric orientation

Evolution of fabric shape

[010] axis distributions

Shape Parameter, $K$

Shear Strain

Experiment
Field

Clustered
Girdled

Modeling the magnitude of localization

**Strain Profile**

- Shear strain vs. Position (m)

**Perturbation Size**

- Normalized size of perturbation vs. Time (s)
Recent laboratory results...

...indicate disGBS is an important mechanism in the upper mantle,

...produces both seismic and viscous anisotropy,

...and allows for significant localization of deformation.