Viscous and elastic anisotropy in partially molten rocks I: Experimental, field, and seismic observations

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I. Consequences of viscous and elastic anisotropy
Causes and a definition of “multi-scale” anisotropy

II. Experimental Observations
melt alignment, melt segregation, melt migration

III. Theory
New diffusion creep model

IV. Applications to a simple oceanic upper mantle structure
predictions for multi-scale effective viscosity structure
Geodynamic consequences of anisotropic viscosity (and reduced effective shear viscosity due to anisotropy)

1) Degree of lithosphere / asthenosphere (convectosphere) coupling?

2) Influences convective patterns - tends to tighten streamlines at boundary layers... (Honda, 1986; Christensen, 1987- and renewed interest now)...

3) Plate boundary rheology (reduction in meso-scale effective viscosity) gives plate like behavior in self-consistent plate generation models, e.g. Tackley, 2000; Bercovici; Ogawa...

uniform and moderate yield stress:

strain rate weakening, melt weakening + asthenosphere:
1) Transverse Isotropy
(Love-Rayleigh discrepancy, Pacific V_sh > V_sv)
e.g. Ekstrom and Dziewonski, Nature 1997; Ritzwoller

2) Anomalous vertical anisotropy
(Love-Rayleigh discrepancy, V_sv > V_sh)
e.g. Reykjanes Ridge, Gaherty, Science, 2001, Delorey et al., JGR, 2007

3) Receiver functions
(e.g. E. N. Am., Rychert et al., Nature, 2005; JGR, 2007)

4) SKS splitting
(e.g. East African Rift, Ethiopia, Kendall et al., 2005; Ayele et al., 2004; Keir et al., 2005; Bastow et al., 2005)
Causes of anisotropy

1) Lattice preferred orientation of anisotropic crystals (in experiments)

1) High T olivine: reference a-axis parallel to shear direction

e.g. Zhang & Karato, 1995
Bystricky et al. 2000

2) Effects of dissolved water and elevated stress on LPO

(Jung and Karato, 2001;
Jung, 2006;
Katayama et al., 2004, 2006)

2) Effects of dissolved water and elevated stress on LPO

3) Effects of pressure and stress

Couvy et al., 2005
Mainprice et al., 2005

3) Effects of pressure and stress

4) Effects of dissolved water and elevated stress on LPO

(Holtzman et al., 2003)
Causes of anisotropy

3) Melt distribution
   Multiple scales of isotropic and anisotropic organization

   a) alignment (~grain size)
   melt pockets aligned relative to stress orientation (e.g. Zimmerman, et al., 1999)

   b) segregation (< compaction length)
   melt segregates into bands at lengthscales much longer than the grain size (e.g. Holtzman et al., 2003)

   c) up-stress migration
   (> compaction length)
   melt migrates UP stress gradients that exist on (seismically observable?) scales of plate boundaries (Takei and Holtzman, in prep. and next talk...)

\[\text{Figure 25}\]
\[\text{Melt distribution:} \text{G3}\]
Deformation experiments:
1) Melt segregation and the effect of increasing strain:

melt first aligns at the grain scale and then segregates into bands (important observation for ideas in next talk...)

\[ \gamma \approx 1 \]

\[ \gamma \approx 2 \]

\[ \gamma \approx 3 \]
Deformation experiments: 2) Effects of boundary conditions on effective viscosity

- Constant load
- Constant strain rate

![Graph showing strain rate vs. stress with markers indicating different conditions.](image)

*Figure: Diagram illustrating the effects of boundary conditions on effective viscosity. The graph shows strain rate as a function of stress with markers for different loading conditions: (a) 3/C210^4 s^-1, (b) 1/C210^3 s^-1. The markers are color-coded for higher and lower stress conditions.*
c) Migration up stress gradients:
in two-phase metal composites, both solid state and partially molten, weak phase
migrates UP the stress gradient

solid state:

Migra on of particles during extrusion of metal matrix composites

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Fig. 5

<table>
<thead>
<tr>
<th>stress</th>
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<tr>
<td>initial</td>
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<td>0 mm +</td>
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partial ly molten state:
Shear deformation at 29% solid during solidification of magnesium
alloy AZ91 and aluminium alloy A356

C. M. Gourlay*, A. K. Dahle

<table>
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in both experiments, weak phase migrates up the stress gradient
A new model for grain-boundary diffusion creep with melt


- formulated in terms of grain boundary contiguity

- relationship between traction and velocity depends on rate of matter diffusion through grain boundary, solved at grain scale and homogenized upwards to give a macroscopic constitutive relation

\[
\varphi = \frac{A_{g-g \, contact}}{A_{surface}}
\]
the presence of a connected melt phase dramatically reduces diffusion path lengths through grain boundaries.

As \( \phi \to 0 \),
\[ D_{\text{melt}} \to D_{g.b.} \]

This model helps resolve large discrepancy between melt-free olivine (Faul and Jackson, 2007) and San Carlos olivine + MORB.
See David Kohlstedt s talk, Weds. [MR33A-01]
effect of homogeneous isotropic and anisotropic melt distribution for three melt fractions:

\[
\begin{align*}
\phi & \quad \eta_\phi / \eta \\
60^0 & \quad 0.02 \quad 0.04 \\
70 & \quad 80 \\
80 & \quad 90 \\
90 & \quad 100 \\
100 & \quad 110 \\
110 & \quad 120
\end{align*}
\]
Effect of segregation, calculated with Backus (1962) averaging of transverse isotropic medium with layers of differing viscosity (Honda, 1986).

\[
\begin{pmatrix}
\sigma_{xx} \\
\sigma_{xy}
\end{pmatrix} =
\begin{bmatrix}
\eta_N & 0 \\
0 & \eta_S
\end{bmatrix}
\begin{pmatrix}
\dot{\varepsilon}_{xx} \\
\dot{\varepsilon}_{xy}
\end{pmatrix}
\]

\[
\eta_S = \langle (\eta_i)^{-1} \rangle^{-1} \\
\eta_N = \langle \eta_i \rangle
\]

Comprised of 0.3 volume fraction bands, (same total melt fractions)
Future work:

We can now calculate elastic and viscous properties from the same melt distribution, and are developing predictive models for a range of hypothetical multi-scale melt distributions...

Conclusions:

1. In experiments, melt aligns under stress at the grain scale, then segregates during deformation, and then can migrate up a stress gradient.

2. In the Earth, such multi-scale processes can cause a significant anisotropy in viscosity and a reduction in effective shear viscosity, easily up to two orders of magnitude.

3. Such viscosity reduction on boundary layers could have significant consequences for plate-mantle interactions, and have a distinct seismic signature.
No
More
in constant load samples, stress is always increasing, so samples cannot reach a steady state (stress and strain rate constant)
Strain rates are limited by lenses in these spatially confined samples

speculation:
the constant rate samples can reach steady state.
the organization of strain partitioning (between low angle and high angle bands) is optimized to minimize dissipation (or viscosity) in steady state.

(current experiments in torsion, see King et al, [ref])
T: conductive+adiabat
Stress: constant
grain size: fcn of stress
viscosity: combined
mechanisms up to peak?

J. Warren and G Hirth:
300 MPa stress in mylonites

max viscosity = $\frac{300 \text{ MPa}}{1 \times 10^{-13} \text{ /s}} = 3 \times 10^{21} \text{ Pa.s}$?
Causes of anisotropy

2) Layered distribution of solid phases of different isotropic or anisotropic properties

Corundum-bearing mafic granulites in the Horoman (Japan) and Ronda (Spain) Peridotite Massifs: Possible remnants of recycled crustal materials in the mantle

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* Island Arc (2006) 15, 2–3

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Figure 4: Semi-log plot of viscosity as a function of melt fraction for samples prepared from sol-gel powders (Faul and Jackson, 2007) and samples fabricated from powdered crystals of San Carlos olivine (Hirth and Kohlstedt, 1995; Hirth and Kohlstedt, 2003). Note the large decrease in viscosity between the high-purity, melt-free sample and the impure sample with 0.2% sample. A key question: "Is this large decrease in viscosity due entirely to the addition of melt or does the associated change in grain boundary chemistry also play a role?"