Rheologic effects of **Crystal Preferred Orientation** in upper mantle flow near plate boundaries

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**Goal**- are fully-coupled models of mantle flow & microstructural (CPO) evolution required?

**Motivation**- understand regional flow patterns and processes

>>> improve interpretation of seismic anisotropy
Linked Micro-Macro Numerical Modeling

- Compute regional mantle flow field using **Isaiah**
  
  *Cornell 3D parallel FEM: deformation in Eulerian frame, coupled flow & temperature fields*

- Calculate velocity gradient tensor along streamlines ending at all elements

- Calculate CPO at each element using Second Order Self Consistent scheme
  
  *Castelnau et al. (JGR 2008; GRL 2009); 1000-grain polycrystals, dislocation glide dominant*

- Determine effective viscosity tensor for polycrystal at each element
  
  *specify stress:strain-rate behavior of polycrystal (linear vs power law n=2-3)*

- Re-compute flow field using updated anisotropic viscosity tensor \((V_{ijkl})\)

- Iterate (flow, \(V_{ijkl}\) stabilize), compute seismic anisotropy

**Dislocation slip systems for Olivine crystals**

<table>
<thead>
<tr>
<th>Slip system</th>
<th>Reference stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(010)[100]</td>
<td>(5.5 \times 10^{-4})</td>
</tr>
<tr>
<td>(001)[100]</td>
<td>(5.5 \times 10^{-4})</td>
</tr>
<tr>
<td>(010)[001]</td>
<td>(5.5 \times 10^{-3})</td>
</tr>
<tr>
<td>{101} &lt; {101}</td>
<td>(5.5 \times 10^{-2})</td>
</tr>
</tbody>
</table>

4th ‘hard’ system allows general deformation
Flow-Induced Crystal Preferred Orientation

BCs: top velocity = Spreading Rate (SR)
- horizontal gradients zero at spreading axis
- stress-free base
- only horizontal flow out of right side

CPO random at base of model

Temperature = 0

10 mm/yr

lithosphere viscosity scaled by $10^3$

T = 1300°C
Flow-Induced Crystal Preferred Orientation

B-1, n=1, intermediate coupling (it1)
Pole Figures (100)

CPO random at base of model

Spreading Rate (SR)
10 mm/yr

Lithosphere Base (1000°C)
Viscosity Tensor

calculate polycrystal strain rate ($\dot{\epsilon}$) response to applied stress ($\sigma$)

polycrystal has CPO that evolved along flowline to element

flow is 2-D, although model & texturing are calculated in 3-D

6 independent $V_{ijkl}$ components

x: spreading direction (1)
z: vertical (3)
y: $\perp$ to plane (2)
Coupled flow/CPO Result

B-1, n=1, iteration 15 (it15s)
Pole Figures (100)

Lithosphere Base (1000°C)

J Index
Compare CPO, flowlines & flow velocities

n=1, iteration 15
Predicted Seismic Anisotropy

**Linear (n=1) case**

**P-wave**

- Isotropic $V^\text{ijkl}_{ijkl}$
- Iteration 15 $V^\text{ijkl}_{ijkl}$

**S-wave**

- Isotropic
- Iteration 15

- Total split (sec)
- Local split (sec)
- Incidence Angle = 20°
Predicted Seismic Anisotropy

compare linear & power law cases, intermediate coupling

>> anisotropy a few percent stronger in flow ‘corner’, seismic effects modest
Coupled flow, power law polycrystal
Variation of $V_{ijkl}$ Between Models

scaled by isotropic value, green $\sim$ isotropic

color scale constant for a given $V_{ijkl}$ component
Summary

- Fully-coupled micro-macro scale modeling is possible
  
  Linear, low resolution runs 10-12 hrs each model iteration — full streamlines (sl), single processor

- Flow field & anisotropy are affected by CPO rheologic feedback
  
  Linear case — modest differences relative to isotropic $V_{ijkl}$ intermediate coupling case
  
  Power law case — more notable differences: off axis anisotropy is stronger & extends deeper below lithosphere, increased shallow anisotropy rotates to horizontal, subaxial zone reduction for B-1
  
  Magnitude of difference off axis is seismically detectable (need larger model space to quantify)

- Computational implications of (more realistic) power law polycrystal behavior
  
  Major increase in convergence time for CPO evolution & viscosity tensor calculation
  
  $>>$ multi-processor, high-speed computing required for further work, update sl from last element

- Details of axial lithosphere will influence shallow results