Interpreting Seismic Anisotropy in Subduction Zones: The Role of Deformation History

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GeoPRISMS SCD TEI
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with contributions from:
Yuval Boneh, Lars Hansen, Greg Hirth, Ed Kaminski, Peter Kelemen, Luiz Morales, & Jessica Warren
after Karato et al., 2008, AREPS
Lattice Preferred Orientation (LPO) describes the statistical alignment of the crystal lattices of individual grains in a polycrystalline rock.

- Deformation by dislocation creep produces LPO.
- Flow typically orients seismically fast [100] axes parallel to direction of flow.
Fig. 7. LPOs of relict olivine grains deformed at 1473 K to different shear strains as indicated; universal stage measurements. Lower hemisphere projection and Karab contour plot were used. S and C represent finite strain ellipsoid and shear plane respectively. N and C.I. are the number of measurements and contour interval respectively. The sense of shear is deduced for all pole figures.

Zhang et al. (2000) Tectonophysics
φ = 0: fast shear wave direction parallel to flow direction
φ ≠ 0: fast shear wave direction oblique to flow direction

Shear Strain

A-type  D-type  E-type  Natural  Experimental  Numerical

Skemer et al. (2012)  G³
Skemer and Hansen (in review)

Experimental samples
- Zhang & Karato (1995) 1200 C
- Zhang & Karato (1995) 1300 C
- Bystricky et al. (2000)
- Hansen et al. (2014)

Numerical models
- D-REX (Kaminski and Ribe, 2001)
- VPSC (Tommasi et al., 2000)
Complexity #1 – Varied Olivine Petrofabrics

- A-type
- B-type
- C-type
- D-type
- E-type

Complexity #2 – Pre-existing CPO

Karato et al. (2008) Annual Reviews

Table 2  Relation between olivine fabrics and seismic anisotropy corresponding to various flow geometries

<table>
<thead>
<tr>
<th>Shear wave splitting (direction of the polarization of the faster, vertically traveling shear wave)</th>
<th>Horizontal flow</th>
<th>Vertical planar flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-type</td>
<td>Parallel to flow</td>
<td>Small splitting</td>
</tr>
<tr>
<td>B-type</td>
<td>Normal to flow</td>
<td>Parallel to the plane</td>
</tr>
<tr>
<td>C-type</td>
<td>Parallel to flow</td>
<td>Normal to the plane</td>
</tr>
<tr>
<td>D-type</td>
<td>Parallel to flow</td>
<td>Small splitting</td>
</tr>
<tr>
<td>E-type</td>
<td>Parallel to flow</td>
<td>Small splitting</td>
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</table>

<table>
<thead>
<tr>
<th>$V_{SH}/V_{SV}$ anisotropy</th>
<th>Horizontal flow</th>
<th>Vertical cylindrical flow</th>
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</thead>
<tbody>
<tr>
<td>Fabric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-type</td>
<td>$V_{SH}/V_{SV} &gt; 1$</td>
<td>$V_{SH}/V_{SV} &lt; 1$</td>
</tr>
<tr>
<td>B-type</td>
<td>$V_{SH}/V_{SV} &gt; 1$</td>
<td>$V_{SH}/V_{SV} &gt; 1$ (weak)</td>
</tr>
<tr>
<td>C-type</td>
<td>$V_{SH}/V_{SV} &lt; 1$</td>
<td>$V_{SH}/V_{SV} &gt; 1$ (weak)</td>
</tr>
<tr>
<td>D-type</td>
<td>$V_{SH}/V_{SV} &gt; 1$</td>
<td>$V_{SH}/V_{SV} &lt; 1$</td>
</tr>
<tr>
<td>E-type</td>
<td>$V_{SH}/V_{SV} &gt; 1$ (weak)</td>
<td>$V_{SH}/V_{SV} &lt; 1$</td>
</tr>
</tbody>
</table>
Complexity #1 – Varied Olivine Petrofabrics

A-type

E-type

Complexity #2 – Pre-existing CPO

low strain

high strain

A-type

E-type

shear sense

Warren et al. (2008) EPSL; Skemer et al. (2010) JPet

**LABORATORY EXPERIMENTS**

Initial LPO
\[ \gamma = 0 \]

Final LPO
\[ \gamma = 3.5 \]

Skemer et al. (2011) Geol. Soc. London

**FIELD EXPERIMENTS**

Initial LPO
\[ \gamma = 0 \]

Final LPO
\[ \gamma = 5.25 \]

Warren et al. (2008) EPSL; Skemer et al. (2010) JPet
$\phi = 0$: fast shear wave direction \textbf{parallel} to flow direction

$\phi \neq 0$: fast shear wave direction \textbf{oblique} to flow direction
Question #1: Does deformation history influence subsequent LPO evolution?

Question #2: What are the conditions under which LPO will achieve steady state?

Expected steady-state LPO based on triaxial experiments of Nicolas et al., 1973:

Boneh and Skemer (2014) EPSL; Boneh et al. (2015) G3
LPO Evolution in Three Experimental Configurations

Perpendicular

<table>
<thead>
<tr>
<th>ε</th>
<th>n</th>
<th>[001]</th>
<th>[010]</th>
<th>[100]</th>
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<td>0.22</td>
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<td>0.33</td>
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Oblique

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<td>0.36</td>
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<tr>
<td>0.68</td>
<td>1026</td>
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Parallel

<table>
<thead>
<tr>
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<th>n</th>
<th>[001]</th>
<th>[010]</th>
<th>[100]</th>
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<td>0.42</td>
<td>1026</td>
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</table>

Boneh and Skemer (2014) EPSL
Seismic Anisotropy in Three Experimental Configurations

(A) Perpendicular ($\epsilon = 0.65$)
- $V_p$ Contours (km/s)
- AVs Contours (%)

(B) Oblique ($\epsilon = 0.68$)
- $V_p$ Contours (km/s)
- AVs Contours (%)

(C) Parallel ($\epsilon = 0.62$)
- $V_p$ Contours (km/s)
- AVs Contours (%)

... and three reference samples:

(D) AG-type
- $V_p$ Contours (km/s)
- AVs Contours (%)

(E) A-type
- $V_p$ Contours (km/s)
- AVs Contours (%)

(F) B-type
- $V_p$ Contours (km/s)
- AVs Contours (%)

Modeling LPO evolution using D-REX

\( \Psi = \) minimum angle between [100] and flow direction (X)

D-Rex model of Kaminski and Ribe calibrated against Boneh and Skemer (2014)

Boneh et al. (2015) G³
Seismic anisotropy is influenced by:

- Mineralogy
- Temperature
- Pressure
- Water concentration in NAMs
- Stress
- Partial melt
- Deformation history

Inferring kinematics of flow in a subduction setting requires consideration of the full spectrum of deformation conditions and history.
bonus slides
Finite deformation during fluid flow

McKenzie (1979)


Dan McKenzie
Department of Geodesy and Geophysics, Madingley Rise,
Madingley Road, Cambridge CB3 6EZ
Becker et al. (2014)

= good fit between surface wave anisotropy and LPO

= poor fit between surface wave anisotropy and LPO

\[
\langle \Delta \alpha \rangle = 23.1^\circ
\]

\[
\langle \Delta \alpha \rangle_p = 20.2^\circ
\]

SL2013SVA vs. LPO @ 200 km

Becker et al. (2014)
For **horizontal shear** and a vertically incident wave:

- Delay times depend strongly on the dip of the LPO.
- Polarization direction does not vary significantly except for extremely steeply dipping structures (where magnitude of splitting is small).

*Skemmer et al (2012)*
For **horizontal shear** and a vertically incident wave:

- Delay times depend strongly on the dip of the LPO.
- Polarization direction does not vary significantly except for extremely steeply dipping structures (where magnitude of splitting is small).
Nicolas et al. (1973)

\[ \varepsilon = 0 \]

\[ \varepsilon = 0.58 \]

Wenk and Tomé (1999)

\[ \gamma = 0.4 \]

\[ \gamma = 1.5 \]

Zhang and Karato (1995)

Zhang et al. (2000)

\[ \gamma = 0.17 \]

\[ \gamma = 1.10 \]

Fig. 7. LPOs of olivine grains deformed at 1473 K to different shear strains as indicated; universal stage measurements, lower hemisphere projection and luhn contour plots were used. S and C represent limit strain ellipse and shear plane respectively, N and C.I. are the number of measurements and contour interval respectively. The sense of shear is denoted for all pole figures.
Issue #1: The Effects of Deformation History
Vauchez et al. (2012) Tectonophysics
**Inverse Approach**

- Observe seismic anisotropy
- Infer LPO
- Relate LPO to Rock Deformation
- Infer Subduction Zone Kinematics/Dynamics

**Forward Approach**

- Forward Model Seismic Anisotropy
- Model LPO evolution
- Rocks Deform
- Model Subduction Zone Kinematics/Dynamics