Investigating Causes of D’’ Anisotropy

J.-M. Kendall and P. G. Silver

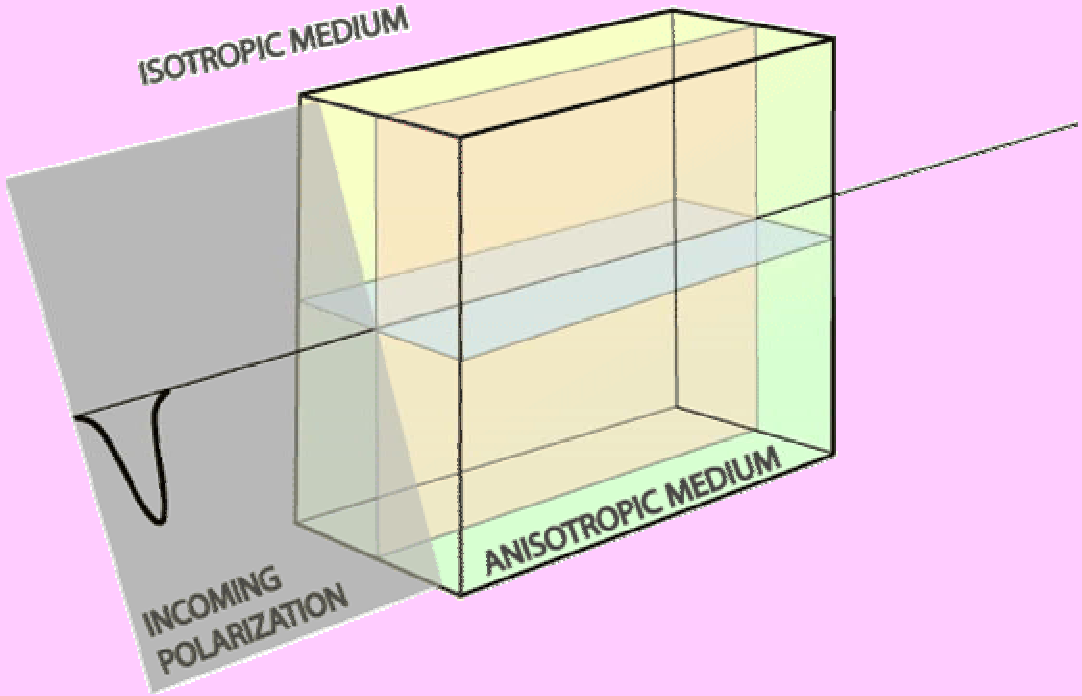
in: *The Core-Mantle Boundary Region*, AGU, 1998.

MDL 3/15/04

- Although most of the lower mantle (below 660km) appears to be isotropic, there is strong evidence for anisotropy in (some parts of) D''.
- Observations of anisotropy are valuable as a geodynamic constraint on this "enigmatic" (that word again!) region.
- Two candidate mechanisms:
  - Lattice preferred orientation (LPO)
  - Shape preferred orientation (SPO)

Seismological observations of D'' anisotropy (I)

- Mostly from shear wave splitting observations of phases traversing D''



Shear wave splitting:

GOOD: unambiguous indicator of anisotropy

BAD: path-integrated measurement; where along path is anisotropy located?!?

Seismological observations of D'' anisotropy (II)

Phases used to measure D''-associated splitting

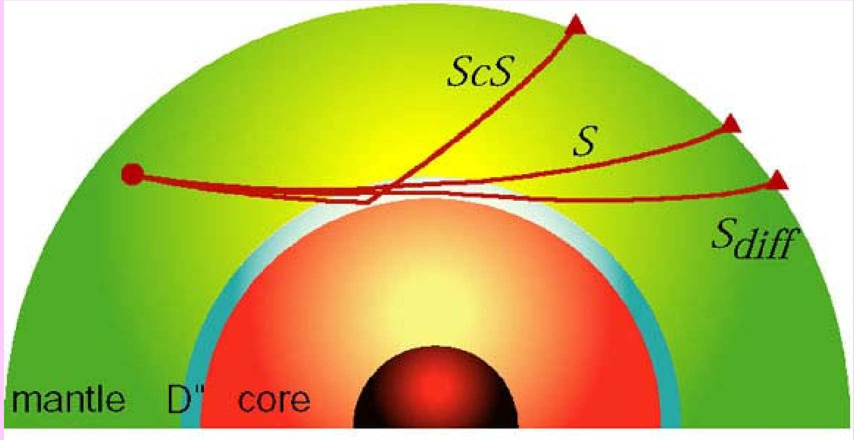


figure: Ed Garnero

Courtesy of Prof. Ed Garnero. Used with permission.

Mostly observations of splitting of "combined" phase: ScS and S that turns in D'' layer (at relevant epicentral distances, ScS arrives just a few seconds after S). Can also look at S_{diff} splitting, although interpretation is more difficult (upper mantle anisotropy can generate an apparent, misleading SV_{diff} arrival). ScS/S splitting can be compared to SKS splitting to 1) correct for upper mantle anisotropy and 2) isolate signal resulting from D'' anisotropy.

A data example

Image removed due to copyright considerations.

The challenges: must correct for effects of upper mantle anisotropy (not always as easy as it sounds!) and lower mantle (generally thought to be isotropic [*Meade et al.,* 1995]; also, the clever use of specific ray geometries can isolate anisotropy in the D'' layer).

Overview of observations

- Alaska/N. Pacific
  - *Lay & Young* [1991], *Matzel et al.* [1996], *Garnero & Lay* [1997] – anisotropy is distributed throughout the Alaskan region; there is lateral variability in the magnitude of the anisotropy. $V_{SH} > V_{SV}$ (transverse component leads).
- Caribbean/Central America
  - *Kendall & Silver* [1996a] - ~1.8% anisotropy, $V_{SH} > V_{SV}$.
- Southern Pacific
  - Appears to be isotropic? [*Kendall & Silver,* 1996b].
- Central Pacific
  - Complicated – little consensus on form/magnitude of anisotropy… Maybe some $V_{SV} > V_{SH}$? [*Pulliam & Sen,* 1996; 1998]

The case for transverse isotropy (TI) beneath Caribbean/Alaska

- TI = a special case of hexagonal symmetry where the symmetry axis is vertical; there is no azimuthal variation in velocity
- Three main arguments:
  - Always see SH arrival leading SV; this indicates azimuthal independence*
  - SKS and SKKS phases do not appear to be affected by D’’ anisotropy
  - Waveform modeling work: data agrees well with synthetics for a TI model beneath Alaska [*Sen et al.* 1998]; *shape* of observed waveforms agree with isotropic synthetics for Americas (only difference is time delay), consistent with TI [*Kendall & Silver* 1996b].

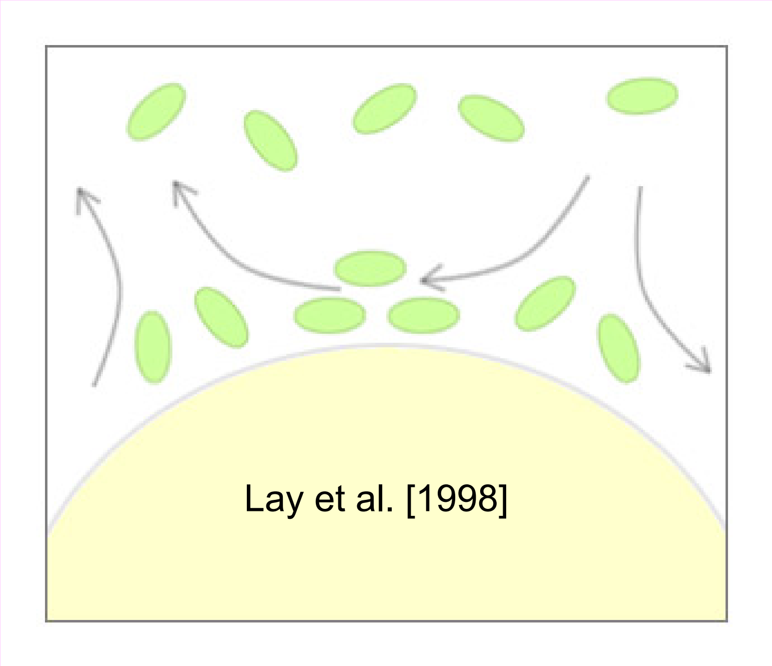
** stay tuned for some editorial commentary on this later…*

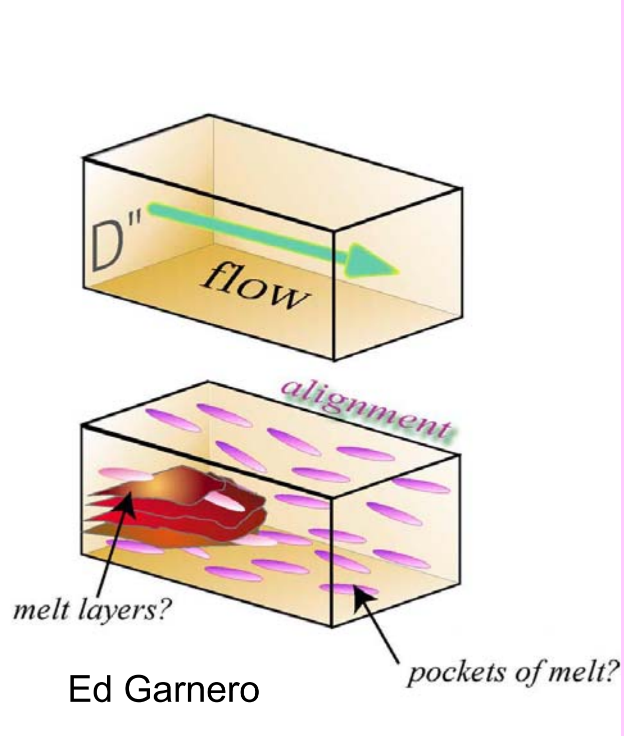
Finding a mechanism…

- Mechanism for Caribbean/Alaska region appears to be different than that for central Pacific.
- In this paper, the authors concentrate on finding a mechanism for the Caribbean/ Alaska-type anisotropy.
- Two basic classes of mechanisms: LPO vs. SPO…

(Courtesy of Prof. Ed Garnero. Used with permission.)

LPO vs. SPO





Lattice preferred orientation or alignment of intrinsically anisotropic crystals due to deformation. LPO of olivine is well-documented as the primary mechanism for upper mantle anisotropy. MUST HAVE **DISLOCATION** CREEP TO CREATE LPO.

Shape preferred orientation taking the form of aligned inclusions or periodic layering of material with contrasting elastic properties. SPO is primary mechanism for crustal anisotropy (fluid-filled cracks).

Is LPO consistent with the seismological observations?

- To evaluate viability of LPO mechanism, need: minerals present, single-crystal elastic constants at CMB, degree of LPO development.
- Candidate minerals: Mg-perovskite (orthorhombic), magnesiowustite (cubic), maybe stishovite (tetragonal), maybe columbite (orthorhombic). Must assume candidate LPO scenarios.
- For pv + (Mg,Fe)O, they conclude that there is no orientation such that SH leads SV ***and*** no vertical (SKS-type) splitting. SiO_2 is unlikely.
- The authors conclude that "**LPO in lower-mantle minerals is an unlikely cause for the anisotropy**"*

** stay tuned for some editorial commentary on this later…*

Is SPO consistent with the seismological observations?

- Aligned inclusions (probably (sub-)parallel to CMB) or periodic (horizontal) layering…
- Use effective medium theory to model SPO-caused anisotropy (disks, tubes, cigars, layers…)
- Their preferred SPO model: high- or low-velocity disk-like inclusions with aspect ratio < 0.1 (or thinly-layered medium).
- The authors conclude that SPO is the more likely mechanisms for generating D’’ anisotropy.

Candidate physical processes

- Two further constraints:
  - Magnitude of anisotropy – they adopt 1.8%
  - Spatial correlation between observations of D’’ anisotropy and D’’ discontinuity (also with high seismic velocities).
- They conclude that both the inclusions *and* the matrix consist of material that is elastically distinct from the overlying mantle… what could explain this?
  - Core infiltration hypothesis (silicate and iron alloy reaction products) – large velocity contrast, but would require *smaller* SH velocities, which are not observed.
  - Aligned melt hypothesis – does not satisfy above constraint!
  - Slab graveyard hypothesis – preferred.

The slab graveyard hypothesis

- Good evidence for slab penetration into lower mantle; paleo-slab locations coincide geographically with D'' anisotropy. Could also explain high velocities…
- Velocity contrast between former basaltic crust (low-T melting component?) and former harzburgitic lithosphere – if ~25% then could satisfy observations.

Conclusions

- D'' anisotropy is not a global feature, but $V_{SH} > V_{SV}$ anisotropy is reliably observed beneath Alaska and the Caribbean.
- LPO does not appear to satisfy seismological constraints, *given our current knowledge of lowermost-mantle mineral physics* [emphasis added].
- Preferred model: SPO in the form of horizontally oriented disk-shaped inclusions. Background *and* inclusions are elastically distinct from overlying mantle.
- Slab graveyard is most likely scenario for D'' anisotropy.

Maureen’s Editorial Commentary (I)

- Do the seismological observations really rule out azimuthally varying velocities?

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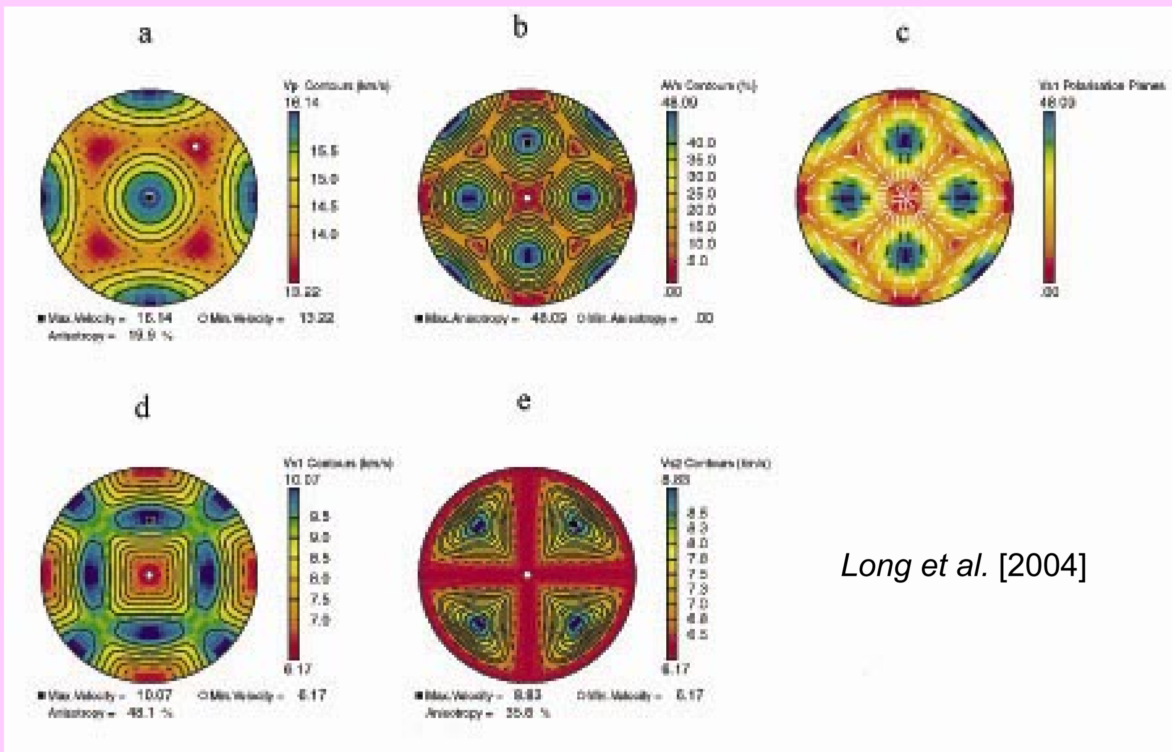
Editorial Commentary (II)

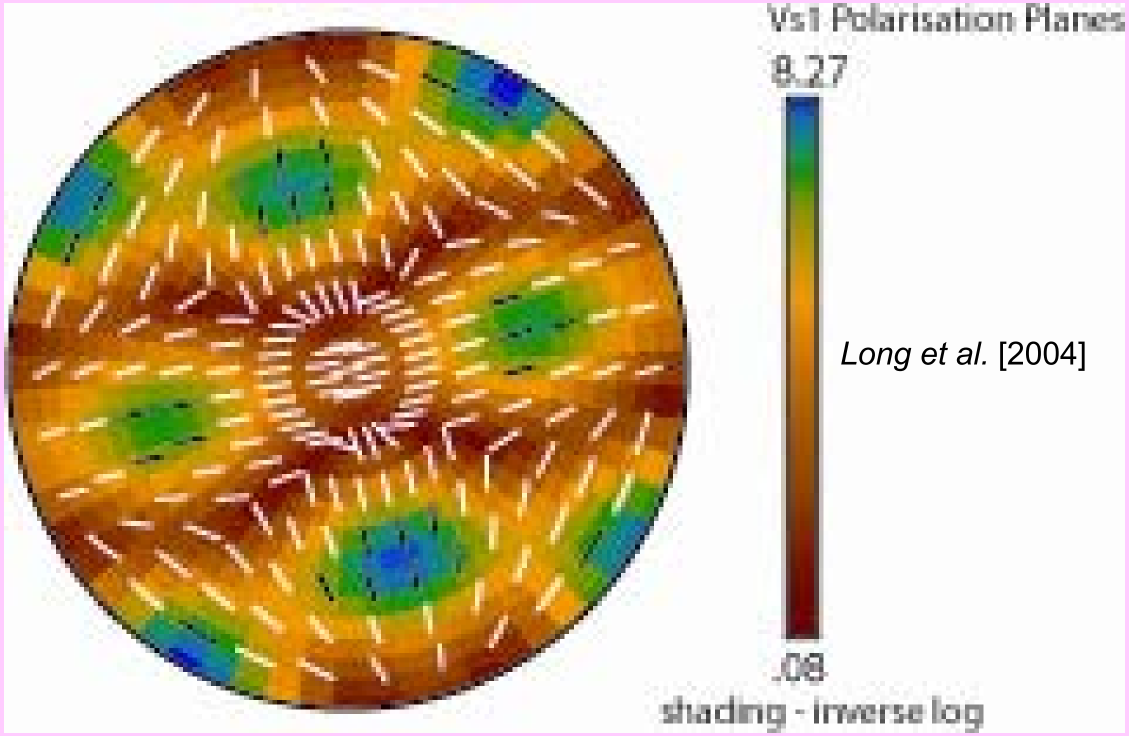
- New elastic constants for MgO at CMB conditions. (In paper: *Meade & Jeanloz* [1998], experimentally determined at 40 GPa.)
- First-principles calculations for 125 GPa: *Karki et al.* [1997].



Long et al. [2004]

Editorial Commentary (III)

Kendall & Silver [1998] are quite right to reject MgO as a candidate based on the assumption that there is no azimuthal variation in the horizontal plane. But: what if there is azimuthal variation? Then, LPO of MgO may satisfy seismological constraints as well as SPO (especially for downgoing slab regions!)…



Long et al. [2004]

(Yamazaki & Karato [2002] obtained similar results for (Mg,Fe)O…)

Editorial Commentary (IV)

Kendall and Silver make an excellent case that the SPO hypothesis satisfies the available seismological constraints for Alaska/Caribbean. However, new mineral physics results suggest that the LPO hypothesis may also be a viable mechanism to explain Alaska/Caribbean anisotropy ($V_{SH} > V_{SV}$) …

How to distinguish between two hypotheses?

Look for *azimuthal* variations of D'' anisotropy for specific regions. Yes? LPO more likely. No? SPO more likely.