Constraints on Global Mantle Flow and Lithosphere Net Rotation from Seismic Anisotorpy

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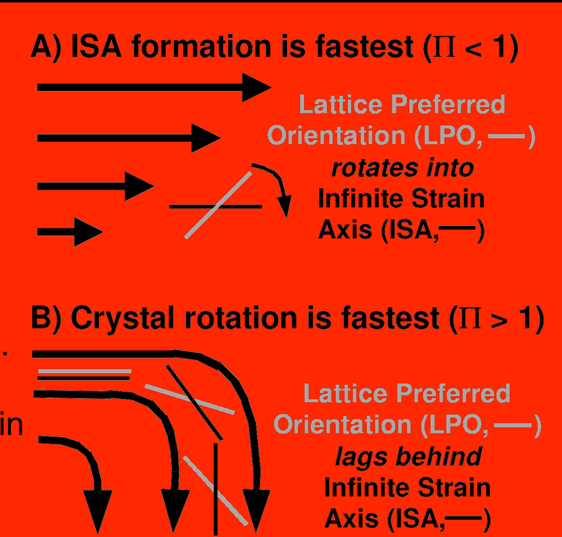
Introduction: Asthenospheric Anisotropy

Viscous shear in the asthenosphere accomodates relative motion between the Earth's surface plates and underlying mantle, generating lattice-preferred orientation (LPO). Thus, observations of anisotropy can be used to constrain shear flow in the asthenosphere, which is produced by relative motion between the mantle and the tectonic plates. Anisotropy observations may also be influenced by lithospheric anisotropy, as well as the finite strain history of asthenospheric flow.

Development of Asthenospheric Anisotropy



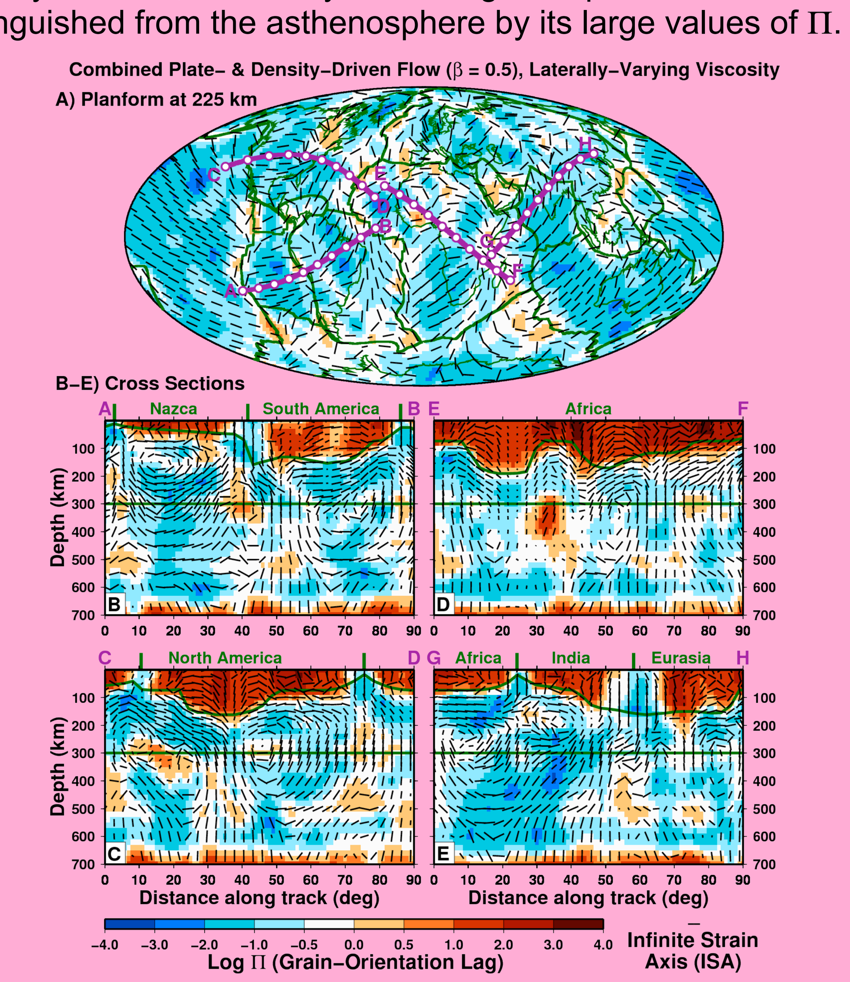
When exposed to simple shear, the fast axis of olivine (A-type fabric) orients 45° from the maximum shear direction. Simple shear rotates this fabric into the infinite strain axis (ISA, the orientation after infinite deformation) at a rate Ω_{ISA} (top). However, olivine crystals may also rotate with the flow (at a rate Ω_{flow}), if the flow deviates from simple shear (bottom). *Kaminski and Ribe* [2002] define the ratio of these two rotation rates as:

$$\Pi = \Omega_{flow} / \Omega_{ISA}$$

Thus, if $\Pi < 1$, the infinite strain axis is a good approximation for the LPO. We measure Π for viscous mantle flow to determine where the ISA may be used to estimate LPO.

The Grain-Orientation Lag (Π)

We measure the Grain-Orientation Lag Parameter, Π, to determine where the infinite strain axis (ISA) approximates the lattice preferred orientation (LPO). We find that $\Pi < 0.5$ for most of the asthenosphere because simple shear orients the LPO in the direction of the ISA faster that the ISA itself rotates with the flow. By contrast, the slowly-deforming lithosphere can be distinguished from the asthenosphere by its large values of Π.



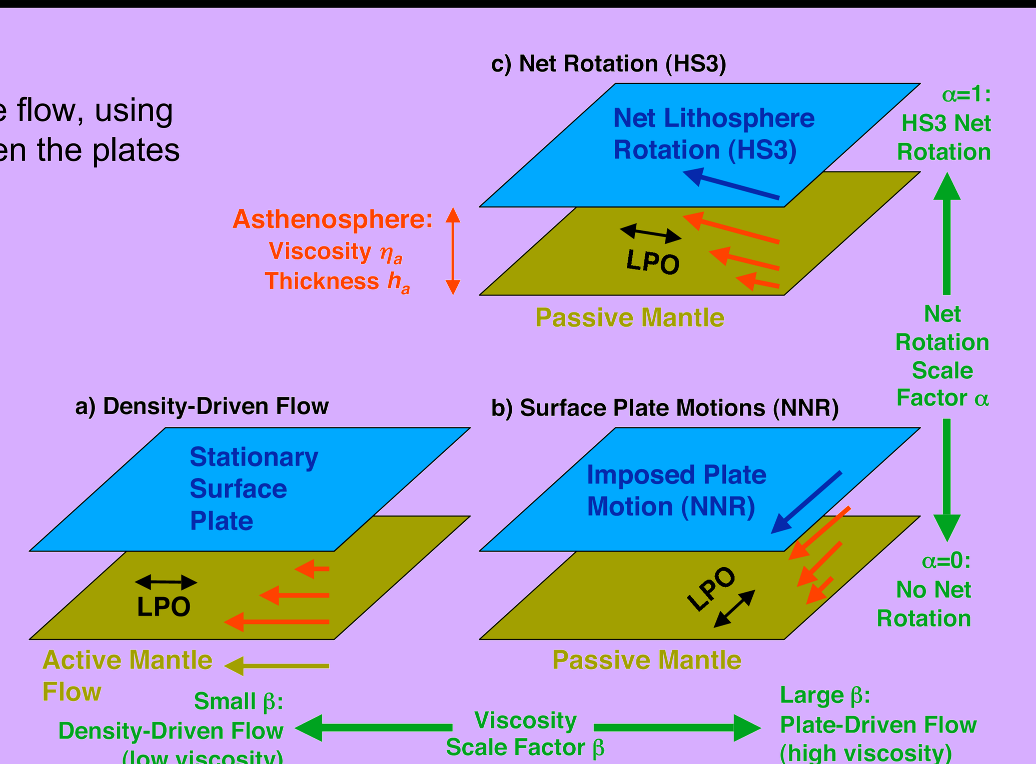
Models of Global Asthenospheric Flow

We use the finite element code CitComS to solve for global mantle flow, using a linear combination of factors that produce relative motion between the plates and the underlying mantle:

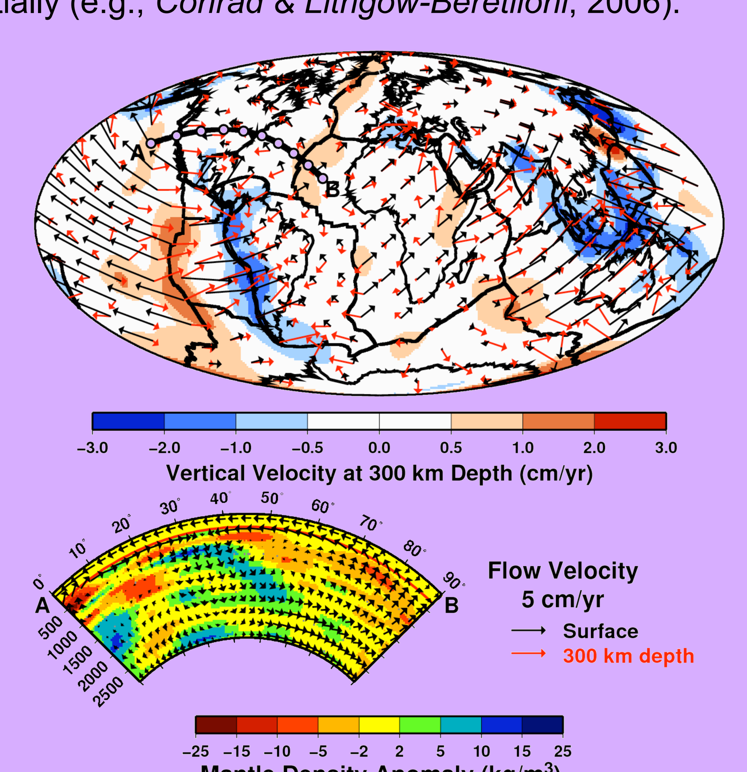
a) Density-Driven Flow: We assign mantle density heterogeneity inferred from seismic tomography (S20RTSb, *Ritemsa et al.*, 2004) using a conversion factor of 0.15 g cm^{-3} km^{-1} s.

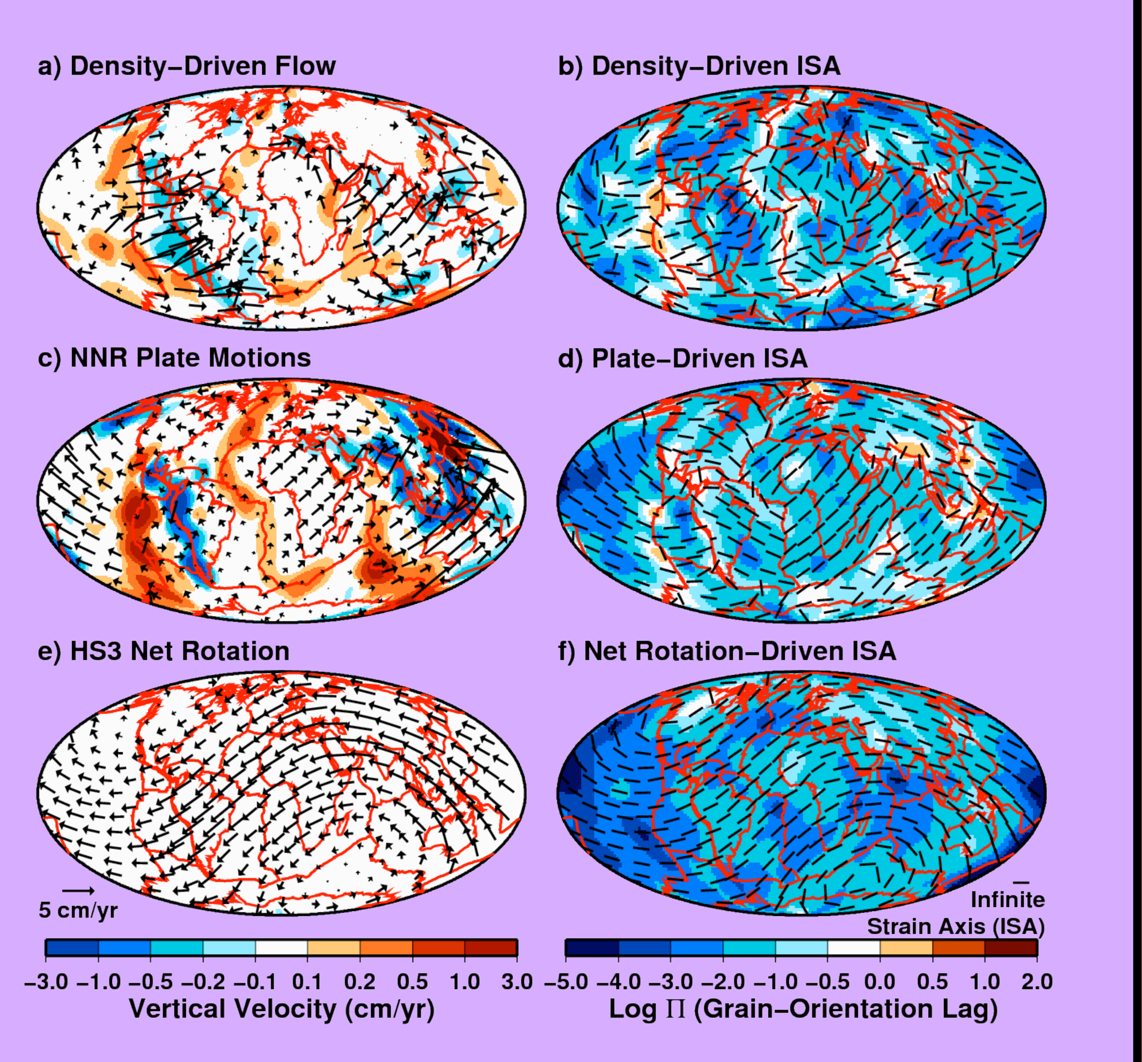
b) Plate-Driven Flow (NNR): We impose plate motions (NUVEL-1A, *DeMets et al.*, 1994) in the no-net-rotation (NNR) reference frame as velocity boundary conditions.

c) Net Rotation (HS3) We impose a net rotation of the lithosphere consistent with the HS3 model of Gripp & Gordon [2002], which features a ~5 cm/yr westward net rotation of the lithosphere.



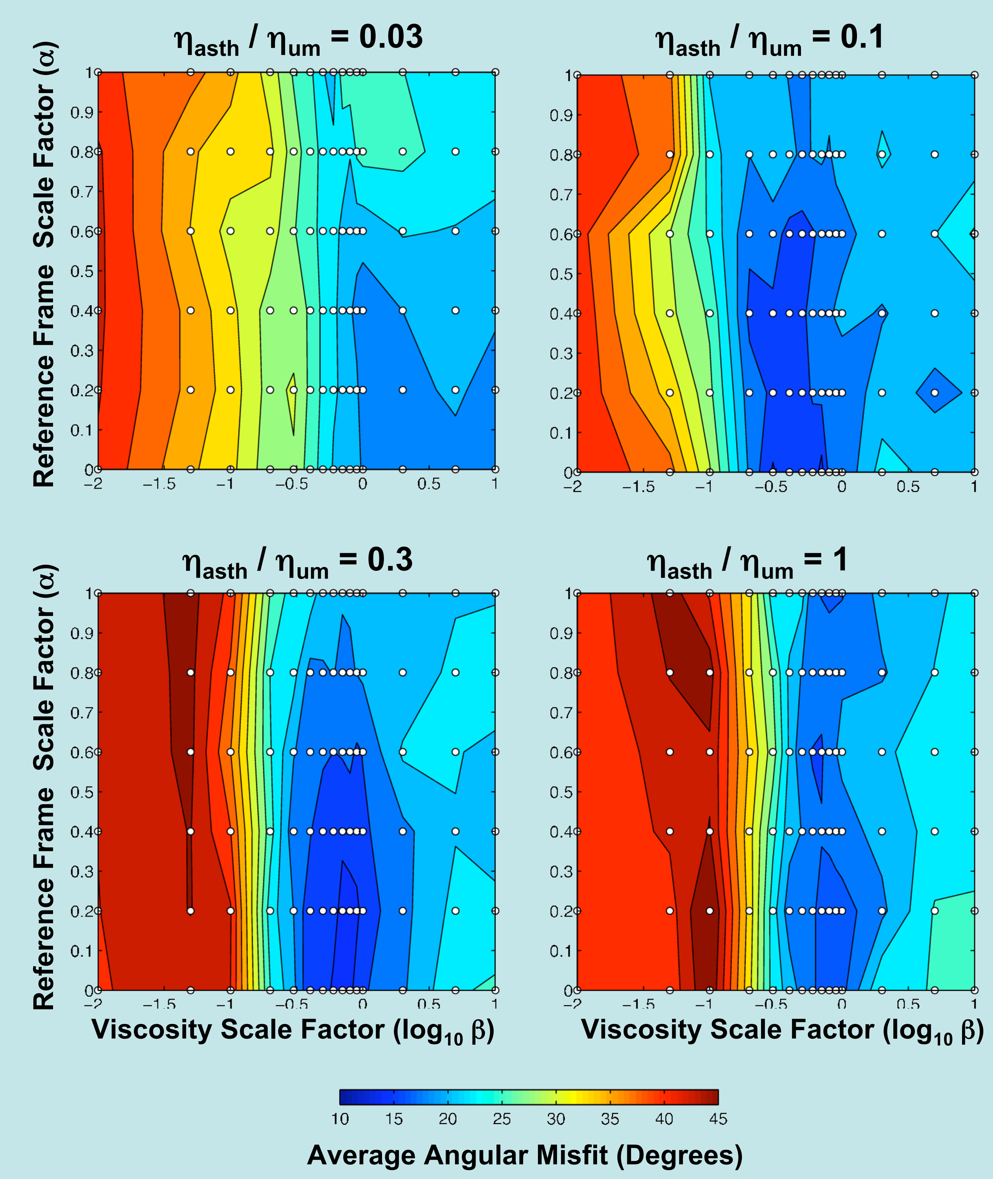
Viscosity Structure: The lower lower mantle and asthenosphere have viscosities 50, and 0.1 times the upper mantle viscosity. The viscosity transition from lithosphere to asthenosphere is gradual and determined by the lithosphere thickness, which varies spatially (e.g., *Conrad & Lithgow-Beretlloni*, 2006).

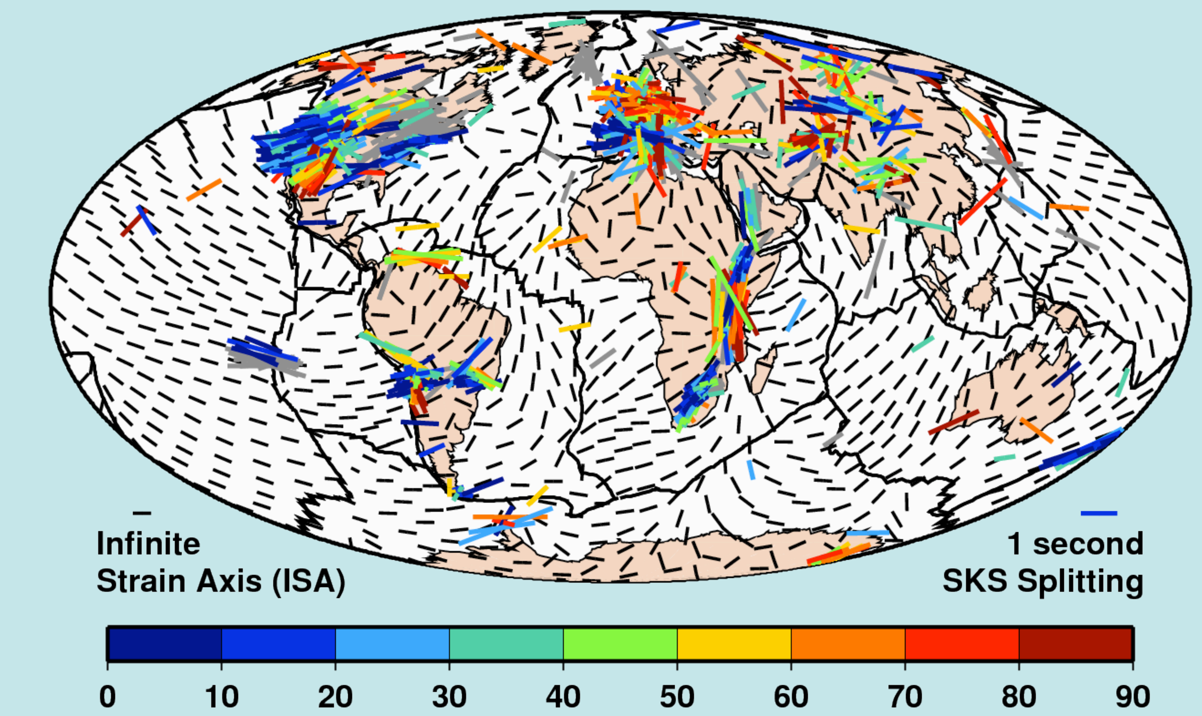




SKS Splitting: A Constraint on Global Mantle Flow and Net Rotation

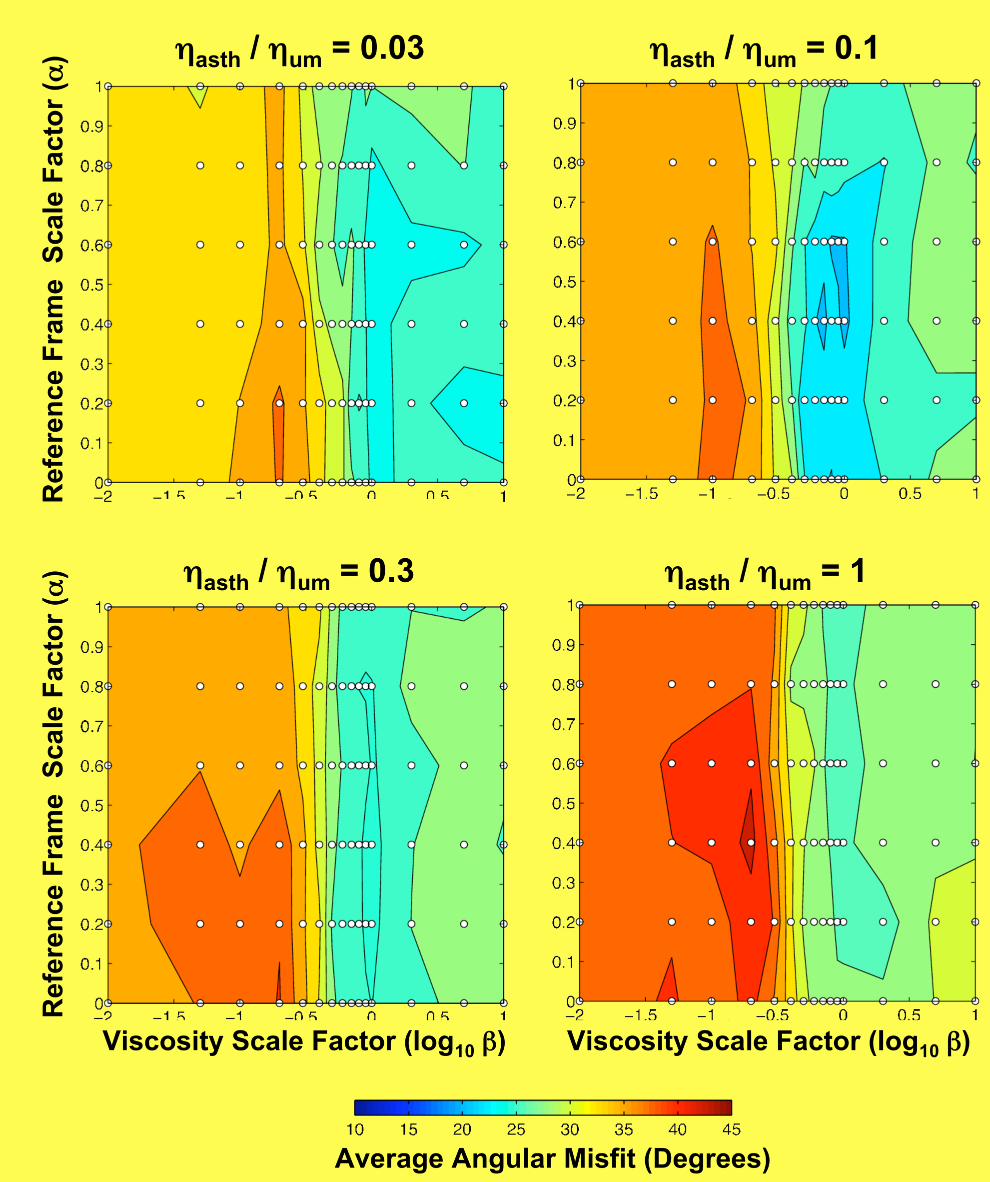
By comparing the ISA direction with a global dataset of SKS splitting observations, we evaluate our global flow model's ability to predict observed anisotropy. Because continental anisotropy may be influenced by a lithospheric component, we use oceanic observations only when calculating misfit. By varying α and β, we can determine relative importance of plate-driven, density-driven, and net rotation flows for an optimal fit to observations. We find $0.3 < \beta < 0.8$ and $\alpha < 0.6$ provide the best fit for an asthenospheric viscosity 10 times smaller than the upper mantle viscosity. More net rotation is permissible if the asthenospheric viscosity is higher, because less of the shear produced by net rotation is accommodated in the asthenosphere.

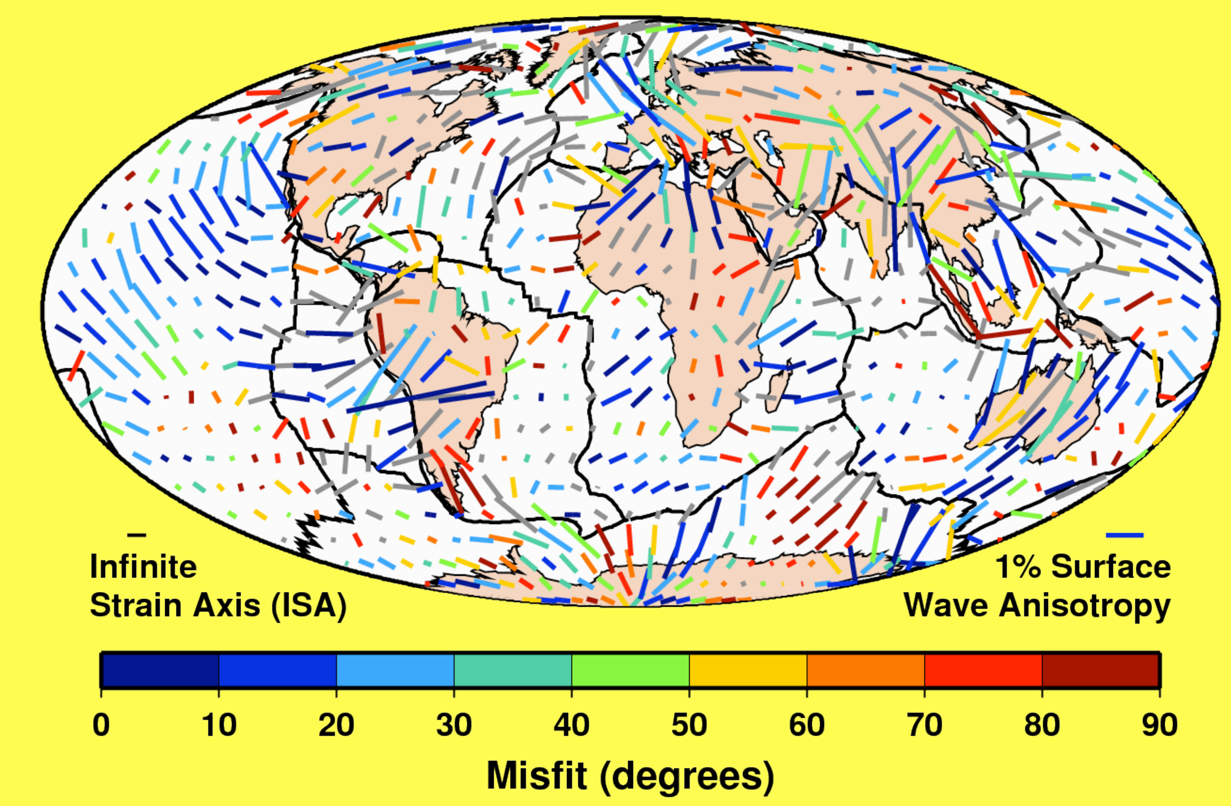




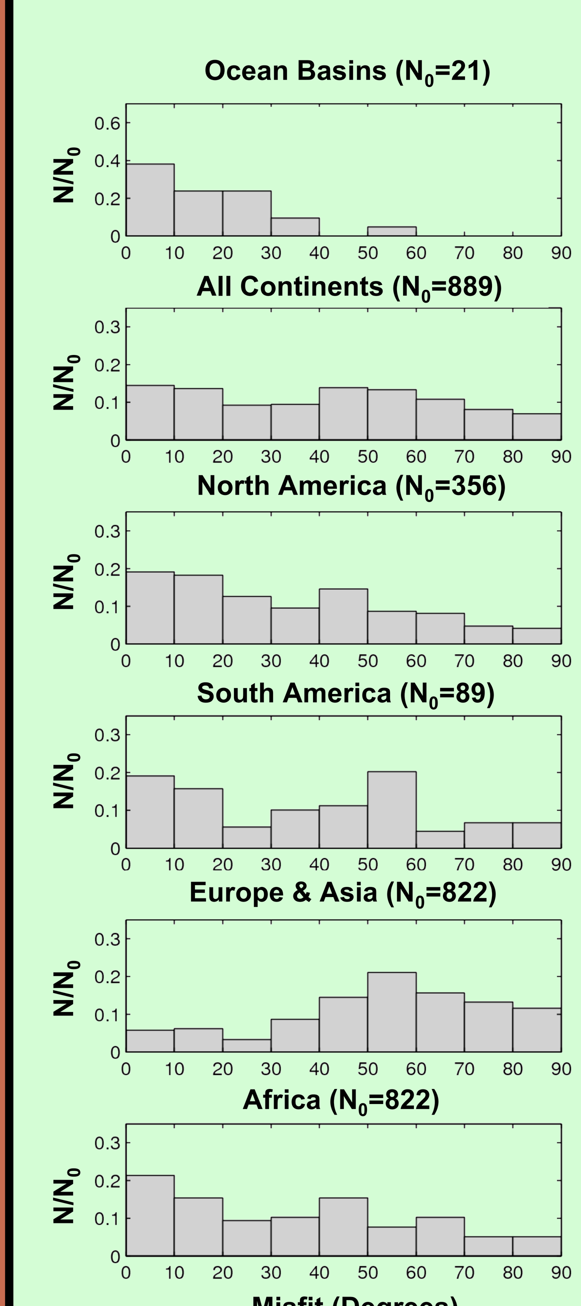
Surface Wave Tomography: Constraint on Mantle Flow Models

We compare the surface wave tomography model of *Debayle et al.* [2005] (at 200 km depth) to our mantle flow model by varying α and β as we did for SKS splitting above. In oceanic regions where the anisotropy magnitude is more than 0.95% (25% of the maximum value, after *Becker et al.*, [2003]), we find a similar pattern to what we found for the SKS splitting measurements (above). For surface wave anisotropy, we find best fits using $0.5 < \beta < 2$ and $\alpha < 0.6$. Again, an asthenospheric viscosity 10 times smaller than the upper mantle viscosity provides the best fit, and higher asthenospheric viscosity permits larger amounts of net rotation (larger α).





Oceanic vs. Continental Anisotropy



We compare a global dataset of observed SKS splitting observations (top panel) with the predicted ISA axis determined from the global flow models. Using an approximate "best fit" choice of α=0.5 and β=0.4 (and an asthenospheric viscosity of η_{asth} / η_{um} = 0.1), we find the distribution of misfits shown on the left. It is clear that while oceanic stations are well fit, the continental stations are, on average, not well fit. We suggest that continents are poorly fit because their anisotropic fabric is dominated by a fossil lithospheric component that depends on a long geologic history of deformation, and cannot be predicted by mantle flow models.

Conclusions

1. **The Infinite Strain Axis (ISA) is a good approximation for the Lattice Preferred Orientation (LPO) of olivine crystals throughout most of the asthenosphere:**
   ISO~LPO because Π<0.5
   This simplifies the anisotropy predictions because strain integration along flow lines is not necessary.
2. **Using seismic anisotropy observations, we find that the combination of plate-driven and density-driven flows constrain upper mantle viscosity to ~0.5 x 10^{21} Pa s, consistent with other estimates.**
3. **A net lithosphere rotation of 2-3 cm/yr (60% of HS3) is permitted by the anisotropy observations, consistnet with *Becker's* [2008] constraint. Larger net rotation is possible for greater asthenospheric visosity, which reduces shear.**
4. **For oceans, anisotropy is dominated by asthenospheric shear flow, and the lithospheric contribution is small. For continents, lithospheric anisotropy is more important because continental lithosphere is thicker, older, and more deformed than its oceanic counterpart.**

References are available upon request. Also see:

Conrad, C.P., M.D. Behn, and P.G. Silver, Global mantle flow and the development of seismic anisotropy: Differences between the oceanic and continental upper mantle, *J. Geophys. Res., 112*, B07317, doi:10.1029/2006JB004608, 2007.