GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L05303, doi:10.1029/2007GL032928, 2008

Azimuthal seismic anisotropy constrains net rotation of the lithosphere

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Received 11 December 2007; revised 20 January 2008; accepted 28 January 2008; published 7 March 2008.

[1] Net rotation (NR) of the lithosphere is found in hot spot reference frames, important for tectonics and plume models, but difficult to constrain. Using mantle flow and crystallographic texture modeling, I show that NRs lead to mantle shearing which is recorded in azimuthal seismic anisotropy. The NR amplitude in some hot spot models is so large that it degrades the model fit to anisotropy significantly. Smaller NRs, such as predicted by flow models with stiff continental keels, are consistent with seismology, however. **Citation:** Becker, T. W. (2008), Azimuthal seismic anisotropy constrains net rotation of the lithosphere, *Geophys. Res. Lett.*, *35*, L05303, doi:10.1029/2007GL032928.

1. Introduction

[2] Plate velocities can be decomposed into poloidal and toroidal parts. The spherical harmonic degree $\ell = 1$ component of the latter corresponds to a net rotation (NR) [e.g., *O'Connell et al.*, 1991] and an overall westward drift of the lithosphere is observed [*Le Pichon*, 1968]. Hot spots are often used as a reference with respect to the lower mantle [*Minster and Jordan*, 1978], and the NR Euler pole location does not differ by more than ~3000 km between recent models [e.g., *Becker*, 2006]. NR amplitudes, however, depend strongly on inversion choices such as hot spot selection [e.g., *Ricard et al.*, 1991] and range from high (0.436°/Ma) for HS3 [*Gripp and Gordon*, 2002] to intermediate (~30% of HS3 [*Ricard et al.*, 1991]), to zero for no net rotation (NNR). If plume distortion in the mantle wind is taken into account, NR is ≈38% of HS3 [*Steinberger et al.*, 2004].

[3] NRs are important for several tectonic problems that rely on kinematic analysis. For example, part of the discrepancies in slab rollback estimates [e.g., *Chase*, 1978; *Lallemand et al.*, 2005] are caused by different reference frames. Rollback may provide information on how regional subduction dynamics affect plate motions, and it is crucial to understand how much NR motion is compatible with other data. NR amplitude is also relevant for tests of its excitation mechanisms. Lateral viscosity variations (LVVs) are required for NRs [*Ricard et al.*, 1991; *O'Connell et al.*, 1991], but how plates and deep flow interact to cause NRs is less clear [e.g., *Olson and Bercovici*, 1991; *Tackley*, 2000]. Candidates for NR excitation include slab dynamics [*Zhong and Gurnis*, 1995; *Enns et al.*, 2005] and the stirring action of stiff continental keels [*Ricard et al.*, 1991; *Zhong*, 2001]. The NR Euler pole for LVV models with keels is close (within ~2100 km) to that of HS3, but none of the geodynamic models predict more than ~30% of HS3 NR [*Becker*, 2006]. We do not know if this magnitude mismatch is due to an incomplete understanding of mantle dynamics, uncertainties in hot spot models, or both. It is therefore useful to take additional constraints into account.

2. Methods

2.1. Estimating Seismic Anisotropy

[4] Upper mantle anisotropy is likely due to lattice preferred orientation (LPO) of olivine [*Nicolas and Christensen*, 1987] and may so provide constraints on mantle currents [e.g., *Tanimoto and Anderson*, 1984]. Azimuthal [e.g., *Gaboret et al.*, 2003; *Becker et al.*, 2003; *Behn et al.*, 2004] and radial [*Becker et al.*, 2008] anisotropy can be matched by flow models, and such successes justify attempts to infer other properties of mantle dynamics from anisotropy. Here, I use the NR component as an adjustable parameter.

[5] LPOs are computed using the method of *Kaminski et al.* [2004] as described by *Becker et al.* [2006]. Anisotropy forms under steady-state circulation everywhere in the upper 410 km up to a logarithmic strain of unity. This is consistent with the observed variability in xenolith LPOs [*Becker et al.*, 2006] and radial anisotropy [*Becker et al.*, 2008], but such choices do not affect the general conclusions. For seismology, I focus on maps of azimuthal (2Ψ) structure by *Ekström* [2001]; to explore depth dependence, phase velocity anomalies at T = 50 s and 100 s period are considered, with peak sensitivity at ~75 km ("lithospheric") and ~125 km ("asthenospheric") depth, respectively.

2.2. Geodynamic Flow Models

[6] The temperature-dependent, power-law η_{eff} rheology from *Becker* [2006] for dry olivine is used. NNR plate velocities are prescribed at the surface, keels are assigned underneath cratons, half-space cooling is used for the oceanic lithosphere [*Conrad and Lithgow-Bertelloni*, 2006], and temperature anomalies are inferred from seismic tomography elsewhere. The resulting flow in this "LVV model" is computed with CitcomS [*Zhong et al.*, 2000; *Tan et al.*, 2006], and all parameters are as in earlier work [*Becker et al.*, 2006]. The rheology then leads to keel viscosities that are ~10,000 times that of the mantle underneath mid-oceanic ridges at 150 km depth. Tests with a free-slip surface boundary condition and weak zones indicate that plate motions and oceanic/continental RMS velocity ratios can be fit well [*Becker*, 2006].

[7] The surface NR component of the LVV model with NW-ward velocities across the Pacific and Euler pole in the Indian Ocean are close to HS3 in direction, but amplitudes are only ~30% of HS3 [*Becker*, 2006]. However, the

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reversal in direction and decay of NR amplitudes over the top ~300 km of the mantle, and the resulting shear, are similar between models with different rheologies [*Becker*, 2006, Figure 5b], and consistent with earlier findings [*Zhong*, 2001]. NRs for the free-slip models are also similar to those of models where NNR plate motions were prescribed at the surface. This implies that the LVV model can provide a useful estimate for the expected style of NR shear on Earth.

[8] To isolate the effect of NR motions on anisotropy, the $\ell = 1$ toroidal component of the LVV model's velocities was added to several flow models. Such tests are complicated by the effects of LVVs in the absence of NR motions: Radial anisotropy predictions are improved by the shear-focusing underneath oceanic plates that results from LVVs [*Becker et al.*, 2008] and *SKS* splitting underneath continents can be matched better with LVVs than without [*Conrad et al.*, 2007a]. However, the fit to surface-wave azimuthal anisotropy is degraded by LVVs, e.g., by disruption of patterns within the central Pacific [*Becker et al.*, 2007]. I therefore analyze two relative velocity models that differ only in rheology: one has only radially-dependent viscosity (RVV model, η_r of *Becker* [2006]), and the other is the LVV model. Both flow fields are first moved to NNR at all depths, and then the NR component of the LVV model is added, scaled with a factor f. For $f = 1$, this reproduces the original velocities of the LVV model. For the RVV model, velocities will have an added NR shear component for $f > 0$ but are otherwise not affected by LVVs.

3. Results

[9] Figure 1 compares asthenospheric anisotropy predictions from RVV flow without any NRs (Figure 1a) with a model where the NR component of LVV is added to RVV, scaled up to HS3 strength (Figure 1b). Both flow models match anisotropy best underneath oceanic plates, as discussed previously [*Becker et al.*, 2003]. Strong shear as induced by the NRs affects anisotropy in an intuitive way: the inferred 2Ψ orientations of Figure 1b are similar to the surface NR velocities [correlation with HS3-NR for $\ell \leq 8$, $r_8 = 0.46$ cf. *Becker et al.*, 2007]. Any NR of the lithosphere with respect to the lower mantle can therefore be expected to leave an imprint on azimuthal anisotropy. The NR shear component in Figure 1 strongly degrades the 2Ψ fit, e.g., in the western Pacific and the central Australian plate. The geographic distribution of the changes in misfit are similar for the lithospheric 2Ψ maps, and the regions where the anisotropy match improves for NRs are not off-setting the overall misfit enough to balance things out. The net effect of net rotations is to decrease the match with anisotropy.

[10] One way to quantify the role of NRs further is by computing correlation coefficients. Figure 2 shows r_8 for RVV and LVV flow with different amounts of net rotation added, at lithospheric and asthenospheric depths. There are discrepancies between seismologically mapped 2Ψ patterns in the upper mantle, and Figure 2 therefore shows results for two distinct seismological approaches, using 2Ψ from *Ekström* [2001] and the *SV* model by *Debayle et al.* [2005], converted to phase velocity anomalies as in work by *Becker et al.* [2007]. Results based the surface wave model by *Trampert and Woodhouse* [2003] (not shown) are very similar to those for *Ekström* [2001], as expected given the similarity of their imaging strategy.

[11] For the RVV model (Figure 2a), any added NR flow degrades the fit at lithospheric depths, where frozen-in structure may be more important than convective LPO formation. The global fit to the asthenospheric 2Ψ of the RVV model actually improves slightly when NR motions are added, but degrades again when NRs are larger than ~30% of HS3. The amplitudes of NR that lead to the best model fits for the asthenospheric 2Ψ roughly bracket the range of the geodynamic models of NR flow and the hot spot models with smaller NR.

[12] Correlations for 2Ψ are statistically 99% significant according to Student's t when $|r_8| > 0.21$, which applies to all low NR models. Also, at $r_8 = 0.45$, a drop of correlation by, e.g., 0.1 is significant at the 70% level based on Fisher's z [cf. *Becker et al.*, 2007]. However, more important than statistical measures is robustness of trends, as illustrated by the comparison between the two seismological models in Figure 2. While absolute values of r_8 differ, the relative dependence of r_8 on NR flow is notably consistent.

[13] Figure 2b shows 2Ψ correlations for the LVV model; the absolute values of r_8 are degraded compared to RVV flow. This is because of flow complexities, e.g. in the central Pacific and underneath continents, and the significance of regional deviations in the light of uneven seismological resolution is not clear [*Becker et al.*, 2007]. For the LVV model at lithospheric depths, the 2Ψ match is best at ~30% of HS3 NR flow (the intrinsic NR component that is generated by the LVV model). The trends for the asthenosphere are similar to the RVV model, with a more pronounced peak at moderate NR for 2Ψ inferred from *Debayle et al.* [2005]. Globally, a range of NRs $\lesssim$ 50% of HS3 is again preferred.

[14] Future refinement of azimuthal anisotropy maps and models will likely bring a better understanding of the importance of regional patterns. However, I interpret Figures 1 and 2 such that azimuthal anisotropy is incompatible with NRs $\gtrsim$ 50% of HS3. The geodynamically predicted NR for strong keels are, however, compatible, particularly at asthenospheric depths.

4. Discussion

[15] We cannot know for certain if our mantle circulation estimates are appropriate for Earth. However, such models are consistent with a wide range of geophysical observables [e.g., *Hager and Clayton*, 1989; *Steinberger and Calderwood*, 2006] and LVV models produce both realistic toroidal flow and relative motions [*Zhong*, 2001; *Becker*, 2006]. Another concern is that our understanding of anisotropy formation may be flawed. Given the strong imprint of NR motions on 2Ψ (Figure 1), it is unlikely, though, that details of the LPO estimates or data set selection will matter. In fact, preliminary results by *Conrad et al.* [2007b] indicate that *SKS* splitting also requires relatively small net rotations.

[16] All LPOs for this study were computed using a "dry" olivine slip system [e.g., *Karato et al.*, 2008]. If there is a high water, or melt, layer in the region where the NR induced shear is highest, this may alleviate the impact on anisotropy. Given that the degradation of model fit in the

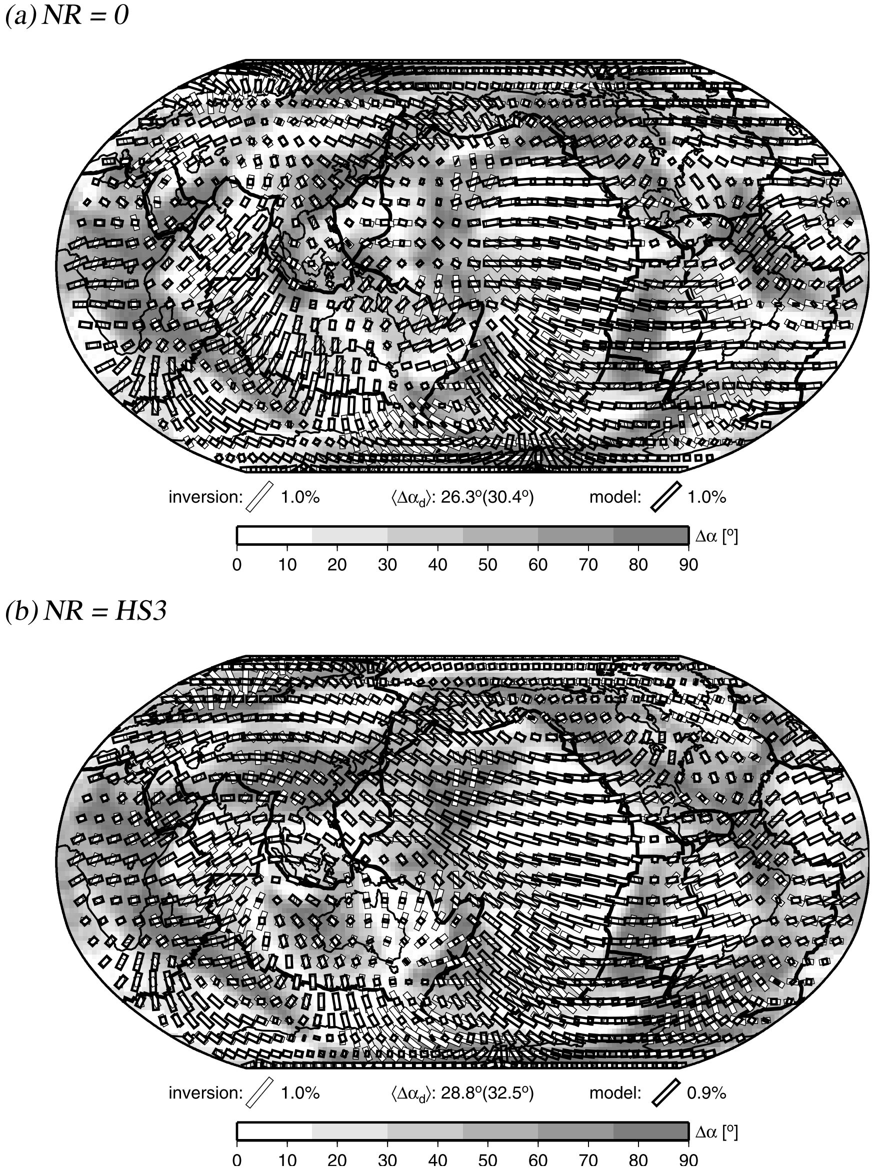

Figure 1. Azimuthal anisotropy up to degree $\ell = 8$ at asthenospheric depths (T = 100 s) for the RVV model with (a) zero NR and (b) NR as in HS3. Thin and heavy-lined sticks are 2Ψ from *Ekström* [2001] and the flow model (amplitudes scaled to match seismology), respectively. Background shading is angular orientation misfit, $\Delta\alpha$; the global (oceanic) average misfit scaled with anisotropy strength, $\langle\Delta\alpha_d\rangle$ [cf. *Becker et al.*, 2003] is given in the legend along with 2Ψ anomaly scale.

presence of large NRs is a global effect (Figure 1), it appears difficult to invoke volatile content to reduce the role of NRs. Also, global computations have yet to address the feedback between mechanical and crystallographic anisotropy [e.g., *Christensen*, 1987]. However, any sustained interactions between NR shear flow and viscosity may lead to an even stronger signature of NRs in anisotropy.

[17] The details of the NR generation of global LVV models are model-dependent, and some of the mismatch may be caused by imperfect modeling of mantle velocities. I therefore conducted additional tests, for some of which surface NR motions were added to RVV flow as a shear-layer which was exponentially tapered off over ~400 km. Those simplified models led to a similar degradation of the model fit as shown in Figure 2, indicating that the exact depth dependence and Euler poles of NR flow are less important than the strength of NR.

[18] Anisotropy records past motions, and the preference of our models for small NRs might be because we had not considered previous tectonic stages. Hence, I also tested flow for which the NRs of plate tectonic reconstructions for the Cenozoic [*Gordon and Jurdy*, 1986; *Lithgow-Bertelloni et al.*, 1993] were applied as a simplified shear to the RVV model. The anisotropy match degraded further compared to present-day NR, both for the *Ekström* [2001] and *Debayle et al.* [2005] maps. This shows that the more recent style of NR may be preferentially preserved over that further in the convective past.

[19] While anisotropy depends non-linearly on NRs, Figure 1 suggests that direct linear superposition of NR motion on LPO may be a useful first approximation.

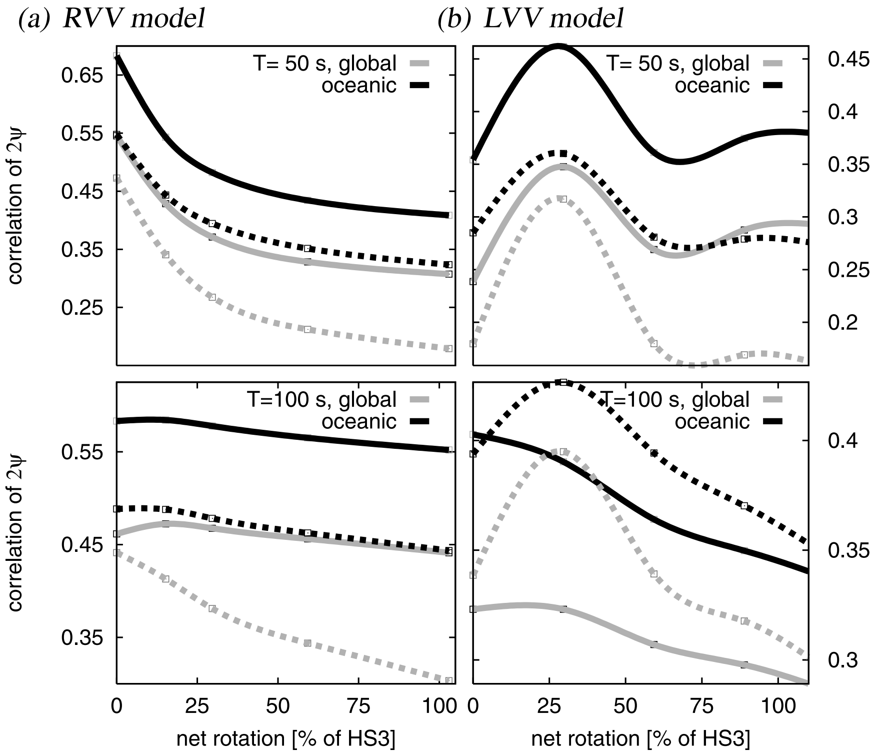

Figure 2. Correlation between geodynamics and seismology 2Ψ, r_8, for (a) RVV and (b) LVV flow for different amounts of net rotation. Values for (top) lithospheric (T = 50 s) and (bottom) asthenospheric (T = 100 s) structure are shown with solid and dotted lines for *Ekström* [2001] and *Debayle et al.* [2005], respectively. Dark and light gray is for global and oceanic regions r_8, respectively [cf. *Becker et al.*, 2007].

Therefore, I inverted for best-fit Euler poles when arbitrary NR was added to the RVV model. Only for the *Trampert and Woodhouse* [2003] maps could r_8 be improved somewhat, by 0.04 (~35% level) for a 214°E, 9°S pole. This central Pacific location leads to ~N-S shear over central Asia, but all of the recorded NR poles within the last 120 Ma from *Lithgow-Bertelloni et al.* [1993] are off to the west by at least 10,000 km from this best-fit Euler pole.

[20] Lastly, I considered models where the full plate reconstructions applied at the surface, striving to estimate circulation back in time to 60 Ma [cf. *Steinberger and O'Connell*, 1997]. Following *Conrad and Gurnis* [2003], the density anomalies were backward-advected, defining continental regions down to 300 km depth. Correlations based on these time-evolving velocities were comparable to those based on steady-state flow without LVVs, consistent with earlier work [*Becker et al.*, 2003]. When a temperature-dependent rheology applied so that the model approximately incorporated the NR-inducing effect of moving keels, misfits again increased compared to a time-evolving model without LVVs.

[21] This indicates that it is unlikely that tectonic history will trade off much with NRs in a fashion that would permit stronger NRs. Anisotropy modeling with plate tectonic histories clearly has to be examined further, but my basic findings here should not be affected.

5. Conclusions

[22] Any net rotation of the lithosphere with respect to the deep mantle will induce a shear component on mantle deformation, and as a consequence affect azimuthal anisotropy. Based on geodynamic modeling, only moderate amounts of NR motions, of the order of 50% of HS3, appear consistent with azimuthal anisotropy. Such NR amplitudes are similar to those of geodynamic models which include stiff continental keels. Inferences based on hot spot models with larger NR amplitudes may need to be revised.

[23] **Acknowledgments.** This is my long overdue answer to a question by S. Zhong. I also thank A. McNamara, an anonymous reviewer, and B. Steinberger for their comments, seismologists who share their models and the authors of CitcomS (cf. geodynamics.org) including L. Moresi, E. Tan, and S. Zhong. This work was supported by NSF (EAR-0509722 and EAR-0643365), and computations were performed at USC's Center for High Performance Computing (www.usc.edu/hpcc). Figure 1 was produced with GMT [*Wessel and Smith*, 1991].

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GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L08308, doi:10.1029/2008GL033946, 2008

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Correction to "Azimuthal seismic anisotropy constrains net rotation of the lithosphere"

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Received 12 March 2008; accepted 1 April 2008; published 24 April 2008.

Citation: Becker, T. W. (2008), Correction to ''Azimuthal seismic anisotropy constrains net rotation of the lithosphere,'' *Geophys. Res. Lett.*, *35*, L08308, doi:10.1029/2008GL033946.

[1] The paper "Azimuthal seismic anisotropy constrains net rotation of the lithosphere" (*Geophysical Research Letters*, *35*, L05303, doi:10.1029/2007GL032928, 2008) contains a misleading sentence in paragraph [19]. The match to one seismological map was improved moderately by addition of a hypothetical net rotation (NR) to the starting model. With respect to this best-fit pole, it was stated: "This central Pacific location leads to ~N-S shear over central Asia, but all of the recorded NR poles within the last 120 Ma from *Lithgow-Bertelloni et al.* [1993] are off to the west by at least 10,000 km from this best-fit Euler pole." While this statement is correct, the 10 Ma stage NR pole is actually within a smaller distance, ~5,000 km, to the east of the central Africa antipode of the best-fit pole, which is equivalent for considerations of anisotropy. The 10 Ma pole had regrettably been omitted from our previous distance estimates by an oversight. The conclusions of the paper remain unaffected.

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