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Shear-Wave Splitting to Test Mantle Deformation Models around Hawaii

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Abstract. Seismic anisotropy allows us to study mantle deformation, and it can thus help to constrain mantle flow in the vicinity of hotspots. Hypotheses for the cause of seismic anisotropy in this environment include the "parabolic asthenospheric flow" (PAF) model: radial flow from a mantle plume impinging on a moving lithosphere is dragged by the plate in the direction of absolute plate motion. In map view, this gives a parabolic pattern of flow, opening in the direction of plate motion. We present new shear-wave splitting observations from land and ocean stations around the Hawaiian Islands that can be explained by the parabolic flow model. The observations suggest asthenospheric anisotropy under the Hawaiian islands, which may be explained if dislocation-creep persists to deeper depths there than in other regions, perhaps due to the higher temperatures near hotspots.

Introduction

If the mantle is anisotropic, teleseismic shear waves are split into a fast and slow wave, which are polarized in two mutually orthogonal directions. Two main causes of this shear-wave splitting are vertically coherent deformation (VCD)[*Silver*, 1996] of the lithosphere, and simple asthenospheric flow (SAF)[*Vinnik et al.*, 1992]. More recently, several regions were found to have two anisotropic layers [*Savage and Silver*, 1994; *Hartog and Schwartz*, 2001; *Levin et al.*, 2000; *Wolfe and Silver*, 1998; *Bokelmann and Silver*, 2000], and it appears that the upper layer of anisotropy may be due to VCD in the lithosphere, while the lower layer may be due to SAF in either the asthenosphere or lower lithosphere.

Simple strain-rate modeling using parameters reported in Karato and Wu [1993] suggests that dislocation creep is the dominant deformation mechanism in the lithosphere of the cold continental interior. However, a hotter geothermal gradient might possibly extend the zone of dislocation creep deeper into the asthenosphere. Thus, lateral variations in upper-mantle temperature may play an important role in explaining why splitting varies so much between tectonic environments.

In this paper, we present new shear-wave splitting data from 5 broadband stations around the Hawaiian Islands. We use these measurements to show that the character of shear-wave splitting under the Hawaiian Islands differs from "more typical" Pacific regions, and that a parabolic asthenospheric flow pattern, originating from the interaction of a plume and a moving plate, may explain much of the splitting near the islands. We speculate that splitting near Hawaii is primarily due to dislocation creep in the asthenosphere, whereas that far from Hawaii may be dominated by "fossil" lithospheric anisotropy frozen into the lithosphere.

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Parabolic Asthenospheric Flow

Ribe and Christensen [1994] calculated a 3D finite-difference fluid-dynamical model that predicted the kinematics and strength of asthenospheric flow beneath the Hawaiian Islands. Their modeling shows that approximately parabolic asthenospheric flow is likely to occur. Lubrication theory also predicts approximately parabolic flow [*Olson*, 1990]. Sleep [1990] calculated the 2D kinematic solution for a generic hotspot using a point-source approximation at the plume impingement point in a horizontal stream of flowing asthenosphere. The point source approximates the 3D problem in 2D, i.e., plume material is created at a point, and flows radially away from it into a fixed-velocity horizontal stream, emulating gravitational spreading of the buoyant plume material. The horizontal stream represents the flow of asthenosphere due to relative motion between the lithosphere and mesosphere. When absolute plate motion is significant compared to plume volumetric flow rate, the radial flow of plume material near the impingement point wraps around into an approximately parabolic flow pattern expanding in the direction of asthenospheric motion relative to the plate (Fig. 1). The results of Ribe and Christensen [1994] confirm that, close to the hotspot, the point-source abstraction is an adequate approximation of the flow kinematics. We assume such flow is accommodated by simple-shear deformation, which is then reflected in anisotropy and thus shear-wave splitting.

Anisotropy Data and Modeling

Wolfe and Silver [1998a] and Barruol and Hoffmann [1999] made shear-wave splitting measurements at Oahu (station KIP) that can be fit with a two-layer model, where the lower layer fast direction is parallel to plate motion and the upper layer subparallel to the Molokai Frature Zone. Temporary broadband deployments on the Hawaiian Islands (by Carnegie Inst. and Northwestern Univ.) have yielded preliminary splitting measurements[*Wolfe et al.*, 1998]; a comprehensive report is in preparation [*Ray Russo, pers. commun., 2000*].

We present new shear-wave splitting measurements from 4 broadband GSN stations and 1 broadband PASSCAL station (Fig. 1). JOHN (Johnston Atoll) and H2O (seafloor NE of Hawaii) serve as a regional reference with which to compare splitting measurements around Hawaii. KIP (Oahu) and POHA (Hawaii) provide hotspot axis coverage. OSN-1 was a temporary ocean-borehole station located ~225 km

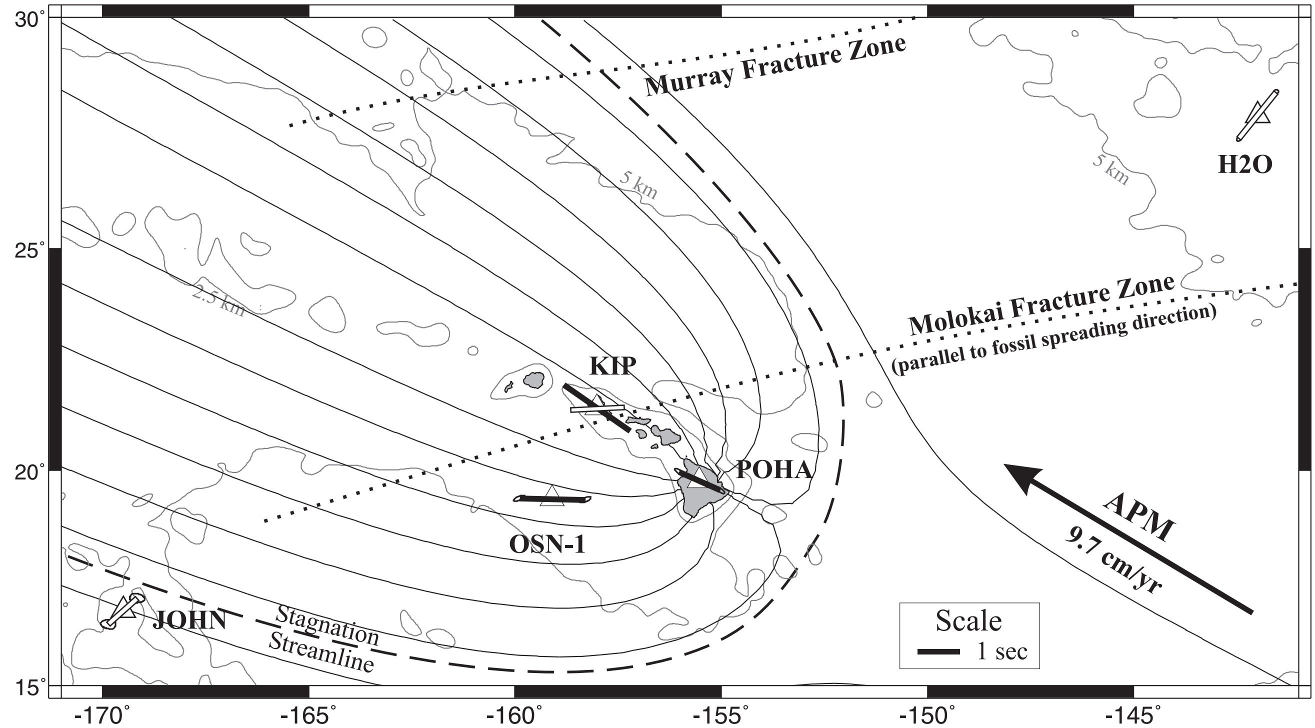

Figure 1. Map of Hawaii and surrounding region. Triangles indicate analyzed stations. Shear-wave splitting estimates are plotted as lines with their orientation parallel to fast polarization direction, and length proportional to delay time. Shade shows their interpreted depth (open=lithospheric, filled=asthenospheric). Formal 95% confidence regions are plotted at ends of vectors for single-layer models. The parabolic flow model is shown via streamlines (see text). Note the good fit with the fast polarization directions at OSN-1, KIP, POHA, and the poor fit at greater distances (H2O and JOHN).

SW of Oahu[*Collins et al.*, 2000], and is of critical importance for resolving PAF because it is off the hotspot axis and can detect a radial component of asthenospheric flow.

We made shear-wave splitting measurements of SKS, S, and ScS phases (the latter two from >300-km-deep hypocenters) using the Silver and Chan (SC) [1991] method. All the data were low-pass filtered at 0.2 Hz. We found the best-fitting "apparent" fast polarization direction (ϕ) and delay time (dt) from a grid search over trial ϕ and dt, calculating the minimum eigenvalue of the covariance between the trial fast and slow waves (Fig. 2). For a single-layer model, ϕ and dt do not vary significantly with initial polarization direction. When this was the case, we employed the variance stacking method of Wolfe and Silver (WS) [1998a] to calculate a single-layer station estimate and its 95% confidence region. Otherwise, we assumed a 2-layer horizontal anisotropy model, and used the method of Savage and Silver (SS) [1994] to solve for the 4 parameters (ϕ_l, dt_l, ϕ_u, dt_u) and their 95% marginal errors. We did this at five different frequencies (0.1, 0.15, 0.2, 0.25, and 0.3 Hz) by minimizing an L2 misfit function.

Using the SC method, we made 38 apparent splitting measurements at the five stations (KIP: 20, POHA: 7, OSN-1: 3, JOHN: 2, H2O: 6). From these, we derived the final station estimates using the WS method (single-layer model) or the SS method (2-layer model)[1]. Data from JOHN, OSN-1, and POHA can be explained by a single-layer model. H2O can almost be explained by a single-layer model, but 2 of the 6 measurements are statistically different from one another at a 95% confidence level (ϕ: $41\pm^{20^o}_{29^o}$ and $127\pm^{28^o}_{42^o}$). This 24^o difference may suggest more complex anisotropy, and we cannot rule out a possible two-layer case for H2O with the given data coverage.

Most stations can be fit by a single-layer model, but KIP clearly can not (Fig. 3). In fact, it is even difficult to fit a simple 2-layer model to all 20 measurements for KIP. Figure 3 shows a consistent variation of ϕ with initial polarization, but the variation in dt appears more random. Very large splitting delays may be due to measurement error (asymmetric distribution of splitting values), and we eliminate values larger than 2 seconds from further analyses. The proportion of data explained by any model can be quantified by $R^2 = 1 - \sum(d_{obs} - d_{mod})^2 / \sum(d_{obs} - mean(d_{obs}))^2$, which in the ideal case reaches the maximum of 1. Using unfiltered particle-motion plots for KIP, we estimated the polarization for first S-motion as $\phi_u \approx 75^o$. We then allowed ϕ_u to vary within $\pm 25^o$ of this estimate, and searched for all four parameters. The best-fitting model for KIP ($\phi_l = 123 \pm 6^o$, $dt_l = 1.9 \pm 0.2$ s, $\phi_u = 87 \pm 6^o$, $dt_u = 1.3 \pm 0.2$ s) was obtained with a 0.3 Hz frequency, and has an R^2 of 0.74. For lower frequencies, we obtain nearly the same parameters for the lower layer but near-zero dt_u for the upper layer. Finally, we applied a Monte Carlo routine for projecting the error region onto a histogram, and found that only ϕ_l and dt_u are well-constrained at 0.3 Hz.

Although a single-layer model explains splitting at POHA, the 7 measurements are also fully consistent with a 2-layer

[1]Supporting material is available at ftp://kosmos.agu.org, directory "apend" (Username="anonymous", Password="guest"); subdirectories in the ftp site are arranged by paper number. See also http://www.agu.org/pubs/esupp_about.html.

model. The best-fitting 2-layer model (ϕ_l=125^o, dt_l=2.2 s, ϕ_u=64^o, dt_u=0.4 s) has an R^2 = 0.88 at a frequency of 0.15 Hz. Although the 2-layer model explains all the data at POHA a little better than the single-layer model, the simple single-layer model is preferred until additional data demand otherwise.

The fast polarization directions for POHA, OSN-1, and the lower layer of KIP are roughly parallel to absolute plate motion (APM $\pm30^o$). However, ϕ for the distant stations (H2O and JOHN) is strikingly different in orientation and closer to the fossil spreading direction. These differences motivated us to calculate a PAF model after Sleep [1990] to compare the orientations of the model's streamlines to the observed ϕ at POHA, OSN-1, and KIP (Fig. 1). This modeling assumed that the Hawaiian plume impinges on the lithosphere beneath Loihi seamount $\pm$ 60 km, a plume mass flux of 4.1kg s^{-1}[*Ribe and Christensen*, 1994], a $\sim$300^o APM direction[*Gripp and Gordon*, 1990], and an asthenospheric thickness of 150 km.

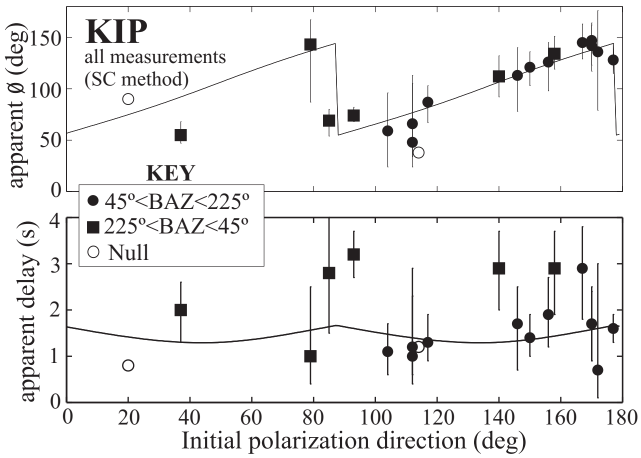

Figure 3. Apparent splitting measurements vs. initial polarization direction for KIP. Error bars indicate constrained measurements. The solid line is the 2-layer model that best predicts the measurements with dt < 2.0 s (R^2=0.74).

Discussion

Splitting at the reference stations (H2O and JOHN) is best explained in terms of a single-layer anisotropy model with a NE ϕ and a moderate *dt* of $\sim$1.3 s (Fig. 1). This layer may be interpreted as the mantle lithosphere with a 5-8% bulk anisotropy due to a NE-preferred alignment of olivine a-axes, which froze into the lithosphere as it cooled during the process of seafloor spreading. However, we note that ϕ for these stations is rotated 25^o counterclockwise from the 70^o fossil spreading direction (parallel to fracture zones), which one would not expect for a single-layer model due to sea-floor spreading at a ridge with a passive upwelling. One can speculate that this discrepancy may be due to a second layer of anisotropy, but hard evidence for this second layer remains to be seen due to the few available data. In addition, H2O and JOHN station estimates are not consistent with those predicted by Montagner and Guillot's [2000] synthetic single-layer splitting map, which was generated from a global 3D surface-wave anisotropy (SV azimuthal) dataset. We speculate that for JOHN, this discrepancy is due to the small number and poor quality of splitting data, and for H2O, poor lateral resolution of the surface-wave dataset (the splitting map is highly variable around H20).

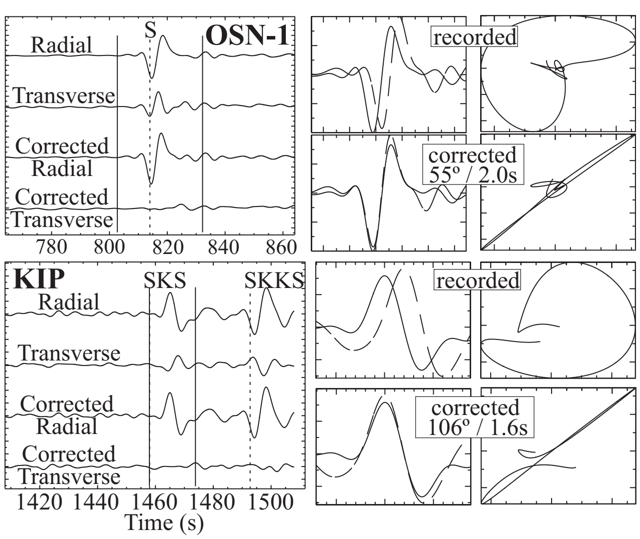

Figure 2. Examples of splitting at OSN-1 (top) and KIP (bottom). From left to right: Original and anisotropy-corrected waveforms on radial and transverse components, fast and slow (f/s) components, and the corresponding f/s particle motion.

Within the resolution of the data, POHA splitting is explained by a single-layer model with ϕ parallel to APM, although a 2-layer model is also consistent with the data. This is surprising because POHA is located close to the proposed Hawaiian plume conduit [*Rümpker and Silver*, 2000]. Similarly for OSN-1, a single-layer model also explains the data. However, two layers are required to explain KIP splitting, with one layer parallel to APM, and the other subparallel to the Molokai Fracture Zone. This result confirms those of other authors [*Wolfe and Silver*, 1998; *Barruol and Hoffmann*, 2000], although our delays are considerably larger. One can explain KIP upper-layer splitting in a number of ways [*Barruol and Hoffmann*, 2000]. We interpret it as primarily due to VCD and microfracturing during simple shear along the fracture zone [*Russo et al.*, 1998] when the fracture zone was a transform fault.

Since POHA splitting and lower-layer KIP splitting have ϕ parallel to APM, SAF may explain these data. However, for OSN-1 the difference between ϕ and APM is $\sim$30^o, and that between ϕ and the fracture zone is $\sim$20^o. Rather than attempt to explain OSN-1 splitting as due to fossil anisotropy (hard to do since it is not required at POHA), we suggest it is associated with the Hawaiian plume, and we call upon a PAF model that is kinematically similar to that which Ribe and Christensen [1994] proposed to explain the bathymetric swell (Fig. 1). This PAF model explains both ϕ for OSN-1 and POHA, and ϕ_l for KIP. Moreover, this model is consistent with Laske and Orcutt's [2000] surface-wave anisotropy results from beneath the SWELL array in that they also resolve a clockwise rotation of ϕ_l from the southwest part of the array to the northeast. Even more remarkable is that such a PAF pattern is also apparent in Montagner and Guillot's [2000] global synthetic ϕ map. Finally, it appears that intrusion/heating may have erased lithospheric anisotropy around Hawaii, but more splitting data are required to confirm this.

The fast polarization directions and delay times of the stations around Hawaii (OSN-1, KIP, and POHA) are quite different from those at greater distances (H2O and JOHN). To us, these geometries suggest that body wave anisotropy is more strongly controlled by the lithosphere far from Hawaii and by the asthenosphere near Hawaii. We speculate that our splitting observations resolve a deflection of the dislocation creep zone from mostly in the lithosphere at H2O and JOHN to deeper levels in the asthenosphere around Hawaii. Our speculation is also consistent with Western U.S. shear-wave splitting observations in that the Basin and Range [*Savage and Sheehan*, 2000] shows weak and spatially variable splitting while the Yellowstone hotspot track [*Schutt et al.*, 1998] shows strong and spatially consistent splitting parallel to absolute plate motion.

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References

Barruol, G. and Hoffmann, R., Upper mantle anisotropy beneath the Geoscope stations, *J. Geophys. Res.*, 104, 10757–10773, 1999.

Bokelmann G.H.R. and Silver, P.G., Mantle variation within the Canadian Shield; travel times from the portable broadband Archean-Proterozoic Transect 1989, *J. Geophys. Res.*, 105, 579–605, 2000.

Collins, J.A., Vernon, F.L., Orcutt, J.A., and Stephen, R.A., Broadband seismology in the oceans: Lessons from the Ocean Seismic Network Pilot Experiment (abstract), *EOS Trans. Suppl.*, 81, F838, 2000.

Gripp, A.E. and Gordon, R.G., Current plate motions relative to the hotspots incorporating the NUVEL-1 plate motion model, *Geophys. Res. Lett.*, 17, 1109–1112, 1990.

Hartog, R. and Schwartz, S.Y., Depth-dependent mantle anisotropy below the San Andreas fault system: Apparent splitting parameters and waveforms, *J. Geophys. Res.*, 106, 4155–4167, 2001.

Karato, S.I. and Wu, P., Rheology of the upper mantle: A synthesis, *Science*, 260, 771–778, 1993.

Laske, G. and Orcutt, J., The Hawaiian SWELL Experiment: An example for the need of broad-band ocean bottom seismograms (abstract), *EOS Trans. Suppl.*, 81, F819, 2000.

Levin, V., Menke, W., and Park, J., Shear wave splitting in the Appalachians and the Urals: A case for multilayer anisotropy, *J. Geophys. Res.*, 104, 17975–17993, 1999.

Montagner, J.P. and Guillot, L., Seismic anisotropy in the Earth's Mantle, *Problems in Geophysics for the Next Millenium*, Erice, July 7-16, 1999, 2000.

Olson, P., Hot spots, swells and mantle plumes, *Magma Transport and Storage*, edited by M.P. Ryan, 33–51, John Wiley, New York, 1990.

Ribe, N.M., and Christensen, U.R., Three-dimensional modeling of plume-lithosphere interaction, *J. Geophys. Res.*, 99, 669–682, 1994.

Russo, R.M., Wolfe, C.J., Okal, E.A., Silver, P.G., and Solomon, S.C., Shear-wave splitting beneath the Hawaiian Islands (abstract), *EOS Transactions Suppl.*, 79(17), 208, 1998.

Rümpker, G. and Silver, P.G., Calculating splitting parameters for plume-type anisotropic structures of the upper mantle, *Geophys. J. Int.*, 143, 507–520, 2000.

Savage, M.K. and Sheehan, A.F., Seismic anisotropy and mantle flow from the Great Basin to the Great Plains, Western United States, *J. Geophys. Res.*, 105, 13715–13734, 2000.

Savage, M.K. and Silver, P.G., The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers, *Geophys. J. Int.*, 119, 949–963, 1994.

Schutt, D., Humphreys, E.D., and Dueker, K., Anisotropy of the Yellowstone hot spot wake, Eastern Snake River Plain, Idaho, *Pure Appl. Geophys.*, 151, 443–462, 1998.

Silver, P.G. and Chan, W.W., Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, 96, 16429–16454, 1991.

Silver, P.G., Seismic anisotropy beneath the continents: Probing the depths of geology. *Ann. Rev. Earth Planet. Sci.*, 24, 385–432, 1996.

Sleep, N., Hot spots and mantle plumes: Some phenomenology, *J. Geophys. Res.*, 95, 6715–6736, 1990.

Vinnik, L.P., Makeyeva, L.I., Milev, A., and Usenko, Y., Global patterns of azimuthal anisotropy and deformation in the continental mantle, *Geophys. J. Int.*, 111, 433–447, 1992.

Wolfe C.J. and Silver, P.G., Seismic anisotropy of oceanic upper mantle: Shear wave splitting methodologies and observations, *J. Geophys. Res.*, 103, 449–771, 1998.

Wolfe, C.J., Solomon, S.C., Silver, P.G., Shen, Y., Russo, R.M., Okal, E.A., Kuehnel, R., and Kuehnel, A. Shear-wave splitting beneath the Hawaiian Islands (abstract). *EOS Trans. Suppl.*, 79(45), 661–662, 1998.

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Comment on "Shear-wave splitting to test mantle deformation models around Hawaii" by Kristoffer T. Walker, Götz H. R. Bokelmann, and Simon L. Klemperer

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[1] *Walker et al.* [2001] (hereinafter referred to as WBK) suggest a "parabolic asthenospheric flow" model to explain observations of shear-wave splitting in the upper mantle around Hawaii. In short, a few stations close to Hawaii display fast directions of anisotropy (counted clockwise from North) around 100°, whereas at two stations at a large distance from Hawaii the direction is very different (around 40°). WBK propose that the fast direction near Hawaii is affected by the asthenospheric flow from the plume, whereas at the other stations the direction is dominated by "fossil" lithospheric anisotropy. One of the two stations with a presumably lithospheric anisotropy is H2O in the east of the Pacific plate (141°59′W, 27°53′N). The data from this station are especially interesting, as it is the only permanent seismograph station on the oceanic floor. The result for H2O reported by WBK contradicts those for the west of the Pacific plate, where all estimates of the fast direction of anisotropy are around 100°, nearly parallel to the direction of the Pacific plate motion [*Farra and Vinnik*, 1994; *Russo and Okal*, 1998]. These observations suggest that shear wave splitting beneath an oceanic plate is mainly a result of recent deformations in the layer between the lithospheric plate and the underlying mantle. So, why this mechanism does not work in the east of the Pacific plate, where the direction of the plate motion and its velocity are almost the same? To answer this question we present results of our own analysis of seismic data from station H2O.

[2] We analysed observations of SKS seismic phase with the algorithm of *Vinnik et al.* [1989]. The estimates of the parameters of splitting (fast direction α and time lag δt) are obtained by minimizing the discrepancy between the theoretical and observed transverse (T) components of SKS waveforms. If variance of the difference between the theoretical and observed T components for the i-th waveform is e_i^2, the estimate for the group of waveforms is obtained by minimizing $(1/n)\Sigma_{i=1}^{n} e_i^2$. As has been shown many times [*Farra and Vinnik*, 1994], the summation of variances for several events is an efficient way to get stable estimates of the parameters of anisotropy. WBK use a similar method, but apply it not only to SKS, but also to S and ScS phases.

[3] We have found 3 recordings of SKS of sufficient quality (Figure 1 and Table 1). The analysis was conducted in 2001. To get meaningful results, we changed polarity of one of the horizontal components. In the diagrams of $e(\alpha, \delta t)$ (Figure 1) for the two recordings (2 and 3), there are clear minima. The solution for recording 1 is nonunique, but consistent with the others and helps to constrain the fast direction for the group of the recordings. The summary diagram (Figure 1) has one clear minimum for α near 105°.

[4] WBK evaluate accuracy of their measurements with the method of *Wolfe and Silver* [1998]. This method is based on the assumption that the errors are caused by additive seismic noise, the level of which is given by the minimal difference between the observed and theoretical T components of SKS or equivalent components of S and ScS. In reality the relation between this difference and the errors is obscure: the difference can be small because the noise and the effect of the errors (both large) cancel each other. Moreover, this difference is often not so much an effect of the noise as of a deviation of the model (very simple) from the real earth's medium (very complicated). In the work of WBK additional errors are introduced by the implicitly assumed linearity of S and ScS particle motions in isotropic earth, which is not necessarily true for large earthquakes. To summarize, the accuracy thus evaluated is doubtful.

[5] We prefer a method [*Dricker et al.*, 2002], which is based on the technique by *Tarantola and Valette* [1982] for determining probability distribution functions (PDFs) for multivariate inverse problems. The most credible indicator of accuracy is the scatter of the estimates of the model parameters for different events, and in this method the differences between the solutions for different events are explicitly taken into account in the estimates of accuracy. Assuming that theoretical and observational errors are gaussian, an a posteriori PDF is determined as

$$\sigma(\alpha, \delta t) = \rho(\alpha, \delta t) exp\left[-0.5 D^T (C_t + C_T)^{-1} D\right]$$

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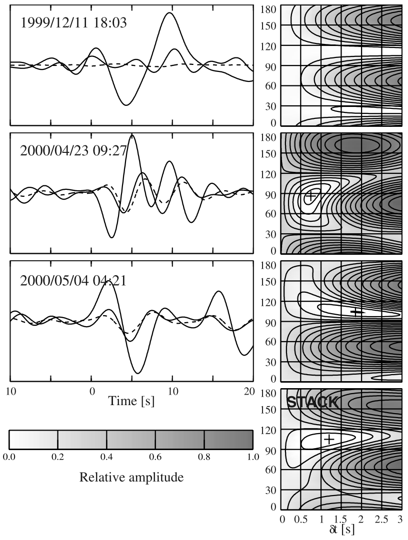

Figure 1. Left column: horizontal components of SKS phase. R and T components of SKS are shown by thin and bold lines, respectively. Dash line is for the synthetic T component for the solution given by combined processing. The corresponding diagrams of e(α, δt) are shown in the right column. The diagram at the bottom is a result of the combined processing of the three recordings. Minima corresponding to the optimum solutions are marked by crosses. The scale bar for the diagrams is shown on the bottom left.

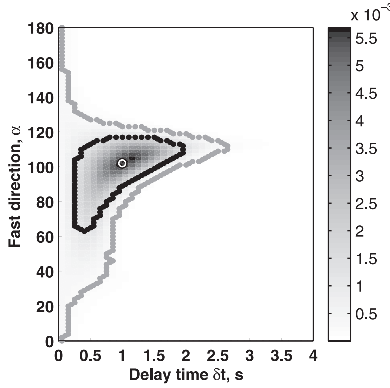

Figure 2. Joint PDF function for recordings in Table 1. Black and grey contours are for 66% and 95% confidence regions.

where D is a vector containing the differences between the computed and the observed T components; C_t is the a priori covariance matrix for observations; C_T is the a priori covariance matrix for theory; ρ is the a priori PDF for α and δt. The joint PDF function for several seismograms is obtained as a product of PDF for individual seismograms. Confidence intervals are defined as the percent volume under the surface described by the PDF. The total uncertainty of one variable can be determined by integration of the PDF over the other variable. In the analysis of data for H2O we assume that a priori all values of α between 0 and 180 deg and those of δt between 0 and 4 s are equally likely, and α and δt are physically uncorrelated. For the events in Table 1 the joint PDF (Figure 2) gives $102 \pm 13.3°$ for α and 1.0 ± 0.4 *s* for δt. The fast direction of about 40° obtained by WBK is hard to reconcile with these data.

[6] Our estimate of the fast direction of anisotropy at H2O with the error bounds taken into account is close to the absolute plate motion direction of 302° [*DeMets et al.*, 1990] (to compare them 180° should be added to α) and thus reveals the same pattern as in the western Pacific. This correlation suggests that anisotropy beneath oceanic basins is dominated by the effect of shear in the sublithospheric mantle, rather than by "fossil" anisotropy in the lithosphere. Surface wave estimates of anisotropy can be translated into the parameters of the shear-wave splitting in SKS [*Montagner et al.*, 2000]. The synthetic SKS parameters at H2O for the model of *Montagner* [2002] are $\alpha_{synth} = 122°$ and $\delta t_{synth} = 0.3s$. Considering their accuracy, both estimates of α are in agreement and incompatible with the estimate given by WBK. Our estimate of the fast direction at H2O, with its accuracy taken into account, is similar to the fast direction reported by WBK for Hawaii, which suggests that the effect of parabolic flow, if present, cannot be recognized in the data.

Table 1. List of Recordings of SKS Phase

No.	d/m/y	lat°	lon°	dis°	baz°	α°	dt(s)
1	11/12/99	15.76	119.74	89.8	288	25,110	-
2	23/04/00	−28.31	−61.99	94.1	120	88	0.8
3	04/05/00	−1.15	123.60	94.4	271	104	1.8

References

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int.*, *101*, 425–478, 1990.
Dricker, I. G., S. W. Roecker, L. P. Vinnik, E. A. Rogozhin, and L. I. Makeyeva, Upper-mantle anisotropy beneath the Altai-Sayan region of central Asia, *Phys. Earth Planet. Int.*, *131*, 205–223, 2002.
Farra, V., and L. Vinnik, Shear-wave splitting in the mantle of the Pacific, *Geophys. J. Int.*, *119*, 195–218, 1994.
Montagner, J.-P., Upper mantle low anisotropy channels below the Pacific plate, *Earth Planet. Sci. Lett.*, *202*, 263–274, 2002.
Montagner, J.-P., D. A. Griot-Pommera, and J. Lave, How to relate body wave and surface wave anisotropy?, *J. Geophys. Res.*, *105*, 19,015–19,027, 2000.
Russo, R. M., and E. A. Okal, Shear wave splitting and upper mantle deformation in French Polynesia: Evidence for small-scale heterogeneity related to the Society hotspot, *J. Geophys. Res.*, *103*, 15,089–15,107, 1998.
Tarantola, A., and B. Valette, Inverse problems—Quest for information, *J. Geophys.*, *50*, 159–170, 1982.
Vinnik, L. P., V. Farra, and B. Romanowicz, Azimuthal anisotropy in the Earth from observations of SKS at Geoscope and NARS broadband stations, *Bull. Seismol. Soc. Am.*, *79*, 1542–1558, 1989.
Walker, K. T., G. H. R. Bokelmann, and S. L. Klemperer, Shear-wave splitting to test mantle deformation models around Hawaii, *Geophys. Res. Lett.*, *28*, 4319–4322, 2001.
Wolfe, C. J., and P. G. Silver, Seismic anisotropy of oceanic upper mantle: Shear wave splitting methodologies and observations, *J. Geophys. Res.*, *103*, 449–777, 1998.

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Reply to "Shear-wave splitting to test mantle deformation models around Hawaii" by Vinnik et al.

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[1] Observations of teleseismic shear-wave splitting from station H2O reported in the Comment from *Vinnik et al.* [2003, hereinafter referred to as VMGDS] show a quite different orientation of the fast azimuth from that we obtained in *Walker et al.* [2001, hereafter referred to as WBK]. We found that azimuth orientations at H2O and JOHN were incorrectly labeled in the waveform headers residing at the archive center. After correcting for this, we recovered a similar station estimate as VMGDS. Additional new events suggest no evidence for two-layer anisotropy beneath either of these stations, despite there being evidence for two-layer anisotropy beneath KIP on Oahu (upper layer parallel to neighboring fracture zone, lower layer parallel to plate motion). A simple pattern of anisotropy emerges in the north-central Pacific that is generally consistent with body-wave and surface-wave anisotropy studies.

[2] VMGDS found a single-layer-anisotropy station estimate fast azimuth $\phi = 102° \pm 13.3°$ and delay time $dt = 1.0 \pm 0.4$ s, which is different from the estimate in WBK ($\phi = 42° \pm 4°$ and $dt = 1.3 \pm 0.2$ s). We investigated the horizontal-component azimuth orientations in the data sets downloaded from the data archive centers and used in WBK for both stations H2O and JOHN. We discovered that most of these azimuths were incorrect. The correct orientations of the horizontal components are HH1 = 258.5°/HH2 = 348.5° for H2O, and BH1 = 75°/BH2 = 165° for JOHN. Due to strict space restrictions, a detailed description of the problem and our analysis is included as supporting material[1]. We conclude that in chronological order for station H2O, the splitting results for the first five events reported in WBK are incorrect, while the sixth event was correct. For JOHN, the two splitting measurements analyzed in WBK are incorrect.

[3] After correcting the azimuths reported in the headers, we reanalyzed all the reported events for H2O and JOHN in WBK using the apparent splitting method of *Silver and Chan* [1991] implemented in an algorithm developed by George Helffrich and revised by Paul Silver, and then stacking the events using the method of *Wolfe and Silver* [1998] implemented in our own code. In addition, we found and analyzed new events for both stations[1]. The new results are: H2O = 103 ± 4°/1.4 ± 0.1 s and JOHN = 103 ± 5°/1.1 ± 0.2 s (Figure 1). Thus anisotropy beneath H2O and JOHN is still very similar, but now is subparallel with the orientation of the plane of Pacific plate motion relative to a fixed hotspot reference frame (~120°; Figure 2) [*Gripp and Gordon*, 1990]. This contradicts our earlier reported station estimates and lithospheric anisotropy interpretation for H2O and JOHN. The revised estimates suggest that anisotropy at H2O and JOHN is related to plate motion.

[4] Our new measurements and station estimates[1] are in agreement with those reported in VMGDS, except that our station estimates have smaller error bars. There are two possible reasons for these smaller error bars: (1) the larger number of events used here, and (2) the difference in the analytical techniques. Included as supporting material due to space restrictions[1], we address the second possibility, but only focus on statistical aspects of the techniques because the splitting results themselves are in agreement.

[5] The corrected data in Figure 2 suggest that mantle anisotropy both around Hawaii and at great distances from it is located in the asthenosphere and perhaps lowermost lithosphere. These fast azimuths are roughly consistent with those predicted from a 3D global surface-wave study [*Montagner and Guillot*, 2000], but the delay times sensed by shear-wave splitting are stronger than those predicted by the surface-wave study. These studies together suggest that the dominant "reference" upper-mantle anisotropy in the north-central Pacific appears to be a result of simple shear between the plate and asthenosphere, an interpretation that also explains some splitting data in the south Pacific [*Farra and Vinnik*, 1994, *Wolfe and Silver*, 1998, *Russo and Okal*, 1998], but not necessarily in the western Pacific where fast directions are apparently 80° [*Farra and Vinnik*, 1994], a deviation of 40° from absolute plate motion. The revisions to our previous station estimates for H2O and JOHN do not change our preferred interpretation of mantle anisotropy around Hawaii, where it may be perturbed by (1) the plume as suggested by the good fit of the station estimates around Hawaii to the flowlines from a parabolic asthenospheric flow model (Figure 2), and (2) the Molokai fracture zone near station KIP, a station that requires a two-layer anisotropy model to explain the many observations of teleseismic shear-wave splitting recorded there.

[1] Supporting material is available at ftp://agu.org, directory "apend" (Username = "anonymous," Password = "guest"); subdirectories in the FTP site are arranged by paper number. See also http://www.agu.org/pubs/esupp_about.html.

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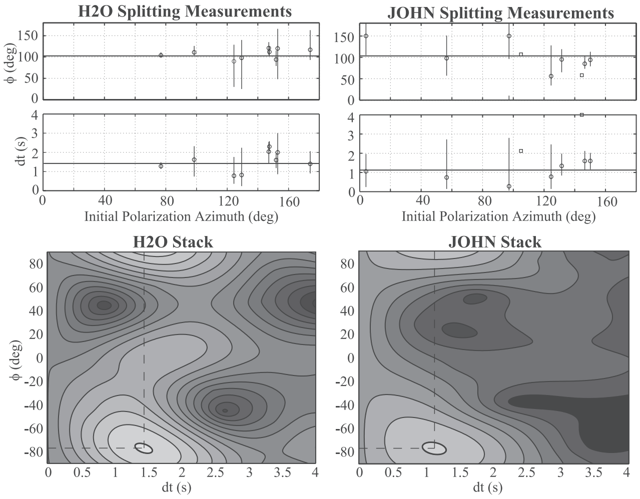

Figure 1. Corrected apparent splitting measurements as a function of initial polarization azimuth for stations H2O and JOHN. Circles represent constrained measurements, and vertical lines are the associated 2σ bars. Squares indicate null measurements. Both stations have measurements that are consistent with a single-layer anisotropy model with a horizontal fast axis. As such, we stack the measurements following the method of *Wolfe and Silver* [1998], and find that both station estimates are almost identical within errors (the 95% confidence contour is bold).

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References

Farra, V., and L. Vinnik, Shear-wave splitting in the mantle of the Pacific, *Geophys. J. Int.*, *119*, 195–218, 1994.

Gripp, A. E., and R. G. Gordon, Current plate motions relative to the hotspots incorporating the NUVEL-1 plate motion model, *Geophys. Res. Lett.*, *17*, 1109–1112, 1990.

Montagner, J. P., and L. Guillot, Seismic anisotropy in the Earth's Mantle, *Problems in Geophysics for the Next Millenium*, Erice, July, 7–16 , 1999, 2000.

Russo, R. M., and E. A. Okal, Shear-wave splitting and upper mantle deformation in French Polynesia: Evidence for small-scale heterogeneity related to the Society hotspot, *J. Geophys. Res.*, *103*, 15,089–15,107, 1998.

Silver, P. G., and W. W. Chan, Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, *96*, 16,429–16,454, 1991.

Walker, K. T., G. H. R. Bokelmann, and Klemperer, Shear-wave splitting to test mantle deformation models around Hawaii, *Geophys. Res. Lett.*, *28*, 4319–4322, 2001.

Wolfe, C. J., and P. G. Silver, Seismic anisotropy of oceanic upper mantle: Shear wave splitting methodologies and observations, *J. Geophys. Res.*, *103*, 449–771, 1998.

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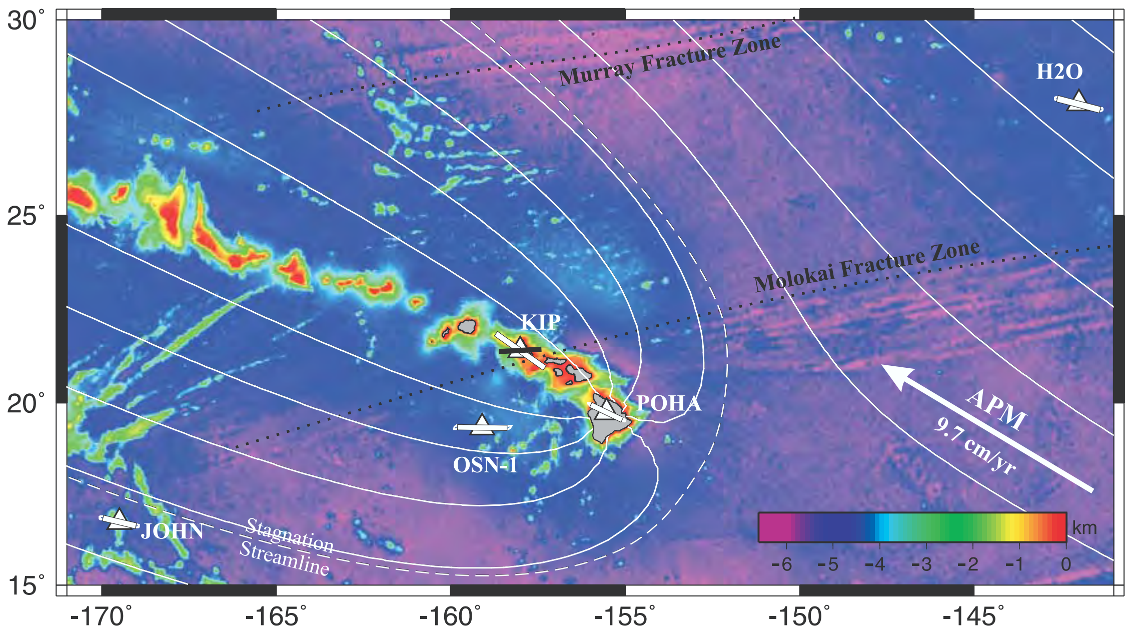

Figure 2. Map of Hawaii and surrounding region showing our corrected shear-wave splitting station estimates for H2O and JOHN. Triangles indicate stations analyzed in *Walker et al.* [2001]. All estimates are plotted as lines with their shade depending on their interpretation (filled = asthenospheric, open = lithospheric), their orientation parallel to fast polarization direction, and length proportional to delay time. 95% confidence regions are plotted at ends of vectors for the single-layer models. The best-fitting parabolic flow model is overlaid. Note the good fit with the fast polarization directions at all stations.