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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

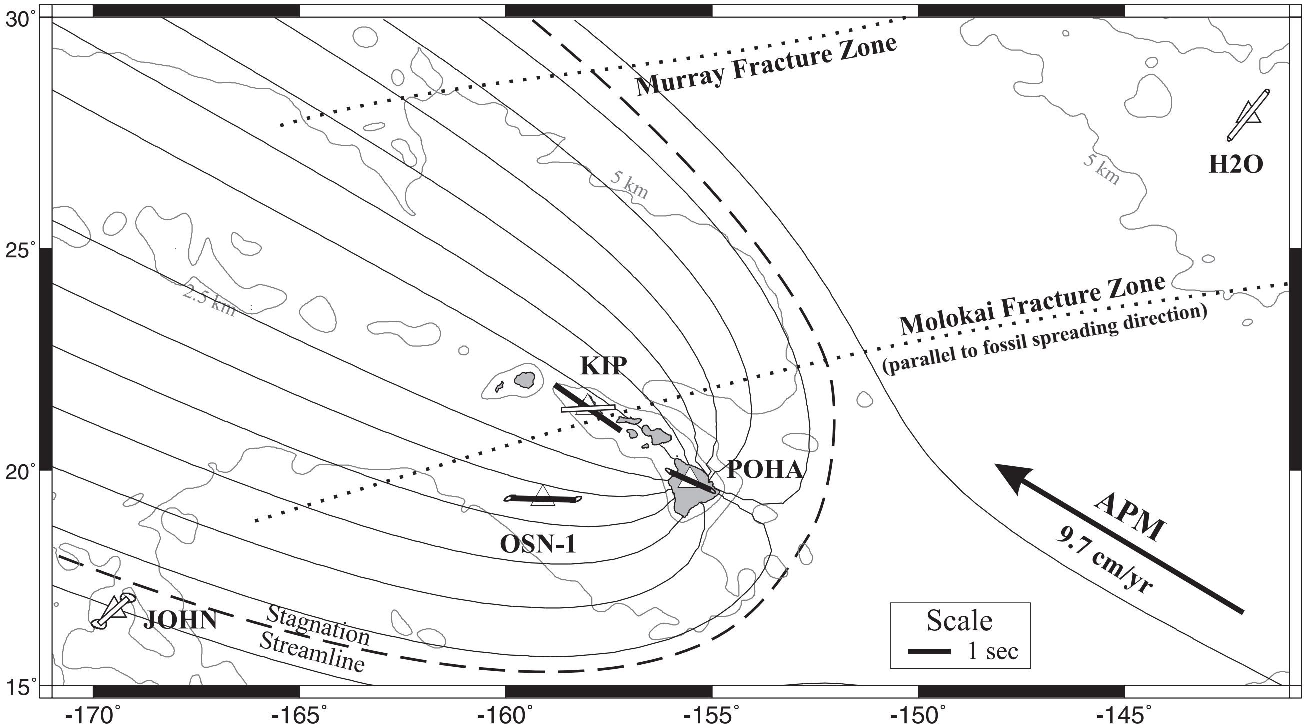

Figure 1. Map of Hawaii and surrounding region. Triangles indicate analyzed stations. Shear-wave splitting estimates are plotted as lines with their orientation parallel to fast polarization direction, and length proportional to delay time. Shade shows their interpreted depth (open=lithospheric, filled=asthenospheric). 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 $\pm 30^o$). 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.

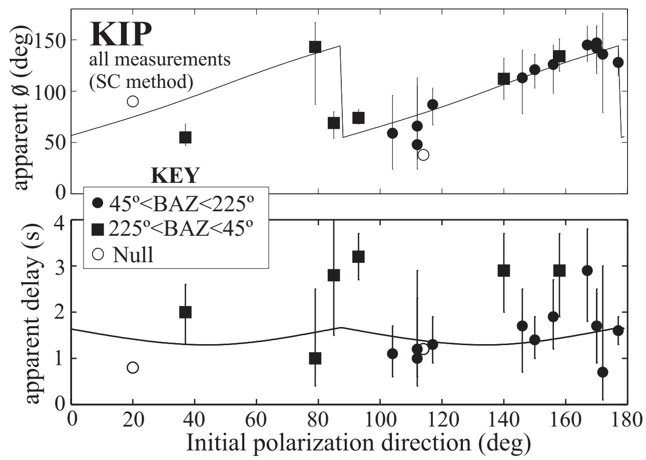

Figure 3. Apparent splitting measurements vs. initial polarization direction for KIP. Error bars indicate constrained measurements. The solid line is the 2-layer model that best predicts the measurements with dt < 2.0 s (R^2=0.74).

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).

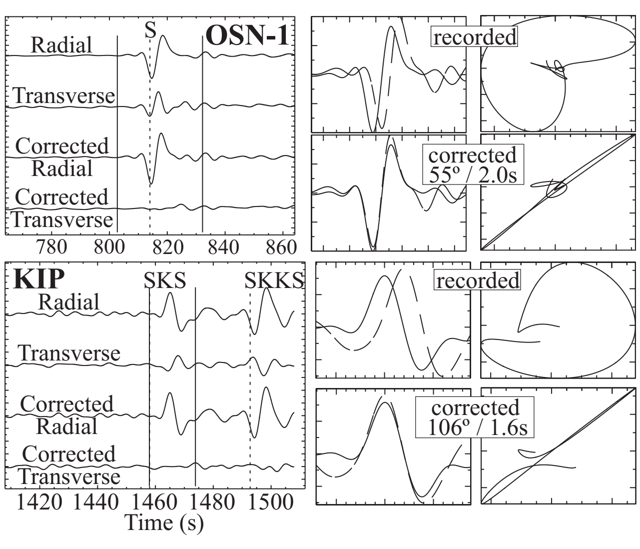

Figure 2. Examples of splitting at OSN-1 (top) and KIP (bottom). From left to right: Original and anisotropy-corrected waveforms on radial and transverse components, fast and slow (f/s) components, and the corresponding f/s particle motion.

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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