Constraints on Upper Mantle Anisotropy Surrounding the Cocos Slab From SK(K)S Splitting

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Abstract

SKS and SKKS splitting observations are used to constrain the pattern of mantle flow in the Central American subduction zone beneath Costa Rica and Nicaragua. After removing the effects of shallow wedge anisotropy on SK(K)S waveforms, a best-fitting model of anisotropy beneath the Cocos Plate and in the deeper mantle wedge is determined. Fast polarization directions and model symmetry axis orientations in both regions (as well as the shallow wedge) are dominated by roughly arc-parallel azimuths and, therefore, are not consistent with sub-lithospheric mantle flow entrained by the subducting Cocos Plate or simple two-dimensional corner flow in the wedge. In conjunction with geochemical data and local-S splitting tomography, the SK(K)S splitting observations and anisotropy models are consistent with flow to the WNW within the mantle wedge on the Caribbean side of the Cocos Plate, possibly drawn through a slab window beneath Panama and southern Costa Rica. Anisotropy in the Pacific mantle beneath the Cocos Plate is also best explained by flow with a component that is roughly parallel to the strike of the slab, although the absolute direction of this flow is not uniquely constrained.
1. Introduction

The preferential alignment of olivine and orthopyroxene (opx) during deformation is often considered to be the dominant source of seismic anisotropy observed in the upper mantle, and shear-wave splitting is one of the most widely used tools for investigating anisotropy in the mantle beneath subduction zones [e.g., Russo and Silver, 1994; Fouch and Fischer, 1996; Smith et al., 2001; Anderson et al., 2004; Levin et al., 2004; Long and van der Hilst, 2005; Pozgay et al., 2007; Greve et al., 2008; Long and Silver, 2008]. By assuming a relationship between the direction of deformation, or flow, and the lattice-preferred orientation (LPO) of these minerals, shear-wave splitting parameters (i.e., fast polarization direction, φ, and delay time, dt) can be used to infer the pattern of flow in the upper mantle [e.g., Silver and Chan, 1991; Mainprice and Silver, 1993; Savage, 1999; Long and Silver, 2008].

Outside of the mantle wedge region in subduction zones, pressures and temperatures in the sub-lithospheric upper mantle are likely to be such that dislocation creep in olivine is the dominant deformation mechanism, and under these conditions the [100]-axis (or a-axis) of olivine is expected to align roughly parallel to the direction of flow during simple shear (e.g., rigid lithosphere driving deformation in the underlying asthenosphere with A-type slip [Zhang and Karato, 1995; Ismaïl and Mainprice, 1998; Mainprice et al., 2000]). Given these assumptions, the fast shear-wave polarization direction in core phases (e.g., PK(K)S, SK(K)S, etc.) with near vertical incidence (5°-15°) is expected to be parallel or sub-parallel to the mantle flow direction. In contrast, within the mantle wedge, the presence of additional water [Jung and Karato, 2001; Jung et al., 2006; Katayama and Karato, 2006; Jacobsen et al., 2008] and melt [Holtzman et al., 2003] and the likelihood of three-dimensional flow patterns [e.g. Kincaid and
Griffiths, 2003; Funiciello et al., 2006; Kneller and van Keken, 2008] complicate the interpretation of shear-wave splitting.

Anisotropy within the mantle wedge beneath Costa Rica and Nicaragua has previously been investigated from shear-wave splitting in local-S waves [Abt et al., 2009]. The highly variable local-S fast directions (Fig. 1) made a direct interpretation in terms of flow difficult, and they were instead utilized in an inversion for anisotropic structure in the mantle wedge [Abt and Fischer, 2008; Abt et al., 2009]. The resulting model displayed a predominance of arc-parallel olivine $a$-axes throughout the mantle wedge and not only in the extreme wedge corner or beneath the volcanic arc where B-type fabric [Jung and Karato, 2001; Kneller et al., 2005] and melt bands [Holtzman et al., 2003], respectively, might affect fabric development and lead to a different relationship between flow direction and olivine $a$-axis orientation. Combined with Pb and Nd isotope data, the best interpretation of the local-S splitting and anisotropy model is that roughly horizontal along-arc flow to the northwest exists in the shallow (<200 km) mantle wedge [Hoernle et al., 2008; Abt et al., 2009].

Along-arc flow in the mantle wedge is not consistent with the standard two-dimensional (2-D) corner flow expected to be present here in Central America given the relatively planar shape (5$^\circ$-15$^\circ$ change in dip over ~400 km along-strike [Protti et al., 1994; Husen et al., 2003; Syracuse and Abers, 2006]) and nearly orthogonal convergence (7$^\circ$ in central Costa Rica, 17$^\circ$ in Nicaragua [Barckhausen et al., 2001; DeMets, 2001]) of the Cocos Plate beneath the Caribbean Plate. A combination of trench motion, slab edge effects, and possible slab-wedge decoupling was suggested as a means of generating this arc-parallel flow [Hoernle et al., 2008; Abt et al., 2009]. However, due to the limited depth of local events (<200 km) and lateral extent of the seismic array used (Fig. 1), a first-order question left unanswered by the local-S splitting study is
whether or not this counter-intuitive pattern of arc-parallel anisotropy exists beyond the shallow mantle wedge. If it is confined to the shallow wedge and the mantle at greater depth possesses a more arc-normal orientation of anisotropy (i.e., that predicted for 2-D corner flow), then it is likely either that the deeper wedge becomes recoupled to the downgoing slab or that the source of shallow arc-parallel anisotropy is not simply mantle flow (e.g., B-type fabric, aligned melt, crustal anisotropy, or some combination of these). On the other hand, pervasive arc-parallel anisotropy throughout the upper mantle would support models in which other drivers of flow (e.g., trench roll-back near a slab edge [Buttles and Olsen, 1998; Kincaid and Griffiths, 2003, 2004; Funiciello et al., 2006; Schellart et al., 2007; Honda, 2009] or global convection patterns [e.g., Conrad et al., 2007]) are locally more influential than down-dip motion of the subducting Cocos Plate.

Here we present SKS and SKKS splitting measurements from Costa Rica, Nicaragua and Honduras that complement the local-S data and help constrain the orientation of flow both deeper in the back-arc wedge and beneath the Cocos Plate. In addition, after taking into account the local-S model of anisotropy [Abt et al., 2009], we calculate a best-fitting crystallographic orientation for both the sub-slab and deeper wedge and find that each region likely contains anisotropy characterized by shallowly dipping, roughly arc-parallel olivine $a$-axes (from here on, referred to as the symmetry axis, given that we will assume hexagonal crystallographic symmetry). This result suggests arc-parallel flow is indeed the most probable source for anisotropy in the shallow wedge imaged by local-S splitting tomography, as well as in the deeper wedge and sub-slab mantle.
2. **SK(K)S Splitting**

2.1. **Calculation of Splitting Parameters**

Shear-wave splitting parameters ($\phi, dt$) are calculated here from the SV and SH components of motion using an eigenvalue minimization technique [Silver and Chan, 1991]. A zero-phase, bandpass filter of 0.05-0.2 Hz (periods of 5-20 sec) is first applied to the raw waveforms, the Z-N-E components are then rotated into Z-R-T, and finally the waveforms are transformed into the P-SV-SH coordinate system by correcting for the effects of the free surface [Kennett, 1991] assuming a surface $V_p$ and $V_s$ of 5.9 km/s and 3.41 km/s, respectively. Ray paths are traced through the 1-D reference Earth model AK135 [Kennett et al., 1995]. While splitting measurements are typically made on the horizontal components of motion (i.e., N-E or R-T [e.g., Silver and Chan, 1991; Fouch and Fischer, 1996; Savage, 1999]), with fast polarization direction measured in degrees east of north, fast directions here are measured clockwise from SV in the SV-SH plane (Fig. 2). Although the difference between the splitting parameters measured in these two coordinate systems is generally minimal (Fig. 3) given the sub-vertical incidence angle of most SK(K)S waves, we choose to use the splitting measurements made from the SV-SH components and not those from the projected N-E, or R-T, components. The window used for analysis is manually chosen and typically includes 20-30 seconds prior to and at least 1.5-2 periods after the phase arrival. Error bars ($\sigma_{\phi, dt}$) are the standard splitting parameter errors given by the maximum distance from the best-fitting $\phi$ and $dt$ to the 95% confidence contour of the $\lambda_2$ surface (e.g., Fig. 3c,f; also see Abt and Fischer [2008]).
2.2. Observations

Our data were recorded by the Tomography Under Costa Rica and Nicaragua (TUCAN) seismic array, a temporary network of 48 broadband seismic stations deployed from July 2004 to March 2006, as well as four permanent stations: BOA (INETER and GEOFON, Program of GFZ Potsdam), HDC (OVSICORI and GEOSCOPE, Institut de Physique du Globe), JTS (OVSICORI and IRIS - Scripps Institute of Oceanography), and TGUH (Caribbean Network, USGS). More than 1900 waveforms from events with magnitude $\geq 6.5$ and epicentral distance between 85° and 170° were visually inspected for clear SKS and SKKS arrivals, and of these, more than 900 were analyzed with the method described above in Section 2.1, resulting in 103 “high quality” splitting measurements (Fig. 1, Table 1). We use four basic criteria for assessing the quality of splitting measurements (as in Abt et al. [2009]): a “high quality” (i.e., interpretable) measurement will (1) possess a clear phase arrival with a high signal-to-noise ratio, (2) display elliptical or circular particle motion, (3) have a single, elliptical 95% contour, and (4) return roughly linear particle motion with dominantly SV energy when the waveforms are corrected for the best-fitting pair of splitting parameters. Although we do not use strict limits on the size of the 95% confidence region, only 3 of the 103 splits presented here have a fast direction error of $>30^\circ$ and 19 have a delay time error $>0.6$ sec (Table 1).

In contrast to the relatively complicated pattern of local-S fast directions [Abt et al., 2009], the teleseismic SK(K)S fast directions observed here are more consistently arc-parallel and sub-arc-parallel (Figs. 1,4,5). SK(K)S delay times (1-3 sec) are also generally much larger than those of local-S (0.1-0.6 sec), indicating a significant amount of anisotropy outside the shallow wedge and upper plate volumes sampled by local-S waves. The azimuthal distribution of events from the splitting measurements is neither uniform nor complete (Fig 5). In addition, one set of ray
paths primarily sample the mantle beneath the subducting Cocos Plate (i.e., Pacific) and another set primarily samples the wedge-side (i.e., Caribbean) mantle (Figs. 5,6; Table 2); note that here and in the modeling (Section 3) we do not include the ray paths and splits to station TGUH because they fall further outside the local-S model space. We find a relatively small difference in splitting parameters (on average, 5° in \( \phi \) and 0.30 sec, or 15%, in \( dt \)) between Caribbean and Pacific rays (Fig. 7); the mean \( \phi \) and \( dt \) of the 66 (27) splits from the Caribbean (Pacific) side are -69° (-74°) and 1.95 sec (1.65 sec).

Qualitatively, the consistency in SK(K)S fast directions suggests a similar orientation of anisotropy in both Pacific mantle beneath the Cocos Plate and Caribbean mantle on the wedge side of the Cocos Plate (e.g., ~arc-parallel symmetry axes). The slight difference in average delay time between waves sampling the two mantle regions could be attributed to differing path lengths through a shallow mantle wedge that possesses a higher degree of anisotropy than the sub-slab or deeper (>200 km) wedge mantle; rays on the Caribbean side generally have a greater fraction of their path within the shallow wedge (Fig. 6). On the other hand, the difference in \( dt \) could also indicate a difference in the strength and/or orientation of anisotropy outside the mantle wedge between the two regions. For example, the predicted strength of anisotropy in a 70% olivine, 30% orthopyroxene aggregate (assuming hexagonal symmetry) for sub-vertical (10° incidence angle) ray propagation decreases from ~8.5% to ~1% as the symmetry axis rotates from horizontal to vertical (Suppl. Fig. S1). To more quantitatively characterize anisotropy, in the following section, we use the local-S splitting tomography model to remove the effects of anisotropy in the shallow wedge on SK(K)S waveforms and calculate best-fitting models of anisotropy in these two mantle regions.
Several studies have documented differences in splitting between SKS and SKKS phases and have attributed them to anisotropy in the deep lower mantle, the core-mantle boundary region in particular [Niu and Perez, 2004; Restivo and Helffrich, 2006; Long, 2009]. In our dataset, differences between SKS and SKKS splitting parameters for common source receiver pairs are very slight. Of the nine cases for which well-resolved SKS and SKKS splitting parameters were obtained for the same source and receiver, five agreed within the confidence limits of the measurements. In three of the other four cases, differences in fast direction exceeded the uncertainties by only 5° or less, and in two cases differences in splitting time exceeded uncertainties by 0.43 s or less. For events at back-azimuths of 321°-324° and distances of 107°-112°, SKKS fast directions tend to be rotated slightly counter-clockwise from SKS fast directions. However, as described above, this trend is not well-resolved at 95% confidence. Therefore, we jointly model the SKS and SKKS splitting in terms of upper mantle anisotropy beneath the TUCAN stations.

3. Sub-slab and Deep Back-arc Anisotropy

3.1. Incorporation of Local-S Splitting Tomography Model

Given the model of anisotropy (i.e., crystallographic orientation and strength of anisotropy) in the shallow (<200 km) mantle wedge determined from local-S splitting tomography [Abt et al., 2009] we can correct for the predicted birefringence that would be accrued by SK(K)S phases during passage through this region. To accomplish this, the observed SK(K)S waveforms from all stations (except TGUH, which lies outside the local-S model region) were progressively
rotated and time-shifted according to the polarization directions (eigenvectors) and phase
velocities (eigenvalues) from the Christoffel matrix \( m_{ik} \) for each well-resolved block touched in
the local-S model

\[
m_{ik} = \frac{1}{\rho(z)} \cdot c_{ijkl}(z) \cdot \hat{n}_j \hat{n}_l
\]

where \( \rho \) is density and a function of depth \( z \) (i.e., pressure and temperature), \( c_{ijkl} \) is the elastic
stiffness tensor of an olivine-opx crystal (also a function of \( P \) and \( T \); Suppl. Table S1), and \( \hat{n} \) is
ray propagation direction [e.g., Babuska and Cara, 1991]. This method is nearly identical to the
forward calculation of predicted splitting utilized in the local-S inversion [Abt and Fischer, 2008;
Abt et al., 2009] except that here we (1) apply the time-shift in the reverse order (i.e., the fast and
slow components are shifted backward and forward in time, respectively) and (2) are working
with real waveforms and not synthetic wavelets. Abt et al. [2009] contains a complete
description of the wedge anisotropy model, including block dimensions and model resolution.

Splitting parameters calculated from the resulting “backed-out” waveforms (e.g., Fig. 8)
provide us with a means of constraining the orientation and strength of anisotropy in the mantle
outside the portion of the wedge sampled by local-S waves (i.e., further and deeper into the back-
arc wedge and beneath the subducting slab). An assumption of the maximum depth of
anisotropy, somewhere between the core-mantle boundary and the surface, must be made, and
here we choose this depth to be the top of the transition zone at 410 km. Comparisons of shear-
wave splitting between deep-focus earthquakes and SKS phases show that in general almost no
splitting occurs on sub-vertical paths in the transition zone and lower mantle, although transition
zone splitting does appear to occur in isolated regions [Fischer and Wiens, 1996; Fouch and
Fischer, 1996]. Decreasing (increasing) the anisotropy cut-off depth in our models would
simply increase (decrease) the strength of anisotropy inferred from the corrected SK(K)S
splitting measurements. We assume the same elastic constants used in the local-S model (i.e., 70% olivine [Anderson and Isaak, 1995; Abramson et al., 1997] and 30% opx [Frisillo and Barsch, 1972] with hexagonal symmetry and the olivine $a$-axis as the symmetry axis; Suppl. Table S1).

This approach assumes SK(K)S waves, which have dominant frequencies of 0.05-0.1 Hz (wavelengths of ~50-100 km), are affected by mantle wedge anisotropy in the same manner as local-S waves, with dominant frequencies of 0.5-1 Hz (wavelengths of ~5-10 km). If anisotropy in the shallow wedge, as sampled and imaged by local-S waves, is the result of structure (e.g., LPO, aligned melt) that varies with a length scale greater than local-S wavelengths but less than SK(K)S wavelengths, then SK(K)S waves would effectively sense an average of the finer-scale anisotropic structure in the local-S model. The local-S model was parameterized with $25^3$ km$^3$ blocks, and individual blocks in the back-arc regions of the model were combined into larger volumes (50 km vertically by up to 100 km laterally). Consequently, SK(K)S waves might be expected to smooth/average the anisotropy in regions of the local-S model beneath the arc and fore-arc. SK(K)S path lengths through the local-S model and subsequent delay times accrued by SK(K)S waves are generally small; on average, the delay times from the backed-out splits differ from those observed at the surface by only 0.12 sec (min=-0.62 sec, max=0.5 sec). Therefore, accounting for finite SK(K)S wavelengths in the local-S model would not likely dramatically change the resulting anisotropy models calculated here.

3.2. Best-Fitting Models of Crystallographic Orientation

The number of SK(K)S splitting measurements (93 to TUCAN stations) is almost an order of magnitude smaller than for local-S (791), and both the distribution of events for the SK(K)S
measurements and their near-vertical incidence result in very few crossing ray paths (Fig. 6), unlike with local-S ray paths (see Fig. 7 in Abt et al. [2009]). Therefore, we do not attempt to tomographically invert for crystallographic orientation using the backed-out SK(K)S waveforms. Instead, we simply conduct a grid-search over all possible symmetry axis orientations and strengths of anisotropy (Fig. 9). We search symmetry axis azimuths ($\theta$) from -180° to 180° at 10° increments, symmetry axis dips ($\psi$) from 0° to 90° at 10° increments, and anisotropy strengths ($\alpha$) from 0% to 100% at 10% increments.

For each SK(K)S ray path, a synthetic wavelet with random noise and a signal-to-noise ratio of 10 (typical for our observed SK(K)S waves) is set as the SV component of motion (SH is random noise) at 410 km and propagated up through the model (blocks 25 km on each side) until reaching the local-S model space (thick black line in Figure 6). Splitting of the resulting synthetic wavelet is calculated at this entry point in the local-S model in the same manner as with the real data and then compared with the observed backed-out splitting measurement from the corresponding ray. The weighted misfits for fast direction ($\varepsilon_{\phi}$) and delay time ($\varepsilon_{dt}$) from $N$ splitting measurements are

$$
\varepsilon_{\phi,dt} = \frac{\sum_{i=1}^{N} \left( \phi_i dt_i^{obs} - \phi_i dt_i^{pred} \right) \left( \frac{\sigma_{\phi,dt_i}^{obs} + \sigma_{\phi,dt_i}^{pred}}{2} \right)^{-1}}{\sum_{i=1}^{N} \left( \frac{\sigma_{\phi,dt_i}^{obs} + \sigma_{\phi,dt_i}^{pred}}{2} \right)^{-1}},
$$

where $\sigma_{\phi,dt_i}^{obs}$ and $\sigma_{\phi,dt_i}^{pred}$ are the half-width of the 95% confidence region for the observed backed-out and synthetic splitting parameters, respectively, at the entry point in the local-S model. The fast direction and splitting time misfits are then normalized by their maximum respective value, and the average of the two yields a combined measure of misfit for a particular set of model parameters ($\alpha, \theta, \psi$),
The resulting misfit volumes are presented as “slices” through the normalized misfit minimum (Fig. 9g) for both the Caribbean (Fig. 9a-c) and Pacific mantle (Fig. 9d-f). The 95% confidence limits for the best-fitting combination of model parameters for each region were calculated using a bootstrap approach and are shown by the yellow shading around the best-fitting model parameters (Fig. 9). Because splitting is dependent on the relationship between crystallographic orientation and ray propagation direction (as well as initial polarization), some combinations of ray paths and model parameters will result in unstable or null measurements. We characterized null measurements in the synthetic waveforms by fast direction errors of >70° and delay time errors of >75% of $dt$, and experimented with different approaches for treating null measurements in the misfit calculation. In the misfit results presented in Figure 9, paths where a given model predicts a null measurement are excluded for that model in the weighted misfit calculation. In addition, if more than 50% of the ray paths from a region for a combination of model parameters result in null measurements, then we consider that model to be unacceptable. These cases most often occur for small strengths of anisotropy (e.g., small values of $\alpha$ and/or larger values of $\psi$) and for azimuths roughly parallel or perpendicular to the ray paths. The result of excluding these sets of model parameters is the appearance of “holes” in the misfit volume (gray regions in Fig. 9a-f). For the best-fitting Caribbean model parameters, no measurements were excluded for unstable/null-like behavior, while only two were excluded for the best-fitting Pacific model. Misfits were also calculated including these predicted null measurements are their associated errors, and the resulting range of model parameters deemed to provide acceptable fits to the data are similar to those shown in Figure 9.
As expected, given the coherent arc-parallel pattern of SK(K)S fast directions (Figs. 1,4,5,7), the best-fitting symmetry axis azimuth for both regions is roughly arc-parallel: \( \theta = -70^\circ \) for the Caribbean mantle, and \( \theta = -80^\circ \) for the Pacific mantle. The 95% confidence regions indicate that \( \theta \) is relatively well-constrained, with uncertainties of less than 20\(^\circ\). In contrast, much larger trade-offs exist between the dip and strength of anisotropy. The best-fitting models show only minor differences between the two regions: \( \psi = 30^\circ \) and \( \alpha = 30\% \) for the Caribbean mantle, and \( \psi = 10^\circ \) and \( \alpha = 20\% \) for the Pacific mantle. These best-fitting symmetry axes are dipping slightly towards the west-northwest, very similar to the relatively horizontal and dominantly arc-parallel symmetry axes imaged in the shallow wedge by local-S splitting tomography [Abt et al., 2009]. However, for the Caribbean mantle, the 95% confidence region around the best-fitting model encompasses dip and strength parameters from \( \psi=10^\circ, \alpha=20\% \) to \( \psi=80^\circ, \alpha=80\% \), and shallow and steep dips also provide acceptable fits to the Pacific data (Fig. 9e). This particular trade-off between strength and dip is expected given the decrease in anisotropy sampled by near-vertical shear phases as the fast symmetry axis of the elastic coefficients rotates from horizontal to vertical (Suppl. Fig. S1).

4. Implications for Mantle Flow

Assuming the origin of observed anisotropy is A-type dislocation creep in olivine [e.g., Zhang and Karato, 1995], the best-fitting symmetry axis orientations and their 95% confidence limits (Fig. 9) indicate that a component of horizontal flow in the along-arc direction occurs in the Caribbean mantle beneath southeastern Central America, and that such flow is also likely, although not technically required, on the Pacific side of the subducting Cocos plate. In both mantle regions, the best-fitting model parameters suggest a relatively large component of along-
arc flow that results in a fast symmetry axis that is aligned roughly parallel to the arc with a shallow dip (≈30° for the Caribbean mantle, ≈10° for the Pacific mantle). Taking the 95% confidence limits of the best-fitting model parameters into account, both shallower and steeper dips are acceptable for the Caribbean mantle. Although a steeper dip could imply a smaller component of horizontal flow, because the azimuth of the fast symmetry axis remains parallel to the arc as dip increases and the dip never reaches 90°, some flow parallel to the slab/arc is still required. In addition, the steepest possible fast symmetry axes (≈80°) are unlikely because they would imply an 80% alignment of olivine grains. This strength of olivine fabric is not typically observed in naturally or experimentally deformed samples [Zhang and Karato, 1995; Mainprice et al., 2000; Jung et al., 2006]. On the Pacific side, along-arc flow is not technically required because the 95% confidence limits overlap cases with a vertical fast symmetry axis. However, exactly vertical $a$-axes would be an unlikely scenario, given that the dip of the slab does not exceed 70° at depths of 200 km or less [Syracuse et al., 2008] and remains non-vertical into the lower mantle [Ren et al., 2007]. In the more likely case that the fast symmetry axis has a dip of less than 90°, some component of along-arc flow would be required to produce the range of fast symmetry axis azimuths. Thus, in the Caribbean mantle, the observed splitting and the acceptable range of anisotropy models rule out purely arc-normal flow as would be predicted by simple entrainment of mantle by the slab; in the Pacific mantle, purely arc-normal flow is unlikely.

Some recent studies have proposed that the arc-parallel shear-wave splitting common to stations in subduction zone arc and near-arc settings may be largely explained by very strong anisotropy due to hydrous phases (such as serpentine) on faults within the subducting slab [Faccenda et al., 2008, 2009; Healy et al., 2009]. However, this mechanism does not appear to
strongly influence the SK(K)S splitting modeled in this study. First, its effects are not evident in
the local S splitting recorded at TUCAN stations [Abt et al., 2009]. Because faulting is thought
to penetrate into the top of slab by no more than 20-30 km [Faccenda et al., 2009], the
associated anisotropy would need to be very large in order to match SK(K)S splitting times
typical of the TUCAN stations or splitting in other subduction zones (1-3 s) [Faccenda et al.,
2008; Healy et al., 2009]. Although the ray angles of the local S phases recorded by the TUCAN
stations are more variable than those of the SK(K)S phases, a highly anisotropic layer in the
upper slab would still produce significant splitting in local S phases, particularly in Nicaragua
where relocated hypocenters [Syracuse et al., 2008] are distributed through the upper 20 km of
the slab. Although anisotropy in the slab was not isolated in the local-S tomography, if strong
slab anisotropy did exist, its effects should be reflected in the local-S model. However, the local-
S model blocks nearest the slab do not manifest particularly large anisotropy [Abt et al., 2009].
In addition, averaged local-S splitting times systematically increase with the path length,
pointing to the mantle wedge (not the upper slab) as the dominant source of anisotropy [Abt et
al., 2009]. Nonetheless, systematic modeling of local-S splitting to bound the strength of
anisotropy in the upper slab would be an interesting future study. A second point is that the
SK(K)S splitting observations modeled in this study have been corrected for the anisotropy
model based on local-S tomography. Therefore, they should be largely free of the effects of slab
anisotropy down to the depths of the local-S events (~10 km into the slab in Costa Rica and ~20
km into the slab in Nicaragua) with the caveat that SK(K)S and local-S incidence angles are not
everywhere identical.

Previous studies provide a broader context for the Central American anisotropy models
presented here. Russo and Silver [1994] hypothesized that teleseismic-S and SKS arc-parallel
fast polarization directions along the Andean margin are the result of roll-back of the Nazca Plate forcing Pacific mantle to the north and south of where flat-slab subduction is occurring (orange arrows in Figure 10). Subsequent splitting observations in the Caribbean and Scotia Seas [Russo et al., 1996, Müller et al., 2008; Piñero-Feliciangeli and Kendall, 2008; Growdon et al., 2009] indicate this flow likely wraps around the edges of the Nazca Plate (empty dashed arrow in Figure 10), a pattern consistent with the Caribbean and Scotia Plates being driven eastward relative to South America as the Pacific mantle shrinks and the Atlantic/Caribbean mantle grows [e.g., Elsasser, 1971; Alvarez, 1982; Garfunkel et al., 1986]. The tectonic feature allowing mantle to flow north from the Pacific realm into the Caribbean and often invoked to explain geochemical and seismological observations [e.g., Herrstrom et al., 1995; Johnston and Thorkelson, 1997; Sallarès et al., 2000; Abratis and Wörner, 2001] is generally thought to be a young (<10 Ma) slab window beneath southern Costa Rica, Panama, and northwestern Colombia, separating the Cocos and Nazca plates (Fig. 10b). Global isotropic velocity tomography models [e.g., Li et al., 2008 (Vp); Ritsema et al., 2004 (Vs)] may also indicate the absence of the Cocos Plate in this same region; the models lack clear evidence of high velocity anomalies in the upper mantle beneath southeastern Central America, as would be expected with the presence of a relatively cold slab.

Mantle flow to the north through a slab window and into the mantle wedge beneath Costa Rica and Nicaragua is consistent with the local-S splitting tomography model as well as trends in Pb and Nd isotope ratios that imply a northwest direction of wedge flow [Hoernle et al., 2008; Abt et al., 2009]. This interpretation could also be used to explain the deeper wedge anisotropy constrained by SK(K)S waves on the Caribbean side of the Cocos Plate (Fig. 6). Beneath the Cocos Plate, the Pacific SK(K)S splitting observations (Figs. 5-7) and corresponding model of
anisotropy (Fig. 9d-f) imply flow roughly parallel to slab strike, but the direction of flow (west-northwest versus east-southeast) is not observationally constrained.

Although these hypothesized flow patterns are based on observed shear-wave splitting and, in some cases, geochemical data, the physical drivers of such flow have not yet been fully demonstrated, but neither has such flow been shown to be implausible. In either the Indo-Atlantic hotspot reference frame [DeMets et al., 1994; O’Neill et al., 2005] (corresponding to the plate and trench motions in Figure 10) or the Pacific hotspot reference frame [Gripp and Gordon, 2000], the South American trench (and presumably the Nazca slab) are retreating [Schellart et al., 2007; Schellart et al., 2008]. Slab retreat tends to drive mantle beneath the slab around the slab edge [Battles and Olsen, 1998; Kincaid and Griffiths, 2003; Funiciello et al., 2006; Schellart et al., 2007; Honda, 2009]. While it is not clear from existing models that sub-slab flow would be strongly aligned with the strike of the slab over the thousands of kilometers, it has been suggested that a low viscosity zone in the mantle just beneath the slab could enhance the development of focused along-arc flow [Long and Silver, 2008, 2009].

In the region sampled in this study, the motions of the Middle America trench and Cocos slab would also play a role in generating and focusing mantle flow. In the Indo-Atlantic plate motion reference frame (Fig. 10), the Middle America trench is retreating at its northern end and advancing in the south, while in the Pacific reference frame, it is retreating along its entire length [Schellart et al., 2008]. However, regardless of reference frame, a relative increase in southwestward trench migration occurs along-strike from Costa Rica to southern Mexico, indicating a counter-clockwise rotation of the trench. Crustal compression in Costa Rica and extension in Nicaragua, along with the progressive trenchward migration of the volcanic arc in northern Nicaragua, are consistent with this plate motion model and suggest that this type of
motion has been relatively long-lived (at least since the early Miocene [Weinberg, 1992]). The flow implications of this along-arc variation in trench and slab migration remain to be modeled. However, the trench rotation could draw mantle wedge material to the northwest, particularly if along-arc flow is enhanced by a low viscosity layer in the wedge above the slab, as suggested in Abt et al. [2009]. Sub-slab mantle under these conditions could be driven to the east-southeast (yellow arrows in Figure 10) and possibly entrained with the northward flow of mantle from beneath the Nazca Plate and forced through the slab window.

5. Conclusions

The primary objective of this study was to constrain the orientation of anisotropy outside the shallow mantle wedge beneath Costa Rica and Nicaragua. The observed SK(K)S splitting in the Caribbean (deeper back-arc wedge) and Pacific (sub-slab) mantle is best fit by anisotropy whose fast symmetry axis (i.e., olivine a-axis) has an azimuth roughly parallel to the arc and a shallow dip. In the Caribbean mantle, steeply dipping symmetry axes (up to 80°) are permitted by the modeling confidence limits, but would require an unrealistically strong fabric alignment. In the Pacific mantle, vertical alignment of symmetry axes lies within the modeling confidence limits, but is unlikely given the non-vertical trajectory of the subducting slab. In order to produce the anisotropy that falls within the range of acceptable scenarios, a significant component of along-arc flow is required in the Caribbean mantle and is highly likely in the Pacific mantle.

The anisotropy in the Caribbean mantle combined with isotopic data indicates along-arc flow to the WNW [Hoernle et al., 2008; Abt et al., 2009]. Such flow could originate from a slab window to the southeast beneath southern Costa Rica and Panama, as has been inferred in numerous previous studies [Russo and Silver, 1994; Herrstrom et al., 1995; Johnston and
Flow beneath the Cocos Plate also likely has a component that is roughly parallel to the strike of the slab. In contrast to wedge flow, the absolute direction of sub-slab flow is unconstrained by geochemical data, but sub-slab flow could be driven ESE by along-arc gradients in slab rollback as well as regional trench and plate motions.

**Acknowledgements**

Pedro Pérez, Allan Morales, Catherine Rychert, Ellen Syracuse, Laura MacKenzie, Mariela Salas-de la Cruz, Alexis Walker, Gustavo Reyes and Tim Parker were instrumental in the TUCAN seismic array deployment, maintenance, and demobilization. The IRIS/PASSCAL program provided seismometers for the TUCAN Seismic Experiment. We also thank Heather Ford, McCall Burau, Tina Rau, Andy Nager, and Arjun Kohli for the splitting analysis at station TGUH. This research and the TUCAN Seismic Experiment were supported by the NSF-MARGINS Program through awards OCE-0203607, OCE-0203650, and EAR-0742282.
References


Piñero-Feliciangeli, L. T., and J.-M. Kendall, Sub-slab mantle flow parallel to the Caribbean


Figure/Table Captions

**Figure 1.** Map of SK(K)S and local-S \cite{Abt2009} splitting observations. SK(K)S splitting vectors (green) are plotted at the station where they were measured, while local-S splits are plotted at ray path midpoints. Vector orientation is parallel to fast polarization direction and scaled to delay time (reference $dt$ of 1 and 2 sec are shown in the legend). The color of the local-S vectors indicates azimuth as well and grades from red (arc-parallel) to blue (arc-normal). Black triangles are seismic stations and yellow triangles are arc volcanoes; stations TGUH (splits not included in modeling) and B5 (example split shown in Figs. 3,8) are identified. Cocos Plate motion relative to the Caribbean Plate (black arrow) is from \textit{DeMets} \cite{DeMets2001}. The Panama fracture zone (PFZ) and inferred edge of the Cocos slab \cite[e.g.,][]{Protti1994,Herrstrom1995,Johnston1997} are also shown with the dashed black and gray lines, respectively. The two major differences between the local-S and SK(K)S splitting parameters are readily apparent here: (1) SK(K)S fast directions are much more consistent (arc-parallel) than local-S fast directions, and (2) local-S delay times are generally much smaller than SK(K)S delay times.

**Figure 2.** Schematic illustration of the relationship between the Z-R-T and P-SV-SH coordinate systems. The free-surface transform \cite{Kennett1991} assuming $V_p = 5.9$ km/sec and $V_S = 3.41$ km/sec is used to obtain the P-SV-SH components. We measure fast polarization direction clockwise from SV in the SV-SH plane (the white line represents the splitting vector). Figure 3 shows an example of the (minor) differences in waveforms and associated splitting parameters between the two coordinate systems.
Figure 3. Example splitting parameter calculation in the SV-SH (a-c) and R-T (d-f) planes. The splitting parameters shown in all other figures and referred to throughout the text are those measured in the SV-SH plane. The windowed waveforms used in the calculation are illustrated in (a,d), particle motions are shown in (b,e), and the $\lambda_2$ (see Section 2.1) values are contoured around the best-fitting splitting parameter pair (black dot) in (c,f), with the 95% confidence region shown with the thick black line. The event for this particular example was at a depth of 39 km and produced a very clear sSKS arrival, which was included in the analysis window together with the SKS phase. This secondary phase can be seen on both the waveforms and in the initial particle motion plots (black line in b and c), with its polarity reversed relative to that of the SKS phase. As expected and demonstrated by the linear corrected particle motion (gray line in b and c), the splitting of both phases is well-characterized by the same pair of $\phi$ and $dt$.

Figure 4. Comparison of SK(K)S and local-S splitting parameters. SK(K)S splits are shown in green and local-S splits grade from red (arc-parallel $\phi$) to blue (arc-normal $\phi$). Error bars on both are the standard splitting errors (e.g., measured from the 95% confidence contour in Fig. 3c; see Section 2.1). The approximate strike of the volcanic arc (N55°W) is shown with the black dashed line. As can also be seen in map view (Fig. 1), SK(K)S fast directions do not show the same variability as local-S fast directions, and delay times for SK(K)S are much larger.

Figure 5. SK(K)S splitting parameters plotted radially as a function of back azimuth and delay time. Vector orientation is parallel to fast direction, with up being north. Splits at TUCAN stations from waves that sample predominantly Caribbean mantle are colored blue and those
sampling mostly Pacific mantle are red (see Figure 6 for ray paths). Black vectors are splits at station TGUH. Again, the approximate strike of the arc is shown with the dashed gray line.

**Figure 6.** TUCAN SK(K)S ray paths beneath Costa Rica and Nicaragua and through the local-S splitting tomography model space. Rays are traced through AK135 [Kennett et al., 1995]; blue paths are those dominantly traveling through Caribbean upper mantle (i.e., deeper wedge), and red paths are those dominantly in Pacific mantle (i.e., sub-slab). The limits of the well-resolved model space from local-S tomography are shown with the thick black line. Hypocenters from local-S splits are the green circles, and the remainder of the re-located local event catalog [Syracuse et al., 2008] is shown with smaller black circles.

**Figure 7.** Comparison of splitting parameters from waves sampling Caribbean and Pacific mantle. The mean values for the two regions are shown with the larger cyan circle (Caribbean) and magenta square (Pacific), with the bars representing +/-1 standard deviation. The smaller blue circles and red squares (with standard splitting errors) are the individual splitting parameters for the Caribbean and Pacific paths, respectively. The Pacific splits have a smaller mean $dt$ relative to Caribbean splits (0.30 sec or ~15%) and also display less coherence in both $\phi$ and $dt$.

**Figure 8.** Example of backing out the effects of anisotropy in the local-S splitting tomography model [Abt et al., 2009] on SK(K)S waveforms. The top row is the same as Figure 3a-c, and the bottom row illustrates the waveforms (d), particle motion (e), and best-fitting splitting parameters (f) after accounting for anisotropy in 6 well-resolved local-S blocks over a path length of 127 km (i.e., the expected observation at the entry point in the local-S model).
Although the two sets of waveforms, particle motions, and λ₂ surfaces look almost identical to the eye (due to the relatively long analysis window), the delay time for each is modestly different: 1.76 sec at the local-S model entry point compared with 2.26 sec at the surface (~28% larger at the surface). We use these estimated splitting parameters (bottom row) to establish the orientation of anisotropy outside the shallow mantle wedge.

**Figure 9.** Results of a grid search over symmetry axis azimuth (θ), symmetry axis dip (ψ), and strength of anisotropy (α) for the model of anisotropy that minimizes misfit between predicted splitting parameters and those estimated from waveforms at their entry point in the local-S splitting tomography model (i.e., the shallow mantle wedge). The surfaces in (a-f) are schematically illustrated in (g) relative to the volume of parameter space searched. Note that due to the symmetry of the elastic tensor, we only need to search the lower hemisphere (i.e., dips down from horizontal). The surfaces in (a-c) are contoured at 5% increments between the minimum (0.078) and maximum (0.923) normalized misfit values for the Caribbean mantle splits, and the normalized misfit range for Pacific splits (0.126-0.853) is contoured in (d-f); note that contours between the Caribbean and Pacific plots do not represent exactly the same misfit values. The 95% confidence limits on the best-fitting model parameters from a bootstrap test are shown by the yellow shading. (a,d) show surfaces with a constant strength of anisotropy (the best-fitting α is 30% for the Caribbean mantle and 20% for the Pacific), (b,e) show surfaces with a constant symmetry axis azimuth (the best-fitting θ is -70° for the Caribbean mantle and -80° for the Pacific), and (c,f) show surfaces with a constant symmetry axis dip (the best-fitting ψ is 30° for the Caribbean mantle and 10° for the Pacific). Note the apparent 180° symmetry for θ (i.e., in a,c,d,f); this is a result of the symmetry of the stiffness tensor and is not perfect here.
because of the non-uniform and non-vertical SK(K)S propagation directions. The gray regions show the combinations of model parameters that resulted in more than 50% of the predicted splitting parameter measurements being unstable or null-like. The dashed black line in (a,c,d,f) shows the approximate strike of the arc. The splitting parameter misfits for these best-fitting models are displayed in (h). The mean weighted misfit for Pacific mantle entry point splitting fast directions is greater than that for Caribbean splits (18° vs. 12°). 67% and 83% of fast directions are fit within their 95% confidence limits for the Pacific and Caribbean regions, respectively. Delay times are both under predicted ($dt$ misfit $>0$) and over predicted ($dt$ misfit $<0$), resulting in mean weighted $dt$ misfits of 0.01 and 0.00 sec for the Pacific and Caribbean splits, respectively; the mean weighted $|dt|$ misfits are 1.00 sec and 0.72 sec. 67% and 44% of splitting times are fit within their 95% confidence limits for the Pacific and Caribbean regions, respectively.

**Figure 10.** Regional mantle flow inferred from SK(K)S and local-S splitting observations and modeling. (a) Map view and (b) three-dimensional schematic view looking south-southeast. The large colored arrows illustrate mantle flow, with yellow showing flow beneath the Cocos Plate, orange represents flow beneath the Nazca Plate [Russo and Silver, 1994], and red is flow in the Central American mantle wedge. The empty, dashed arrow is inferred from splitting observations in the Caribbean [e.g., Russo et al., 1994,1996]. The green arrow in (b) illustrates shallow mantle wedge flow imaged by local-S splitting tomography [Abt et al., 2009]. We display the slight dip of inferred sub-slab and deeper wedge flow with the yellow and red arrows in (b), but as discussed in Sections 3.2 and 4, the dip of anisotropy/flow is not uniquely resolved.
Black and blue arrows show plate and trench motions from Schellart et al. [2008] (i.e., DeMets [1994] and O’Neill et al. [2005]); vector lengths indicate velocity. The westward pointing blue arrows on the Andean trench show trench retreat, and the two vectors on the Middle America trench show the along-strike change in motion (i.e., counter-clockwise rotation of the Cocos slab) discussed in Section 4. The East Pacific Rise (EPR) and Cocos Nazca Spreading Center (CNSC) are labeled.

**Table 1.** Observed SK(K)S splitting parameters. Event information for each split can be obtained by associating Event IDs given here with the year, Julian day, and hour in Table 2. Fast directions are measured east of north. Errors (σ_φ and σ_dt) are measured on the 95% confidence contour of the λ_2 surface (e.g., Fig. 3c, Section 2.1).

**Table 2.** SK(K)S event origin times and location information. Back azimuth and distance for all TUCAN splits (#1-93) are measured from a rough estimate of the TUCAN seismic array center: 11.5°N, 85.5°W. For TGUH, the back azimuth and distance are measured from the station.

**Supplementary Figure S1.** Predicted strength of shear-wave anisotropy for a range of symmetry axis dips and ray path incidence angles. Note that here we are referring to δV_s as a percentage of anisotropy and not α, as in the tomography model parameterization; δV_s is the difference between the fast and slow shear-wave velocities relative to their mean. For this example, initial polarization is 45° from the symmetry axis azimuth (0° or N-S) and the hexagonally averaged elastic properties of 70% olivine and 30% opx (Suppl. Table S1) at 100 km depth are assumed, as well as a temperature profile with a 30 km conductive lid overlying an
adiabatic mantle gradient with a temperature of 1350°C just below the lid. Line color grades from red (vertical incidence) to blue (incidence angle of 20°). For a typical SK(K)S path (~10° incidence angle), $\delta V_S$ starts at ~8.5% for a horizontal symmetry axis, drops to ~8.2% for a 15° symmetry axis dip, peaks at ~9.2% for a 35° dip, and then decreases to ~0.8% for a 90° dip (vertical). These values will not change considerably for different ray path azimuths (i.e., initial polarizations) and symmetry axis azimuths.

**Supplementary Table S1.** Elastic coefficients assumed in the calculation of predicted splitting parameters (Section 3). The orthorhombic coefficients of olivine (Fo$_{90}$) and opx (Bronzite) with their pressure and temperature derivatives (top) and their transformation to hexagonal coefficients (bottom, from Montagner and Anderson [1989]) are given. The $c$-axis of opx is aligned parallel to the $a$-axis of olivine [Mainprice and Silver, 1993]. See Abt et al. [2009] for further details.
### Table 1

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Table 2.

Origin Time, Latitude, Longitude, Depth, Magnitude, Back Azimuth, Distance, # of Splits

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Station: B5
Event ID: 2004.333.18
BAZ: 324°
Distance: 108.94°

\[ \phi = -18° \text{ (54° from N) } +/− 7° \]
\[ dt = 2.26 \text{ sec } +/− 0.37 \text{ sec} \]
~strike of arc (-55°)
Delay Time (sec)

Fast Direction

Caribbean (N=66) Mean
Pacific (N=27) Mean

~strike of arc (-55°)
Graphs a and b show the amplitude of SV and SH waves over time, with initial and corrected values. The phase angle φ is given as -18° (-54° from N) ± 7°, and the delay time is 2.26 sec ± 0.37 sec.

Graphs c and d present the Fast Direction, φ_{SV}, with best and 95% confidence regions. The phase angle φ is given as -24° (-60° from N) ± 12°, and the delay time is 1.76 sec ± 0.38 sec.