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Seismic anisotropy in southern Costa Rica confirms upper mantle flow from the Pacific to the Caribbean

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ABSTRACT

Surrounded by subducting slabs and continental keels, the upper mantle of the Pacific is largely prevented from mixing with surrounding areas. One possible outlet is beneath the southern part of the Central American isthmus, where regional observations of seismic anisotropy, temporal changes in isotopic composition of volcanic eruptions, and considerations of dynamic topography all suggest upper mantle flow from the Pacific to the Caribbean. We derive new constraints on the nature of seismic anisotropy in the upper mantle of southern Costa Rica from observations of birefringence in teleseismic shear waves. Fast and slow components separate by ~1 s, with faster waves polarized along the 40°–50° (northeast) direction, near-orthogonally to the Central American convergent margin. Our results are consistent with upper mantle flow from the Pacific to the Caribbean and require an opening in the lithosphere subducting under the region.

INTRODUCTION

Along the eastern margin of the Pacific Ocean, subducting oceanic lithosphere and thick continental keels form a nearly continuous barrier impeding the flow of the upper mantle (Hayes, 2018; Becker et al., 2014). The shrinking area of the Pacific requires an outflow, with possible outlets at the opposite ends of the South American subduction zone: beneath the South Sandwich Islands and beneath the Central American isthmus (e.g., Alvarez, 1982; Fig. 1A). Russo and Silver (1994) used the pattern of seismic anisotropy observations in South America to support the concept of regional upper mantle flow with an outlet beneath the isthmus, although later work showed the anisotropy pattern to be more complex (Fig. 1B). Systematic age progressions in volcanism with Galápagos hotspot isotopic signatures require transport of mantle material from the Pacific to the Caribbean, and then along the back arc of the Central American subduction zone (Hoernle et al., 2008; Gazel et al., 2011). Considerations of dynamic topography in the Caribbean adjacent to Costa Rica and Panama favor an inflow of material from the Pacific side (Chen et al., 2019). Flow-induced alignment of olivine in the upper mantle rocks beneath the isthmus would be detectable through measurements of seismic anisotropy (Long and Silver, 2009), however such measurements have not been performed to date (Fig. 1B).

Upper mantle material cannot flow between the Pacific and the Caribbean if the slab of the subducting Cocos plate is present under the isthmus. A local seismic imaging study by Dzierma et al. (2011) and a study combining local seismicity and modeling of the gravity field (Lücke and Arroyo, 2015) argue for the presence of the slab down to at least 200 km depth. On the other hand, there are no fast anomalies consistent with recently subducted lithosphere in the upper 200 km of the global model with adequate lateral resolution in the Central American isthmus region (van Benthem et al., 2013).

We present new observations of seismic anisotropy in southern Costa Rica that require a well-developed upper mantle flow oriented near-orthogonally to the strike of the Central American subduction zone. This finding bolsters the previously proposed scenarios of Pacific to Caribbean mantle flow and limits the area where a continuous slab of subducted lithosphere may be present.

TECTONIC SETTING

The Cocos, Nazca, and Caribbean plates form a triple junction (Fig. 1B), with convergent margins separating the Cocos and Nazca plates from the Caribbean plate, and the Panama fracture zone accommodating Cocos-Nazca obliquely divergent relative motion (Kobayashi et al., 2014). Plate tectonic reconstructions (e.g., Morell, 2015) show this configuration to be relatively recent. The overriding Caribbean plate is a former oceanic plateau (or Caribbean large igneous province) likely formed ~100–90 m.y. ago from the plume head of the present-day Galápagos hotspot (Kerr et al., 2003). The Cocos and Nazca plates entering the convergent margin are much younger; their lithosphere ranges in age from 14.5 to 19.5 Ma (Morell, 2015).

The shape of the subducting Cocos slab becomes progressively less certain from the northwest to the southeast. While the global compilation of Hayes (2018) extends the ~200-km-long slab to the Panama fracture zone, local seismicity suggests a progressive change in slab depth, from 200 km at ~11°N to ~70 km at 9°N, near the inland projection of the Panama fracture zone (Protti et al., 1994; Kyriakopoulos et al., 2015). Lateral changes in the extent of the Benioff-Wadati zone are accompanied by corresponding changes in arc volcanism. Numerous volcanic centers follow the ~100 km depth contour of the slab from Mexico to central Costa Rica but are absent in southern Costa Rica. Only one active volcano (Barú; Fig. S3 in the Supplemental Material[1]) exists further southeast in Panama. Alternative scenarios of flat subduction (Fischer et al., 2004), slab windows (Johnston and Thorkelson, 1997), and slab detachment (Gazel et al., 2011) have been put forth to explain these rapid lateral changes in geodynamic conditions.

[1]Supplemental Material. Data sources, details of data analysis methodology, and additional diagrams and maps of shear wave splitting measurements. Please visit https://doi.org/10.1130/~~XXXXX~~ to access the supplemental material, and contact editing@geosociety.org with any questions.

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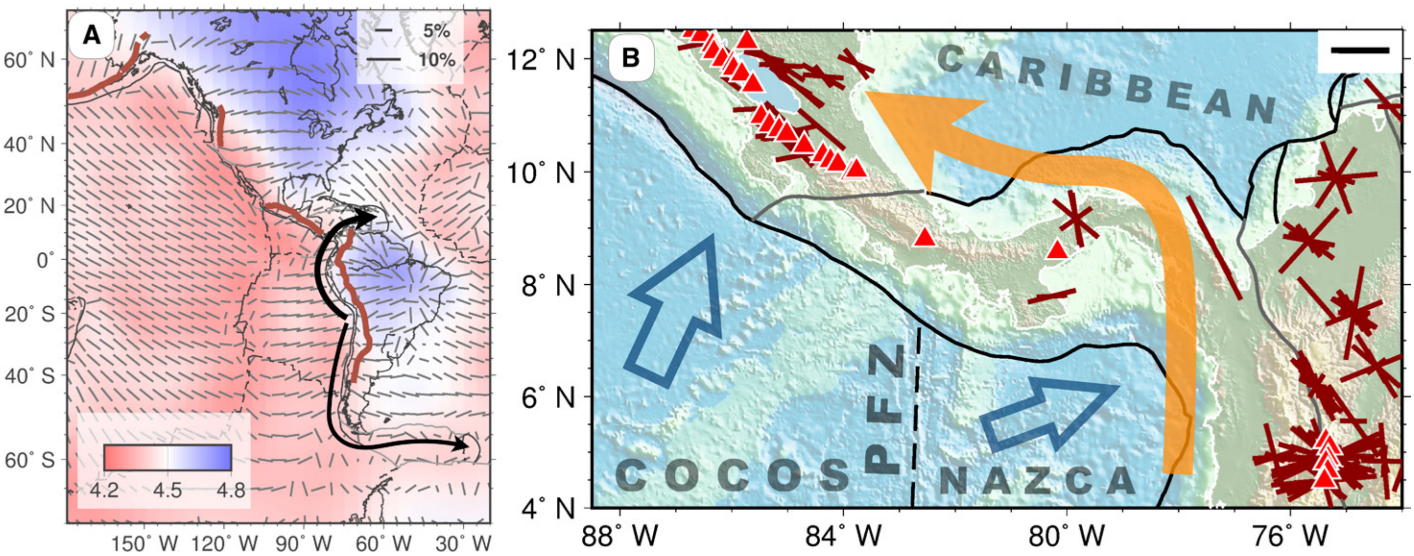

Figure 1. (A) Mantle flow and obstacles to it in eastern Pacific region. Azimuthal anisotropy at 150 km depth (thin bars, scale in upper right) is proxy for mantle flow strength and orientation (Becker et al., 2014). Shear wave velocity (in km/s) at 150 km depth (color) outlines deep continental keels (Moulik and Ekström, 2014; scale in lower left). Thick red lines show 160 km depth contours of subducted slabs (Hayes, 2018). Black arrows show mantle flow pattern proposed by Russo and Silver (1994). (B) Regional map with tectonic units, plate boundaries (convergent shown as solid lines; transform as gray), Cocos and Nazca plate motion vectors relative to Caribbean plate (blue arrows; DeMets et al., 2010), and active volcanoes (red triangles). Red bars show published observations of shear wave splitting (2 s scale bar in upper right; data sources are described in the Supplemental Material [see footnote 1]). Relief data are from https://topex.ucsd.edu/WWW_html/srtm30_plus.html. PFZ (thick dashes)—Panama fracture zone. Orange arrow shows mantle flow pattern from Abt et al. (2010).

EXPECTED MANTLE FLOW PATTERNS

Competing models of slab configuration in southern Costa Rica make easily distinguishable predictions for the expected upper mantle flow and the associated systematic alignment of the olivine crystals that makes mantle rocks seismically anisotropic. If the slab is truncated and there is an opening, the flow between the Pacific and the Caribbean regions is likely. Assuming the most common scenario where seismically fast *a*-axis of olivine crystals aligns with the shear direction (Ribe, 1989; Long and Silver, 2009), we expect shear waves polarized approximately northeast-southwest (across the Central American isthmus) to be systematically faster everywhere. Conversely, if there is an impediment to flow, distinct orientations of olivine alignment and the corresponding fast shear wave polarizations will be likely on the opposite sides of the isthmus, respectively in front of and beneath the subducting slab.

SHEAR WAVE SPLITTING OBSERVATIONS

We use records of core-refracted shear waves SKS, SKKS, and PKS observed at nine broadband seismic observatories in southern Costa Rica chosen for their location above the proposed flat subduction and/or slab window. Birefringence in their particle motion reflects propagation through anisotropic materials (Vinnik et al., 1984; Silver and Chan, 1988), with the most likely locus of anisotropy being the uppermost mantle (Savage, 1999). Station locations and full citations for the data are provided in the Supplemental Material.

To detect and quantify the birefringence (splitting) of shear waves, we use the rotation-correlation (RC) method (Ando et al., 1983) and the splitting intensity (SI) technique (Chevrot, 2000) as our two primary methods, and employ the minimum transverse energy method (Silver and Chan, 1988) as a check of measurement stability. Li et al., (2019) provided a detailed description of procedures we follow, including selection criteria for data to be measured and the logic of defining NULL (absence of splitting) measurements. An abbreviated synopsis of that description is presented in the Supplemental Material.

We report 304 new single-phase observations of shear wave splitting, with 132 measurable values of fast polarization and delay, and 172 NULL measurements (Table S2 in the Supplemental Material). Given different durations of data collection, the number of measurements at individual sites varies from 14 to 80.

Examples of observations for two sites (POTG and VERF; Figs. 2 and 3A) illustrate the value of using multiple measurement methods. Splitting parameters shown in stereonet diagrams vary with direction at both sites, possibly due to the vertical and/or lateral changes in anisotropic fabric at depth (Savage, 1999). We compare averaged values of splitting parameters (fast polarization direction φ_a and delay δt_a) to best-fit estimates of these values (δt_f, φ_f) derived from a harmonic function in the form $\delta t_f \times \sin[2(\varphi_o - \varphi_f)]$ that describes expected directional variation of SI values with back azimuth φ_o (Chevrot, 2000). This sinusoid function is obtained by a least-squares fit to all SI observations at a site (Li et al., 2019). A close match of two estimates is expected if anisotropy at depth is relatively uniform. This is observed at site POTG, with two methods yielding very similar estimates (φ_a ~44° and φ_f ~43°; δt_a ~1.2 s and δt_f ~1.1 s). Close match of two estimates is confirmed by a nearly complete overlap of the sinusoid fit to the SI data (blue curve in Fig. 2) and another one predicted using average splitting parameters φ_a and δt_a and the formula above. At site VERF, estimated delays are similar (δt_a ~0.9 s and δt_f ~1.0 s) while fast polarization directions differ somewhat (φ_a ~17° versus φ_f ~9°), and consequently the sinusoids predicted from splitting parameters and derived by a least-squares fit to SI values are noticeably offset. A relatively small number of observations may cause this discrepancy, however lateral variation in the upper mantle fabric may also lead to such an outcome.

Despite some variation between sites, our results are remarkably consistent (Fig. 3A; Fig. S3). We find unambiguous evidence of shear wave splitting throughout southern Costa Rica, with relatively large (0.7–1.6 s) delays evaluated by two different methods. Locations on the Caribbean side of the Central American isthmus show some mismatch in estimates of the average fast polarization from two techniques, while those estimates are nearly identical for sites west of the central mountain range of southern Costa Rica. Delays on the western

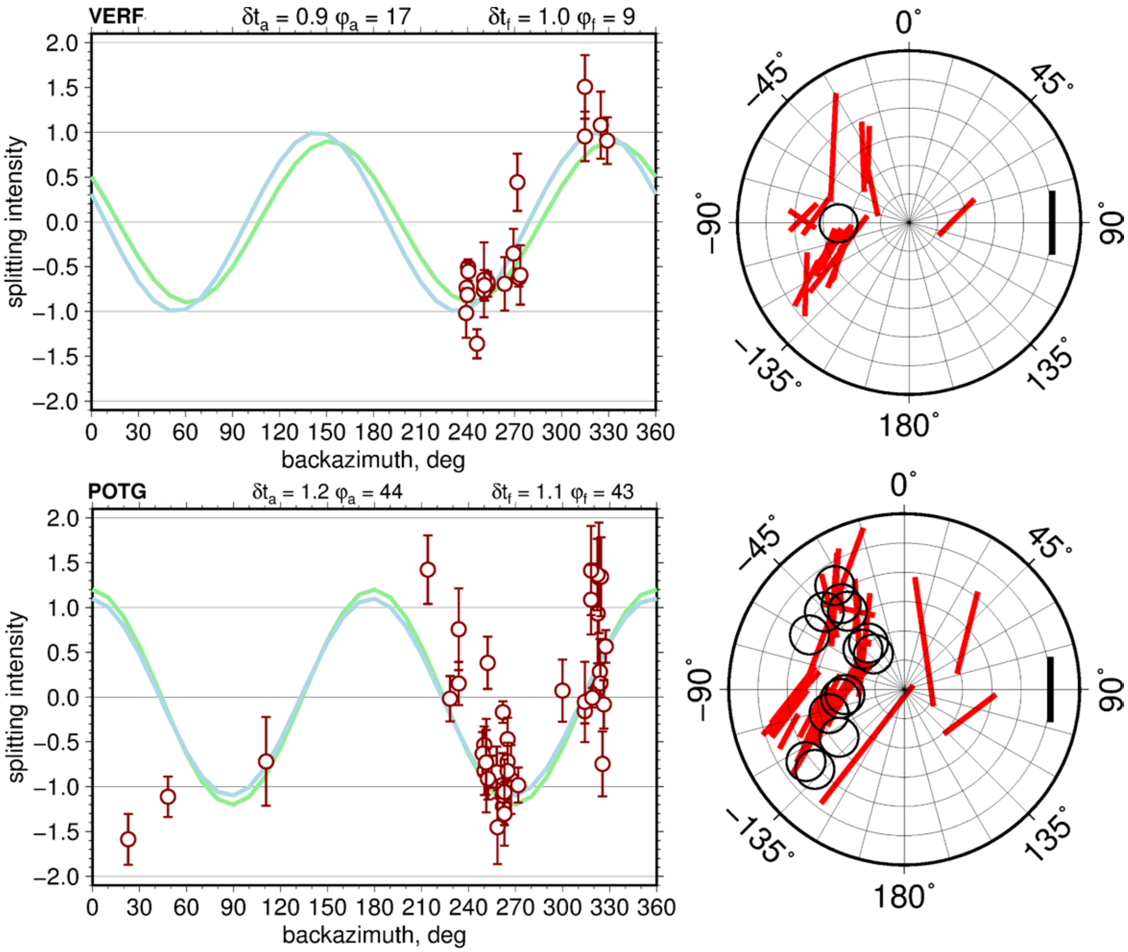

Figure 2. Shear wave splitting in southern Costa Rica (top, site VERF; bottom, site POTG; see Fig. 3A for site locations). (Right) Single phase measurements as bars aligned with fast polarization direction (north is up, as in map view), scaled with delay, referenced to attributes of ray back azimuth (direction to earthquake source, marked on rim) and incidence angle (0° to 18°, from center to rim, in 3° increments); circles are NULL measurements. (Left) Splitting intensity values (red circles with error bars showing 95% confidence range), sinusoid fit to those data (blue curve), and sinusoid computed from average of non-null observations shown at right (green curve). See the text for the meaning of values on top of the plots.

(Pacific) side of the isthmus appear to be systematically smaller. The average fast polarization direction of 40°–50° seen on the western side of the isthmus is nearly orthogonal to the strike of the Central American subduction zone. Sites on the Caribbean have average fast polarization directions between 30° (northeast) and due north.

DISCUSSION

We measure splitting in shear waves propagating along near-vertical paths using two methods based on the same simplifying assumption

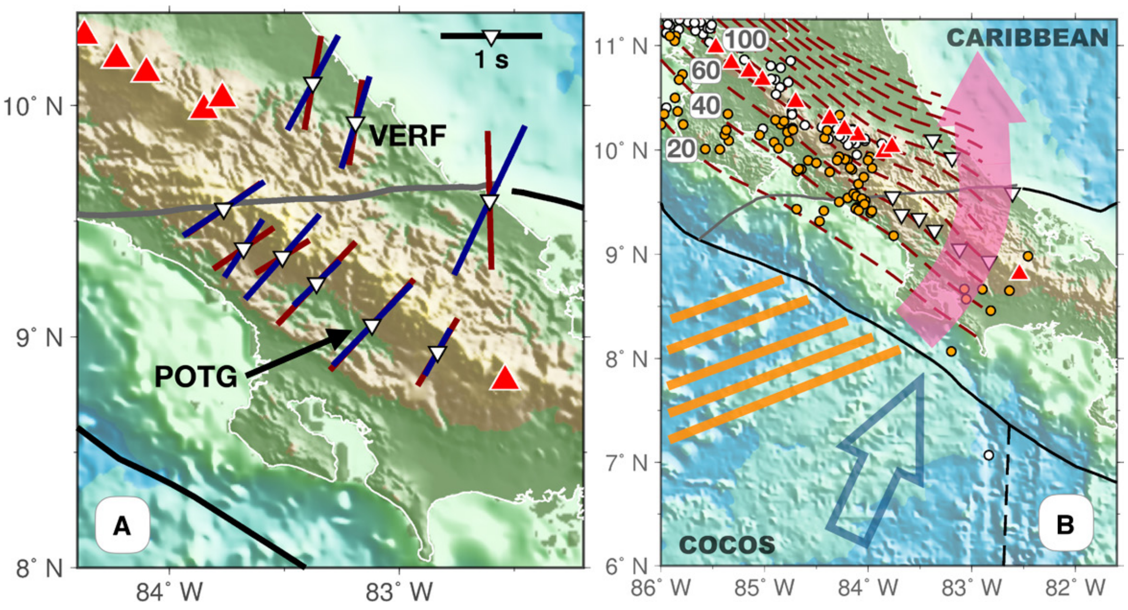

Figure 3. (A) Average splitting parameters (blue bars) and predictions from fit to splitting intensity values (red bars). Stations mentioned in the text are labeled. (B) Schematic depiction of likely mantle flow pattern (magenta arrow) compared with distribution of M >4 earthquakes (circles: orange, 40–80 km; white, >80 km; Linkimer et al. [2018], events from 2007 to 2017) and Slab2.0 model (https://earthquake.usgs.gov/data/slab/) of subducted lithosphere (dashed red lines, depth contours labeled in km; Hayes, 2018). Open blue arrow shows Cocos plate motion; orange stripes show 15–18 Ma magnetic anomalies (after Barckhausen et al., 2001). In both panels, red triangles are volcanoes; inverted white triangles are seismic stations. Tectonic units and relief as in Figure 1B.

of a single source (layer) of anisotropy with a horizontal symmetry axis (Chevrot, 2000; Savage, 1999). When real structure is more complex, anisotropic parameters (delays and fast polarizations) estimated by two methods will differ (Long and Silver, 2009). Thus, where both methods yield similar answers, an interpretation in terms of a single anisotropic layer with near-horizontal axis has considerable merit. This is true of most sites we have examined, with an exception of site RGM0 (see Figs. S2 and S3), where a significant mismatch in φ_a and φ_f values implies a deviation from this simplest model. Due to a relatively small number of measurements at site RGM0 (Table S2), it is not possible to discriminate between vertical and lateral variations of anisotropy in a formal way. Projecting splitting measurements to depth (Fig. S3) reveals considerable similarity in directional dependence of fast polarization seen at many sites, favoring regionally consistent vertical stratification (Savage, 1999). While some of these directional changes may be attributed to the use of the RC method (Wüstefeld and Bokelmann, 2007) we do not believe it is the dominant cause (see Fig. S4). With continuing data recording, we hope to revisit this issue in a few years.

Our results identify a region of clear and regionally similar rock fabric beneath the Central American isthmus. Crustal thickness estimates in central and southern Costa Rica do not exceed 40 km (Linkimer et al., 2010; Hayes et al., 2013), which is insufficient to produce delays of ~1 s with realistic values of anisotropy (Long and Silver, 2009).

The downgoing Cocos plate is 15–19 m.y. old at the Central American convergent margin (Morell, 2015), with magnetic anomalies oriented at a high angle to the strike of the margin (Fig. 3B). Assuming a half-space cooling model (Turcotte and Schubert, 2002) with temperature $T = T_0 erf\left(\frac{L}{2\sqrt{\kappa t}}\right)$ (where *erf* is the error function), ambient mantle temperature $T_0 = 1300°$, plate age $t = 15$–19 m.y., thermal diffusivity $\kappa \sim 10^{-6}$ m²/s, and taking plate thickness L to follow the $T = 1100°$ isotherm, we obtain an estimate of 44–49 km for the likely thickness of the Cocos plate lithosphere. Anisotropy on the order of 8% would be required throughout the lithosphere to produce the delays of ~1 s we observe in split shear waves (Savage, 1999). Furthermore, taking magnetic anomalies as markers of the spreading-center strike, we expect the rock fabric frozen in at the time of lithosphere formation to be near-normal to them, yielding a present-day NNW-SSE fast shear wave polarization, very different from what we observe. We thus do not believe that the anisotropic material responsible for our observations resides within the Cocos plate lithosphere.

Another candidate process for the observed splitting parameters is the corner flow in the upper mantle on the back-arc side of the intact subducting lithosphere (Long and Silver, 2009). This scenario may indeed apply to the sites on the Caribbean coast (Fig. 3A), but conflicts with inferences of flat or nearly flat underthrusting of the Cocos plate under the sites on the western side (Protti et al., 1994; Fischer et al., 2004). If there is any mantle wedge material present beneath those locations, its vertical extent would be <30 km (cf. Lücke and Arroyo, 2015, their figure 4), insufficient to produce the observed splitting signal.

Our preferred explanation of the scale and the pattern of shear wave splitting in southern Costa Rica is the southwest-northeast–oriented flow in the upper mantle beneath the Central American isthmus. While deformation-induced rock fabric inferred from anisotropy does not have a sense of direction, subsidiary considerations like the history of distinct volcanism (Hoernle et al., 2008; Gazel et al., 2011) and dynamic topography on opposite sides of the isthmus (Chen et al., 2019) favor flow from the Pacific into the Caribbean region. This scenario is consistent with the large-scale view of regional mantle dynamics (Alvarez, 1982; Russo and Silver, 1994) and adds important details to the more localized mantle flow scenario of Abt et al. (2010) developed assuming that the Cocos slab extended beneath Costa Rica and Panama (Fig. 1B). A plausible path of mantle flow is shown in Figure 3B and reflects a ~30° northward rotation of average fast polarization directions between the western and eastern groups of sites (Fig. 3A). Flow crossing the isthmus and then turning northward is consistent with both our new data and the shear wave splitting observations of Abt et al. (2010) farther to the northwest.

Our results are incompatible with the presence of deeply subducted lithosphere of the Cocos plate in the area where our seismic stations are located, leading us to favor tectonic scenarios of a flat and/or truncated Cocos slab there (Protti et al., 1994; Fischer et al., 2004; Gazel et al., 2011). We contend that inclusion of an opening in the eastern Pacific mantle flow barrier under southern Costa Rica would be an essential addition to future generations of mantle flow models like those of Becker et al. (2014), and that a proper mapping of the flow is crucial for understanding complex and evolving geodynamic conditions in this region.

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