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FAST TRACK PAPER

A teleseismic shear-wave splitting study to investigate mantle flow around South America and implications for plate-driving forces

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SUMMARY

Closure of the Pacific Ocean basin by the convergence of its surrounding plates, some of which have deep continental roots, implies that there is net mass flux out of the mantle under the Pacific. Here we report on a shear-wave splitting study designed to test the prediction that there should be flow around its southern margin. Our results show no evidence for present-day flow around the tip of southern South America. Instead, the results suggest present-day flow directions in the southern Atlantic that parallel the South American absolute plate motion direction, even under Antarctica. The results also provide evidence for absolute plate motion driven by the basal drag of ocean basin-scale mantle flow, and suggest that ~200 km thick flow boundary layers exist under South America and Antarctica, and also demonstrate that mantle flow directions cannot be reliably inferred from present-day plate morphology.

Key words: mantle flow, shear-wave splitting.

1 INTRODUCTION

The mechanisms that move the mosaic of plates covering the Earth's surface are imperfectly understood. South America's motion is particularly enigmatic because it lacks significant subducting margins (Fig. 1), which draw plates trenchward on account of the negative buoyancy of the subducted plate (Forsyth & Ueyda 1975; Harper 1978; Stoddard & Abbott 1996). One proposed mechanism to move non-subducting plates is through basal tractions arising from convective flow of the mantle (Stoddard & Abbott 1996; Russo & Silver 1996; Silver *et al.* 1998). Convective upwelling of the deep mantle associated with hot spots might also play a role as the ascending material spreads laterally under the plate, since hot spots seem to be associated with continental breakup and changes in relative plate motion (Wilson 1988; Cox 1989; Silver *et al.* 1998). Continents may be particularly susceptible to basal forces because they contain deep, seismically visible cratonic roots (Grand 1994; Bokelmann & Silver 2000). Indeed, continental shear-wave splitting patterns suggest organized flow around their roots (Fouch *et al.* 2000).

One region in which there must be a significant lateral component of mantle convection is around the margin of the Pacific Ocean. Alvarez (1982) observed that this ocean basin is closing because all its surrounding plates are moving into it. Consequently, the infra-Pacific mantle must be laterally displaced by the roots of the surrounding, advancing continents. The limited egress afforded by the continents might channel flow laterally between them. The channelled flow could be responsible for tectonic features such as the Drake Passage and the Caribbean Ocean and the small subduction margins at their eastern extents. Mantle flow is detectable seismically through the anisotropic effects upon wave propagation through oriented mantle material (characterized by a fast polarization direction ϕ and a delay time δt) that arise due to lattice-preferred orientation in olivine (Silver & Chan 1991). Russo & Silver's (1994) used the pattern of shear-wave splitting observations and geoid features around South America to infer that there was lateral flow along its western margin and eastward flow into the Caribbean in the north as predicted by Alvarez (1982) (Fig. 1). The physical and chemical features of the seafloor between Australia and Antarctica also suggest lateral mantle flow out of the Pacific basin (Alvarez 1990; Christie *et al.* 1998). If Russo & Silver's (1994) inferences are valid, there should be a similar flow through the Drake Passage around the southern boundary of South America that is evident in the pattern of shear-wave splitting there. In order to test this hypothesis, we deployed portable seismic stations around the Drake Passage to collect records of seismic anisotropy in the form of splitting of teleseismic shear waves.

2 DATA AND METHODS

The network consisted of temporary, portable broad-band seismometers and autonomous dataloggers deployed in Patagonia

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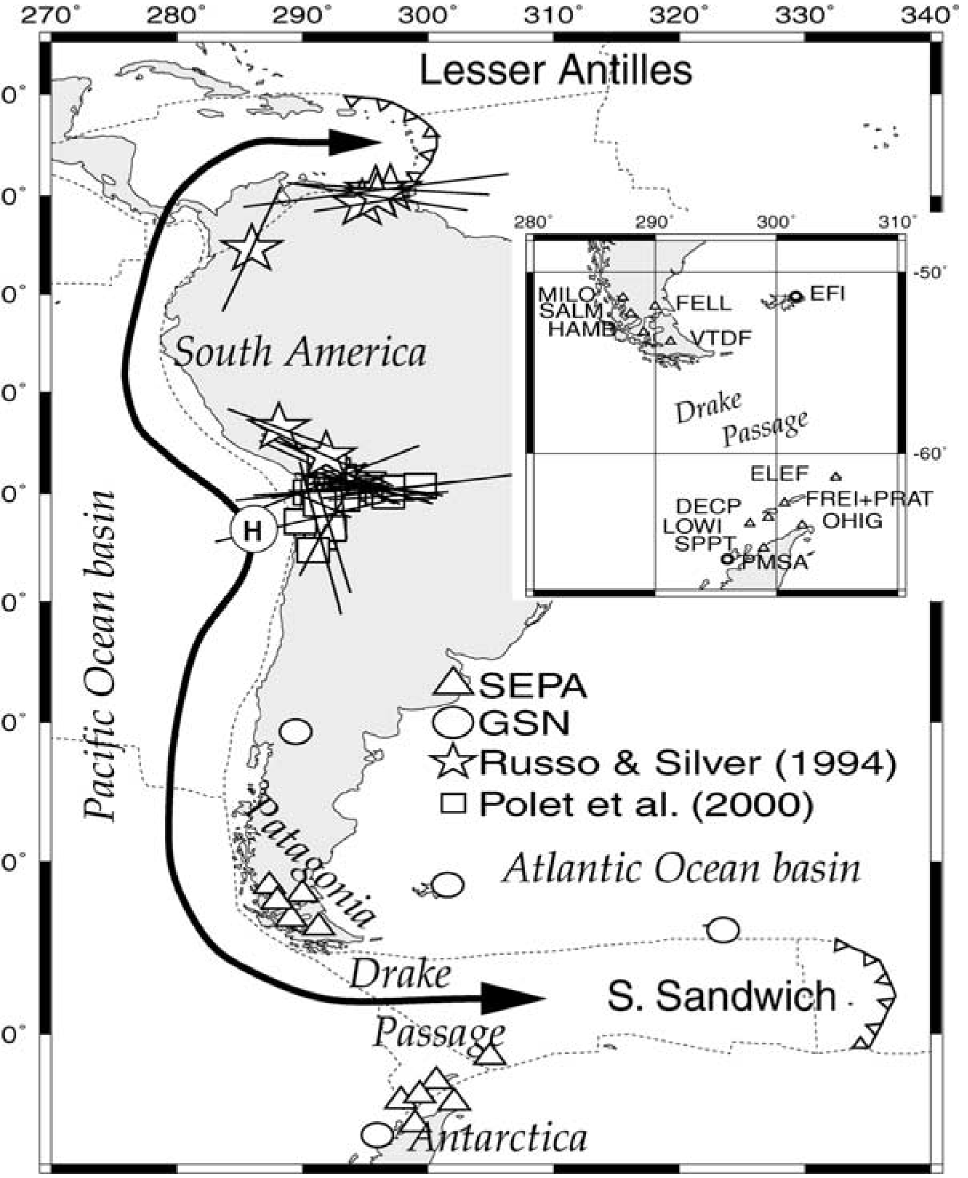

Figure 1. Maps showing hypothesized South American mantle flow patterns, and location of seismic stations deployed in the experiment to detect them. Russo & Silver (1994) interpreted the pattern of fast polarization directions on the around South America (lines denote directions and stars the stations used in their study; squares from Polet *et al.* 2000) as indicating mantle flow (arrows) from a stagnation point corresponding to a geoid high (H circle). Flow may be responsible for west-facing subduction in the Lesser Antilles and the South Sandwich arcs. Inset shows locations of portable seismic stations (SEPA, Seismic Experiment in Patagonia and Antarctica, triangles) deployed around the Drake Passage to detect the southerly flow component. Small circles in both panels indicate locations of permanent Global Seismic Network (GSN) stations.

and Antarctica (Fig. 1). The temporary stations recorded natural earthquakes for approximately two years, including S, ScS, SKS, SKKS, PKKS and PKS arrivals used for splitting measurements. We augmented these recordings with additional data from permanent stations on Antarctica and South Atlantic islands (Fig. 1). 81 different earthquakes provided 168 recordings that were processed (Silver & Chan 1991) and combined (Wolfe & Silver 1998; Restivo & Helffrich 1999) to yield splitting estimates beneath each station (Table 1).

Fig. 2 shows an example of a split SKS arrival and the analysis method used, and Fig. 3 summarizes all the results. As a group, the Antarctic results indicate fast polarization directions oriented NE–SW to ENE–WSW, roughly parallel to the western margin of the Antarctic Peninsula (uncharacterized or poorly characterized sites are consistent with this trend). δt ranges from over 2 s down to 1 s in the region. In the south Atlantic, fast polarization directions ϕ trend similarly but with slightly lower δt, between 0.6 and 1.2 s. In Patagonia, δt is small (zero within uncertainty in all cases) and fast polarization directions lack a consistent orientation. Farther north where the Nazca Plate subducts under the Andean Cordillera, the delay time is 0.75 s and ϕ is easterly. The depth extent of anisotropy is unconstrained, but waveform inversion of surface waves suggest 4 per cent polarization anisotropy extending from 40–120 km depth in southern South America (Robertson *et al.* pers. comm. 2001).

3 RESULTS

Unlike the mantle flow pattern envisaged by Russo & Silver (1994), around northern South America from their splitting results (Fig. 1),

Table 1. Combined splitting results. PRAT and FREI (Base Arturo Prat and Base Presidente Frei, Chilean Antarctic region) processed jointly due to ~50 km station separation yielding virtually identical mantle sampling by upgoing *S* waves. APM indicates the South American plate motion direction in the hotspot reference frame (Gordon 1995), and ϕ-APM the difference between the fast polarization direction and APM.

Site	Lat. (°N)	Lon. (°E)	ϕ (°)	±	δt (s)	±	APM (°)	ϕ-APM (°)
				Temporary stations				
FELL	−52.088	−70.008	74.	22.5	0.36	1.26	256.2	2.2
HAMB	−53.617	−70.934	49.	22.5	0.44	1.02	256.3	27.3
MILO	−51.571	−72.625	32.	22.5	0.48	1.26	257.3	45.3
VTDF	−54.140	−68.711	−83.	22.5	0.45	0.85	255.4	−21.6
SALM	−52.530	−71.989	30.	22.5	0.15	0.72	256.9	46.9
FREI + PRAT	−62.332	−59.324	45.	22.5	0.90	0.85	249.4	24.4
ELEF	−61.170	−55.100	90.	10.0	2.05	0.62	248.1	−21.9
SPPT	−64.296	−61.051	67.	22.0	2.75	0.94	249.4	2.4
DECP	−62.977	−60.670	−65.	22.5	0.62	1.69	249.7	45.3
				Permanent stations				
HOPE	−54.280	−36.480	49.	22.5	0.60	0.50	244.1	15.1
EFI	−51.480	−58.410	70.	4.0	1.20	0.20	252.2	2.2
PMSA	−64.770	−64.050	79.	9.0	1.85	0.50	250.6	−8.4
PLCA	−40.733	−70.551	70.	9.0	0.75	0.20	257.9	7.9
				Backazimuths for high S/N nulls				
OHIG	−63.317	−57.900	212.9	223.6	210.3	208.9		
LOWI	−63.247	−62.181	238.5	238.5	235.0			

there does not seem to be evidence in our own results for a corresponding present-day southern flow. This is because there is neither uniform orientation nor large delay times in our Patagonian results. Delay times are small enough in southern Patagonia to be due to crustal structure (Barruol 1993). Excepting Patagonia, the larger delay times in southern South America and the South Atlantic islands suggest a mantle signal, and trend northeasterly. Some complexity in Patagonian splitting results may arise due to the Nazca–South American–Antarctic triple junction changing the subduction geometry along the southern South American margin (Murdie & Russo 1999), but this same trend is seen north of the triple junction (at PLCA, Fig. 3), suggesting that it is a larger scale pattern. Fig. 3 shows a cross-section along western South America, showing the seismicity shallowing to the south. If this indicates the absence of a slab, easterly upper-mantle flow would be expected along with east-west fast polarization directions, which is not observed. If an aseismic plate does extend here, as suggested by volcanism in western Patagonia (Gill 1981; Simkin *et al.* 1981), the splitting signal would be a combination of the subplate anisotropy, the mantle wedge anisotropy, and any lithospheric anisotropy. In central South America, Polet *et al.* (2000) found ϕ orientations in both the down-dip direction and trench-parallel directions, and explained them as resulting from either slab-normal stresses due to slab rollback, or as due to lateral along-strike mantle flow channelled by the slab. Interpreting results from PLCA and EFI similarly would require rotations in subducted slab strike >45°, eliminating any barrier to flow in the south. On this account, there is no seismological evidence for flow in this region nor for a role for Pacific mantle flow in maintaining rollback in the South Sandwich arc. However, because the seismological results only reflect essentially present-day mantle structure, they do not rule out a mantle flow role for the formation of the Scotia Sea ~30 Ma, as suggested by Pacific mantle affinities detected in both Drake Passage basalts and in South Sandwich backarc and arc lavas (Livermore *et al.* 1997; Pearce *et al.* 2001).

The Antarctic splitting results are more consistent in their orientation and their magnitudes (Fig. 3) but there is no unique explanation for their uniformity. We observe margin-parallel orientations compatible with either fossil lithospheric anisotropy, some scenarios of active rifting, or with trench-parallel flow. The former source is unlikely because the stations are close to the trench developed by recent subduction along the western Antarctic Peninsula margin and thus have no underlying Antarctic lithosphere (Roult & Rouland 1994; Danesi & Morelli 2000), but their fast polarization directions parallel the orogenic axis (Silver 1996; Nicolas 1993). The South Shetland Islands presently are rifting away from the Antarctic Peninsula via backarc spreading in the Bransfield Strait (Cunningham *et al.* 1995), so the regional ϕ orientation may carry a rifting signature similar to the rift axis parallel trend seen in the northern Rio Grande Rift (Sandvol *et al.* 1992). Alternatively, the slab associated with waning subduction on the western Antarctic Peninsula margin may be orienting flow, apparently in a wide region extending to EFI and HOPE and oblique to the Drake Passage. The large delay times (≥1.85 s) we observe are difficult to reconcile with this. Local seismicity in the slab is no deeper than 60 km (Robertson *et al.* 2000) and subduction was short-lived on this margin, which would not create a barrier to flow capable of orienting olivine down to ~200 km depth, which the δt values suggest (Silver & Chan 1991).

4 DISCUSSION

If Pacific mantle is discharging into the Atlantic through the Drake Passage, our results show that it is not occurring as envisaged by Alvarez (1982) and Russo & Silver (1994). Surface wave dispersion around Antarctica and southern South America does not indicate that lithospheric barriers exist under either continent bordering the Drake Passage (Roult & Rouland 1994; Danesi & Morelli 2000). There should be no structures impeding upper-mantle flow in this region, yet we find no shear-wave splitting evidence for flow channelled by South America. The simplest model capable of explaining the uniform ϕ in the Antarctic, S. Atlantic island and South America splitting results (excluding Patagonia) is to invoke Atlantic

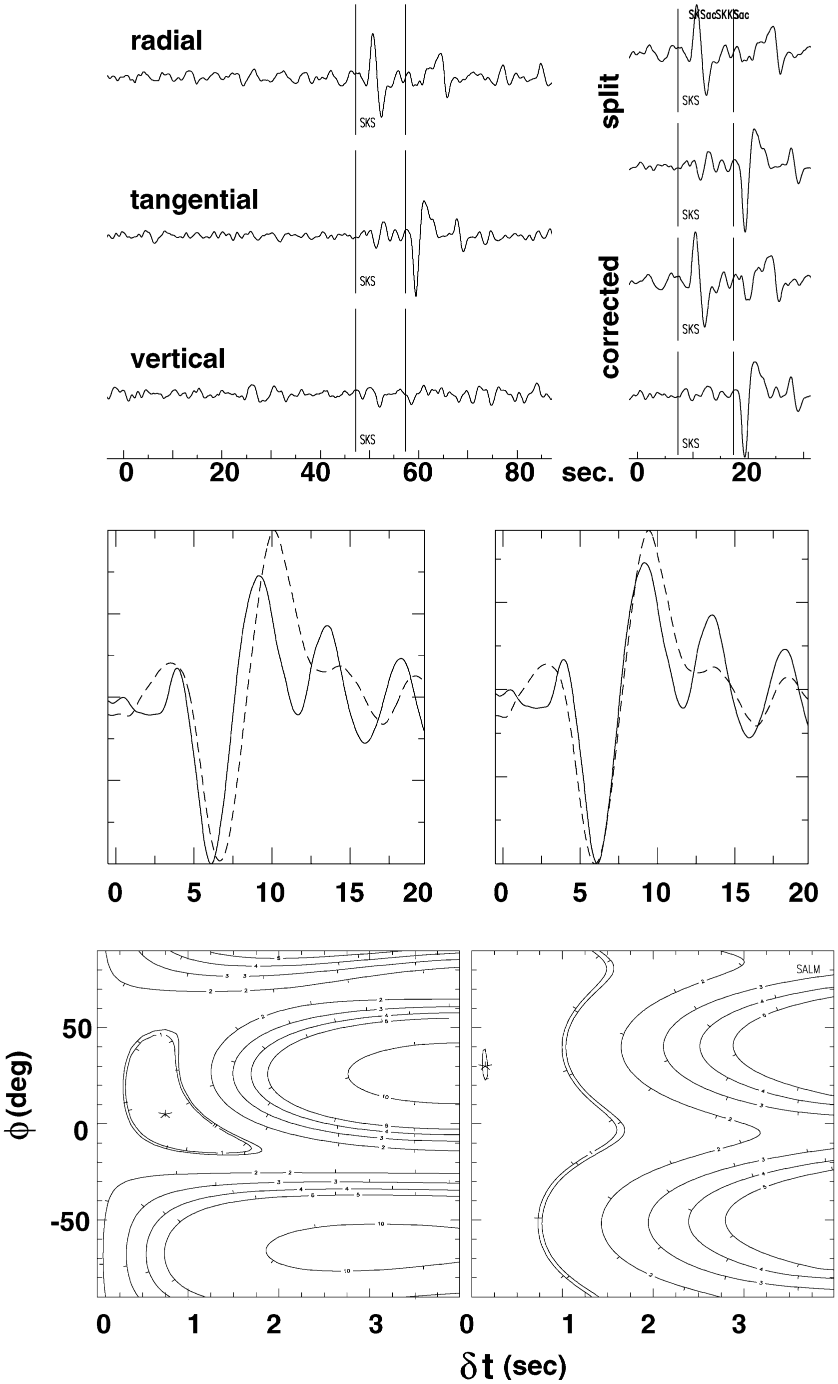

Figure 2. Example of splitting analysis method. Three-component seismogram (*upper left*) is windowed to isolate the shear-wave arrival of interest (in this case, SKS). The method seeks the inverse splitting operator (ϕ, δt) that minimizes the energy on the tangential component in the analysis window without *a priori* assumption of incoming polarization. Original radial and tangential components shown before applying and after applying the operator (*upper right*). The operator shifts the tangential component in time (δt) to align with the radial component (*middle*). Optimal (ϕ, δt) values (star) and their uncertainties (extent of double contour) shown on *bottom left*. Combining individual observations yields the overall uncertainty (extent of double line) for a single station, which is (30 ± 22.5°, 0.15 ± 0.72 s), indistinguishable from zero at the 95 per cent confidence level (*bottom right*). We assume single-layer splitting.

mantle flow due to plume buoyancy flux (Silver *et al.* 1998) driven into the Pacific Basin. Comparing South American absolute plate motion directions (APM) (Gordon 1995) and fast polarization directions (Fig. 4 and Table 1), we see that they cluster around the predicted South American APM, even for stations on the Antarctic plate rather than South America (Fig. 1). When comparing ϕ with Antarctic APM for stations on the Antarctic plate, we find larger deviations, averaging -42°. Our model is sketched in Fig. 4, and invokes shallow lateral Atlantic flow under southern South America accommodated by Nazca plate rollback, and Atlantic mantle flow under the Antarctic Peninsula where a deep lithospheric root is absent (Roult & Rouland 1994; Danesi & Morelli 2000). Flow in the Drake Passage must be weak, eastward Pacific mantle flow in order to result in the small Patagonian δt values we observe and to satisfy

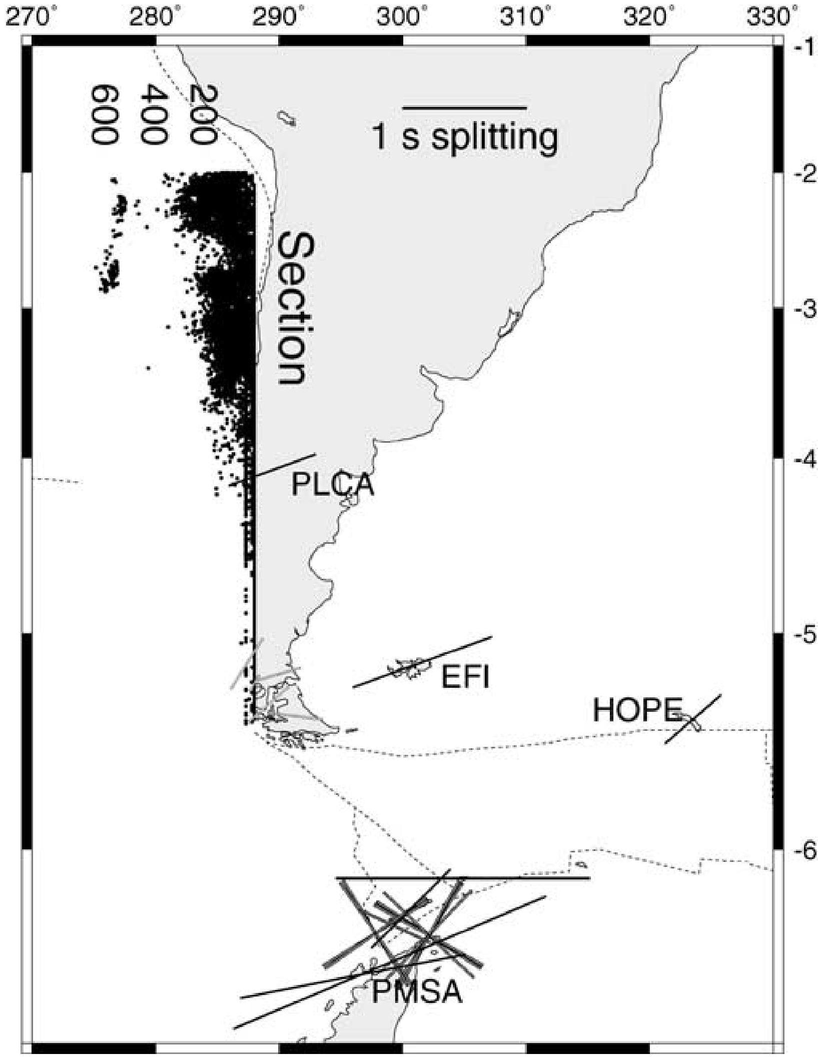

Figure 3. Splitting results and seismicity along western South American margin. Map shows splitting results (ϕ given by bars, δt by bar length) and seismicity projected along a vertical section (depths shown). Grey bars indicate stations with δt indistinguishable from zero within measurement uncertainty, and large crosses the possible fast-polarization directions compatible with null splitting observations from some Antarctic temporary stations. Seismicity shallows southwards towards Patagonia, suggesting either no slab (and thus no barrier to flow), or an aseismic slab.

the Pb isotopic signature in Drake Passage MORB, which originated in Pacific mantle (Pearce *et al.* 2001).

Our results indicate that eastward mantle flow out of the southern Pacific Basin is not channelled by western South American slabs or lithospheric roots. The inferred South American APM-parallel flow directions under Antarctica imply that that a single, ocean-basin scale mantle flow field exists in the South Atlantic. This result is somewhat unique in splitting studies, where there is typically an ambiguity between the motion of the plate relative to the mantle or vice versa, both of which lead to the same ϕ orientation. Since the same South American APM-relative ϕ exists under two plates with different APM directions, the splitting signal must be due to the mantle flow field itself. The flow extends under Antarctica and probably drives the westward motion of South America by basal drag on the plate, a result compatible with a quantitative balancing of South American plate torques (Meijer & Wortel 1992). We suspect that the reason Antarctica is not moving in a similar direction is because it is surrounded by ridges that constrain its lateral motion (Silver *et al.* 1998), while South America's subduction margin, in contrast, allows westward movement. We may estimate the thickness of the anisotropic part of the flowing layer from the average Antarctic delay times, ~1.9 s, which suggests a ~200 km thick layer for a horizontal foliation orientation developed by an order 1 shear strain (Mainprice & Silver 1993). This estimated thickness, which depends on the 4 per cent anisotropy observed in continental mantle xenoliths (Mainprice & Silver 1993), is compatible with the estimated thickness of APM-related anisotropy from Indian Ocean surface wave analyses (Lévêque *et al.* 1998). The estimated 200 km thick near-surface region of flow contrasts with the ~600 km thick section of mantle that moved with the South American plate under southern Brazil (VanDecar *et al.* 1995). Here, SKS fast polarization directions under the Parana Basin also parallel South American APM (James & Assumpcao 1996), and delay times correspond to a ~100 km thick layer. If flow is restricted to levels deeper than the cratonic root—about 250 km here (Grand 1994; VanDecar *et al.* 1995)—then a 100 km thick layer could be accommodated above the 410 km discontinuity below which anisotropy is small (Meade *et al.* 1995). Hence, in our study area and under southern Brazil, the anisotropy appears to arise in a foliated boundary layer between the rigid plate and the asthenosphere. VanDecar *et al.* (1995) study

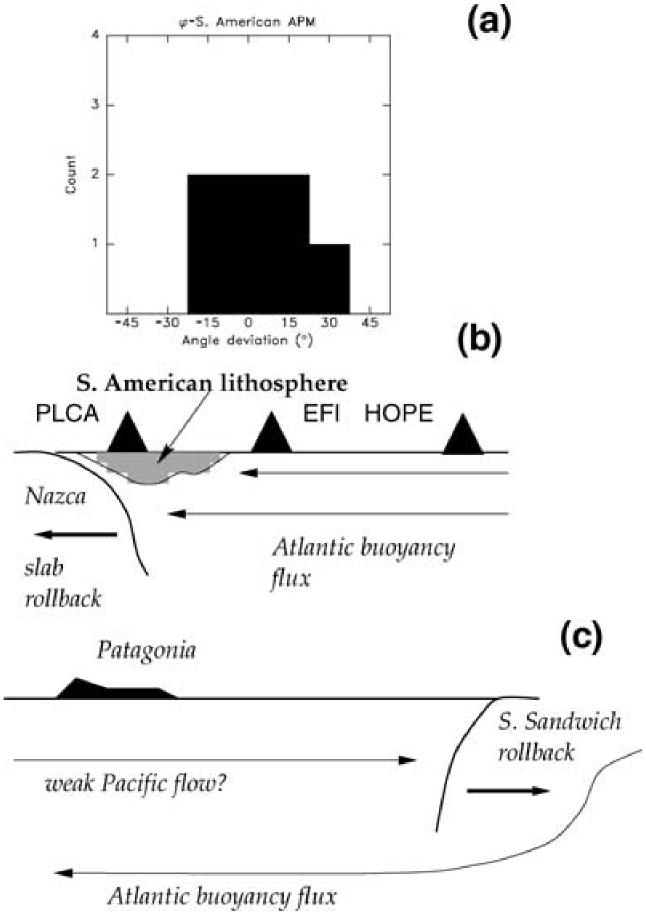

Figure 4. Comparison between absolute plate motion directions and a model proposed to explain regional splitting results. (a) The S. American APM and observed fast polarization directions are roughly parallel, shown by the histogram of deviations between APM direction and observed fast polarization directions ϕ when $\delta t > \sigma_{\delta t}$ (Table 1). This is true even for Antarctic stations, which have larger ϕ-APM values when calculated with the Antarctic rotation pole. (b) Model for ϕ directions in South America and southern Atlantic. The mantle flow field acts on South American cratonic roots, moving it westward and possibly causing rollback of the subducted Nazca plate. The flow field also extends under South Atlantic island stations (EFI, HOPE). Schema under Antarctic Peninsula is similar, but no slab analogous to the Nazca slab is present. (c) Inferred flow under Patagonia and Drake Passage. The combination of the Pacific geochemical signature in Drake Passage MORB and small δt values in Patagonia require weak Pacific flow, possibly related to S. Sandwich arc rollback. Atlantic flow must be forced deeper because there are no geoid anomalies in this region attributable to flow stagnation in the Drake Passage (Russo & Silver 1994), but the depth of the Pacific flow and the nature of its interaction with the Atlantic flow are unconstrained.

implies mantle lithosphere mechanical coherence to ∼600 km, but if an order 1 shear strain is distributed below the 250 km-deep cratonic root, the tomographic image would not be seriously affected. Thus, the flow boundary layers where tractions are exerted at the bases of South America and Antarctica appear to be ∼200 km thick, and possibly characteristic of all continents.

SUPPLEMENTARY MATERIAL

The supplementary material, Table S1 and Fig. S1 are available online at http://blacksci.co.uk/products/suppmatt/GJI/GJI1636/GJI1636sm.pdf.

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