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Mantle flow in the South Sandwich subduction environment from source-side shear wave splitting

Christian Müller,[1,2] Bettina Bayer,[2] Alfons Eckstaller,[2] and Heinrich Miller[2]

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[1] The occurrence of seismic anisotropy in the Earth's upper mantle is a global phenomenon related to subcrustal deformation and flow processes. The shear wave splitting analysis method has led to a global set of anisotropy maps mainly derived from receiver-side analysis. Remote places with few seismometers deployed remain unexamined. Source-side splitting analysis allows mapping of mantle fabrics in these regions. Here, we investigate seismic anisotropy in the South Sandwich Islands subduction environment. Core-reflected ScS waves recorded at the Neumayer seismograph network are corrected for well constrained receiver anisotropy and then analysed for source anisotropy. Sub-slab mantle minerals are aligned horizontally almost parallel to the trench indicating a westward flow around the subducting slab. This is consistent with a model of horizontal mantle flow due to slab rollback that was previously inferred from marine and geochemical studies in the back-arc region. **Citation:** Müller, C., B. Bayer, A. Eckstaller, and H. Miller (2008), Mantle flow in the South Sandwich subduction environment from source-side shear wave splitting, *Geophys. Res. Lett.*, *35*, L03301, doi:10.1029/2007GL032411.

1. Introduction

[2] There has been considerable discussion regarding the driving mechanisms of plate tectonics, especially the coupling of the oceanic lithospheric plates to the underlying asthenosphere. A question that has major implications for mechanisms of mantle flow is whether flow is strongly coupled to the plates or whether there are escape flows forced by asthenospheric barriers such as deep continental roots or subducting slabs. Consideration of the shrinking area of Pacific oceanic crust led *Alvarez* [1982] to propose horizontal mantle return flow patterns around the subducting slabs bounding the Pacific Ocean, which may have influenced Caribbean and Scotia Sea tectonic evolution (Figure 1). In particular, retrograde motions of subducting slabs should force mantle material to escape horizontally towards and around the slabs' edges. In part, this hypothesis has been supported by shear wave splitting measurements. The investigation of shear wave splitting reflects seismic anisotropy caused by the preferred orientation of mantle olivine crystals and therefore allows mapping of corresponding mantle strain and thus flow orientations.

[3] Recent studies of shear wave splitting imaging mantle flow in subduction zones suggest horizontal flow directions parallel to the strike of the trenches. *Russo and Silver* [1994] report trench-parallel, sub-slab fast anisotropy patterns beneath the Nazca plate. Trench-parallel and slab corner flow were observed in other strong retrograde subduction systems characterized by slab-rollback, for example, in the South America [*Anderson et al.*, 2004], New Zealand [*Gledhill and Gubbins*, 1996], Kamchatka [*Peyton et al.*, 2001], Lau Basin [*Smith et al.*, 2001], and Mediterranean [*Baccheschi et al.*, 2007] subduction zones. According to *Alvarez* [1982] and *Russo and Silver* [1994], horizontal mantle return flow patterns around subducting Pacific Ocean plates may also have influenced the evolution of Caribbean and Scotia Sea tectonics. For the Caribbean, eastward mantle flow patterns from the Pacific were verified by *Russo et al.* [1996] from shear wave splitting and by *Abratis and Wörner* [2001] from geochemical data. A teleseismic shear wave splitting study at the southern tip of South America does not confirm flow around its southern margin [*Helffrich et al.*, 2002]. Nevertheless, geochemical data indicate evidence for mantle material fluxes of Pacific mantle into the Drake Passage but also show an Atlantic mantle signature in some parts of the Scotia Sea [*Pearce et al.*, 2001]. There are a variety of indications for Atlantic mantle flow controlling the spreading mechanisms of the East Scotia back-arc system [*Livermore et al.*, 1997; *Bruguier and Livermore*, 2001; *Fretzdorff et al.*, 2002; *Livermore*, 2003; *Leat et al.*, 2004] from marine geophysical investigations of the spreading center and geochemical analyses of back-arc material. These authors infer an Atlantic mantle and Bouvet plume influence, but do not show direct evidence for the mantle flow mechanisms. Thus, the intent of the study presented here is to provide such evidence through mapping mantle flow in the South Sandwich subduction environment by means of shear wave splitting.

[4] The South Sandwich plate (SAN), located roughly between 55°S and 61°S, 24°W and 30°W, is bounded to the east by the deep sea trench of the westward subducting oceanic South American plate (SAM) and to the west by the back-arc spreading ridge separating SAN from the Scotia plate (SCO). The development of the Scotia Sea began about 40 Ma ago by separation of the southern tip of South America and the Antarctic Peninsula and initiation of an eastward migrating subduction zone. The present tectonic configuration in the East Scotia Sea persisted since at least 15 Ma [*Barker*, 2001, and references therein; *Larter et al.*, 2003]. The South Sandwich subduction system is characterized by a slab rollback of the SAM plate being overridden by the eastward- moving SAN plate. *Thomas et al.* [2003] developed a new model for relative plate motions of the

[1]FIELAX Gesellschaft für Wissenschaftliche Datenverarbeitung mbH, Bremerhaven, Germany.
[2]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

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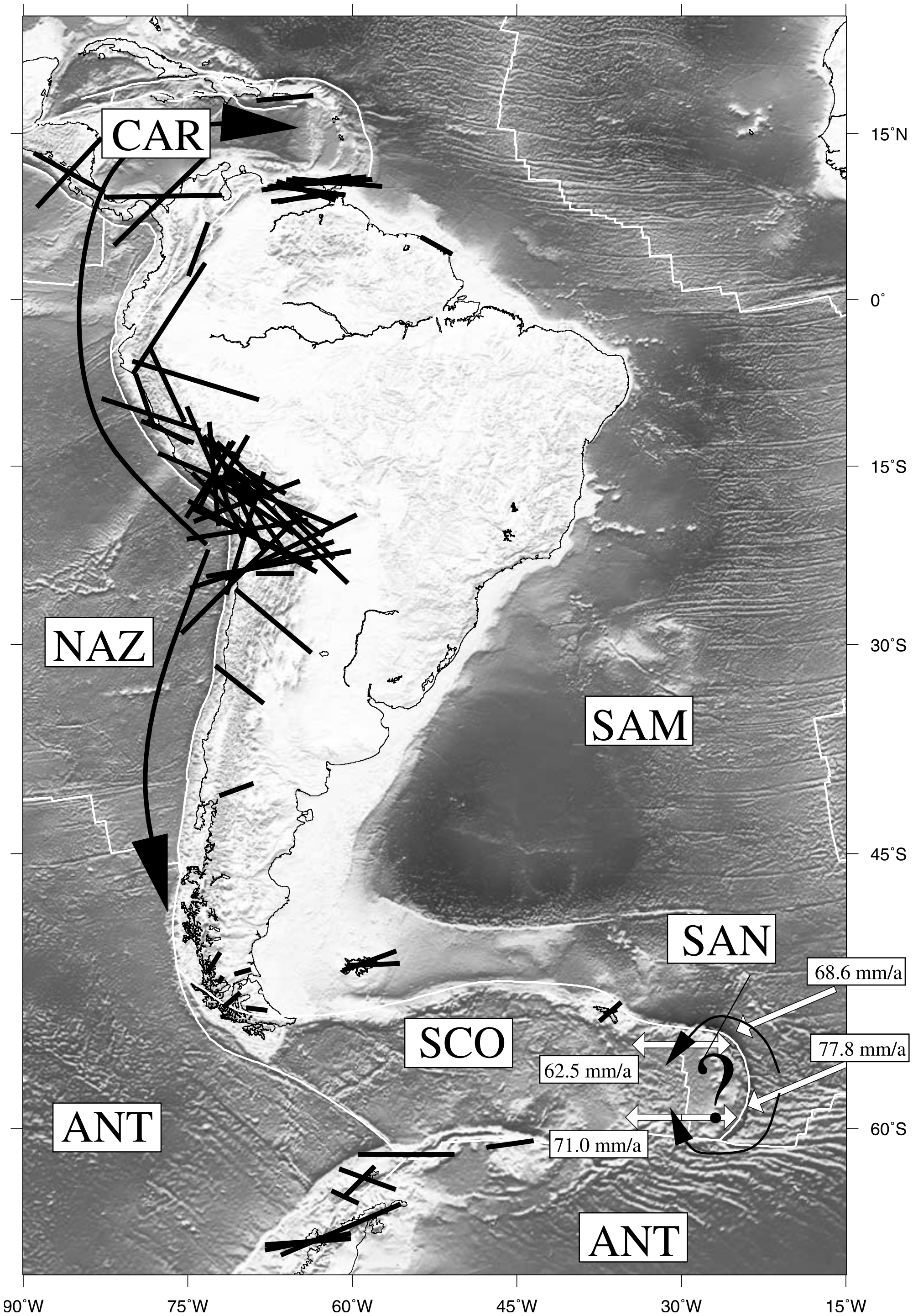

Figure 1. Shear wave splitting and hypothesis of mantle flow from the Pacific mantle reservoir around the subducting Nazca (NAZ) slab and controlling Scotia Sea (SCO) and Caribbean (CAR) tectonic evolution [*Alvarez*, 1982; *Russo and Silver*, 1994]. Shear wave splitting results from *Helffrich et al.* [2002], *Kaneshima and Silver* [1992, 1995], *Müller* [2001], *Russo and Silver* [1994], and *Russo et al.* [1996] supporting the mantle flow hypothesis are shown. Relative plate motion vectors for the East Scotia Ridge (SCO-SAN plate boundary) and the South Sandwich Trench (SAN-SAM plate boundary) are from *Thomas et al.* [2003]. Abbreviations: ANT, Antarctic plate; CAR, Caribbean plate; NAZ, Nazca plate; SAN, Sandwich plate; and SAM, South American plate.

Scotia Sea plates (model TLP2003). According to TLP2003, SAN-SAM converge with high rates of 69 mm/a in the northern part of the trench and up to 78 mm/a in the southern part, while back-arc spreading at the East Scotia Ridge occurs EW-directed with spreading rates of about 65 mm/a.

[5] Here, we show results of seismic anisotropy mapping in the South Sandwich subduction zone region. Standard

analysis of SKS splitting reveals the anisotropy patterns of the receiver side mantle beneath a seismic station. Mapping of seismic anisotropy in the upper mantle allows retrieval of deformation fabrics due to recent differential strain (e.g. mantle flow) and/or frozen deformational events from former tectonic episodes [*Silver and Chan*, 1991; *Savage*, 1999]. During deformation processes mantle minerals, particularly olivine, which are intrinsically anisotropic, align to produce a net anisotropy that causes shear wave splitting. The use of this standard technique is not applicable at remote places where no seismic recordings are available as in the South Sandwich Islands region. As an alternative method, we use ScS recordings from seismographs VNA2 and VNA3 of the Neumayer station seismograph network, Antarctica, where receiver anisotropy is well known. Source-side anisotropy may be investigated when receiver-side splitting parameters have already been determined from SKS analysis [*Kaneshima and Silver*, 1992; *Vinnik and Kind*, 1993; *Russo and Silver*, 1994; *Schoenecker et al.*, 1997]. Seismograms may then be corrected for the receiver contribution and residual splitting must have originated elsewhere on the ray path, most probably in the source-side region.

2. Source-Side ScS Splitting

[6] To investigate source-side anisotropy of the South Sandwich Islands region ScS-waveforms recorded at seismographs VNA2 and VNA3 of the Neumayer seismological network, Dronning Maud Land, Antarctica, were used. Both stations are equipped with intermediate-period Lennartz 20 s sensors. Three-component recordings are sampled by a rate of 62.5 sps and telemetered to the Neumayer Station. Receiver side anisotropy was determined by *Müller* [2001] from SKS-splitting. Both stations are appropriate for source anisotropy studies since a large number of receiver analyses exists showing sufficiently stable SKS-splitting results (VNA2: fast direction φ = 64°, delay time δt = 1.16 s from 28 SKS records; VNA3: φ = 64°, δt = 1.18 s from 28 SKS records). The use of ScS in the existing source-receiver geometry has the advantage of steep incidence angles for sampling the source region nearly vertically in the below-slab region. Events with magnitudes larger than m_b = 5.0 and very high signal-to-noise-ratios on both horizontal components were chosen for analysis. As diagnostics for source anisotropy we consider large inconsistencies of estimated splitting parameters for uncorrected ScS from SKS splitting results. In the period 1992–2007, we found in total 20 events of sufficient quality for ScS splitting analysis. We analysed 14 events recorded at VNA2 and 12 recorded at VNA3, with six of these events analysed from both stations (Table S1).[1] Because both seismographs operate autonomously at remote sites, station outages often occur and recordings are not available continuously. To enhance ScS-waveforms, seismograms were individually filtered within a pass band between 0.2 and 0.8 Hz. Identified ScS waveforms were cut from the seismogram and corrected for receiver anisotropy. These corrected waveforms were analysed using the method of *Silver and Chan* [1991] by minimization of the smaller eigenvalue of the horizontal covariance matrix. This method yields the best fitting parameter pairs (fast anisotropy direction in the receiver coordinate system (φ_r) and delay time between split waves (δt)) that removes the anisotropy effect from the seismograms. Projection of φ_r along the ScS ray path assigns the source regions anisotropy fast direction φ_s. Figure 2 shows a typical example of a ScS splitting analysis.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032411.

3. Results

[7] In general, fast anisotropy directions follow the curvature of the South Sandwich trench (Figures 3a and 3b). Delay times δt range between 0.35 s and 1.60 s, depending on the location with respect to the trench as well as hypocentral depths. Hypocentral depths range from 10.1 km (δt = 1.2 s) up to 274.3 km (δt = 0.64 s) based on the ISC (before 2005) and NEIC earthquake catalogues. Generally, events with hypocentral depths shallower then 110 km yield delay times δt > 1 s, while for deeper events δt < 1 s. Colour codes in Figures 3a and 3b show the depth dependences of splitting times. In addition to depth, there is also a dependency of location along the slab: the largest delay times were measured towards the slab edges while in the middle segment delay times range around 0.5 s. Due to the geometrical distribution of hypocentres along the subduction zone with respect to the recording stations, the down going ScS waves traverse the upper mantle directly beneath the slab (Figure 3a).

[8] Beneath the northern part of the trench, fast polarization directions are NNW-SSE directed. Towards the middle part directions turn to NNE-SSW and rotate to NE-SW beneath the southern part. Thus, fast anisotropy directions generally follow the strike of the subduction trench. The directions are independent of the hypocentral depths of the events used.

[9] In total, four 'null' measurements were derived. 'Null' measurements may originate from the absence of anisotropy or by radiation of S-wave polarization parallel or orthogonal to the anisotropy symmetry axes (white crosses in Figures 3a and 3b). One of these measurements was from a single event not located along the Sandwich trench, but located at the Northern Scotia Ridge at 54°S 51°W. The three 'nulls' in the South Sandwich region were observed in the northern and central segments of the trench. The two events in the northern region in particular occurred where other events yielded clear anisotropic signatures. Therefore, it seems likely that the radiation pattern was responsible for the absence of measurable anisotropy.

[10] In the southern part, at 59°S, one event was analysed (06.149 in Figure 3b) with fast anisotropy nearly perpendicular to the strike of the trench. The robustness of this result is demonstrated by similar results for splitting analyses for both stations VNA2 and VNA3. All earthquake parameters and splitting measurement results are presented in Table S1.

4. Discussion

[11] By use of source-side anisotropy investigations of sub-slab mantle in combination with local S above-slab splitting measurements, we have the unique opportunity to

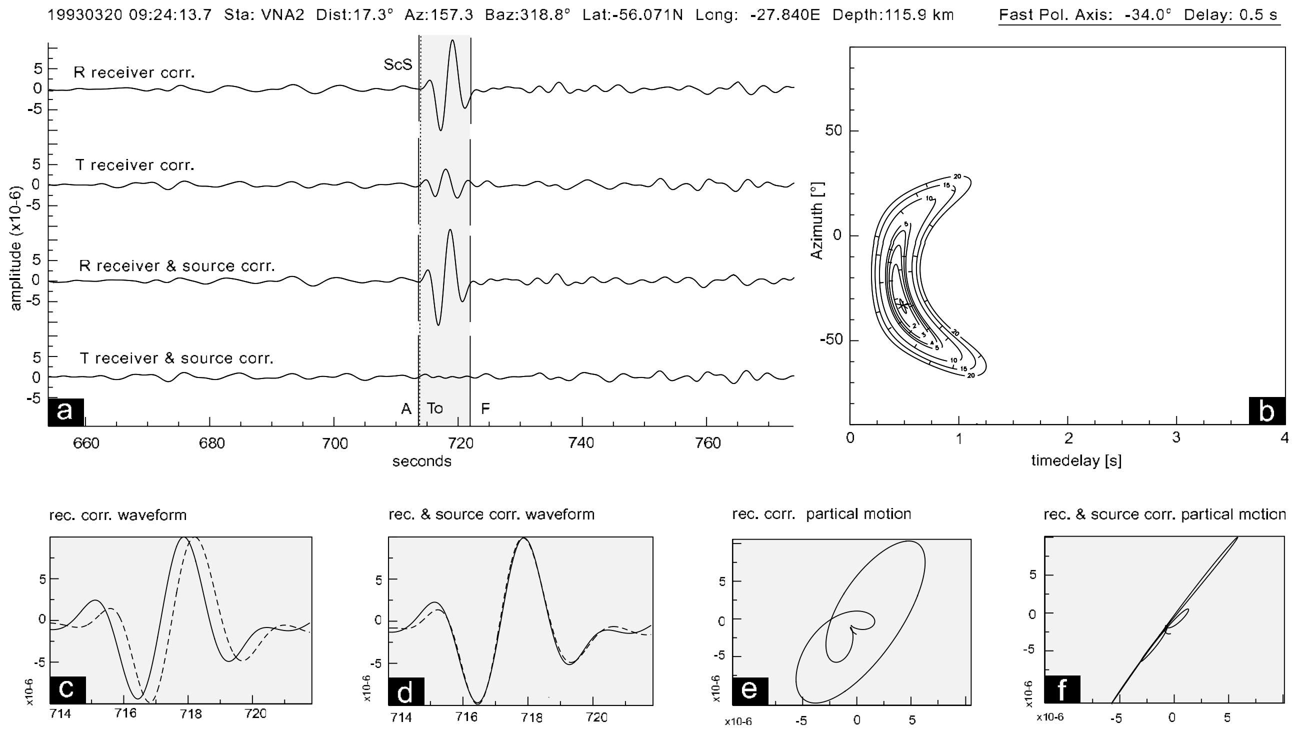

Figure 2. Example of a ScS source-side splitting measurement at station VNA2. (a) Traces 1 and 2: radial and transverse components after correction for receiver anisotropy. Traces 3 and 4: radial and transverse components after correction for source anisotropy. (b) Contour plot of net grid search analysis of the parameter space (φ_r, δt) by minimizing the smaller of the eigenvalues of the covariance matrix. The azimuth $\varphi_r = -34°$ corresponds to the receiver coordinate system and has to be projected along the ray path to the source region which yields an azimuth with respect clockwise against north of φ_s = 165.0°. Source anisotropy fast and slow ScS waveforms (c) before and (d) after correction for time delay δt. The same in a particle motion plot (e) before correction for δt and (f) thereafter.

describe mantle flow patterns separated by their anisotropy source regions in a relatively simple subduction environment. In general, fast anisotropy directions derived from below-slab ScS waveforms follow almost perfectly the curvature of the subduction trench. Thus, these directions indicate mantle return flow induced by the rollback of the retreating slab. The geographical distribution of epicenters does not allow mapping the anisotropy around the slabs edges, but geochemical analyses of back-arc samples indicate strong influence of Atlantic component mantle material especially in the northern- and southern-most segments of the back-arc spreading system [*Bruguier and Livermore*, 2001; *Fretzdorff et al.*, 2002; *Leat et al.*, 2004; *Livermore*, 2003].

[12] Delay times (δt) are small compared to delay times observed at other subduction zones (e.g., up to δt = 4 s for the subducting Nazca plate [*Russo and Silver*, 1994] and up to δt = 3 s for the Calabrian slab [*Baccheschi et al.*, 2007]). Assuming an anisotropy coefficient of 2% (maximum value for below-slab regions after *Savage* [1999]), this corresponds to an assumed shear-wave velocity of 4.6 km/s for observed delay times and corresponding hypocentral depths to a base of the anisotropic flow regime of 250–450 km. Even the event with the deepest hypocenter (event 97.278, d = 273 km, δt = 0.64 s) reveals a thickness of 147 km corresponding to a base of the anisotropic layer of 420 km depth. The cumulative length of the slab was estimated by *Livermore* [2003] from the opening history of the East Scotia Sea as 650 km (a slightly higher value of 723 km was estimated by *Vanneste and Larter* [2002]), which corresponds to a slab tip depth of 500 km assuming a dip of 50° as estimated by *Brett* [1977]. This is similar to the thickness of the anisotropic region, which means that the slab is a plausible barrier to mantle flow.

[13] Measurements of splitting parameters from direct S-waves above the slab were reported from *Müller* [2001] derived from a temporary deployment (CAND, Figure 3b) in early 1998. Delay times were measured between 0.4 s < δt < 0.6 s and fast directions mainly trend EW. These observations are best explained by a past flow direction frozen into the sub-arc lithosphere and/or coupled flow induced in the mantle wedge. A deviation with directions slightly biased to WNW-ESE was observed for the more northerly events.

[14] The unusual fast anisotropy direction retrieved from event 2006.149 suggests a different mechanism for its splitting origin. We speculate that this azimuth deviating from the general pattern originates from westward mantle material inflow through a slab tear inside the subducting slab. Alternatively, since this relatively shallow event (hypocentral depth of 46.7 km) was located towards the western part of the forearc, it might be influenced by a long travel path within the slab and mainly influenced by in-slab anisotropic structures. This second explanation is supported by a hypocentre section constructed by *Vanneste et al.* [2002] showing a slab bending after initial low-angle subduction for a distance of about 100 km from the trench.

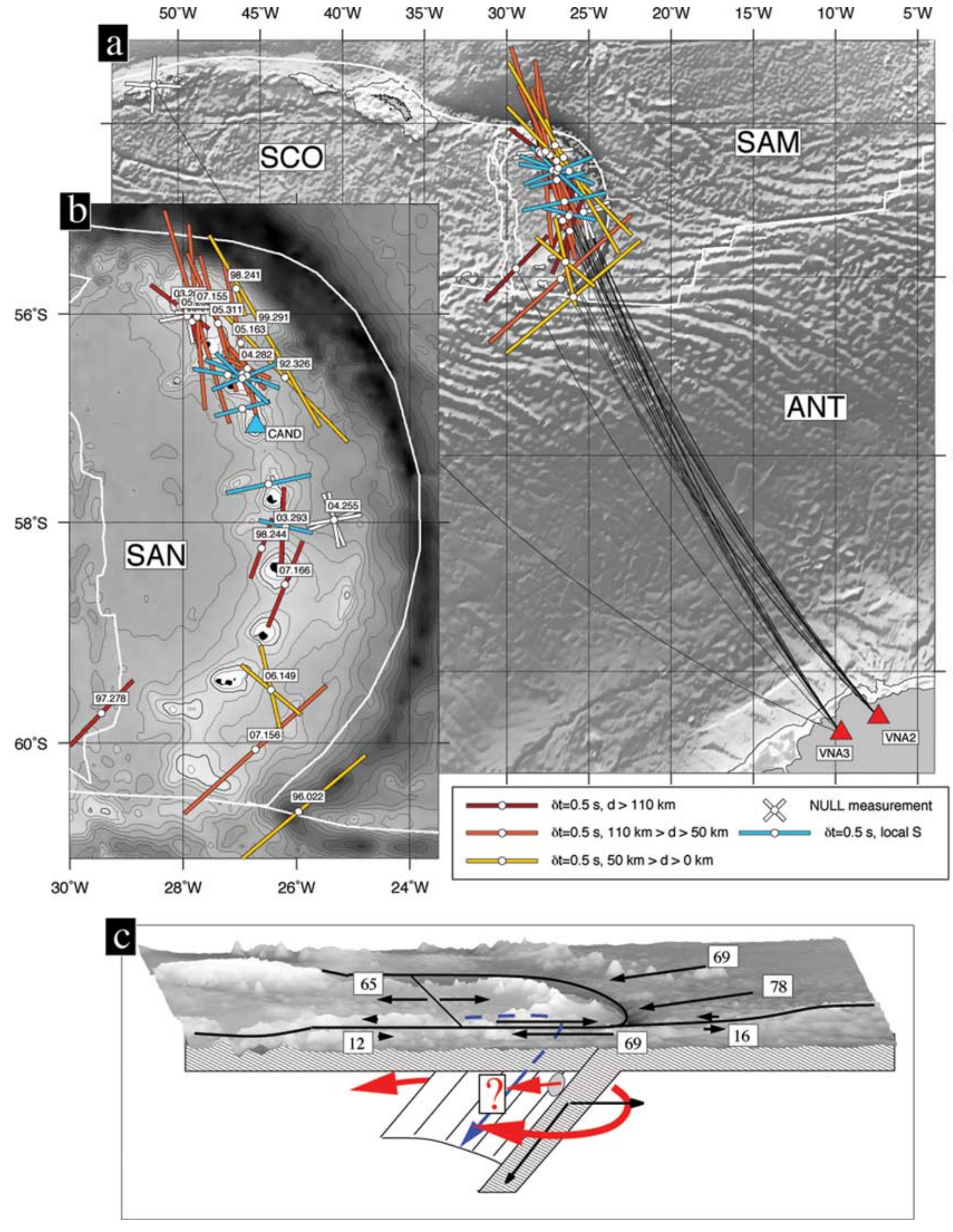

Figure 3. Results of source-side ScS anisotropy analysis and local S analysis. (a) Map showing results of source-side splitting analysis in the South Sandwich Islands region. VNA2 and VNA3: seismographs of the Neumayer seismological network in western Dronning Maud Land, Antarctica. Receiver-side anisotropy is well constrained for these stations [*Müller*, 2001]. Abbreviations: ANT, Antarctic plate; SAM, South American plate; SAN, Sandwich plate; and SCO, Scotia plate. (b) Shear wave splitting results, red/orange/yellow bars (d denotes hypocentral depth): depth dependent ScS-splitting analysis reflecting mantle anisotropy fast directions beneath the slab, blue bars: results from analysis of local events recorded at the temporary seismograph CAND (blue triangle) from *Müller* [2001] reflecting anisotropy features in the mantle wedge above the slab. Crossed bars denote null measurements from ScS analysis. (c) Schematic view showing plate geometries, dynamics, and possible mantle flow patterns of the South Sandwich subduction environment. Black arrows, plate motion vectors based on *Thomas et al.* [2003] (velocities in mm/a); red arrows, mantle return flow around the subducting slab and possible westward flow through a slab window (its tentative existence is represented by a question mark); and blue arrow, coupled flow in the subduction mantle wedge.

[15] Geochemical findings and unusual geomorphological features in the northern- and southernmost segments of the East Scotia back-arc spreading system are interpreted as being strongly influenced by Atlantic mantle material inflow [e.g., *Livermore*, 2003]. This model is strongly supported by the observed mantle flow patterns around the retreating subduction plate.

[16] In summary, Figure 3c shows a compilation of origins of mantle flow systems which could be mapped by means of our splitting observations.

[17] 1. Due to rollback of the overridden SAM slab, Atlantic mantle material is forced to escape around the slab's edges into the Scotia Sea region, influencing back-arc spreading mechanisms of the East Scotia back-arc system.

[18] 2. Possibly, there exists westward directed flow through a slab window within the southern part of the slab. An alternative explanation for these anisotropy fast directions might be a strong influence of anisotropic structures inside the slab itself. This may be resolved by analysis of future events from this part of the subduction system.

[19] 3. EW fast anisotropy directions inside the slab wedge from direct S splitting analysis can be explained by fossil anisotropy reflecting the back-arc spreading system and/or mantle flow coupled inside the mantle wedge.

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References

Abratis, M., and G. Wörner (2001), Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm, *Geology*, *29*, 127–130.

Alvarez, W. (1982), Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics, *J. Geophys. Res.*, *87*, 6697–6710.

Anderson, M. L., G. Zandt, E. Triep, M. Fouch, and S. Beck (2004), Anisotropy and mantle flow in the Chile-Argentina subduction zone from shear wave splitting analysis, *Geophys. Res. Lett.*, *31*, L23608, doi:10.1029/2004GL020906.

Baccheschi, P., L. Margheriti, and M. S. Steckler (2007), Seismic anisotropy reveals focused mantle flow around the Calabrian slab (southern Italy), *Geophys. Res. Lett.*, *34*, L05302, doi:10.1029/2006GL028899.

Barker, P. F. (2001), Scotia Sea regional tectonic evolution: Implications for mantle flow and palaeocirculation, *Earth Sci. Rev.*, *55*, 1–39.

Brett, C. P. (1977), Seismicity of the South Sandwich Islands region, *Geophys. J. R. Astron. Soc.*, *51*, 453–464.

Bruguier, N. J., and R. A. Livermore (2001), Enhanced magma supply at the southern East Scotia Ridge: Evidence for mantle flow around the subducting slab?, *Earth Planet. Sci. Lett.*, *191*, 129–144.

Fretzdorff, S., R. A. Livermore, C. W. Devey, P. T. Leat, and P. Stoffers (2002), Petrogenesis of the back-arc East Scotia Ridge, South Atlantic Ocean, *J. Petrol.*, *43*, 1435–1467.

Gledhill, K., and D. Gubbins (1996), SKS splitting and the seismic anisotropy of the mantle beneath the Hikurangi subduction zone, New Zealand, *Phys. Earth Planet. Inter.*, *95*, 227–236.

Helffrich, G., D. A. Wiens, E. Vera, S. Barrientos, P. Shore, S. Robertson, and R. Adaros (2002), A teleseismic shear-wave splitting study to investigate mantle flow around South America and implications for plate-driving forces, *Geophys. J. Int.*, *149*, F1–F7.

Kaneshima, S., and P. G. Silver (1992), A search for source side mantle anisotropy, *Geophys. Res. Lett.*, *19*, 1049–1052.

Kaneshima, S., and P. G. Silver (1995), Anisotropic loci in the mantle beneath central Peru, *Phys. Earth Planet. Inter.*, *88*, 257–272.

Larter, R. D., L. E. Vanneste, P. Morris, and D. K. Smythe (2003), Structure and tectonic evolution of the South Sandwich arc, *Geol. Soc. Spec. Publ.*, *219*, 255–284, doi:10.144/GSL. SP. 2003.219.01.13.

Leat, P. T., J. A. Pearce, P. F. Barker, I. L. Millar, T. L. Barry, and R. D. Larter (2004), Magma genesis and mantle flow at a subducting slab edge: The South Sandwich arc-basin system, *Earth Planet. Sci. Lett.*, *227*, 17–35.

Livermore, R. (2003), Back-arc spreading and mantle flow in the East Scotia Sea, *Geol. Soc. Spec. Publ.*, *219*, 315–331.

Livermore, R., A. Cunningham, L. Vanneste, and R. Larter (1997), Subduction influence on magma supply at the East Scotia Ridge, *Earth Planet. Sci. Lett.*, *150*, 261–275.

Müller, C. (2001), Upper mantle seismic anisotropy beneath Antarctica and the Scotia Sea region, *Geophys. J. Int.*, *147*, 105–122.

Pearce, D. W., P. T. Leat, P. F. Barker, and I. L. Millar (2001), Geochemical tracing of Pacific-to-Atlantic upper mantle flow through the Drake Passage, *Nature*, *410*, 457–461.

Peyton, V., V. Levin, J. Park, M. Brandon, J. Lees, E. Gordeev, and A. Ozerov (2001), Mantle flow at a slab edge: Seismic anisotropy in the Kamchatka region, *Geophys. Res. Lett.*, *28*, 379–382.

Russo, R. M., and P. G. Silver (1994), Trench-parallel flow beneath the Nazca Plate from seismic anisotropy, *Science*, *263*, 1105–1111.

Russo, R. M., P. G. Silver, M. Franke, W. B. Ambeh, and D. E. James (1996), Shear-wave splitting in northeast Venezuela, Trinidad and the eastern Caribbean, *Phys. Earth Planet. Inter.*, *95*, 251–275.

Savage, M. K. (1999), Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?, *Rev. Geophys.*, *96*, 65–106.

Schoenecker, S. C., R. M. Russo, and P. G. Silver (1997), Source-side splitting of S-waves from Hindu Kush-Pamir earthquakes, *Tectonophysics*, *279*, 149–159.

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

Smith, G. P., D. A. Wiens, K. M. Fisher, L. M. Dorman, S. C. Webb, and J. A. Hildebrand (2001), A complex pattern of mantle flow in the Lau backarc, *Science*, *292*, 713–716.

Thomas, C., R. Livermore, and F. Pollitz (2003), Motion of the Scotia Sea plates, *Geophys. J. Int.*, *155*, 789–804.

Vanneste, L. E., and R. D. Larter (2002), Sediment subduction, subduction erosion, and strain regime in the northern South Sandwich forearc, *J. Geophys. Res.*, *107*(B7), 2149, doi:10.1029/2001JB000396.

Vanneste, L. E., R. D. Larter, and D. K. Smythe (2002), Slice of intraoceanic arc: Insights from the first multichannel seismic reflection profile across the South Sandwich island arc, *Geology*, *30*, 819–822.

Vinnik, L., and R. Kind (1993), Ellipticity of teleseismic S-particle motion, *Geophys. J. Int.*, *113*, 165–174.

B. Bayer, A. Eckstaller, and H. Miller, Alfred Wegener Institute for Polar and Marine Research, Postfach 120161, Bremerhaven, D-27515 Germany.

C. Müller, FIELAX GmbH, Schifferstr. 10–14, D-27568 Bremerhaven, Germany. (mueller@fielax.de)