Lithospheric anisotropy of Northeast Brazil from receiver function analysis

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Abstract

We aim at improving our understanding of the current anisotropic fabrics under northeast Brazil, which may include deformation of the lithosphere from past tectonic processes and on-going mantle flow at asthenospheric levels. We performed receiver function analysis at 75 seismic stations in the Borborema Province of northeast Brazil, and retrieved orientation and depth of the main anisotropic fabrics in the crust and lithosphere. Our results complement a previous SKS-splitting study in the region, which revealed a lack of splitting in the continental interior. We observe the presence of an anisotropic layer between 30 and 60 km depth beneath the seismic stations located in the Borborema Province. The orientation of anisotropy (fast axis for an anisotropic layer or dip for a dipping interface) is perpendicular to the coast beneath stations located along the eastern margin, suggesting the presence of frozen anisotropy in the lithosphere due to stretching and rifting during the opening of the South Atlantic Ocean. More interestingly, stations located in the continental interior also record the presence of seismic anisotropy within the lithosphere. Our findings exclude the absence of plate-scale anisotropic fabrics, as interpreted from unsplit SKS arrivals, and suggest the presence of layered anisotropic structures under the Province.

Introduction

Northeast Brazil has recorded the geodynamic evolution of the continent since (at least) Neoproterozoic times. Understanding the evolution of this region is challenging, because it involves past and current tectonic processes. Deformation during the Brasiliano-Pan African orogeny is well represented by the network of shear zones that scar the Borborema Province (Vauchez et al., 1995; Neves et al., 2000), which separate several tectonic terrains of Paleoproterozoic and Archean age that were amalgamated during the orogeny (Jardim de Sá et al., 1992; Cordani et al., 2003). Major Neoproterozoic shear zones thus constitute inherited structures that could have influenced the geometry of subsequent tectonic processes, such as the opening of the South Atlantic Ocean (Tommasi and Vauchez, 2001; Kirkpatrick et al., 2013). Also, current topography of the Borborema Plateau and the Sertaneja Depression may have resulted from a combination of on-going deep processes, such as edge-driven convection in the asthenospheric mantle and/or stretching and thinning of the lithosphere during Mesozoic times (Oliveira and Medeiros, 2012; Almeida et al., 2015).

Recent seismological studies from receiver functions (Pinheiro and Julià, 2014; Almeida et al., 2015; Luz et al., 2015a,b), ambient noise tomography (Dias et al., 2014), and SKS splitting (Bastow et al., 2015) have contributed to understanding the relationships between inherited Precambrian structures, Mesozoic extensional processes, and episodes of post-breakup volcanism and uplift. In particular, SKS-splitting analysis revealed a marked anisotropic signature in the lithosphere along the Borborema Province's continental margin. Results from this study, however, showed contrasting results between stations located along the coast near the South Atlantic rifted margin, and stations located in the continental interior. On one hand, coastal stations displayed fast polarization directions approximately parallel to Mesozoic extension with delay times between fast and slow S-waves up to 1.6 s, which were related to preservation of fossil deformation in the mantle lithosphere from the breakup of Gondwana. On the other hand, stations located in the continental interior showed no evidence of splitting of the SKS arrivals, which were difficult to interpret due to a combination of poor azimuthal coverage and lack of depth-dependence of the splitting parameters. An absence of plate-scale anisotropic fabrics was deemed unlikely, as multiple deformation processes during the Brasiliano orogeny and stretching in the Mesozoic must have left an imprint in the lithosphere. Depth-dependent anisotropy, perhaps involving two layers of orthogonally oriented fast-axes of anisotropy, was thus proposed as an alternative explanation.

Here, we determine depth-dependent anisotropy in the Borborema lithosphere (crust and mantle) from analysis of receiver functions. Our results confirm that SKS splitting at coastal stations is likely caused by fossil anisotropic fabrics in the lithospheric mantle, likely originating from Mezosoic extension. In the continental interior, our results reveal consistent fast-axis orientation with the major regional shear zones, suggesting their continuation at depth into the lithospheric mantle. The apparent unsplit SKS arrivals could then be explained through the combined effect of perpendicular E-W fossil lithospheric structures and N-S asthenospheric flows, as predicted by global viscous mantle flow models (Conrad et al., 2007).

Data and processing

Receiver functions were developed at 75 seismic stations, including both short-period and broadband sensors, in the Borborema Province. The stations belong to several networks: the *Rede Sismográfica do Nordeste* (RSISNE), the *Instituto Nacional de Ciência e Tecnologia em Estudos Tectônicos* (INCT-ET), the *Institutos do Milênio, the Brazilian Lithosphere Seismic Project* (BLSP), and the

Global Seismological Network (GSN) (Figure 1). Most of the waveforms were developed in previous studies by Luz et al. (2015a) and Almeida et al. (2015). For this study, we developed ~1400 new receiver function estimates, following the same procedures described in detail in Luz et al. (2015a). The vertical components of teleseismic P-wave recordings were deconvolved from the corresponding radial and tangential components. We considered events with magnitude (Mb) greater than 5.0 and occurring at epicentral distances between 30° and 90° from the selected station. The deconvolution removes the effects of the source time function, near-source propagation effects, and the instrumental response from the seismograms. The selected waveforms were windowed 10 s before and 120 s after the P-wave arrival time, demeaned, detrended, and tapered with a 5% cosine window. The waveforms were high-pass filtered above 20 s to remove low-frequency noise and, in order to avoid aliasing, all waveforms were also low-pass filtered below 8 Hz and re-sampled to 20 samples per second (sps). Before deconvolution, the waveforms were low-pass filtered below 1.25 Hz with an acausal Gaussian filter (Gaussian width 2.5). The deconvolution procedure was implemented through the iterative, time-domain procedure of Ligorría and Ammon (1999), with 500 iterations. The deconvolved time series were finally filtered with the same Gaussian filter of width 2.5.

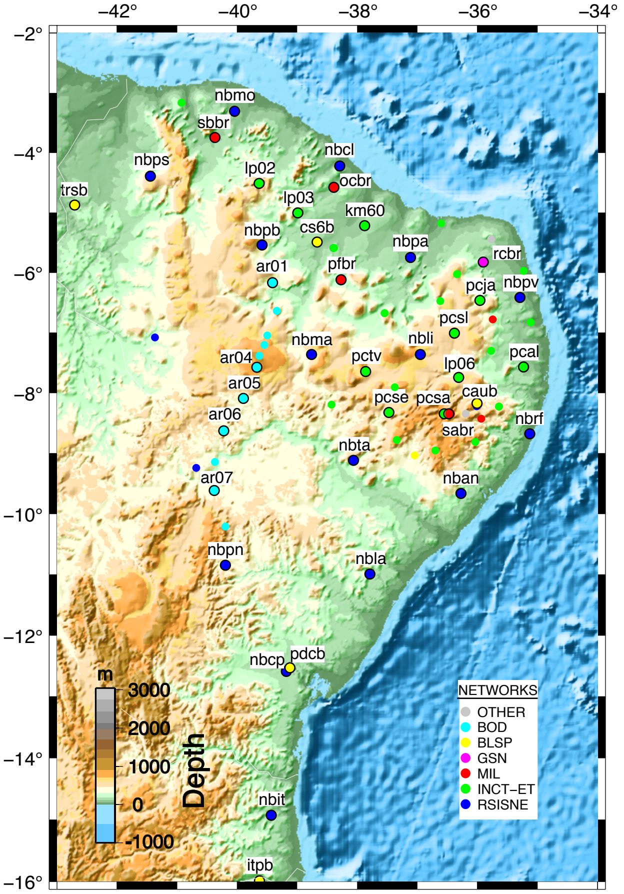

Figure 1: *Topographic map of northeast Brazil with locations of broadband and short-period stations considered in this study. Stations were color-coded by network (see legend). Only the stations shown in this extended abstract have been named.*

Prior to implementing the anisotropy analysis, each radial and tangential receiver function was migrated to depth using the AK-135-F global velocity model (Kennett et al., 1995; Montagner and Kennett, 1996). The purpose of the migration is to correct the phase move-out introduced by varying incidence angles, effectively equalizing the receiver function waveforms in the depth domain (Dueker and Sheehan, 1997).

Method

Stations were considered for anisotropy analyses only when the recorded receiver functions sampled the structure around the station in, at least, a 90° back-azimuth span (either continuously or discontinuously). An example of data processing is shown for station NBMO in Figure 2. For each selected station we first grouped all the receiver functions with back-azimuth within a range of ±5°, and then stack the receiver functions within each group in the depth domain. For example, all radial receiver functions with a back-azimuth between 5 and 15° are stacked and attributed to a median back-azimuth of 10°. Similar stacks were done for the tangential receiver functions. Group-stacked radial and tangential receiver functions for station NBMO are show in Figure 2 in panels "R" and "T", respectively.

We then processed the group-stacked radial and tangential receiver functions (up to 36 bins) following the procedure described by Schülte-Pelkum and Mahan (2014): (1) The azimuthal average of all group-stacked receiver functions is subtracted from the individual group-stacked waveforms at each depth point (see Figure 2, panel "R-R0"); the azimuthal average (R0) represents the isotropic flat-layered structure, from the radial component receiver function; (2) The tangential receiver functions are rotated 90° in back-azimuth (as shown in Figure 2, panel "T(Ø+90)") in order to improve the azimuthal coverage of the radial receiver function (as they should be theoretically identical); (3) the two corrected components are then stacked (see Figure 2 panel "C"); (4) at each 3km point, we calculate the mean amplitude arrival for a 5km-thick layer for every back-azimuth. The largest mean amplitude indicate the depth of the main anisotropy, located at 45 to 50km depth in the case of station NBMO as shown by the vertical green line in Figure 2, panel "C". We then extract the mean amplitude over back-azimuth function and approximate it by a sinusoidal function with a periodicity of 2π and search for which back-azimuth the sinusoidal function is equal to zero. The best solution obtained at station NBMO is shown in Figure 2 by the horizontal green line. We also show few examples of sinusoidal functions estimated to fit the amplitude over-back-azimuth function at station NBMO for the 45 to 50 km depth layer in Figure 3.

The procedure constrains either the strike of the interface or the strike of the plane perpendicular to the symmetry axis in the case of a dipping anisotropic layer (the strike of the foliation plane in the case of slow axis of symmetry). It is possible to discriminate an isotropic, dipping interface from a plunging axis of anisotropy through the presence of an arrival at the surface with the same amplitude pattern but opposite polarity to that of the later arrival. In the case of a horizontal anisotropic layer, however the tangential component is shifted by 45° rather than 90°. In that case, the amplitude over back-azimuth function at each depth point is approximated by a sinusoidal function with a periodicity of π. The back-azimuth for which the sinusoidal function is equal to zero corresponds then to the azimuthal orientation of the fast (or slow) axis of symmetry and the axis perpendicular to it.

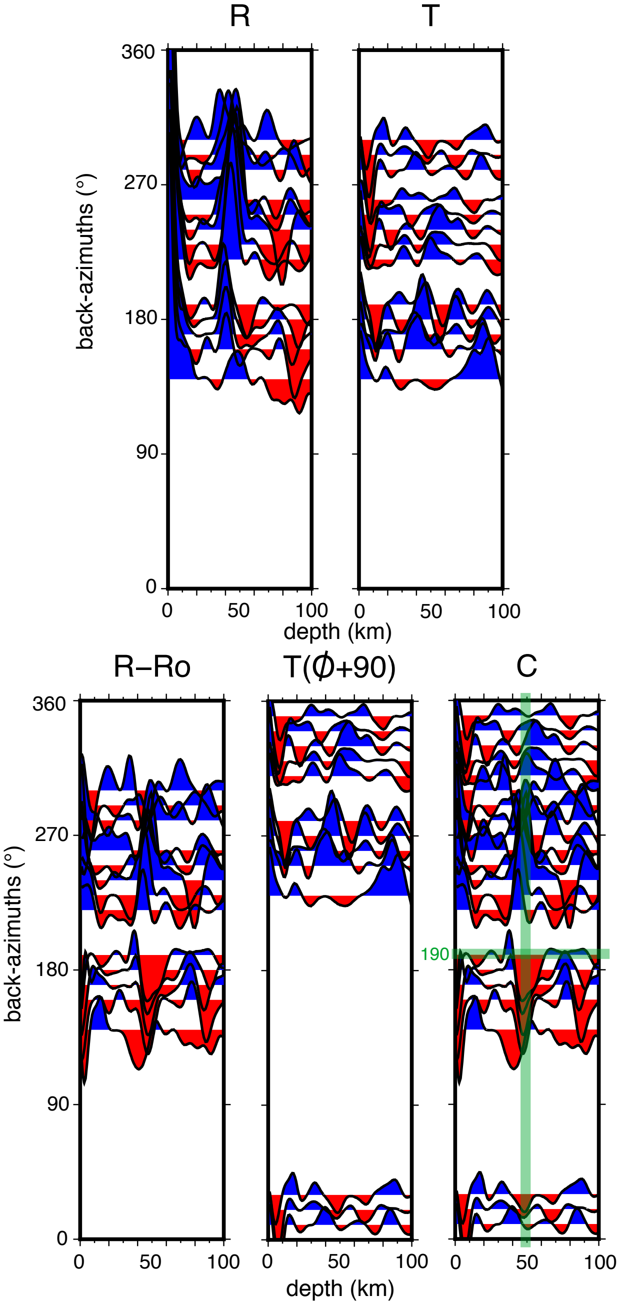

Figure 2: *Receiver functions after migration to depth, shown binned by backazimuth, at station NBMO. Amplitude scale is the same between all panels. R is radial component, T is tangential component, R−R0 is radial component but with azimuthal average removed at every depth step, T (Ø+90) is tangential component shifted by +90° and C is the stacked later two. Green lines mark strike orientation and depth of the largest arrival fitting a sinusoidal function over backazimuth.*

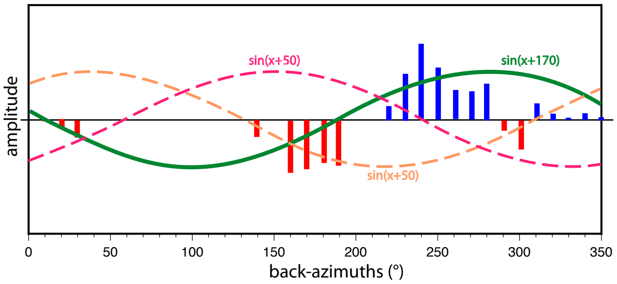

Figure 3: *Examples of sinusoidal functions estimated to fit the amplitude over back-azimuth function at station NBMO. Mean amplitudes for the 45 to 50km depth layer are represented in red (negative) and blue (positive) lines for every sampled back-azimuth. Three sinusoidal are shown. The best fitting solution corresponds to the sin(x+170) function represented in green.*

Anisotropic fabrics in the Borborema Province

Results obtained at the selected stations are shown in Figure 4. The anisotropic layer or dipping interface identified with the method of Schülte-Pelkum and Mahan (2014) represents the strongest region of anisotropy at depth recorded within the lithosphere beneath the station.

A quick inspection of Figure 4 reveals that the large majority of stations record anisotropy close to the Moho discontinuity (between 30 and 60 km deep), either within the lower crust (at stations AR04, PCTV and ITPB) or in the uppermost portion of the lithospheric mantle (remaining stations). Stations located along the eastern margin show anisotropy with a fast axis of symmetry perpendicular to the coast, consistent with measurements from SKS splitting (Bastow et al., 2015). Along the equatorial margin the fast-axis is in the general EW direction, parallel (NBMO, SBBR, CS6B) or oblique (NBCL) to the margin. These directions are consistent with the opening trend of the equatorial margin and the presence of alternate segments of transform and divergent character (Moulin et al., 2010). This observation, however, contrasts with SKS-splitting directions in Bastow et al. (2015), which were oriented with the shear zone at SBBR and parallel to the coast at NBCL. The strong difference in fast axis azimuths between SKS and RFs studies suggests a complex mantle structure beneath these stations, probably composed by several anisotropic layers that recorded deformation from different tectonic events. Nonetheless, general agreement between these two types of anisotropy measurements confirms that the recorded anisotropy beneath coastal stations is mainly located in the lithospheric mantle and that it is related to fossil fabrics developed during the opening of the Atlantic Ocean and the formation of the Brazilian passive margins.

Stations located in the interior also record the presence of seismic anisotropy within the lithosphere. This observation excludes the absence of plate-scale anisotropic fabrics, as suggested by the unsplit SKS arrivals reported in Bastow et al. (2015). The absence of SKS splitting could then be due to the presence of two anisotropic layers (one in the lithosphere and one in the asthenosphere) with perpendicular orientations, resulting in a cancellation effect with an apparent absence of anisotropy. Note that, as reported in Figure 4, the large majority of stations located in the continental interior display a fast axis of anisotropy oriented parallel or sub-parallel to the main E-W to NE-SW shear zone directions (stations AR01, NBLI or NBMA, for example); a few exceptions, however, are observed (stations AR04, PCSE, SABR and PCSA). On the other hand, Conrad et al. (2007) predict viscous mantle flow oriented N-S beneath the Borborema Province. The combination of fossil lithospheric structures oriented E-W and viscous asthenospheric flows oriented N-S could explain the apparent unsplited SKS results previously obtained by Bastow et al. (2015).

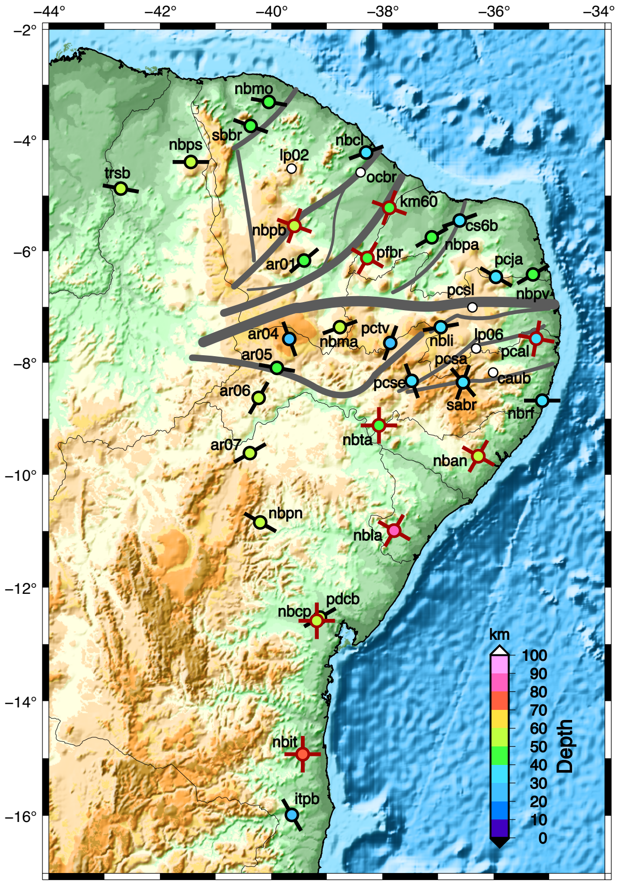

Figure 4: *Topographic map of the Borborema Province with anisotropy parameters determined from the northeast Brazil network. Heavy grey lines represent major shear zones. At each station, the colors scale with the depth of largest amplitudes arrival occurring between the surface and 100km deep. The black lines indicate the fast (or slow) axis of symmetry in the case of anisotropic layer with plunging axis of symmetry, or the azimuth of the interface dip (in the case of dipping interface). The red lines indicate the azimuthal orientation of the fast or slow axis symmetry and the axis perpendicular to in the case of anisotropic layer with horizontal axis of symmetry.*

Finally, realize that the consistency of the fast axis direction of anisotropy with local structures suggest a continuation of the main shear zones into the lithospheric mantle (Vauchez et al., 2012).

Conclusions

The study of lithospheric anisotropy from receiver functions in northeast Brazil reveals the presence of quasi-systematic lower crust to upper lithospheric mantle anisotropy from 30 to 60 km depth. Our results allowed an assessment of earlier interpretations of anisotropic fabrics formulated by Bastow et al. (2015) from splitting of SKS waveforms in the same region. We show that coastal stations along the equatorial and eastern rifted margins display anisotropy with an axis of symmetry sub-parallel to Mesozoic extension, confirming the imprint of the rifting process at lithospheric levels in the continent. Our study also reveals the presence of anisotropy within the lithosphere at stations located in the continental interior, with a fast axis oriented E-W to NE-SW generally consistent with the direction of the main shear zones in the region. This observation advocates for a rooting of the major Neoproterozoic shear zones in the lithospheric mantle. Moreover, when combined with N-S oriented asthenospheric flow (as predicted by global viscous mantle flows models), the unsplit SKS observations reported by Bastow et al. (2015) are explained through a cancellation effect.

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