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Interactive comment on "Lithospheric and sub-lithospheric deformation under the Borborema Province of NE Brazil from receiver function harmonic stripping" *by* Gaelle Lamarque and Jordi Julià

Gaelle Lamarque and Jordi Julià

gaelle.lamarque@ifremer.fr

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In order to make answers as clear as possible, we copy in black the reviewer comments, and answer with blue color. Proposed changes in the original text are indicated in red.

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Review of Lamarque and Julia, Solid Earth Discussions, 2019

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Discussion paper

This paper calculates teleseismic P-wave receiver functions to investigate the depth dependence of seismic anisotropy in the crust and lithospheric mantle in NE Brazil. The analysis considers the back-azimuth variations in observed receiver function signal and performs a harmonic decomposition to provide a quantitative estimate of anisotropy in terms of: 1) a plunging axis of symmetry and/or dipping interface; or 2) a horizontal axis of symmetry. The depth decomposition of the anisotropy is able to retrieve the average anisotropy in the crust and lithospheric mantle. The results show consistent anisotropy in the crust and mantle, indicating a control by lithospheric-scale shear zones that develop during the Brasiliano-Pan African orogeny. The lack of well characterized anisotropy at some stations is taken as an indication of re-heating of the lithosphere by an asthenospheric channel. Stations along the Atlantic coast resolve fast anisotropic directions perpendicular to the margin, suggesting lithospheric inheritance during rifting.

General comments:

The paper compiles all available receiver function (RF) data and calculates new RF data for 11 recently installed stations. The RF analysis is adequately described and follows the standard procedures to obtain high-quality data. The novelty of this paper lies in the application of the harmonic decomposition to reveal depth-dependent anisotropy from back-azimuthal variations in the amplitude of both radial and tangential components of RF data, for individual stations. The results are discussed in an appropriate way, although part of the methodology lacks reference to original work that implemented variants of the technique (see specific comments). The condition for rejecting anisotropy (and therefore interpreting the subsurface structure as isotropic) could also be subject to debate. Overall the paper addresses an important question about the structure of fabrics beneath NE Brazil in relation with lithospheric inheritance and the significance of lithospheric-scale shear zones.

We greatly thank the reviewer for a detailed reading of our manuscript. In particular, we appreciate the remark on our interpretation of the stations with large variability in anisotropic parameters, which helped us improve our interpretation of the results and their geodynamic implications.

Specific comments:

The discussion of RF analysis is appropriate and includes proper referencing up to line 19 on page 7. There the authors describe an additional preliminary step in the harmonic decomposition analysis, where they migrate the time signals to depth using a 1D seismic velocity model to correct for the move-out of teleseismic waves. The migration to depth (before harmonic decomposition) was first proposed by Bianchi etal. (2010), who performed common-conversion (CCP) stacking using a dense line of stations and carried out the decomposition at CCP points. This method was further applied in Piana Agostinetti et al. (2011) and Piana Agostinetti and Miller (2015). The step proposed here by the authors (converting time to depth at individual stations, as opposed to CCP stacking), was proposed by Audet (2015) and further applied in Cossette et al. (2016) and Tarayoun et al. (2017). The optimization of energy on one of the k=1 components (as done here) was also proposed by Audet (2015) to retrieve the dominant angle of anisotropy.

The reviewer is correct when pointing out that migration before harmonic stripping was already proposed in previous works. We have added the missing references to the updated manuscript. The proposed change in the text is:

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"Prior to implementing the anisotropy analysis, each radial and tangential receiver function was migrated to depth after P to S ray-tracing through the global velocity model ak135-f (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 among the incoming teleseismic P-wavefronts, effectively equalizing the receiver function waveforms in the depth domain (Dueker and Sheehan, 1997).Migration before harmonic stripping at individual stations was previously utilized by Audet (2015), Causette et al. (2016) and Tarayoun et al. (2017). Similarly, Bianchi et al (2010), Piana Agostinetti et al (2011), and Piana Agostinetti and Miller (2015) applied harmonic decomposition on depth-migrated cross-sections obtained through CCP stacking of receiver functions. Next, the migrated radial and transverse receiver functions for each station were grouped by back-azimuth in 36 non-overlapping, ..."

On page 10, the authors discuss the reliability of the anisotropic directions using a bootstrap analysis and consider that a measurement is unreliable if the bootstrap uncertainty is greater than 20 degrees. The bootstrap analysis returns an estimate of the standard error on the mean value on modeled parameters (such as the dominant angle of anisotropy), and confidence intervals are normally calculated from the standard error. Is this what is meant by “uncertainty” here? Is it 1-sigma (68% confidence) or 2-sigma (95%)?

Uncertainties refer to the 2-sigma standard error obtained from a population of 200 angle estimates developed from bootstrapping the original dataset. Additional text will be added to the manuscript to clarify that point:

"In order to estimate uncertainties, we applied a bootstrap statistical approach by randomly re-sampling with replacement our receiver functions. We performed such analysis with 200 replications at each of the selected stations.From these 200 values,

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we estimated the standard error (2-sigma), which corresponds to the uncertainty in the direction of the fast-axis of symmetry.A measurement is considered as not reliable, and then rejected, if the estimated uncertainties are larger than 20°

Furthermore, large variability in the recovered angle might not necessarily imply that the medium is isotropic. Strong structural heterogeneity might produce large-amplitude signal with apparent back-azimuth distribution with k>2. Alternatively, crystal symmetries might not always produce seismic anisotropy that can be modeled with the k=1 or k=2 components. So, it is still of interest to show the strength of the signal on the k=1 and k=2 energy components despite the large variability in bootstrap angles. Following up from this comment, Figure 6 could be improved by plotting the relative amplitude of the corresponding energy components. On the maps, the anisotropy (length of bars) appears to be equal in magnitude at all stations, though I suspect that the energy components vary significantly from one station to another and regionally. This additional piece of information could also be included in the Discussion and compared with SKS splitting results. Finally, it would be insightful to look at the receiver functions before application of the harmonic decomposition (e.g., in back-azimuth panels) to see why the “unreliable” stations have large uncertainty in anisotropic direction. This could be added to the Supplementary Information.

The reviewer is correct that large variability in the recovered angles at ÂńunreliableÂż stations is not necessarily related to weak anisotropy under those stations. Following her/his advice, we have now calculated the energy and inspected transverse component amplitudes in detail. We found that energy at the “unreliable” stations is as strong as that found at the “reliable” ones (see results for station cs6b in the additional supplementary material). To make this clear, Figure 6 has been updated to display energy level at each station (for clarity reasons, we prefer to keep constant bar lengths and denote energy through color-coding the station symbol). The new legend for

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Figure 6 will be:

Figure 6: A) Map of symmetry directions (dark lines) obtained for the crust (0-32 km). When one line is plotted at the station, it represents either the trend of the dip, in the case of dipping interface, or the trend of the fast axis in the case of plunging anisotropy. When two lines are plotted, they refer to the fast axis and to its perpendicular direction for horizontal anisotropy. Light colors represent 2ïĄş uncertainties estimated from the bootstrap (after re-sampling 200 times). B) Same as for the lithospheric mantle (32-100 km).Station symbols have been color-coded according to the energy level of the dominant harmonic degree.

Thus, we believe the non-azimuthal anisotropy recorded at stations located along this trend is more likely related to complex fossil anisotropic fabrics resulting from a combination of deformation along the ancient collision between Precambrian blocks, Mesozoic extension, and thermo-mechanical erosion/mantle dragging by sub-lithospheric flow.

Modifications within the manuscript:

5.3. Non-azimuthal anisotropy along the aborted Cariri-Potiguar rift

At a number of stations (ar05, nbma, pfbr, nbpa, cs6b), uncertainties for the direction of the fast axis of anisotropy are larger than 20.Interestingly, those stations seem to form a remarkable line trending NE-SW that approximately coincides with the location of the Cariri-Potiguar trend. Stations nbta and pcse also seem to align along the same direction more to the East.. This NE-SW oriented line is located above a NE-SW trending channel of thin lithosphere imaged by the tomographic study of Simões Neto et al. (2019). We suggest that deformation from thermo-mechanical erosion by horizontal, sub-lithospheric flow along the channel - also postulated by Simões Neto et al. (2019) - must be ongoing above this NE-SW channel. Also, as initial thinning of the lithosphere along the channel was triggered by Mesozoic extension along the Cariri-Potiguar trend, alterations to the original Precambrian anisotropic fabric by Mesozoic extension might still be present. Additionally, we note that the location of the Cariri-Potiguar trend also marks the boundary between the EW striking shear zones in the southern Province from the NE-SW striking shear zones in the western Province (Figure 1). This suggests the Cariri-Potiguar trend also marks the location of a former paleo-suture that later acted as a zone of weakness along which the Mesozoic rift (now aborted) could develop. Thus, we believe the non-azimuthal anisotropy recorded at stations located along this trend is likely related to complex fossil anisotropic fabrics resulting from a combination of deformation along the ancient collision between Precambrian blocks, Mesozoic extension, and thermo-mechanical erosion/mantle dragging by sub-lithospheric flow.

Technical corrections:

Page 8, line 3: “presents” -> present.

Done.

Page 10, lines 6 and 10: the interval “[0,2]” ->. Do you mean [0, 2pi]?

Yes, it’s been modified accordingly

Page 11, line 2: “Realize that” -> We note that

Done.

Page 12, line 3: “mantellic” -> mantle

Done.

Caption of Figure 6. It’s not clear to me why the direction perpendicular to the fast axis is required in the case of horizontal anisotropy. Is it to differentiate between k=1 and k=2 directions? Which one of the two is the fast axis?

In the case of anisotropy with pure horizontal fast axis of symmetry, the energy is only on the k=2 harmonics and receiver functions display a 4-lobed back-azimuthal pattern. A synthetic example of that case is visible in Schulte Pelkum and Mahan (2014), Figures 2a and 3a. This 4-lobed back-azimuthal pattern implies maximum amplitudes for 4 directions, which correspond to: (i) the direction of the fast axis of symmetry, (ii) the direction opposite to the fast-axis of symmetry, (iii) the direction perpendicular to the fast axis of symmetry, and, (iv) the direction opposite to the perpendicular. It is thus not possible to discriminate between the fast axis of symmetry and the direction perpendicular to it through analysis of the k=2 harmonics.

Page 14, line 14: “Bastow et al. (2011); Assumpçao et al. (2011)” -> Bastow et al.(2011) and Assumpçao et al. (2011)

Done.

Page 14, line 22: “sensible” -> sensitive

Done.

References (not appearing in paper):

Cossette et al.: Structure and anisotropy of the crust in the Cyclades, Greece, using receiver functions constrained by in situ rock textural data, J. Geophys. Res., 121,2661-

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2678 (2016). Piana Agostinetti et al.: Fluid migration in continental subduction: The Northern Apen-nines case study, Earth Planet. Sci. Lett., 302-267-278 (2011).

Piana Agostinetti and Miller: The fate of the downgoing oceanic plate: Insight from the Northern Cascadia subduction zone, Earth Planet. Sci. Lett., 408, 237-251 (2015).

Tarayoun et al.: Architecture of the crust and uppermost mantle in the northern Canadian Cordillera from receiver functions, J. Geophys. Res., 122, 5268-5287 (2017).

All the missing references have now been added to the reference list.

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