SBGF00097

Upper Mantle Seismic Velocity Structure Beneath SE Brazil From P- and S-Wave Travel Time Inversions

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Abstract

We present preliminary results from teleseismic travel time inversions for P- and S-wave data mainly recorded at portable broadband stations in SE Brazil. The stations have been employed at more than 27 sites within an area of 500 km x 1000 km during the years 1992 - 1998. More than 3800 relative P- and 3900 relative S-wave arrival times, including core phases, have been obtained from the waveforms simultaneously recorded at 4 or more stations. The model is parameterized by splines under tensions and the P and S relative phase times are independently inverted for slowness perturbations, earthquake relocations, and station corrections. The final models represent the least amount of structure required to explain the residuals within a defined standard error. The results confirm the existence of a fossil plume conduit, permit a more detailed separation of geological structures and velocity perturbations down to about 1000 km depth.

INTRODUCTION AND MOTIVATION

A prime tool to illuminate mantle structure is seismic tomography. Although it lacks the resolving power to constrain mantle discontinuities it provides us with images of the long and intermediate scale structure which are evidence for the dynamics of the slowly cooling Earth. We use this tool and invert teleseismic travel times to image the P- and S-wave velocity perturbations under SE Brazil. A motivation is to determine the tectonic regimes and to better understand the forces and geological evolution of the continent. This study is a continuation of VanDecar et al. (1995) who revealed a shallow high-velocity region beneath the São Francisco craton, deep high velocities to the southwest, and a low-velocity cylindrical structure in the upper mantle to a depth of at least 500 - 600 km. The cylindrical structure has been interpreted as the fossil conduit through which the initial Tristan da Cunha plume head traveled to generate the Parana flood basalts. This structure continues to lie beneath the Parana basin indicating that the upper mantle has been in coupled motion with the overlying plate since the opening of the South Atlantic Ocean. The increased aperture of the seismic network, with more station sites and a larger data set, permit a more detailed separation of geological structures such as the São Francisco craton and an extension of the study to larger depths. The greater resolution at depth is important for determining the base of the inferred conduit and therefore for characterizing the coupling between upper and lower mantle beneath SE Brazil.

STATIONS, DATA BASE AND DATA PROCESSING

The stations have been employed at more than 27 sites within an area of about 500 km x 1000 km during the years 1992 - 1998. Up to 13 stations have been in operation at any time and almost all stations are equipped with three-component broadband seismometers. Most stations are from a joint project (BLSP92) of the Carnegie Institution of Washington and the University of São Paulo (USP) and from a continuation of this project by the USP (BLSP95). Figure 1 shows a map with the station locations used so far to create a relative travel time data base. The triangles, squares and circles mark the locations of stations from the BLSP, the University of Brasilia (UnB), the Global Telemetered Seismic Network (GTSN), and GEOSCOPE. One short period station (open circle) was used to increase the P-wave data set.

Data selection. We selected high quality P and S phases from events at angular distances between 30^o and 95^o with body wave magnitude (m_b) larger than 4.6. For this distance range, the P and S-waves turn in the lower mantle. Thus we avoid difficulties with the upper mantle triplications and the non-linearity of the ray path for turning points, where the heterogeneities are strongest. In addition, we picked events which permit an unambiguous detection of ScS, PKPdf, SKSac, and SKKSac phases. These core phases propagate to the stations along steep paths.

Relative travel time picking. The data used in the inversion are relative arrival times of P- and S-waves simultaneously recorded at 4 or more stations. An adapted version of the 'multi-channel cross-correlation' (mccc) technique of VanDecar and Crosson (1990) was used to determine relative arrival times. This mccc-technique uses all possible pairs of waveforms and solves in the least square sense for the best set of relative arrival times for all stations. We incorporated a new cross-correlation function (Schimmel, 1998) into the mccc-technique and call this modified derivative mcpcc. Figure 2 shows an

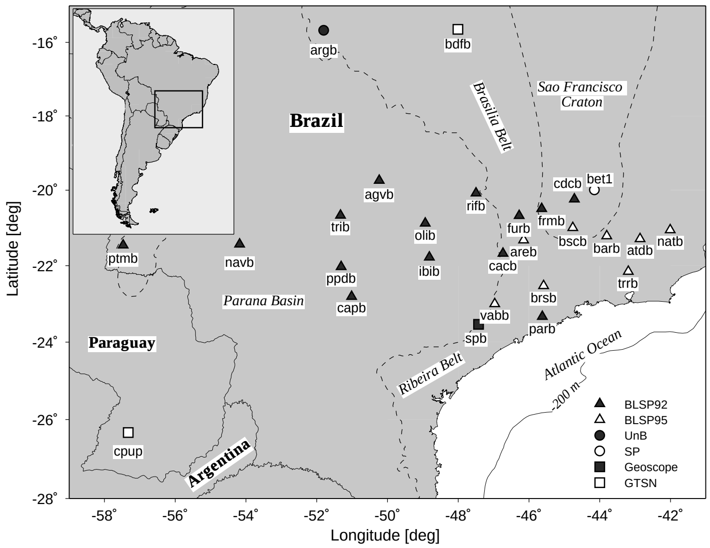

Figure 1: Map with seismic stations used for the relative arrival time data set and gross geological provinces.

example of the picking procedure using an event at the North Atlantic ridge (1996 October 6, 13.23 ^{o}N 44.97^{o}W, 10 km depth, m_b = 5.1). The epicentral distance to station spb is 36.7^o. Figure 2a shows the unfiltered vertical recordings from 5 broadband stations. The seismograms have been aligned with respect to their theoretical P-wave arrival time. Note the identification of the P phases requires the use of appropriate filters to the data. Figure 2b shows the data after band-passing (0.8 - 1.6 Hz) and application of the mcpcc-technique to determine the relative arrival times. The data are now aligned with respect to their relative times. In Figure 2c they are plotted on top of each other to demonstrate the correctness and quality of their alignment. We perform this analysis at different frequency bands and for different cross-correlation windows to be sure to achieve robust relative time measures. The uncertainties of the measurements depend on the amount of noise and other signals which interfere with the considered waveforms. The standard deviations of the time measures obtained for different filter and window settings are less than 20 ms for registrations with quality similar to the data of Figure 2. Presently, we determined the relative phase times for 3109 P (509 events), 694 PKP (102 events), 2427 S (395 events), 360 ScS (60 events), 463 SKS (76 events), and 658 SKKS (106 events) arrivals. The standard deviation for relative P- and S-wave times are 0.41 s and 1.12 s, respectively.

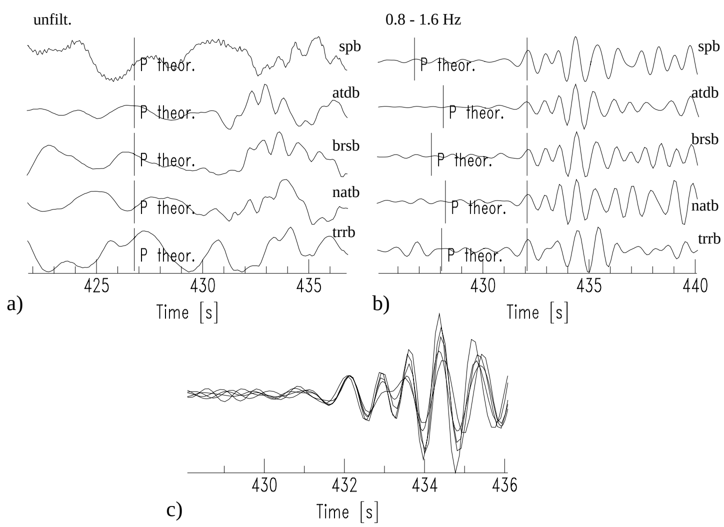

Figure 2: a) Unfiltered vertical component broadband recordings for an event at the North Atlantic ridge. The traces are aligned with respect to their theoretical P-wave arrival time. The time axis corresponds to the top trace from station spb. b) Same as a), but the data have been band-passed (0.8 - 1.6 Hz) and aligned with respect to their relative arrival times. c) The recordings from b) are overlayed to show signal coherence.

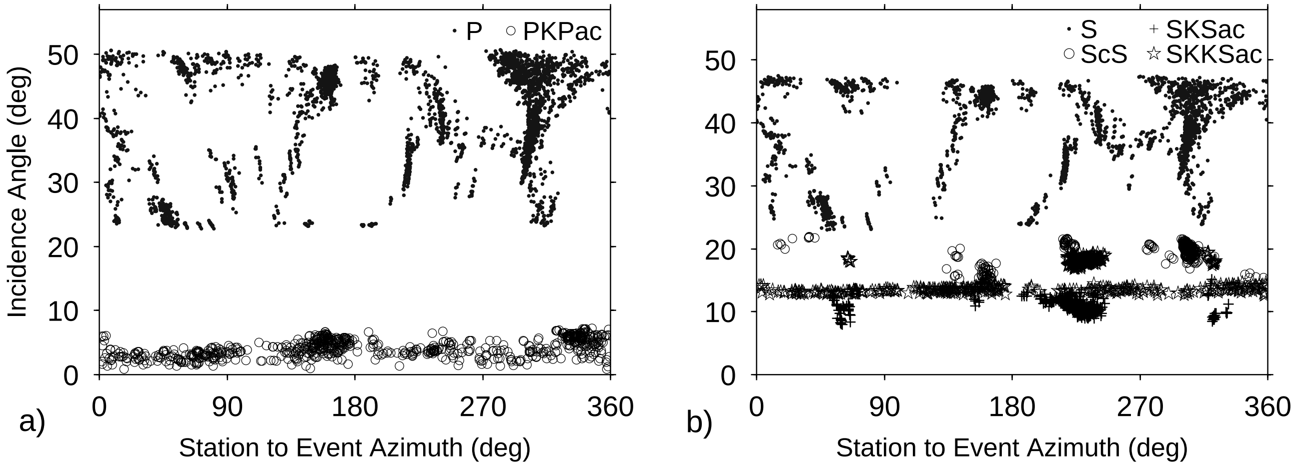

Figure 3: Distribution of ray incidence angles at 400 km depth and back azimuths for the P- (a) and S-wave (b) data set. The band-shaped occurrence of incidence angles is due to the selected distance ranges.

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The picking is performed at a high frequency band since a high frequency approximation of wave propagation (ray theory) is applied in the inversion procedure. The most common frequencies used for the P arrivals range between 0.8 Hz and 2.5 Hz. The corresponding seismic wavelengths in the upper mantle are smaller than 12 km.
The identification of the S phases is more difficult owing to larger noise on the horizontal components and larger attenuation along the wave paths. Therefore, we are restricted to low frequencies. The lowest frequency band used is from 0.05 Hz to 0.1 Hz with corresponding wavelength of about 60 km. Generally higher frequency bands could be applied which decreased the seismic wavelength to 40 km or less. As consequence, we are able to image structure with smallest wavelengths of about 100 km. Smaller scale structures can only be resolved using the P-wave data set.
Ray coverage. Figure 3 shows the corresponding ray incidence angles at the depth of 400 km as function of back azimuth. The band-shaped distribution of the ray incidence angles is owing to the selected distance ranges. A large distribution of angles guarantees that the ray paths criss-cross at high angles which permits to isolate anomalies in the travel time inversion. The resolution is primarily a function of the ray distribution.

THE TRAVEL TIME INVERSION

The inversion follows the approach described by VanDecar et al. (1995).
Model parameterization. The model perturbations underneath the stations are parameterized by splines under tensions (Neele et al., 1993) which are pinned at a series of regular knots. This interpolation scheme allows for a smooth slowness distribution and accurate ray tracing. The considered volume extends from -31 ^{o} to -11^o in latitude, -63^o to -36^o in longitude, to 1600 km in depth. A fine grid with $\frac{1}{3}$ degree node spacing is defined for latitudes between -28 ^{o} and -14^o, longitudes between -60^o and -39^o, and down to a depth of 700 km. A total of 89280 nodes are used to parameterize the slowness perturbations.
Assumptions. The travel time inversions are based on the assumptions that the velocity perturbations are weak and that the seismic energy travels on a ray path to the stations. The forward problem has been linearized based on the assumption of weak perturbations. This means it is expected that the true rays and earthquake locations are linearly close to the initial guess.
Inversion. The P- and S-wave relative phase times are independently inverted for model perturbations, earthquake relocations and station corrections. The linear problem is under-determined which means that the inversion is non-unique. Occam's philosophy is followed to search for the model with the least amount of structure to explain the relative time residuals within a defined standard error. Numerically, the conjugate gradient method is employed for the inversion. Several inversions are iteratively performed which systematically down-weight the large outlying residuals. This approach leads to a robust solution with L2 residual minimization within 1.5 residual standard deviations and L1 minimization of the equations with larger residuals.

DISCUSSION OF PRELIMINARY RESULTS

Figure 4a shows a horizontal cross-section at a depth of 300 km through a preliminary S-velocity perturbation model. The squares indicate the stations used for the inversion and the white line (AA') shows the location of the vertical cross-section from Figure 4b. The gray shaded areas indicate the velocity perturbations. Lower than average velocities are displayed with a light gray tone. The vertical cross-section starts at 50 km depth since shallow structures are difficult to be resolved. This is owing to the absence of crossing ray path just underneath the stations.

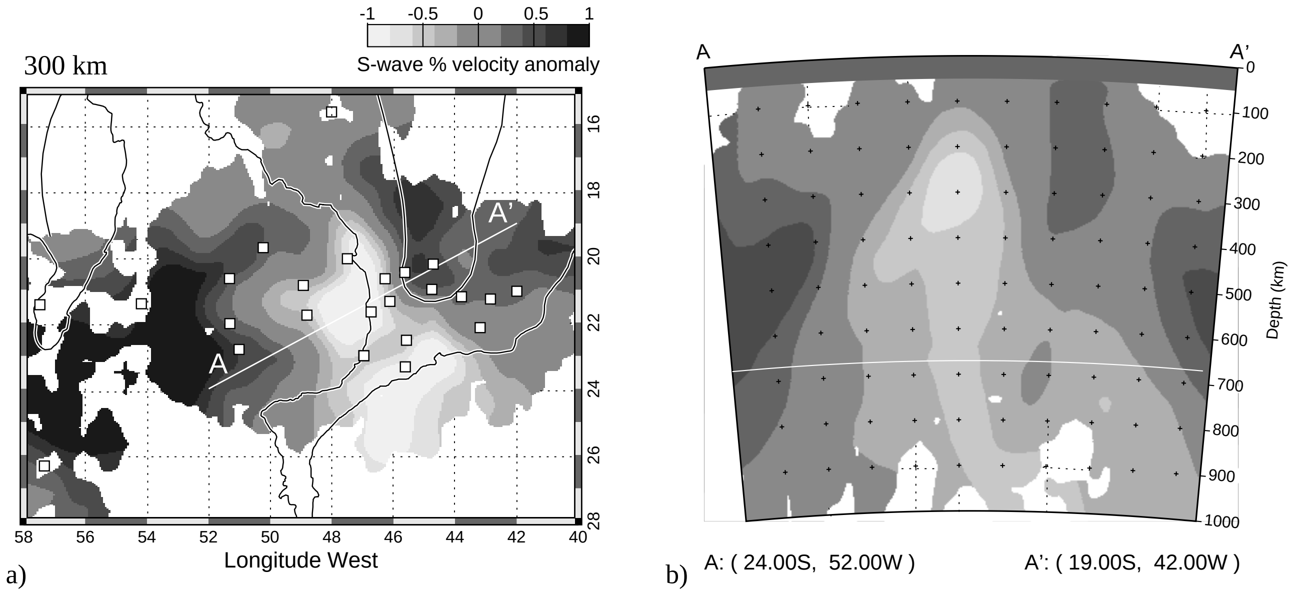

Figure 4: Cross-section through a preliminary S-velocity perturbation model at 300 km depth (a) and vertical cross-section (b) at the location of the white line AA'. Squares mark the stations used and the dotted lines indicate the region with poor resolution, with ray density lower than 30 rays per (100 km)^3. The white line in Figure b marks the postion of an unperturbed 660-km discontinuity. (During the oral presentation we present colored cross-sections.)

The low-velocity structure in the middle of the images (Figure 4) is the fossil plume conduit revealed by VanDecar et al. (1995). The initial Tristan da Cunha plume head traveled through this conduit to generate the Parana flood basalts before the opening of the South Atlantic Ocean. The opening of the ocean 130 Myr ago and the motion of the South American plate over several thousand kilometers did not prevent the persistence of the plume trace underneath the Parana basin. This implies that the upper mantle is in coupled motion with the overlying South American plate.
The employment of the BLSP95 stations drastically improved the snapshot of the much older and colder S ão Francisco craton which is visible as high velocity anomaly at the northeast side of the fossil conduit. The S ão Francisco craton seems to extend to a depths of 300 to 400 km.

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ACKNOWLEDGMENTS

The data are from GTSN, GEOSCOPE, UnB, and BLSP stations and we are grateful to all the researchers and technicians who somehow contributed to this data. This work is supported by the FAPESP (Fundaç ão de Amparo à Pesquisa do Estado de São Paulo) grants 97/03640-6 and 97/04780-6 and CNPq-grant 30.0227/79.