Lithospheric Architecture of the Paranapanema Block and Adjacent Nuclei Using Multiple-Frequency \( P \)-Wave Seismic Tomography

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Abstract We present a new \( P \)-wave seismic tomographic model for the region of the Paraná Basin and surroundings using a multiple-frequency approach, providing better resolution than previous regional studies. We processed a total of 62,692 cross-correlation delays for \( P \), PKIKP, \( PcP \), and PP phases distributed among 1,081 events using six different central frequencies (0.03, 0.06, 0.13, 0.25, 0.50, and 1 Hz). We merged our data with a previous multiple-frequency study of the Amazonian Craton to cover regions outside of the study area, obtaining a total of 75,187 cross-correlation delays. The data used are from the stations of the Brazilian Seismographic Network, and mainly from a temporary network (XC network) installed exclusively to study the region. The basement of the Paraná Basin is represented as a NE-SW trending \( P \)-wave high-velocity anomaly, extending from the northern limit of the basin to the southwestern border of Brazil, consistent with previous reports. The limit between this block and the São Francisco Craton is characterized by decreased amplitude of the \( P \)-wave high-velocity anomaly. Synthetic tests show that a narrow boundary between these two blocks displays the same behavior. At the southeastern portion of this anomaly, decreasing amplitude is consistent with the limit of the Luiz Alves Craton, which was also corroborated by synthetic tests. The northern portion of the Rio Apa Block agrees with a previous tomographic model, confirming that it does not extend under the Pantanal Basin, however, in our model this structure does not extend as far south.

1. Introduction

The basement of the Paraná Basin (PrB—Figure 1) has been a subject of discussion in many studies. Cordani et al. (1984, 2009) and Mantovani et al. (2005) proposed a single cratonic block under the basin’s center, although they disagree about its boundaries. Milani and Ramos (1998) suggested a basement formed of fragmented cratonic blocks surrounded by mobile belts, supported by the study of Julià et al. (2008) using receiver functions and Rayleigh-wave dispersion. Proposed by Dragone et al. (2017), the Western Paraná Suture Zone (WPSZ—Figure 1) extends from the southeast Brazilian continental margin to the northeast of the Pantanal Basin (PtB—Figure 1), marking the Neoproterozoic boundary between the Paranapanema Block (PB—Figure 1), to the east, and the Rio Apa, Rio Tebicuary, and Rio de la Plata cratons (RAC, RTC, and RDLPC, respectively—Figure 1), to the west. The ambient noise tomography study of Shirzad et al. (2020) concluded that the Chaco-Paraná (ChB—Figure 1) and Paraná basins have distinct crustal properties, being separated by a zone partly consistent with the WPSZ.

With the use of a recent temporary network in southwestern Brazil (XC network, “3-Basins Project”), deployed since 2016 and funded by FAPESP (São Paulo Research Foundation), and the use of data from the Brazilian Seismographic Network (RSBR—Bianchi et al., 2018), new \( P \)-wave tomography results could be achieved to image the upper mantle beneath the Paraná Basin and adjacent areas. A recent tomographic study in the region (Rocha, Assumpção, et al., 2019) improved tomographic images relative to previous studies (Rocha et al., 2011; Schimmel et al., 2003), extending the imaged area west and south to entirely image the Pantanal and Paraná basins and the northern portion of the Chaco-Paraná Basin. The improved resolution allowed the authors to discuss the limits of the Paranapanema Block, the geometry of the Rio Apa Craton and its relationship with the basement of the Pantanal Basin, and the implications of thick
Although the study of Rocha, Assumpção, et al. (2019) provided good resolution for the central and northern portions of the Paraná Basin, Brasilia Belt (BrBe—Figure 1) and southern São Francisco Craton (SFC—Figure 1), the areas south of 29°S and west of 56°W, where the stations were installed recently and are located near the edges of the array, could not be satisfactorily sampled, severely affecting the interpretation. In addition, that work is based on ray theory, in which the seismic sensitivities are concentrated on the seismic ray (assumption of infinite frequency), further limiting the resolution.
Contrary to ray theory-based tomography, in Multiple Frequency Tomography (MFT, Sigloch et al., 2008) the seismic information is distributed in a volume around the seismic ray, sampling a larger region compared to one sampled only by the seismic ray and improves the resolution of the tomographic models. MFT is based on the theory developed by Dahlen et al. (2000), in which the wave's frequency content, healing and diffraction effects are taken in consideration to get the travel-time measures, resulting in frequency dependent Fréchet Kernels, also called Banana-Doughnut Kernels (Marquering et al., 1999). This method was recently used by Costa et al. (2020) in Brazil to study the Amazonian Craton, providing tomographic images with higher resolution than the works done in the region with ray theory (Azevedo, 2017), allowing the discussion of the compartmentation of that craton and its metallogenic implications.

In order to improve the resolution of the tomographic images in this study, we used MFT to image the mantle beneath the Paraná Basin and its surrounding areas. Our objectives were to define the geometry of its basement and the relationship with the surrounding blocks and to discuss the tectonic implications. Our study area (Figure 1) is similar to that of Rocha, Assumpção, et al. (2019), and is located in the central portion of the South American Platform (SAP), focusing on the basement of the Paraná, Chaco-Paraná, and Pantanal basins.

2. Geology

2.1. Tectonic Setting

The SAP basement is composed of Archean and Proterozoic cratonic blocks connected by Neoproterozoic Brasiliano mobile belts and is separated by the Transbrasiliano Lineament (TBL—Orange dashed line in Figure 1) into two large domains: the Amazonian Domain, north of the TBL and related to Laurentia; and the Brasilian Domain (or Extra-Amazonian), south of the TBL and related to west Gondwana (Brito Neves & Fuck, 2014; Cordani & Sato, 1999). The Paraná Basin, located mostly south of the TBL, is a Paleozoic intracratonic basin with flood basalts dating to the Mesozoic (immediately before the South Atlantic rift) throughout the entire basin (Almeida et al., 2000; Cordani et al., 1984). The Chaco-Paraná Basin is a Paleozoic intracratonic basin with flood basalts from the Mesozoic in its northeastern portion (Almeida et al., 2000). The Paraná and Chaco-Paraná basins are separated by the Asunción and Rio Grande arches, ASA and RGA in Figure 1, respectively (Rosa et al., 2016). The Pantanal Basin is a Quaternary basin located mainly in the western portion of Brazil, with faults related to the Transbrasiliano Lineament. The formation of the basin is a matter of debate, with Ussami et al. (1999) proposing that the basin's depression is related to the extensional stresses from the loads in the Andes. Alternatively, Assumpção and Suarez (1988) and Dias et al. (2016) characterized the seismicity in the basin as reverse faults, incompatible with an extensional system.

2.2. Basement of the Paraná Basin

The first model for the Paraná Basin's basement, proposed by Cordani et al. (1984) through geochronological dating from borehole samples and geological inferences, suggest a single cratonic block in the basin's center. Using gravimetric data, Mantovani et al. (2005) proposed the existence of a single block with a SSW-NNE orientation that is much larger than the craton proposed by Cordani et al. (1984), calling it the Paranapanema Block. The study of Cordani et al. (1984) was later updated by Cordani et al. (2009), who propose a Paranapanema Block similar to Mantovani et al. (2005), with a SW-NE direction (Figure 1), that is separated from the Luiz Alves Craton (LAC—Figure 1) by the Apaiá Belt (ApBe—Figure 1). The regional tomography study of Rocha, Assumpção, et al. (2019) proposes a model similar to Mantovani et al. (2005), suggesting a single cratonic block, but shifted to the southwest (Blue dashed line in Figure 1). Another model for the basin's basement by Milani and Ramos (1998) states that the existence of a stable domain in the region of the syneclysis is incompatible with the basin's subsidence. In this model, the basement is formed of a mosaic of cratonic blocks surrounded by mobile belts. To the west of the Paraná Basin, Dragone et al. (2017) propose that the Pantanal Basin's basement is entirely formed of the Rio Apa Craton, an exposed part of the Amazonian Craton (AmC—Figure 1, Faleiros et al., 2016; Lacerda-Filho et al., 2016).
2.3. Basement of the Chaco-Paraná Basin

The basement of the Chaco-Paraná Basin is formed mostly of the Rio de la Plata Craton and, as suggested by Dragone et al. (2017) through gravimetric data, of the Rio Tebicuary Craton. The limits of the RDLPC are a matter of debate, with four main models being discussed. While Rapela et al. (2011) and Oyhantçabal et al. (2011) place the RDLPC northern limit (purple and light blue dashed lines in Figure 1, respectively) to the south of the Ibaré Shear Zone (ISZ—Figure 1), the models of Rapela et al. (2007) and Dragone et al. (2017) suggest its continuity beyond this zone, placing it near the southern limit of the Paranapanema Block proposed by Mantovani et al. (2005). The recent tomographic model presented by Rocha, Assumpção, et al. (2019) agrees with the first case. Using gravimetric data, Dragone et al. (2017) also propose the existence of the Western Paraná Suture, a suture zone extending from the southeast Brazilian continental margin to northeast of the Pantanal Basin, that separates the western Rio Apa, Rio Tebicuary, and Rio de la Plata cratons from the Paraná Basin’s basement, to the east.

3. Materials and Methods

Our database includes records acquired by 70 broadband seismic stations distributed throughout the study area (Figure 1) from 2016 to 2019. The main data are provided by the XC network (Assumpção et al., 2016), which comprises 38 temporary stations installed through the “3 Basins Project—FAPESP” (red triangles in Figure 1). These data are supplemented by data from several permanent station networks (black, blue, cyan, green, and orange triangles in Figure 1). We selected P, PKIKP, PcP, and PP phases from seismic events with magnitude ≥5.5 (mb). To avoid triplication zones and low energy that could lead to phase misidentification, we set distance intervals for each phase: P (30°–95°), PKIKP (150°–180°), PcP (25°–40°), and PP (60°–130°).

The multiple-frequency tomography requires the calculation of relative delay times for several frequency bands, which are obtained by Multichannel Cross-Correlation approach (MCCC, VanDecar & Crosson, 1990). We employed the semiautomatic method proposed by Bonnin et al. (2014), which modifies the MCCC method by imposing previous regularization, a correlation coefficient constraint, and a cross-correlation window for each frequency band. The theoretical travel times were obtained using the IASP91 velocity model (Kennet & Engdahl, 1991). In this work, we measured the cross-correlation delays in six frequency bands, with central frequencies of 0.03, 0.06, 0.13, 0.25, 0.50, and 1 Hz. The corner frequencies at half the amplitude of the Gaussian filters’ power spectrum are: 0.01–0.05, 0.03–0.10, 0.06–0.20, 0.12–0.41, 0.25–0.82, and 0.59–1.64 Hz, respectively. The theory can be found at Hung et al. (2000).

To avoid cycle skips and guarantee the high quality of our delay database, we employed a minimum correlation coefficient of 0.9, the same used by Nolet et al. (2019). This coefficient is more conservative compared with previous studies that employed 0.8 (Mercerat & Nolet, 2013) or 0.85 (Bonnin et al., 2014; Costa et al., 2020). We also impose a minimum of five intercorrelations between seismograms for at least one band for an event to be accepted for processing.

All the events crossed visual quality control to confirm the coherence of the cross-correlation delays, at which time bad signals were removed or reprocessed with different cross-correlation window parameters. The resulting database is composed of 22,747 delays for P phase, 13,357 for PKIKP, 3,922 for PcP, and 22,666 for PP, resulting in a total of 62,692 new cross-correlation delays distributed among 1,081 events. Finally, we merged this database with the previous multiple-frequency study of the Amazonian Craton (Costa et al., 2020) to cover regions outside the study area, avoiding potential border effects. Therefore, the final database includes 75,187 cross-correlation delays.

Although we have access to data recorded by stations that operated as early as the 1980s, we avoided using data recorded before 2011, since these stations were mostly from temporary networks and with low overlap of the operating period. The usage of relative residuals with such data might lead to the presence of large-scale biases in the model, as stated by Maupin (2021). RSBR permanent stations are included in both our new data set and the data set of Costa et al. (2020) serving as reference stations across data time windows, thus minimizing such biases. The mantle was discretized using the parametrization developed by Charléty et al. (2013), known as the Cubed Earth. In this parametrization, the mantle is divided into six chunks with 128 × 128 × 37 voxels each, totaling 3,637,248 cells. The voxels show an average horizontal size of 78 km
near the surface, and 40 km at the core-mantle boundary (CMB). The average vertical size is around 90 km, with refining near known discontinuities (e.g., crust and CMB), reducing it to ≈45 km. The employed regularization uses damping and smoothing, with the regularized linear system for travel time data (Nolet, 2008; Nolet et al., 2019; Tian et al., 2009):

\[
\begin{bmatrix}
K_V^t \\
\varepsilon_1 I \\
\varepsilon_2 D
\end{bmatrix} m = \begin{bmatrix} d \\
0 \\
0
\end{bmatrix},
\]

(1)

where \(K_V^t\) is the frequency dependent velocity sensitive kernels for relative delay times \(\delta t\) contained in the data vector \(d\), \(I\) is the identity matrix, \(D\) is the smoothing operator, \(m\) is the parameters vector and \(\varepsilon_1\) and \(\varepsilon_2\) are the weights given to the damping and smoothing, respectively, with \(\varepsilon_1 + \varepsilon_2 = 1\). For the regularization, we tested six damping/smoothing (\(\varepsilon_1 / \varepsilon_2\)) ratios \(R\) to find the best fit for our database (Figure S1). Based on this test, the \(R\) used for the final tomographic model was 0.13/0.87 ≈ 0.15 since its results did not present extensive smoothing that prevented the distinction of structures, like the 0.05/0.95 ratio, and did not impose an extreme roughness like the 0.5/0.5 ratio, that generated small anomalies incompatible with the homogeneities imaged by regional tomography.

We also tested six values for a higher damping outside the study area (Figure S2). This uneven damping consisted of a sphere centered at 19°S 57°W with 3,500 km of radius, with the external damping being increased by a constant factor “\(f\)” to reduce the effect of external anomalies. The established radius encompasses all the stations, including those used by Costa et al. (2020), and it is far outside the target region. The results showed a slight increase in roughness for higher damping factors, with values \(f = 2\) and \(f = 3\) showing almost no change when compared to no extra external damping. Starting with \(f = 5\), some anomalies start to be better recovered, while for \(f = 15\) we start to see presence of possible artifacts due to the roughness imposed. This led us to use a factor of 10, for which the anomalies are characteristic to known geology while avoiding artifacts.

The three-dimensional banana-doughnut kernels used for the formulation of the linearized inverse problem were based on the theory described in Dahlen et al. (2000) and Nolet (2008), being calculated by the algorithm presented at Tian, Montelli, et al. (2007). The corrections (ellipticity, crustal, and topographic) were computed using the dynamic ray tracing algorithm proposed by Tian, Hung, et al. (2007). The model used to calculate crustal corrections was the CRUST 2.0 (Bassin et al., 2000—http://igppweb.ucsd.edu/~gabi/rem.html).

Defined as the weighted sum of squares of the difference between the observed and predicted data, the initial relative model misfit \(\chi^2/N\) was 19.974, with a standard deviation \(\sigma = 0.59\) s. After the first inversion with minimal smoothing, residuals beyond 2.5\(\sigma\) were considered outliers and were removed, totaling 0.4% of our data (333 residuals). Figure 2 shows the histogram for the initial data set of time residuals. After the outliers were suppressed, the model misfit \(\chi^2/N\) of the data set used for the inversion was 19.111, with a standard deviation \(\sigma = 0.58\) s. The final model has a misfit \(\chi^2/N = 0.918\), with the tradeoff curve between model misfit \(\chi^2/N\) and model norm RMS \(\langle m, 1/M \rangle\), where \(M\) is the number of elements in the parameter vector \(m\) shown in the Figure S3.

4. Model Resolution

4.1. Kernel Density

We evaluated the tomographic model sensitivity through the kernel column densities \(D_j\); Tian et al., 2009). Figure 3 shows the horizontal \(D_j\) slices for six depths: 68, 135, 226, 316, 497, and 700 km, with the values
presented as the base-10 logarithm ($\log_{10}(D_j)$). Our results show that the greatest values of $D_j$ are for the depths of 135–497 km, where the wider banana-doughnut kernels overlap and result in higher densities. The kernels are also more homogeneously distributed for these depths. For the depth of 68 km, the smaller diameter of the kernels results in small $D_j$ values, greatly concentrated beneath the seismic stations. For the depth of 700 km, despite the data being regularly distributed, the values of $D_j$ do not exceed 3.5. This indicates that our model is best sampled for structures between 135 and 497 km, with the best sensitivity being achieved for depths 125 and 226 km.

4.2. Checkerboard Tests

We performed checkerboard resolution tests for input models of $4 \times 4 \times 4$ (312 $\times$ 312 km in the horizontal) and $5 \times 5 \times 5$ (390 $\times$ 390 km in the horizontal) voxels with P-wave anomalies of $\pm 1.5\%$ (Figures 4 and 5, respectively). The regularization employed in these tests was the same as that applied to the real data. Gaussian noise with the same standard deviation of real data was added to the synthetic data.

For $312 \times 312$ km structures (Figure 4), our synthetic model shows proper geometry and amplitude recovery for the depths of 135 and 226 km. Structures are better recovered mostly beneath the PrB and PtB, with the area between the Paraná and ChB basins also showing good recovery, despite being on the edge of the study.

Figure 3. Horizontal images for the kernel column density for the depths of 68, 135, 226, 216, 497, and 700 km.
Figure 4. Checkerboard resolutions tests for the input model (left) of 312 × 312 km structures in the horizontal dimension. The recovered model is shown on the right for the depths of 135, 226, and 497 km. The black squares indicate the seismographic stations used in this study.
**Figure 5.** Checkerboard resolutions tests for the input model (left) of 390 × 390 km structures in the horizontal. The recovered model is shown on the right for the depths of 135, 226, and 497 km. The black squares indicate the seismographic stations used in this study.
area. On the other hand, the recovery starts to decrease for the depth of 497 km, especially at the edges of our model but with reasonable recovery in the center of the Paraná Basin.

For 390 × 390 km structures (Figure 5), our model also shows good geometry and amplitude recovery for the depths of 135 and 226 km throughout the study area, with a slight decrease in resolution for the depth of 497 km. Both models (with input structures of 312 and 390 km²) do not show enough resolution to study structures deeper than 497 km. We also implemented a resolution test for 3 × 3 × 3 structures (234 × 234 km in the horizontal dimension); however, the results do not show enough resolution for the study area, except for a minimal geometry recovery for the shallow depths (135 and 226 km) in the center of the Paraná Basin (Figure S4). One important result is the improved recovery for structures south of 29°S when compared to the previous work of Rocha, Assumpçao, et al. (2019), mainly in the southern and northern part of the Paraná Basin.

The vertical slices (Figure 6) show the recovery for the 4 × 4 × 4 input model. The recovered model reinforces the good recovery for the first 226 km that reaches down to 497 km for some areas. The central area shows the best recovery down to 497 km (profile W-W’).

5. Results

The results are presented as tomographic horizontal (Figure 7) and vertical (Figure 8) slices. The anomalies are relative to the regional mean of velocities, presented as a red-white-blue color scale assuming ±1.0% values.

5.1. High-Velocity Anomalies

A large high-velocity anomaly is observed in the center of our study area Paraná Basin Positive Anomaly (PrBPA) and is almost entirely contained beneath the Paraná Basin, with a small portion extending westwards at 21°S, in the south of the Pantanal Basin (Figure 7a). At depths of 226 and 316 km (Figures 7b, 7c, and 8 profiles A-A’ and C-C’), the anomaly decreases in amplitude before connecting to another high-velocity anomaly in the São Francisco Craton area. For the depth of 497 km (Figure 7d), the PrBPA amplitude...
Figure 7. Horizontal slices for depths of 135, 226, 316, and 497 km. The Amazonian (AmC) and São Francisco (SFC) cratons are shown as black dashed lines. PtB, PrB, and ChB are the Pantanal, Paraná, and Chaco-Paraná basins, respectively. Blue and green dashed lines are, respectively, the limits of the Paranapanema Block (PB′) and Luiz Alves Craton (LAC) proposed by Cordani et al. (2009). The red dashed line is the model for the Paranapanema Block (PB) proposed by Mantovani et al. (2005). The patterned area in (a) is the Western Paraná Suture Zone. ASA, PGA, and RGA are the Asunción, Ponta Grossa and Rio Grande arches. BrBe, RiBe, ApBe, and DfBe are the Brasilia, Ribeira, Apiaí, and Dom Feliciano belts. The black squares indicate the seismographic stations used.
reduces significantly in the western portion, with the anomaly extension beneath the Pantanal Basin disappearing almost completely. This high-velocity structure is mostly concentrated between 20°S and 28°S and 52°W and 58°W and appears to reach depths between 500 and 700 km, while the north and northeastern portions of the anomaly reach depths of 300–350 km.

The southeastern portion of the PrBPA is segmented in a NNE-SSW direction (Figure 7b), with its amplitude tending to zero, which is consistent with the Paranapanema Block limits of Mantovani et al. (2005) and Cordani et al. (2009), respectively. LAC is the Luiz Alves craton as proposed by Cordani et al. (2009). PrB is the Pantanal Basin. RAC and RTC are the Rio Apa and Rio Tébicuary cratons. SFC and AmC are the São Francisco and Amazonian cratons. BrBe, RiBe, ApBe, and DFBBe are the Brasilia, Ribeira, Apiai, and Dom Feliciano Belts. TBL is the Transbrasiliano Lineament.

The high-velocity anomaly observed at 21°S with a depth of ∼300 km (Figures 7a–7c), extending from the Paraná Basin to the south of the Pantanal Basin, does not extend northwards beyond 20°S. Also, this anomaly does not extend to greater depths as the main anomaly under the Paraná Basin. Furthermore, there is also no evidence of a connection between this positive anomaly and the Amazonian Craton.

5.2. Low-Velocity Anomalies

A low-velocity anomaly can be observed between the Chaco-Paraná and Paraná basins (near the Rio Grande and Asunción arches), extending from southern Brazil to northern Uruguay and Argentina. The amplitude of this anomaly increases southwards, up to the end of our station array.
To the east of the study area, near the coastline, three high-amplitude low-velocity peaks connected by weaker anomalies can be observed (Figures 7a and 7b). The two strong low-velocity anomalies connected by a weaker low-velocity zone northeast of the Paraná Basin seem to be related to the Ribeira Belt (RiBe—Figure 1). This region appears to be limited southwards by a rapid decrease in the low-velocity amplitude, coincident with the Ponta Grossa Arch (PGA—Figure 1) and with the northeastern limits of the Luiz Alves Craton, where the amplitude starts increasing again up to 28°S (Figure 8, end of profile BB’), coinciding with the Dom Feliciano Belt (DFBe—Figure 1).

To the north of the study area, a low-velocity anomaly with constant amplitude, roughly parallel to the TBL and to the AmC (Figures 7a and 7b), can be seen. This anomaly continues up to a strong low-velocity anomaly under the Pantanal Basin and Amazonian Craton. This low velocity zone was observed in previous regional tomography works (Azevedo et al., 2015; Rocha et al., 2011, 2016; Rocha, Assumpção, et al., 2019), and is strongly correlated with a thin lithosphere according to Priestley et al. (2018) and with the seismicity concentration, indicating a lithospheric thinning among the AmC, SFC, PrB, and PtB (Assumpção et al., 2004; Azevedo et al., 2015; Rocha et al., 2016; Rocha, Assumpção, et al., 2019).

A roughly circular shaped low velocity anomaly can be seen starting at the depth of 226 km (Figures 7b and 7c) northeast of the Paraná Basin and centered at 20.7°S 47.4°W. This anomaly is consistent with the results observed in previous tomography studies, first interpreted as Tristan da Cunha’s fossil plume (Van-DECAR et al., 1995).

### 5.3. Geometric Synthetic Model

To verify the model sensitivity to large structures, we simulated the presence of multiple cratonic blocks based on our real tomography results, with maximum depths of 135 and 226 km in the study area, and an amplitude of +1%. In this model, the São Francisco Paleocontinental Block (SFPB—that incorporates the SFC) was modeled based on the results of Rocha, Azevedo, et al. (2019), with a maximum depth of 226 km. The Paranapanema Block and the Luiz Alves and Rio Apa cratons were simulated based on the final tomographic model (Figure 7). We obtained the least mismatch between the true and the synthetic model with the base of the Rio Apa Craton at a depth of 135 km. Due to reduced high-velocity anomalies to the southeast of the PB, area of the Luiz Alves Craton, we defined the synthetic craton depth in this region to 135 km. In the Paranapanema Block region, increased high-velocity anomaly amplitude indicates the presence of a thicker cratonic block, resulting in the defined Paranapanema Synthetic Block to be set to a depth of 226 km and having horizontal limits similar to the model of Mantovani et al. (2005). We called the final input model as Cratonic Blocks Synthetic Model (CBSM—Figure 9).

The lateral boundaries for the recovered model (Figure 10) are consistent with the input model, reinforcing the good horizontal resolution, mainly for larger structures. However, it is possible to observe that the limits between the simulated blocks are not clear, as there is smearing between them. For example, the SFPB and PB blocks appear completely connected, and their boundary is marked by a slight decreasing in the high-velocity anomaly. This behavior is expected, since the limit between these blocks must be less than the resolution capacity of our model (on the order of 230 km), as shown in the checkerboard tests (Figures 4–6 and S4). Thus, the lack of resolution of a limit between these two blocks in the real data is natural for the distribution of stations currently used. Imaging this boundary with higher resolution will depend on a denser array of stations.

The same issue occurs defining the limits of the Paranapanema Block with the synthetic test of the blocks of the Rio Apa and Luiz Alves cratons. The anomalies related with these two cratons also appear connected to the Paranapanema Block (Figures 10a and 10b), with some decrease in amplitude at their boundaries. This is similar to what is observed in our model using the real data, indicating that the two cratonic nuclei may be separated.

Regarding the depths of the structures, it is possible to observe that they are recovered at depths greater than their vertical synthetic limit, with vertical smearing of the anomalies indicating low vertical resolution of the method.
Although the input model contains only positive anomalies, the recovered model contains strong low velocity anomalies throughout the entire area. This result is expected, since we are using relative residuals and the final model is referenced to a regional mean, giving information on the contrast of the medium, instead of absolute velocities. This is observed not only in our model, with other studies in the area that used synthetic models also recovering strong anomalies of opposite sign to the input model (e.g., Rocha et al., 2011; Schimmel et al., 2003).

We also performed two more tests based on the CBSM, slightly modifying the separation between the cratonic nuclei. In the first test (Figure S5), we increased the separation between the PB and the SFPB to evaluate our model response, calling it CBSMI. The recovered model (Figure S6) showed that the gap between the PB and the SFPB would be more distinguishable for the CBSMI when compared to the real data and the unmodified CBSM (Figures S9a, S9b, and S9c), reinforcing that the two nuclei have minimal separation, more consistent with the proposed CBSM. In the second test, we merged the RAC, LAC, and SFPB with the PB (Figure S7), calling it CBSMM. For the limits between the PB and SFPB, the recovered model showed no amplitude reduction as observed in the real data and recovered CSBSM (Figures S8, S9a, S9b, and S9d), discouraging interpretations that the two nuclei are amalgamated. For the limits between the PB and the RAC and LAC, the CBSMM shows an increased amplitude between the cratonic nuclei (Figures S8 and S9d) that is not observed in the real model or separated blocks (Figures S9a, S9b, and S9c), suggesting minimal separation.

6. Discussion

6.1. Paranapanema Block

The observed high velocities beneath the Paraná Basin are consistent with a single block similar to the Paranapanema Block proposed by Mantovani et al. (2005), or that interpreted by Rocha, Assumpção, et al. (2019), discouraging interpretations related to a mosaic of cratonic blocks (Milani & Ramos, 1998).
However, some parts of this anomaly (e.g., southeast of the Paraná Basin and south of the Pantanal Basin) observed by Rocha, Assumpção, et al. (2019) seem to be related to other adjacent blocks. The geometric resolution tests showed that narrow limits between the blocks are not completely resolved by our model, with slight reductions in amplitude intensity being observed. Based on the decrease in amplitude between

Figure 10. Horizontal images for the recovered CBSM. The gray lines connect the outmost nodes for each cratonic block.
the blocks, it is possible to interpret the large high-velocity anomaly under the Paraná Basin as related to at least three different cratonic blocks: Paranapanema, Rio Apa and Luiz Alves (Figure 11).

For the north and northeast, the limit between the Paranapanema Block and the São Francisco Craton is characterized by a decreased high velocity amplitude, also observed in the geometric synthetic tests (Figures 9 and 10). In this area, the observed limits for our tomographic results are located between the models of Mantovani et al. (2005) and Rocha, Assumpção, et al. (2019). While the former propose limits near the end of the Paraná Basin’s limits, the latter propose a limit farther south, suggesting that the cratonic basement either does not reach the limits proposed by Mantovani et al. (2005) or that the cratonic lithosphere was metasomatized by the magmatism of the Alto Parnaíba and Iporá igneous provinces, resulting in a thinner lithosphere. Our model is most consistent with the second hypothesis, with a low velocity anomaly starting from the depth of 226 km and extending southwards to greater depths, interpreted as the Tristan da Cunha fossil plume (VanDecar et al., 1995).

To the west, our limits are better correlated with each model for different portions. To the northwest, it is consistent with the model proposed by Rocha, Assumpção, et al. (2019), being slightly extended to the west, while to the southwest, we find a better correlation with the model of Mantovani et al. (2005). This might be caused by an improved resolution for this area, as a result of the multiple-frequency tomography and extended period of acquisition for the stations in the area.

6.2. Luiz Alves Craton

The southeastern limit of the Paranapanema Block is consistent with the Rio Grande and Asunción arches, and with the model of Mantovani et al. (2005). Our proposed southern limit (Figure 11) diverges from Rocha, Assumpção, et al. (2019) for the southeastern portion, being placed north of the RGA. This is the result of the improved resolution of the tomographic method used here when compared to the ray-theory methods. To the southeast, the decreased high velocity anomaly (Figure 11) appears to indicate a thinner
Paranapanema Block, or another adjacent cratonic core (Luiz Alves Craton). This is supported by the geometric synthetic tests, with an input depth of 135 km for this region, where the boundary between the blocks is an amplitude decrease in the high-velocity anomaly.

### 6.3. Paranapanema Block/Rio de la Plata Craton Suture Zone

The improved resolution in the south of our study area, when compared to the work of Rocha, Assumpção, et al. (2019), allowed for a much more consistent delimitation of the zone between the Paranapanema Block and the Rio de la Plata Craton. This zone is characterized by a low velocity anomaly, roughly parallel to the RGA, and is believed to be the fold belt between the PB and the RDLPC. Our results diverge from the Western Paraná Suture Zone, based on gravity (Dragone et al., 2017), as the proposed structure would be coincident with our high-velocity anomaly in an area with great resolution. Due to the limits of our stations array, we were not able to image the Rio de la Plata Craton, suggesting that the most likely model for this craton was proposed by Oyhantçabal et al. (2011).

### 6.4. Rio Apa Craton

The high-velocity anomaly interpreted as the Rio Apa Craton does not extend northwards, beneath the Pantanal Basin, as proposed by Dragone et al. (2017), and does not connect to the Amazonian Craton beneath the same basin, which would corroborate the geochronological studies of Faleiros et al. (2016) and Lacerda-Filho et al. (2016). Unlike the results of Rocha, Assumpção, et al. (2019), that proposed a much larger Rio Apa Block (high velocity anomaly extending between latitudes 20°S and 26°S), our results show an anomaly concentrated mostly between latitudes 20°S and 22°S (Figure 11). It is probably related to the improvement in resolution reached using Multiple Frequencies Seismic Tomography. We also do not observe a high-velocity anomaly that might indicate the presence of the Rio Tebicuary Craton to the south, as proposed by Dragone et al. (2017). Instead, we observe a low velocity anomaly, consistent with the Southern Paraguay Seismic Zone (Figure 12) and with a thinner lithosphere, observed in the results of Priestley et al. (2018).

Considering the recovered CBSM and the tomographic model, with both presenting a decreased high velocity amplitude between the craton and the Paranapanema Block, we propose that these two cratonic nuclei are indeed separated by the Transbrasiliano Lineament (Figure 11), as supported by geology and aeromagnetic data (e.g., Curto et al., 2014), with the Rio Apa Block to the west, and the Paranapanema to the east.

### 7. Conclusions

We successfully imaged the upper mantle beneath the Paraná Basin and adjacent regions, obtaining tomographic results with better and more homogeneous resolution when compared to recent previous regional tomography studies in the same area. This was possible mainly due to the adoption of the multiple-frequency approach, instead of the classic infinite frequency ray-theory, allied with the greater acquisition period for the new XC network stations.

The Paranapanema Block is characterized by a robust strong high-velocity anomaly beneath the Paraná Basin, corroborated by the synthetic test. The limits proposed (Figure 12) reach farther north when compared to those proposed by previous regional tomography studies. Its limit with the São Francisco Craton is characterized by a decreased high-velocity anomaly, also seen in the recovered CBSM with a separation of ~75–150 km. To the northeast of the Paraná Basin, we observed the low-velocity anomaly previously interpreted as the Tristan da Cunha Fossil Plume. The cratonic basement in this region may have been affected by Late Cretaceous intraplate magmatism, reducing the cratonic lithosphere thickness and preventing its observation with regional tomography.

The Paranapanema Block’s southern limit proposed in this study is located north of the Rio Grande and Asunción arches, not reaching the Rio de la Plata Craton. It is our understanding that the improved resolution in the area (see Section 4.2), when compared to previous tomographic studies, resulted in a more reliable interpretation. Also, there is no relation between the anomalies in this study and the Western Paraná Suture Zone.
The segmentation of the Paraná Basin high-velocity anomaly to the southeast, with the eastern portion presenting weaker high-velocity anomalies when compared to the main anomaly to the west, is consistent with the Luiz Alves Craton. The limits proposed are similar to those obtained by geological inference, and the weaker amplitude of this anomaly suggests that the craton is thinner than the adjacent Paranapanema Block.

The high-velocity anomaly interpreted as the Rio Apa Craton suggests that it is thinner than the adjacent Paranapanema Block. Our results show that this craton does not extend beneath the Pantanal Basin. We do not observe an extension of this positive anomaly to the south. Instead, the low-velocity anomalies seen south of the Rio Apa Craton are consistent with the Southern Paraguay Seismic Zone, suggesting that this area is characterized by stress concentration in the upper crust due to lithospheric thinning, resulting in greater seismic activity. These findings also discourage the presence of another craton south of the Rio Apa.

North of the Rio Apa Craton, under the Pantanal Basin, a very strong low-velocity anomaly is recorded, correlated with the increased seismicity due to stress concentration in the upper crust, similar to what happens with the Southern Paraguay Seismic Zone.

Due to the spatial limitation of our seismographic stations array, we were not able to image the northern portion of the Rio de la Plata Craton, which should be seen as a high-velocity anomaly.

**Figure 12.** Contours of the seismic velocities anomalies to help the interpretation of the cratonic blocks beneath the Paraná Basin. The final limits for Paranapanema, Rio Apa, and Luiz Alves area were indicated. The red circles are the events from the Brazilian Seismic Catalog (Assumpção et al., 2004). The contour lines are separated by anomaly values of 0.1%.
Data Availability Statement

The data and instructions for downloading them can be found on the websites of RSBR (http://www.rsbr.gov.br/), OBSIS/UnB (http://obsis.unb.br/), and the Seismological Center of USP (http://moho.iag.usp.br/). Tomographic models are available at https://10.5281/zenodo.4472862. Data were used from additional stations of the Seismological Center of the University of São Paulo (USP), São Paulo State Institute of Technological Research (IPT), Seismological Observatory (OBSIS/UnB), and Laboratory of Lithospheric Studies of the University of Brasilia, GTSN and GEOSCOPE Networks, and a temporary deployment by ETH-Zürich.

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