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A 1D Velocity Model for the Carajás Province from the Inversion of P- and S-Wave Travel Times

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Abstract

In this study, the shallow crustal structures of the Carajás Province, located in the southeast of the Amazon Craton, were investigated. For this purpose, a 1D seismic velocity model was generated from the inversion of P and S-wave travel times recorded by a network of 38 seismographic stations and regional seismic events. After reviewing and refining the earthquake catalogue, 184 natural events were relocated, followed by simultaneous inversion of the hypocentres and velocity model. Several tests were performed to verify convergence and stability, including perturbations in layer thicknesses and seismic velocities. The final model reveals well-defined discontinuities consistent with the expected interfaces, namely the Conrad (approximately 22 km deep) and the Moho (approximately 39 km deep). In addition, it exhibits an average Vp/Vs ratio of 1.73, indicative of an intermediate to mafic crustal composition, which is consistent with regional geology.

Introduction

The characterisation of the Earth's crust is crucial for reconstructing the geological history of different regions. The variability of the Earth crust and the presence of heterogeneities reflect tectonic, magmatic, and metamorphic processes that shaped regional geological evolution, particularly thinning, thickening, and the influence of volcanic episodes or mafic subplates at the base of the Earth's crust (Assumpção et al., 2013), also associated with lithospheric evolution.

In Brazil, the average thickness of the crust is 39 (±5) km, with variations depending on the region analysed. Important areas such as the São Francisco Craton, Amazonian Craton, and Paraná Basin have thicker crusts, exceeding 41 (±2) km, while regions of orogeny, crystalline shields, or passive margins, such as the South Rio Grande Shield and the southeast coast, are less thick (≈38 km) (Assumpção et al., 2013). These variations reflect Brazil's complex tectonic history, marked by events of continental collision, rifting and accretion of land.

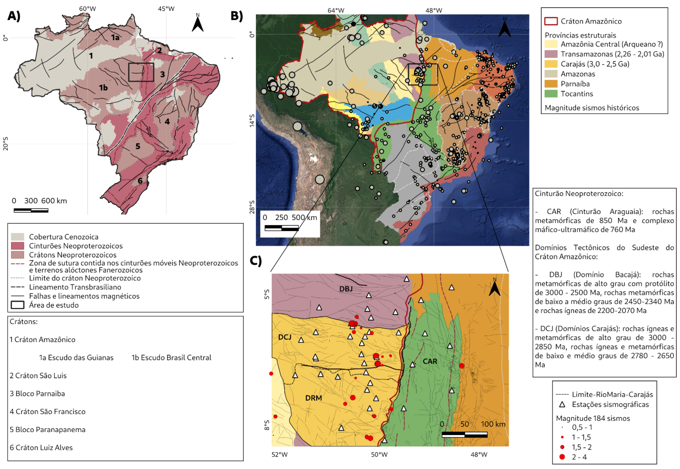
Between 1987 and 2023, 116 seismic events with magnitudes greater than 2.5 were recorded in the Province of Carajás (PC) (Source: SISBRA), evidencing significant seismic activity within a cratonic context. While these events highlight the need for local studies in the region, they can also provide data for studies of the crustal structure or even local heterogeneities, which may be associated with the likelihood of their occurrence.

In this context, this work presents the construction of a 1D seismic velocity model for the PC based on travel times of regional events, which can be used both for event relocation and for the development of a local 3D velocity model. Our specific objectives are to catalogue the events, relocate them, and validate the 1D layer model.

Geotectonic Context

The study area (Carajás Province - CP) is located in the southeastern Amazonian Craton, within the Central Brazil Shield (CBS), which is subdivided into Tectono-Geochronological Provinces (Fig. 1). The Rio Maria Domain (RMD, southern CP) was marked by intense magmatic activity related to subduction and crustal accretion processes, characteristic of Archean magmatic arc systems, crucial in the formation of the Granite-Greenstone terrain. This domain contains the oldest rocks in the entire Amazonian Craton (Mesoarchean crust), consisting of metamorphosed mafic rocks associated with accretionary orogenic events (2817–3002 Ma). Paleoproterozoic sedimentary cover overlies the Archean crust of the CP, establishing a continental platform (Santos, 2003).

In contrast, the Carajás Domain (CJD, northern CP) is characterized by complex tectonic processes, including orogenic events and magmatic arc formation between 2.763 and 2.566 Ma, primarily comprising the Itacaiúnas Belt.



The Itacaiúnas Belt comprises rocks deposited in a volcano-sedimentary setting resulting from rifting of the pre-existing basement, followed by volcanic and hydrothermal activity. The sedimentary cover overlying the belt dates from the Neoarchean to Paleoproterozoic. The Carajás Domain (CJD) is predominantly composed of high-grade metamorphic rocks with a minor proportion of supracrustal rocks (Trunfull et al., 2020).

Fig. 1: Geotectonic subdivision of the Central Brazil Shield (CBS) into Tectono-Geochronological Provinces (B), along with historical Brazilian seismicity (SISBRA). These are further subdivided into Tectonic Domains (C)), detailing the events and stations used in this study. Adapted from Vasquez et al. (2008).

Method

The analysis considered records of seismic events automatically detected by the SeisComP software (GFZ/2008) from 10/2021 to 01/2024, using a temporary network of 38 stations operated by the University of Brasília and partners. Initially, 347 possible events were identified in the considered period, between 21:00 and 09:00 local time (defined to avoid blasts with low signal-to-noise ratio and difficulty in S-wave picking). After manual review, 184 events were confirmed by re-reading P and S phases and relocating them using the IASP91 velocity model (Kennett, 1991).

To validate the detections, we applied a statistical analysis of the frequency-magnitude relationship of the events, as well as evaluating day-time diagrams to determine whether the events were anthropogenic (blasts) or natural. The preference for natural earthquakes is justified by their broader geographic distribution compared to blasts and greater accuracy in phase picking. Relocation considered a root mean square error ≤ 0.60 s. Event depth was fixed at 1 km, consistent with the Seismotectonics context.

The optimization of the 1D velocity model used the Velest program (Kissling, 1994). The initial model was obtained from the average of joint inversions of receiver function and surface wave data at each station, provided by researcher Cíntia Rocha (UFOPA). Velest allows focusing on either hypocentral relocation or combined relocation and model inversion. Before inverting the model, we relocated the events using the proposed initial model. This result was used for the combined model optimization, performed in stages, leading to the final adopted model. Specific parameters of the Velest inversion process were used, which regulate the inversion by controlling the magnitude of adjustments in sensitive variables such as origin time (regularization of 0.01), hypocentral location (0.01), station correction (0.1), and seismic velocities (1.0), resulting in a stable 1D model.

Additional tests included varying the number of layers in the initial model, focusing on major discontinuities, random perturbations (±1 km) of initial hypocenters to verify location sensitivity, exclusion of events with magnitude <1.0 MLv (resulting in 160 earthquakes), and finally, the analysis of 800 initial models with perturbations in layer thickness (±1 km), P or S velocity (±0.5 km/s), or both velocities (±0.25 km/s) per layer.

Results and Discussion

Through the analysis of 6,662 seismic phase arrival time readings, considering the geometry of the deployed network and event distribution (maximum distance of 200 km), we achieved an investigation depth of ≈45 km in the velocity models, within the resolution limit. The defined parameters helped constrain the spatial limits and the quality of local modeling of the PC (Parnaíba Craton), serving as a basis for interpreting the results presented in Figure 2.

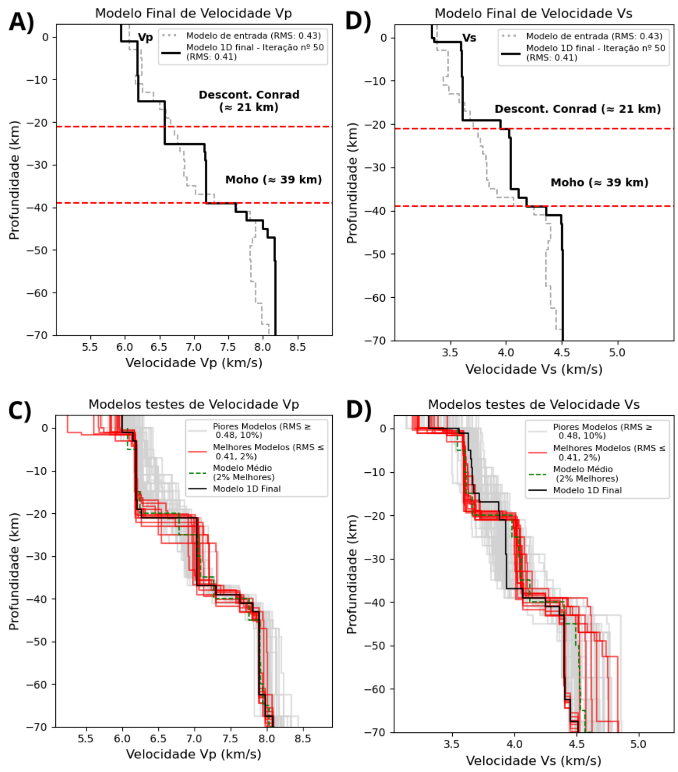
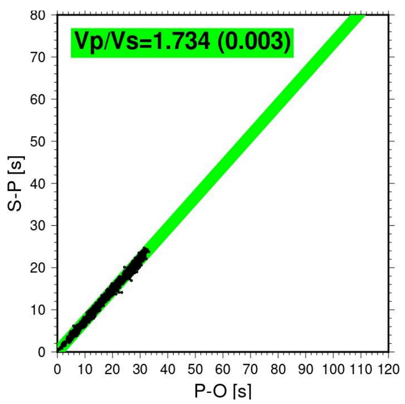


Fig. 2: Resulting model from the inversion of 184 earthquakes, highlighting the main seismic discontinuities down to 40 km depth. The inversion was performed with damping as described in Table 1. **A)** and **B)** Final Vp and Vs models, respectively. **C)** and **D)** Vp and Vs resulting from a subset of tests with 800 randomly perturbed models. The top 2% of models (in red) show overlap in the main seismic discontinuities, such as Conrad and Moho, with low dispersion around the mean (green dashed line), indicating stability and reliability of the adopted final model (black line).

The different tests performed showed a considerable level of significance in the equivalence between the final velocity models, as they delineated the main known discontinuities in the obtained models. All results converge with the velocity model shown in Figure 2 (final model), which is considered the most representative for this dataset and regional geology, in addition to showing a significant reduction in the root mean square (RMS) of the event of approximately 52%.

The final model shows well-defined seismic discontinuities, with velocities showing no significant variations across successive iterations, stable convergence, and compatibility with the different sensitivity tests performed. It also exhibits the lowest RMS value in the final iteration (0.42 s). Comparing the mean of the best models with the final model, we observe good agreement for P-waves, whereas for S-waves, the final model shows lower velocities in the lower crust and mantle. This discrepancy may result from difficulties in identifying S-waves, particularly the Sn phase at larger distances, indicating greater challenges in obtaining the Vs profile for the PC.

Among the features common to all models, the increase in P- and S-wave velocities at around 22 km depth stands out, interpreted as the Conrad discontinuity, more pronounced in P-wave velocity. The Mohorovičić discontinuity (Moho) is identified at ≈39 km depth.



Considering the final model presented in Fig. 2, we obtained the average Vp/Vs ratios for each layer: upper crust (1.69), lower crust (1.79), and mantle down to 125 km (1.79). The average crustal value (estimated at 1.73) was validated by constructing a Wadati Diagram (Fig. 3), which provides an approximately independent estimate of the Vp/Vs ratio since it can be derived solely from travel-time readings.

Fig. 3: Wadati Diagram based on the final velocity model.

The Wadati Diagram fitting resulted in a Vp/Vs ratio of 1.73 for the PC, identical to the final model estimate. This value indicates an intermediate-to-mafic crust, consistent with the predominant terrains of the PC, such as granite-greenstone complexes with significant mafic content, metamorphosed mafic volcanic-sedimentary belts, and mafic intrusions. Therefore, this ratio aligns with the lithological composition of these domains, supporting the mafic origin and geotectonic evolution of the crust and validating the consistency between the obtained seismological data and geological evidence in the area.

The station corrections in the final velocity model follow a pattern attributable to network geometry, with values not deviating significantly from the mean. However, a preliminary analysis did not identify zones of high or low seismic velocity, which we expect to address more precisely through tomographic inversion in future studies.

Conclusions

The obtained 1D model for the PC (Parnaíba Craton) characterized its structure, revealing seismic discontinuities with depths consistent with previous studies in the region. The derived Vp/Vs ratio aligns with the presence of mafic and ultramafic rocks associated with the province's geotectonic evolution. The final model demonstrated convergence across different tests and exhibited stability against applied perturbations.These results provide a robust foundation for future applications of Local Seismic Tomography, aiming to map lateral P- and S-wave velocity anomalies and refine tectonic models of the Amazonian Craton.

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Referências

Bizzi, L., Schobbenhaus, C.; Vidotti, R. (2003). Geologia, Tectônica e Recursos Minerais do Brasil: texto. [S.l.: s.n.]

Assumpção, M., Bianchi, M., Julià, J., Dias, F. L., Sand França, G., Nascimento, R., Drouet, S., Pavão, C. G., Albuquerque, D. F., & Lopes, A. E. V. (2013). Crustal thickness map of Brazil: Data compilation and main features. Journal of South American Earth Sciences, 43, 74–85. https://doi.org/10.1016/j.jsames.2012.12.009

Fischer, K. M., Ford, H. A., Abt, D. L., & Rychert, C. A. (2010). The Lithosphere-Asthenosphere Boundary. Annual Review of Earth and Planetary Sciences, 38(1), 551–575. https://doi.org/10.1146/annurev-earth-040809-152438

Geosciences, H.-C. P.-G. G. R. C. F., & GmbH, G. (2008). The SeisComP seismological software package. GFZ Data Services. https://doi.org/10.5880/GFZ.2.4.2020.003

Kennet, B. L. N. (1991). IASPEI 1991 SEISMOLOGICAL TABLES. Terra Nova, 3(2), 122. https://doi.org/10.1111/j.1365-3121.1991.tb00863.x

Kissling, E., Ellsworth, W. L., Eberhart-Phillips, D., & Kradolfer, U. (1994). Initial reference models in local earthquake tomography. Journal of Geophysical Research: Solid Earth, 99(B10), 19635–19646. https://doi.org/10.1029/93jb03138

SISBRA, https://seiscode.iag.usp.br/CSUSP/sisbra/releases/tag/v2024May09

Trunfull, E. F., Hagemann, S. G., Xavier, R. P., & Moreto, C. P. N. (2020). Critical assessment of geochronological data from the Carajás Mineral Province, Brazil: Implications for metallogeny and tectonic evolution. Ore Geology Reviews, 121, 103556. https://doi.org/10.1016/j.oregeorev.2020.103556

Vasquez, L. V., Rosa-Costa, L. R., Silva, C. G., Ricci, P. F., Barbosa, J. O., Klein, E. L., Lopes, E. S., Macambira, E. B., Chaves, C. L., Carvalho, J. M., Oliveira, J. G., Anjos, G. C., Silva, H. R. (2008). Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas – SIG: Texto Explicativo dos Mapas Geológico e Tectônico e de Recursos Minerais do Estado do Pará. Organizadores: M.L Vasquez, L.T. Rosa-Costa. Escala 1:1.000.000. Belém: CPRM