Cratonic Basin Formation: A Case Study of the Parnaíba Basin of Brazi 2018
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Crust and upper mantle structure beneath the Parnaíba Basin, Brazil, from wide angle reflection-refraction data

José E. P. Soares, Randell Stephenson, Reinhardt A. Fuck, Marcus V. A. G. de Lima,
Vitto C. M. de Araújo, Flávio T. Lima, Fábio A. S. Rocha, Cíntia R. da Trindade

Abstract

The Parnaíba Basin is a Phanerozoic intracontinental basin within the South America plate, lying atop and within Precambrian terranes. The PBAP wide angle reflection-refraction (WARR) profile lies E-W and is 1,150 km long crossing the basin and its margins. The WARR results show that the crust and uppermost mantle along the profile consist of the Amazonian Craton and Borborema Province, and the Grajaú and Teresina domains comprising the Parnaíba block hidden below the sedimentary cover of the basin itself. The lithospheric characteristics of the Parnaíba block and their differences with the adjacent Precambrian Amazonian Craton and Borborema Province elucidate some aspects of the present-day existence of the sedimentary basin covering it. Important elements include the presence of a high mantle velocity and high velocity lowermost crustal region, interpreted as linked to intrusion of mafic material into the crust underlying the Grajaú domain, and indications that the crust in this area has been intruded since its consolidation in the Neoproterozoic. It is tentatively proposed that magmatism is related to inferred thinning of the lower crust of the Teresina and Borborema segments of the profile, with this, in turn, linked to Cretaceous extensional tectonics and the opening of the South Atlantic Ocean.

Together with the Amazonas-Solimões, Parecis and Paraná basins, the Parnaíba Basin is part of a set of Palaeozoic intraplate basins within the South America plate. Its depositional history spans Silurian to Cenozoic time and it is typically associated with an extensional event, similar to the formation of Palaeozoic intraplate basins around the world, such as, among others, the Williston and Illinois basins in North America, the Congo and Taoudeni basins in Africa and the Siberian basin in Russia (Condie 2004; Kearey *et al.* 2009; Allen & Allen 2013). All these basins appear to represent widespread extensional tectonics on the Gondwana supercontinent following the Brasiliano/Pan-African Orogeny at the end of the Neoproterozoic and early Palaeozoic.

The deeper structure of the Parnaíba Basin, until now, has been mainly inferred from geological (e.g. Cordani *et al.* 1984; 2009) and potential data observations (Nunes 1993; Castro *et al.* 2014; 2016) and poorly constrained by seismological (Assumpção *et al.* 2013a; 2013b; Feng *et al.* 2004) and seismic data (Daly *et al.*, 2014), its structure and genesis being the subject of some controversy and debate.

Recently the BP petroleum company sponsored the multidisciplinary program PBAP (Parnaíba Basin Analysis Program), involving universities and research centres from Brazil and the UK with the aim of investigating the deep structure of the Parnaíba Basin and illuminating its genesis and evolution. As part of this effort, Daly *et al.* (2014) presented a dense CDP image of the Parnaíba Basin crust (range of 20 seconds of two-way travel-time) along a 1,400 km E-W transect, crossing the basin and its western and eastern borders roughly at the latitude 5.35°S (Fig. 1).

The WARR (wide angle reflection-refraction) experiment, presented here, was carried out along almost the same path of the Daly *et al*. (2014) CDP profile and has allowed a 2D velocity model of the crust and upper mantle of the basin to be constructed. Field acquisition was carried out in September 2015 by the Lithosphere Research Lab of the University of Brasília in partnership with the Pampa Federal University (Caçapava do Sul) and the University of Aberdeen

Tectonic setting

The Parnaíba Basin is a sag basin occupying an area of approximately 660,000 km^2 (Cordani *et al.* 1984) in north-northeastern Brazil and, in contrast to the Amazonas-Solimões, Parecis and Paraná basins, it does not show any preferential rift direction controlling its sedimentary infill. Nevertheless, the basement of the Parnaíba Basin presents a series of small N-S-, NW-SE- and NE-SW-trending rift-like structures, mainly defined by potential data analyses, which have been considered the precursory structures of the overlying sag basin (Nunes 1993; Oliveira & Mohriak 2003; Castro *et al.* 2016). Among these the largest is the Jaibaras rift (Oliveira & Mohriak 2003; Pedrosa Jr. *et al.* 2015, 2017), exposed along and apparently controlled by the Transbrasiliano Lineament, which crosscuts the Parnaíba Basin in its southeastern segment (Fig. 2). The Transbrasiliano Lineament (Schobbenhaus *et al.* 1975) is a continental shear zone crossing the South America plate and continuing into the Africa plate (where it is known as the Kandi Lineament) and is defined as the scar of a transcontinental terrain amalgamation that took place at the end of the Neoproterozoic as part of the formation of West Gondwana (Cordani *et al.* 2013; Brito Neves & Fuck 2014).

The Parnaíba Basin as a whole records a complex history of deposition, and can be sub-divided into the Parnaíba (Silurian-Carboniferous), Alpercatas (Permian-Jurassic) and Grajaú (Cretaceous-Cenozoic) sub-basins (Vaz *et al.* 2007) (Fig. 2). Strictly speaking, the Parnaiba Basin consists only of the Silurian-Carboniferous succession, although the term is used to connote the whole of the sedimentary basin succession including the overlying Permian-Jurassic and Cretaceous-Cenozoic successions (known as the Alpercatas and Grajaú basins, respectively).

The Parnaíba Basin is marked by regional mafic magmatism of the Triassic-Early Jurassic Mosquito Formation (199+/-2.4 Ma, Merle *et al.* 2011), related to the opening of the central Atlantic Ocean, and by dykes and sill-like intrusions of the Cretaceous Sardinha Formation (129-124 Ma, Fodor *et al.* 1990), linked to the opening of the South Atlantic Ocean. The total thickness of magmatic rocks derived from these two events is some 600-800 m intruded into a sedimentary pile of maximum 3.5 km thickness (Daly *et al.* 2014).

The initial Early Palaeozoic basin depocentre shifted to the central part of the basin realm during Early Carboniferous-Jurassic time and migrated again, northwestwards, in the Cretaceous (Vaz *et al.* 2007 and references therein), suggesting a temporal relation with Mosquito and Sardinha magmatism, respectively. The basin realm was initially broader than it is today, having a link with the Amazonas and Paraná basins and possibly even with the Congo Basin in Africa (Melo 1988).

At present the Parnaíba Basin exhibits a sharp fault contact with the Tocantins Province (Araguaia Belt) in the west (Daly *et al.* 2014), a tectonic/erosional contact with the Tocantins Province to the south, and a smooth northward sedimentary contact with the São Luis Craton and with the São Francisco Craton southeastwards. Along the eastern border, the limit of the basin with the Borborema block is erosional, with basal Silurian sediments of the basin being exposed.

The basement of the Parnaíba Basin comprises a collage of at least three main domains, classified as the Amazonian, Parnaíba and Borborema blocks, which are marked by steep contacts between them (Daly *et al.* 2014; Castro *et al.* 2014).

Wide-Angle Reflection-Refraction (WARR) experiment

The WARR transect is a 1,150 km long E-W profile, beginning over the Amazonian Craton (~150 km west of Marabá), crossing the Parnaíba Basin and finishing over the Borborema Province, 100 km east of the basin margin, close to Independência (Figs. 1 and 2). Its path is regionally almost a straight line, following paved and secondary dirt roads, passing through an isolated, mainly sparsely populated part of northeastern Brazil. It coincides with the path of the CDP profile (Daly *et al.* 2014) except between Imperatriz and Barra do Corda and between Altos and Castelo, where the WARR experiment avoided bends in the previous reflection profile.

The data were recorded by 36 short period 3-component stations (recorder model RefTek DAS130 with triaxial sensor model Sercel L-4A 3D from PEG-BR) installed at 30 km intervals, mainly covering the western and eastern parts of the line (cf. Figs 1 and 2), and 600 vertical component stations (300 RefTek "Texans" with vertical sensor model Sercel L4-A from PEG-BR and 300 "Texans" with 4.5 Hz vertical geophones from PASSCAL) evenly distributed along the deployment line (cf. Figs 1 and 2).

The 3-component short period stations were installed before the active source acquisition fieldwork began, with these instruments working in a continuous recording mode with sample rate of 100 sps for a period of six months, aimed at obtaining a teleseismic dataset for receiver function studies complementary to the WARR acquisition. The vertical component stations were specifically deployed for the WARR acquisition and they recorded during pre-programmed windows of ten minute duration, during which shots were detonated, and sampled at a rate of 200 sps. The Texans have very accurate internal clocks, calibrated with GPS time before and after deployment, for timing.

The shots were loaded in boreholes of 25 cm diameter and 45 m depth with the lower two-thirds (of the boreholes) filled with a chemical emulsion corresponding to 1.5 tonnes of dynamite explosive charge and the upper one-third packed with soil. The experiment was planned with a shot every 50 km along the line, making a total of 24 shots. No eventual permission was granted for shots 3 and 23 so that shots 2 and 24 were duplicated, with two boreholes and 3.0 tonnes of explosive for each. The shots were detonated during four nights with shot times controlled with a precision of ten milliseconds. Shots 5 and 8, unfortunately, did not deliver sufficient energy to be recorded and were discarded.

The final dataset is accordingly composed of 20 shot gather seismic sections (see Appendix 1).

Data processing and data quality

The recorded dataset (Appendix 1) is of good quality. For most shot gathers it is possible to obtain information to an offset of 350 km, allowing for good control of crustal structure and Moho discontinuity disposition, as well as the velocity in the uppermost lithospheric mantle. For some shots (e.g. shots 7 and 9; Fig. 3) there are clear phase alignments along the whole profile, which means far offsets up to 850 km (cf. shot 7; Fig. 3). Reflections coming from a discontinuity or discontinuities below the Moho (PmantleP) are well recorded by these shots.

The main phases are generated at boundaries in the sediments of the Parnaíba Basin and the metasedimentary rocks of the Araguaia fold belt (Psed); within the upper crust (Pg) and as a reflection at the base of the upper crust (Pb1P); as a refraction crossing the lower crust (Pb) and as reflected phases at a lower crustal boundary and the Moho (Pb2P and PmP, respectively); and, finally, the Moho refraction (Pn) from the uppermost mantle. It is also possible to identify some very deep reflections (i.e, PmantleP), suggesting an interface within the upper mantle, below the Moho discontinuity.

In general the shot gathers of the shots located within the basin display lower signal to noise ratio and are more reverberatory than those outside the basin. The seismograms from shots 1, 2 (Amazonian Craton) and 24 (Borborema Block), for example (Fig. 4), are clean in appearance with clear phase alignments, including the Moho reflected (PmP) and refracted (Pn) phases. In contrast, the constituent seismic traces from shot gathers from shots within the basin present a more scattered aspect (Figs 3 and 5, also see Appendix 1), mainly due to reverberations within the layers of the sedimentary basin itself.

Modelling and results

An initial velocity model is required at the start of the modelling process and this was derived from a direct analysis of the alignment of identifiable phases in the shot gathers in conjunction with a tomographic model along the profile computed from first arrival phases only (done by the authors but not shown here or published elsewhere) combined with the main features of the deep CDP profile published by Daly *et al.* (2014). Some consideration was also taken of Moho depth estimates from the preliminary receiver functions results computed (by the authors but not yet published elsewhere) from teleseismic data recorded at the 3-component stations along the WARR profile (located in Figs. 1 and 2). Once a good approximation of the velocity distribution was achieved via forward modelling, the inversion mode of “Rayinvr” was applied (Zelt & Ellis 1988) to improve the geometry and travel-time fits of some of the more complex parts of the forward model.

The resulting seismic velocity model is shown in Figure 6. It comprises five layers. The uppermost layer represents sedimentary rock; the next three are upper crust, lower crust and a high-velocity lower crustal layer, respectively; and the lowermost layer is the lithospheric upper mantle. The sedimentary layer is up to 3 km thick with a P-wave velocity ranging from 3.0 to 3.9 km/s (top) to 3.5 to 5.5 km/s (bottom). Its boundaries at the surface and base as well as its geometry are well constrained by geological and well data. The bottom of the upper crustal layer ranges in depth from 19.7 to 26.0 km, corresponding to a thickness variation between 17.6 and 24.0 km, respectively. P-wave velocity varies from top to bottom between 5.9-6.3 km/s in the central portion of the profile, between 6.27-6.40 km/s in the easternmost segment, and between 6.1-6.5 km/s elsewhere. The lower crustal model layer displays a velocity range of 6.6-6.9 km/s and has a thickness varying between 13 and 23 km. The base of the crust represents the Moho in the model, except between model distances of 150-650 km where the WARR data imply the presence of high velocity (7.0-7.45 km/s) material up to 6 km thick immediately above the Moho. The Moho depth displays a highly irregular behaviour along the seismic line, ranging from 51.0 to 33.5 km. Sub-Moho upper mantle P-wave velocities range between 8.0 and 8.4 km/s. Figure 7 presents the ray-tracing and the fit obtained between theoretical and observed times for all shots from the shallow part and for shots 1, 6, 12, 20, and 24 for the whole model. The complete modelled dataset is shown in Appendix 1.

The statistics summarized in Table 1 give an idea of the quality of the model in terms of replicating observed and computed phase travel-times. It shows the number of observations, the pick uncertainties (assigned qualitatively), the residual Trms of computed times with respect to the observed data and the chi-squared value (χ^2) for each phase separately and for all picks together. The average χ^2 of 1.4 for the whole dataset seems very reasonable in view of the extensive length of the profile and that there are twenty shot gathers considered.

The model statistics can also be considered in terms of all phases on individual shots rather than individual phases on all shots and the average Trms per shot point are shown on Figure 8. The smallest misfits between observed and model computed travel-times are for shots located outside the Parnaíba Basin (i.e., shots 1-7 within the Amazonian craton and shots 18-24 within the Borborema block). The shots inside the basin (shots 9-17) present significantly higher Trms.

Discussion of the WARR velocity model

Parnaíba Basin

The WARR dataset and modelling allows some observations to be made not only on the deeper crustal structure but also on the shallow part of the crust and on the structure of the Parnaíba Basin itself (Fig. 6, upper panel). The western part of the profile is characterized by three shallow grabens over the Araguaia belt, resolved in the WARR data, resting over the Amazonian Craton basement. They are deeper to the east, with a maximum depth of 1 km. The Cretaceous sedimentary rocks infilling these graben present an average velocity of 3.6 km/s and the Amazonian Craton basement a velocity of 6.23 km/s, which is the highest shallow velocity along the profile.

The contact between the Araguaia belt rocks and the sedimentary rocks of the Parnaíba Basin is tectonic and represented by a sharp fault, as modelled in this work and seen in the CDP profile of Daly *et al.* (2014). The shape of the basin is asymmetric, reaching a maximum depth of 3.2 km in its central part (distance 600 km) and thinning strongly eastwards. As the basin as a whole thins, older layers are exposed at the surface until the outcrop of the Silurian succession, near the eastern margin of the basin (cf. Figs 2 and 6).

The average velocity of the sedimentary package is around 3.6 km/s, being higher than 5.0 km/s in the distance range 560-800 km. This increase in P-velocity is associated with the mafic igneous rocks of the Sardinha and Mosquito formations, which are exposed as discontinuous outcrops as well as revealed in the subsurface within abundant boreholes in this area, which has been a target of hydrocarbon exploration. Due to the lack of resolution of the refraction data, it is not possible to differentiate the type of magmatic rock or to define their position within the sedimentary succession. Nevertheless, the velocity field indicates where magmatic rocks occur in the basin. They were emplaced east of the deepest part of the basin.

Crustal layers

The basement velocity, immediately below the sedimentary layer, along the WARR profile is 5.9-6.1 km/s, increasing to 6.2 km/s at a distance of 850 km, and locally decreasing to 6.1 km/s between 950-1.000 km, possibly indicating the Jaibaras graben and the Transbrasiliano Lineament. The set of early Phanerozoic rifts underlying the Parnaíba Basin recognized from other work (e.g. Nunes 1993; Oliveira & Mohriak, 2003; Castro *et al.*, 2016), including the Jaibaras graben, are not seen in the

WARR velocity model, probably due to their small dimensions and/or because the velocity of the strata in these rifts is close to the velocity of the adjacent and underlying basement rocks.

The upper crustal layer is almost regular in thickness with its base at an average depth of 24 km (Fig. 6, lower panel). Beneath the Parnaíba Basin (distances 300-900 km), the upper-lower crust boundary is roughly parallel with the basin basement horizon. Elsewhere, the upper-lower crust boundary is somewhat undulated under the Amazonian Craton and more or less flat in the Borborema block. At distances 300-600 km both basin and upper crust dip gently eastwards, the depocentre of the basin coinciding with the deepest point of the upper crustal layer lower boundary. From this point eastwards until distance 900 km both the basin-upper crust and upper crust-lower crust layer boundaries become shallower. The latter undulates in the range 600-900 km and follows the top of the high amplitude body identified in the CDP section and interpreted as a sill-like intrusion by Daly *et al.* (2014). At the western end of the profile the shallow upper crust of the Amazonian Craton is characterized by anomalously high velocities (6.25 km/s on average) and by a smooth and small velocity gradient, reaching 6.4 km/s at the base of the upper crust. In contrast to the Amazonian Craton, the west Parnaíba block (labelled the Grajaú domain in Fig. 6) presents a steep upper crustal velocity gradient ranging from 6.1 km/s to 6.5 km/s. This high gradient coincides with the eastward-dipping upper crust-lower crust boundary (to about 500 km in Figure 6). To the east the velocity distribution in the upper crustal layer is more irregular, being 5.9-6.1 km/s in its upper part and 6.2-6.3 km/s in its lower part, presenting a smooth gradient that characterizes the east Parnaíba domain, known as the Teresina block (Castro *et al.* 2014). From 900 km through to the eastern end of the profile, the velocity in the Borborema block is 6.0 km/s in the upper part of the basement and 6.4 km/s at the bottom, and characterized by a strong velocity gradient. The upper crust-lower crust boundary is flat in this area.

The lower crustal layer in the model has a velocity varying from 6.7 to 6.9 km/s, except where there is anomalously high velocity material (7.0-7.4 km/s) within the lowermost part of the lower crust in the distance range 150-640 km. Excluding this high velocity material, the P-wave velocity in the lower crust is quite uniform throughout the profile, 6.7 km/s at the top of the layer and 6.9 km/s at the bottom, and, accordingly, has a similar velocity gradient throughout.

Shot gather 12 (Barra do Corda; Fig. 5) shows that the crust to the west of Barra do Corda presents a reverberatory aspect between offsets -50 to -150 km and reduced time axis 5-9 s, suggesting that the lower crust and even the upper crust in this region may have been intruded and affected by mafic magmatism. Such mafic bodies disturb the propagation of the wave front, generating multiples and discontinuous reflections, and even obscuring the Moho reflection (PmP). In contrast, the same shot gather in its eastern part shows a crust that is not affected in this way.

Moho character and upper mantle

Depth to Moho along the WARR velocity model is quite irregular, varying from 51 km in the Amazonian Craton to 33.5 km at the profile's eastern end within the Borborema block. In general there is a trend for Moho depth to shallow, and thus crust to thin, towards the east along the profile. The eastward crust-thinning trend is underlined by zones of Moho structure that can be correlated with the crustal domains along the profile labelled in Figure 6.

The most striking structure on the Moho is beneath the Amazonian Craton where it deepens from 38 km to 51 km at the front of the Neoproterozoic Tocantins-Araguaia suture, between 100-200 km, before thinning sharply to 41 km at a distance of 300 km. Part of the thickened crust (and hence deeper Moho) in this zone is due to the high velocity material (7.4 km/s) added to the lower crustal layer. Together with the seismic fabric imaged in the CDP section (Daly *et al*. 2014), the Moho geometry suggests that this very thick crust is formed by lower crustal underthrusting and duplication.

The Moho reflection (PmP) is usually clear, indicating the strong contrast of impedance between the rocks of the lowermost crust and the top of the mantle. The PmP phases between shots 4-9 and 17-19 of the present dataset, however, are not well defined. These phases are unclear in the shot gathers (see Appendix 1), suggesting that in both regions the Moho is not a first order discontinuity. These segments are geographically related to the Amazonian Craton-Parnaíba and Parnaíba-Borborema block sutures, respectively, and probably are an indication of the complexity of the Moho below both these zones. Mafic intrusions within the crust can affect the Moho reflection as well. They reduce the velocity and impedance contrasts between the crust and mantle, transforming the Moho into more of a transition layer rather than a first order boundary and diminishing the PmP phase.

The upper mantle velocity inferred from the WARR dataset is 8.2-8.4 km/s under the Parnaíba Basin and around 8.0 km/s outside the basin, under the Amazonian Craton and the Borborema block. The anomalously high velocity directly under the basin could represent mantle that has been differentiated, enriched and densified, forming a strong mantle foundation under the Parnaíba

Basin probably isostatically linked to the present day mapped basin limits (that is, a higher density uppermost mantle isostatically compensating the overlying low density Parnaíba sediments).

Crustal domains along the WARR profile and implications

Any 2D WARR model presents a relatively smooth velocity field geometry defining heterogeneities within model layers and the lateral variations along the length of the model. Sometimes the differences of interest between geological (or crustal) domains are better expressed by velocity gradients rather than by absolute velocities themselves. For the present model, a series of velocity-depth profiles, evenly extracted along the model domain, have been stacked and allow the differentiation of four domains along the profile (Fig. 9): the Amazonian and Borborema blocks, exposed outside the basin and the Parnaíba block hidden below sedimentary cover and herein sub-divided into the Grajaú and Teresina domains.

The Grajaú domain is characterized by high velocity material in the lower crust (6 km thick with a velocity of 7.0-7.2 km/s), where the Moho is 44 km deep on average (Figs. 6 and 9). This region, although modelled as an independent velocity layer coupled to the lower crust, is more likely a transitional layer resulting from upper mantle and lower crustal extension, decompression and mafic magma intrusion, affecting the crust as a whole, but mainly expressed in the velocity model as the higher velocity material in the lowermost lower crust (cf. Christensen & Mooney 1995). A non-abrupt limit is, accordingly, inferred between the lower crust, the high velocity material and the upper mantle.

The lower crustal accretionary material, considered here as an “underplate” in the sense of Thybo & Artemieva (2013), is geographically coincident with the surface extent of Cretaceous sediments in the Parnaíba Basin (cf. Fig. 2) with this same segment of the crust interpreted to have been affected by magmatism, as shown by shot gather 12 (Fig. 5). Considering that this youngest basin depocentre was established in the Cretaceous (e.g. Vaz *et al.* 2007), a genetic link between magmatic underplating (resolved by the velocity model) and crustal depth magmatism (although not enough to significantly affected crustal velocities) and surface subsidence defining the Cretaceous basin depocentre seems possible.

The Teresina domain is marked by a flat Moho at 39 km depth. It is separated from the Grajaú domain by a step of 4 km in the Moho (600 km), accommodated almost totally by the termination of the high velocity lower crustal layer (interpreted as being evidence of underplating, as defined above), and from the Borborema block by a step of 2 km (900 km). The nature of the limit between the Grajaú and Teresina domains is not well defined and, indeed, Figure 9 shows that the average velocity of these blocks is very similar, the main differences being in upper crustal velocity gradient and the crust-Moho transition linked to the high velocity ”underplate”. Thus, it is not clear from the WARR data whether the Grajaú and Teresina domains represent distinct tectonic domains since their amalgamation in the Neoproterozoic, or whether the differences that are observed now are the result of later processes, including magmatism that took place in Jurassic-Cretaceous times. The CDP section of Daly *et al.* (2014) is also not conclusive in this regard since it is completely transparent in the Grajaú domain.

The contact between the Teresina and the Borborema blocks is tectonic and considered to be a suture zone with the former subducted under the Borborema block to the east, as revealed in the CDP section of Daly *et al.* (2014). The WARR data resolved the Moho depth around 39-41 km in the area of this suture zone, suggesting that any Moho structure that was associated with it has been since removed.

The Borborema domain displays Moho shallowing continuously eastwards, from 41.0 km to 33.4 km at the end of the WARR profile. The upper crustal layer does not display similar thinning; its thickness is nearly constant in the Borborema domain such that at the eastern extremity of the profile the upper crust is more than twice the thickness of the lower crust. The crustal structure of the Borborema block obtained here replicates the structure determined along the NW-SE Borborema deep seismic refraction line (Tavares *et al.* 2012; Lima *et al.* 2015), performed northeastwards of this profile. The Borborema Province, as a whole, displays a thin crust (Soares *et al.* 2011; Lima *et al.* 2015; Luz *et al.* 2015) and a thin lithosphere. Its crust and probably lithospheric mantle were affected by extension linked to the opening of the South Atlantic Ocean in the Cretaceous. This may be linked to marginal uplift of the Borborema Province and exposure of basement rocks during and after the Cretaceous and to the present erosional margin of the eastern border of the Parnaíba Basin.

Integrated WARR results and their implications

The main WARR results are integrated in Figure 10. They show that the crust and uppermost mantle along the profile consist of four domains, distinct in their seismic velocities and layering and crustal thicknesses. These are the Amazonian Craton and Borborema Province, to the west and east of the Parnaíba Basin, respectively, and the Grajaú and Teresina domains together comprising the

Parnaíba block hidden below the sedimentary cover of the Parnaíba Basin itself. The lithospheric characteristics of the Parnaíba block and its constituent domains and their differences with the adjacent Amazonian and Borborema blocks are relevant to the present-day existence of the sedimentary basin covering it, summarized as follows.

Starting at the base of the model, the upper mantle velocity below both domains of the Parnaíba block is higher – up to 8.4 km/s – than elsewhere. This isostatically compensates the Early Palaeozoic (and, in part, younger) sedimentary succession above the crust and is likely to have been a factor in the initial development of the Early Palaeozoic sedimentary basin, subsequent to the Neoproterozoic (and possibly earliest Palaeozoic) Brasiliano-Pan-African consolidation of the crust of the Parnaíba block. Regarding the lower crust of the Parnaíba block and its age, it is noted to have been in part reworked eastwards from the Tocantins-Araguaia suture, with the adjacent Amazonian Craton lower crust, in contrast, appearing to have been basically preserved, maintaining Neoproterozoic structures. Nevertheless, the whole of the suturing area also displays the presence of a high velocity lowermost crustal material, which can be interpreted as caused by magmatic underplating and lower crustal intrusion. The age of this magmatic event is possibly Cretaceous because it spatially coincides with the Cretaceous and younger depocentre of the Parnaíba Basin. In this case, there is a possible genetic link between Cretaceous basin subsidence and magmatism within the sedimentary succession, although the latter is spatially offset somewhat from the lower crustal high velocity body. Since the crust was intruded (as inferred from the character of observed seismic traces) in the Grajaú domain, it is reasonable to suggest that it may also have been stretched at the same time (e.g. Mooney et al. 1983). There is strong evidence that the Borborema block was stretched in the Cretaceous (linked to South Atlantic opening; Soares *et al.* 2011; Lima *et al.* 2015; Luz *et al.* 2015) so it follows that the Teresina domain of the Parnaíba block, along with the Grajaú domain, would also have been stretched at this time. There is no remnant structure at the Moho related to the suturing of the Parnaíba and Borborema blocks according to the WARR model and this can be taken as support for Cretaceous stretching of this part of the model and the removal of any such structure. It is also noted that there is no discrete signature of the Transbrasiliano Lineament resolved by the WARR data in the lower crust of the Parnaíba Basin.

The upper crust along the profile does not display any structural effects of extensional tectonics in the Mesozoic, as inferred for the lower crust and Moho, although there was some degree of magmatic intrusion in the Grajaú domain and the upper crust appears to have been uplifted at the eastern border of the Parnaíba Basin, as shown by the erosional margin of the basin there. Normally an extended upper crust presents a brittle behaviour. The graben structures recorded in the Araguaia belt, in the westernmost segment of the WARR profile, are a good example of this. However, no rift-like structures or large faults, or strong thickness variations are resolved in the WARR model of the upper crust beneath the Parnaíba Basin. This includes the set of late Neoproterozoic-early Cambrian rifts (including the Jaibaras rift), that may have played a local role in the early basin formation and evolution but not in the later Mesozoic phase of basin development. As seen at the scale of the WARR data, the crust as a whole beneath the basin has been flexed downwards, in keeping with the sub-parallel basement horizon of the basin itself, and shows no typical rift-type control on basin formation.

Summary and conclusions

The Parnaíba Basin WARR profile is 1,150 km long and runs E-W approximately coincident with the deep seismic reflection profile of Daly et al. (2014). Its western terminus is within the Archaean-Paleoproterozoic Amazonian Craton some 150 km west of the margin of the Parnaíba Basin and its eastern terminus is within the Brasiliano-Pan-African (Neoproterozoic) Borborema Province, some 100 km east of the margin of the basin.

In particular, the velocity model of the crust and upper mantle beneath the Parnaíba Basin (from ray-tracing of the WARR data) documents lateral velocity changes in the upper mantle – with higher upper mantle velocities beneath the present-day preserved Phanerozoic sediments of the Parnaíba Basin – as well as lateral changes in seismic character and velocity within the crust – with higher lower and upper crustal velocities and evidence of magmatic intrusion into the crust beneath the Cretaceous and younger sedimentary depocentre of the Parnaíba Basin.

The existence of high velocity-high density lower crust-upper mantle material under the basin itself provides new constraints on the geodynamic history of the Parnaíba Basin and brings new insights for intracontinental basin formation in general.

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Figure captions

Figure 1 – Physiographic map of north Brazil highlighting the limit of the Parnaíba Basin (thick grey line) and showing the paths of the CDP profile (Daly *et al.*, 2014) in white and the WARR profile in black. The profiles are coincident except between Imperatriz and Barra do Corda and between Altos and Castelo. Stars indicate the locations of WARR profile shot points and the triangles are the locations of 3-components seismograph stations used for preliminary Receiver Function estimates of Moho depth. The dashed line is the inferred location of the Transbrasiliano Lineament (CPRM 2015) and reference cities along the profile are indicated as shown. The inset map shows the Parnaíba Basin in the context of the South America continent (modified from CIGIAR 2017).

Figure 2 – Geological map of the Parnaíba Basin with legend as for Figure 1 (modified from CPRM 2015).

Figure 3 – Shot gathers 7 and 9 (top and bottom), shot within the Parnaíba Basin and recorded along the whole profile, presenting maximum offsets of 850 km and 650 km, respectively. These broad offset recordings provide good constraints on upper mantle velocity. Examples of seismic phases mentioned in the text are labelled. The reducing velocity on the vertical (time) axis is 8.0 km/s and a bandpass filter of 2-8 Hz has been applied to the seismic traces. Note that the scale of the horizontal axis differs from shotpoint to shotpoint. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

Figure 4 - Shot gathers 1, 2 and 24 (top to bottom), shot in the Amazonian Craton (shots 1 and 2) and in the Borborema block (shot 24), presenting well-defined phase alignments. Examples of seismic phases mentioned in the text are labelled. The reducing velocity on the vertical (time) axis is 8.0 km/s and a bandpass filter of 2-8 Hz has been applied to the seismic traces. Note that the scale of the horizontal axis differs from shotpoint to shotpoint. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

Figure 5 - Shot gather 12 (Barra do Corda; Fig.1). The zoomed insets (a and b) show the difference between the (a) negative and (b) positive parts of the section at offsets 50-150 km. The negative side is more reverberatory between the arrivals of the Pg and PmP phases, indicating the presence of mafic intrusions throughout the crust. The shot gather is reduced with 8.0 km/s and filtered in the bandpass of 1-10 Hz. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

Figure 6– 2D WARR crustal velocity model across the Parnaíba Basin and its western and eastern margins (lower panel). Also shown is the topography along the profile and the locations of shotpoints (yellow stars) and 3-component seismometers (red triangles). The model is divided into four main domains defined from west to east as: i) Amazonian Craton (0-250 km); ii) Grajaú domain (250-550 km); iii) Teresina domain (550–850 km) and iv) Borborema block (850-1150 km offset), the middle two domains comprising the Parnaíba block. In general the model crust thins eastward, especially through the thinning of lower crust. The upper panel details the shallow part of the model (uppermost 15 km) showing the graben of the Araguaia belt, the asymmetry of the sedimentary basin and a high velocity region (> 5.0 km/s) inside the sedimentary basin, indicating that part of the basin along the profile was affected by magmatic intrusions. The ray-trace coverage can be seen in the background of both panels.

Figure 7 – Ray-tracing and the fit between theoretical and observed travel-times for the shallow part of the model (upper panels) and for the deeper crust and upper mantle (lower panels). Fits for all shots are plotted in the former but, for clarity, only those of shots 1, 4, 9, 13, 16, 17, 22 and 24 are shown in the latter. The observed travel-times are plotted as error bars (the length being an indication of uncertainty in picking the phase arrival times) and the theoretical travel-times computed from the velocity model shown in Figure 6 are the continuous lines. The precision of the misfits is shown in Table 1. A complete modelling dataset is presented in Appendix 1.

Figure 8 – Histograms showing the quality of the misfit (Trms) between theoretical and synthetic phases per shot. The average Trms of 0.125 s is a good result considering the amount of data and the basin environment, which normally increases uncertainties due to reverberation in the recorded traces.

Figure 9 – Average 1D P velocity curves of the main crustal domains recognized along the profile (as seen in Figure 6). The main differences are in the velocity gradient of the upper crust, the upper-lower crust transition and lower crust-upper mantle transition. The upper mantle velocity is higher under the basin (up to 8.4 km/s) than outside the limits of the basin (8.0 km/s).

Figure 10 – A cartoon integrated interpretation of the WARR velocity model. Continuous lines are structures (faults, fractures, etc.) interpreted from CDP session, as are the speculative positions of the Amazonian-Parnaíba and Parnaíba-Borborema sutures, and the dashed lines are the authors' complementary interpretations. The thick red-coloured body interpreted as a sill in the mid-crust of the Teresina domain was extracted from deep CDP interpretation (Daly *et al.* 2014). The thin line network in the Grajaú domain represents magmatic intrusions throughout the crust inferred from the WARR data.