**The pre-Silurian Riachão basin: a new perspective on the basement of the
Parnaíba basin, NE Brazil**

Amanda Porto^{1*}, Michael C. Daly², Emanuele La Terra¹ & Sergio Fontes¹

*¹Department of Geophysics, Observatorio Nacional/MCTI, 20921-400 São
Cristovão, Rio de Janeiro, Brazil*

*²Department of Earth Science, University of Oxford, South Parks Road, Oxford OX1
3AN, UK*

**Corresponding author (e-mail: amandaporto@on.br)*

Abstract: We present a new interpretation of the basement immediately below the pre-Silurian unconformity in the mid-western part of the Parnaíba cratonic basin. Regional seismic reflection data, constrained by well and gravity data, have revealed the remnants of a pre-Silurian basin named the Riachão basin. It has a north-south trend, is about 120km wide with a minimum area of ~35,000km² and maximum thickness of 4km. Seismic interpretation shows the Riachão basin is defined by erosional unconformities at its top (Pre-Silurian Unconformity) and base (top of pre-Riachão basement). The basin fill is formed of three stratigraphic sequences: Riachão I, II and III, separated by seismic discontinuities and laterally bounded by monoclinal folds and basement uplifts related to thrust faults. Exploration wells show the Riachão sediments to be Pre-Silurian, clastic, and a minimum of 1 km thick, unconformably overlying a heterogeneous metamorphic basement. The formation mechanism of the basin is unclear. However, our seismic stratigraphic interpretation suggests that Riachão II and III are remnants of marine, clastic, foreland basin sequences of opposed polarity, related to late Neoproterozoic tectonics. The banded, high amplitude, Riachão I sequence is interpreted as a carbonate platform preceding the main subsidence and clastic input of the Riachão basin.

Four Phanerozoic cratonic basins cover a large area of continental Brazil: the Amazonas basin, Solimões basin, Paraná basin and Parnaíba basin. (Milani & Zalán, 1999). The basement history of these cratonic basins is key to the understanding of their genesis. In this context, we examine the pre-Silurian sedimentary section of the Parnaíba basin, integrating recent industry seismic reflection, exploration well and gravity data from the mid-western part of the basin, near the city of Riachão, in Maranhão state.

The Parnaíba basin lies in NE Brazil and covers an area of approximately 600,000 km². It has a maximum thickness of 3.5 km in its central part. The Parnaíba stratigraphy can be divided into five major depositional sequences, varying in age from the Late Ordovician to the Cretaceous, and marked by a progressive change in the depositional environment, from marine to continental. During the Mesozoic, two phases of tholeiitic magmatism occurred, resulting in the Mosquito Formation in the Triassic and Jurassic and Sardinha in the Early Cretaceous (Vaz *et al.*, 2007; Cordani *et al.*, 2009a; 2009b).

The Parnaíba basin is developed on the South-American platform (Fig. 1). The basement of the platform is composed of Archean and Proterozoic continental blocks accreted during the Paleoproterozoic (Trans-Amazonian orogenic cycle), Late Mesoproterozoic and Neoproterozoic (Brasiliano/Pan-African orogenic cycle). The platform was consolidated during the latter orogenic cycle and the final stages of the formation of the Gondwana Supercontinent. (Cordani *et al.*, 2009a; Brito Neves & Fuck, 2013). The region of the Parnaíba basin comprises two major domains: the Pre-Neoproterozoic Amazonian domain and the Neoproterozoic Brasiliano domain (Fig. 1; Brito Neves & Fuck, 2014). These domains are bounded by major structural features

developed during the Neoproterozoic, the Araguaia-Rokelides suture and associated Araguaina Fault Zone (Daly *et al.*, 2014) in the west, and the Transbrasiliano Lineament, in the east. Both features represent important structural elements of the Parnaíba basin basement (Fig. 2).

Several authors have commented on the basement of the Parnaíba basin. Brito Neves *et al.* (1984) pointed out that the deposition of the Parnaíba cratonic basin started after the Brasiliano-Pan African cycle due to thermal contraction of elevated geothermal gradients during the post-orogenic period. Using available surface geology and wellbore information, they defined the presence of a central cratonic block and a molassic basin in the southwest Riachão area (Fig. 2a). Cordani *et al.* (2009b; Fig. 2b), interpreted a major north-south graben in the Riachão area, defined by a negative gravity anomaly. Castro *et al.* (2014; Fig. 2c), using gravity and magnetic data, mapped a dense array of supposed rift basins throughout the unexposed block. They went on to define two different rift phases in the period between the end of the Neoproterozoic-Cambrian Brasiliano orogeny and the initiation of sag deposition in the Silurian. The first is located in the central basement inliers and is represented by overall north-south oriented low gravity anomalies. The second phase is represented by NE-SW linear Cambro-Ordovician grabens, mainly along the Transbrasiliano Lineament. These grabens partially outcrop in the eastern and northeastern margins (Jaibaras basin) of the Parnaíba basin.

Daly *et al.* (2014) demonstrated that a major pre-Silurian unconformity defines the base of the Parnaíba basin. They defined three basement blocks beneath the Parnaíba basin on the basis of seismic character and major, steep, crustal scale discontinuities. The deep seismic reflection profile did not image the large and extensive rift structures

proposed by Castro *et al.* (2014). However, it did image one narrow rift feature around Campo Maior, along the boundary between the Borborema Province and the Parnaíba block. They linked this boundary to the Transbrasiliano Lineament feature at Jaibaras and concluded that it represented a major crustal boundary beneath the Parnaíba basin. Recently, Castro *et al.* (2016) modified their previous interpretation, defining far fewer rifts and identifying two rift zones (Fig. 2d) that developed during the early Paleozoic. They then postulated a link with the sag deposition of the Paleozoic Parnaíba basin. They also mapped supracrustal strips within the basement that caused negative gravity anomalies, suggesting a very heterogeneous basement composition within the Parnaíba basin.

This paper builds on these previous ideas through new geophysical and legacy well data to generate a detailed seismic stratigraphic and structural interpretation of the geology immediately below the Parnaíba basin pre-Silurian unconformity. It identifies a remnant stratigraphic package, the Riachão basin, formed of three seismostratigraphic sequences deposited during three separate tectonic phases. The Late Brasiliano molasse basin of Brito Neves *et al.* (1984) is compatible with the interpretation presented here.

Geophysical Dataset

The geophysical dataset includes nine 2D seismic reflection profiles, one ground gravity profile and a gravity airborne survey (Fig. 3). Exploration wells were also used to calibrate seismic data and to constrain the 2D forward modelling (Table 1). The dataset is public, provided and acquired by the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP).

The 2D seismic reflection survey 0317_2D_ANP_BACIA_DO_PARNAÍBA was acquired in 2013. The nine lines were released already processed and pre-stack time

migrated, with a two-way-time of 7 seconds. The lines are oriented NE-SW and NW-SE and their lengths range from 85 km to 200 km, comprising a total of 1276 line km of seismic data.

Two different gravity datasets were used: an airborne gravity survey and a ground gravity profile. The ground data were acquired in 2013, during the acquisition campaign for the seismic data. The profile 317-115 is NE-SW oriented (Fig. 3) and it was acquired along the seismic line of the same name, with an interval of 200 m between each station, totalling 964 stations. The airborne gravity survey 0050_GRAVIMAG002_ANP was flown between 2005 and 2006 and covered an area of 748,612.4 km². However, only a subset of 154,677.6 km² was used in this study (Fig. 3). The flight lines are east-west oriented with 6-km-spacing and the tie lines are north-south oriented with 24 km spacing. The flight velocity was 280 km/h, at a height of 1800 m, and data were recorded at intervals of 0.04 s, and approximately 3 m of interval between each sample.

Both airborne and ground gravity data were originally processed by ANP using the software OASIS MONTAJ (Geosoft) and involved a quality control of the raw data, necessary corrections and compensations, and basic filters. The processing of the ground and the airborne surveys includes latitude and terrain corrections, free-air and Bouguer reductions. Dynamic acceleration, Eötvös and leveling corrections were also carried out for the aerogravity data.

Seismic Interpretation

Methodology

The nine 2D seismic profiles were qualitatively analyzed in time to identify the main seismic facies. This identification was based mainly on the following criteria: the frequency and the amplitude of the seismic signal and the continuity and geometry of

the reflections (Table 2). Seismic-to-well calibration was undertaken in order to integrate seismic and well data. The calibration consisted of matching the synthetic seismogram extracted from well logs to the real seismograms extracted from the seismic profiles. Eight wells were calibrated to six seismic profiles, as presented in Table 1. This table also shows the exploration wells that reached the pre-Silurian basement, added to the lithological and chronological information, where available. Finally, to convert the seismic profiles from two-way-time to depth, a velocity model was created using the available velocity values from the time vs. depth tables from the eight wells and the grid of five key interpreted seismic horizons. Figure 4 shows the Vereda Grande well (1-VG-1R-MA) calibrated to seismic line 105. The figure shows six seismic horizons that define seven seismostratigraphic sequences, as detailed in Table 2. The well did not reach all the seven sequences and its final depth is located near the base of Riachão III sequence. However, it is possible to observe three distinctive seismic sequences below the well, Riachão II, Riachão I and the Pre-Riachão basement.

Results

A composite seismic reflection profile is presented in Figure 5 to show an example of a dip cross section through the Riachão basin and to illustrate the main stratigraphic and structural features. The section is formed of five parts taken from five seismic lines, 317-104, 115, 105, 103 and 106, oriented either NW-SE or SE-NW to display a general east-west 2D view.. The uninterpreted seismic reflection profile is shown in Figure 5a, with a line drawing interpretation at the same scale in Figure 5b, and a final colour interpretation in Figure 5c. The same layout was adopted for Figure 6, which represents more detailed views on the eastern and western margins of the Riachão basin.

The composite section maps out three broad groups of seismic facies that define three distinct stratigraphic sequences (Fig. 5). At the base of the profile, the area of

complex and confused seismic facies terminates at an abrupt boundary, interpreted as the top of the Pre-Riachão basement. The Riachão basin itself lies above this basement and has a broadly trapezoidal shape. It is composed of three seismostratigraphic sequences: Riachão I, Riachão II and Riachão III (Fig. 5). Unconformably above the Riachão basin lies the Phanerozoic Parnaíba cratonic basin formed of three seismic sequences (Silurian, Early-Middle Devonian and Late Devonian to Present-day). The Riachão basin is therefore bounded, above and below, by pronounced, erosional unconformities: the Pre-Silurian unconformity (PSU) and the top of pre-Riachão basement, respectively (Fig. 5).

The Pre-Riachão Basement

The composite section shows the complex internal seismic facies of the Pre-Riachão basement (PRB). The western part of the PRB is characterized by short, discontinuous reflections, dipping variably westwards (seismic facies 1B in Table 2). In contrast, to the eastern side, the PRB seismic pattern is much more opaque (seismic facies 1A in Table 2). The depth to the top of PRB also varies from west to east. It is very shallow in the eastern margin, at around 1.2km depth, as constrained by the Carolina well (1-CL-1-MA). To the west it deepens to around 2.5km, as constrained by the Mangabeiras well (1-MS-1-MA). The Carolina well found quartz diorite gneiss at 1160m that yielded a K-Ar biotite age of 608 Ma (Cordani *et al.*, 2009a). The Mangabeiras well reached quartz-mica schist at 2470m that revealed a Rb/Sr whole rock age of 1420 Ma (Cordani *et al.*, 2009a). These age differences, derived from very different methods, are not easily used to draw a regional comparison.

Cordani *et al.* (2009a) interpreted the age of the gneiss penetrated by the Carolina well to be similar to lithologies of the Estrondo Group of the Araguaia fold belt, western border of the basin. They also interpreted the area of the Mangabeiras well

as comprising two possibilities: a cratonic inlier of Mesoproterozoic age or a rejuvenated pre-Brasiliano unit within a Neoproterozoic fold belt.

The Riachão Basin

The Riachão basin comprises three seismically defined stratigraphic sequences: Riachão I (RI), II (RII) and III (RIII). These sequences are defined on the basis of seismic facies, seismic event terminations and their relative juxtaposition. Four discontinuities were mapped in the Riachão basin, from base to top: top of PRB unconformity; top of RI; top of RII; and top of RIII which is the aforementioned PSU (Fig. 7).

The Riachão I sequence is characterized by a continuous band of parallel and high amplitude reflections (seismic facies 2 in Table 2). This section has not been tested by exploration wells, so its true lithology is unknown. However, the distinctive character of the banded package suggests it could be a platform carbonate sequence. RI extends across most of the Riachão basin area with an average thickness of 250m and a maximum thickness of 800m (Fig. 8b). The base is defined by an erosional unconformity above the PRB and the top is marked by the onlap surface of the RII sequence (Fig. 7).

The RI sequence defines a gentle central arch, shown in the composite line, that becomes more pronounced in line 101. On lines 104 (Fig. 5) and 115 (Figs. 6a, 6b and 6c) two basement-involved thrust faults imbricate the Riachão I sequence, defining an east facing monoclinical structure. On the opposed eastern margin (Figs. 6d, 6e and 6f), similar basement-involved thrusts deform the sequence, forming a monocline and interrupting abruptly the continuity of the reflections.

Both Riachão II and Riachão III sequences have a broadly wedge shape geometry. The Riachão II sequence onlaps the top of Riachão I and thins eastwards

towards the central arch, whilst the Riachão III onlaps Riachão II (Fig.7). Riachão II has a maximum thickness of 2km and thins to the east; and the overlapping Riachão III has a maximum thickness of 3km and thins to the west (Figs. 8c and 8d).

The Riachão II sequence presents a chaotic seismic facies at the top, followed by continuous reflections at the base (seismic facies 3 in Table 2). This difference suggests either a change in lithology or structure. The upper section appears to be chaotically folded and associated with the Pre-Silurian deformation the basin has experienced. At the western margin of the basin (Fig. 5), almost vertical reflections terminate at the PSU. This feature shows that the marginal, basement cored uplifts, also deformed the RII sequence.

In the Vereda Grande exploration well (1-VG-1R-MA; Fig. 4), the Riachão III sequence is composed mainly of clastic sediments: an intercalation of shales and siltstones from -1,416m to -1,740m and sandstone from -1,815m to -2,500m (True Vertical Depth). Seismic data show long and continuous reflectivity (seismic facies 4 in Table 2), dipping eastwards and normally terminating as erosive truncations against the PSU (Fig.7). At the eastern margin, the RIII sequence is folded in a west facing monocline and overthrust by basement (Figs. 6d, 6e and 6f).

The Riachão basin is bounded by two large monoclinal structures, defining the major basinal area. In the west the monocline faces east and in the east the monocline, overthrust by basement, faces west. Both sides of the basin have elevated basement and these structures are interpreted as basement-involved thrust faults. This geometry indicates that the whole Riachão basin is a remnant of something larger, preserved between two basement-involved, thrust elevated, uplifts at the east and western margins.

In the RIII sequence, high amplitude reflections, interpreted as igneous sills (seismic facies 7 in Table 2), are widely developed. They appear to connect to other sills

in the shallower Phanerozoic Parnaíba basin, implying that they are related to the regional Mesozoic magmatic episodes described in the basin (Merle *et al.*, 2011). The Vereda Grande well (1-VG-1R-MA) penetrated a 65m thick diabase sill in the middle of RIII sequence (Fig.4), that yielded a K-Ar age of 201 Ma (Nunes *et al.* 1973). Normally, igneous sills preferentially intrude ductile stratigraphic levels, such as shales, or along stratigraphic discontinuities, such as unconformities (Gudmundsson, 2001; Thomson & Schofield, 2008). The top of RII sequence is marked by high amplitude reflections (Figs. 4 and 7), interpreted as a diabase sill emplaced along this unconformity.

The Phanerozoic Parnaíba Basin

The Phanerozoic (Lower Paleozoic to Recent) Parnaíba basin lies unconformably above the Pre-Riachão basement and the Riachão basin. Its base is regionally defined by the flat Pre-Silurian unconformity. In the study area the Parnaíba basin thickness varies from a maximum of 2.47 km in the northeast part of line 115 to a minimum of 1.16 km in the western part of line 104.

Generally the Paleozoic sequences of the Parnaíba basin appear as long, continuous and sub-horizontal reflections (seismic facies 5 in Table 2). From well data the Lower Paleozoic sequences comprise intercalations of shale and sandstone. Two packages were mapped and correlated with the lithostratigraphic tops of the Devonian Pimenteiras Formation and the Silurian Jaicós Formation.

Aerogravity Data Analysis

In the polygon of Figure 3 the aerogravity data was gridded using the bi-directional interpolation method with a cell size of 250m. The complete Bouguer anomaly was recalculated using a typical crustal density of 2,670 kg.m⁻³ for the

Bouguer slab (Blakely, 1995) and the topographic correction released by ANP in the original database.

A regional-residual separation was applied to the complete Bouguer grid using the statistical methodology developed by Spector & Grant (1970). The shape of the mean radial power spectrum of the observed gravity data was analyzed and a clear break between low- and high-frequency components was identified (Porto, 2017). The part of the curve with a steep slope and a wavelength greater than 95km was assigned to the regional gravity signal. Using a Gaussian filter in OASIS MONTAJ software, a standard deviation of 0.0105 rad/km was chosen in order to separate shallow and deep gravity sources (Geosoft, 2015).

A qualitative analysis of the gravity data, based on the complete Bouguer (Fig. 9a), the regional (Fig. 9b) and the residual (Fig. 9c) maps, allowed the identification of three domains in the study area (Fig. 9d): domain I, II and III. These domains were defined mainly by the amplitude of the Bouguer anomalies, higher or lower than the average value of -65 mGal, and their main geometries and trends.

Domain I, in the west, presents the highest Bouguer anomaly values of the study area (from -38 mGal to -55 mGal). In the southern-central part, a strong N-S fabric, defined by elongated gravity highs and lows, is observed in both regional and residual maps. This trend weakens towards north, where rounded to amorphous high anomaly features occur. Domain III, in the east, is characterized by low and high amplitude gravity anomalies with an approximately NNE-SSW trend. The complete Bouguer and regional anomalies increase from the SE to the NE of the study area.

Domain II is characterized by lower amplitude gravity anomalies and is located in the central part of the study area, where the Riachão basin was located. It can be divided into two subdomains, IIA and IIB, on the basis of amplitude anomaly. Domain

IIA is characterized mainly by intermediate Bouguer anomaly values of approximately -50 mGal. Domain IIB is characterized by a very pronounced north-south elongated low anomaly that ranges from -77 mGal to -85 mGal. This negative anomaly is also noticed in both regional and residual maps, with the same trend.

Integrating these observations with the seismic and well data, several correlations enhance the regional context of the Riachão basin. Domain I reflects the basement subcrop of Brasiliano age metamorphic rocks of N-S trend, constrained by the Carolina well (1-CL-1-MA). The high anomalies of Domain III coincide with the subcrop of the pre-Riachão basement at shallower depths (around 2.5 km in Mangabeiras well; 1-MS-1-MA) beneath the Parnaíba basin, and appear to be influenced by the wide deformation zone of the Transbrasiliano Lineament.

The reduced anomaly of Domain II marks the west and center of the Riachão basin and shows a strong and enduring N-S orientation. The low Bouguer anomaly of Domain IIB marks the 2km thick Riachão III sequence (Fig. 8d); its eastern edge coincides with the basement uplift of the eastern margin of Riachão basin. In both regional and residual map, the eastern basement uplift coincides with low anomalies. Castro *et al.* (2016) observed that the maximum depocenter of this basin does not coincide with the minimum gravity anomaly of the region. This may be explained by a less dense crust in this region, or a lower Moho; both possibilities are evaluated in the forward models of line 115.

2D Forward Modelling

Gravity based forward modeling takes an initial geological model and calculates the associated gravity anomaly. It then compares the modeled anomaly with the observed anomaly (Blakely, 1995). The geological model is then adjusted, by varying the density and the geometry of the layers, to find the best fit between both anomalies.

Due to the non-uniqueness of gravity interpretation, two initial models were tested, Model 1 (M1) and Model 2 (M2), as shown in Figure 10. Both models considered geometric and density heterogeneities within six crustal domains (Table 3). The calculated anomalies for each model were then compared to the observed complete Bouguer anomaly along line 115.

The density values (Table 3) for the igneous sills, the Phanerozoic Parnaíba basin and the Mesoproterozoic metasediments were extracted from the core density values available in the Mangabeiras (1-MS-1-MA) well report. For the Riachão III sequence, the value was extracted from the Vereda Grande (1-VG-1R-MA) well report. The other density values were estimated from the regional literature (Castro *et al.*, 2014; 2016). Down to 7.5 km the geometry of the layers was extracted mainly from the seismostratigraphic interpretation of line 115.

Using only parameters derived from seismic and well data, it was not possible to adjust the total calculated anomaly to the observed anomaly. Therefore, we were required to introduce density heterogeneities within the upper crust and geometric variations of the Moho relief based on available publications for the study area (Assumpção *et al.*, 2013; Castro *et al.*, 2014; Daly *et al.*, 2014). The seismic patterns within the pre-Riachão basement (seismic facies 1A and 1B in Table 2) were the main criteria to subdivide the upper crust into four different layers (Table 3).

The observed complete Bouguer anomaly ranges from -50 mGal to -90 mGal in the 115 profile; the minimum values are located where the eastern basement uplift was interpreted, between traces 7166 and 12746. In order to adjust this low gravity anomaly, two possibilities were tested. In Model 1 (Fig. 10b), it was interpreted a crystalline basement ($2,790 \text{ kg.m}^{-3}$) supported by a thicker crust, where the Moho reaches 42km depth. In Model 2 (Fig. 10d), it was added a lighter layer ($2,680 \text{ kg.m}^{-3}$),

interpreted as a metasedimentary sequence, covering the crystalline basement down to 10km. Both models achieved reasonable fits (with RMS Error < 1.55).

Castro *et al.* (2016) also noticed this shift between the low gravity anomaly and the depocenter of the pre-Silurian basin when modelling line 103. To adjust their model to the observed data, these authors considered heterogeneities within the upper crust, adding low-density vertical prisms to mimic distinct geotectonic units within the basement.

Discussion

The pre-Silurian basement of the Parnaíba basin, revealed by seismic reflection, gravity and well data, is complex and heterogeneous. Cordani *et al.* (2009b) describe it as comprising part of the São Luís/West African Craton in the north, Granja and Parnaíba blocks in the center, the western portion of the Borborema Province in the east, and part of the Araguaia belt in the west (Fig.2b). Daly *et al.* (2014), from an E-W oriented, deep seismic reflection profile, identified four crustal units underlying the basin, from west to east the Amazonian craton, the Araguaia fold belt, the central Parnaíba block, and the Borborema Province,. The present study area lies within the Parnaíba block, where a remnant of a pre-Silurian basin, here named the Riachão basin, has been identified and mapped from seismic reflection, gravity and exploration well data.

The north-south trend of the Riachão basin parallels the gravity anomalies in the western margin of the study area. This is also the orientation of the Araguaia fold belt that underlies the western edge of the Parnaíba basin, where Daly *et al.* (2014) interpret a west verging thrust belt above a lateral equivalent of the Quatipuru suture (Paixão, 2008; Moura *et al.*, 2008). Seismic interpretation of the pre-Riachão basement to the west of the Riachão basin (seismic facies 1B in Table 2) shows the presence of a

pronounced seismic fabric dipping westwards (Figs. 5 and 6a). Together, these observations appear to indicate a broad zone of structural divergence associated with the Araguaia orogenic belt structure. The west dipping structure is reactivated as a basement-involved thrust along the western margin of the Riachão basin. This tectonic relationship suggests that the deposition and subsequent deformation of the Riachão basin occurred during the late development of the Brasiliano orogenic cycle, with the driving, orogenic load located to the west in the vicinity of the Araguaia fold belt.

The eastern flank of the Riachão basin is defined by a large monoclinal fold of Riachão I and Riachão III sequences that are in part overthrust by an east dipping basement cored thrust (Figs. 5 and 6d). The Riachão III sequence appears to thin westwards and may have been deposited in a later phase of orogenic sedimentation associated with a basin centered in the east (Figure 11). The thrust faults are interpreted as the effect of far-field deformation towards the end of the Brasiliano orogenic cycle, associated with, for example, the Rio Preto and the Riacho do Pontal belts along the northern margin of the São Francisco Craton (Caxito *et al.*, 2016).

We have shown that three distinct sedimentary sequences form the Riachão basin and lie unconformably upon the pre-Riachão basement. The lack of chronological data precludes precise stratigraphic correlations and dating of the Riachão basin. However, in well reports (2-VBST-1-MA and 1-FM-1-MA) the similarity is pointed out between the clastic sediments of the Riachão Formation (the Riachão III sequence) and the lower part of the Bambuí Group, in the São Francisco basin, to the SE. Zalán & Silva (2007) classified the Bambuí Group as an intracratonic/foreland supersequence and Reis *et al.* (2017) observed in seismic sections a typical wedge-shaped geometry for it, with ca. 3km maximum thickness in the presumed western foredeep area. Recent studies revealed late Ediacaran zircon grains in the basal sediments of the Bambuí

Group, setting its maximum depositional age at around 560Ma (Pimentel *et al.*, 2011; Paula-Santos *et al.*, 2015; Kuchenbecker *et al.*, 2016). These data, together with our seismic facies interpretation of the Riachão I sequence as a carbonate dominated section, open the possibility of several coeval, regional analogues. The basal carbonate rocks of the Sete Lagoas Formation (BambuÍ Group), to the SE of the ParnaÍba basin, and the Frecheirinha Formation (Ubajara Group), in the MÍdio CoreaÍ belt to the NE, are both possible, coeval analogues of RI. The Frecheirinha Formation underlies the Jaibaras Formation and has a Late Ediacaran depositional age (ca. 575-555 Ma), inferred from palynological content (Chiglino *et al.*, 2015). Based on this similarity with the adjacent Late Neoproterozoic BambuÍ and Ubajara Groups, a maximum depositional age of circa. 570 Ma is proposed for the Riachão I sequence. Figure 12 presents an update of the chronostratigraphic chart of the ParnaÍba basin (Vaz *et al.* 2007) and places the three Riachão sequences between the Late Ediacaran and the end of the Early Cambrian.

The complex pre-Silurian basement, including the Riachão basin, was deformed and eroded, developing a regional planation surface before the deposition of the Phanerozoic ParnaÍba basin. The formation of the ParnaÍba basin does not show any obvious structural relationship with the basement structure of the Riachão study area. Daly *et al.* (2014) observed this planation surface and interpreted it as a post-Brasiliano peneplain. The sketch of Figure 11 summarizes the compressive evolution of the Riachão basin. An analogue for this interpretation is the Greater Green River Basin, in southwestern Wyoming, United States (Fig. 13). This basin is bounded by uplifts and thrust faults of opposed polarities at its margins and is divided into structural and topographic sub-basins by intra-basin anticlines. The structural framework was formed

in front of the evolving Rocky Mountains during the Laramide orogeny (Smithson *et al.*, 1979 Roehler, 1992;).

Our data, observations and interpretation do not support the interpretation of an extensional tectonic style for the Riachão basin (Castro *et al.* 2016). Large monoclinal folds of the Riachão sediments and the apparent emplacement of the pre-Riachão basement over them indicate major basement-involved thrust faulting. The thrust faults may have been reactivated basement structures from the early Brasiliano tectonics or inverted pre-existing extensional faults as proposed by Oliveira & Mohriak (2003).

Conclusions

- Seismic reflection data reveal a remnant basin beneath the pre-Silurian unconformity and base of the sediments of the Phanerozoic Parnaíba cratonic basin. This pre-Silurian basin covers an area of at least 35,000 km², along a north-south trend and is here named the Riachão basin.
- The Riachão basin has a maximum sedimentary thickness of 4km and is formed of three seismostratigraphic sequences (Riachão I, II and III) defined by onlaps and erosive unconformities. The Riachão I sequence is a thin, banded package of high amplitude reflections that extend across most of the basin area and define a broad arch. Riachão II and III sequences are wedge-shaped and onlap the top of Riachão I to the east and west, respectively. The Riachão II sequence has a maximum thickness of 2km in the western margin of the basin. And the overlapping Riachão III sequence occurs in the eastern side, with a maximum thickness of 3km in the southeast.
- The east and west margins of the Riachão basin are, in part, defined by basement-involved thrust faults that generate large basement uplifts and monoclinal folds, and also emplace the basement over the Riachão

sediments. The thrust faults in the west face eastwards, and may be reactivated basement structures associated with the Araguaia orogenic belt. The eastern basement uplift is characterized by a low gravity anomaly, which may correspond to a less dense pre-Riachão basement unit or a thicker continental crust in this area.

- The Riachão basin is interpreted as a remnant of a foreland/molasse basin developed between Brasiliano orogenic belts, to the east (Borborema) and west (Araguaia). Although its chronology is poorly constrained, it is broadly coeval to Late Ediacaran/Cambrian geological units in the adjacent region of the Parnaíba basin (BambuÍ and Ubajara Groups). The sediments of the Riachão II sequence were deposited in the first foreland phase, centered in the west, followed by the deposition of clastic sediments of the Riachão III sequence to the east. In this context the Riachão I sequence is interpreted as a carbonate marine platform sequence, preceding the main foreland subsidence and subsequent clastic input.
- The Phanerozoic Parnaíba basin overlies a pronounced Pre-Silurian unconformity. Its deposition appears to have little to do with the previous development and deformation history of the structure of the Riachão basin. The subsidence and deposition of the Parnaíba basin occurred after a profound planation stage that eroded part of the Riachão basin and the pre-Riachão basement. The interpreted thrust faults that deformed the Riachão basin do not show any evidence of reactivation during the deposition of the Parnaíba basin sediments.

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References

Assumpção, M.S., Bianchi, M., Julià, J., Dias, F.L., França, G.S.L., Pavão, C.G., Albuquerque, D.F., Lopes, A.E.V., 2013. *Crustal thickness map of Brazil and adjacent areas: data compilation and main features*. Journal of South American Earth Sciences **43**, 74–85, <http://dx.doi.org/10.1016/j.jsames.2012.12.009>

Blakely, R. J. 1996. *Potential Theory in Gravity & Magnetic Applications*. Cambridge: Cambridge University Press, **441**.

Brito Neves, B.B., Fuck, R.A., Cordani, U.G., Thomaz Filho, A., 1984. *Influence of basement structures on the evolution of the major sedimentary basins of Brazil*. Journal of Geodynamics, **1**, 495–510.

Brito Neves, B.B., Fuck, R.A., 2013. *Neoproterozoic evolution of the basement of the South American Platform*. Journal of South American Earth Sciences **47**, 72–89.

Brito Neves, B. B. & Fuck, R. A. 2014. *The basement of the South American platform: Half Laurentian (N-NW) C half Gondwanan (E-SE) domains*. Precambrian Research, **244**, 75–86. <http://dx.doi.org/10.1016/j.precamres.2013.09.020>

de Castro, D. L., Fuck, R. A., Phillips, J. D., Vidotti, R. M., Bezerra, F. H. R. & Dantas, E. L. 2014 *Crustal structure beneath the Paleozoic Parnaíba basin revealed by airborne gravity and magnetic data, Brazil*. Tectonophysics, **614**, 128–145, <http://dx.doi.org/10.1016/j.tecto.2013.12.009>

de Castro, D. L., Bezerra F.H.R., Fuck R. A., Vidotti R.M. 2016. *Geophysical evidence of pre-sag rifting and post-rifting fault reactivation in the Parnaíba basin, Brazil*. Solid Earth, **7**, 529–548, doi:10.5194/se-7-529-2016

Caxito, F.A., Uhlein, A., Dantas, E., Stevenson, R., Egydio-Silva, M., Salgado, S.S. 2017. *The Rio Preto and Riacho do Pontal Belts*. In: U.G. Cordani *et al.* (eds.), São Francisco Craton, Eastern Brazil, Regional Geology Reviews, 221-240. DOI 10.1007/978-3-319-01715-0_12

Chiglino, L., Gaucher, C., Sial, A. N., Ferreira, V. P. 2015. *Acritarchs of the Ediacaran Frecheirinha Formation, Ubajara Group, Northeastern Brazil*. Anais da Academia Brasileira de Ciências, **87**(2), 635-649. <https://dx.doi.org/10.1590/0001-3765201520140430>

Cordani, U.G., Brito Neves, B.B., Fuck, R.A., Porto, R., Thomaz Filho, A., Cunha, F.M.B., 2009a. *Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras (Republicação)*. Boletim de Geociências da Petrobras, Rio de Janeiro, **17** (1), 133–204.

Cordani, U.G., Brito Neves, B.B., Thomaz Filho, A. 2009b *Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras (Atualização)*. Boletim de Geociências da Petrobras, Rio de Janeiro, **17** (1), 205–219.

Daly, M.C., Andrade, V., Barousse, C.A., Costa, R., McDowell, K., Piggott, N., Poole, A.J., 2014. *Brasiliano crustal structure and the tectonic setting of the Parnaíba basin of NE Brazil: results of a deep seismic reflection profile*. Tectonics, **33**, 2102–2120, <http://dx.doi.org/10.1002/2014TC003632>

Geosoft Oasis Montaj 8.2, 2015. *MAGMAP Filtering How-To Guide*. Geosoft Incorporated, 25, <http://www.geosoft.com/support/downloads/technical-documentation>

495 Gudmundsson, A. 2011. *Deflection of dykes into sills at discontinuities and magma-*
 496 *chamber formation*. Tectonophysics, **500**, 50–64.

497 Kuchenbecker, M., Babinski, M., Pedrosa-Soares, A.C., Lopes-Silva, L., Pimenta, F.
 498 2016. *Chemostratigraphy of the lower Bambuí Group, southwestern São Francisco*
 499 *Craton, Brazil: insights on Gondwana paleoenvironments*. Brazilian Journal of
 500 Geology, **46**, 145-162.

501 Merle, R., Marzoli, A., Bertrand, H., Reisberg, L., Verati, C., Zimmermann, C.,
 502 Chiaradia, M., Belleini, G. & Ernesto, M. 2011. *$^{40}\text{Ar}/^{39}\text{Ar}$ ages and Sr-Nd-Pb-Os*
 503 *geochemistry of CAMP tholeiites from Western Maranhao basin (NE Brazil)*. Lithos,
 504 **122**, 137–151, <http://dx.doi.org/10.1016/j.lithos.2010.12.010>

505 Milani, E.J., Zalan P.V. 1999. *An outline of the geology and petroleum systems of*
 506 *the Paleozoic interior basins of south America*. Episodes Journal of International
 507 Geoscience, **22**, 199–205.

508 Moura, C. A. V., Pinheiro, B. L. S., Nogueira, A. C. R., Gorayeb, P. S. S. &
 509 Galarza, M. A. 2008. *Sedimentary provenance and palaeoenvironment of the Baixo*
 510 *Araguaia Supergroup: Constraints on the palaeogeographical evolution of the*
 511 *Araguaia Belt and assembly of West Gondwana*. In: Pankhurst, R. J., Trouw, R. A. J.,
 512 Brito Neves, B. B. & De Wit, M. J. (eds) *West Gondwana: Pre-Cenozoic Correlations*
 513 *Across the South Atlantic Region*. Geological Society of London, London, Special
 514 Publications, **294**, 173-196, doi:10.1144/SP294.10

515 Nunes, A. B., Lima, R. F. F. & Filho, C. N. B. 1973. *Geologia da folha SB.23*
 516 *Teresina e parte da folha SB.24 Jaguaribe*. Rio de Janeiro, RJ, DNPM. Projeto
 517 RADAM, Levantamento de Recursos Naturais, v.2.

Oliveira, D.C., Mohriak, W.U. 2003. *Jaibaras trough: an important element in the early tectonic evolution of the Parnaíba interior sag basin, Northern Brazil*. Marine Petroleum Geology, **20**, 351–383.

Paixão, M. A. P., Nilson, A. A., Dantas, E. L. 2008. *The Neoproterozoic Quatipuru ophiolite and the Araguaia fold belt, central northern Brazil, compared with correlatives in NW Africa*. In: Pankhurst, R. J., Trouw, R. A. J., Brito Neves, B. B. & De Wit, M. J. (eds) West Gondwana: Pre-Cenozoic Correlations Across the South Atlantic Region. Geological Society of London, London, Special Publications, **294**, 297–318, doi:10.1144/SP294.16.

Paula-Santos G.M., Babinski M., Kuchenbecker M., Caetano-Filho S., Trindade R.I.F., Pedrosa-Soares A.C. 2015. *New evidence of an Ediacaran age for the Bambuí Group in southern São Francisco craton (eastern Brazil) from zircon U-Pb data and isotope chemostratigraphy*. Gondwana Research, **28**, 702–720.

Pimentel M., Rodrigues J.B., Della Giustina M.E.S., Matteini S.J.M., Armstrong R. 2011. *The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil, based on SHRIMP and LA-ICPMS U-Pb sedimentary provenance data: A review*. Journal of South American Earth Sciences, **31**, 345–357.

Porto, A. L. 2017. *The pre-Silurian Riachão basin, a new perspective into the basement configuration of the cratonic Parnaíba basin, NE Brazil*. MSc Thesis, Observatório Nacional, Rio de Janeiro.

Reis, H.L.S., Alkmim, F.F., Renato, Fonseca, C.S., Nascimento, T.C., Suss, J.F., and Prevatti, L.D. 2017. *The São Francisco Basin*. In: M. Heilbron et al. (eds.), São Francisco Craton, Eastern Brazil, Regional Geology Reviews, 117–144. DOI: 10.1007/978-3-319-01715-0_7

Roehler, H. W. 1992. *Introduction to greater Green River basin geology, physiography, and history of investigations*. In: U.S. Geological Survey (Editor) *Geology of the Eocene Wasatch, Green River, and Bridger (Washakie) formations, greater Green River basin, Wyoming, Utah, and Colorado*. Series: U.S. Geological Survey professional paper 1506-A, United States Government Printing Office, Washington, **14**.

Smithson, S. B., Brewer, J. A., Kaufman, S., Oliver, J. E. & Hurich, C. A. 1979. *Structure of the Laramide Wind River uplift, Wyoming, from cocorp deep reflection data and from gravity data*. Journal of Geophysical Research, **84** (B11), 5955-5972.

Spector, A. & Grant, F.S. 1970. *Statistical models for interpreting aeromagnetic data*. Geophysics, **35**, 293–302.

Thomson, K. & Schofield, N. 2008. *Lithological and structural controls on the basins emplacement and morphology of sills in sedimentary*. Geological Society of London, London, Special Publications, **302**, 31-44.

Vaz, P. T., Rezende, N. G. A. M., Wanderley Filho, J. R. 2007. *A Bacia do Parnaíba*. Boletim de Geociências da Petrobras, Rio de Janeiro, **15** (2), 253-263.

Zalán, P. V., Romeiro-Silva, P. C., 2007. *Bacia do São Francisco*. Boletim de Geociências da Petrobras, Rio de Janeiro, **15** (2), 561-571.

Figure captions

Fig. 1. A simplified map of the Precambrian basement of South America showing the location of the Parnaíba basin, between an eastern Amazonian domain, and western Brasiliano domain. The two domains are separated by the Araguaia suture zone and the Transbrasiliano lineament (after Brito Neves & Fuck, 2014 and Daly et al., 2014).

Fig. 2. Maps of the basement architecture of the Parnaíba basin, showing the differing interpretations of basement inliers and pre-Silurian sedimentary areas through time. **(a)**

Adapted from Brito Neves et al., 1984. **(b)** Adapted from Cordani et al., 2009b. **(c)** Adapted from Castro et al., 2014. **(d)** Adapted from Castro et al., 2016. Pre-Brasiliano basement inliers: GN - Northern Granja ; GS – Southern Granja; P – Parnaíba; MAC – Monte Alegre-Conceição. Tectonic lineaments/boundaries: AR - Araguaia belt/Eastern limit of Amazonian plate; AR1 - Eastern margin of Amazonian palaeocontinent; AR2 - Araguaia basement; TB - Transbrasiliano lineament; GP - Gurupi belt; SP - Senador Pompeu fault/shear zone, PA - Patos shear zone; PE - Pernambuco shear zone; RP - Rio da Prata lineament; CC - Correntes Correntina lineament.

Fig. 3. Location map of the study dataset: aerogravity data (green polygon), nine 2D seismic reflection profiles (blue lines), one land gravity profile (green line) and ten exploration wellbores (black crosses). Composite section of figure 5 marked in red.

Fig. 4. Seismic to well correlation between line 105 and the Vereda Grande well (1-VG-1R-MA). The figure shows that the sediments of the Riachão basin are Pre-Silurian, dominantly clastic and a minimum of 1 km thick (Reference Table 1).

Fig. 5. (a) Pre-stack time migration of the seismic reflection composite section converted to depth. **(b)** Line interpretation of the composite section. **(c)** Geoseismic interpretation of the composite section showing the three stratigraphic components of the Riachão basin and the fault bounded margins. Composite section location shown on figure 3.

Fig. 6. (a), (b) and (c) Seismic detail of the monoclinal structure of the western margin of the Riachão basin (Line 115). **(d), (e) and (f)** Seismic detail of the monocline and the basement overthrust of the eastern margin of the Riachão basin (Line 105).

Fig. 7. Seismic detail of onlaps and erosional truncations defining the stratigraphic packages of Riachão I, II and III (Line 115).

Fig. 8. Isopach contour maps and the main thrust faults of **(a)** Riachão basin in its totality, **(b)** Riachão I sequence, **(c)** Riachão II sequence, and **(d)** Riachão III sequence. Note the two isopach thicks that represent the Riachão II and III sequences either side of the central arch.

Fig. 9. Aerogravity anomaly maps: **(a)** Bouguer, **(b)** regional, and **(c)** residual, with the qualitative interpretation of the gravity anomaly domains. **(d)** The interpretation of the domains and the isopach contour map of the Riachão basin.

Fig. 10. **(a)** and **(b)** 2D forward model 1 of the complete Bouguer anomaly along line 115. **(c)** and **(d)** 2D forward model 2 of the complete Bouguer anomaly along line 115. Note the offset of the gravity low and the center of the Riachão basin, as pointed out by Castro *et al.*, (2016).

Fig. 11. Conceptual tectonic evolution sketch of the Riachão Basin, from Late Neoproterozoic until Paleozoic. Arrows indicate the main tectonic displacement.

Fig. 12. Chronostratigraphic chart of the Parnaíba basin including the Neoproterozoic Riachão basin sequences (modified after Vaz *et al.*, 2007; Pimentel *et al.*, 2011; Chiglino *et al.*, 2015; Paula-Santos *et al.*, 2015; Kuchenbecker *et al.*, 2016). Uncoloured formations are not lithostratigraphically constrained by well data.

Fig. 13. Schematic geological section of the Green River basin, southwestern Wyoming, United States (Smithson *et al.*, 1979), a potential analogue for the thrust bounded Riachão basin interpretation.

Table 1. Data from exploration wells used in this study, showing depths and where calibrated to the seismic profiles.

Table 2. Diagnostic seismic characteristics used to define the respective seismic intervals with geological interpretation.

Table 3. Density data used for each sequence or layer in both 2D forward models. M1 represents the Model 1 (Fig. 10b) and M2 represents Model 2 (Fig. 10d).