

# Cratonic basin formation: a case study of the Parnaíba Basin of Brazil

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**Abstract:** Cratonic basins comprise a significant component of the Earth's continental crust and surface geology. Their subcircular form and large areas of flat-lying, largely undeformed sedimentary rocks characterize the central regions of many continents, and are also a significant habitat for water, mineral and petroleum resources. These basinal regions have been extensively studied, yet there is little consensus on the driving mechanism of their subsidence or their greater tectonic context. Here we present the results of an integrated basin analysis of the Paleozoic–Early Mesozoic Parnaíba cratonic basin of NE Brazil. The analysis integrates existing geological and geophysical data, and a new deep-crustal geophysical dataset, to determine the deep structure of the basin and the underlying crust and mantle. Several major features have emerged from this which constrain the basins genesis: (1) continental–shallow-marine stratigraphy characterized by an exponentially decreasing tectonic subsidence with a relatively long time constant of the order of 70–90 myr; (2) a complex Proterozoic–Early Paleozoic basement that comprises at least three major crustal blocks defined by seismic facies and conductivity contrasts with no evidence of an extensive rift system beneath the basin; (3) a mid-crustal fabric that appears to define the top of a dense and seismically fast lower crust ( $V_p$  6.7–6.8 km s<sup>-1</sup> and  $V_s$  3.7–3.8 km s<sup>-1</sup>) and upper mantle ( $V_p$  8.2–8.4 km s<sup>-1</sup>) directly beneath the basin, and which correlates with a sediment-corrected Bouguer gravity anomaly high of +40–60 mGal; (4) a Moho that is generally as deep or deeper beneath the basin (40–45 km) than its surrounding region (34–40 km), and which appears stepped at the terrane boundaries; (5) a relatively conductive crust and upper mantle beneath the basin, and relatively resistive crust along the boundaries of the basement blocks; and (6) igneous events immediately before and after formation of the cratonic megasequence and a geochemically enriched mantle beneath the basin that sourced two major episodes of Mesozoic igneous intrusions. These latter events are responsible for the development of an atypical gas-prone petroleum system dependent on local magmatic events for heat generation and trapping configurations. The data describing these features are presented and discussed, and their implications used to draw conclusions about the formation of the Parnaíba Basin specifically and cratonic basins more generally.

Cratonic basins are large, isolated, basinal areas developed exclusively on continental lithosphere (Fig. 1). They occupy a little over 10% of today's exposed continental crust and are characterized by large areas of mostly undeformed, flat-lying sedimentary rocks. Several features are universal in

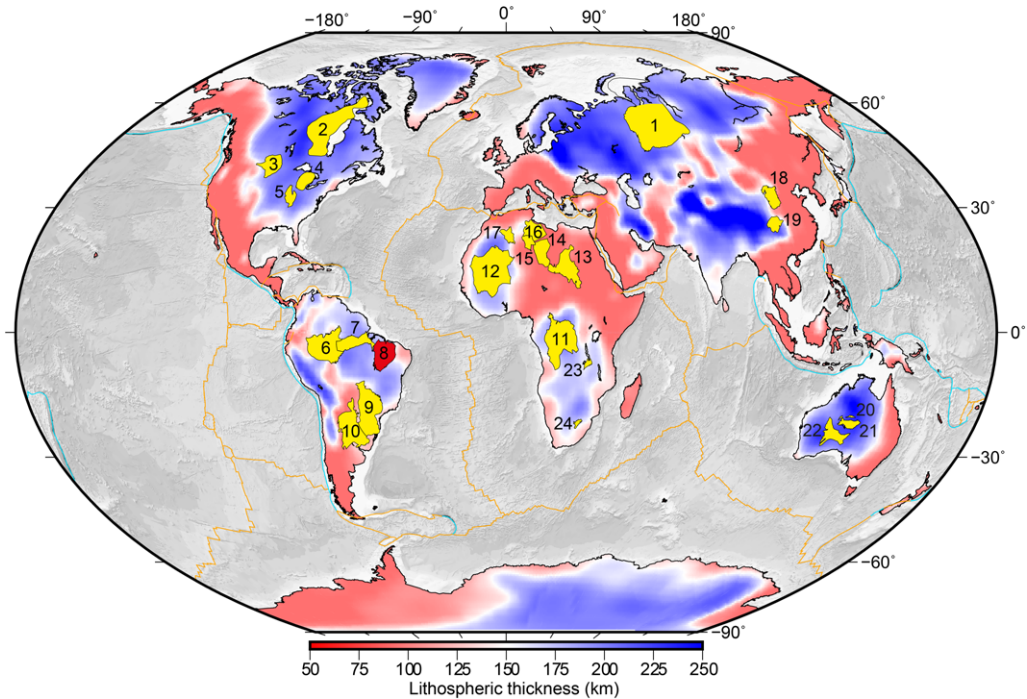
the categorization of a cratonic basin, notably: development upon thickened lithosphere (>150 km) (McKenzie & Priestley 2016); a subcircular to equant outline; a pronounced basal unconformity of the cratonic megasequence (Daly *et al.* 2014); a long-lived stratigraphic megasequence of shallow-marine and

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**Fig. 1.** World map showing a selected group of cratonic basins superimposed on continental lithospheric thickness (based on Priestley & McKenzie 2013). The cratonic basins are coloured yellow, with the exception of the Parnaíba Basin of Brazil which is coloured red (8). Key to the basins: (1) Southern West Siberian Basin; (2) Hudson Basin; (3) Williston Basin; (4) Michigan Basin; (5) Illinois Basin; (6) Solimões Basin; (7) Amazon Basin; (8) Parnaíba Basin; (9) Paraná Basin; (10) Chaco Basin; (11) Congo Basin; (12) Taoudenni Basin; (13) Kufra Basin; (14) Murzuq Basin; (15) Illizi Basin; (16) Ghadames Basin; (17) Tindouf Basin; (18) Ordos Basin; (19) Sichuan Basin; (20) Georgina Basin; (21) Amadeus Basin; (22) Officer Basin; (23) Mporokoso Basin; (24) Witswatersrand Basin.

terrestrial sediments (Sloss 1963); little or no evidence of associated rifting or Moho elevation beneath the basin (Sleep 1976); and a deep-sourced gravity anomaly (Haxby *et al.* 1976). However, in contrast to the established global consensus on the formation of foreland basins (Price 1973; Beaumont 1981; Jordan 1981) and rift basins (McKenzie 1978), these continental basins, known as cratonic, intra-cratonic or sag basins, have remained controversial in their origin and driving mechanism. A wide array of different models has been proposed to answer an apparently simple question: What is a cratonic basin, and how did it form?

Sloss (1963) first described North America's intra-continental Michigan Basin, pointing out its characteristic bowl shape, distinctive megasequences of shallow-water to terrestrial sediments and its long-lived character. He perceived cratonic basins, like Michigan, to be vertically subsiding areas in mid-continental locations. Sleep (1976), following on from his earlier work on the subsidence of continental passive margins (Sleep 1971), concluded that the downwards flexure of the lithosphere that

resulted in the Michigan cratonic basin was a result of thermal contraction. In the same year, Haxby *et al.* (1976) argued from gravity data that a dense body in the lower crust of the Michigan Basin could represent a mechanical load that drives the subsidence. Later, studying the adjacent Williston Basin, Fowler & Nisbet (1985) concluded a deep load driven origin for the Williston Basin. Similarly, Stel *et al.* (1993) proposed that dyke intrusion, basaltic underplating and the resultant cooling caused both thermal and mechanical loading of the lithosphere that could drive cratonic basin subsidence. A different mechanical driving mechanism of a metamorphic phase change of mafic crustal roots to eclogite was proposed by Baird *et al.* (1995) and developed by Gac *et al.* (2013). Working on the cratonic basins of Central Australia, Lambeck (1983) suggested that cratonic basins resulted from lithospheric folding driven by far-field compressional stress. Hartley & Allen (1994) preferred a convective downwelling model beneath Africa as the driving force for the Congo Basin. Following on from these many hypotheses, a recent tendency has been

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to try to fit cratonic basins into a mechanism based on the McKenzie (1978) lithospheric stretching and thermal contraction model. Armitage & Allen (2010) argued that cratonic basin subsidence resulted from low-strain-rate extension of thick lithosphere over time periods of up to 75 myr. Recognizing the shortcomings of this model, McKenzie & Priestley (2016) took a completely new route, arguing that cratonic basin subsidence is driven by lithospheric cooling following a compressional period of lithospheric shortening and rapid erosion. Compatible with this, and also the other thermally- and load-driven models, Daly *et al.* (2018) argue that the initiation of cratonic basins in Gondwana and Laurentia occurred during a period of continental stability that followed major continental accretion, and some significant time ( $\geq 150$  myr) before major continental rifting and break-up. A feature of this array of different, and occasionally contradictory, models is that they are often developed from a single data source and tectonic perspective.

The contributions in this volume are directly linked to the Parnaíba Basin of NE Brazil (Fig. 1), and the BP-sponsored Parnaíba Basin Analysis Project (PBAP) undertaken between 2012 and 2017. The papers present diverse and unique geophysical and geological datasets that provide insight into the formation of this long-lived (c. 240 myr) Silurian–Triassic basin. The cratonic basin megasequence is succeeded by a shallow passive-margin-related basin that developed due to the Jurassic and Cretaceous break-up of Africa and the Americas (Azevedo 1991). Whilst the data and interpretations presented do not claim to finally answer the question posed above, they do bring new and significant constraints to the issue and present a platform from which further progress can be made.

The volume is organized into five sections. Firstly, an introductory section focusing on different perspectives of cratonic basins, and comparing the Parnaíba Basin with the Michigan and Congo cratonic basins. Secondly, a section on the lithospheric and crustal structure of the Parnaíba Basin, based on reflection and wide-angle refraction seismic data, teleseismic data, potential field and magnetotelluric data. Thirdly, a section based on the stratigraphic and sedimentological evolution of the basin. Fourthly, a section that discusses the magmatic episodes associated with the basin. And, finally, a section that describes the atypical petroleum resource system of the Parnaíba Basin and its potential.

### Cratonic basin context

Early studies of cratonic basins focused on the Michigan cratonic basin (Sleep 1976; Haxby *et al.* 1976), and the adjacent Hudson Bay and Williston basins

(Fowler & Nisbet 1985). Sleep (2018) opens this volume with a review of the Michigan Basin, and concludes that thermal subsidence is an appropriate mechanism for its formation and points out that a means of heating the lithosphere is required. He also observes that a preceding phase of crustal stretching is not evident but speculates that undetected rifts may exist. However, he points out that the ponding of mantle plume material at the base of the crust could provide this heat and does not thin the crust. He expands this thinking to the NW Europe continental margin where continental stretching is apparent, and to the more controversial Congo cratonic basin of Central Africa. The thermal subsidence theme for cratonic basin evolution is continued by McKenzie & Rodríguez Tribaldos (2018), but with a very different conclusion. They point out the growing evidence that neither cratonic basin basement nor stratigraphy show evidence of extensive crustal stretching and thinning (Hajnal *et al.* 1984; Daly *et al.* 2014). On the basis of these data, and their own backstripping of exploration wells and numerical modelling, they propose that the required thermal perturbation could be achieved by crustal thickening of the crust, subsequent radiogenic heating and then removal by erosion of a 35–40 km-thick crustal layer; citing the Himalayas as a potential active analogue for this process. They also point out that this model is testable by the study of the detailed metamorphic history of the basement rocks of a cratonic basin.

Taking a comparative approach to the same question, Watts *et al.* (2018) have compiled geophysical and geological data to compare the structure, subsidence history and evolution of the Parnaíba, Congo and Michigan cratonic basins. Of the many commonalities between the basins, they focus on the central gravity high evident in each of them. Given that seismic refraction, reflection and teleseismic data indicate the Moho is at the same depth or deeper beneath the basin than at the flanks, they propose that the central high reflects an extensive igneous intrusion rather than an elevated Moho. This leads them to interpret the subsidence-driving mechanism in terms of a mechanical load generated by cooled and solidified igneous bodies. They interpret the off-lapping stratigraphic relationships characteristic of cratonic basins in terms of a load-induced viscoelastic stress relaxation of the lithosphere with time.

These three contributions all mention the lack of evidence of crustal thinning and Moho elevation as a key factor in the analysis of the driving mechanism of cratonic basin subsidence. In addition, they all recognize the broadly exponentially decreasing tectonic subsidence profiles of these basins and the relatively long thermal time constants associated with them that are compatible with the thermal contraction of thick lithosphere. The remaining contributions go

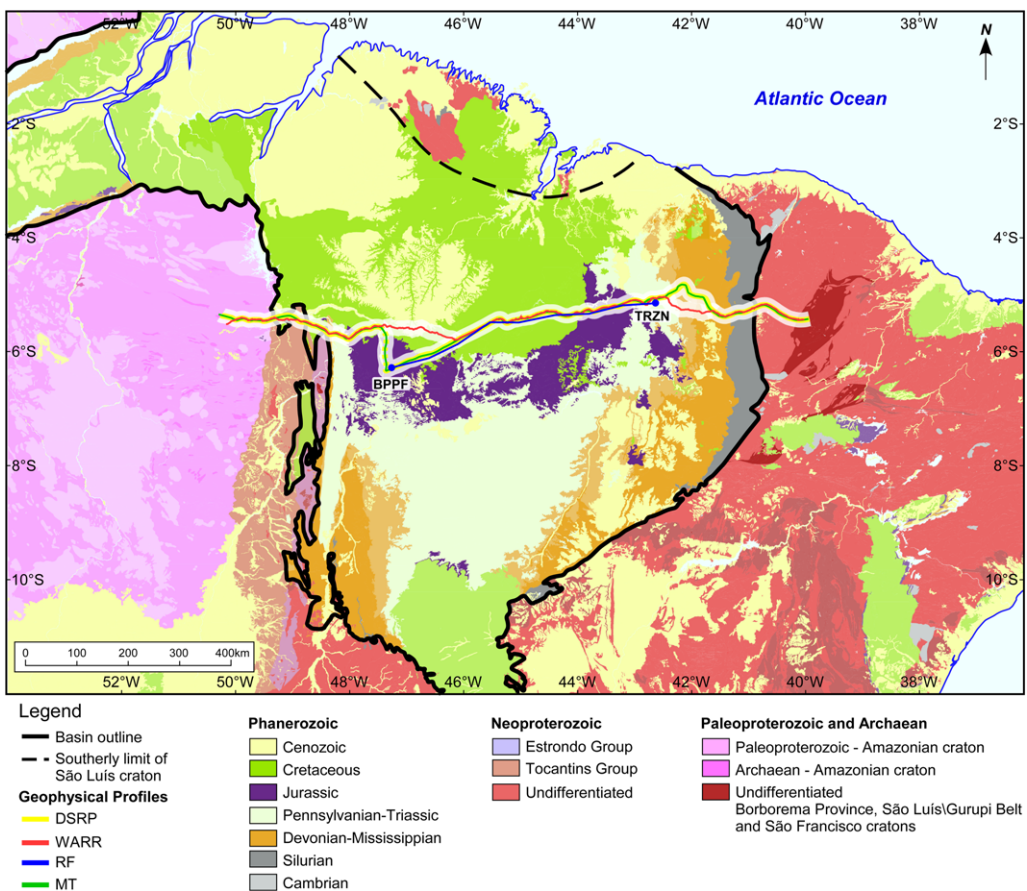
into these and other issues of the Parnaíba Basin specifically, presenting new and compelling data to define the Parnaíba Basin and address the uncertainties discussed above.

### Lithospheric and crustal structure of the Parnaíba cratonic basin

The development of surface-wave tomography over the past few decades has increasingly converged on a definition of the lithosphere–asthenosphere boundary (LAB) beneath continents, and therefore the variations in lithospheric thickness. McKenzie & Priestley (2016) demonstrated that most cratonic basins are underlain by thick lithosphere (Fig. 1). In the area of the Parnaíba Basin, the McKenzie & Priestley

(2016) tomography indicates a 150–180 km-thick lithosphere.

Deep-crustal reflection profiling, wide-angled refraction, teleseismic and magnetotelluric profiles acquired along the same crustal corridor (Fig. 2) have greatly informed the crustal structure beneath the Parnaíba Basin. Daly *et al.* (2014) analysed a 1430 km-long, deep seismic reflection profile across the Parnaíba Basin and interpreted three basement crustal units beneath it: the Borborema Province in the east; a central Parnaíba Block; and the Araguaia thrust belt and Amazonian Craton to the west. The boundary between each unit was defined by a seismic facies change and a pronounced step in the Moho. The Moho was variably imaged, but generally mapped out at c. 40 km beneath the basin, shallowing to 35 km to the east beneath the Borborema



**Fig. 2.** Surface geological map of the Parnaíba Basin showing the routes of the individual geophysical profiles conducted as a part of the Parnaíba Basin Analysis Project and discussed in this volume. DSRP, deep seismic reflection profile (Daly *et al.* 2014); WARR, wide-angle reflection and refraction seismic profile (Soares *et al.* 2018); RF, teleseismic receiver function profile (TRZN to BPPF) (Coelho *et al.* 2018); MT, magnetotelluric profile (Solon *et al.* 2018).



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Province. A distinctive layer of mid-crustal reflectivity (MCR) was also mapped within the centre of the Parnaíba Block. These features can be seen in the reflection seismic data and line interpretation in [Figure 3a and c](#). The saucer-shaped, Phanerozoic-age, Parnaíba cratonic basin overlies this complex basement terrane with a marked regional unconformity ([Fig. 3b](#)). The geophysical experiments discussed below build on the data from this deep seismic reflection profile.

[Soares \*et al.\* \(2018\)](#) discuss the results of the wide-angle refraction–reflection (WARR) experiment conducted from east to west across the middle of the Parnaíba Basin, approximately along the same route as the deep seismic reflection profile of [Daly \*et al.\* \(2014\)](#) ([Fig. 2](#)). The P-wave velocity model of the crust and mantle beneath the Parnaíba Basin reveals a Moho at 42–45 km, and shows it shallowing to 34 km to the east in the Borborema Province and to 40 km to the west beneath the Amazonian Craton ([Fig. 3d](#)). Three Moho steps are mapped at the boundaries between the major crustal units beneath the basin ([Fig. 3d](#)): between the Borborema Province and Parnaíba Block; the Parnaíba Block and the Amazonian Craton, where the Moho locally reaches a depth of 52 km below the Tocantins–Araguaia suture of the Araguaia belt ([Fig. 3d](#)); and within the Parnaíba Block itself. This latter Grajau domain, is characterized by a zone of high P-wave velocity material in the lower crust ( $V_p$  7.0–7.2 km s<sup>−1</sup>) and a 44 km-deep Moho ([Fig. 3d](#)). Regionally, beneath the basin, the WARR velocity model shows high-velocity lower crust ( $V_p$  6.7–6.8 km s<sup>−1</sup>) and upper mantle ( $V_p$  8.2–8.4 km s<sup>−1</sup>). It also distinguishes a lower crust–upper crust boundary along the top of the zone of MCR ([Daly \*et al.\* 2014](#)), separating an upper crust of P-wave velocities of 6.15–6.3 km s<sup>−1</sup> from a lower crust of P-wave velocities of 6.7–6.8 km s<sup>−1</sup> ([Fig. 3d](#)).

Supporting and augmenting these observations, [Coelho \*et al.\* \(2018\)](#) analysed teleseismic data along a 600 km-long transect crossing the central portion of the basin. From the resulting receiver function waveforms, it is shown that the Parnaíba Basin crust thickens into the basin, from 39 km beneath the eastern margin to 45 km in the basin centre ([Fig. 3e](#)). They divide the crust into a 2.0–3.5 km-thick layer of low-velocity sediments (the Parnaíba Basin megasequence), a 15–20 km-thick upper crust and an 18–22 km-thick lower crust. Beneath the centre of the basin, where the crust is at its thickest, the bottom 10–12 km are characterized by high S-wave velocities of 3.7–3.8 km s<sup>−1</sup>. These data further confirm that there is no evidence of crustal thinning beneath the basin, but more probably a small amount of crustal thickening. They also suggest that the basin formation is compatible with flexural subsidence of the lithosphere and

speculate about an upper-mantle load driving that subsidence.

To further define the geometry of the lower crust and Moho, [Manenti \*et al.\* \(2018\)](#) present a new processing flow and stacked seismic reflection image. The paper also links the surface outcrops of the two Mesozoic volcanic provinces in the basin to the poorly imaged lower crust and Moho, explaining this in terms of signal loss.

Exploring the resistivity of the Parnaíba lithosphere down to about 100 km, [Solon \*et al.\* \(2018\)](#) acquired broadband and long-period magnetotelluric (MT) data spanning from 0.001 to 50 000 s along the same corridor as the deep reflection and refraction profiles ([Fig. 2](#)). Their data show a series of conductive crust and upper-mantle blocks beneath the Parnaíba Basin, bounded by major electrically resistive discontinuities ([Fig. 2f](#)). These boundaries correlate well with the major crustal boundaries defined on the deep reflection profile ([Daly \*et al.\* 2014](#)). They image the Araguaia Fault Zone as the boundary between the Amazonian Craton and the Parnaíba Block, and also clearly show the Borborema–Parnaíba Block suture zone. In addition, two new steep boundaries are also identified ([Fig. 2f](#)): one beneath the western half of the basin and one to the east of the Borborema–Parnaíba Block suture zone, roughly coincident with the mapped surface location of the Transbrasiliano Lineament ([de Castro \*et al.\* 2014](#)). They also record an unexpected bulk conductivity increase in the crust beneath the central part of the Parnaíba Basin. This broadly corresponds to the observations of the sediment-corrected Bouguer gravity anomaly high of +40–60 mGal of [Watts \*et al.\* \(2018\)](#), and the anomalously high, upper-mantle ( $V_p$  8.2–8.4 km s<sup>−1</sup>) and lower-crust ( $V_p$  6.7–6.8 km s<sup>−1</sup>) P-wave velocities of [Soares \*et al.\* \(2018\)](#) and lower-crustal S-wave velocities ( $V_s$  3.7–3.8 km s<sup>−1</sup>) of [Coelho \*et al.\* \(2018\)](#). [Solon \*et al.\* \(2018\)](#) suggest this zone may be related to Brasiliano orogenesis or to the igneous events of the Triassic and Cretaceous. A further possibility is that the zone records the dense load required to generate the subsidence of the basin in the early Phanerozoic as postulated by [Watts \*et al.\* \(2018\)](#).

Concentrating on the nature of the upper crust, [Porto \*et al.\* \(2018\)](#) discuss the basement of the mid-western part of the Parnaíba Basin, south of the regional geophysical profile corridor. From an array of c. 1300 line km of legacy 2D seismic data and nine exploration wells they have mapped the remnants of a north–south trending, pre-Silurian sedimentary basin, surrounded by Proterozoic crystalline basement beneath the Parnaíba Basin. This 120 km-wide stratigraphic remnant, named the Riachão Basin, comprises three, unconformity-bounded, marine, sedimentary sequences of Ediacaran–Cambrian age, extensively intruded by gabbroic sills.

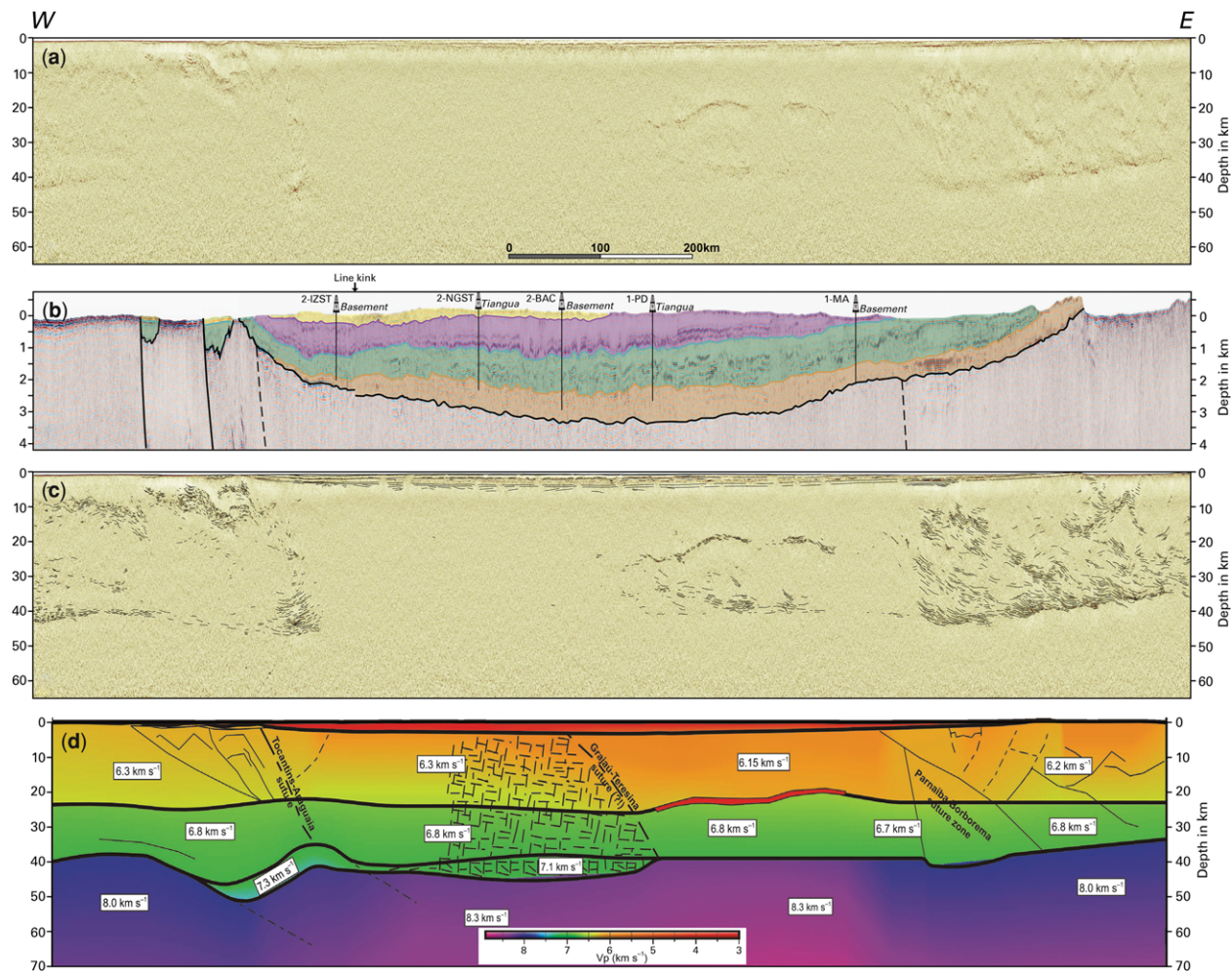


Fig. 3. Continued.

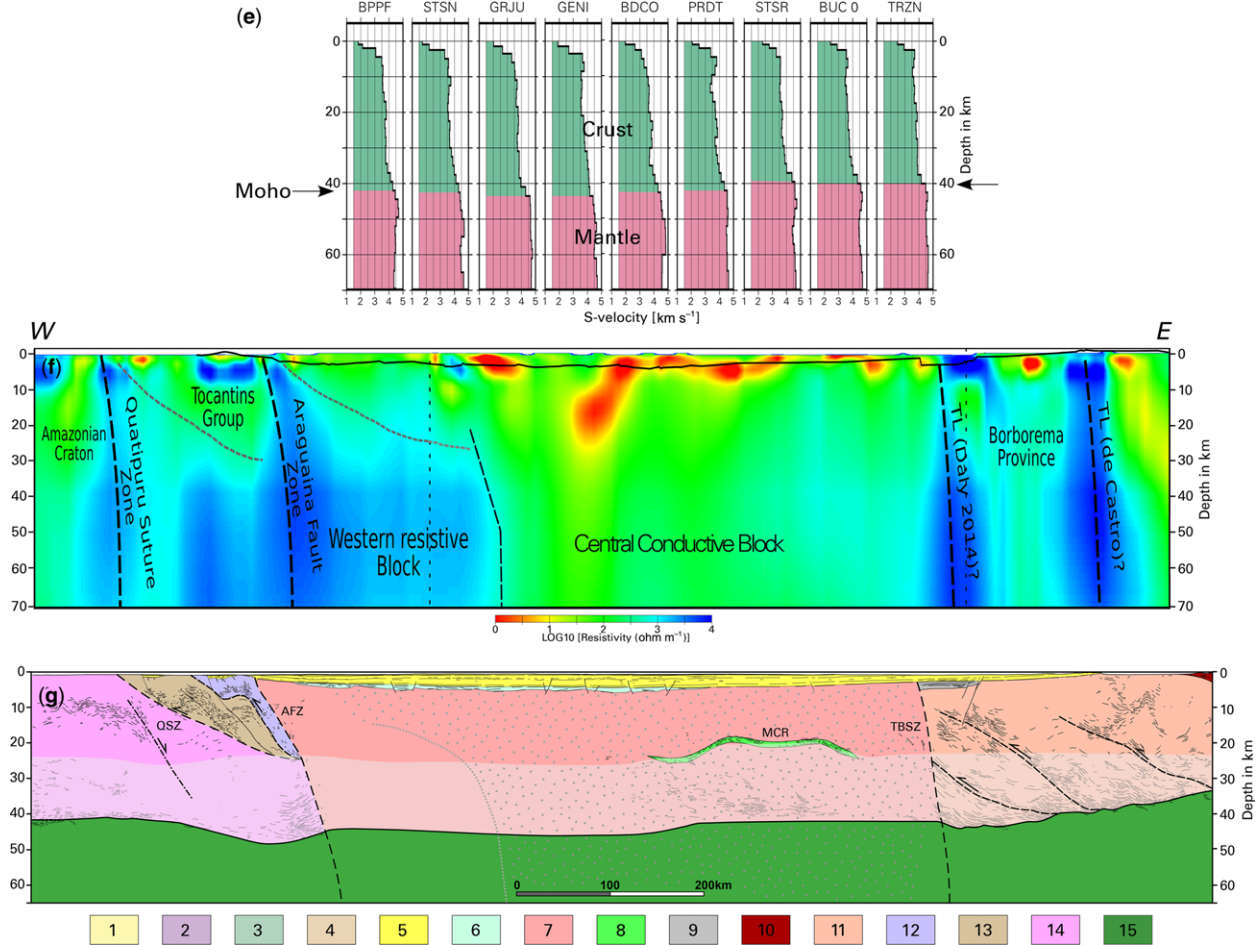


Fig. 3. Continued.

The basin margins are folded into large monoclinical folds or overthrust by basement, all truncated by the erosional Silurian unconformity of the Parnaíba Basin. Their paper interprets the basin as a remnant of a larger Brasiliano-age foreland basin, deformed by deep-rooted basement-cored folds and thrusts in the Cambrian. This interpretation implies a different, although potentially coeval, tectonic history to the narrow pull-apart basins developed along the Transbrasiliano shear zone.

Integrating the deep seismic reflection data with geological and exploration well data, **Rodríguez Tribaldos & White (2018)** conclude that the cratonic megasequence comprises a series of stratigraphic packages of relatively undisturbed sediments bounded by basin-wide disconformities. Backstripped subsidence curves from 21 wells through the cratonic megasequence show an exponentially decreasing tectonic subsidence profile over *c.* 300 myr, with thermal time constants ranging from *c.* 70 to *c.* 90 myr. Although this underlying subsidence appears largely continuous, they point out minor deviations associated with the regional disconformities and interpret them as transient, epeirogenic uplift events caused by changing patterns of dynamic topography.

These six perspectives of the lithospheric and crustal structure and evolution of the Parnaíba Basin show significant convergence on a number of key observations. Firstly, that the crustal thickness beneath the basin varies between 40 and 45 km, compared to the surrounding crust outside of the basin, which varies between 34 and 40 km. Secondly, beneath the centre of the Parnaíba Basin there is a broad lower-crustal and upper-mantle zone of anomalously high seismic velocities and high

conductivity. Thirdly, several major steep crustal boundaries are present at the margins and beneath the basin, defined by zones of relatively high resistivity and/or abrupt changes in seismic facies. Fourthly, a major, regional erosional unconformity occurs between the basement and cratonic basin megasequence, and three stratigraphic discontinuities occur within the cratonic megasequence. Finally, the cratonic megasequence has an exponentially decreasing tectonic subsidence profile with a thermal time constant of the order of 70–90 myr. These data provide a series of tight constraints on the evolution of the Parnaíba Basin.

### Parnaíba Basin stratigraphic and sedimentological evolution

The following contributions build on the chronostratigraphy and lithostratigraphy of the Parnaíba Basin established by **Góes & Feijó (1994)** and **Vaz *et al.* (2007)**, and discuss the sediment provenance, architecture and palaeoenvironments of the sedimentary fill of the basin.

**Menzies *et al.* (2018)** observe that the basin-wide stratigraphic packages described by **Vaz *et al.* (2007)** are an oversimplification when the basin margins are considered. Based on mapped outcrop patterns and seismic data, they note a complex of local unconformities, particularly developed along the western margin and driven by local tectonics associated with the Araguaína Fault Zone. They consider this indicates that the basin margins have been periodically active, locally, throughout the subsidence history of the basin (**Daly *et al.* 2014**). Regional palaeocurrent data are used to propose a consistently

**Fig. 3.** The results and interpretation of the Parnaíba Basin geophysical experiments are converted to depth and presented as a series of west–east profiles at the same horizontal and vertical scale to facilitate their comparison. The final tectonic profile (g) attempts to represent the dataset in a single compiled profile. The location of the individual profiles is shown in **Figure 2**. (a) The uninterpreted Parnaíba post-stack depth-migrated deep seismic reflection profile (**Daly *et al.* 2014**). (b) The Phanerozoic section of (a) showing the cratonic basin megasequence and major stratigraphic groups including the Cretaceous (**Daly *et al.* 2018**). Note the extreme vertical exaggeration of 1:30. For the key to the colours see (g). (c) Line interpretation of the Parnaíba deep seismic reflection profile (a) (**Daly *et al.* 2014**). (d) Summary of the wide-angle refraction and reflection (WARR) profile of the Parnaíba Basin (**Soares *et al.* 2018**). (e) Summary of the teleseismic receiver function profile of the central Parnaíba Basin, BPPF to TRZN (**Coelho *et al.* 2018**). (f) Summary of the magnetotelluric profile of the Parnaíba Basin (**Solon *et al.* 2018**). (g) A composite profile of these four geophysical datasets. Key: the lightly shaded crust in (g) depicts the high-velocity lower crust of **Soares *et al.* (2018)**; the stippled area beneath the Parnaíba Basin shows the conductive central region of **Solon *et al.* (2018)**. The key at the base of (g) represents the following geology: (1) Cretaceous Grajaú Group; (2) Late Carboniferous–Middle Triassic Balsas Group; (3) Lower Devonian–Late Carboniferous Caninde Group; (4) Early Silurian–Lower Devonian Serra Grande Group; (5) Early Silurian–Triassic cratonic basin megasequence; (6) Late Neoproterozoic and Cambrian sedimentary remnants of the Riachão Basin; (7) Parnaíba Block crystalline basement; (8) mid-crustal reflectivity (MCR); (9) Cambrian volcanics and sediments of the Campo Maior graben; (10) Neoproterozoic Cruzeta Complex of the Borborema Province; (11) Neoproterozoic granitic gneisses of the Borborema Province; (12) Neoproterozoic schists of the Estrondo Group; (13) Neoproterozoic phyllites of the Tocantins Group; (14) Paleoproterozoic Amazonian Craton; (15) lithospheric mantle. NB. Colours 2, 3 and 4 represent the three groups of the cratonic basin megasequence shown in (b); colour 5 is the whole cratonic basin megasequence shown in (g).



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NE-directed sediment-transport direction across the basin. Detrital heavy minerals and zircon U–Pb ages indicate a source terrane of dominantly Neoproterozoic age, with subsidiary Mesoproterozoic and Paleoproterozoic ages also present. They conclude that the source is dominantly the crystalline rocks of the uplifted and eroding Neoproterozoic Araguaia Fold Belt that lies along the western margin of the basin. This source area appears to have fed a major sediment-routing system, SW to NE, across the subsiding Paleozoic basin.

Taking an intensive and focused approach to the provenance of the basin fill, **Hollanda *et al.* (2018)** analysed zircon U–Pb ages from 99 sandstone samples from throughout the cratonic megasequence. They record a regionally consistent pattern characterized by three distinct age populations: Neoproterozoic (Cryogenian–Ediacaran: 800–540 Ma); Mesoproterozoic (Stenian: 1100–900 Ma); and Paleoproterozoic (Rhyacian–Orosirian: 2300–1800 Ma). From the heavy minerals, detrital metamorphic minerals and the zircon age spectra, they conclude that a direct source to sink connection existed between Parnaíba sediments and both, or either, of the Borborema Province to the east and the Tocantins Province (Araguaia Fold Belt) to the west and south. The consistency of provenance characteristics throughout the 240 myr of deposition of the Parnaíba cratonic megasequence indicates a constant external sediment source area. Also consistent with this conclusion is the postulated intrabasinal recycling associated with the basins widespread disconformities.

Taking a very different perspective by examining mudrocks from the Parnaíba Basin, **Jaju *et al.* (2018)** argue that there is evidence of distinct palaeoenvironmental differences from west to east across the 1000 km width of the basin. Based on 150 geochemical and mineralogical samples from the Silurian to the Triassic, they conclude that different climatic environments existed from west to east during basin formation, and link this to latitudinal position and the plate motion of Gondwana.

Following the palaeoenvironmental theme, **Iannuzzi *et al.* (2018)** focus on the Permian section of the Parnaíba Basin, towards the end of cratonic basin subsidence. From the macrofossil assemblage, they conclude that the Early Permian Pedra de Fogo and Motuca formations are largely, and possibly entirely, of terrestrial facies, but were deposited in wetter conditions than typically predicted for this region. They also conclude that a high degree of endemism in the Permian flora and fauna implies that the Parnaíba Basin was a distinct biogeographical province within the greater Pangea biogeographical province.

These four contributions emphasize the constant sediment provenance areas for the basin through

time, and conclude the presence of a long-lived, SW–NE-directed major sediment-routing system. It is noteworthy that this trend is broadly parallel to the remnant mountain ranges of the Brasiliano orogen that continued to the NE into what is today West Africa. They also conclude that the provenance areas lie dominantly to the south and west of the basin, potentially sourced from the marginal Brazilian fold belts of the Araguaia and Brasília fold belts of the Tocantins province, and possibly the Borborema Province to the east. They also point out that basin reworking during transient periods of exhumation is compatible with the provenance pattern. The terrestrial facies argued for the Early Permian section is compatible with the latter stages of an exponentially declining subsidence profile that commenced in the Silurian but is still experiencing slow subsidence (**Rodríguez Tribaldos & White (2018); Watts *et al.* 2018**). The suggestion of Parnaíba representing a distinct biogeographical province, perhaps opens up a new level of palaeogeographical definition for Pangea.

### Mesozoic igneous activity in the Parnaíba Basin and its implications

Three phases of magmatic activity are known historically in the region of the Parnaíba Basin. One precedes the basin formation in the Cambro-Ordovician, and is typified by the Jaibaras Trough granites and volcanics (**Oliveira & Mohriak 2003**). The other two phases post-date the formation of the Parnaíba cratonic basin. Occurring in the Mesozoic, they are seen at outcrop as the Jurassic Mosquito and Cretaceous Sardinha formations. The following papers discuss these magmatic events and explore their implications for the evolution of the Parnaíba lower crust and mantle.

**Heilbron *et al.* (2018)** present new data from the eastern part of the Parnaíba Basin and define four Phanerozoic igneous events. The first, in the basement to the basin, is a Cambrian (508–506 Ma) felsic volcanic–subvolcanic event recorded along the SE margin of the basin. Rocks relating to this event are widespread in the Borborema Province, and correlate with the Jaibaras volcanics and plutonics (**Oliveira & Mohriak 2003**). They occur some 50 myr before the initiation of the cratonic basin. New results also identify three different Mesozoic magmatic episodes that post-date the formation of the cratonic basin: a Toarcian (*c.* 181 Ma) magmatic episode; and two Early Cretaceous episodes dated at Barremian (*c.* 126 Ma) and Aptian (*c.* 118 Ma). The Jurassic age Mosquito Formation is best developed in the west of the basin and is time correlated with the Central Atlantic Magmatic Province. The more extensively studied Cretaceous

Sardinha, 'Large Igneous Province' is dominant in the east and is linked to the opening of the South Atlantic. The large volume of Cretaceous-age quartz tholeiite sills in the east has led to the recognition of some geochemical provinciality characterized by low-TiO<sub>2</sub> suites to the NW of the Senador-Pomepeu Lineament, and the high-TiO<sub>2</sub> suites to the south of it. These data are interpreted as evidence of derivation from potentially different subcontinental lithospheric mantles, either side of the lineament.

Based on <sup>87</sup>Sr/<sup>86</sup>Sr, low Nd isotopic composition, and associated enrichment in large-ion lithophile (LIL) and high-field strength (HFS) elements, [Oliveira et al. \(2018\)](#) conclude that the tholeiitic magmas of the westerly located Mosquito Formation were derived from an enriched mantle. The Cretaceous Sardinha Formation dykes and alkali basalts that dominate in the east of the basin have trace element and isotopic characteristics also characteristic of an enriched mantle. Whilst both Mesozoic magmatic events share these similarities, they are differentiated by trace elements, petrography and spatially into association with the Jurassic Central Atlantic Magmatic Province (Mosquito Formation) and Paraná-Etendeka Magmatic Province (Sardinha Formation).

[Klöcking et al. \(2018\)](#) modelled major trace and rare earth element compositions for primitive melts from both the Mosquito and Sardinha provinces. They calculated melt fraction as a function of depth to determine melt volumes and mantle potential temperatures, and concluded that both episodes of magmatism result from shallow decompression melting within the subcontinental lithospheric mantle. As with [Heilbron et al. \(2018\)](#) and [Oliveira et al. \(2018\)](#), they correlate the Jurassic Mosquito basaltic magmas with the Central Atlantic Magmatic Province and the initial break-up of Gondwanaland. Similarly, they correlate the younger Sardinha basalts with the rifting between South America and Africa, and the formation of the Paraná-Etendeka Large Igneous Province. They speculate that both magmatic episodes were associated with periods of regional uplift of the basin.

Addressing the issue of the Mesozoic sills and their emplacement, [Trosdorf et al. \(2018\)](#) discuss their geometry and emplacement mechanism. Using reflection seismic data and exploration well logs, they have mapped the sills to understand their 3D geometry. In general, the sills intrude the cratonic basin sequence parallel to bedding and along the contacts between the thick shale and mudstone beds and sandstones. Stratigraphically, they are preferentially developed between the Longá (shale) and Poti (sandstone) formations; the Pimenteiras (shale) and Cabeças (sandstone) formations; and the Tanguá (shale) and Jaicós (sandstone) formations. The

most common geometry is layer parallel, but saucer shapes, ramps and flats and the so-called 'top hat' geometries are evident. Individual sills can extend for several hundred kilometres and reach a maximum thickness of 250 m. In the middle of the basin, the Mesozoic sills can account for up to 20% of the cratonic basin stratigraphy ([Daly et al. 2014](#)).

With the exception of the Cambrian igneous event discussed by [Heilbron et al. \(2018\)](#), most of the exposed magmatic rocks associated with the Parnaíba Basin developed after the subsidence and deposition of the cratonic megasequence. However, the bimodal Cambrian volcanics and intrusive plutons are important as they appear after the main Brasiliano deformation, but before initiation of the cratonic basin sedimentation. They also appear to be directly associated with the major fault zones and small pull-apart basins developed along the Transbrasiliano Shear Zone at the eastern margin of the Parnaíba Basin. In contrast, the Mesozoic intrusions and extrusives are widespread, the Jurassic most evident in the west and the Cretaceous in the east. They occur as swarms of thick basaltic sills emplaced along stratigraphic boundaries and, in the case of the Jurassic, large lava flows. They are Toarcian, Barremian and Aptian in age, and have an isotopic, trace element and rare earth footprint that appears to be conclusively sourced from an enriched, subcontinental lithospheric mantle.

## The Parnaíba Basin petroleum system

Petroleum exploration began in the Parnaíba Basin in the late 1940s; however, it only became a producing region in 2010. The creation of Petrobras in 1953 led to a period of exploration and the recording of both oil and gas shows during the 1950s, but no economic discoveries. Only in the 2000s, as gas increasingly became a target, did economic discoveries occur and the basin become productive. Today, the basin ranks as one of Brazil's most prolific dry gas basins, with four fields producing 5.6 million cubic metres of gas per day, and with 12 further discoveries under appraisal and development. This recent and widespread success in thermogenically-generated gas is paradoxical for such a shallow basin (maximum depth 3.5 km) on thick lithosphere, with the associated very low geothermal gradient of the order of  $c. 20^\circ \pm 7^\circ\text{C km}^{-1}$  ([Zambruscki & Campos 1988](#)).

[Miranda et al. \(2018\)](#) describe the atypical but conventional gas accumulations of the Parnaíba Basin petroleum system reservoirised in three Devonian and Carboniferous sandstone intervals. They explain the paradox alluded to above through the seismic and well log mapping of extensive and thick Mesozoic dolerite sills. The sills intruding the

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organic-rich shales with total organic carbon (TOC) levels of up to 5% are shown to be responsible for maturing the Silurian, Devonian and Carboniferous organic-rich intervals of the basin. The complex ramp–flat intrusion geometry of the sills is also shown to have created several four-way dip-closed structures that appear to trap the gas of the main gas fields. The magmatic intrusion-driven maturation and sill-defined trapping geometry has created an atypical petroleum system in this shallow basin. The sills present significant seismic-imaging challenges remarked upon in earlier papers (Trosdorf *et al.* 2018). In the petroleum context, that challenge is acquiring enough signal for the imaging of sub-dolerite plays and the steep to vertical ramps that seal the gas fields. In addition, understanding the controls on the location of ramp–flat trajectories and potential traps, and how to explore for them in such a very large basin, is a significant challenge. The recognition of this atypical situation has unlocked huge energy potential in the Parnaíba Basin and appears to offer a new analogue for gas exploration globally.

Abelha *et al.* (2018) also review this atypical petroleum system, taking the perspective of Brazil's national exploration strategy and recent exploration history. They comment on the paradox of a thermally-immature cratonic megasequence producing thermogenic gas, and conclude that an extensive heat flux occurred, provided by the widespread, large Mesozoic sill intrusions, that resulted in the source rocks reaching gas maturity. They also discuss the future direction of exploration in this large and underexplored basin, and the clues left by earlier exploration wells that indicated both oil and gas phases were present. Specifically, the underexplored pre-Silurian section of the remnant Riachão Basin (Porto *et al.* 2018) in the SW and the narrow, volcanic-prone, pull-apart rifts developed along the Transbrasiliano Fault Zone are both seen as areas of interest. In conclusion, it seems likely that new and insightful data will continue to flow from exploration of this underexplored and increasingly important region as Brazil's energy endowment is further assessed and developed.

## Discussion and conclusions

The papers presented in this Special Publication discuss the key issues associated with the formation, subsidence and evolution of cratonic basins in general, and with the Parnaíba cratonic basin in particular. Several areas of convergence have emerged during the integrated geological, geophysical and geochemical approach followed in the Parnaíba Basin Analysis Project. These points are discussed below as the 'Conclusions' of this volume. Areas where

conflicting data or interpretations remain are listed as 'Future work' for further investigation into the elusive issue of the origin of cratonic basins.

## Conclusions

- There is good agreement on the high seismic velocity of the lower crust and upper mantle beneath the Parnaíba cratonic basin between the teleseismic receiver function data of Manenti *et al.* (2018) and the WARR of Soares *et al.* (2018). In line with these observations, Watts *et al.* (2018) used gravity modelling to conclude that from the zone of mid-crustal reflectivity (MCR) downwards to the Moho and possibly into the upper mantle, there is a zone of relatively dense mafic material that underlies the basin centre. Further supporting these observations of anomalous crust, Solon *et al.* (2018) define a central conductive zone beneath the centre of the basin extending down c. 100 km. Whilst difficult to interpret uniquely, together these data indicate a lower-crustal and upper-mantle area of dense, fast and conductive material (Fig. 3). In addition, geochemistry and isotope data from the Mesozoic dolerite sills and extrusives (Oliveira *et al.* 2018) argue that an area of enriched subcontinental lithospheric mantle underlies the Parnaíba Basin. These data imply an Early Cretaceous or older mantle and lower-crust enrichment event.
- There is good convergence between the reflection, refraction and teleseismic techniques on the absolute and relative crustal thickness (Fig. 3). The crust beneath the basin is demonstrably thicker than that around its flanks to the east, south and west. The receiver function data show a maximum thickness beneath the central part of the basin of 45 km, thinning to the east and west (Manenti *et al.* 2018). The wide-angled refraction and reflection data (WARR) agree with this, and show that to the east the crust thins to 35 km outside of the basin. To the west, the Moho is undulatory; and after the Moho step to c. 52 km at the Tocantins–Araguaia suture zone, crustal thickness returns to about 40 km beneath the Amazonian Craton (Daly *et al.* 2014; Soares *et al.* 2018).
- There is also agreement on the existence, attitude and location of a series of crustal 'blocks' bounded by major, steeply-dipping crustal structures adjacent to and beneath the Parnaíba Basin (Fig. 3g). Daly *et al.* (2014) mapped two such crustal-scale boundaries: the Araguaia Fault Zone as the boundary between the Amazonian Craton and the western margin of the Parnaíba Block; and the Transbrasiliano suture as the eastern boundary between the Parnaíba Block and the Borborema Province. They also mapped the low-

angled Quatipuru suture zone between the overthrust Tocantins Province and the lower-plate Amazonian Craton. The WARR of [Soares \*et al.\* \(2018\)](#) also recognized these three fundamental features and added a further steep boundary within the Parnaíba Block ([Fig. 3c](#)). The magnetotelluric (MT) analysis of [Solon \*et al.\* \(2018\)](#) distinguished these same boundaries directly from the electrical conductivity, and also points out a mid-Parnaíba Block boundary. In addition, they noted a further crustal boundary within the Borborema Province, beneath the eastern edge of the basin. This location roughly coincides with the surface expression of the Transbrasiliano Lineament ([Fig. 3f](#)). In the MT profile, generally steep narrow regions of highly resistive crust characterize the crustal boundaries, whereas the cratonic root of the basin appears to comprise a deep conductive zone of lower crust and upper mantle.

[Padilha \*et al.\* \(2015\)](#) described a similar increase in bulk conductivity in the crust and upper mantle beneath the central part of the Paraná Basin. They suggested that this was associated with impregnation of the lithosphere by conducting minerals related either to unspecified tectonic events in the Ordovician, or to dispersed magmatic residues of an Early Cretaceous magma differentiation contaminating the entire lithosphere. The enriched mantle source of the Parnaíba magmas ([Heilbron \*et al.\* 2018](#); [Klöcking \*et al.\* 2018](#); [Oliveira \*et al.\* 2018](#)) perhaps favours the earlier option as the means of generating the enrichment of an old cratonic mantle.

- The points above describe the significant heterogeneity of the crust beneath the Parnaíba Basin. This theme is further developed by the description of remnants of Ediacaran–Cambrian stratigraphy incorporated within the crystalline basement ([Porto \*et al.\* 2018](#)) and the narrow pre-Silurian graben associated with the Transbrasiliano Lineament ([Abelha \*et al.\* 2018](#)).
- There is general agreement on the existence of an extensive and profound basal unconformity to the cratonic megasequence, and three disconformities between the major stratigraphic units within it ([Daly \*et al.\* 2014](#); [Menzies \*et al.\* 2018](#); [Porto \*et al.\* 2018](#); [Rodríguez Tribaldos & White 2018](#)). The cratonic basin phase of subsidence appears to have ceased by the end of the Triassic (c. 200 Ma). [Iannuzzi \*et al.\* \(2018\)](#) document this through their recognition of increasingly continental facies throughout the Permian and Triassic. This supports the broadly exponential tectonic subsidence and large thermal time constant (70–90 myr) required to describe the subsidence history of the basin ([Tozer \*et al.\* 2017](#); [Rodríguez Tribaldos & White 2018](#); [Watts \*et al.\* 2018](#)).

- [Hollanda \*et al.\* \(2018\)](#) and [Menzies \*et al.\* \(2018\)](#) both tie the sediment fill to the Proterozoic basement terranes surrounding the basin. These areas appear to have provided the sediment input into the basin throughout the life of the basin. Similarly, a long lived, NE-directed sediment-routing system has existed over the same time period ([Menzies \*et al.\* 2018](#)), orientated broadly parallel to the gross NNE–SSW Brasiliano orogenic trend. [Hollanda \*et al.\* \(2018\)](#) also point out that their data are consistent with the reworking of the cratonic basin sediments as a valid secondary sediment source during phases of transient uplift.
- The magmatic influence in the Parnaíba Basin is dominated by the Mesozoic events. The geochemical and isotopic signature of this magmatism indicates derivation from an enriched upper mantle ([Oliveira \*et al.\* 2018](#)). In addition, [Heilbron \*et al.\* \(2018\)](#) describe an earlier, pre-cratonic basin, Cambrian volcanic and magmatic event associated with the Transbrasiliano fault structures and narrow pull-apart basin formation.
- The atypical, conventional petroleum system that has been successful in the Parnaíba Basin is being increasingly understood. The paradox of a shallow basin, low heat flow and commercial quantities of thermogenic gas has been solved by heating and maturation due to a large magmatic sill intrusion event, invading, surrounding and thermally maturing to gas the source intervals. The same sills also act as closed structures, traps and seals for gas ([Abelha \*et al.\* 2018](#); [Miranda \*et al.\* 2018](#); [Trosdorf \*et al.\* 2018](#)).

### *Future work*

- The origin and age of the anomalous high-velocity, conductive and enriched lower crust and upper mantle appears key to understanding basin formation, whether it reflects a post-cratonic basin Mesozoic event, or something earlier and related to the cratonic basin initiation. If it is an Early Paleozoic event, a possibility raised by [Padilha \*et al.\* \(2015\)](#) for the Paraná Basin, it may be indicative of the subsidence-driving mechanism of the basin as proposed, for example, by [Watts \*et al.\* \(2018\)](#). The isotopic and trace-element analysis of mantle nodules from kimberlite pipes across the basin could greatly enlighten this issue.
- Similarly, the crustal thickening, radiogenic heating, exhumation and thermal contraction model of [McKenzie & Rodríguez Tribaldos \(2018\)](#) can be tested by analysis of the metamorphic history of the basement to the basin. A precise definition of the pre-Silurian pressure and temperature history of the basement terrane should reveal the degree of thickening, heating and



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exhumation experienced in the 100 myr prior to cratonic basin initiation required in the **McKenzie & Rodríguez Tribaldos (2018)** model.

- The crustal thickening beneath the Parnaíba Basin, evidenced by the WARR, seismic reflection and receiver function data, and the lack of evident widespread rifting argues against any appreciable extensional strain in the formation of the basin. This conclusion can be further tested by the analysis of new industry seismic data that are acquired in the basin, and more detailed mapping of the localized and narrow NE–SW-orientated graben associated with the Transbrasiliano Lineament. It could also be verified by a second deep seismic profile running broadly north–south across the basin and intersecting the existing PBAP seismic and MT corridor in the region of the MCR. Such a profile would be a test of the conclusions drawn here, and would also enable a link to be made with the surface geology and lithospheric structure of the Equatorial Atlantic passive margin. As a result, it would shed light onto the nature of the lower crust and upper mantle relationships, and the transition between continental and ocean crust.
- **Watts et al. (2018)** compared Parnaíba with the Congo and Michigan basins, and pointed out a number of similarities that indicate a genetic relationship. A further expansion of this rigorous approach to the description of these enigmatic basins globally can test the characteristics defined in Parnaíba, and continue to further define and understand these basins.

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