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Age and provenance of the Cryogenian to Cambrian passive margin to foreland basin sequence of the northern Paraguay Belt, Brazil

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ABSTRACT

The Paraguay Belt in central South America developed in response to the collision of the Amazonian craton, the São Francisco craton, and the Paranapanema block. The alleged "Brasiliano" age (ca. 620 Ma) of orogenesis has recently been questioned by paleomagnetic and radioisotopic ages that indicate the closing stages of orogenesis occurred well into the Cambrian. We investigated the timing of deposition and source areas for these sedimentary rocks overlying the Amazonian craton using integrated U-Pb and Hf isotope data of detrital zircons from within this sequence. In total, 742 detrital zircon U-Pb ages were analyzed from samples taken from the base to the top of this sedimentary succession. Maximum depositional ages from the uppermost part of this sequence of rocks, the Diamantino Formation, indicate that final deposition began no earlier than 560 ± 13 Ma and possibly as young as the Cambrian. Given that zircon inheritance in these rocks continues up until this age and that known Amazonian craton ages are older than ca. 950 Ma, we considered other potential sources for these sediments. This was achieved by integrating the U-Pb detrital zircon data with Hf isotopic data from these zircons that have ε_{Hf} values ranging from –18 to 12. The ε_{Hf} signature is consistent, with a predominantly Amazonian source until the early Neoproterozoic, at which point the signal becomes significantly more evolved. These data, when combined with other evidence discussed here, are consistent with an ocean to the east of the present-day Amazonian craton that did not close until the latest Ediacaran–Cambrian.

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INTRODUCTION

Reconstruction of the paleogeography and the timing of formation of the Paleozoic supercontinent Gondwana has received significant attention in the literature for many decades (e.g., Collins and Pisarevsky, 2005; Stern, 1994). A fundamental requirement of these reconstructions is that they fulfill available geological constraints, including correlations based on ages of events in neighboring orogenic belts, paleomagnetic constraints, and relationships among sedimentary, geochemical, and temporal provenance patterns. Early Gondwana reconstruction models of a collision between large fragments of east and west Gondwana at ca. 650 Ma (Stern, 1994) have evolved to incorporate current evidence that identifies a network of suturing events between relatively small Neoproterozoic continents that amalgamated to form Gondwana during the Ediacaran and Cambrian (e.g., Collins and Pisarevsky, 2005; Meert, 2003; Pisarevsky et al., 2008). The Paraguay Belt in Brazil is part of this network of Gondwana-forming orogens that for some time has been considered as "Brasiliano" (ca. 940–620 Ma) in age (Cordani et al., 2009, 2013). This interpretation is based upon ages from the western border of the São Francisco craton and implies that amalgamation of western Gondwana occurred at around 620 Ma.

This hypothesis was brought into question by the presentation of a paleomagnetic pole from carbonates of the Araras Group, from the northern Paraguay Belt, that indicated Amazonia was at low latitudes at the beginning of the Ediacaran (Trindade et al., 2003). This finding suggested that Amazonia was separated from proto-Gondwana by a large ocean—the Clymene Ocean—up until the Cambrian (Trindade et al., 2006). In this model, a major orogenic belt encompassing the Araguaia, Paraguay, and Pampean belts represented the suture zone of this ocean and the final amalgamation of Gondwana. This proposition promoted interest in these regions, and several studies incorporating paleomagnetic, Sm-Nd, geochronological, sedimentary, and stratigraphic methodologies have since followed.

In this study, we present a large U-Pb data set to complement these previous works in order to better understand the provenance of these sediments. In addition to these temporal constraints, we present accompanying Lu-Hf isotope data that provide information about the crustal evolution of the source region and allow for comparisons between sedimentary packages. We go on to discuss the implications of these finding on the tectonic and paleogeographic reconstructions for Amazonia in the context of Gondwana amalgamation.

REGIONAL SETTING

The Paraguay Belt is located in central South America (Fig. 1A) and marks the boundary between the Amazon, São Francisco, Paranapanema, and Rio de la Plata cratons. It consists of metamorphosed Neoproterozoic and Cambrian sedimentary strata that were deposited in a passive margin environment (Alvarenga and Trompette, 1992), with some evidence for rifting in the lower part of the sequence (Tokashiki and Saes, 2008). These metasedimentary and sedimentary rocks are divided into the older pelites, diamictites, and siliciclastics of the Cuiabá Group in the core of the orogen (Barros et al., 1982), diamictites of the Puga Formation, carbonates of the Araras Group, and siliciclastics of the upper Alto Paraguay Group (Figs. 1A and 1B). The Cuiabá Group exhibits low-grade metamorphism and polycyclic deformation with an overall southeast vergence (Alvarenga and Trompette, 1992). While the nature of the contact between the Cuiabá Group and Puga Formation is not well understood due to its lack

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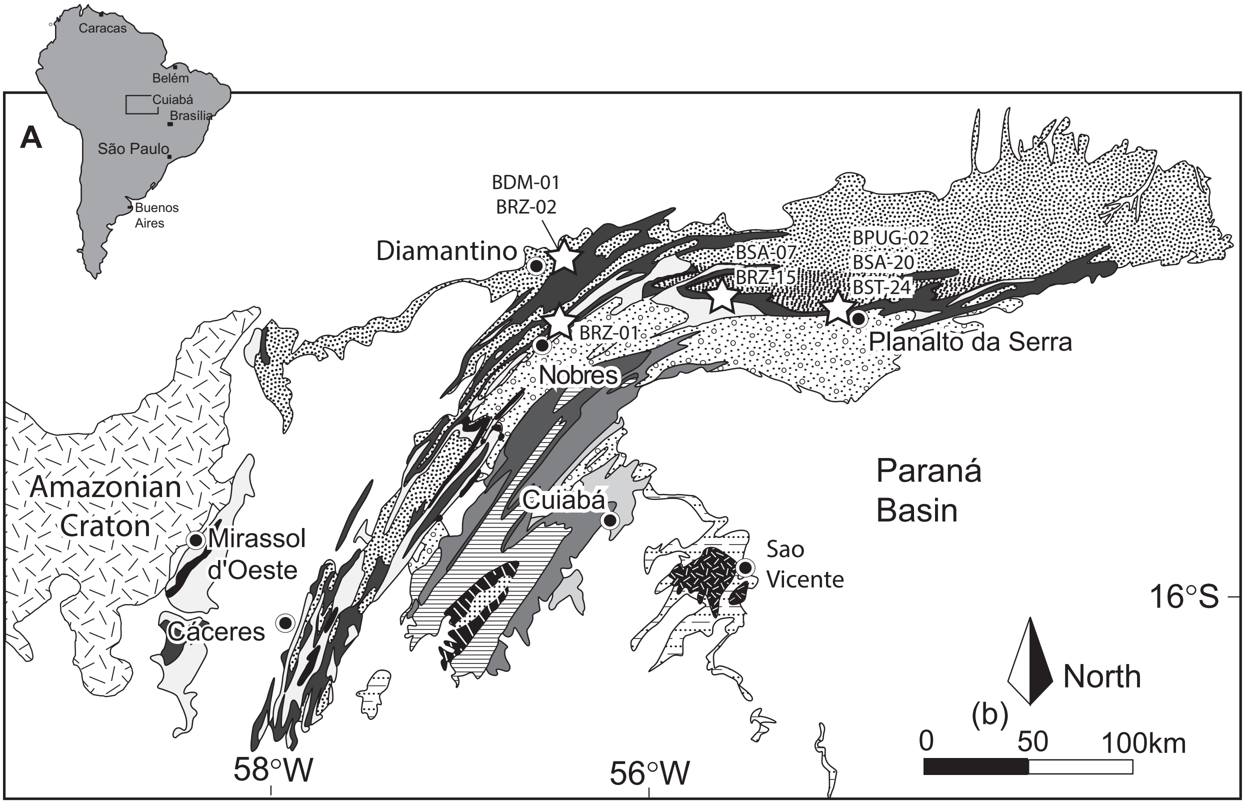

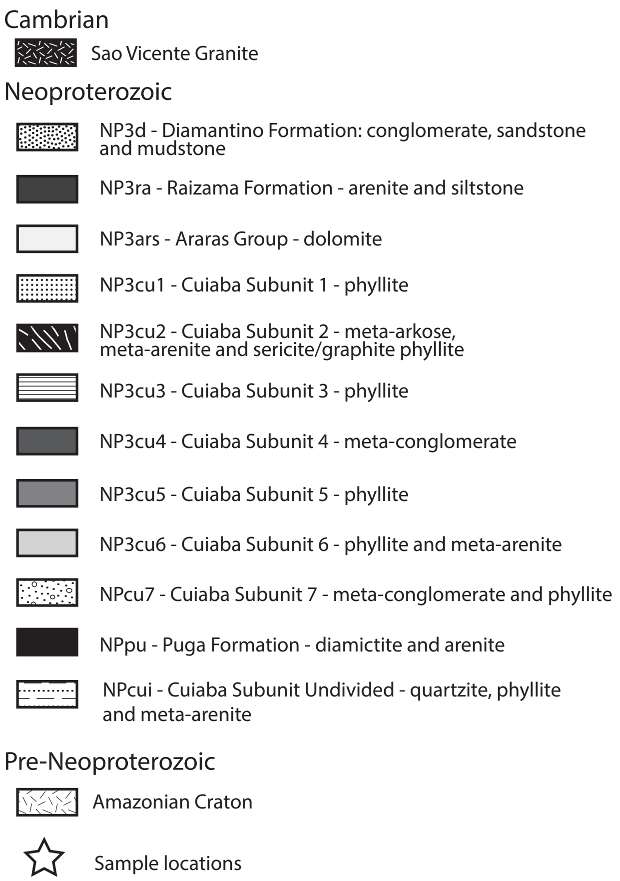

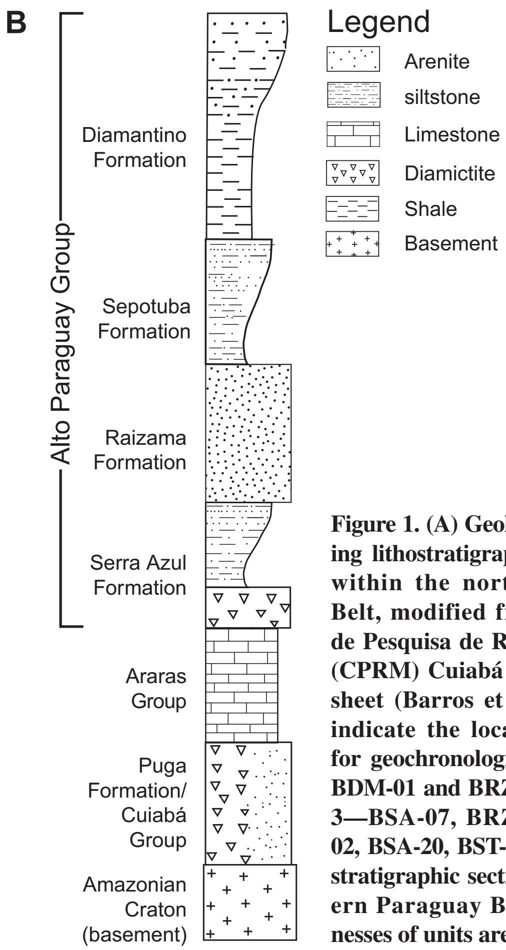

Figure 1. (A) Geological map showing lithostratigraphic relationships within the northern Paraguay Belt, modified from Companhia de Pesquisa de Recursos Minerais (CPRM) Cuiabá 1:1,000,000 map sheet (Barros et al., 1982). Stars indicate the location of samples for geochronological analysis: 1—BDM-01 and BRZ-02; 2—BRZ-01; 3—BSA-07, BRZ-15; 4—BPUG-02, BSA-20, BST-24. (B) Schematic stratigraphic section for the northern Paraguay Belt. Note: thicknesses of units are not to scale.

of exposure, recent interpretations describe the Puga diamictite as the proximal "shelf" facies of the Cuiabá Group (Alvarenga et al., 2009). The age of the youngest detrital zircon in the Puga Formation (706 ± 9 Ma; Babinski et al., 2013) and correlation of the $\delta^{13}C$ (–5.0‰) and $^{87}Sr/^{86}Sr$ (0.7080) ratios from carbonates directly overlying the diamictites (Nogueira et al., 2003) with the global signature suggest that these represent the ca. 635 Ma end-Cryogenian glaciation.

In the northern Paraguay Belt, the stratigraphic framework of the Alto Paraguay Group was first described by Almeida (1964), who divided it into ~1600 m of sands, silts, and shale of the Raizama Formation, ~900 m of shale, silts, and sandstones of the Sepotuba Formation, and ~600 m of Diamantino Formation rhythmites and sandstones. More recently, Figueiredo (2006) and subsequently Alvarenga et al. (2007) described a new unit, the Serra Azul Formation, in between carbonates of the Araras Group and the siliciclastics of the Alto Paraguay Group (Fig. 1B). The basal part of this formation is composed of a glaciogenic diamictite, containing multiply striated sandstone clasts (Alvarenga et al., 2007) and striated, polished, and bullet-shaped mudstone clasts (McGee et al., 2013), which is overlain by a transgressive package of interlayered silts and fine sands. The siltstone and sandstone of the upper Alto Paraguay Group were shed off rising topography—the Paraguay orogen—in response to collision of the Amazonian craton, the São Francisco craton, and the Paranapanema block between ca. 540 Ma and 520 Ma (Bandeira et al., 2012). In contrast to the metamorphosed Cuiabá Group, the Alto Paraguay Group shows an absence of metamorphism and only a single stage of deformation with northwest vergence. The termination of orogenesis was marked by intrusion of postorogenic granites into the base of these metasediments at ca. 518 Ma (McGee et al., 2012).

ANALYTICAL METHODS

Zircon U-Pb Laser-Ablation–Multicollector–Inductively Coupled Plasma–Mass Spectrometry (LA-MC-ICP-MS) Analysis

The locations of samples collected for geochronological analysis are shown in Figure 1. These samples were prepared using the methods described in McGee et al. (2012) at the University of Adelaide. U-Pb fractionation was corrected using the GEMOC GJ-1 zircon standard (thermal ionization mass spectrometry [TIMS] normalization data $^{207}Pb/^{206}Pb$ = 608.3 Ma, $^{206}Pb/^{238}U$ = 600.7 Ma, and $^{207}Pb/^{235}U$ = 602.2 Ma; Jackson et al., 2004), and accuracy was checked using the recognized zircon standard Plesovice with $^{206}Pb/^{238}U$ = 337.13 ± 0.37 Ma (Sláma et al., 2008). Data reduction was performed using GLITTER (Van Achterbergh et al., 2001). The average normalized ages for GJ-1 during the course of this study were 608.6 Ma ± 9.2 Ma (mean square of weighted deviates [MSWD] = 0.030), 601.4 ± 2.4 Ma (MSWD = 0.094), and 602.7 ± 2.3 Ma (MSWD = 0.058) for the $^{207}Pb/^{206}Pb$, $^{206}Pb/^{238}U$, and $^{207}Pb/^{235}U$ ratios, respectively (2σ, n = 362). The average normalized $^{206}Pb/^{238}U$ age for Plešovice is 337.9 ± 1.3 Ma (2σ, MSWD = 0.057; n = 139). Probability density plots were constructed using Isoplot version 3.0 (Ludwig, 2003).

Zircon Hf Isotopic Analysis

The same zircon mount discs prepared for U-Pb isotopic analysis were used for Hf. Hafnium analyses were conducted via LA-MC-ICP-MS at the University of Adelaide and the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) joint facility at the Waite campus in South Australia. Ablation was achieved using a New Wave UP-193 Excimer laser (193 nm) using a spot size of 50 µm, frequency of 4 Hz, 4 ns pulse length, and an intensity of 8–10 J/cm². Hafnium ablation pits targeted the same textural cathodoluminescence (CL) zone as the corresponding U-Pb ablation pit and were made in a helium atmosphere and subsequently mixed with argon upstream of the ablation cell. The attached Thermo-Scientific Neptune MC-ICP-MS measured ^{171}Yb, ^{173}Yb, ^{175}Lu, ^{176}Hf, ^{177}Hf, ^{178}Hf, ^{179}Hf, and ^{180}Hf on Faraday detectors with 10^{11} Ω amplifiers. In total, 500 sweeps of this isotope array were made, each of 0.262 s length, for a total analysis time of 131 s, including a 30 s helium gas background measurement. Hf mass bias was corrected using an exponential fractionation law with a stable $^{179}Hf/^{177}Hf$ ratio of 0.7325. Yb and Lu isobaric interferences on ^{176}Hf were corrected using the methods of Woodhead et al. (2004). The ^{176}Yb interference on ^{176}HF was corrected through direct measurement of Yb fractionation using measured $^{171}Yb/^{173}Yb$ with the Yb isotopic values of Segal et al. (2003). The applicability of these values was verified by analyzing JMC 475 Hf solutions doped with varying levels of Yb with interferences up to $^{176}Yb/^{177}Hf$ = ~0.5. Lu isobaric interference on ^{176}Hf was corrected using a $^{176}Lu/^{175}Lu$ ratio of 0.02655 (Vervoort et al., 2004) assuming the same mass bias behavior as Yb.

Setup of the system prior to ablation sessions was conducted using analysis of JMC475 Hf solution and an AMES Hf solution. Confirmation of accuracy of the technique for zircon analysis was monitored using a combination of the Plešovice, Mudtank, and QGNG standards. The average value for Plešovice for the analytical session was 0.282471 ± 0.000017 (2σ; n = 24), which statistically overlaps the published value of 0.282482 ± 0.000013 (2σ; Sláma et al., 2008). Depleted mantle model age (T_{DM}) and crustal age ($T_{DM\ crustal}$) were calculated using the ^{176}Lu decay constant after Scherer et al. (2001). $T_{DM\ crustal}$ was calculated using the methods of Griffin et al. (2000) with an average crustal composition of $^{176}Lu/^{177}Hf$ = 0.015.

RESULTS

Zircon U-Pb LA-ICP-MS Isotopic Results

Eight samples were selected for geochronological analysis that gave the broadest temporal range, from the base of the Puga Formation to the top of the Alto Paraguay Group (Fig. 1). Sample BPUG-02 is a green-gray diamictite with a coarse matrix from the Puga Formation. Samples BSA-07 and BSA-20 are from the Serra Azul Formation and are a brown-maroon diamictite with a fine silty matrix and a pale-green diamictite with a fine sandy matrix, respectively. Samples BRZ-01, BRZ-02, and BRZ-15 are medium and coarse arenites with lenses of matrix-supported pebble conglomerate from the Raizama Formation. Sample BST-24 is from the Sepotuba Formation and is a deep red–purple, coarse-grained arenite. BDM-01 is from the top of the sequence—the Diamantino Formation—and is a mature, white coarse sandstone.

Geochronological data are presented in Figures 2 and 3, and analytical data are provided in Supplemental Table DR1.[1] Ages are reported using the $^{206}Pb/^{238}U$ ratio; all errors are quoted at the 2 sigma (2σ) level, and weighted averages are at 95% confidence. Laser-ablation spots targeted oscillatory-zoned magmatic cores where possible (Fig. 4).

Age Estimates

BDM-01 (mature pale arenite). In total, 98 LA-ICP-MS analyses of 96 zircon grains were collected from sample BDM-01 (Table DR1 [see footnote 1]), targeting moderately luminescent cores and rims, in some cases with oscillatory zoning (Fig. 4A). BDM-01 is the only sample that shows Cambrian zircon inheritance (Fig. 3), with the youngest grain at 528 ± 9 Ma (Fig. 2).

[1]GSA Data Repository item 2014271, Table DR1: Zircon U-Pb isotopic data; Table DR2: Zircon hafnium isotopic data, is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.

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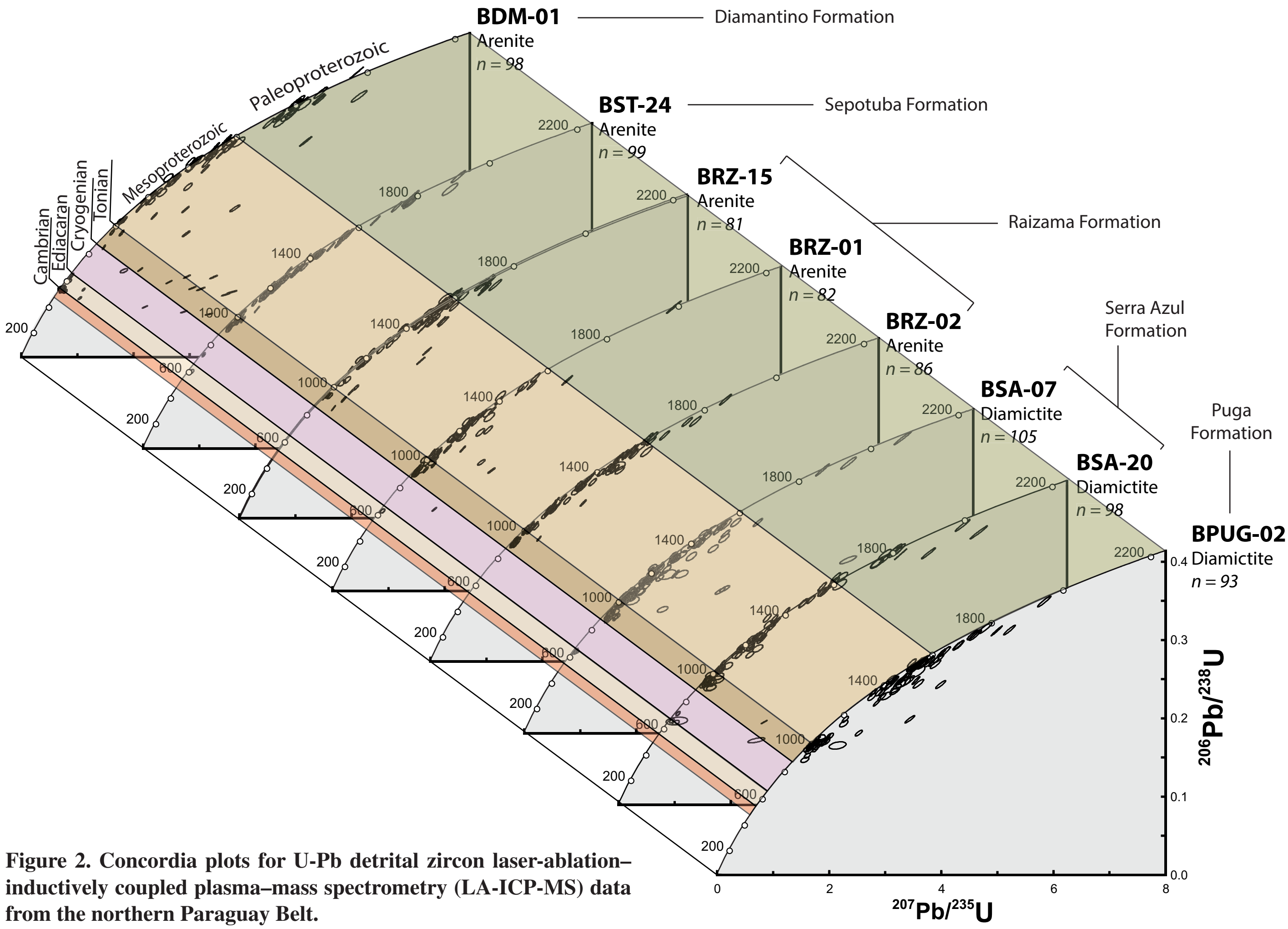

Figure 2. Concordia plots for U-Pb detrital zircon laser-ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) data from the northern Paraguay Belt.

The next two youngest concordant grains are 554 ± 18 Ma and 564 ± 16 Ma, respectively, producing a weighted average of 560 ± 13 Ma. The majority of other grains are Mesoproterozoic, with another peak in the Paleoproterozoic (Fig. 3).

BST-24 (deep purple, coarse-grained arenite). In total, 99 LA-ICP-MS analyses of an equal number of zircon grains were collected from sample BST-24 (Table DR1 [see footnote 1]), targeting moderately luminescent, oscillatory-zoned magmatic growth regions (Fig. 4B). All analyses are highly concordant (Fig. 2) and lie between 615 Ma and 1950 Ma (Fig. 3).

BRZ-15 (coarse-grained arenite). In total, 81 LA-ICP-MS analyses of an equal number of zircon grains were collected from sample BRZ-15 (Table DR1 [see footnote 1]), targeting moderately to highly luminescent oscillatory-zoned magmatic regions (Fig. 4C). The analyses are predominantly concordant (Fig. 2) and lie between 950 Ma and 1800 Ma (Fig. 3), with one large peak at 1550 Ma.

BRZ-01 (medium-grained arenite). In total, 82 LA-ICP-MS analyses of an equal number of zircon grains were collected from sample BRZ-01 (Table DR1 [see footnote 1]), targeting moderately luminescent, oscillatory-zoned magmatic growth regions (Fig. 4D). The analyses are generally concordant (Fig. 2) and mainly spread between 900 Ma and 1560 Ma, with two outliers, one at 635 Ma and the other at 1984 Ma (Fig. 3).

BRZ-02 (Coarse grained arenite). In total, 86 LA-ICPMS analyses of 85 zircon grains were collected from sample BRZ-02 (Table DR1 [see footnote 1]), targeting moderately luminescent, oscillatory-zoned magmatic growth regions (Fig. 4E). The majority of analyses are highly concordant (Fig. 2) and lie between 900 Ma and 1850 Ma (Fig. 3).

BSA-07 (green-gray diamictite). In total, 105 LA-ICP-MS analyses of 103 zircon grains were collected from sample BSA-07 (Table DR1 [see footnote 1]), targeting moderately to highly luminescent oscillatory-zoned magmatic growth zones (Fig. 4F). The majority of grains are concordant, with a small number of discordant grains with no obvious common-Pb or Pb-loss trend (Fig. 2). The three youngest analyses are grouped around 650 Ma, the youngest at 646 Ma, with the majority of grains spread between 900 and 1700 Ma (Fig. 3). Three prominent peaks occur at 1860 Ma, 1975 Ma, and 2090 Ma, respectively.

BSA-20 (green-gray diamictite). In total, 98 LA-ICP-MS analyses of 97 zircon grains were collected from sample BSA-20 (Table DR1 [see footnote 1]), targeting moderately luminescent, oscillatory-zoned magmatic growth regions (Fig. 4G). The majority of samples lie along concordia (Fig. 2) from 665 Ma to 2050 Ma (Fig. 3).

BPUG-02 (red-brown to purple diamictite). In total, 93 LA-ICP-MS analyses of an equal number of zircon grains were collected from sample BPUG-02 (Table DR1 [see footnote 1]), targeting dark to moderately luminescent oscillatory-zoned magmatic growth regions (Fig. 4H). The analyses are highly to moderately concordant, with a slight spread of data below concordia (Fig. 2). Two main clusters of data are apparent: at 1050 Ma and spread between 1400 Ma and 1800 Ma (Fig. 3).

Zircon Hf Isotopic Results

Hf isotopic results are presented in an ε_{Hf} versus time plot in Figure 5, and the corresponding data are in supplemental Table DR2 (see footnote 1). Hf data were collected for each of the eight samples that were analyzed for U-Pb isotopes in order to determine the provenance of the protoliths for the sedimentary rocks of the northern Paraguay Belt. The analyses are plotted in their respective formations, and of the total 255 zircons that were analyzed, 240 analyses are plotted, limited to <10% age discordancy. By sample, 42 grains were analyzed and 33 are plotted for BDM-01; 35 grains were analyzed and 34 are plotted for BPUG-02; all grains analyzed (32) are plotted for BRZ-01; all grains analyzed (10) are plotted for BRZ-02; all grains analyzed (35) are plotted for BRZ-15; all grains analyzed (38) are plotted for BST-24; 23 grains were analyzed and 22 are plotted for BSA-07; and 40 grains were analyzed and 35 are plotted for BSA-20.

The zircons from sample BRZ-01 with ages between 1984 and 636 Ma have ε_{Hf} values between –4 and +7. The zircons from sample BRZ-02 with ages between 1556 and 937 Ma have ε_{Hf} values between –2 and +5. The zircons from sample BRZ-15 with ages between 1818 and 929 Ma have ε_{Hf} values between –6 and +11. The zircons from sample BST-24 with ages between 1916 and 615 Ma have ε_{Hf} values between –8 and +6. The zircons from sample BSA-20 with ages between 1863 and 653 Ma have ε_{Hf} values between –22 and +7. The zircons from sample BSA-07 with ages between 1542 and 651 Ma have ε_{Hf} values between –8 and +6. The zircons from sample BDM-01 with ages between 1950 and 528 Ma have ε_{Hf} values between –24 and +27. The zircons from sample BPUG-02 with ages between 1975 and 968 Ma have ε_{Hf} values between –14 and +5.

Crustal model ages were calculated for each zircon assuming average continental crust with $^{176}Lu/^{177}Hf$ of 0.0015 as the zircon grain growth reservoir. Based on this crustal model, an age range of 1.4 Ga to 2.9 Ga is obtained for this package of sediments, represented by the envelope drawn on Figure 5. Overall, the compiled $\varepsilon_{Hf}(t)$ data for all formations are widely dispersed. The mid-Paleoproterozoic data show a large proportion of evolved $\varepsilon_{Hf}(t)$ values with a smaller component of moderately juvenile grains (Fig. 5). After ca. 1750 Ma, the $\varepsilon_{Hf}(t)$ signal is predominantly juvenile for the remainder of the Paleoproterozoic and all of the Mesoproterozoic. At the end of the Mesoproterozoic era, the $\varepsilon_{Hf}(t)$ signal trends toward more evolved values, with only a few juvenile zircon grains.

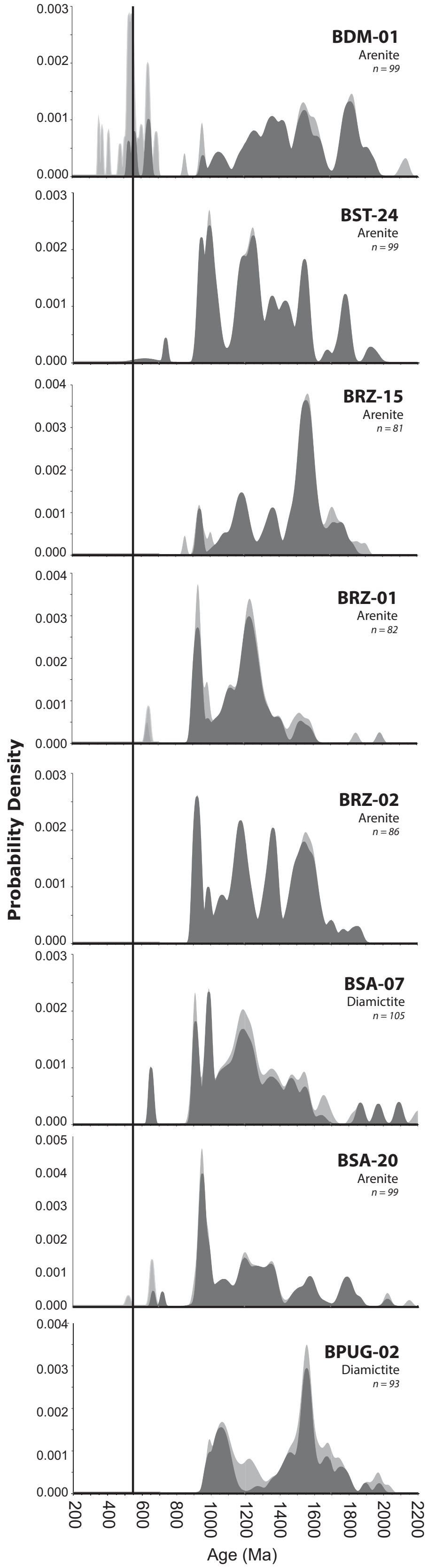

Figure 3. Relative probability plots for U-Pb detrital zircon analyses. Light-gray shading represents all detrital grains analyzed; dark gray represents detrital grains between 90% and 110% concordant. Black line represents the Cambrian-Ediacaran boundary.

DISCUSSION

U-Pb Isotopic Age Constraints and Maximum Depositional Ages

The U-Pb data reported here complement recent detrital muscovite ^{40}Ar-^{39}Ar analyses (McGee et al., 2014a) by providing constraints on source regions and recognizing the age of higher-temperature events in the northern Paraguay Belt. The maximum depositional ages presented here are based on the ages of the youngest detrital zircon grain for each respective formation.

The U-Pb data presented here for the Puga Formation show only pre-Cryogenian inheritance (>918 Ma) and do not improve the maximum depositional age of 706 Ma provided by Babinski et al. (2013). Analyses of the glaciogenic Serra Azul Formation give a maximum depositional age of 646 Ma. This age constraint means that the Serra Azul Formation permissibly correlates with either the Marinoan (ca. 635 Ma) or Gaskiers (ca. 582 Ma) glaciation. Given that the Serra Azul Formation diamictite lies stratigraphically above a supposed Marinoan cap carbonate (Babinski et al., 2006; Nogueira et al., 2003), several authors have correlated the Serra Azul diamictite with the ca. 582 Ma Gaskiers glaciation (Alvarenga et al., 2007; McGee et al., 2013). The maximum depositional ages of the Raizama and Sepotuba Formations are constrained by the youngest analyzed grains at 635 Ma and 615 Ma, respectively. The youngest <10% discordant analyzed zircon from the Diamantino Formation is 528 ± 9 Ma. The next two youngest concordant analyses yield a weighted mean of 560 ± 13 Ma, which we interpret conservatively as the maximum depositional age for this formation. If the youngest grain is considered to represent the maximum depositional age, this is some 15 m.y. younger than the 541 ± 7 Ma age previously reported for the Diamantino Formation by Bandeira et al. (2012), indicating that deposition in the foreland of the Paraguay orogen continued well into the Cambrian.

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Figure 4. Cathodoluminescence images of representative zircon grains from sample (A) BDM-01; (B) BST-24; (C) BRZ-15; (D) BRZ-01; (E) BRZ-02; (F) BSA-07; (G) BSA-20; and (H) BPUG-02. Displayed spot ages younger than 1000 Ma and older than 1000 Ma are $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages, respectively. Small circles (30 µm) and large circles (50 µm) represent the locations of U-Pb and Lu-Hf analyses, respectively.

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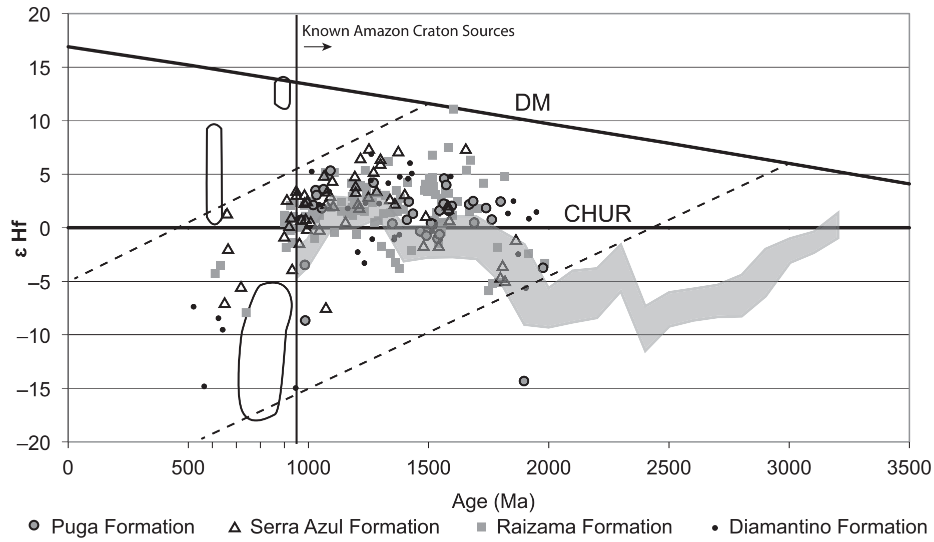

Figure 5. The ε_{Hf} values plotted against age (Ma). Grains with more than 10% discordancy have been omitted. The gray envelope represents the first to third quartile of modern-day zircons collected from the Amazon River (Iizuka et al., 2010). White polygons represent ε_{Hf} data from the Goiás Massif after Matteini et al. (2010). DM—depleted mantle; CHUR—chondritic uniform reservoir.

U-Pb and Hf Isotopic Results and Correlation with Potential Source Regions

Integrated U-Pb and Hf isotope composition data of detrital zircons from the sedimentary rocks of the northern Paraguay Belt provide insight into the tectonomagmatic evolution of their source areas. The age spectra represented by the samples are characterized by polymodal zircon age spectra (Fig. 3). Suitable source regions would need to contain the same zircon populations to be considered viable. The series of ages can be considered as a diagnostic pattern for the source of the strata in the northern Paraguay Belt. The ε_{Hf} values of zircons at the times of their crystallization ($\varepsilon_{Hf[t]}$) provide the petrological signature of the melt in which the zircons crystallized. Positive $\varepsilon_{Hf(t)}$ values broadly indicate derivation from juvenile (mantle-derived) sources, while nonradiogenic Hf isotopic compositions with negative $\varepsilon_{Hf(t)}$ values indicate derivation, in part, from preexisting continental crust (Amelin et al., 1999). By coupling the U-Pb and Hf isotopic results, it is possible to gain some insight about the source regions for these rocks.

The data presented in the ε_{Hf} versus time plot in Figure 5 begin with predominantly evolved values until close to the end of the Paleoproterozoic era, when the signal becomes predominantly juvenile for all of the Mesoproterozoic era. This trend is consistent with the global data set (Belousova et al., 2010) and also matches the signal for modern-day ε_{Hf} from detrital zircons from the Amazon River represented by the gray envelope (Fig. 5). Since the Paraguay Belt is considered to be a sequence of folded sediments that formed on a passive margin on the southeastern margin of the Amazonian craton, this is a logical source area for these sediments. This craton consists of two small Archean cores—the Central Amazonian Province (>2600 Ma), surrounded by predominantly accretionary Paleoproterozoic belts; the Maroni-Itacaiunas Province (2250–2050 Ma); the Ventuari-Tapajós Province (1980–1810 Ma); the Rio Negro–Juruena Province (1780–1550 Ma); the Rondonian–San Ignácio Province (1550–1300 Ma); and the ca. 1250–950 Ma Sunsás Province (Cordani and Teixeira, 2007; Cordani et al., 2009; Tassinari et al., 2000). The similarities in age and the ε_H signature with modern-day Amazon River detrital zircons indicate that the Amazon craton was a major contributor to the Paraguay Belt sediments. However, the vertical line in Figure 5 represents the minimum age of currently known sources on the Amazonian craton (ca. 950 Ma). If this is taken as the minimum age limit for rocks on this craton, alternative regions must be considered as sources.

Another potential source region to consider are the blocks underneath the Paraná Basin. While some authors have suggested the existence of several blocks under the Paraná Basin (e.g., Cordani et al., 2003; Milani, 1997), a recent review by Mantovani and Brito Neves (2009) suggested that a simpler interpretation—the existence of one body, the Paranapanema block—was more favorable. Based on deep oil exploration wells that intersected basement, the Paranapanema block was described by Mantovani and Brito Neves (2009) as "pre-Brasiliano in general." This block is likely to have contributed sediment to the Paraguay Belt, but due to its burial beneath the Paraná Basin, it is difficult to assess to what degree.

Bandeira et al. (2012) used paleocurrent indicators from the upper Diamantino Formation to show that the prevailing source regions were located to the east of the present-day Paraguay Belt. Potential source regions they identified include the 790–600 Ma Brasília Belt and the Neoproterozoic Goiás magmatic arc. In Figure 5, we have represented Hf data after Matteini et al. (2010) from the Goiás magmatic arc as closed polygons. These polygons show that the Goiás contains highly juvenile material, but also more evolved material that could have been a potential source for the Paraguay Belt sediments. Bandeira et al. (2012) interpreted the rest of the sediments as having been cannibalized from the rising topography of the Paraguay Belt. The proven presence of zircons with a similar age from within the core of the Paraguay Belt (today to the southeast of the sample site) strongly suggests that the Diamantino Formation was sourced from elevated topography developed during Paraguay Belt orogenesis. This interpretation is supported by the Sm/Nd data of Dantas et al. (2009).

Tectonic Model and the Paraguay Belt within South America and Gondwana

Owing to the scarcity of reliable Neoproterozoic paleomagnetic poles, the location of the Amazonian craton and its role in Gondwana amalgamation have been the subject of debate for some time (e.g., Cordani et al., 2009, 2013; Pisarevsky et al., 2008). The Paraguay Belt on the southern margin of the Amazonian craton is at the center of this debate, with several models for its evolution being presented over the last four decades (Almeida, 1974, 1984). Currently, there are two competing models for the tectonic evolution of the Paraguay Belt and surrounding orogens. The first model considers the ages of juvenile arcs (940–620 Ma) at the western border of the São Francisco craton to represent the age of collision of the Amazonian craton with proto-Gondwana, implying suturing at ca. 620 Ma (Cordani et al., 2009, 2013). In this scenario, the Paraguay Belt sediments would presumably represent a rift basin that was subsequently inverted. However, little evidence for ca. 620 Ma orogenesis exists, with ages of metamorphism and intrusive plutons much younger in age.

The second model, proposed by Trindade et al. (2006), used a paleomagnetic pole (Trindade et al., 2003) that suggested that the Amazonian craton was at low latitudes and not joined to Gondwana until Cambrian times. The hypothesis infers that the Amazonian craton and other minor adjoining blocks were separated from proto-Gondwana by the Clymene Ocean and collided in the Cambrian, forming a major orogenic belt consisting of the Araguaia, Paraguay, and Pampean Belts. Several other contributions have since provided evidence that corroborate such an evolution for the Paraguay Belt based on a range of different evidence.

Sedimentation and provenance studies have helped to constrain the depositional environments and sources for the Paraguay Belt sediments. Geochemical provenance patterns of the northern Paraguay Belt were investigated by Dantas et al. (2009), where they studied the Nd isotopic signature of rocks in the sequence. They found that the lower part of the succession was dominated by Nd isotopic ratios and T_{DM} model ages that suggest a continental source from the Amazonian craton, while the upper siliciclastic succession shows lower Nd isotopic ratios that are consistent with a source from the Paraguay Belt itself, or another Neoproterozoic continental source. More recently, detrital zircon ages from the Diamantino Formation of 541 ± 7 Ma (Bandeira et al., 2012) and $^{40}Ar/^{39}Ar$ muscovite ages from the upper part of the Alto Paraguay Group of 544 Ma (McGee et al., 2014b) indicate that final sedimentation within the Paraguay Belt occurred up to the Cambrian. The U-Pb data presented here add to this database of maximum depositional ages for the sediments of the Paraguay Belt.

Several authors have also investigated the timing of deformation and metamorphism within the orogen. Regional metamorphism of the Cuiabá Group was estimated between 541 and 531 Ma based on $^{40}Ar/^{39}Ar$ cooling ages of biotite flakes (Geraldes et al., 2008). The incipient stage of deformation in the form of early thrusting was inferred to be associated with clay mineral transformations and chemical remagnetization of carbonates in the Araras Group at ca. 528 Ma (Tohver et al., 2010). In this contribution, Tohver et al. (2010) showed that oroclinal bending of the Paraguay Belt was caused by a 90° clockwise rotation of the east-limb sometime after 528 Ma. Tohver et al. (2010) also pointed out that the age of the Paraguay Belt overlaps with that of the Pampean Belt further south, suggesting coeval closure for the Clymene Ocean separating the Amazonian craton from the São Francisco and Rio de la Plata cratons. Tohver et al. (2012) elaborated on the theory of a Cambrian formation for Gondwana with evidence from the Sierra Australis, including late Ediacaran to Late Cambrian magmatism, and evidence showing a close overlap of geochronological data with Clymene collision belts to the north—the Paraguay and Araguaia Belts.

A geophysical study that combined magnetotelluric and gravimetric data proposed that a plate interaction zone exists at the western border of the Paraná Basin, proposing a collision between the Rio Apa craton to the west and the Paranapanema block to the east (Woldemichael, 2003). Woldemichael (2003) modeled this interaction as a subduction zone from 550 to 520 Ma of the Rio Apa oceanic crust under the Paranapanema, with the development of an Andean type magmatic arc. A subsequent investigation of the geochemistry of the granitic bodies that outcrop at the western margin of the Paraná Basin showed that these rocks are potassic to high-K, calc-alkaline, peraluminous to metaluminous, type-I granitoids that plot in the syncollisional field of the tectonic classification diagrams (Godoy et al., 2007). Early work constraining the ages of these intrusives includes a ca. 503 Ma K/Ar age (Almeida, 1968) and ca. 483 Ma Rb/Sr age (Almeida and Mantovani, 1975) for the postorogenic São Vicente granite (Fig. 1). These ages have been supported by more recent U-Pb zircon analyses of the same intrusive batholith of ca. 521 Ma (Ferreira, 2009) and ca. 518 Ma (McGee et al., 2012). Other granitic intrusions from the interior of the belt have similar ages, including a U-Pb sensitive high-resolution ion microprobe (SHRIMP) zircon age of 510 ± 12 Ma for the Araguainha Granite (Tohver et al., 2012) and a U-Pb zircon age of 505.4 ± 4.1 Ma for the Lajinha Granite (Manzano, 2009).

The paleomagnetic result of Trindade et al. (2003) that suggested the Amazon was not connected to proto-Gondwana until the Cambrian has recently been questioned, after McGee et al. (2014b) reproduced similar geomagnetic reversals of an orientation very similar to those of Trindade et al. (2003) much higher in the stratigraphy, from the Alto Paraguay Group. McGee et al. (2014b) suggested that this result is indicative of a remagnetization, potentially associated with Jurassic tholeiitic basalts that intrude into the western part of the northern Paraguay Belt. If this is the case, the paleomagnetic database no longer provides information about the location of the Amazonian craton for much of the Neoproterozoic, leaving the tectonic evolution of the belt open to debate. Despite this uncertainty in the paleomagnetic database, the amount of other supporting evidence for a late (Cambrian) collision of Amazonia is difficult to ignore.

Based on this amalgam of evidence and our new U-Pb and Hf data, we propose a tectonic model (Fig. 6) that incorporates all of this information. The first sediments found on the Amazonian craton are the glacial diamictites of the Puga Formation and the more distal turbidites of the Cuiaba Group. The thickness (4–6 km) and spatial extent (~700 km) of these units are suggestive of a large marine basin, which has previously been proposed by numerous authors (e.g., Alvarenga and Trompette, 1992; Alvarenga et al., 2009; Nogueira et al., 2007). The depositional model proposed for these units is that of a passive margin environment from platformal to outer slope from west to east, respectively (Alvarenga and Trompette, 1992). This period of deposition was followed by a period of glaciation responsible for depositing the Serra Azul Formation in a glaciomarine environment inferred to be related to the Gaskiers glaciation (Alvarenga et al., 2007; McGee et al., 2013).

The conformable nature of the Raizama Formation with the upper Serra Azul Formation implies the gradual initiation of topography and that the deposition of the Raizama Formation was tectonically controlled by this rising topography. We propose that the incipient stages of deformation—the "proto-Paraguay orogeny"—formed as a peripheral bulge (Fig. 6A) in response to the flexural warping of the lithosphere. This lithospheric deformation and associated basin inversion began as oceanic crust connected to the Amazonian craton was thrust under the Paranapanema block and the Goiás Massif. In such a system, a downwarp is generated proximal to the orogen, the foreland basin, and a low-amplitude, long-wavelength upwarp, the peripheral bulge, develops proximal to subduction (Pelletier, 2008). A minor influence from volcanic arcs is interpreted in the Raizama Formation based on the U-Pb ages reported in this study. This is also supported by Nd isotopic ratios that indicate the Raizama Formation began deriving material from a young source (Dantas et al., 2009). These arcs are probably now buried under the Paraná Basin, to the southeast of the Paraguay Belt (Fig. 1), and their presence and morphology have been interpreted based on petroleum wells and geophysical techniques (Mantovani and Brito Neves, 2009). Based on currently available ages, the Raizama Formation was deposited after middle Ediacaran times (ca. 582 Ma). The Raizama Formation also does not contain the prominent ca. 544 Ma detritus seen in the overlying Diamantino Formation, suggesting that it probably predates this time.

After deposition of the Raizama Formation, a major decrease in sand content and the predominance of siltstone (McGee et al., 2014a) indicate deepening of the foreland basin (Fig. 6B). This most likely occurred in response to increased lithospheric flexure as the collision

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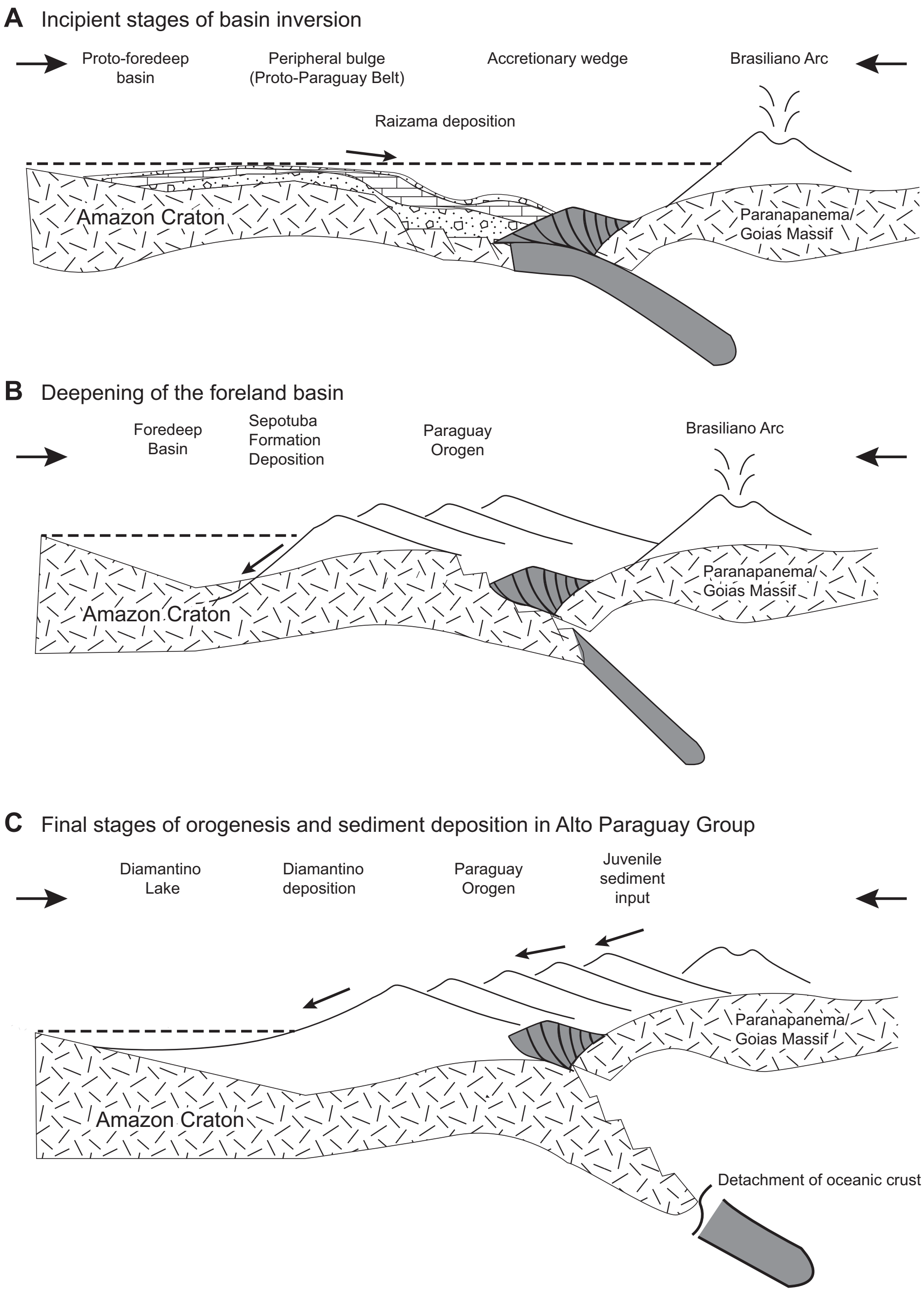

Figure 6. Tectonic model for the evolution of the Paraguay Belt. (A) Initiation of compression, resulting in flexural warping of the lithosphere and deposition of the Raizama Formation into the proto-foredeep basin. (B) Continued lithospheric flexure and deepening of the foredeep basin. (C) Termination of orogenesis and deposition of the Diamantino Formation into the Diamantino Lake.

advanced on the Amazonian margin. At this time, the interlayered sandstones and siltstones of the Sepotuba Formation were deposited into the foreland basin.

The stacking of progradational parasequences indicates that the basin was progressively filled with coarser sediment of the Diamantino Formation (Fig. 6C). Bandeira et al. (2012) interpreted the Diamantino Formation to record the final exhumation and erosion of the orogen that was deposited into the foreland basin—which they interpreted to be a closed system by this stage—the "Diamantino Lake." Another indicator that the Diamantino Formation is likely to have been lacustrine is that the majority of correlative marine Cambrian sequences contain fossils (Iizuka et al., 2010), while none has been reported for the Diamantino Formation. The predominance of much younger detrital zircon ages in the Diamantino Formation most likely represents the increased input from the upper plate of the colliding blocks (the Paranapanema block and Goiás magmatic arc; Fig. 6C) and, as previously discussed, the cannibalization of igneous plutons from within the belt. These zircon data are supported by the presence of numerous ca. 545 Ma detrital muscovites in the Diamantino Formation (McGee et al., 2014a). These ages for final sedimentation and exhumation at ca. 540–530 Ma are in agreement with the observed intrusion of postorogenic granites at ca. 518 Ma (McGee et al., 2012) and indicate that detachment of the downgoing oceanic slab and subsequent removal of the slab-pull force, resulting in the cessation of compressional tectonics, occurred around this time (Fig. 6C). All these data are consistent with an ocean to the east of the Amazonian craton that did not close until the Cambrian.

CONCLUSIONS

The maximum depositional ages provided by the U-Pb zircon analyses from the uppermost part of this sequence of rocks, the Diamantino Formation, indicate that a conservative estimate for final sedimentation in the Paraguay Belt began no earlier than 560 Ma but possibly as late as 528 Ma. Based on the integrated U-Pb and Hf isotope data of detrital zircons presented here, potential sources for these sediments are consistent with a predominantly Amazonian source until the early Neoproterozoic, at which point the signal becomes significantly more evolved, and influence from the Paranapanema block and Goiás magmatic arc to the east is inferred. Based on the combination of magnetotelluric, gravimetric, geochemical, geochronological, and sedimentological evidence discussed here, we propose that the Paraguay Belt initiated as a peripheral bulge as the Paranapanema block began to overthrust the Amazonian margin. Available evidence suggests that final sedimentation, deformation, and metamorphism in the Paraguay Belt occurred between 540 and 510 Ma.

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