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THE PANGEA CONUNDRUM: IMPLICATIONS OF A NEW PALEOMAGNETIC POLE FROM THE PERMO-TRIASSIC ARAGUAINHA IMPACT STRUCTURE (CENTRAL BRAZIL)

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ABSTRACT

The configuration of the Pangea supercontinent has been a topic of intense debate for almost half a century, a controversy that stems from discrepancies between the geology-based Pangea A and the paleomagnetically-based Pangea B. Recent paleomagnetic compilations aimed at resolving this controversy have identified the poor quality of paleomagnetic data from Gondwana for late Permian times as a major obstacle. Specifically, the vast majority of Gondwanan poles come from sedimentary rocks that are prone to biases from compaction or are poorly dated. Here we present a new paleomagnetic pole for cratonic South America based on impact-melts from the 254.7 ± 2.5 Ma Araguainha impact structure, an unusual target for paleomagnetic studies. The impact-generated melt sheet and veins were sampled at 22 sites (137 samples) and provide a reliable paleomagnetic record, similar to that of volcanic rocks. Alternating field and thermal demagnetization indicate stable, usually univectorial magnetizations carried by both magnetite and hematite. All sites but one show a single paleomagnetic direction of normal polarity with a mean direction of Dec = 356.4°; Inc = -38.7°; N = 21; k = 91.1; α_{95} = 3.3°, yielding a paleomagnetic pole (AIS) at Lat = -83.7; Lon = 340.1; K = 83.5; A_{95} =3.5°; S_B =8.3°. The new pole provides a firm constraint on the position of Gondwana within a Pangea A configuration.

Keywords: Pangea; Paleomagnetism; Permo-Triassic; Impact Crater; Araguainha.

Introduction

The relative position of southern and northern parts of Pangea (fig. 1A) in the Late Paleozoic has been a topic of intense debate for almost half a century, since when T. Irving showed dramatic inconsistencies between the original Wegener's Pangea (A-type) and the then-available pre-Jurassic paleomagnetic data (Irving, 1977). Strictly interpreted, paleomagnetic data for the late Paleozoic indicate a ~ 1500 km overlap between Gondwana and Laurussia; simply put, Gondwana is too far north and Laurussia is too far south. To solve these inconsistencies, Irving proposed a new paleogeography, the Pangea-B, where Gondwana is longitudinally displaced relative to Laurussia, placing, for example, NW South America next to SE North America in the late Paleozoic. This configuration needs a huge dextral movement across the Laurussia-Gondwana boundary during the Triassic to accommodate the transition from the Pangea-B to the classical Pangea-A (Irving, 2004), which is well-constrained from Jurassic paleomagnetic data and marine magnetic anomalies from the central Atlantic Ocean. More recently, paleomagnetic studies by Muttoni *et al*. (2003) suggested that the transition from Pangea-B to Pangea-A was completed earlier, by the Late Permian–Early Triassic, coeval with the Neo-Tethys opening. In order to provide better paleomagnetic constraints for the southern hemisphere of Pangea, we studied an unusual paleomagnetic target: impact melts of the Permo-Triassic Araguainha impact structure, which was recently dated by Tohver *et al*. (2012).

Geological setting and sampling rationale

The Araguainha impact structure (16° 47' S,52° 59' W) affected the sedimentary rocks of the northern Paraná Basin in central Brazil. The 40-km-diameter rim is defined by radial and concentric faults, annular rings and a 10-km-wide central uplift composed of exhumed *ca*. 512 Ma granite core surrounded by a collar of sedimentary rocks of the Paraná Group (Lana *et al*., 2007, 2008; Tohver *et al*., 2012). Impact-related melts are observed in contact with the granite (Yokoyama *et al*., 2012), both in the form of veins that crosscut the porphyritic granite, and small bodies of melt sheet with polymict breccia deposits on the top (fig. 1B). A recent geochronological investigation using U-Pb SHRIMP and ^{40}Ar/ ^{39}Ar dating of neocrystallized phases in the melt rock provides a precise age for the impact at 254.7 ± 2.5 Ma, coinciding with the Permo-Triassic limit (Tohver *et al*., 2012). In our case, we have targeted the entire stratigraphy of the melt pile, including the melt sheet but also the melt veins that cut across the granitic target, comprising a total of 22 sampling sites (17 in the melt sheet and 5 in melt veins) (fig. 1). Standard 2.2 × 2.5 cm cylindrical specimens were subjected to alternating field (AF) and/or thermal demagnetization in 15 to 20 steps, up to 160 mT and 700° C, respectively using either a three-axis AF-demagnetizer coupled with the SQUID magnetometer, a LDA AGICO tumbler demagnetizeror an ASC oven (peak temperatures within ± 2º C; total heating time of 1 hour). Remanent magnetizations were measured with a SQUID magnetometer (model 755UC, 2G) or an AGICO JR-6 magnetometer (Agico). These instruments are housed in a magnetically shielded room (ambient field < 1000 nT) at the Paleomagnetic Laboratory of the University of São Paulo (USP). Magnetic mineralogy was characterized in representative samples using hysteresis cycles, isothermal remanent magnetization (IRM) acquisition curves and thermomagnetic curves. Hysteresis measurements were made using a MicroMag VSM (Princeton Instruments corp.). IRM acquisitions were performed up to 2800 mT in more than 40 steps using a pulse magnetizer MMPM10 (Magnetic Measurements Ltd.) and a spinner magnetometer (Molspin Ltd.). Thermomagnetic curves were obtained through heating and cooling cycles from room temperature up to 700º C in a CS3 furnace coupled with a KLY4S Kappabridge susceptometer (Agico). Experiments were done in Argon atmosphere to inhibit alteration during heating.

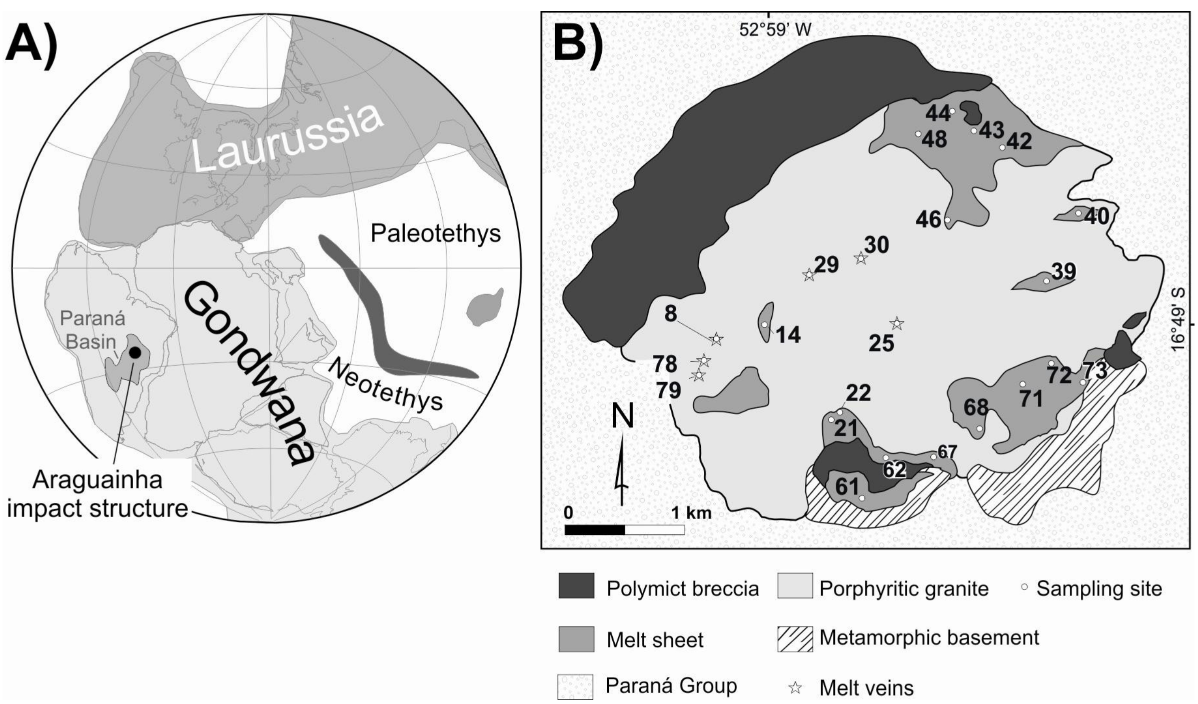

Figure 1. (A) Location of the Araguainha crater (circle) and outline of the Paraná basin into the Pangea A paleogeography; (B) Geological map of the Araguainha central uplift and location of sampling sites.

Results

The alternating field (AF) demagnetization up to 140 mT effectively removed up to 80 percent of the remanence for most samples. The remaining remanence was fully demagnetized after 680° C. Two magnetic carriers (magnetite and hematite) are indicated by thermal demagnetization patterns, thermomagnetic curves, hysteresis and IRM acquisition curves. In thermal demagnetization (fig. 2) and susceptibility against temperature curves, magnetic susceptibility typically decays steeply at about 580 ºC (pure magnetite) followed by a continuous decrease until 700º C (hematite). From the 137 analyzed specimens, 108 present a single stable magnetic direction with a negligible viscous overprint (fig. 3). Some secondary directions correspond to coercivities until 20 mT and maximum unblocking temperatures of 350º C. For 20 specimens (9 sites) this secondary direction was not completely isolated from the ChRM by vectorial subtraction. In this case they were analyzed by great circles (Halls, 1970). PCA for vectors and great circles presented Maximum Angular Deviation (MAD) below 10°. Mean directions for each site are presented in Figure 4. Directions are always well-grouped as attested by k values higher than 100 for most sites.The Araguainha ChRMs are all of normal polarity, compatible with the magnetization being acquired after the Permo-

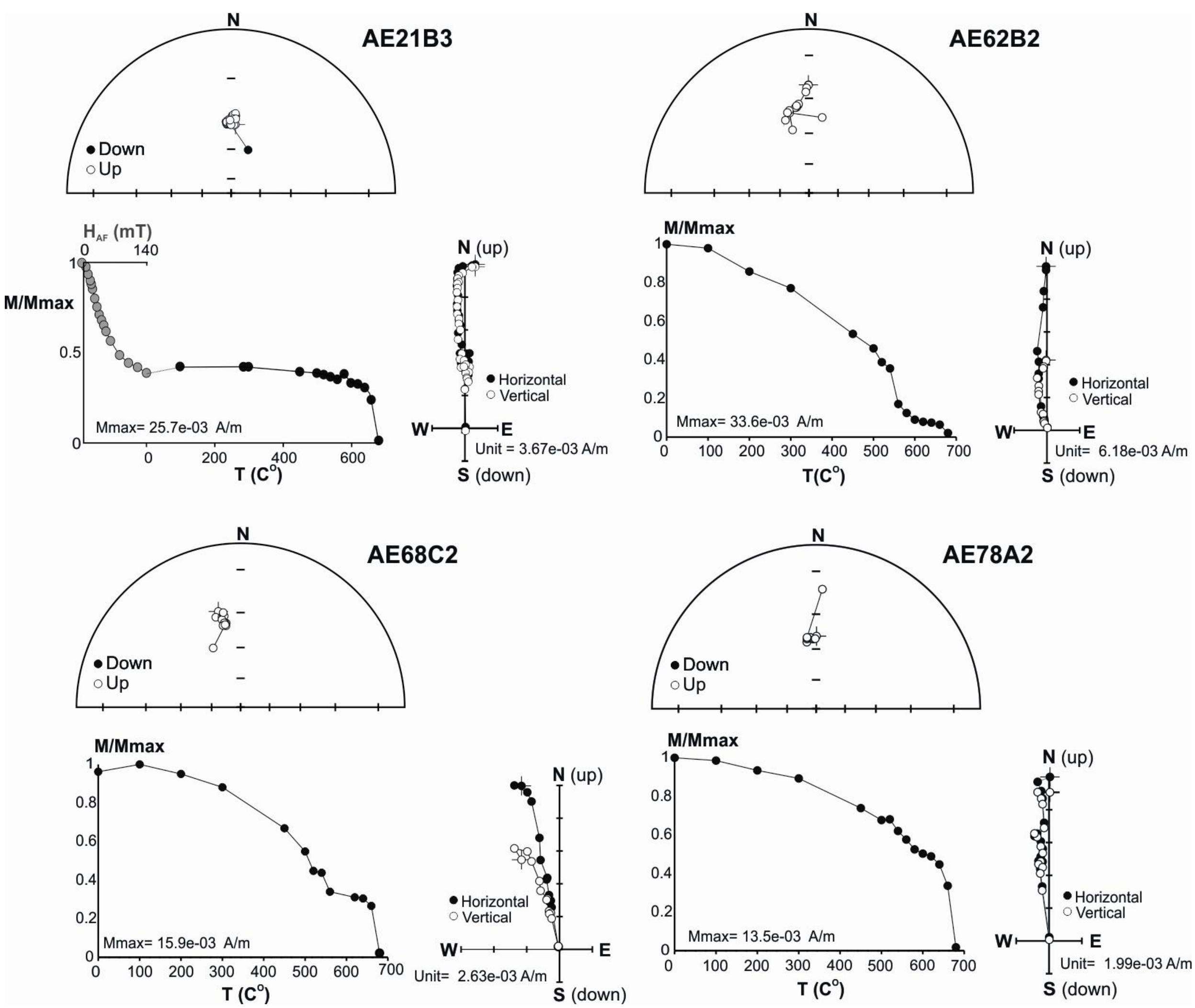

Figure 2. Examples of AF and thermal demagnetizations (stereographic projections, orthogonal projections, and magnetization intensity decay curves) for melt sheets and melt veins samples.

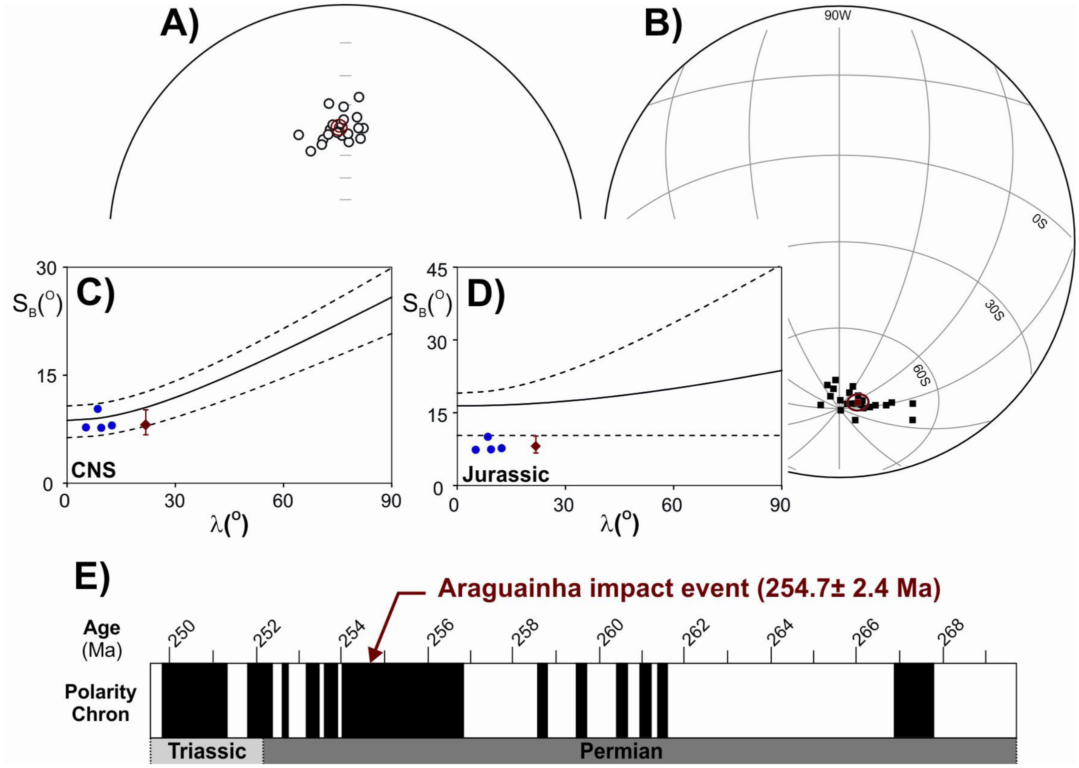

Figure 3. Mean directions and S-parameter curves for the Araguainha collection (in red): (A) Site mean characteristic directions; (B) Site mean virtual geomagnetic poles; comparison of S-parameter with (C) Cretaceous Normal Superchron (CNS) and (D) Jurassic models (from Biggin *et al*., 2008), solid blue circles represent the S-parameter for PCRS from Kruiver *et al*. (2000); (E) Detail of the geological time scale and magnetic polarity chart for the Permo-Triassic boundary with indication of the age of the Araguainha impact event (scale adapted from Gradstein *et al*., 2012).

Carboniferous Reversed Superchron (PCRS), which ended ca. 269 Ma, and the secondary direction found is random. Before defining the paleomagnetic pole, the cutoff method of Vandamme (1994) was applied for data selection. The final cutoff angle was 20.6º after rejection of only one data (site 72), which corresponds to the highest intra-site dispersion (Swi = 63.8°). The dispersion parameter of the mean paleomagnetic pole was $S_B = 8.3°^{10.4}_{6.9}$ $S_B = 8.3°^{10.4}_{6.9}$ (Fig. 4).The final paleomagnetic pole of Araguainha impact structure (AIS) falls at Lat = -83.7°; Lon = 340.1° (K = 83.5; A_{95} = 3.5º, N = 21).

Discussion and conclusions

The dispersion of site-based paleomagnetic directions was evaluated to test whether sampling had averaged out the secular variation, which generally increases with latitude. We use the dispersion pole parameter (S_B) of Biggin *et al*. (2008), which takes into account only the secular variation and eliminates variations associated to experimental errors or intra-site dispersion. Unfortunately, there are no models of SV dispersion for Permo-Triassic so we compared our results to models for the Cretaceous Normal Superchron (CNS) and the Jurassic, which represent extremes of reversal rate (fig. 3). The dispersion factor of paleomagnetic directions for Araguainha melt rocks is $S_B = 8.3°^{10.4}_{6.9}$ $S_B = 8.3°^{10.4}_{6.9}$. This value is comparable with that determined for the Dôme de Barrot red beds deposited during the Permo-Carboniferous Reversal Superchron (PCRS). They are also within the lower range of S_B values for the CNS and just below model estimates of PSV for the rapidly reversing geomagnetic field of the Jurassic. On this basis, it appears that most, if not all paleosecular variation is recorded by the Araguainha impact melt material.

Figures 4A and 4B show the Araguainha pole (AIS) together with other paleomagnetic poles of West

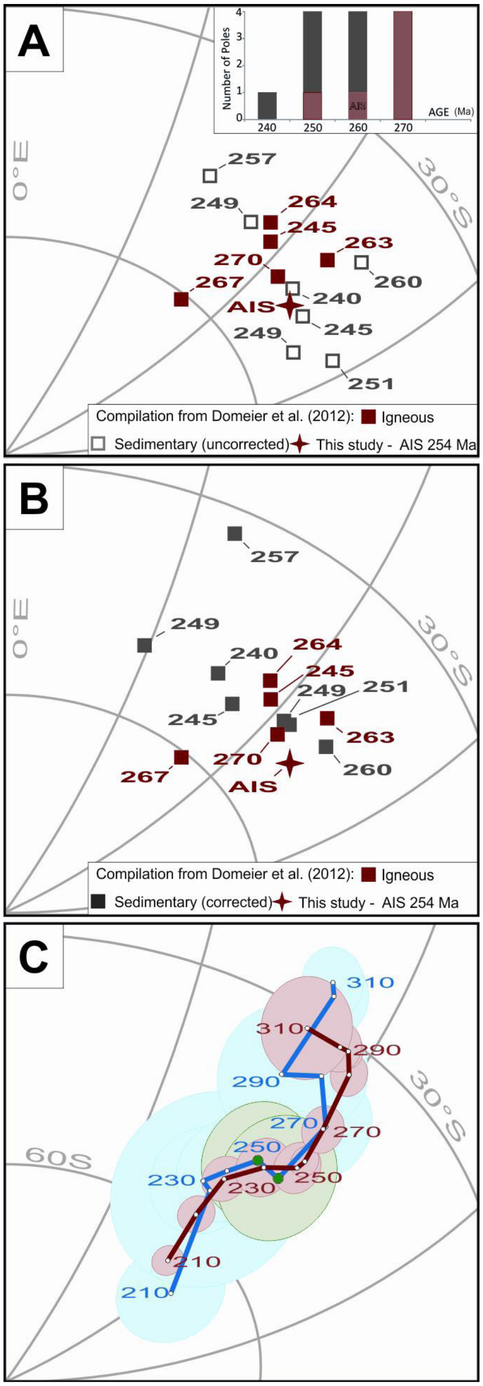

Figure 4. Comparison between igneous (red) and sedimentary (white and grey) 270 to 240 Ma poles from West Gondwana, (A) before shallowing correction and (B) after a uniform correction of f = 0.6. The histogram in the top panel shows a lack of igneous poles for this period of time. (C) Modified 310-200 Ma APWP segment of West Gondwana including the AIS pole (original APWP was defined by Domeier *et al*. 2012). The green circles and their respective confidence error ellipses represent the mean poles recalculated

Gondwana from the compilation of Domeier *et al*. (2012). This figure shows paleomagnetic poles from 270 to 240 Ma, which are derived from the study of both sedimentary (white and grey) and volcanic rocks (red). Igneous based poles are very scarce after 270 Ma, but the available poles are more clustered than those obtained for sedimentary rocks. This contrasting behavior probably results from the processes of remanence acquisition and preservation in igneous and sedimentary rocks. Paleomagnetic poles on sedimentary rocks are vulnerable to biases caused by inclination shallowing, age uncertainties and remagnetization events (*e.g*., Biladerllo and Kodama, 2010). Several poles from South America suffer from poor radiometric dating or undersampling (preventing a complete removal of the secular variation), thus resulting in large uncertainties in their position in time and space. Some of these poles were clearly interpreted as a record of remagnetization, their age being assigned by their tectonic context and position in the apparent polar wander path (*e.g*., Font *et al*., 2012). But the most important effect contributing to the Pangea controversy seems to be the inclination shallowing of magnetic directions due to vertical compaction since most reference poles for the Carboniferous to Triassic were obtained on sedimentary units (*e.g*., Domeier *et al*., 2012). Some paleomagnetic poles on both sides of Pangea were corrected for their potential shallowing in inclination using different methods, with flattening factors varying from 1.0 to 0.5 (*e.g*., Brandt *et al*., 2009; Bilardello and Kodama, 2010). In addressing this problem, Domeier *et al*. (2012) has applied a single flattening factor of 0.6 to all Pangean sedimentary units (fig. 4B). This procedure minimized the misfit between Gondwana and Laurentia into a Pangea A configuration. Interestingly, this correction brings sedimentary poles close to the coeval igneous poles (figs. 4A and 4B), further attesting to systematic effect of inclination shallowing in the sedimentary units.

The ca. 254 Ma AIS pole falls within the igneous group, close to the the new 263 Ma Sierra Chica pole from the Colorado volcanic province of Argentina (Domeier *et al*., 2011), suggesting that the latter area is structurally coherent with Gondwana. We have then recalculated mean poles for West Gondwana for 260 Ma and 250 Ma incorporating the new AIS result using the selection criteria of Domeier *et al*. (2012). After recalculation, the cone of 95% confidence of 260 Ma and 250 Ma averages improve from 8.0° and 9.0° to 7.4° and 7.9°, respectively. In addition, the position of the new mean poles is closer to the Laurussia APWP implying a tight fit of both halves of the supercontinent into in a Pangea-A configuration (fig. 4C).

Conclusions

A systematic paleomagnetic study was carried out on the 254.7 ± 2.5 Ma melts of the Araguainha impact structure (Central Brazil), part of the stable interior of the Gondwanan supercontinent. The normal magnetization is consistent with a late Permian to early Triassic age for the impact event, given the preponderance of normal polarity magnetozones from this time period. The analysis of paleomagnetic dispersion suggests that most if not all SV was averaged out. Comparison of the Araguainha paleomagnetic pole (AIS) with igneous and sedimentary paleomagnetic poles from middle Permian to early Triassic South America reinforces the observation that sedimentary poles are biased to shallow inclinations. Restricting paleogeographic interpretations to igneous poles such as that obtained from the Araguainha melts reduces the overlap of Gondwana with Laurussia and favors a Pangea-A configuration.

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