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Amazonia in Cambrian times: reconciling discordant paleomagnetic dataset with a geocentric axial dipole?

Abbreviated title: Amazonian Craton paleogeography in Cambrian times

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Abstract: 200 words

The paleomagnetic behavior for the Ediacaran to Cambrian periods is problematic with many discordant directions, suggesting a non-uniformitarian Earth's magnetic field during the development of the first complex Life on Earth 540 million years ago. To better understand the global nature of such discrepancies, this study provides new geochronological and paleomagnetic data from the Parauapebas dyke swarm, located in the western Amazonian Craton (Carajás Province), Brazil. U-Pb on apatite and Ar-Ar whole rock ages from different dykes agreed for an emplacement of this mafic dyke swarm at ~522 Ma. Most of the sites revealed a stable characteristic remanent magnetization of $D_m = 290.6^\circ$, $I_m = -42.4^\circ$ ($N = 15$, $k = 8$, $a_{95} = 14.4^\circ$) yielding a paleomagnetic pole located at 21.8°S and 14.4°E ($K = 8.3$, $A_{95} = 14.1^\circ$) for Amazonia. The primary origin of this pole is confirmed by a positive baked contact, petrography and magnetic mineralogy experiments. Yielding a R-criteria of 6, this is the first reliable pole for Amazonia during the Cambrian. While a persistent anomalous magnetic field since the Ediacaran cannot be dismissed with the available dataset, such discrepancies could be attributed to uncertainties in global reconstructions or data-related issues. Without additional constraints, a Cambrian GAD may be considered.

KEYWORDS: AMAZONIA, CAMBRIAN, GAD, GONDWANA, PALEOGEOGRAPHY

Supplementary material: [description of material] is available at <https://doi.org/xxxx>.

The Ediacaran – Cambrian transition (~539 Ma) is a key interval in the Earth’s history marked by the sudden emergence of complex bilaterian metazoans, a time period for which the paleogeography remains highly debated ([Brasier et al. 1994](#); [Rooney et al. 2020](#)). This turning point in the life evolution is associated with an astonishingly complex paleomagnetic database, characterized by discordant paleomagnetic poles whose significance is widely disputed (see [Domeier et al. \(2023\)](#) for a review). Intriguingly, such anomalies in the paleomagnetic record persist into the Cambrian, suggesting a long-term and sustained geodynamic process. Early Cambrian true polar wander events (TPW) have often been invoked to explain these discrepancies ([Kirschvink et al. 1997](#); [Meert 1999](#); [Mitchell et al. 2015](#); [Antonio et al. 2021a](#)). TPW events imply a fast motion of the solid Earth in relation to the fixed spin axis to restore the Earth’s inertia moment following mantle reorganization ([Gold 1955](#); [Evans 1998](#); [Raub et al. 2007](#)). Despite new data in recent decades, the Cambrian TPW hypothesis remains debated due to a challenging paleomagnetic dataset ([Torsvik et al. 1998](#); [Shatsillo et al. 2020](#); [Cukjati et al. 2024](#)). Alternatively, an unusual Earth’s magnetic field was also invoked for the Ediacaran times, including a stable or transient equatorial dipole ([Abrajevitch and Van der Voo 2010](#); [Halls et al. 2015](#)), enhanced paleosecular variation ([Pierce et al. 2024](#)), and high-frequency reversal ([Bazhenov et al. 2016](#); [Meert et al. 2016](#); [Kodama 2021](#); [Levashova et al. 2021](#)). High-resolution geochronological constraints on an Ediacaran disturbed sequence have further supported the hypothesis of an anomalous Earth’s magnetic field, showing velocities incompatible with TPW events ([Robert et al. 2023](#)). In addition, such Ediacaran departure from the geocentric axial dipole (GAD) may persist to the Cambrian (<540 Ma) ([Shatsillo et al. 2020](#); [Pescarini et al. 2024b](#)), corroborated by evidence of extreme geomagnetic reversal frequency ([Gallet et al. 2019](#)). This anomalous geomagnetic field is also linked to ultra-low paleointensity values ([Bono et al. 2019](#); [Shcherbakova et al. 2020](#); [Thallner et al. 2021a](#); [Thallner et al. 2021b](#); [Lloyd et al. 2022](#); [Thallner et al. 2022](#); [Huang et al. 2024](#)), leading some authors to suggest that the Ediacaran marks the nucleation of the Earth’s inner core ([Zhou et al. 2022](#); [Li et al. 2023a](#); [Zhou et al. 2024](#)). Other explanations for Ediacaran – Cambrian discordant paleomagnetic data include pervasive remagnetization and/or tectonic processes ([Cukjati et al. 2024](#); [Pescarini et al. 2024b](#); [Pescarini et al. 2024a](#)), which underlines the paramount importance to verify the primary origin of paleomagnetic directions in order to sort out all these hypotheses. In this study, the ~535 – 507 Ma Parauapebas-Piranhas dyke swarm in Amazonia ([Santos et al. 2002](#); [Teixeira et al. 2019b](#)) is investigated to document the unusual Cambrian Earth’s magnetic field. Emplaced at the southeastern margin of the Amazonian Craton, the Parauapebas swarm provides a unique opportunity to obtain the first Cambrian paleomagnetic pole for this craton ([D’Agrella-Filho et al. 2021](#)). In addition, as the Gondwana megacontinent was assembled before the Cambrian times, this new pole will help to refine the apparent polar wander path (APWP) of Gondwana and to identify any departure from this path, which is mostly represented by data from the Rio de la Plata and Congo-São Francisco cratons ([Rapelini 2006](#); [Tohver et al. 2006](#); [Rapelini et al. 2021](#); [Pescarini et al. 2024a](#)).

Geological setting of the Parauapebas dyke swarm

The Carajás Province

The Carajás Province is located in the southeastern margin of the Amazonian Craton and is known for its concentration of world-class mineral deposits (**Fig. 1**) ([Almeida et al. 1981](#); [Hirata et al. 1982](#)). This metallogenic province is divided into two domains: the Carajás Domain to the north and the Rio Maria Domain to the south, separated by the Canaã dos Carajás shear zone, and bounded to the north by the Cinzento shear zone ([Santos 2003](#); [Vasquez et al. 2008](#)). Basement rocks in the study area, *i.e.*, the Carajás domain, comprise a complex assemblage of Palaeo- to Mesoarchean metamorphic units, ranging from ca. 3.4 to ca. 3.0 Ga ([Pidgeon et al. 2000](#); [Feio et al.](#)

2013; Moreto *et al.* 2015). The Mesoarchean units are intruded and overlain by various mafic-ultramafic layered intrusions, kilometers-thick basaltic series and associated iron formations (DOCEGEO 1988; Barros *et al.* 2004; Dreher *et al.* 2008; Barros *et al.* 2009; Barros *et al.* 2010; Moreto *et al.* 2015; Mansur and Ferreira Filho 2016; Martins *et al.* 2017; Rossignol *et al.* 2023) of the ca. 2.75 Ga Parauapebas large igneous province (Rossignol *et al.* 2022). Neoproterozoic sedimentation resumed with the deposition of the folded Igarapé Bahia Group by ca. 2.68 Ga (Rossignol *et al.* 2020). The Paleoproterozoic Era is mainly characterized by the undeformed ca. 1.88 – 1.86 Ga Uatumã silicic large igneous province, which involved the emplacement of A-type granites and numerous felsic and mafic dykes (Dall'Agnol *et al.* 2005; Silva *et al.* 2016; Antonio *et al.* 2017; Teixeira *et al.* 2019a; Teixeira *et al.* 2019b; Antonio *et al.* 2021b). The tectonically stable Carajás Province is bounded to the east by the Neoproterozoic north-south Araguaia Belt, which is part of the Brasiliano orogen (Almeida *et al.* 1976; de Freitas *et al.* 2023). At ca. 535 – 500 Ma, Cambrian mafic sills and dykes may represent late intrusions marking the final stages of the Araguaia orogenic system (Tavares *et al.* 2018; Giovanardi *et al.* 2019; Teixeira *et al.* 2019b). A younger generation of mafic dykes, dated at ~200 Ma, is associated with the large Central Atlantic Magmatic Province, underscoring the tectonic stability of the Carajás Province since the Araguaia orogeny (Gorayeb *et al.* 2013; Teixeira *et al.* 2019b).

FIGURE 1

The Parauapebas dyke swarm

K-Ar and Rb-Sr ages obtained from doleritic dykes (whole rock) ranging between 560 and 495 Ma provided the first evidence for an Ediacarian-Cambrian magmatic event in the Carajás Province (Gomes *et al.* 1975; Cordani 1981; Hirata *et al.* 1982). According to Rivalenti *et al.* (1998), these dykes are predominantly oriented N-S, geochemically classified as high-Ti basalt, and yield a Rb-Sr isochron at ~500 Ma. Using the rock collection of Rivalenti *et al.* (1998), Teixeira *et al.* (2019b) obtained a U-Pb baddeleyite age of 531 ± 1 Ma on a sample that has been collected during early reconnaissance fieldwork in the 80's and for which no precise location is available. A baddeleyite age of 507 ± 4 Ma was obtained for a dolerite dyke in Tapajós (Santos *et al.* 2002), which constrain this large magmatic event between 535 and 507 Ma. Although they both share the name of the main local town (Parauapebas; Fig. 1), there is no connection between these dykes and the ~2.7 Ga Parauapebas Formation. The early Cambrian Parauapebas dykes are medium- to fine-grained dolerites with a tholeiitic affinity (Giovanardi *et al.* 2019). Due to challenging outcrop conditions (Fig. 2a, b), it remains difficult to estimate the widths and trends of some dykes. In field outcrops, margins are not exposed, and the outcrops are mostly represented by clusters of mafic blocks, making it difficult to determine whether they are *in situ*. In addition, open pit outcrops were investigated, where the margins of the sampled dykes are visible. These include a 0.6-1 m width dyke crosscutting the Central do Carajás granite (Fig. 2c) and a 30 m width vertical Salobo dyke (Fig. 2d).

FIGURE 2

Methodology

Sampling and petrography

Most of the sites sampled for paleomagnetism are located between the towns of Parauapebas and Curionópolis, where it was possible to obtain access authorizations for private properties. Two *in situ* dykes were sampled in restricted areas (SA01 and GC01). Standard paleomagnetic oriented cores (diameter of ~2.54 cm) were collected by a Pomeroy Model 261 portable gasoline-powered drill and oriented by using a Brunton compass inside a Pomeroy orienting fixture. The cores were oriented by using magnetic and solar compasses. The use of solar compass is essential in this area, where the compass can be easily deflected (frequent lightning strikes and/or high-magnetic rocks).

The 10 hand-blocks collected in the mine pits (5 blocks for SA01 and 5 blocks for GC01) were also oriented with a solar compass. Although the Archean host rock of the Salobo dyke in the mine pit is a banded iron formation ([deMelo et al. 2017](#)), no difference ($< 5^\circ$) was observed between the solar and magnetic compasses. This guarantees that these hand-blocks were properly oriented to perform a robust baked contact test: 3 blocks were collected from the Salobo dyke (2 at the center - 1 at the margin), and two blocks in the host rock (1 at contact with the dyke - 1 far away at $\sim 14\text{m}$). Additional baked contact tests were attempted to sites PC08 and PC33 when the host rock was visible but not necessarily the contact.

Petrographic investigations were carried out using classical optical microscopy (transmitted and reflected light) complemented by scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDS) to characterize specific mineral phases using a JEOL JSM 7100F TTLS LV scanning electron microscope at Centre de microcaractérisation Raimond Castaing, Toulouse. Investigated samples are composed of plagioclase, clinopyroxene (\pm altered), and rare amphiboles. Primary inclusions of apatite, Fe-Ti oxides, and some iron sulfides are present. Sphalerite, baddeleyite, and zircon, are also present as accessory minerals.

Geochronology

Three sites sampled for paleomagnetism were selected for geochronological investigations: (i) the Salobo dyke in the mine pit (SA01), which was previously dated at 561 ± 16 Ma using Rb-Sr isochron ([Cordani 1981](#)), (ii) The PC18 dyke, and (iii) the PC13 dyke (**Fig. 1**). Samples PC13 and PC18 have been dated by U-Pb on apatite. Apatite grains were extracted following a classical mineral separation procedure at Géosciences Environnement Toulouse, France, before analysis by Laser Ablation – Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS), using a ThermoScientific Neptune Plus Multicollector (LA-MC-ICP-MS) linked to a HeEX 193 nm wavelength laser source, using the facilities of the Applied Isotope Research Group, Ouro Preto, Brazil. Detailed results and analytical set-up are given in **supplementary material S1 and S2**, respectively. Age were calculated by unanchored regressions ([Apen et al. \(2024\)](#) with IsoplotR ([Vermeesch 2018](#)). Sample SA01 has been dated using whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. The sample was irradiated by epithermal fast neutron flow in the TRIGA research reactor (CLICIT) of OSU/Oregon, USA, for 14 hours, together with the Fish Canyon sanidine (28.01 ± 0.04 Ma; ([Phillips and Matchan 2013](#))). After a cooling period of approximately 40 days, the samples were analyzed by step heating using a Nd:YVO₄ solid state laser (532 nm - model Verdi 6W Coherent) at the Laboratory of Thermochronology of the Center for Geochronological Research, University of São Paulo, Brazil, following the procedure detailed in [Vasconcelos et al. \(2002\)](#). The laser extraction system is coupled to a purification system equipped with SAES-GP50 getters and an ARGUS VI multi-collector mass spectrometer. Results and detailed analytical set-up are given in **supplementary material S3 and S4**, respectively. Plateau age includes at least 70% of $^{39}\text{Ar}_K$ and the maximum number of contiguous steps with $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio consistent with each other at a 95% confidence level ([McDougall and Harrison 1999](#)). Raw data were processed using ArArCALC software ([Koppers 2002](#)). Uncertainties on both apatite U-Pb and Ar-Ar plateau ages are quoted at the 95% confidence level.

Paleomagnetic directions and Rock magnetism

Standard specimens (height/diameter: 2.2/2.5 cm) were prepared and cut from the oriented cores and blocks at the Instituto de Astronomia, Geofísica e Ciências Atmosféricas, University of São Paulo (IAG-USP, USPMag, Brazil). A characteristic remanent magnetization (ChRM) was revealed by

standard stepwise alternating field (AF) and thermal demagnetizations. For AF, the following steps were used: 2.5 mT until 20 mT, 5 mT until 50 mT and 10 mT to complete demagnetization. Steps of 50°C were used to 500°C and 20°C to 600°C by using an ASC TD48SC thermal demagnetizer. For specimens carrying a strong natural remanent magnetization (NRM > 10 A/m), an AGICO JR6-A spinner was used combined to an AGICO LDA5 AF demagnetizer. Otherwise, a vertical 2G RAPID DC-SQUID superconducting rock magnetometer ([Kirschvink et al. 2008](#)) was used by cutting the specimens into two pieces. To reduce interferences with the ambient Earth's magnetic field, the USPMag shielded room yields an internal magnetic field lower than 1000 nT. Principal component analysis (PCA) ([Kirschvink 1980](#)) and great circle analysis ([Halls 1978](#)) were used to determine the magnetic components by using orthogonal vector ([Zijderveld 1967](#)) and/or equal-area diagrams. Site mean directions and paleopoles were calculated with [Fisher \(1953\)](#)'s statistics in PALEOMAC ([Cogné 2003](#)), and GPlates was used for paleogeographic reconstructions ([Müller et al. 2018](#)). Rock magnetism was investigated with the acquisition of hysteresis and isothermal remanent magnetizations curves by using a Princeton/Lake Shore MicroMag model 3900 VSM system at Instituto Oceanográfico (IO-USP, Brazil). Thermomagnetic curves (magnetic susceptibility *versus* temperature) were performed at Géosciences Environnement Toulouse (France) in an argon atmosphere by using an AGICO KLY3-CS3 apparatus.

Geochronological results

Apatite grains from sample PC13 are euhedral and range in size from a few tens to a few hundreds of micrometers. Data obtained from 47 grains define a linear array with an unforced lower intercept date of 522 ± 57 Ma (MSWD = 0.6) and an initial $^{207}\text{Pb}/^{206}\text{Pb}$ (hereafter $(^{207}\text{Pb}/^{206}\text{Pb})_0$) of 0.848 ± 0.028 ; **Fig. 3a**). This date is interpreted as the emplacement age of the dyke. Similarly to sample PC13, apatite grains from sample PC18 are euhedral and range in size from a few tens to sixty micrometers. The unforced lower intercept calculated for 14 apatite analyses yield a 521.5 ± 5.1 Ma date ($(^{207}\text{Pb}/^{206}\text{Pb})_0 = 0.795 \pm 0.016$; MSWD = 2.4; **Fig. 3a**). This date is interpreted as the emplacement age of the dyke. Sample SA01 yielded a plateau age defined by 74% of the released ^{39}Ar of 521.5 ± 5.0 Ma (MSWD = 3; **Fig. 3b**). This plateau age is concordant within error with an inverse isochron age of 521.7 ± 5.2 Ma with a $^{40}\text{Ar}/^{36}\text{Ar}$ intercept of 297.9 ± 4.5 Ma (MSWD = 3.3) and is interpreted as the emplacement age of the dyke. Together, apatite U-Pb and Ar-Ar plateau ages consistently point towards an emplacement age of ca. 522 Ma (early Cambrian) for the Parauapebas dykes.

FIGURE 3

Rock magnetism

In the Day's plot for the magnetite, all the samples from dykes fall inside the pseudo-single (PSD)-to single (SD) domains ([Day et al. 1977](#); [Dunlop 2002](#)) (**Fig. 4a**). Dominance of PSD/vortex state is usual for such lithology. Most of the samples present a hysteresis curve with a narrow-waisted behavior typical of SD-PSD titanomagnetite (**Fig. 4b**). The ferromagnetic signal dominates for the stronger samples but a paramagnetic signal is visible on some samples (*e.g.*, PC08A1). Coercivity values range from 3.4 mT (PC13) to 27.3 mT (PC08A1) and were obtained by using the HystLab software package ([Paterson et al. 2018](#)). Isothermal remanent magnetization curves reveal a saturation at applied field less than 200 mT and usually one major component dominates the IRM unmixing ([Maxbauer et al. 2016](#)) (**Fig. 4c**). Thermomagnetic curve for the PC13 dyke is reversible and shows a slight drop between 300 and 350°C that may represent the presence of pyrrhotite in this sample (**Fig. 4d**). In addition a narrow Hopkinson peak is well-defined between 565 and 575°C and followed by a steep decay in magnetic susceptibility, giving the typical Curie temperature interval of the magnetite ([Petrovský and Kapička 2006](#)). Large magnetite grains (> 100 µm) with ilmenite exsolution are observed in the Parauapebas doleritic dykes with variable degree of alteration (**Fig. 4e, f**). Different types of sulfides are usually associated with as sphalerite or

pyrrhotite. The rock magnetic mineralogy shows that the main magnetic carriers for the Parauapebas dykes are reliable SD to PSD magnetite. The selected host rock samples for rock magnetism (mainly from the Estrela gneiss or associated amphibolite) are unstable or dominated by a paramagnetic assemblage (**Supplementary Figure S5**). Therefore, it is expected that the attempt baked contact tests will be challenging and mainly inconclusive to obtain a stable remanent magnetization far away from the dyke.

FIGURE 4

Paleomagnetic results

Normal and anomalous remanence

The paleomagnetic directions were divided into two groups: “normal” and “anomalous” directions. This classification is based on the results obtained from contact tests (see below) and the fact that it is difficult to interpret the origin of anomalous directions. Most of dykes (15 sites) belong to the “normal” group. Two polarities were observed in this dataset. The characteristic remanent magnetization (ChRM) of the cluster with negative inclination show a northwestern to western direction with moderate inclination ranging from -64.2° to -27.3° (**Fig. 5a, b**). ChRM of the cluster with positive inclination show a southeastern to eastern direction with moderate inclination ranging from 61.6° to 9.9° (**Fig. 5c, d**). After the removal of a secondary direction, the high-temperature component is carried by magnetite with blocking below 600°C (**Fig. 5a, d**). Alternating field (AF) demagnetizations show that this ChRM is carried by a coercivity greater than 20 mT (**Fig. 5b, c**). Some dykes contain a strong contribution of pyrrhotite that can show the same direction of magnetite (**Fig. 5d**).

FIGURE 5

Six sites were classified as “anomalous” directions. ChRMs of the anomalous directions can be a southeastern direction with steep negative inclination as for the PC13 dyke (**Fig. 6a**). Thermal demagnetizations show that such ChRM is carried by magnetite. In addition, anomalous directions also include ChRM with eastern direction associated to a low negative inclination (**Fig. 6b, c**) and ChRM with western direction associated to a low positive inclination (**Fig. 6d**). In these examples, such ChRM is carried by magnetite as showed by thermal demagnetizations. it should be noted that it is possible to observe both normal and anomalous directions within the same dyke, it is the case for the well-dated PC18 dyke where both directions were revealed at different locations (**Fig. 6d**).

FIGURE 6

The Parauapebas paleomagnetic pole was calculated by using the “normal” directions. The ChRM site-mean direction of 15 sites is $D_m = 290.6^\circ$, $I_m = -42.4^\circ$ ($k = 8$, $a_{95} = 14.4^\circ$) yielding a paleomagnetic pole located at 21.8°S and 14.4°E ($K = 8.3$, $A_{95} = 14.1^\circ$) (**Fig. 7a, Table 1**). The estimated paleolatitude places Amazonia at 24.5° . All the virtual geomagnetic poles pass a fixed cutoff of 45° , or a Vandamme cutoff of 42.3° ([Vandamme 1994](#)). Albeit at the upper limit, the A_{95} of 14.1° is comprised within the [Deenen et al. \(2011\)](#)'s envelope (4.1° - 14.9°). These results show a S value of 28.5, which is clearly higher than expected at such latitude. The 8 sites with negative inclination have a site-mean direction of $D_m = 296.2^\circ$, $I_m = -37.8^\circ$ ($k = 7.1$, $a_{95} = 22.3^\circ$) and the 7 with positive inclination have a site-mean direction of $D_m = 103.3^\circ$, $I_m = -47.1^\circ$ ($k = 9$, $a_{95} = 21.3^\circ$). While the [McFadden and McElhinny \(1990\)](#)'s reversal test is classified as indetermined, this paleomagnetic dataset shares a common true mean direction test ([Tauxe 2010](#)). No paleomagnetic

pole was calculated by using the anomalous directions as the primary nature of these directions cannot be assessed (**Fig. 7b, Table 1**).

FIGURE 7 **Table 1**

Baked contact tests

The first attempts of baked contact tests at PC08 and PC33 sites were negative (**Supplementary Figures S6 and S7**). For both PC08 and PC33 sites, the margins of the dykes are not visible, so contact distances can only be approximate. At PC08, the width of the dyke, which is intrusive into the ~2.7 Ga Estrela gneiss, is estimated at around 15m. Two outcrops has been investigated and appeared to be *in situ* as they have the same NS-trending foliation: the cores J and K were sampled close to the dyke's margin (<2m) and the cores K and M were sampled far away (>25 m) (**S6**). The southwestern direction with positive steep inclination obtained for samples J and K turns out to be quite different from the dyke's ChRM. Far away from the contact, the cores K and L show a northern direction with positive low inclination. While the direction of the host rock at contact is different from that of the dyke, the far away's direction is similar to the direction considered as "anomalous" for the PC08 dyke (GHI core samples). This could suggest that this anomalous direction observed in different sites (PC08, PC18, **Fig. 7b**) is not a spurious direction but a later remagnetization. The origin of the host rock's direction at contact is not known. The ChRM of the Estrela host rock is characterized by a significant contribution of pyrrhotite with a blocking temperature around ~320°C. Although this test is negative, such mineralogy is not favorable for obtaining primary magnetizations. At site PC33, it is impossible to estimate the width of the dyke (**S7**). The only *in situ* outcrop was at the side of an untarred road, where a northwestern direction with negative inclination component has been obtained. At this site, the host rock consists of a layer of amphibolite perpendicular to the dyke and the Estrela gneiss. These two lithologies show totally random directions and different magnetic mineralogy (pyrrhotite for the amphibolite, and magnetite for Estrela). The direction of the dyke is not characterized in this magnetically unstable Archean rock, making this baked contact test negative.

The Salobo open pit mine (SA01) gave the best results for such baked contact tests in this challenging area (**Fig. 8**). For the dyke, the ChRM is well-preserved in the hand samples at the middle of the dyke (SA01/02). At margin, however, the obtained eastern direction with negative inclination is considered as spurious because it does not appear stable in the Zijderveld diagram. This interpretation is corroborated by the fact that the host rock at contact (SA04 hand sample) has the same direction than the one observed at the middle of the dyke. Therefore, it seems that the host rock at contact was baked during the dyke's intrusion. This host rock is a banded iron formation whose ChRM is carried by magnetite. While the magnetic mineralogy is similar at the hand-sample SA05 at ~14m from the dyke's margin, the magnetization clearly changed for an eastern direction with a steep positive inclination. Therefore, this positive baked contact test (although based on only one hand-sample far from contact) supports the idea that the normal direction is of primary origin and dated at ~522 Ma, the Ar-Ar age of this dyke (**Fig. 8**).

FIGURE 8

Discussion

A new robust pole at 522 Ma for Amazonia

The Parauapebas paleomagnetic pole, calculated using 15 sites of doleritic dykes, fulfills 6 quality criteria defined by [Meert et al. \(2020\)](#). (R1) The age of the Parauapebas pole is newly constrained by a multimethod approach with an error below 15 Ma for two dykes ([Meert et al. 2020](#)). The two dated dykes gave a ~522 Ma age, with an U-Pb apatite age of 521.5 ± 5.1 Ma for the PC18 dyke, and a whole rock Ar-Ar plateau age of 521.5 ± 5.0 Ma for the SA01 dyke. (R2) The ChRM were isolated by alternating field and thermal demagnetizations and calculated by using principal component and great circle analysis ([Halls 1978](#); [Kirschvink 1980](#)). 15 sites were used and the site-mean direction yielded a precision parameter K-value of 8.3 and an A95 of 14.1° (**Table 1**). Such K-value is below to the arbitrary threshold of 10 proposed by [Meert et al. \(2020\)](#) but our study suggests averaged secular variations based on the [Deenen et al. \(2011\)](#)'s statistical model (A95min: $4.1^\circ < A95: 14.1^\circ < A95max: 14.9^\circ$). However, this R2-criterion must be looked at carefully, as the characteristics of the Ediacaran–Cambrian Earth's magnetic field may not be known. (R3) The magnetic mineralogy (hysteresis curves, isothermal remanent magnetization curves, and thermomagnetic curves) for the Parauapebas dykes show that the main carrier is a SD-PSD magnetite (**Fig. 4a**). Presence of magnetite is confirmed by using microscopic investigations (**Fig. 4e, f**). Future work should include First-Order-Reversal-Curve ([Roberts et al. 2000](#)) to precise the Parauapebas magnetic mineralogy. (R4) The baked contact test performed at the Salobo open pit mine shows similar directions between the dyke and the baked zone. The direction carried by the host rock far away (~14m) from the dyke is only constrained by one hand-sample but such direction seems stable and well-defined. Therefore, this baked contact test is considered as positive (R4_{C+}). To be more precise, it would be interesting to complete this test to assess the stability and the origin of this magnetization in this iron banded formation at different locations in the mine. (R5) The Parauapebas dykes are located in an area considered as stable at the southeastern margin from Amazonia. These mafic dykes intruded the cratonic area of the Carajás Province during the end of the Araguaia orogeny ([Tavares et al. 2018](#)). No younger tectonic events are documented in this area, only the intrusion of Jurassic dolerite dykes dated at ~200 Ma ([Teixeira et al. 2019b](#)). (R6) Two antipodal directions were obtained from the Parauapebas dykes with 8 sites showing negative inclinations and 7 sites positive inclinations. These two clusters pass a common mean direction test ([Tauxe 2010](#)). (R7) The Parauapebas pole is not overlapping the Global apparent polar wander path for Gondwana between 550 and 200 Ma proposed by [Torsvik et al. \(2012\)](#). In addition, the obtained directions are different from the direction obtained for the ~200 Ma Jurassic dykes during the emplacement of the Central Atlantic Magmatic Province in Amazonia ([Nomade et al. 2000](#); [Antonio et al. 2021b](#); [Moreira et al. 2023](#)), the most relevant event that took place in the area. In summary, the ~522 Ma Parauapebas paleomagnetic pole, located at 21.8°S and 14.4°E ($K = 8.3$, $A95 = 14.1^\circ$), fulfills 6 of the 7 R-criteria. This paleopole does not pass the R2 criterion because $K < 10$. Nevertheless, it can be considered as a robust pole to define Amazonia during the Cambrian.

A Cambrian discordant paleomagnetic dataset for the Gondwana

The assembly of Western Gondwana is still a matter of debate and involves at least nine craton blocks (Amazonia, West Africa, Sahara, Congo, Kalahari, São Francisco, Paranapanema, Rio de la Plata, et Pampia) (**Fig. 9a**) ([Schmitt et al. 2018](#); [Schmitt et al. 2023](#)). It is widely accepted that most of the orogens show a major activity before 540 Ma although some orogenic-systems may have been tectonically active until ~500 Ma ([Schmitt et al. 2023](#)). Most of paleogeographic models agree that all these cratons were closed and/or already consolidated between ~540 and 500 Ma ([Torsvik and Cocks 2013](#); [Merdith et al. 2021](#); [Li et al. 2023b](#); [Murphy et al. 2024](#); [Wu et al. 2024](#)). Nevertheless, with the lack of robust paleomagnetic data numerous alternative reconstructions have been proposed to explain the relationship between Gondwanan cratons and the Laurentia before 550 Ma ([Robert et al. 2021](#)). Within South America, two contrasting views were proposed for the kinematics amalgamation of Amazonia: a first model proposes that Amazonia was isolated

from the Western Gondwana by the Clymene ocean until a Cambrian assembly at ~530 – 520 Ma ([Trindade et al. 2006](#); [Tohver et al. 2010](#); [Tohver et al. 2012](#); [Tohver and Trindade 2014](#)). This model is supported by recent detrital zircon provenance study from the Paraguay Belt ([Leite et al. 2024](#)), a series of magmatic and metamorphic ages from the Araguaia and Paraguay Belts ([Moura et al. 2008](#); [Godoy et al. 2010](#); [Gorayeb et al. 2013](#); [Leite et al. 2021](#)), and geophysical signatures ([Assumpção and Sacek 2013](#)). Alternatively, a second model proposes that Amazonia was already joined to the São Francisco craton at ~600 Ma, before the Cambrian, by the closure of the Goiás-Pharusian Ocean ([Cordani et al. 2009](#); [Cordani et al. 2013](#); [Ganade de Araujo et al. 2014](#)). Unfortunately, the paleomagnetic database for Amazonia between ~550 and 520 Ma is sparse and mainly constrained by (i) remagnetized carbonates from the Araras Group (Puga B carbonate with a poorly constrained age, **estimated at ca. XXX Ma**) ([Trindade et al. 2003](#); [Font et al. 2006](#); [Donardelli Bellon 2024](#)), and (ii) the new ~522 Ma Parauapabas pole calculated from a mafic dyke swarm (this study). Regardless the paleogeographic model, we should expect that the main paleopoles for the South American craton are concordant or closed at the end of Brasiliano orogeny between 540 and 500 Ma, following a tight-fit reconstruction ([Reeves et al. 2004](#)). Among the available paleomagnetic poles, five poles fulfil R-criteria over 5 indicating that they are robust enough to be used in paleomagnetic reconstructions (**Fig. 9b, Table 2**). The Monteiro pole (SF1, R = 7), from the Borborema Province, is dated at 538 ± 4 Ma by U-Pb zircon and passes a positive baked contact tests ([Antonio et al. 2021a](#)). The Itabaiana pole (SF2, R = 7) is considered as a key pole for the Borborema Province and dated at 525 ± 5 Ma by Ar-Ar whole rock and its primary origin is supported by a positive baked contact test ([Trindade et al. 2006](#)). The Parauapebas pole (AM1, R = 6) from Amazonia, which is well-dated by U-Pb apatite and Ar-Ar whole rock, passes a positive baked contact test (this study). The Campanario Formation (PA1, R = 7) from the Pampia terrane, obtained on sedimentary rocks ([Franceschinis et al. 2020](#)). This pole passes a positive fold test and has a maximum depositional age of 519 ± 5 Ma (U-Pb on detrital zircon). A new robust pole (SF7, R = 7) was obtained from the Araçuaí orogen (south São Francisco craton) on the Santa Angelica and Venda Nova post-collisional plutons ([Temporim et al. 2021](#)). These plutons were emplaced between 506 ± 3 Ma and 498 ± 5 Ma (U-Pb on zircon) and even if there is no positive contact test, the primary character is supported by thermal modelling and this pole matches with the global apparent polar wander path from Gondwana ([Torsvik et al. 2012](#)). The last reference pole for South America at ~480 Ma added to this database is the La Pedrera Formation (PA2, R = 6), which was obtained far away from area with tectonic rotations ([Rodriguez Picada et al. 2018](#)). Most of the different paleomagnetic poles for Africa between 535 and 482 Ma are well-clustered with the exception of the anomalous ~507 Ma Sidi-Said Maachou volcanics (WA2, R = 6), while passing a positive contact test ([Khattach et al. 1995](#)) (**Fig. 9c**). Unfortunately, while the poles from the Pan-African Belts are well-dated, most of them are from metamorphic units and do not pass the R4-criteria to support a primary origin. For the Australia and East-Antarctica blocks (**Fig. 9d**), the Cambrian dataset is well-clustered but three poles are distant with the Lower Arumbera sandstone pole (A1, R = 7), the Upper Arumbera sandstone pole (A2, R = 7), and the Todd River Dolomite pole (A4, R = 6) ([Kirschvink 1978](#)). These are precisely the poles that have field tests to show that they are of primary origin ([Kirschvink 1978](#)). From this Cambrian (~550 – 500 Ma) paleomagnetic dataset for Gondwana (**Fig. 9, Table 2**), it is obvious that many poles seem to be discordant at the end of the assembly of Gondwana, especially the five robust paleomagnetic poles (R >5) for South America (**Fig.9b**).

FIGURE 9

Table 2

Departures from a geocentric axial dipole (GAD) in Cambrian?

Recent studies suggest that during the Ediacaran the geomagnetic field exhibited anomalous behaviour, including an extraordinarily high frequency of polarity reversals, high secular variation, and ultralow dipole field strength ([Shatsillo et al. 2020](#); [Domeier et al. 2023](#); [Robert et al. 2023](#)). In particular, scenarios have been proposed in which the geodynamo could deviate from a purely geocentric axial dipole (GAD) structure ([Abrajevitch and Van der Voo 2010](#)). These findings raise the question of whether similar irregularities could have persisted into the Cambrian. To explore non-GAD zonal contributions to the Cambrian geomagnetic field, a dataset from Gondwana has been compiled and incremented with the new data obtained for the Parauapebas Dyke Swarm (**Fig. 9, Table 2**). At this time (approximately 550 – 500 Ma), the Gondwana megacontinent extended from the South Pole to the equator, making it possible to assess the long-term non-dipolar contribution of the Earth’s magnetic field and test the GAD model via the ‘single-plate test’ ([Bazhenov and Shatsillo 2010](#)) (**Fig. 10a**). The broad latitudinal coverage is advantageous because, in principle, it can detect systematic deviations from expected inclinations if non-dipole zonal components are significant. Despite uncertainties regarding the rigidity of East and West Gondwana, a robust statistical approach can still be employed by carefully accounting for potential outliers and uncertainties in paleomagnetic data. Computing the true dipole pole (TDP) was performed by incorporating error through a nonparametric, bootstrapping procedure ([Gallo et al. 2017](#); [Gallo et al. 2018](#)). This involves leave-one-out resampling to address the possibility that some data points may represent tectonically deformed blocks or other sources of error. The resulting TDP and its 95% confidence region (**Fig. 10a**) form the basis for calculating the inclination at each site under a 100% dipolar field. By comparing observed inclinations with these idealized GAD predictions, a quantity $\Delta I = I_{\text{obs}} - I_{\text{dip}}$ is obtained for each site, where I_{obs} is the observed inclination and I_{dip} is the expected inclination for a pure GAD field. To quantify the potential influence of non-dipolar zonal terms, the intensity of the axial quadrupole ($G2 = \frac{g_2^0}{g_0^0}$) and octupole ($G3 = \frac{g_3^0}{g_0^0}$) coefficients is estimated by minimizing the sum of squared residuals between the observed data and the theoretical curve of a pure GAD field (**Fig. 10b**). A nonlinear conjugate gradient algorithm has been used to solve this optimization problem. In a purely GAD, both $G2$ and $G3$ would approach zero, and the dataset would lie exactly on the GAD reference curve (blue line in **Fig. 10b**).

Applying this method to the Cambrian dataset gives best-fit values of $G2 = -0.05$ and $G3 = 0.20$. While the small, negative $G2$ value might indicate a modest quadrupole contribution, the large positive $G3$ value suggests a substantial octupolar term, though this result must be interpreted with caution given the inherent uncertainties in the data. Interpreting paleomagnetic results from the Cambrian poses several challenges. Potential issues include incomplete sampling site coverage, limited age constraints, inclination shallowing, and tectonic complexities. Consequently, even if a non-GAD signal were present, it might be obscured by these uncertainties. Nonetheless, despite these uncertainties, the non-GAD signal inferred from the Cambrian dataset contrast with the Carboniferous-Permian, for which data from widely distributed regions of Pangea support a GAD model as a first-order approximation (Gallo et al., 2017). However, uncertainties in inclination measurements often exceed the magnitude of any potential departures, making it challenging to detect small non-GAD components ([Bazhenov and Shatsillo 2010](#)). Additionally, Gondwana is confined to a single hemisphere, so the lack of symmetric data coverage further complicates an unambiguous assessment of non-dipolar contributions.

Taken together, the results from the Cambrian dataset remain inconclusive. Several explanations could account for any observed scatter or systematic deviation from GAD predictions:

- Non-zonal field contributions: If Gondwana behaved as a rigid plate from the early Cambrian onwards, the anomalous behaviour might reflect significant higher-order non-zonal terms or temporal variability of the geodynamo.

- Uncertain Gondwana reconstruction: The geometry and timing of amalgamation between East and West Gondwana remain debated ([Robert et al. 2021](#)). Potential misalignments could scatter the paleomagnetic poles and generate apparent deviations from GAD.
- Under-averaged palaeosecular variations in paleomagnetic poles: this could partly explain the dispersion observed in paleomagnetic poles ([Vaes et al. 2022](#)). In particular, if palaeosecular variation during the early Cambrian was extremely high, it would likely lead to significant deviations from the expected poles. This could explain the low K-value obtained for the Parauapebas pole.

In summary, while Cambrian paleomagnetic data offer an opportunity to test for potential departures from a GAD field structure, additional constraints on plate reconstructions and more thorough temporal averaging are essential. These factors will help reduce uncertainties and yield clearer insights into the dynamical behavior of the Cambrian geodynamo.

FIGURE 10

Conclusions

This study reports a new paleomagnetic pole from the Cambrian Parauapebas dyke swarm in Amazonia at 21.8°S and 14.4°E (A95 = 14.1°). Two ages for two dolerite dykes constrain the remanence acquisition at ~522 Ma by using a multimethod approach (U-Pb on apatite: 521.5 ± 5.1 Ma, Ar-Ar whole rock: 521.5 ± 5.0 Ma). Magnetic mineralogy, petrography, and a positive baked contact test suggest that the remanence of the Parauapebas pole is carried by a stable SD-PSD magnetite and primary. This pole fulfills 6 of the R-criteria ([Meert et al. 2020](#)), thus, it can be considered as the first reliable paleomagnetic pole for Amazonian during the Cambrian. The sparse paleomagnetic dataset during the Cambrian for Gondwanan poles is discordant. This study shows that a persistent anomalous magnetic field since the Ediacaran cannot be ruled out. However, the uncertainties in paleogeographic reconstructions or under-averaged palaeosecular variations could also explain such discrepancies, showing the importance of obtaining new quality data for the Cambrian to accurately track any departure from a geocentric axial dipole.

Tables

Table 1: S.lat – site latitude, S.lon site longitude, n/N – number of samples used in the mean site / analyzed samples.; Dec(°) – declination; Inc(°) – inclination, r, k, a95 (and R, K, A95) – Fisher’s resultant vector, and precision parameter and confidence cone for mean direction (and paleomagnetic pole). VGP – Virtual Geomagnetic Pole, P. Lat – Paleolatitude and P. Long – Paleolongitude. Distance from dyke’s margin is indicated for host rocks collected.

Table 2: Paleomagnetic database for the Gondwana between ~550 and 483 Ma. S.lat – site latitude, S.lon – site longitude, Dec – declination, Inc – inclination, k – parameter precision, a95 – confidence of mean direction, A95 – confidence of pole, Plat (°N) – pole latitude, Plong (°E) – pole longitude, Paleolat – paleolatitude. Nominal age attributed to the pole (**Fig. 9**). R-criteria according to [Meert et al. \(2020\)](#).

Figure captions

Fig. 1. (a) Inset map for South America showing the study area. (b) Geological map of the sampling area in the Carajás Province, modified from [Vasquez et al. \(2008\)](#). Sampling sites are indicated as a green square and the dated sites with a yellow star.

Fig. 2. Field photographs of (a) dyke PC18 (b) dyke PC34, (c) dyke GC01, and (d) dyke SA01. It should be noted that outcrop conditions in the Carajás area are challenging for paleomagnetic study, with the exception of outcrops in mines (*e.g.*, at the Salobo mine pit).

Fig. 3. (a) U-Pb Terra-Wasserburg diagrams for apatite dating of two Parauapebas dykes (PC18 and PC13 dykes). Quoted dates are unanchored. **(b)** Apparent ages (Ma) as a function of cumulative ^{39}Ar released for whole rock (SA01 dyke).

Fig. 4. (a) Day's plot of Mrs/Ms versus Hcr/Hc ([Day et al. 1977](#)) for the doleritic samples of Parauapebas dykes Mrs/Ms: ratio of remanent saturation magnetization to saturation magnetization. Hcr/Hc: ratio of coercivity of remanence to coercivity. SD: single-domain, PSD: pseudo-single domain, MD: multi-domain. **(b)** Hysteresis curves of PC36D1A and PC08A1. **(c)** Isothermal remanent curve of PC36D1A and associated unmixing performed by MAX UnMix ([Maxbauer et al. 2016](#)). **(d)** Reversible thermomagnetic curve for the PC13 dyke. Petrography: SEM-BSE micrographs of **(e)** PC18 and **(f)** PC36 showing large titanomagnetite. *Mineral abbreviations from [Whitney and Evans \(2010\)](#)*: Cpx (clinopyroxene), Pl (plagioclase), Ap (apatite), Mag (magnetite), Ilm (ilmenite), Sp (spharelite), Po (pyrrhotite).

Fig. 5. Representative examples of alternating field and thermal demagnetizations from four sites of the Parauapebas dykes with normal remanences: **(a)** SA02C2A, **(b)** PC36B3. **(c)** PC14OB1E2B. **(d)** PC08C1A. Figure shows the equal area (open/filled symbols for positive/negative inclination respectively), the orthogonal Zijderveld projections and the magnetization intensity decay (M/Mmax) diagrams. Vertical and horizontal projections are shown by open/filled circles in the Zijderveld plots. NRM = Natural Remanent Magnetization.

Fig. 6. Representative examples of alternating field and thermal demagnetizations from four sites of the Parauapebas dykes with "anomalous" remanences: **(a)** PC13-A1A, **(b)** PC30-B1. **(c)** PC34-C1A. **(d)** PC18-A1A. Symbols same as in **Fig. 5**.

Fig. 7. (a) Equal-area projection showing mean site directions and α_{95} errors for the sites with normal remanences. **(b)** Equal-area projection showing mean site directions and α_{95} errors for the sites with anomalous remanences. Sites with ages calculated in this study are indicated. See **Table 1** for individual results.

Fig. 8. (a) Field photograph of the ~30 m Salobo dyke (in green) with relative position of the collected hand-samples used for this baked contact test. Five specimens are illustrated, at the middle to the dyke at the margin within the dyke, the host rock at contact within the baked zone (alternating field and thermal demagnetizations), and the host rock far away (~14 m from the dyke). Equal-area projections, orthogonal vector diagrams, and M/Max intensity decay curves are illustrated.

Fig. 9. (a) Main cratons with paleomagnetic poles for the Gondwana in a tight-fit reconstruction (Africa fixed) ([Reeves et al. 2004](#)). Paleomagnetic poles available between ~550 and 483 Ma for **(b)** the cratons from South America between, **(c)** the cratons from Africa, and **(d)** from the Antarctica and Australia continents. R-criteria ([Meert et al. 2020](#)) is indicated if ≥ 5 . *Abbreviations used for cratons and associated paleomagnetic poles: AM – Amazonia (blue), WA – West Africa (red), SF – São Francisco (brown), Pa – Pampia (light green), RP – Rio de la Plata (light green), MA – Madagascar (yellow), AN – Antarctica (blue), A – Australia (purple), and P – Pan-African Belts (grey) which includes the Maieberg Fm in south Congo (C).*

Fig. 10. Single-plate test of the geocentric axial dipole model. **(a)** Intersection of the computed site sampling (in blue) – paleomagnetic poles (in red) great circles for the ~550 – 483 Ma dataset to calculate the true dipole pole (TDP). **(b)** Plot of the difference between the observed inclination ($^{\circ}$) and the latitude. The curve in blue is the inclination expected from GAD ($G_2 = 0$, $G_3 = 0$), and the curve in red a non-GAD behavior ($G_2 = -0.05$, $G_3 = 0.20$). G_2 and G_3 are the axial and octupole terms.

Supplementary Table S1. U–Pb apatite isotope data.

Supplementary Table S2. Analytical conditions for apatite LA-ICP-MS dating.

Supplementary Table S3. Ar-Ar results from SA01 dyke

Supplementary Table S4. Analytical conditions for Ar-Ar dating.

Supplementary Figure S5. Rock magnetism of Archean rocks. (a) Hysteresis curve for the PC31Q-h Estrela gneiss. (b) Hysteresis curve for the PC31L-h Estrela gneiss. (c) Day's plot for some Archean Host rocks sampled for baked contact tests ([Day et al. 1977](#)).

Supplementary Figure S6. Attempted baked contact test at PC08 site.

Supplementary Figure S7. Attempted baked contact test at PC33 site, which included the PC31 and PC32 sites (host rocks).

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Author contributions This is generated from information entered during submission

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Data availability Authors are asked to provide a statement as part of the submission process.

References

- Abrajevitch, A. and Van der Voo, R. 2010. Incompatible Ediacaran paleomagnetic directions suggest an equatorial geomagnetic dipole hypothesis. *Earth and Planetary Science Letters*, **293**, 164-170, <https://doi.org/http://dx.doi.org/10.1016/j.epsl.2010.02.038>.
- Almeida, F.F.M., Hasui, Y., Neves, B.B.D. and Fuck, R.A. 1981. Brazilian Structural Provinces: An Introduction. *Earth-Science Reviews*, **17**, 1-29, [https://doi.org/10.1016/0012-8252\(81\)90003-9](https://doi.org/10.1016/0012-8252(81)90003-9).
- Almeida, F.F.M.d., Hasui, Y. and Brito Neves, B.B.d. 1976. The upper precambrian of South America. *Boletim IG*, **7**, 45-80.
- Antonio, P.Y.J., Trindade, R.I.F., Giacomini, B., Brandt, D. and Tohver, E. 2021a. New high-quality paleomagnetic data from the Borborema Province (NE Brazil): Refinement of the APW path of Gondwana in the Early Cambrian. *Precambrian Research*, **360**, 106243, <https://doi.org/https://doi.org/10.1016/j.precamres.2021.106243>.
- Antonio, P.Y.J., D'Agrella-Filho, M.S. et al. 2017. Turmoil before the boring billion: Paleomagnetism of the 1880–1860Ma Uatumã event in the Amazonian craton. *Gondwana Research*, **49**, 106-129, <https://doi.org/http://dx.doi.org/10.1016/j.gr.2017.05.006>.
- Antonio, P.Y.J., D'Agrella-Filho, M.S. et al. 2021b. New constraints for paleogeographic reconstructions at ca. 1.88 Ga from geochronology and paleomagnetism of the Carajás dyke swarm (eastern Amazonia). *Precambrian Research*, **353**, 106039, <https://doi.org/https://doi.org/10.1016/j.precamres.2020.106039>.
- Apen, F.E., Gaynor, S.P., Schoene, B. and Cottle, J.M. 2024. Evaluating reference materials and common-Pb corrections for high-resolution apatite UPb geochronology. *Chemical Geology*, **661**, 122191, <https://doi.org/https://doi.org/10.1016/j.chemgeo.2024.122191>.
- Assumpção, M. and Sacek, V. 2013. Intra-plate seismicity and flexural stresses in central Brazil. *Geophysical Research Letters*, **40**, 487-491, <https://doi.org/https://doi.org/10.1002/grl.50142>.
- Barros, C.E.d.M., do Nascimento, V.M. and Medeiros Filho, C.A. 2010. Revisão da estratigrafia das rochas da Serra Leste, Província Mineral de Carajás: a revision. *Revista brasileira de geociências*, **40**, 167-174.

- Barros, C.E.d.M., Macambira, M.J.B., Barbey, P. and Scheller, T. 2004. Dados isotópicos Pb-Pb em zircão (evaporação) e Sm-Nd do Complexo Granítico Estrela, província Mineral de Carajás, Brasil: implicações petrológicas e tectônicas. *Revista Brasileira de Geociências*, **34**, 531-538.
- Barros, C.E.d.M., Sardinha, A.S., de Oliveira Barbosa, J.d.P., Macambira, M.J.B., Barbey, P. and Boullier, A.-M. 2009. STRUCTURE, PETROLOGY, GEOCHEMISTRY AND ZIRCON U/Pb AND Pb/Pb GEOCHRONOLOGY OF THE SYNKINEMATIC ARCHEAN (2.7 Ga) A-TYPE GRANITES FROM THE CARAJÁS METALLOGENIC PROVINCE, NORTHERN BRAZIL. *The Canadian Mineralogist*, **47**, 1423-1440, <https://doi.org/10.3749/canmin.47.6.1423>.
- Bazhenov, M.L. and Shatsillo, A.V. 2010. Late Permian palaeomagnetism of Northern Eurasia: data evaluation and a single-plate test of the geocentric axial dipole model. *Geophysical Journal International*, **180**, 136-146, <https://doi.org/10.1111/j.1365-246X.2009.04379.x>.
- Bazhenov, M.L., Levashova, N.M., Meert, J.G., Golovanova, I.V., Danukalov, K.N. and Fedorova, N.M. 2016. Late Ediacaran magnetostratigraphy of Baltica: Evidence for Magnetic Field Hyperactivity? *Earth and Planetary Science Letters*, **435**, 124-135, <https://doi.org/http://dx.doi.org/10.1016/j.epsl.2015.12.015>.
- Bono, R.K., Tarduno, J.A., Nimmo, F. and Cottrell, R.D. 2019. Young inner core inferred from Ediacaran ultra-low geomagnetic field intensity. *Nature Geoscience*, **12**, 143.
- Brasier, M., Cowie, J. and Taylor, M. 1994. Decision on the Precambrian-Cambrian boundary stratotype. *Episodes Journal of International Geoscience*, **17**, 3-8.
- Cogné, J.P. 2003. PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions. *Geochemistry, Geophysics, Geosystems*, **4**, 1007, <https://doi.org/10.1029/2001GC000227>.
- Cordani, U. 1981. Comentários sobre as determinações geocronológicas da região da Serra dos Carajás. *Report, Universidade de São Paulo-Docegeo*.
- Cordani, U.G., Teixeira, W., D'Agrella-Filho, M.S. and Trindade, R.I. 2009. The position of the Amazonian Craton in supercontinents. *Gondwana Research*, **15**, 396-407, <https://doi.org/10.1016/j.gr.2008.12.005>.
- Cordani, U.G., Pimentel, M.M., Ganade De Araújo, C.E., Basei, M.A.S., Fuck, R.A. and Girardi, V.A.V. 2013. Was there an Ediacaran Clymene Ocean in central South America? *American Journal of Science*, **313**, 517-539, <https://doi.org/10.2475/06.2013.01>.
- Cukjati, A., Franceschinis, P.R., Arrouy, M.J., Gómez-Peral, L.E., Poiré, D.G., Trindade, R.I.F. and Rapalini, A.E. 2024. New paleomagnetic data from the sedimentary cover of the Tandilia System: Further geodynamic or geomagnetic complexities in the Late Ediacaran. *Gondwana Research*, **132**, 220-248, <https://doi.org/https://doi.org/10.1016/j.gr.2024.05.002>.
- D'Agrella-Filho, M.S., Antonio, P.Y.J., Trindade, R.I.F., Teixeira, W. and Bispo-Santos, F. 2021. Chapter 6 - The Precambrian drift history and paleogeography of Amazonia. In: Pesonen, L.J., Salminen, J., Elming, S.-Å., Evans, D.A.D. and Veikkolainen, T. (eds) *Ancient Supercontinents and the Paleogeography of Earth*. Elsevier, 207-241, <https://doi.org/https://doi.org/10.1016/B978-0-12-818533-9.00010-2>.
- Dall'Agnol, R., Teixeira, N.P., Rämö, O.T., Moura, C.A.V., Macambira, M.J.B. and de Oliveira, D.C. 2005. Petrogenesis of the Paleoproterozoic rapakivi A-type granites of the Archean Carajás metallogenic province, Brazil. *Lithos*, **80**, 101-129, <https://doi.org/10.1016/j.lithos.2004.03.058>.
- Day, R., Fuller, M. and Schmidt, V.A. 1977. Hysteresis properties of titanomagnetites: Grain-size and compositional dependence. *Physics of the Earth and Planetary Interiors*, **13**, 260-267, [https://doi.org/http://dx.doi.org/10.1016/0031-9201\(77\)90108-X](https://doi.org/http://dx.doi.org/10.1016/0031-9201(77)90108-X).
- de Freitas, G.B.F., Meira, V.T., Cioffi, C.R., Rocha, B.C., Luvizotto, G.L., Vervoort, J. and da Trindade, R.I.F. 2023. Metamorphic and geochronological constraints on the final assembly of West Gondwana: an Ediacaran-Cambrian collisional setting in the northern Araguaia Orogen, central Brazil. *International Geology Review*, 1-23, <https://doi.org/10.1080/00206814.2023.2262695>.
- Deenen, M.H.L., Langereis, C.G., van Hinsbergen, D.J.J. and Biggin, A.J. 2011. Geomagnetic secular variation and the statistics of palaeomagnetic directions. *Geophysical Journal International*, **186**, 509-520, <https://doi.org/10.1111/j.1365-246X.2011.05050.x>.
- deMelo, G.H.C., Monteiro, L.V.S. et al. 2017. Temporal evolution of the giant Salobo IOCG deposit, Carajás Province (Brazil): constraints from paragenesis of hydrothermal alteration and U-Pb geochronology. *Mineralium Deposita*, **52**, 709-732, <https://doi.org/10.1007/s00126-016-0693-5>.

- DOCEGEO. 1988. Revisão litoestratigráfica da província mineral de Carajás. *Província Mineral de Carajás–Litoestratigrafia e principais depósitos minerais. In Anexo do 35. Congresso Brasileiro de Geologia (Belém)*, 11-56.
- Domeier, M., Robert, B., Meert, J.G., Kulakov, E.V., McCausland, P.J.A., Trindade, R.I.F. and Torsvik, T.H. 2023. The enduring Ediacaran paleomagnetic enigma. *Earth-Science Reviews*, 104444, <https://doi.org/https://doi.org/10.1016/j.earscirev.2023.104444>.
- Donardelli Bellon, U. 2024. Clay Minerals and Continental-Scale Remagnetization: A Case Study of South American Neoproterozoic Carbonates. *Journal of Geophysical Research: Solid Earth*, **129**, <https://doi.org/10.1029/2023JB028538>.
- Dreher, A.M., Xavier, R.P., Taylor, B.E. and Martini, S.L. 2008. New geologic, fluid inclusion and stable isotope studies on the controversial Igarapé Bahia Cu–Au deposit, Carajás Province, Brazil. *Mineralium Deposita*, **43**, 161-184, <https://doi.org/10.1007/s00126-007-0150-6>.
- Dunlop, D.J. 2002. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc). 1. Theoretical curves and tests using titanomagnetite data. *Journal of Geophysical Research*, **107**, EPM4.1-EPM4.22.
- Evans, D.A. 1998. True polar wander, a supercontinental legacy. *Earth and Planetary Science Letters*, **157**, 1-8, [https://doi.org/http://dx.doi.org/10.1016/S0012-821X\(98\)00031-4](https://doi.org/http://dx.doi.org/10.1016/S0012-821X(98)00031-4).
- Feio, G.R.L., Dall’Agnol, R., Dantas, E.L., Macambira, M.J.B., Santos, J.O.S., Althoff, F.J. and Soares, J.E.B. 2013. Archean granitoid magmatism in the Canaã dos Carajás area: Implications for crustal evolution of the Carajás province, Amazonian craton, Brazil. *Precambrian Research*, **227**, 157-185, <https://doi.org/http://dx.doi.org/10.1016/j.precamres.2012.04.007>.
- Fisher, R. 1953. Dispersion on a Sphere. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, **217**, 295-305, <https://doi.org/10.1098/rspa.1953.0064>.
- Font, E., Trindade, R.I.F. and Nédélec, A. 2006. Remagnetization in bituminous limestones of the Neoproterozoic Araras Group (Amazon craton): Hydrocarbon maturation, burial diagenesis, or both? *Journal of Geophysical Research: Solid Earth*, **111**, <https://doi.org/https://doi.org/10.1029/2005JB004106>.
- Franceschinis, P.R., Rapalini, A.E., Escayola, M.P. and Rodríguez Picada, C. 2020. Paleogeographic and tectonic evolution of the Pampia Terrane in the Cambrian: New paleomagnetic constraints. *Tectonophysics*, **779**, 228386, <https://doi.org/https://doi.org/10.1016/j.tecto.2020.228386>.
- Gallet, Y., Pavlov, V. and Korovnikov, I. 2019. Extreme geomagnetic reversal frequency during the Middle Cambrian as revealed by the magnetostratigraphy of the Khorbusuonka section (northeastern Siberia). *Earth and Planetary Science Letters*, **528**, 115823, <https://doi.org/https://doi.org/10.1016/j.epsl.2019.115823>.
- Gallo, L.C., Tomezzoli, R.N. and Cristallini, E.O. 2017. A pure dipole analysis of the Gondwana apparent polar wander path: Paleogeographic implications in the evolution of Pangea. *Geochemistry, Geophysics, Geosystems*, **18**, 1499-1519, <https://doi.org/10.1002/2016GC006692>.
- Gallo, L.C., Cristallini, E.O. and Svarc, M. 2018. A nonparametric approach for assessing precision in georeferenced point clouds best fit planes: Toward more reliable thresholds. *Journal of Geophysical Research: Solid Earth*, **123**, 10,297-210,308.
- Ganade de Araujo, C.E., Rubatto, D., Hermann, J., Cordani, U.G., Caby, R. and Basei, M.A.S. 2014. Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. *Nature Communications*, **5**, 5198, <https://doi.org/10.1038/ncomms6198>.
- Giovanardi, T., Girardi, V.A.V., Teixeira, W. and Mazzucchelli, M. 2019. Mafic dyke swarms at 1882, 535 and 200 Ma in the Carajás region, Amazonian Craton: SrNd isotopy, trace element geochemistry and inferences on their origin and geological settings. *Journal of South American Earth Sciences*, **92**, 197-208, <https://doi.org/https://doi.org/10.1016/j.jsames.2019.02.017>.
- Godoy, A.M., Pinho, F.E.C., Manzano, J.C., Araújo, L.M.B.d., Silva, J.A.d. and Figueiredo, M. 2010. Estudos isotópicos das rochas granitóides neoproterozóicas da Faixa de Dobramento Paraguai.
- Gold, T. 1955. Instability of the Earth's Axis of Rotation. *Nature*, **175**, 526-529.
- Gomes, C.B., Cordani, U.G. and Basei, M.A.S. 1975. Radiometric Ages from the Serra dos Carajás Area, Northern Brazil. *Geological Society of America Bulletin*, **86**, 939-942, [https://doi.org/10.1130/0016-7606\(1975\)86<939:raftsd>2.0.co;2](https://doi.org/10.1130/0016-7606(1975)86<939:raftsd>2.0.co;2).

- Gorayeb, P.S.d.S., Chaves, C.L., Moura, C.A.V. and da Silva Lobo, L.R. 2013. Neoproterozoic granites of the Lajeado intrusive suite, north-center Brazil: A late Ediacaran remelting of a Paleoproterozoic crust. *Journal of South American Earth Sciences*, **45**, 278-292, <https://doi.org/http://dx.doi.org/10.1016/j.jsames.2013.04.001>.
- Halls, H.C. 1978. The use of converging remagnetization circles in palaeomagnetism. *Physics of the Earth and Planetary Interiors*, **16**, 1-11, [https://doi.org/http://dx.doi.org/10.1016/0031-9201\(78\)90095-X](https://doi.org/http://dx.doi.org/10.1016/0031-9201(78)90095-X).
- Halls, H.C., Lovette, A., Hamilton, M. and Söderlund, U. 2015. A paleomagnetic and U–Pb geochronology study of the western end of the Grenville dyke swarm: Rapid changes in paleomagnetic field direction at ca. 585 Ma related to polarity reversals? *Precambrian Research*, **257**, 137-166, <https://doi.org/http://dx.doi.org/10.1016/j.precamres.2014.11.029>.
- Hirata, W.K., Rigon, J.C., Kadekaru, K., Cordeiro, A. and Meireles, E. 1982. Geologia regional da província mineral de Carajás. *Simpósio de Geologia da Amazônia*, **1**, 100-110.
- Huang, W., Tarduno, J. *et al.* 2024. Near-collapse of the geomagnetic field may have contributed to atmospheric oxygenation and animal radiation in the Ediacaran Period. *Communications Earth & Environment*, **5**, <https://doi.org/10.1038/s43247-024-01360-4>.
- Khattach, D., Robardet, M. and Perroud, H. 1995. A Cambrian pole for the Moroccan Coastal Meseta. *Geophysical Journal International*, **120**, 132-144, <https://doi.org/10.1111/j.1365-246X.1995.tb05916.x>.
- Kirschvink, J. 1978. The Precambrian-Cambrian boundary problem: paleomagnetic directions from the Amadeus Basin, central Australia. *Earth and Planetary Science Letters*, **40**, 91-100.
- Kirschvink, J.L. 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal International*, **62**, 699-718, <https://doi.org/10.1111/j.1365-246X.1980.tb02601.x>.
- Kirschvink, J.L., Ripperdan, R.L. and Evans, D.A. 1997. Evidence for a Large-Scale Reorganization of Early Cambrian Continental Masses by Inertial Interchange True Polar Wander. *Science*, **277**, 541-545, <https://doi.org/10.1126/science.277.5325.541>.
- Kirschvink, J.L., Kopp, R.E., Raub, T.D., Baumgartner, C.T. and Holt, J.W. 2008. Rapid, precise, and high-sensitivity acquisition of paleomagnetic and rock-magnetic data: Development of a low-noise automatic sample changing system for superconducting rock magnetometers. *Geochemistry, Geophysics, Geosystems*, **9**, <https://doi.org/10.1029/2007GC001856>.
- Kodama, K.P. 2021. Combined magnetostratigraphy from three localities of the Rainstorm Member of the Johnnie Formation in California and Nevada, United States Calibrated by Cyclostratigraphy: A 13 R/Ma Reversal Frequency for the Ediacaran. *Frontiers in Earth Science*, **9**, 764714.
- Koppers, A.A. 2002. ArArCALC—software for 40Ar/39Ar age calculations. *Computers & Geosciences*, **28**, 605-619.
- Leite, A.F.G.D., Fuck, R.A., Dantas, E.L. and Ruiz, A.S. 2021. Appinitic and high BaSr magmatism in central Brazil: Insights into the late accretion stage of West Gondwana. *Lithos*, **398**, 106333.
- Leite, A.F.G.D., Fuck, R.A., Dantas, E.L., Ruiz, A.S., Moniê, P. and Iemmolo, A. 2024. Tectonic significance of the late-Ediacaran syn-orogenic basin in the easternmost portion of the Paraguay Belt, Tocantins Province, central Brazil. *Journal of South American Earth Sciences*, **133**, 104735, <https://doi.org/https://doi.org/10.1016/j.jsames.2023.104735>.
- Levashova, N.M., Golovanova, I.V., Rud'ko, D.V., Danukalov, K.N., Rud'ko, S.V., Sal'manova, R.Y. and Sergeeva, N.D. 2021. Late Ediacaran Hyperactivity Period: Quantifying the Reversal Frequency. *Izvestiya, Physics of the Solid Earth*, **57**, 247-256, <https://doi.org/10.1134/S1069351321020026>.
- Li, Y.-X., Tarduno, J.A. *et al.* 2023a. Late Cambrian geomagnetic instability after the onset of inner core nucleation. *Nature Communications*, **14**, 4596, <https://doi.org/10.1038/s41467-023-40309-7>.
- Li, Z.-X., Liu, Y. and Ernst, R. 2023b. A dynamic 2000–540 Ma Earth history: From cratonic amalgamation to the age of supercontinent cycle. *Earth-Science Reviews*, **104336**, <https://doi.org/https://doi.org/10.1016/j.earscirev.2023.104336>.
- Lloyd, S., Biggin, A.J., Paterson, G. and McCausland, P. 2022. Extremely weak early Cambrian dipole moment similar to Ediacaran: Evidence for long-term trends in geomagnetic field behaviour? *Earth and Planetary Science Letters*, **595**, 117757, <https://doi.org/10.1016/j.epsl.2022.117757>.
- Mansur, E.T. and Ferreira Filho, C.F. 2016. Magmatic structure and geochemistry of the Luanga Mafic–Ultramafic Complex: Further constraints for the PGE-mineralized magmatism in Carajás, Brazil. *Lithos*, **266-267**, 28-43, <https://doi.org/https://doi.org/10.1016/j.lithos.2016.09.036>.

- Martins, P.L.G., Toledo, C.L.B., Silva, A.M., Chemale Jr, F., Santos, J.O.S. and Assis, L.M. 2017. Neoproterozoic magmatism in the southeastern Amazonian Craton, Brazil: Petrography, geochemistry and tectonic significance of basalts from the Carajás Basin. *Precambrian Research*, **302**, 340-357.
- Maxbauer, D.P., Feinberg, J.M. and Fox, D.L. 2016. MAX UnMix: A web application for unmixing magnetic coercivity distributions. *Computers & Geosciences*, **95**, 140-145, <https://doi.org/https://doi.org/10.1016/j.cageo.2016.07.009>.
- McDougall, I. and Harrison, T.M. 1999. *Geochronology and Thermochronology by the ⁴⁰Ar/³⁹Ar Method*. Oxford University Press, USA.
- McFadden, P.L. and McElhinny, M.W. 1990. Classification of the reversal test in palaeomagnetism. *Geophysical Journal International*, **103**, 725-729, <https://doi.org/10.1111/j.1365-246X.1990.tb05683.x>.
- Meert, J.G. 1999. A paleomagnetic analysis of Cambrian true polar wander. *Earth and Planetary Science Letters*, **168**, 131-144, [https://doi.org/http://dx.doi.org/10.1016/S0012-821X\(99\)00042-4](https://doi.org/http://dx.doi.org/10.1016/S0012-821X(99)00042-4).
- Meert, J.G., Levashova, N.M., Bazhenov, M.L. and Landing, E. 2016. Rapid changes of magnetic Field polarity in the late Ediacaran: Linking the Cambrian evolutionary radiation and increased UV-B radiation. *Gondwana Research*, **34**, 149-157, <https://doi.org/http://dx.doi.org/10.1016/j.gr.2016.01.001>.
- Meert, J.G., Pivarunas, A.F. et al. 2020. The magnificent seven: A proposal for modest revision of the Van der Voo (1990) quality index. *Tectonophysics*, **790**, 228549, <https://doi.org/https://doi.org/10.1016/j.tecto.2020.228549>.
- Merdith, A.S., Williams, S.E. et al. 2021. Extending full-plate tectonic models into deep time: Linking the Neoproterozoic and the Phanerozoic. *Earth-Science Reviews*, **214**, 103477, <https://doi.org/https://doi.org/10.1016/j.earscirev.2020.103477>.
- Mitchell, R.N., Raub, T.D., Sillva, S.M. and Kirschvink, J.L. 2015. Was the Cambrian explosion both an effect and an artifact of true polar wander? *American Journal of Science*, **315**, 945-957.
- Moreira, G., Ernesto, M., De Min, A., Marzoli, A., Machado, F.B., Vasconcellos, E.M.G. and Bellieni, G. 2023. Paleomagnetism of the Penatecaua magmatism: The CAMP intrusive rocks in the Amazonas Basin, northern Brazil. *Physics of the Earth and Planetary Interiors*, **342**, 107075, <https://doi.org/https://doi.org/10.1016/j.pepi.2023.107075>.
- Moreto, C.P.N., Monteiro, L.V.S. et al. 2015. Neoproterozoic and Paleoproterozoic Iron Oxide-Copper-Gold Events at the Sossego Deposit, Carajás Province, Brazil: Re-Os and U-Pb Geochronological Evidence*. *Economic Geology*, **110**, 809-835, <https://doi.org/10.2113/econgeo.110.3.809>.
- Moura, C.A.V., Pinheiro, B.L.S., Nogueira, A.C.R., Gorayeb, P.S.S. and Galarza, M.A. 2008. Sedimentary provenance and palaeoenvironment of the Baixo Araguaia Supergroup: constraints on the palaeogeographical evolution of the Araguaia Belt and assembly of West Gondwana. *Geological Society, London, Special Publications*, **294**, 173-196, <https://doi.org/10.1144/sp294.10>.
- Müller, R.D., Cannon, J. et al. 2018. GPlates: Building a Virtual Earth Through Deep Time. *Geochemistry, Geophysics, Geosystems*, **19**, 2243-2261, <https://doi.org/10.1029/2018gc007584>.
- Murphy, J.B., Nance, R.D. and Mitchell, R.N. 2024. The assembly of Pangaea: geodynamic conundrums revisited. *Journal of the Geological Society*, **181**, jgs2024-2006, <https://doi.org/doi:10.1144/jgs2024-006>.
- Nomade, S., Théveniaut, H., Chen, Y., Pouclet, A. and Rigollet, C. 2000. Paleomagnetic study of French Guyana Early Jurassic dolerites: hypothesis of a multistage magmatic event. *Earth and Planetary Science Letters*, **184**, 155-168, [https://doi.org/http://dx.doi.org/10.1016/S0012-821X\(00\)00305-8](https://doi.org/http://dx.doi.org/10.1016/S0012-821X(00)00305-8).
- Paterson, G.A., Zhao, X., Jackson, M. and Heslop, D. 2018. Measuring, processing, and analyzing hysteresis data. *Geochemistry, Geophysics, Geosystems*.
- Pescarini, T., Trindade, R.I.F., Hoffman, P.F. and Sant'Anna, L.G. 2024a. Paleomagnetic investigation of the basal Maieberg Formation (Namibia) cap carbonate sequence (635 Ma): Implications for Snowball Earth postglacial dynamics. *GSA Bulletin*, <https://doi.org/10.1130/b37378.1>.
- Pescarini, T., Trindade, R.I., Evans, D.A., Kirschvink, J.L., Pierce, J. and Fernandes, H.A. 2024b. Magnetic Mineralogy and Paleomagnetic Record of the Nama Group, Namibia: Implications for Large-Scale Remagnetization of West Gondwanaland and Ediacaran Geomagnetic Instability. *Authorea Preprints*.
- Petrovský, E. and Kapička, A. 2006. On determination of the Curie point from thermomagnetic curves. *Journal of Geophysical Research: Solid Earth*, **111**, n/a-n/a, <https://doi.org/10.1029/2006JB004507>.

- Phillips, D. and Matchan, E.L. 2013. Ultra-high precision $^{40}\text{Ar}/^{39}\text{Ar}$ ages for Fish Canyon Tuff and Alder Creek Rhyolite sanidine: New dating standards required? *Geochimica et Cosmochimica Acta*, **121**, 229-239, <https://doi.org/https://doi.org/10.1016/j.gca.2013.07.003>.
- Pidgeon, R., Macambira, M. and Lafon, J.-M. 2000. Th–U–Pb isotopic systems and internal structures of complex zircons from an enderbite from the Pium Complex, Carajás Province, Brazil: evidence for the ages of granulite facies metamorphism and the protolith of the enderbite. *Chemical Geology*, **166**, 159-171.
- Pierce, J., Evans, D. *et al.* 2024. Magnetostratigraphic resolution of the late Ediacaran paleomagnetic enigma.
- Rapalini, A.E. 2006. New late Proterozoic paleomagnetic pole for the Rio de la Plata craton: Implications for Gondwana. *Precambrian Research*, **147**, 223-233, <https://doi.org/https://doi.org/10.1016/j.precamres.2006.01.016>.
- Rapalini, A.E., Franceschinis, P.R., Bettucci, L.S., Arrouy, M.J. and Poiré, D.G. 2021. The Precambrian drift history and paleogeography of Río de la Plata craton *Ancient Supercontinents and the Paleogeography of Earth*. Elsevier, 243-261.
- Raub, T., Kirschvink, J. and Evans, D. 2007. True polar wander: Linking deep and shallow geodynamics to hydro- and bio-spheric hypotheses. *Treatise on geophysics*, **5**, 565-589.
- Reeves, C.V., de Wit, M.J. and Sahu, B.K. 2004. Tight reassembly of Gondwana exposes Phanerozoic shears in Africa as global tectonic players. *Gondwana Research*, **7**, 7-19, [https://doi.org/10.1016/s1342-937x\(05\)70302-6](https://doi.org/10.1016/s1342-937x(05)70302-6).
- Rivalenti, G., Williamson, A. *et al.* 1998. Petrogenesis of the Paleoproterozoic basalt-andesite-rhyolite dyke association in the Carajas region, Amazonian craton. *Lithos*, **43**, 235-265, [https://doi.org/10.1016/S0024-4937\(98\)00015-2](https://doi.org/10.1016/S0024-4937(98)00015-2).
- Robert, B., Domeier, M. and Jakob, J. 2021. On the origins of the lapetus ocean. *Earth-Science Reviews*, 103791, <https://doi.org/https://doi.org/10.1016/j.earscirev.2021.103791>.
- Robert, B., Corfu, F., Domeier, M. and Blein, O. 2023. Evidence for large disturbances of the Ediacaran geomagnetic field from West Africa. *Precambrian Research*, **394**, 107095, <https://doi.org/https://doi.org/10.1016/j.precamres.2023.107095>.
- Roberts, A.P., Pike, C.R. and Verosub, K.L. 2000. First-order reversal curve diagrams: A new tool for characterizing the magnetic properties of natural samples. *Journal of Geophysical Research: Solid Earth*, **105**, 28461-28475, <https://doi.org/10.1029/2000JB900326>.
- Rodríguez Piceda, C., Franceschinis, P., Escayola, M. and Rapalini, A. 2018. Paleomagnetismo del Grupo Santa Victoria en la sierra de Mojotoro, Salta: aportes a la reconstrucción paleogeográfica de Pampia en el Paleozoico temprano. *Revista de la Asociación Geológica Argentina*, **75**, 518-532.
- Rooney, A.D., Cantine, M.D. *et al.* 2020. Calibrating the coevolution of Ediacaran life and environment. *Proceedings of the National Academy of Sciences*, 202002918, <https://doi.org/10.1073/pnas.2002918117>.
- Rosignol, C., Siciliano Rego, E. *et al.* 2020. Stratigraphy and geochronological constraints of the Serra Sul Formation (Carajás Basin, Amazonian Craton, Brazil). *Precambrian Research*, **351**, 105981, <https://doi.org/https://doi.org/10.1016/j.precamres.2020.105981>.
- Rosignol, C., Rego, E.S. *et al.* 2023. Neoproterozoic environments associated with the emplacement of a large igneous province: Insights from the Carajás Basin, Amazonia Craton. *Journal of South American Earth Sciences*, **130**, 104574, <https://doi.org/https://doi.org/10.1016/j.jsames.2023.104574>.
- Rosignol, C., Antonio, P.Y.J. *et al.* 2022. Unraveling one billion years of geological evolution of the southeastern Amazonia Craton from detrital zircon analyses. *Geoscience Frontiers*, **13**, 101202, <https://doi.org/https://doi.org/10.1016/j.gsf.2021.101202>.
- Santos, J.O.S. 2003. Geotectônica do Escudo das Guianas e Brasil-Central. *Geologia, Tectônica e Recursos Minerais do Brasil*. Texto, mapas & SIG: CPRM—Serviço Geológico do Brasil, 169-226.
- Santos, J.O.S., Hartmann, L.A., McNaughton, N.J. and Fletcher, I.R. 2002. Timing of mafic magmatism in the Tapajós Province (Brazil) and implications for the evolution of the Amazon Craton: evidence from baddeleyite and zircon U–Pb SHRIMP geochronology. *Journal of South American Earth Sciences*, **15**, 409-429, [https://doi.org/http://dx.doi.org/10.1016/S0895-9811\(02\)00061-5](https://doi.org/http://dx.doi.org/10.1016/S0895-9811(02)00061-5).
- Schmitt, R.d.S., Fragoso, R.d.A. and Collins, A.S. 2018. Suturing Gondwana in the Cambrian: The Orogenic Events of the Final Amalgamation. *In: Siegesmund, S., Basei, M.A.S., Oyhantçabal, P. and Oriolo, S. (eds) Geology of*

- Southwest Gondwana*. Springer International Publishing, Cham, 411-432, https://doi.org/10.1007/978-3-319-68920-3_15.
- Schmitt, R.d.S., Trouw, R.A., Da Silva, E.A., de Jesus, J.V.M., da Costa, L.F.M. and Passarelli, C.R. 2023. The role of crustal-scale shear zones in SW Gondwana consolidation–transatlantic correlation.
- Shatsillo, A., Rud’ko, S., Latysheva, I., Rud’ko, D., Fedyukin, I., Powerman, V. and Kuznetsov, N. 2020. A Devious Equatorial Dipole Hypothesis: on the Low-Latitude Glaciations Problem and Geomagnetic Field Configuration in Late Precambrian. *Izvestiya, Physics of the Solid Earth*, **56**, 833-853.
- Shcherbakova, V.V., Bakhmutov, V.G., Thallner, D., Shcherbakov, V.P., Zhidkov, G.V. and Biggin, A.J. 2020. Ultra-low palaeointensities from East European Craton, Ukraine support a globally anomalous palaeomagnetic field in the Ediacaran. *Geophysical Journal International*, **220**, 1928-1946, <https://doi.org/10.1093/gji/ggz566>.
- Silva, F.F., de Oliveira, D.C., Antonio, P.Y.J., D’Agrella Filho, M.S. and Lamarão, C.N. 2016. Bimodal magmatism of the Tucumã area, Carajás province: U-Pb geochronology, classification and processes. *Journal of South American Earth Sciences*, **72**, 95-114, <https://doi.org/http://dx.doi.org/10.1016/j.jsames.2016.07.016>.
- Tauxe, L. 2010. *Essentials of paleomagnetism*. Univ of California Press.
- Tavares, F.M., Trouw, R.A.J., da Silva, C.M.G., Justo, A.P. and Oliveira, J.K.M. 2018. The multistage tectonic evolution of the northeastern Carajás Province, Amazonian Craton, Brazil: Revealing complex structural patterns. *Journal of South American Earth Sciences*, <https://doi.org/https://doi.org/10.1016/j.jsames.2018.08.024>.
- Teixeira, M.F.B., Dall’Agnol, R., Santos, J.O.S., Kemp, A. and Evans, N. 2019a. Petrogenesis of the Paleoproterozoic (Orosirian) A-type granites of Carajás Province, Amazon Craton, Brazil: Combined in situ HfO isotopes of zircon. *Lithos*, **332-333**, 1-22, <https://doi.org/https://doi.org/10.1016/j.lithos.2019.01.024>.
- Teixeira, W., Hamilton, M., Girardi, V.A.V., Faleiros, F.M. and Ernst, R.E. 2019b. U-Pb baddeleyite ages of key dyke swarms in the Amazonian Craton (Carajás/Rio Maria and Rio Apa areas): tectonic implications for events at 1880, 1110 Ma, 535 Ma and 200 Ma. *Precambrian Research*, **329**, 138-155.
- Temporim, F.A., Bellon, U.D., Domeier, M., Trindade, R.I.F., D’Agrella-Filho, M.S. and Tohver, E. 2021. Constraining the Cambrian drift of Gondwana with new paleomagnetic data from post-collisional plutons of the Araçuaí orogen, SE Brazil. *Precambrian Research*, **359**, 106212, <https://doi.org/https://doi.org/10.1016/j.precamres.2021.106212>.
- Thallner, D., Biggin, A. and Halls, H. 2021a. An extended period of extremely weak geomagnetic field suggested by palaeointensities from the Ediacaran Grenville dykes. *Earth and Planetary Science Letters*, **568**, 117025.
- Thallner, D., Biggin, A.J., McCausland, P.J. and Fu, R.R. 2021b. New paleointensities from the Skinner Cove Formation, Newfoundland, suggest a changing state of the geomagnetic field at the Ediacaran-Cambrian transition. *Journal of Geophysical Research: Solid Earth*, **126**, e2021JB022292.
- Thallner, D., Shcherbakova, V.V., Bakhmutov, V.G., Shcherbakov, V.P., Zhidkov, G.V., Poliachenko, I.B. and Biggin, A.J. 2022. New palaeodirections and palaeointensity data from extensive profiles through the Ediacaran section of the Volyn Basalt Province (NW-Ukraine). *Geophysical Journal International*, **231**, 474-792, <https://doi.org/10.1093/gji/ggac186>.
- Tohver, E. and Trindade, R.I. 2014. Comment on “Was there an Ediacaran Clymene Ocean in central South America?” by UG Cordani and others. *American Journal of Science*, **314**, 805-813.
- Tohver, E., D’Agrella-Filho, M.S. and Trindade, R.I.F. 2006. Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. *Precambrian Research*, **147**, 193-222, <https://doi.org/http://dx.doi.org/10.1016/j.precamres.2006.01.015>.
- Tohver, E., Cawood, P.A., Rosselo, E.A. and Jourdan, F. 2012. Closure of the Clymene Ocean and formation of West Gondwana in the Cambrian: Evidence from the Sierras Australes of the southernmost Rio de la Plata craton, Argentina. *Gondwana Research*, **21**, 394-405.
- Tohver, E., Trindade, R.I.F., Solum, J.G., Hall, C.M., Riccomini, C. and Nogueira, A.C. 2010. Closing the Clymene ocean and bending a Brasiliano belt: Evidence for the Cambrian formation of Gondwana, southeast Amazon craton. *Geology*, **38**, 267-270, <https://doi.org/10.1130/G30510.1>.
- Torsvik, T.H. and Cocks, L.R.M. 2013. Gondwana from top to base in space and time. *Gondwana Research*, **24**, 999-1030, <https://doi.org/http://dx.doi.org/10.1016/j.gr.2013.06.012>.
- Torsvik, T.H., Meert, J.G. and Smethurst, M.A. 1998. Polar wander and the Cambrian. *Science*, **279**, 9-9.

- Torsvik, T.H., Van der Voo, R. *et al.* 2012. Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews*, **114**, 325-368, <https://doi.org/http://dx.doi.org/10.1016/j.earscirev.2012.06.007>.
- Trindade, R.I.F., D'Agrella-Filho, M.S., Epof, I. and Brito Neves, B.B. 2006. Paleomagnetism of Early Cambrian Itabaiana mafic dikes (NE Brazil) and the final assembly of Gondwana. *Earth and Planetary Science Letters*, **244**, 361-377, <https://doi.org/http://dx.doi.org/10.1016/j.epsl.2005.12.039>.
- Trindade, R.I.F., Font, E., D'Agrella-Filho, M.S., Nogueira, A.C.R. and Riccomini, C. 2003. Low-latitude and multiple geomagnetic reversals in the Neoproterozoic Puga cap carbonate, Amazon craton. *Terra Nova*, **15**, 441-446, <https://doi.org/10.1046/j.1365-3121.2003.00510.x>.
- Vaes, B., Gallo, L.C. and van Hinsbergen, D.J.J. 2022. On Pole Position: Causes of Dispersion of the Paleomagnetic Poles Behind Apparent Polar Wander Paths. *Journal of Geophysical Research: Solid Earth*, **127**, e2022JB023953, <https://doi.org/https://doi.org/10.1029/2022JB023953>.
- Vandamme, D. 1994. A new method to determine paleosecular variation. *Physics of the Earth and Planetary Interiors*, **85**, 131-142, [https://doi.org/https://doi.org/10.1016/0031-9201\(94\)90012-4](https://doi.org/https://doi.org/10.1016/0031-9201(94)90012-4).
- Vasconcelos, P.M., Onoe, A.T., Kawashita, K., Soares, A.J. and Teixeira, W. 2002. ⁴⁰Ar/³⁹Ar geochronology at the Instituto de Geociências, USP: instrumentation, analytical procedures, and calibration. *Anais da Academia Brasileira de Ciências*, **74**, 297-342.
- Vasquez, L., Rosa-Costa, L. *et al.* 2008. Geologia e Recursos Minerais do Estado do Pará: Sistema de Informações Geográficas-SIG: texto explicativo dos mapas Geológico e Tectônico e de Recursos Minerais do Estado do Pará. *Organizadores, Vasquez ML, Rosa-Costa LT Escala*, **1**, 000.
- Vermeesch, P. 2018. IsoplotR: A free and open toolbox for geochronology. *Geoscience Frontiers*, **9**, 1479-1493, <https://doi.org/https://doi.org/10.1016/j.gsf.2018.04.001>.
- Whitney, D.L. and Evans, B.W. 2010. Abbreviations for names of rock-forming minerals. *American Mineralogist*, **95**, 185-187, <https://doi.org/10.2138/am.2010.3371>.
- Wu, L., Pisarevsky, S., Li, Z.-X., Murphy, J.B. and Liu, Y. 2024. A new reconstruction of Phanerozoic Earth evolution: Toward a big-data approach to global paleogeography. *Tectonophysics*, **874**, 230198, <https://doi.org/https://doi.org/10.1016/j.tecto.2023.230198>.
- Zhou, T., Tarduno, J., Cottrell, R. and Nimmo, F. 2022. *Early Cambrian renewal of the geodynamo and the origin of inner core structure*. Copernicus Meetings.
- Zhou, T., Ibañez-Mejia, M. *et al.* 2024. Magnetization and age of ca. 544 Ma syenite, eastern Canada: Evidence for renewal of the geodynamo. *Earth and Planetary Science Letters*, **639**, 118758, <https://doi.org/https://doi.org/10.1016/j.epsl.2024.118758>.
- Zijderveld, J. 1967. AC demagnetization of rocks: analysis of results. *Methods in paleomagnetism*, **3**, 254.