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# Age constraints on the Paleozoic Yaguarí-Buena Vista succession from Uruguay: paleomagnetic and paleontologic information

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A R T I C L E I N F O

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A B S T R A C T

The Yaguarí and the Buena Vista formations from Uruguay are historically correlated to the Brazilian Rio do Rasto and Sanga do Cabral formations, respectively, as they have some lithostratigraphic similarities, indicating a Permo-Triassic or even Triassic age of the Yaguarí-Buena Vista succession. However, they differ in the fossil indexes that characterize the faunistic communities present in both countries. A paleomagnetic work was carried out on some sections of the Buena Vista and the Yaguarí formations, as well as on some layers of bentonites, underlying the Buena Vista sediments. The alternating field and thermal demagnetization procedures revealed both normal and reversed magnetization components, but the samples showed evidence of secondary magnetic minerals and possibly remagnetizations. The calculated paleomagnetic pole for the Yaguarí-Buena Vista Formation plots near to the poles for the Choiyoi magmatism that is believed to be responsible for the bentonite accumulation, it is also in agreement with other Permian paleomagnetic poles for South America. Based on the paleomagnetic results, the available radiometric data for the bentonites, and the fossiliferous content, a Late Permian (Lopingian) age is assigned to the Yaguarí-Buena Vista rocks.

## 1. Introduction

The greatest mass extinction in the earth's history that eliminated up to 96% of the marine species (Hoffman, 1985; Erwin, 2006) took place at the end of the Permian period (e.g., Payne and Clapham, 2012) at about 252 Ma. Raup (1979) argues that 70% of the terrestrial vertebrates were also decimated, although some recent studies have minimized the effects of the extinction in the continental realm because of the high rate of survivorship showed by taxa like procolophonoids (Modesto et al., 2001, 2003), therapsids (Huttenlocker et al., 2011), and also by plants (Nowak et al., 2019). However, this is still a controversial issue, because our knowledge of the P-Tr boundary comes mainly from marine sequences, and it is not certain whether the terrestrial extinction occurred at the same time as the marine extinction (De Kock and Kirschvink, 2004). These decimation events are normally linked to catastrophic geological-geophysical phenomena that had consequences for the evolution of animal life. During the P-Tr interval, the Earth experienced a long period of superanoxia (Isozaki, 1997), marked by the initial process of the Pangea breakup evidenced by a large magmatic activity in Siberia (Ivanov et al., 2013). In South America, three major catastrophic events deserve mentions: 1) the Choiyoi magmatism was active from the Artinskian to the P-Tr boundary (e.g., Rocha-Campos et al., 2011); 2) the Central Atlantic magmatism (~201 Ma) related to the final stages of the Pangea breakup are both related to faunal annihilations (Davies et al., 2017; Spalletii and Limarino, 2017); and 3) at least one large impact event (the Araguainha crater; Lana and Marangoni, 2009) occurred at ~255 Ma, near the P-Tr boundary. Furthermore, at the end of the Permian, the Earth's magnetic field started a new period of high-frequency polarity reversals, after a long period of stable reversed field, the Permian-Carboniferous Reversed Superchron, also known as the Kiaman Interval. The end of the Kiaman is marked by the beginning of the Illawarra mixed polarity interval at approximately 267 Ma (Hounslow and Balabanov, 2016).

The Karoo Basin in South Africa contains a near-complete stratigraphic record of the Permo-Triassic boundary (PTB), and a continuous record across the massive extinction event and the recovery period as well (*e.g.*, De Kock and Kirschvink, 2004). No analogs were so far

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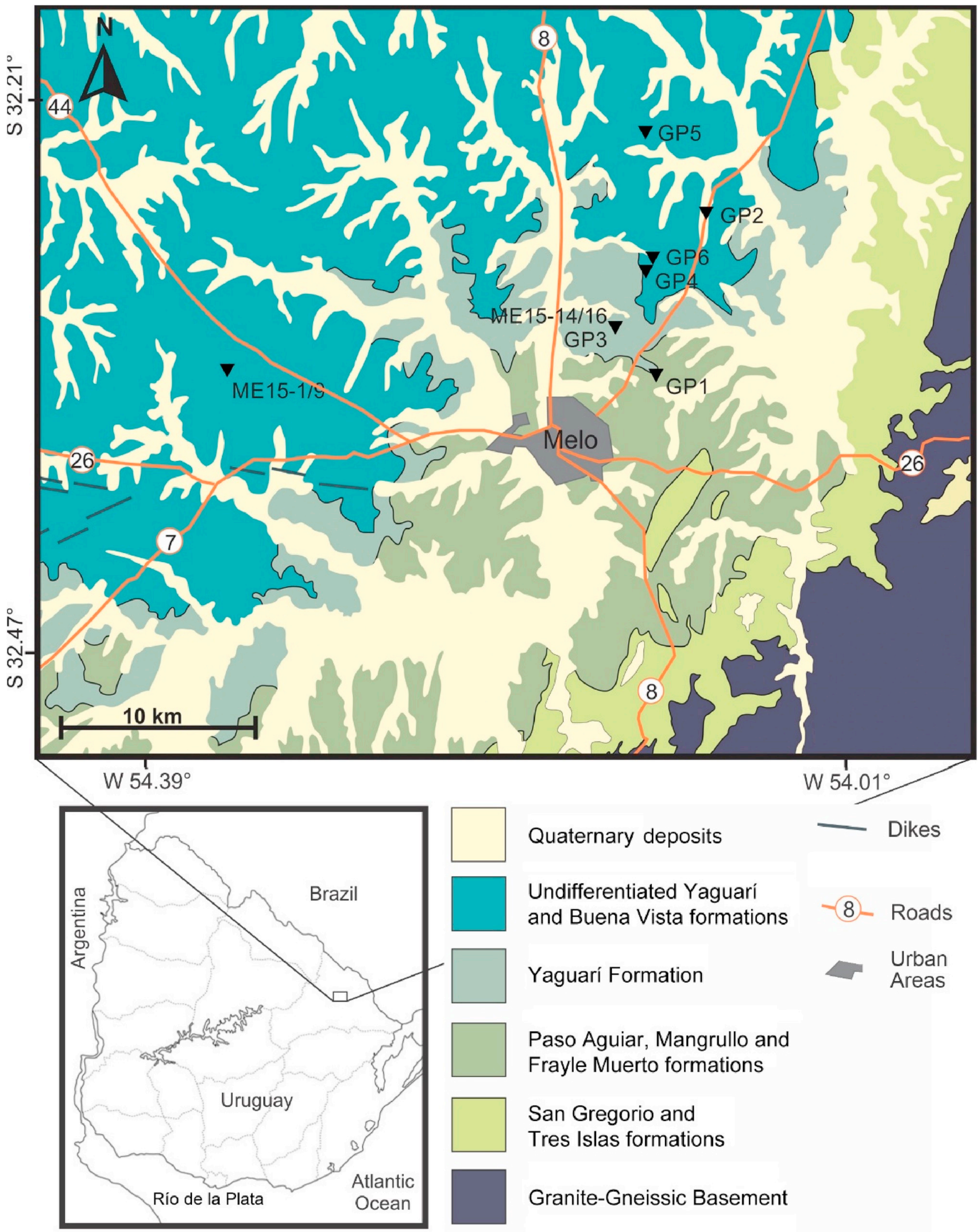


**Fig. 1.** Geological map of the studied area in the Cerro Largo County, near the city of Melo, Uruguay. Sampling sites are denoted by inverted triangles and respective codes.

described in South America, and apparently, the PTB is not present within the Paraná Basin. However, according to Tohver et al. (2013, 2018) the chronostratigraphic marker between the Paleozoic and Mesozoic in the Paraná Basin is the event bed (the so-called Porangaba debrite bed, an ejecta-bearing tsunami deposit) related to the Araguainha impact. Moreover, Tohver et al. (2018) describe seismites (soft-

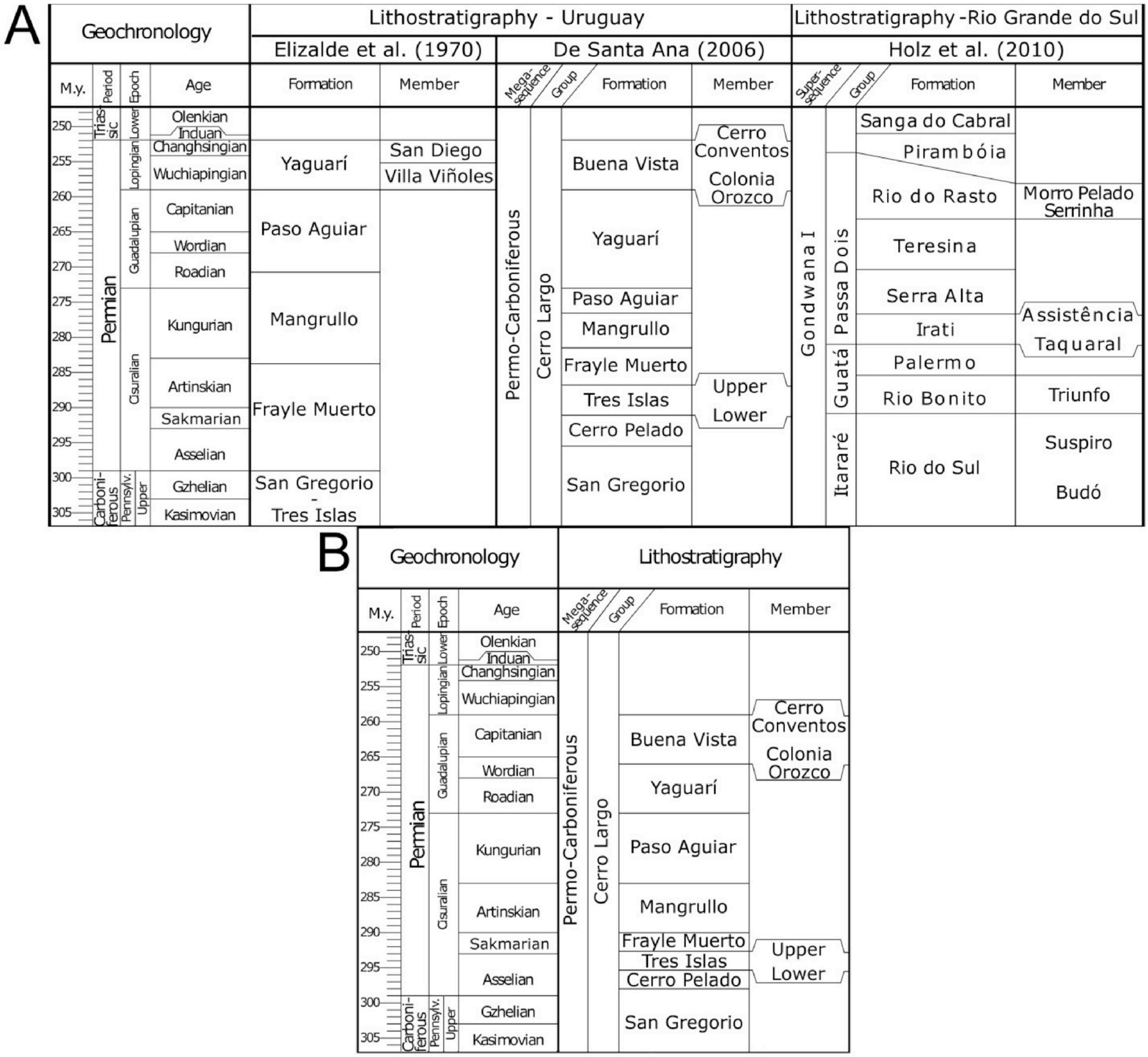


**Fig. 2.** Stratigraphic and chronostratigraphic columns for the continental Carboniferous-Permian to Permo-Triassic successions at the Paraná Basin (Brazil) and the Cuenca Norte Basin (Uruguay) according to the hypotheses suggested by different authors (A), and our proposal based on the results obtained in this work (B). Chronostratigraphy is based on the 2018 Chart of the International Commission on Stratigraphy.

sediment deformation features related to seismic activity) associated to the Araguainha impact which are overlain by the Porangaba debrite bed; this includes brecciated mudstones and clast-supported conglomerates dated at 253.0 ± 3.0 Ma by SHRIMP U–Pb dating of detrital zircon grains, very close to the end of the Permian or the beginning of the Triassic.

SHRIMP U–Pb dating of detrital zircon grains from the Araguainha event bed indicates a maximum depositional age of 253.0 ± 3.0 Ma (Tohver et al., 2018). The impact affected layers of the Permian Corumbataí, Teresina and Rio do Rasto formations (and perhaps also the Pirambóia Formation) around the Araguainha crater. There are no in situ Porangaba debrite beds in the Uruguayan succession, but large isolated blocks having a brecciated structure, with angled and relatively small clasts exist in several of the studied outcrops of the Yaguarí-Buena Vista deposits as well as deformational structures interpreted as seismites.

In Uruguay, the extension of the Paraná basin is called the Norte Basin and includes a record of sedimentation from the Carboniferous to the end of the Permian (De Santa Ana et al., 2006). In the eastern sector of the basin, the Permo-Carboniferous sequence crops out as the Cerro Largo Group (Bossi, 1966; Goso, 1995; Goso et al., 1996; De Santa Ana et al., 2006), which includes the San Gregorio, Cerro Pelado, Tres Islas, Frayle Muerto, Mangrullo, Paso Aguiar, Yaguarí and Buena Vista formations, listed from the oldest to the youngest. Deposits overlying the marine-lagoonal and estuarine environments of the Frayle Muerto, Mangrullo and Paso Aguiar formations (the Melo Formation after Bossi and Navarro, 1991) in the Norte Basin, constitute a well-documented progression to continental sedimentation, including deltaic, fluvial and eolian deposits of the Yaguarí and Buena Vista formations. According to some authors (e.g., Bourquin et al., 2011), these formations characterize the end of the Permian and the beginning of the Triassic. The Buena Vista Formation (BVF), the last Palaeozoic sedimentation, has relative ages associated with the Late Permian (Piñeiro and Ubilla, 2003; Piñeiro et al., 2007a, 2007b, 2007c; Piñeiro et al., 2012, Ezcurra et al., 2015) or to the Early Triassic (Bossi and Navarro, 1991; Dias-da-Silva et al., 2006) so that it may be a good candidate to represent the P-

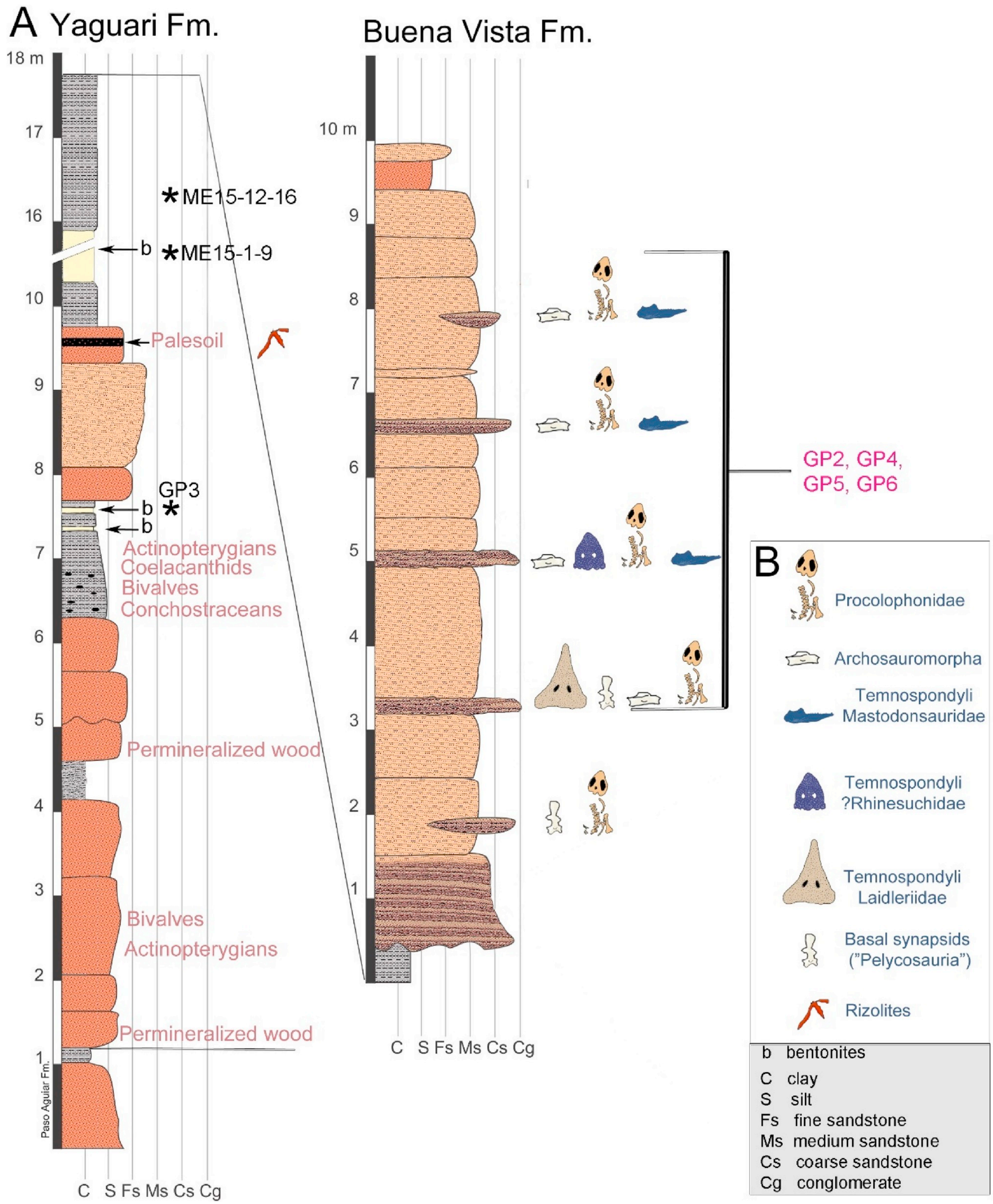


**Fig. 3.** A) Simplified stratigraphic profiles for the Yaguarí and the Buena Vista formations showing the main fossiliferous levels, and the position of the analyzed bentonitic levels. At least 6 m of bentonites were omitted in the uppermost bentonite layer (top of the Yaguarí Formation), where the deposition of volcanic ashes increased substantially, in comparison with the thinner (15 mm) layers from below. Asterisks indicate the approximate position of the paleomagnetic sampling sites from the Yaguarí Formation (in black) and the Buena Vista Formation (in red). B) Legend. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

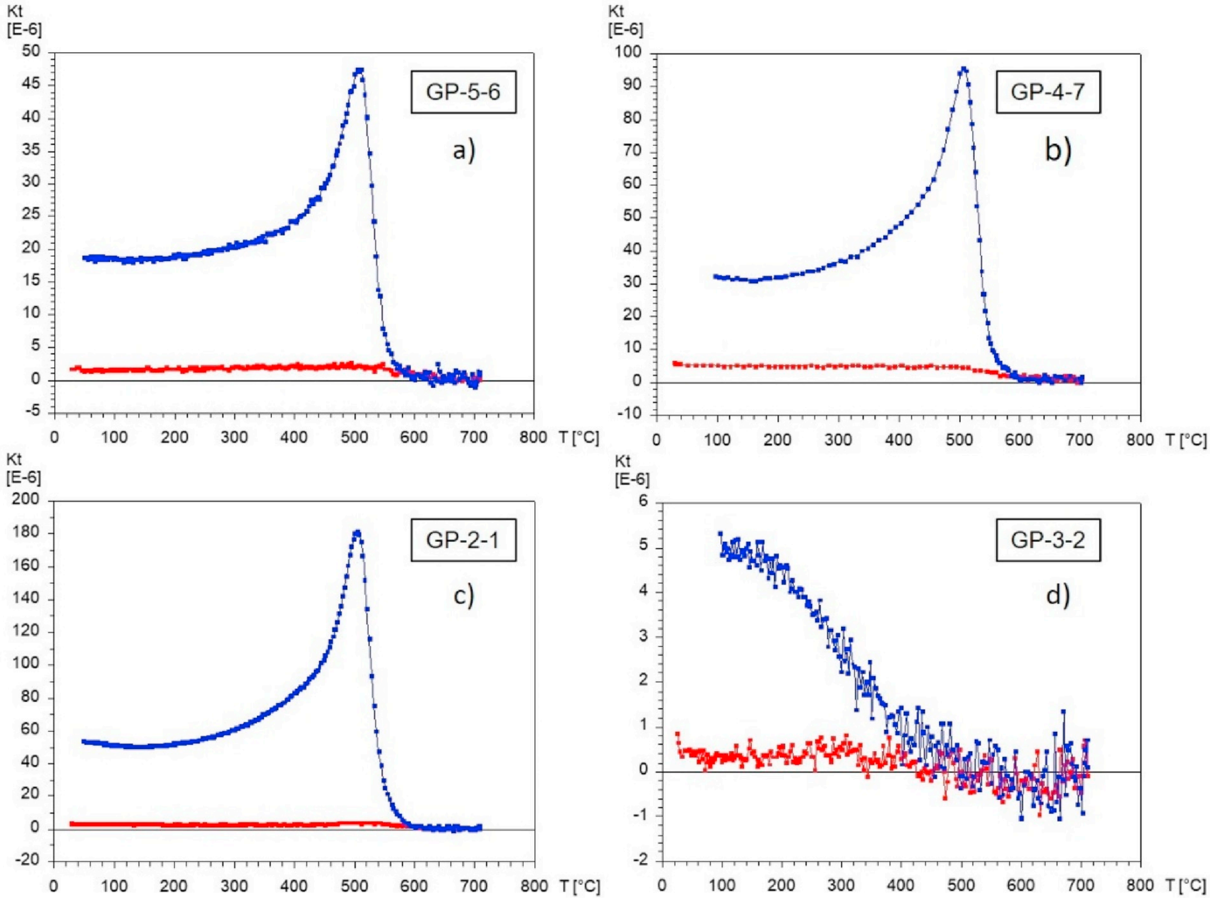


**Fig. 4.** Characteristic thermomagnetic curves for samples from different outcrops of Buena Vista and Yaguarí formations showing the behavior during the heating (red curves) and cooling (blue curves) processes. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Tr interval in the Paraná Basin (Piñeiro et al., 2012). However, the age of the BVF is poorly constrained "because of the absence of index taxa and the presence of taxa that are documented in either Late Permian or earliest Triassic assemblages from elsewhere" (Piñeiro et al., 2007c, 2012).

This paper aims to put some constraints on the age of the BVF using paleomagnetism associated with the already described paleontological data.

## 2. Geological background

The Paraná Basin is an intracratonic basin that covers an area of about $1.7 \times 10^6$ km$^2$ in southern Brazil, and part of Uruguay, Paraguay, and Argentina. The sedimentary fill of the basin started during the Ordovician and extended to the Mesozoic.

In Uruguay, the southern extension of the Paraná basin is called the Norte Basin, which covers an area of 90–100 $\times$ 10$^3$ km$^2$ in the north and northwestern portion of Uruguay (Zalán et al., 1987; Veroslavsky et al., 2006). Its average thickness is greater than 2300 m and may be close to 3500 m locally, having been filled with sedimentary and volcanic rocks at Eodevonian to Neocretaceous ages (Bossi, 1966; Bossi and Navarro, 1991; De Santa Ana, 2004). This sedimentary package was divided by De Santa Ana (2004) into four tectonosequences: Eodevonian, Permo-Carboniferous, Jurassic-Cretaceous, and Neocretaceous, which are, according to Soto (2014), correlatable to four of the Milani's (1997) supersequences in Brazil. In this conception, only the Ordovician-Silurian and Middle-Late Triassic supersequences from Brazil would not correlate in Uruguay. The Neopermian and (?)Eotriassic deposits discussed herein are contained in the Permo-Carboniferous Tectonosequence, which started under the influence of profound tectonic and climatic alterations (Milani's, 1997). The development of the Norte Basin is marked by a morphotectonic control of NW-SE Precambrian lineaments, which underwent reactivations along the Phanerozoic (Fulfaro et al., 1982; De Santa Ana, 2004). Rossello et al. (2006) proposed the existence of a structural high, oriented NNW-SSE, between the Paraná Basin and the Chaco-Paraná Basin, the Asunción-Rio Grande Dorsal. The Permo-Carboniferous Tectonosequence, corresponding to the Cerro Largo Group (Bossi and Navarro, 1991), is correlated with the Gondwana I Supersequence (Milani, 1997). De Santa Ana (2004) recognized three stages of deposition within a complete cycle of marine transgression-regression in this sedimentary package, which would have been controlled by compressive episodes of the Hercinian Orogeny (also called Sanrafaelic; Milani, 1997). The third phase consists of the Mangrullo, Paso Aguiar, Yaguarí and Buena Vista formations, representing the sea regression and continentalization phase of the basin, whose deposition is restricted to the eastern domain.

### 2.1. *The Buena Vista Formation intraformational conglomerates*

The Buena Vista Formation intraformational conglomerates are channel lags rich in mud intraclasts, formed by reworking and erosion of fluvial flood plains in a regressive tidal-fluvial transition to the implantation of continental conditions in the Norte Basin. They are rich in bones and fragmentary partial skeletons of fossil tetrapods. There were identified at least five penecontemporaneous conglomerate levels intercalated into the Buena Vista red sandstone, meaning that they may have roughly the same age. Mud pebbles are usually large in the

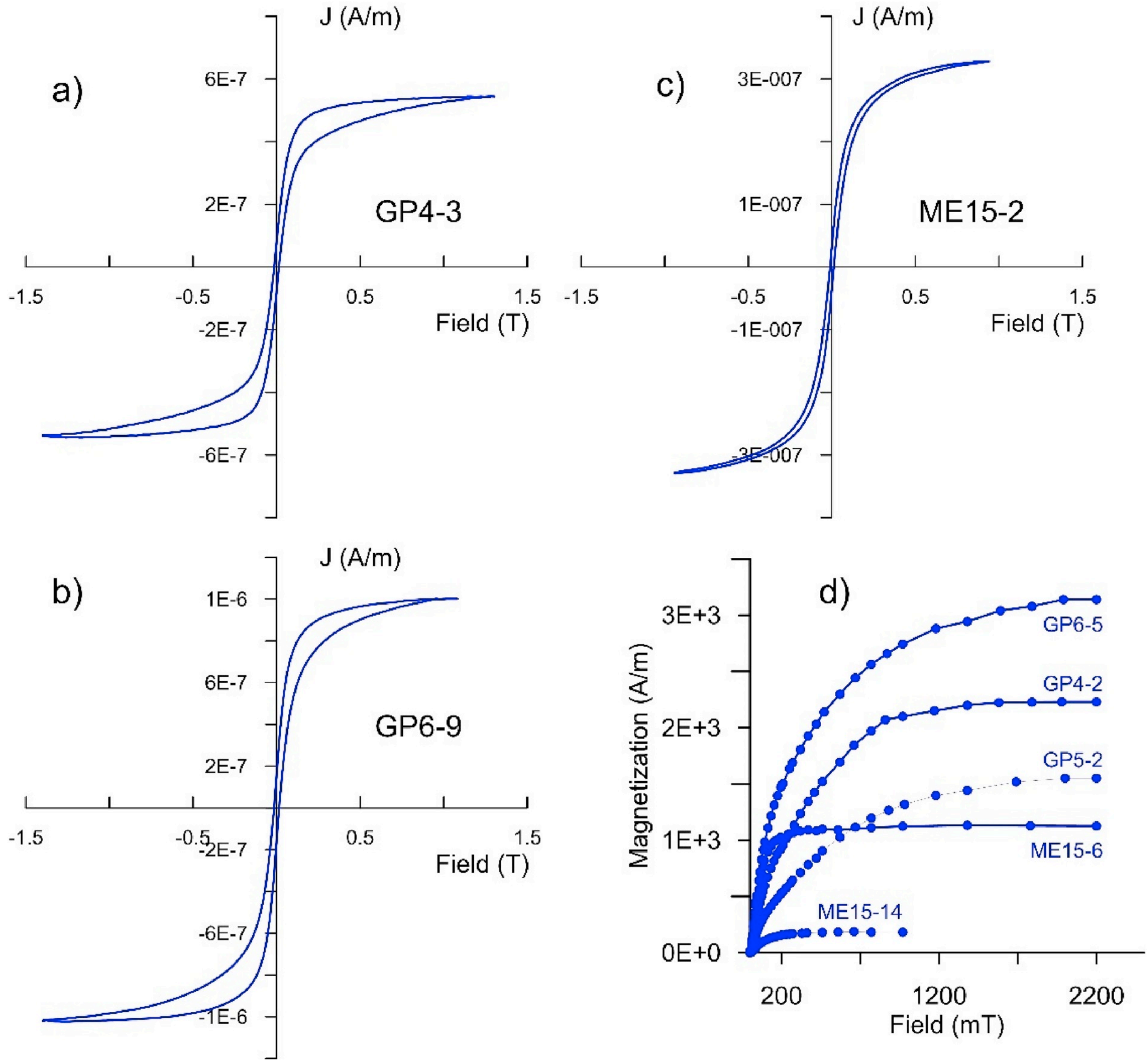


**Fig. 5.** Representative hysteresis loops (a to c) and IRM acquisition curves (d) for the Yaguarí-Buena Vista samples.

basalmost of these layers and somewhat tabular in shape, and they become smaller angled clasts to the top. The alternation between sandstones and intraformational conglomerates can be allied to seasonal variations of rainfall frequency and concomitant increasing of fluvial energy. Accordingly, fossils are more abundant and better preserved in the lowermost intraconglomerates rather than in the uppermost where they are scarce and appear deteriorated. As mud is more abundant in the lowermost intraconglomerate levels, carbonate content is higher, so it is possible that skeletons were accumulated in the flood plains and then reworked and included into the lag channels that could have migrated laterally carrying the fossils, which could have suffered additional disarticulation, and a low degree of erosion. This migration is evidenced by the finding of several lenses of intraconglomerates separated by discontinuities within the containing layer. Due to the lateral migration of the channels, there could have been a reworking of older levels, which can be the case for the Buena Vista intraconglomerates (see Piñeiro et al., 2012).

### 2.2. Chronostratigraphy

Absolute dating for the Permo-Carboniferous tectonosequence in the Norte Basin has been obtained mainly from the Yaguarí Formation, which includes thick beds of bentonite (Calarge et al., 2006) reaching more than 6 m in the subsurface; about 3 m are exposed on Route 7 and correspond to the Bañados de Medina bentonites. Radiometric dating of the Yaguarí Formation has been controversial (see Fig. 2); Calarge et al. (2006; see also De Santa Ana et al., 2006) assigned to it an age of 269.8 ± 4.7 Ma, while Rocha Campos et al., (2006, 2019) obtained ages of 273.5 and 272.5 Ma, respectively. Comparatively, Rocha-Campos et al. (2006, 2019) assign similar ages to the underlying Paso Aguiar and Estrada Nova formations (275.9 ± 5.4 Ma) and also to the Mangrullo Formation (275.9 ± 4.8 and 274.9 ± 2.1), which is not consistent with the thickness and the low deposition rate suggested by these deposits. Otherwise, as Rocha-Campos et al. (2006, 2019) suggested, the possibility of the recent loss of radiogenic Pb from the analyzed zircon grains may have interfered with the correct calibration of the obtained results. Therefore, the fossil associations present in these lithostratigraphic units become the most reliable tool to determine the age of the rocks. Particularly, most of the taxa recovered from the Mangrullo Formation are suggestive of an Early Permian or even a Permian-Carboniferous age for these deposits (see Piñeiro et al., 2016; Calisto and Piñeiro, 2019). Thus, we adopted the hypothesis of Santos et al. (2006) figuratively, taking into account that it will need to be updated according to new studies describing new fossils. Moreover,

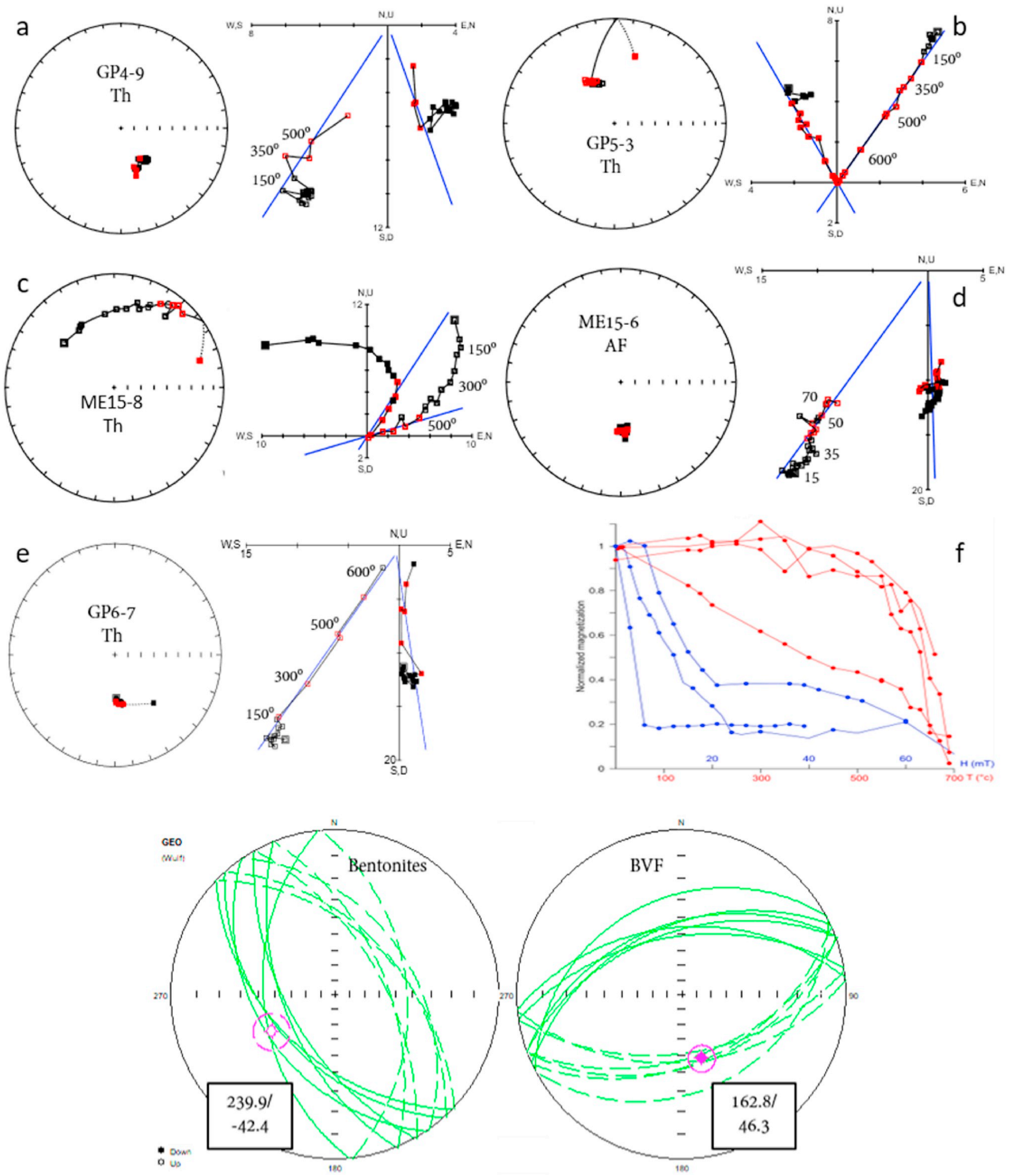


**Fig. 6.** Stereographic and orthogonal plots of the remanence vector under step-demagnetization (a to e). Red points are the selected points for the calculation of the magnetization components. Blue lines are the best fit of the segments using the principal component analysis. Magnetization units are $10^2$ A/m. Plots are the output of the PuffinPlot software (Lurcock and Wilson, 2012). Demagnetization curves (f) for some samples submitted to AF (blue) and thermal (red) cleaning. The bottom diagrams (g) are great circles for samples from the bentonites (ME15 series), and for the BVF sites GP4 to 6; red symbols are the calculated mean directions along with the confidence circles. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

additional radiometric dating of the Mangrullo bentonites that are associated to the fossiliferous levels will bring some light to this controversial issue.

Chemical analysis performed on the Yaguarí Formation bentonite indicated that this layer resulted from two different volcanic ash flows deposited in a short time interval preventing sedimentation between them (Calarge et al., 2006). Similar but less developed bentonitic levels are also found in the Rio do Rasto Formation of Brazil, near the city of Aceguá, about 70 km from the Bañados de Medina bentonites.

The BVF conformably overlies the fine sandstones at the top of the

**Table 1**
Paleomagnetic results for the Buena Vista–Yaguarí succession.

| Site | Relative Elev. (cm) | Dec. (°) | Inc. (°) | MAD | PGV-long (°) | PGV-lat (°) |
|---|---|---|---|---|---|---|
| Buena Vista Fm. – Site 4, Colonia Orozco (32.292°S 54.117°W) | | | | | | |
| GP4-9 | 100 | 160.0 | 48.5 | 6.9 | 39.9 | −72.6 |
| GP4-7 | 70 | 166.4 | 51.3 | 2.3 | 33.9 | −78.5 |
| GP4-2 | 15 | 354.7 | −45.2 | 13.4 | 264.9 | 82.8 |
| GP4-1 | 0 | 351.7 | −41.2 | 13.9 | 263.6 | 78.7 |
| Buena Vista Fm. – Site 5, Colonia Orozco (32.229°S 54.117°W) | | | | | | |
| GP5-14 | 200 | 16.4 | −41.4 | 4.3 | 9.7 | 73.3 |
| GP5-11[a] | 190 | 255.4 | 37.0 | 15.7 | 226.7 | −22.8 |
| GP5-9a | 145 | 40.4 | −54.4 | 17.9 | 51.8 | 56.5 |
| GP5-9b | 145 | 41.1 | −51.5 | 11.4 | 47.2 | 55.2 |
| GP5-8 | 145 | 43.9 | −50.1 | 5.8 | 45.9 | 52.8 |
| GP5-8/9 mean | 145 | | | | 48.2 | 54.9 |
| GP5-7 | 140 | 7.5 | −57.5 | 10.8 | 82.3 | 81.5 |
| GP5-6 | 75 | 146.9 | 77.5 | 18.8 | 326.4 | −50.8 |
| GP5-4 | 70 | 188.7 | 77.5 | 5.8 | 299.6 | −55.8 |
| GP5-3 | 0 | 326.4 | −61.9 | 9.5 | 183.8 | 61.5 |
| Buena Vista Fm. – Site 6, Colonia Orozco (32.287°S 54.114°W) | | | | | | |
| GP6-9 | 120 | 175.0 | 52.6 | 11.0 | 22.5 | −85.7 |
| GP6-8 | 100 | 137.7 | 58.4 | 9.6 | 12.4 | −55.3 |
| GP6-7 | 80 | 176.7 | 55.5 | 3.8 | 341.0 | −85.4 |
| GP6-6 | 50 | 172.1 | 52.1 | 4.3 | 30.1 | −83.3 |
| GP6-5 | 40 | 170.1 | 54.1 | 4.1 | 17.3 | −81.4 |
| GP6-4[a] | 30 | 222.6 | 1.1 | 3.4 | 186.3 | −38.9 |
| GP6-3[a] | 0 | 337.4 | −54.1 | 2.4 | 202.6 | 71.0 |
| Yaguarí Bentonites – (32.336°S 54.344°W) | | | | | | |
| ME15-2 | 65 | 334.3 | −13.4 | 4.2 | 256.9 | 55.0 |
| ME15-4b[a] | 45 | 243.6 | 46.2 | 3.9 | 228.4 | −35.4 |
| ME15-5[a] | 30 | 189.9 | 43.1 | 2.4 | 178.1 | −78.7 |
| ME15-5c[a] | 30 | 290.8 | 31.9 | 3.5 | 241.5 | 7.3 |
| ME15-6 | 15 | 174.6 | 66.1 | 12.5 | 318.3 | −73.4 |
| ME15-8[a] | 0 | 74.4 | −20.5 | 9.1 | 36.5 | 18.8 |
| Yaguarí Fm. – (32.318°S 54.134°W) | | | | | | |
| ME15-14 | – | 2.3 | −35.0 | 3.2 | 315.4 | 76.8 |
| ME15-16 | – | 326.7 | −10.7 | 3.9 | 249.6 | 48.9 |
| GP3-1a | – | 174.5 | 23.8 | 14.3 | 110.4 | −69.5 |
| GP3-2a | – | 215.8 | −33.3 | 6.9 | 165.3 | −29.0 |
| GP3-3[a] | – | 147.1 | −18.0 | 0.3 | 83.0 | −37.9 |
| GP3-5 | – | 102.4 | −43.1 | 0.3 | 63.4 | 3.6 |
| GP3-6 | – | 167.9 | 80.7 | 12.0 | 311.7 | −49.9 |
| GP3-7[a] | – | 118.1 | −5.3 | 0.3 | 54.1 | −21.9 |
| GP3-8[a] | – | 137.1 | −11.7 | 12.6 | 71.0 | −34.1 |

* Lat. and Long. are the site coordinates; Elev. is the relative elevation of the sampled layers; Dec. and Inc. are the declination and inclination of the remanence; MAD is the maximum angular deviation; VGP-long and VGP-lat are the coordinates of the virtual geomagnetic poles. Shaded lines indicate specimens from the same level for which a mean was calculated.

[a] Sites rejected for the overall means.

Yaguarí Formation and contains at least two intercalated, poorly developed paleosols bearing numerous thin plant roots (Piñeiro, 2004; Piñeiro et al., 2012), but there are no datable bentonites in this formation. The BVF includes red fine -to medium-grained sandstones of alluvial-fluvial and aeolian origin, including pelitic intercalations and intraformational conglomerates (Fig. 3). It is divided into the Colonia Orozco and the Cerro Conventos members (De Santa Ana et al., 2006), the latter corresponding to the upper part, and including paleodunes in the type locality. The lower member includes conglomerates, which are rich in fossils. Basal synapsids (particularly varanopids) (Piñeiro et al., 2003), basal diapsids (Piñeiro, 2004; Ezcurra et al., 2015), temnospondyls (Piñeiro et al., 2007a, 2007b, 2007c; 2012) and procolophonoids (Piñeiro et al., 2004; Velozo, 2017) are the main groups recovered from the conglomerates. This fauna was considered as transitional between the Permian and the Triassic continental communities (i.e., Piñeiro et al., 2012), although for some authors both the BVF in Uruguay and the Sanga do Cabral Formation (SCF) in Brazil may be only Triassic in age (i.e., Dias-da-Silva et al., 2006). This proposal follows the view of Andreis et al. (1980), who stated that the SCF was deposited in a continental Triassic depocenter in southern Brazil that extends into Uruguay, where it is called the Buena Vista Formation (BVF). The faunal content (Dias-da-Silva et al., 2017) points to an Early Triassic age for the SCF by the overwhelming presence of *Procolophon* remains in almost all fossil-bearing strata. However, the fossils in the SCF are almost always represented by disarticulated- and often fragmented-bones, for which Bertoni et al. (2008) identified different diagenetic patterns in both bones and concretions from the same layer, meaning that these deposits are time-averaged, but the exact extent of this phenomenon cannot be determined precisely.

## 3. Paleomagnetic work

### 3.1. Sampling and sample preparation

The paleomagnetic sampling was performed on four sections of the BVF, one section of the Yaguarí Formation (including the overlying bentonite layer) and one of the Paso Aguiar Formation near the city of Melo, in northern Uruguay (Fig. 1). Sampling sites are located within a small area of less than 10 km in latitude, and no faults were observed in the area. Mesozoic dikes are mapped south of the sampling area (Fig. 1). A thin dike crops out cutting Route 7 to the south of site ME15-1/9 which was not sampled due to the deep weathering of the rocks. All sections are flat-lying with maximum dips of 2-4° to SW measured in the Yaguarí section. Standard paleomagnetic cores were collected from six sampling sites and 55 different stratigraphic levels, covering a few meters in each site. Cores were cut using a gasoline-powered drill and oriented using both magnetic and solar compasses whenever possible. From the Bañados de Medina bentonites, eight different levels were sampled extracting small hand blocks as the rocks were too soft to cut cylinders. In the laboratory, samples were prepared into specimens (2.5 cm diameter and 2.2 cm long) and stored in a magnetically shielded room in the Laboratory of Paleomagnetism, University of São Paulo, Brazil.

### 3.2. Rock magnetism

The thermomagnetic curves (susceptibility vs. temperature; Fig. 4) for samples from the studied outcrops showed irreversible behaviors indicating some mineralogical transformation after heating. In general, it is possible to note an inflection near the Curie temperature of magnetite (~560–580 °C) indicating the presence of this mineral, although with low initial susceptibilities. However, the large increase of susceptibility during cooling in all samples is due to the formation of magnetite. The reduction of goethite or hematite under heating could produce a new (authigenic) magnetite as seen in the thermomagnetic curves. Therefore, it is probable that the magnetic minerals in the Buena Vista-Yaguarí samples are affected by weathering. Some samples have a very weak magnetic signal (Fig. 4d) and seem not to be good candidates for keeping stable magnetic records.

The hysteresis curves (Fig. 5a, b, c) for the BVF samples are of the wasp-waisted type indicating the presence of a mineral assemblage of different types. The isothermal remanent magnetization (IRM) curves (Fig. 5d) show that magnetization saturation requires fields up to 2500 mT, except for the Yaguarí (GP3-1) samples, indicating the presence of high coercivity minerals such as hematite or goethite plus a low coercivity phase such as magnetite.

### 3.3. Identification of the magnetization components

Samples were submitted to AF-magnetic cleaning up to 70 mT and/or to thermal cleaning (up to 680 °C); thermal cleaning was preferred as the AF method, in many cases, was not efficient to eliminate secondary magnetic components or to reveal the characteristic magnetization due to noise. Some samples retained about 70% of the remanence intensity after submitted to fields of 80 mT; in other cases, the signal became very noisy for fields greater than 30 mT. Thermal demagnetization was

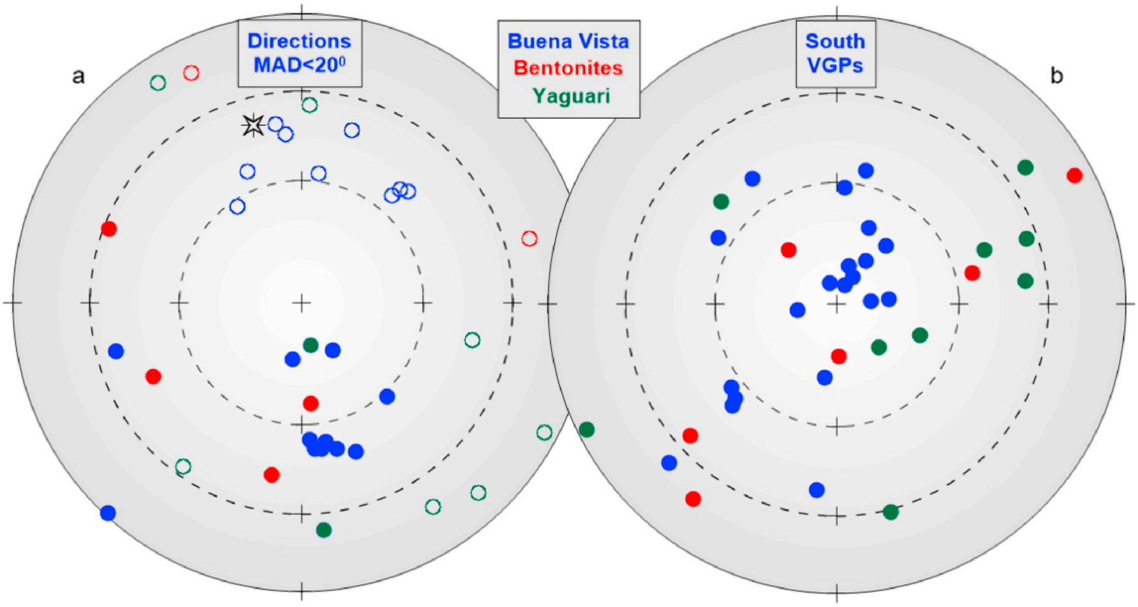


**Fig. 7.** a) Remanent magnetizations for specimens of the Buena Vista and Yaguarí formations on a stereogram (left). Open (full) symbols represent negative (positive) magnetic inclinations. Only results with MAD < 20° are shown. The star represents the present geomagnetic field in the study area. b) Corresponding virtual geomagnetic poles (right)for the same specimens as seen from the south pole. Color code applies to both figures. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)


**Fig. 8.** Green to brownish mudstone change at the top of the Yaguarí Formation. A. Panoramic view of the outcrop Baeza, Cerro Largo County. B. Detailed photograph of the mudstones containing thin intercalated layers of bentonite. C. A level showing high mortality of bivalves and conchostracan (red arrow) associated with the green-brownish color transition layer and the deposition of the bentonites (white arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

performed after some initial steps of AF demagnetization, and magnetization was erased at temperatures above 600 °C or near the unblocking temperature of hematite (Fig. 6). We used a 2G cryogenic magnetometer to measure the remanent magnetization.

Magnetic components were identified and calculated using the Remasoft/Agico software (Fig. 6); large secondary magnetizations were common, sometimes not completely removed. Best results came from the sections GP4, GP5 and GP6 from the BVF, even so, there was considerable within-site dispersion. Great circles analysis (Fig. 6) performed for the BVF samples gave a mean direction in accordance with the isolated components in the majority of the individual specimens. For the bentonites, the best-determined remagnetization circles converge to a mean direction that is discrepant from the BVF result and not compatible with the expected directions produced for the paleomagnetic field at the Late Paleozoic times.

The most stable components of magnetization identified in the specimens are displayed in Table 1 and Fig. 7. The majority of sampling sites showed large within-site dispersion, particularly the Paso Aguiar (no reliable results) and the Yaguarí formations. For this reason, the figure and table show the result per specimen and considering only the most reliable (MAD < 20°). Both normal and reversed polarity components were identified in all outcrops. The means of the normal and reversed directions differ by about 10° in inclination indicating a negative reversal test, however, the statistical parameters are too bad to consider a conclusive test. The basal samples from the Yaguarí section (GP3 in Table 1) are too scattered with no within site consistency

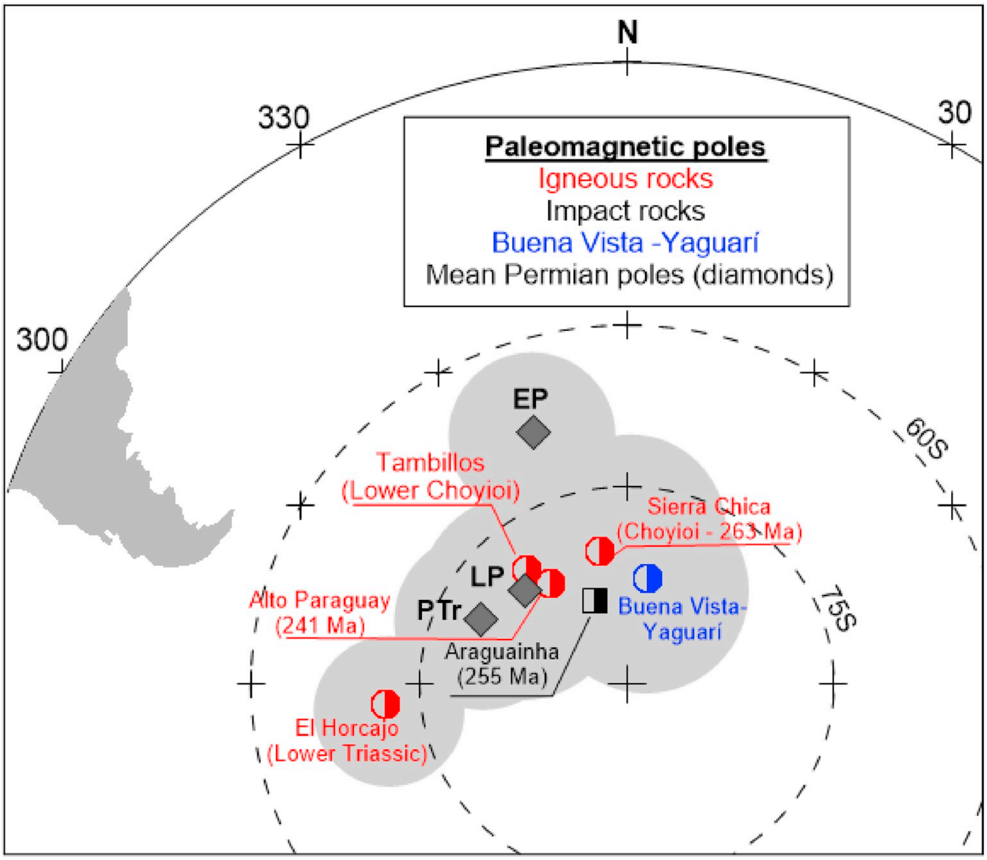


**Fig. 9.** The Buena Vista-Yaguarí paleomagnetic pole (blue symbol) compared to available Choiyoi poles and some other Permo-Triassic poles based on well-dated igneous rocks from South America. Red symbols refer to poles from igneous rocks and the square represents the Araguainha impact rocks (Yokoyama et al., 2014). Numbers in brackets are the radiometric ages. Half-full symbols indicate mixed polarities. Full diamonds are mean poles for the Early Permian (EP), Late Permian (LP) and Permo-Triassic (PTr) according to Domeier et al. (2011). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

perhaps due to the presence of the fine conglomerates.

The virtual geomagnetic poles (VGPs) corresponding to each selected magnetization direction (Fig. 7B) concentrate within a distance of 30° from the geographic pole, but when considering all VGPs their distribution has an elongated pattern mainly caused by the scattered results from the Yaguarí Fm. and the bentonites. However, considering the presence of both normal and reversed polarities, some transitional VGPs can be expected.

## 4. Discussion and conclusions

### *4.1. Geological and paleontological considerations*

The Yaguarí and the Buena Vista formations here under study have been the subject of litho, bio and chronostratigraphic controversy. For instance, Elizalde et al. (1970) considered the Yaguarí and the Buena Vista formations as a single unit, the Yaguarí Formation, divided into the lower San Diego member and the upper one Villa Viñoles. A basal section plus one in the middle and other at the top can also be differentiated at the Villa Viñoles member. Subsequent studies (Ferrando and Andreis, 1986; Bossi and Navarro, 1991) followed the same line of evidence of Elizalde et al. (1970) but considered the middle layer and the top of the upper member (Villa Viñoles) as a different unit, the Buena Vista Formation. Thus, while the lower part of the succession that includes the Yaguarí-like deposits shows a typical deltaic faciologic arrangement containing levels of predominantly multicolor limolites and very fine-grained sandstones (although also including some dark, reduced levels at the base), the middle and upper Buena Vista-like sections grade to fine- and medium-grained sandstones with oxidative pink and brownish-red colors (Bossi, 1966; Bossi and Navarro, 1991; Goso et al., 2001). At the base of the upper member of Elizalde et al. (1970) (the Colonia Orozco Member of De Santa Ana et al., 2006), several levels of fossiliferous intraformational conglomerates are intercalated in the red sandstones (Fig. 3). This package represents the establishment of a continental fluvio-aeolic environment including the well-developed dunes of the Cerro Conventos, the upper (or maybe lateral?) member of the BVF according to De Santa Ana et al. (2006). Therefore, our investigations support more the Elizalde et al. (1970) hypothesis that the Yaguarí and Buena Vista deposits represent a single unit with two members, rather than two separate and sufficient well-distinguished formations.

The Yaguarí and the Buena Vista formations historically correlate to the Brazilian Rio do Rasto (Falconer, 1930, 1937) and Sanga do Cabral formations on the basis of their lithostratigraphic similarities (Caorsi and Goñi, 1958; Andreis et al., 1980, Andreis and Ferrando, 1982) (Fig. 2A). However, we found scarce coincidence among the fossil indexes that characterize the faunal communities present in both countries. Even though the whole assemblage found in the BVF (Late Permian) is in general taxonomically equivalent to that present in the SCF (Early Triassic), both dominated by temnospondyls but with important representation of procolophonoid and protorosaurid reptiles (Barberena et al., 1985a, 1985b; Piñeiro, 2004, 2006; Dias-da-Silva et al., 2006; Dias-da-Silva and Schultz, 2008; Da-Rosa et al., 2009; Piñeiro et al., 2012; Ezcurra et al., 2015; Velozo, 2017). It is worth noting that all these taxa have representation since the Late Permian in the fossil record from outside the Paraná Basin (see Langer et al., 2007; Langer and Lavina, 2000). Therapsids are intriguingly absent from both lithostratigraphic units, with the only exception of some isolated and fragmentary remains found in the SCF that were assigned to non-mammalian therapsids (Schwanke and Kellner, 1999; Langer and Lavina, 2000; but see Dias-da-Silva et al., 2017; Abdala et al., 2002). As a pinpointing contrast, basal synapsids are common in the Uruguayan deposits (Piñeiro, 2002; Piñeiro et al., 2003), at least at the basalmost conglomerate levels (Fig. 3). Also intriguing is the presence of possible diadectomorph-like vertebrae recently described from the SCF (Piñeiro et al., 2015, but see also Dias-da-Silva et al., 2006, 2017; Modesto and

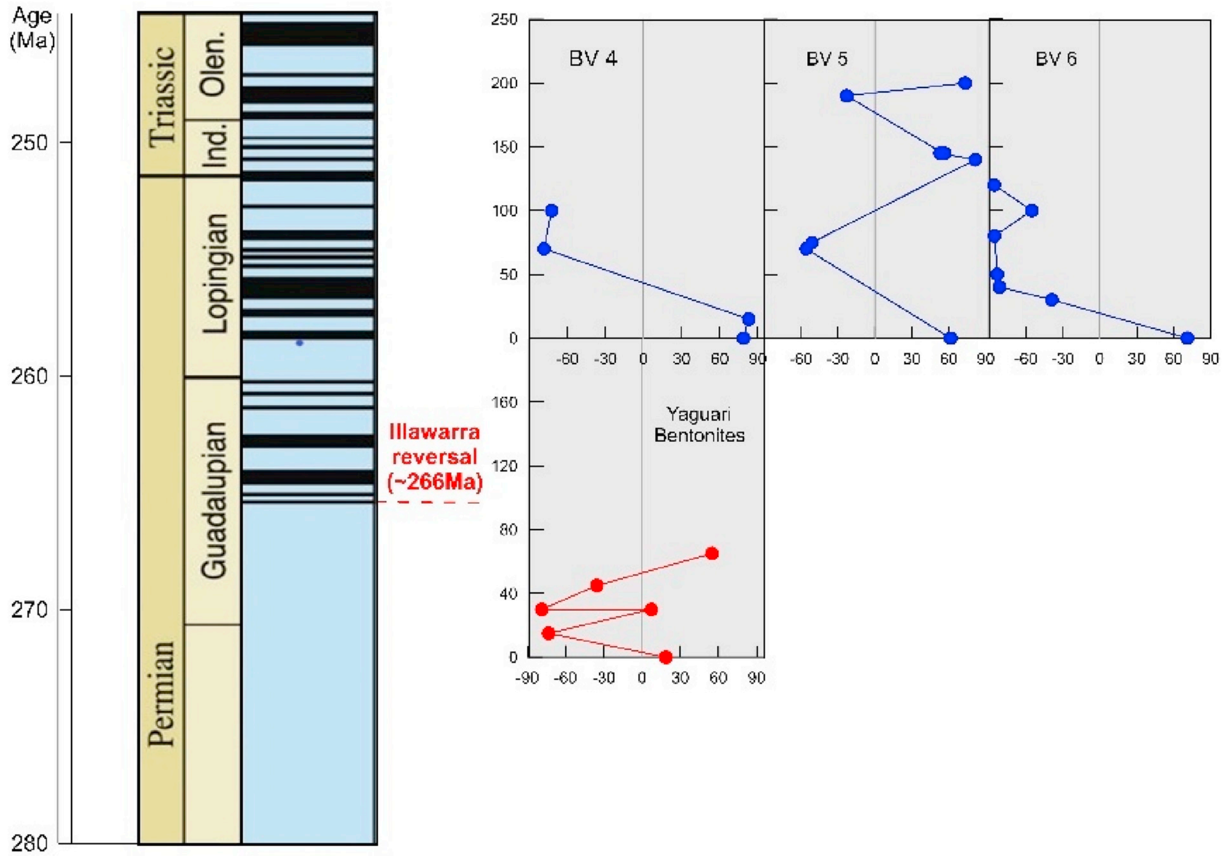


**Fig. 10.** (Left) Geomagnetic polarity scale (modified from Kirschvink et al., 2015) or the middle-late Permian and Early Triassic, showing the first reversal (Illawarra) after the Permo-Carboniferous Reversed Superchron (Kiaman). (Right) Variation in the VGP latitudes in the investigated sections. Negative (positive) latitudes correspond to the reversed (normal) polarity of the geomagnetic field. Elevations are relative stratigraphic positions measured in cm.

Botha-Brink, 2010), and other not yet described specimens that show affinities with Permian taxa (Jorge Ferigolo personal comment, 2013; G.P. personal observation).

A possible explanation for this apparent temporal diachronism between the SCF and the BVF can be related to the fact that there is a transitional, rather than an abrupt, sharp change in the sedimentation of the Yaguarí and the Buena Vista formations. The transition includes grey to reddish multicolor mudstones, carrying the bentonites (Piñeiro et al., 2012) (Fig. 8), also described for the Rio do Rasto Formation (Warren et al., 2008) and dated as Middle-Late Permian (Cisuralian-Early Guadalupian, Di-Pasquo Lartigue et al., 2018) that grade to brownish-red sandstones bearing the fossiliferous conglomerates of the BVF. Moreover, the Brazilian Rio do Rasto Formation has a transitional contact with the overlying aeolian sandstones of the Piramboia Formation (according to Warren et al., 2008), which in turn is overlain by the Sanga do Cabral Formation, which occurs only at the southern end of the Brazilian portion of the Paraná Basin, in Rio Grande do Sul State. The Piramboia Formation seems to be absent in Uruguay or it overlies the BVF as it does the also aeolian in origin, Cerro Conventos Formation (De Santa Ana et al., 2006). Therefore, the stratigraphic arrangement may appear to be different in both the successions, unless we consider the Cerro Conventos sandstone to be stratigraphically equivalent to the Piramboia Formation from Brazil, and both representing lateral migrations of large aeolian dunes in deltaic plains. In these planes distributary channels are predominant with a rectilinear character such as the observed in the upper Morro Pelado Member of the Rio do Rasto Formation (Warren et al., 2008) and possibly, in the BVF intraformational conglomerates. Such lithostratigraphic arrangement would suggest that the BVF may be equivalent to the uppermost section of the Rio do Rasto Formation, with both grading conformably into desertic or semi desertic (considering the SCF) continental system in the Triassic (Warren et al., 2008) (See Fig. 2B).

Some of the fossils recovered from the Buena Vista basal conglomerates – such as a possible tupilakosaurid mandible described by Piñeiro (2004) – show affinities with specimens collected at the upper part of the Rio do Rasto Formation (G.P. personal observation). Accordingly, a dipnoan dental plate recovered from the Yaguarí uppermost mudstones shows morphological similarities to materials described from the Rio do Rasto Formation (see Richter and Langer, 1998; Toledo and Bertini, 2005). All these fossils will be described in detail in a forthcoming paper. Thus, it is possible that the fossiliferous conglomerates intercalated in the Buena Vista red sandstones have been formed by the reworking of basal layers possibly equivalent (or chronologically close) to the Brazilian Permian Rio do Rasto rather than to the Triassic SCF. This hypothesis is partially supported by the paleomagnetic studies performed herein, as explained below.

### 4.2. Paleomagnetic considerations

The characteristic magnetization components from the Buena Vista and Yaguarí (BVY) formations allowed the calculation of a paleomagnetic pole (Fig. 9) with coordinates 82.3 °S 11.1 °E (N = 23; k = 12; $\alpha_{95}$ = 9.1°) giving unit weight to the VGPs and after a cutoff according to the Vandamme's (1994) method. Sites excluded from the mean are indicated in Table 1; to avoid bias very similar results from the same stratigraphic level (GP8, GP9a, and 9b) were grouped in a mean before pole calculation. The BVY pole places the sampling area at ~34 °S at the time of the magnetization acquisition, but not necessarily at the deposition time.

The BVY pole is comparable to other Permo-Triassic poles for South America and correlates well with paleomagnetic poles for the Choiyoi rhyolitic province of Chile and Argentina. This magmatic activity was emplaced at the SW margin of Gondwana during the Permian and is thought to be the source for the ash flows deposited during the Yaguarí times.

Shrimp U–Pb zircon crystals from the volcanic-sedimentary Choiyoi sequences (Rocha-Campos et al., 2011) placed this magmatism in the time span from 281 ± 2.5 Ma (Artinskian) to 251.9 ± 2 Ma (Permo-Triassic boundary). Similar results were reported by Sato et al. (2015) based on six U–Pb data (~279–253 Ma). Therefore, the Yaguarí bentonites (269.8 ± 4.7 Ma; Calarge et al., 2006) are in good agreement with that of the major Choiyoi flare-up at 269–263 Ma (Nelson and Cottle, 2019).

The BVY pole is based on normal and reversed polarity magnetizations, as are the Choiyoi poles, placing those units in post-Kiaman. The first mixed polarity superchron postponed to Kiaman (the Illawarra event) started at 265.8 ± 0.7 Ma (Bowring et al., 1998; Wardlaw et al., 2004) or even earlier at 266.66 ± 0.76 Ma (Hounslow and Balabanov, 2016) so that the radiometric age of 269.8 ± 4.7 Ma for the bentonitic layer of the Yaguarí Formation matches well with the Illawarra event, placing the overlying sedimentary package in post-Kiaman times.

The BVY paleomagnetic pole, although not a reference pole, helps to constrain well the age of the BVY sequence, although the indicated age must be seen as minimum age due to the eventually unremoved secondary magnetization components. It is mainly based on the results from the sections GP4 to GP6, which gave the most reliable results. The magnetic behaviors of these three sections are consistent as seen in Fig. 10. The figure shows the latitude variation of the calculated VGPs from the bottom to the top of the sections. Relative positions of the sampled layers are approximate. The VGPs migrate from one hemisphere to the other as the paleomagnetic field flips from one polarity to the other, and at least one geomagnetic reversal was recorded in each section (maybe more in the Buena Vista section GP5). This is compatible with the reversal frequency during the Middle Permian (Late Guadalupian or Lopingian) as seen in the polarity time scale (Kirschvink et al., 2015).

### *4.3. The Permo-Triassic boundary*

The obtained paleomagnetic data place the Yaguarí bentonites in agreement with the global magnetostratigraphic scheme (Kirschvink et al., 2015) for the Middle Permian (Late Guadalupian) Kiaman superchron and the Buena Vista fossiliferous conglomerates in agreement with the mixed polarities of the Late Permian (Lopingian)-Early Triassic times. According to the fossiliferous assemblage found in the conglomerates, and the absence of discontinuities in the studied succession, a Lopingian age is suggested for the Buena Vista upper deposits. Taking into account the lithostratigraphic and biostratigraphic considerations explained above, we postulate that the Permo-Triassic boundary might be absent in Uruguay because we would have a succession of units that conformly represent the greatest part of the Permian as its fossil content, and the geochronological and paleomagnetic data suggest.

## Author contribution statement

Marcia Ernesto, conceived and designed the research, collected part of the samples, performed the experiments, analyzed the data, and wrote the manuscript, reviewed drafts of the paper, approved the final draft. Graciela Piñeiro, conceived and designed the research, wrote the manuscript, prepared figures and/or tables, reviewed drafts of the paper, approved the final draft. Pablo Nuñez, wrote the manuscript, prepared figures and/or tables, reviewed drafts of the paper, approved the final draft. Pedro L. Xavier, wrote the manuscript, prepared figures and/or tables, approved the final draft. Cesar Schultz wrote the manuscript, reviewed drafts of the paper, and approved the final draft. Leda Sánchez collected part of the samples, wrote the manuscript and approved the final draft.

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