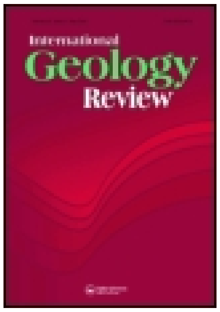

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The Earth's magnetic field prior to the Cretaceous Normal Superchron: new palaeomagnetic results from the Alto Paraguay Formation

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The Earth's magnetic field prior to the Cretaceous Normal Superchron: new palaeomagnetic results from the Alto Paraguay Formation

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We report a detailed palaeomagnetic investigation of 28 lava flows (221 standard palaeomagnetic cores) collected from the Paraguayan part of the Paraná flood basalts (the Alto Paraguay Formation). The initial aims of our study were to (i) document variability of the Earth's magnetic field during the time interval sampled, (ii) obtain a new Early Cretaceous palaeomagnetic pole (PP) for stable South America, and (iii) estimate the extrusion rate of the Paraná magma. We precisely determined the palaeofield direction for 26 sites for which the characteristic remanent magnetizations exhibit small within-site dispersion and high directional stability. No palaeodirections were determined for two sites because of a very complex and erratic behaviour of the remanence during the palaeomagnetic treatments. Nine sites display normal polarity magnetization, whereas nine others are reversely magnetized and the remaining eight sites yield intermediate palaeodirections. The mean palaeomagnetic direction of normal polarity sites give $I = -41.8°$, $D = 4.9°$, $k = 112$, and $\alpha_{95} = 4.9°$, whereas reversely magnetized sites give $I = 37.1°$, $D = 181.4°$, $k = 23$, and $\alpha_{95} = 11.1°$. The reversal test as defined by McFadden and McElhinny (1990; Classification of the reversal test in paleomagnetism: Geophysical Journal International, v. 103, p. 725–729) is positive, corresponding to Type B with $\gamma = 8.7°$ and $\gamma_0 = 3.7°$. This ensures that the palaeomagnetic treatment successfully removed the secondary natural remanent magnetization and that the sampling adequately averaged the palaeosecular variation (PSV). The mean PP position obtained from 18 sites is palaeolongitude (*P*long) = 359.2° and palaeolatitude (*P*lat) = 86.2° S. We show by means of probability plots and formal testing procedures that a Fisher distribution with a concentration parameter $K = 65$ satisfactorily fits the distribution of virtual geomagnetic poles (VGPs). The PP obtained in this study agrees reasonably well with coeval pole positions, in particular with those obtained from the Central Paraná Magmatic Province in Brazil, Los Adobes, and Misiones in Argentina. However, some other similar age PPs show significant departure that may be attributed to local tectonic rotations or insufficient sampling needed to overcome the PSV. This new PP differs slightly from the reference poles at 135 Ma for South America given by Besse and Courtillot (2002; Apparent and true polar wander and the geometry of the magnetic field in the last 200 million years: Journal of Geophysical Research, v. 107, no. B11, p. 2300). The PSV parameters are in agreement with those obtained from selected data reported for the Cretaceous Normal Superchron (CNS). In contrast, VGP angular dispersion found here is lower with respect to the Jurassic and Plio–Pleistocene data. The intermediate VGPs determined in the present geographical frame show a northern hemisphere cluster of seven VGPs located east of India, whereas one other VGP is located in the vicinity of Australia.

Keywords: large igneous province; Paraná flood basalts; palaeomagnetic poles; palaeosecular variation; the Alto Paraguay Formation

Introduction

During geological history, the continental and the oceanic Earth periodically suffered voluminous eruptions of basaltic magmas in intra-plate settings to constitute the so-called large igneous provinces (LIPs). Most of these events, which include continental flood basalts and oceanic plateaus, occurred in the Mesozoic through Cenozoic. There is now a general agreement that LIPs are ascribed to mantle plume hyperactivity and were emplaced in very short time periods of a few million years (Courtillot and Renne 2003; Kelley 2007; Thiede and Vasconcelo*s* 2010, among others). Coffin and Eldholm (1994) estimated that

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giant LIPs account for as much as 50% of the mass and energy expelled from the Earth's mantle into the lithosphere in Cretaceous time. In contrast, today's plume-associated volcanism accounts for only about 5–10% (Stein and Hofmann 1994), suggesting a substantial change in mantle dynamics from the Cretaceous to the present. In addition, an important effect on global climate has been suggested (Wignall 2001; Clive *et al*. 2008). Continental flood basalts seem to be contemporaneous with major mass extinctions since 300 Ma (Courtillot *et al*. 1999; Courtillot and Renne 2003). Oceanic anoxias are also correlated with LIPs. Moreover, widespread evidence indicates that during the Early Cretaceous the climate was considerably warmer, sea level was significantly higher, and episodes of oceanic anoxia and black shale deposition were more frequent (Larson 1991; Larson and Olson 1991; Coffin and Eldholm 1994; Larson and Erba 1999). Another major geophysical event that occurred ca. 125 Ma is the inhibition of geomagnetic reversals. The Cretaceous Long Normal Superchron (duration approximately 35 million years) attests to probable drastic changes at the core–mantle boundary. Courtillot and Olson (2007) proposed that deep mantle plumes link these processes. The variations in mantle convection induce temporal and spatial variations in heat flow at the core–mantle boundary. The plumes may ascend through the mantle on a 20 million year timescale, producing continental flood basalt eruptions, rapid climatic change, and massive faunal depletions. The geodynamo that might have been in an anomalously high-energy state during the Early Cretaceous could explain the Cretaceous Normal Superchron (CNS) (Cande and Kent 1995; Courtillot and Olson 2007) and an anomalous high palaeosecular variation (PSV; McFadden *et al*. 1991). In addition, it has been suggested that a fast true polar wander (TPW) episode occurred at this time (Prévot *et al*. 2000). A very fast TPW is, however, still a matter of debate (Besse and Courtillot 2002).

The whole Cretaceous and more precisely the time interval from 140 to 80 Ma was characterized by extremely intense geodynamic processes in South America with high magmatic activity, continental breakup, and rifting (e.g. Anderson *et al*. 1992; Anderson 1994; Coffin and Eldholm 1994). The Paraná flood basalts (PFBs) extend through southern Brazil, northern Argentina, Paraguay, and Uruguay covering about 1.6 million km^2. The different magma types range from high Ti to low Ti showing only very slight fractionation effects. Its Early Cretaceous age (ca. 134 Ma after Renne *et al*. 1996a) coincides with this period in the Earth's history of major geodynamic changes. The PFB has been the subject of extensive palaeomagnetic studies, yielding a large data base of palaeomagnetic directions (Ernesto *et al*. 1999; Tamrat and Ernesto 1999). Palaeomagnetic data from the Paraná Magmatic Province (PMP) are, however, of low quality because of their poor exposure. In addition, most studies come from the Brazilian part of PFB, whereas some limited data are available from Uruguay (Cervantes *et al*. 2010) and Argentina (Mena *et al*. 2011). In this study, we present new palaeomagnetic directional data from 28 sites sampled in Paraguay.

Brief description of local geology and sampling

The Paraná Basin is an important and large intra-cratonic basin developed exclusively on continental crust and filled with widespread Cretaceous sedimentary and volcanic rocks. It is located in the central-eastern part of the South American Platform (Figure 1). This basin comprises a thick (~6000 m) sedimentary–magmatic sequence that covers an area of approximately 1,600,000 km^2 in Brazil, Uruguay, Argentina, and Paraguay. In Paraguay, the Paraná–Etendeka basalts are named the Sapucaí Magmatic Suite or the Alto Paraguay Formation (Harrington 1950; Putzer 1962). They extend in a N–S direction, along the

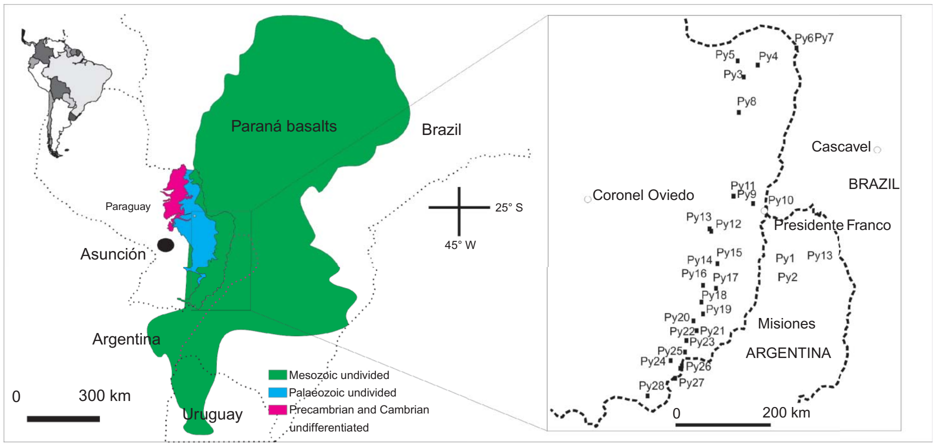

Figure 1. Simplified geologic map of eastern Paraguay (right) showing the location of studied sites (left). The lavas sampled here represent the road.

Paraná River, and are correlated with Serra Geral (Brazil), Curuzú Cuatiá-Posadas (Argentina), and Arapey (Uruguay) formations. De Salvo (1991) suggests a variable thickness between 37 and 90 m covering an area of 25,000 km^2 (Fariña 2009).

The PFB lies on the Iratí Formation, which belongs to a Permian sedimentary sequence (Daemon and Quadros 1970; Santos *et al*. 2006; Rohn 2007). The study area is located at the eastern border of Paraguay (Figure 1). The best outcrops are found in Nakunday quarry located near Santa Rita village (25° 45′53.88″ S and 55° 7′53.67″ O) in eastern Paraguay. The thickness of massive basalts is generally more than 10 m, whereas the total altitude difference reaches 227 m in our sampling area. Because the sampling is performed along the road cuts (occasionally quarries) and not along vertical sequences with known relative stratigraphy, an estimation of total thickness involved is impossible.

Locally, the flows include blocks of dark pelitic and whitish carbonatic sediments from the Iratí Formation uprooted by the basaltic extrusion. A conspicuous feature of these xenoliths is their mottled appearance due to greenish-black inclusions in the sediments. At the same time, sedimentary material occurs inside the basalts. Some fractures are filled by spathic calcite. The basalts are olive-green (5Y 4/1) to brownish or orange-black (5YR 2/1, 5YR 4/1) and microporphyric due to the presence of some crystals of grey-green pyroxene and plagioclases from intersertal to subophitic matrix related to the position inside the flow. Opaque minerals represent approximately 12% volume and around 5% volume consists of secondary minerals. Apatite needle-like crystals appear disseminated in the matrix. Opaque granules and fern devitrification textures are common tabular crystals of secondary minerals (specularite). Some native copper is also observed here, probably related to hydrothermal fluids (Pinto *et al*. 2006) or deuteric alteration. In some sectors, basalts have zoned amygdule (7 mm) filled dominantly by phyllosilicates.

This study is part of an inter-institutional effort to study huge PFBs. Ernesto *et al*. (1990) reported a comprehensive palaeomagnetic study from more than 300 sites belonging to PFB. This pioneering study, however, presents a major limitation because only three orientated hand samples per site are investigated and thus does not meet some basic criteria to study the fine characteristics of geomagnetic PSV (Biggin *et al*. 2008). The same is true for the study conducted by Mena *et al*. (2006), who only used one or two hand samples on the Argentinean part of PMP (the Posadas Formation). The recent study conducted by Mena *et al*. (2011), again on the Argentinian part of Paraná lavas, is definitively of high palaeomagnetic standard. However, the magnetic mineralogy is quite complex – many of the studied sites show evidence for a self-reversal of the thermoremanent magnetization. This proves that, from a palaeomagnetic point of view, the PFB is inhomogeneous, and thus more studies are needed.

In total, we took 221 standard palaeomagnetic cores from 28 sites (Figure 1) distributed along road outcrops of eastern Paraguay during the 2009 sampling campaign. Between 6 and 10 cores were distributed throughout each flow both horizontally and vertically. All lava flows sampled are subhorizontal (dip less than 3°). In general, samples were obtained with the hope of collecting rocks with the finest grain size. Cores were obtained using a gasoline-powered portable drill and then orientated with the help of a magnetic compass and in most cases also with a sun compass.

Rock-magnetic and palaeomagnetic measurements

Continuous susceptibility measurements

In order to identify the carriers of the remanent magnetization and to obtain information on their thermal stability, low-field susceptibility measurements (*K–T* curves) in air were carried out with a Kappabridge (KLY-3) susceptibility meter equipped with a furnace in the palaeomagnetic laboratory of Saint Maur (Institut de Physique du Globe de Paris). One sample per site was heated to about 600°C at a heating rate of 10°C/min and then cooled to room temperature at the same rate. Curie temperatures were determined by means of the Prévot *et al*.'s (1983) method.

Four major types of behaviour were identified. Only a few samples (11% of total) yielded evidence of a single ferromagnetic (magnetite) phase (Type A) that remains stable during the heating–cooling cycle (Figure 2). The majority of samples (72% of total) indicate evidence of Ti-poor titanomagnetites (Type B), but the heating and cooling curves show a strong irreversibility, probably due to the oxidation process during the laboratory heating. Type C behaviour (Figure 2, sample 09P034C) is characterized by two major magnetic phases (Curie temperatures range between 320°C and 365°C for the first one and between 540°C and 580°C for the second one) during the heating process, whereas only magnetite (or Ti-poor titanomagnetite) is detected during the cooling process. Such a behaviour may be attributed to the presence of (titano) maghemite that transforms to almost pure magnetite at relatively low/medium temperatures. Type 4 is basically similar to Type 3 (sample 04P183C). The only difference is that at least three phases (with Curie temperatures at ∼350°C, 520°C, and 585°C) are detected during the heating process, whereas only two of them subsist during the cooling process. This unusual behaviour in basaltic rocks is probably due to the coexistence of (titano)magnetites and (titano)maghemites with variable titanium content.

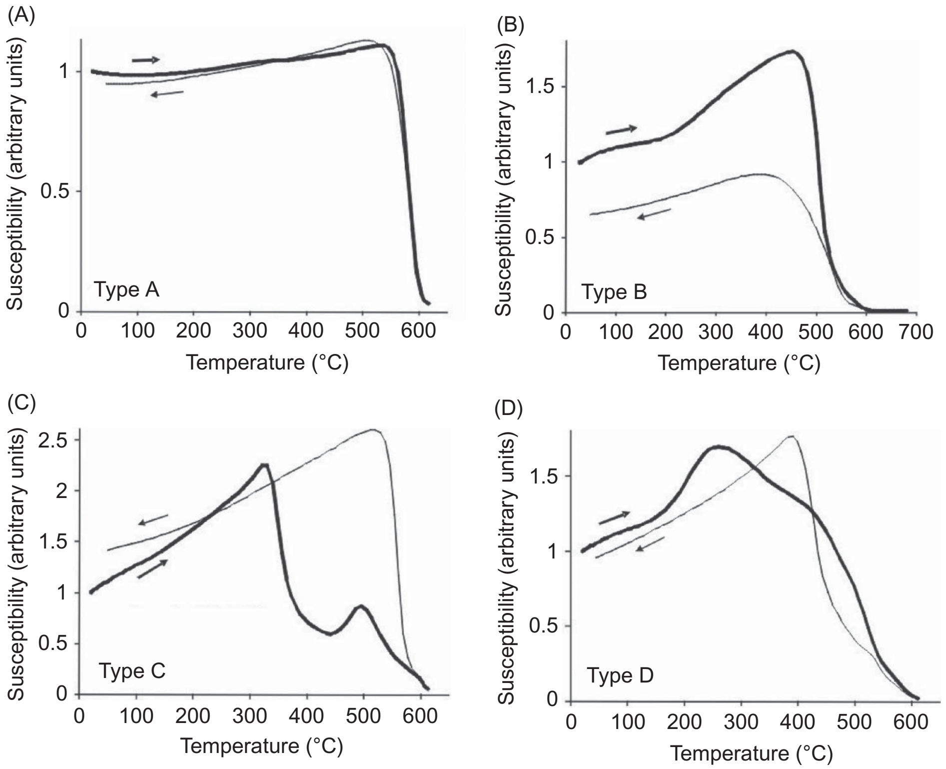

Figure 2. Susceptibility versus temperature (in air) curves of representative samples. The arrows indicate the heating and cooling curves. (A) 09P206C, (B) 09P099B, (C) 09P034C, and (D) 09P183C.

Hysteresis cycles

Hysteresis measurements at room temperature were performed on one sample per site using home-made (IPGP, Saint Maur, France) electromagnets in induction fields up to 0.65 T. The saturation remanent magnetization (J_{rs}), the saturation magnetization (J_{s}), and the coercive field (H_{c}) were calculated after correction for the paramagnetic contribution. The coercivity of remanence (H_{cr}) was determined by applying progressively increasing backfield after saturation. The typical hysteresis plots are presented in Figure 3. In general, the curves show no evidence of pot-bellied or wasp-waisted forms. $H_{\mathrm{cr}}/H_{\mathrm{c}}$ ratios range between 1.75 and 2.73, while $J_{\mathrm{rs}}/J_{\mathrm{s}}$ values vary from 0.11 to 0.88. The hysteresis parameter values imply that either pseudo-single-domain grains (Day *et al*. 1977) or a mixture of multi-domain (MD) and a significant amount of single-domain (SD) grains (Dunlop 2002) carry the remanence (see Figure 4).

Remanence measurements

Prior to magnetic treatments, a 2 week viscosity index was determined following the procedure described in Prévot *et al*. (1983). This allows the estimation of the capacity of a sample to acquire a viscous remanent magnetization, and is therefore useful to obtain information on its palaeomagnetic stability. Two samples from each site were subjected to these experiments. Viscosity indices varied between 0% and 6.7%, but most values were lower than 5%. Thus, the studied samples have no big capacity to acquire a viscous component.

We analysed the magnetic remanence for all samples (6–10 specimens per site), using both stepwise alternating magnetic field (AF) and thermal demagnetization techniques. AF and thermal demagnetization were performed using a Molspin Ltd demagnetizer and using an ASC TD48 furnace, respectively. Most of the studied samples carry basically a single and stable component of magnetization observed on both AF (Figure 5, sample 09P086A) and thermal (sample 09070A) treatment. A commonly minor secondary component is present but was easily removed after 10 mT or 150°C treatment. The median destructive fields range mostly in 30–40 mT intervals, suggesting the existence of small pseudo-single (mainly) to single-domain magnetic grains as remanence carriers (Dunlop and Ozdemir 1997). The larger part of remanent magnetization in most cases was removed at temperatures between 530°C and 570°C, which suggests that low-Ti titanomagnetites are responsible for magnetization. A particular case is observed for samples from the site PY17 (Figure 5, samples 09P136A and 09P133B). Almost half of the remanence still remains after 570°C, whereas

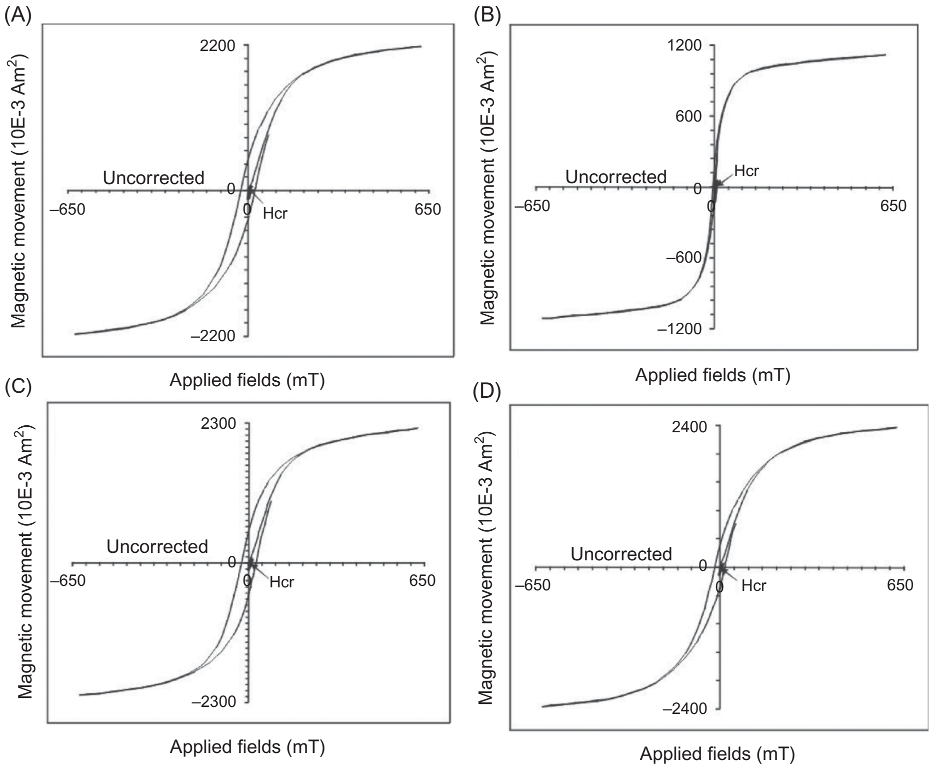

Figure 3. Typical examples of hysteresis loops (corrected for dia/paramagnetism) of small chip samples from the studied volcanic units. (A) 09P006A, (B) 09P034C, (C) 09P089A, and (D) 09P127A).

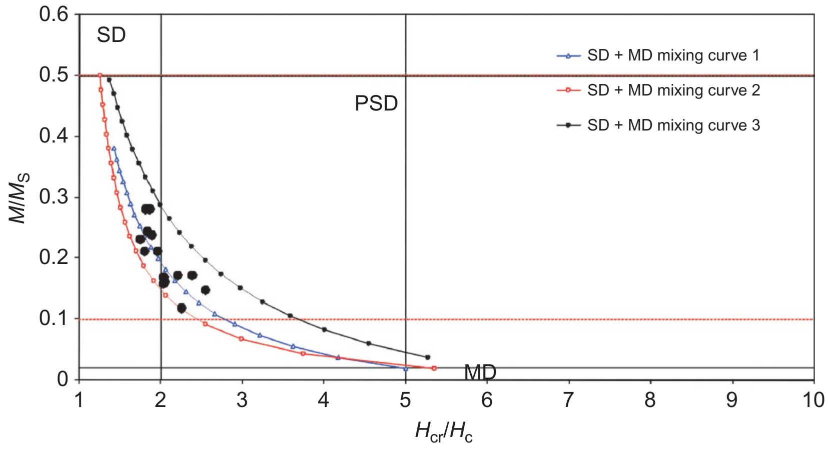

Figure 4. Day plot (Day *et al*. 1977) updated by Dunlop (2002) showing the relationship among different hysteresis parameters.

only one-third of the initial magnetization is removed applying 95 mT AF peak value. These factors indicate that some endmembers of ilmenite–haematite solid solutions carry a large fraction of the remanence.

Main results and discussion

The average unit directions are very precisely determined (Table 1, Figure 6) for 26 out of 28 sites. All α_{95} are less than 7.7°, which points to small within-site dispersion and high directional stability. No palaeodirections were determined for sites PY26 and PY28 because of their very complex and erratic behaviour during the palaeomagnetic treatments. One of the objectives of this study was to calculate a mean palaeomagnetic pole (PP). By definition, a PP has to be calculated from the local field directions that are representative of the axial dipole model. Thus, we need first to identify and exclude the data, if present, representative of the transitional field, i.e. recorded during the period when the geomagnetic field reverses its

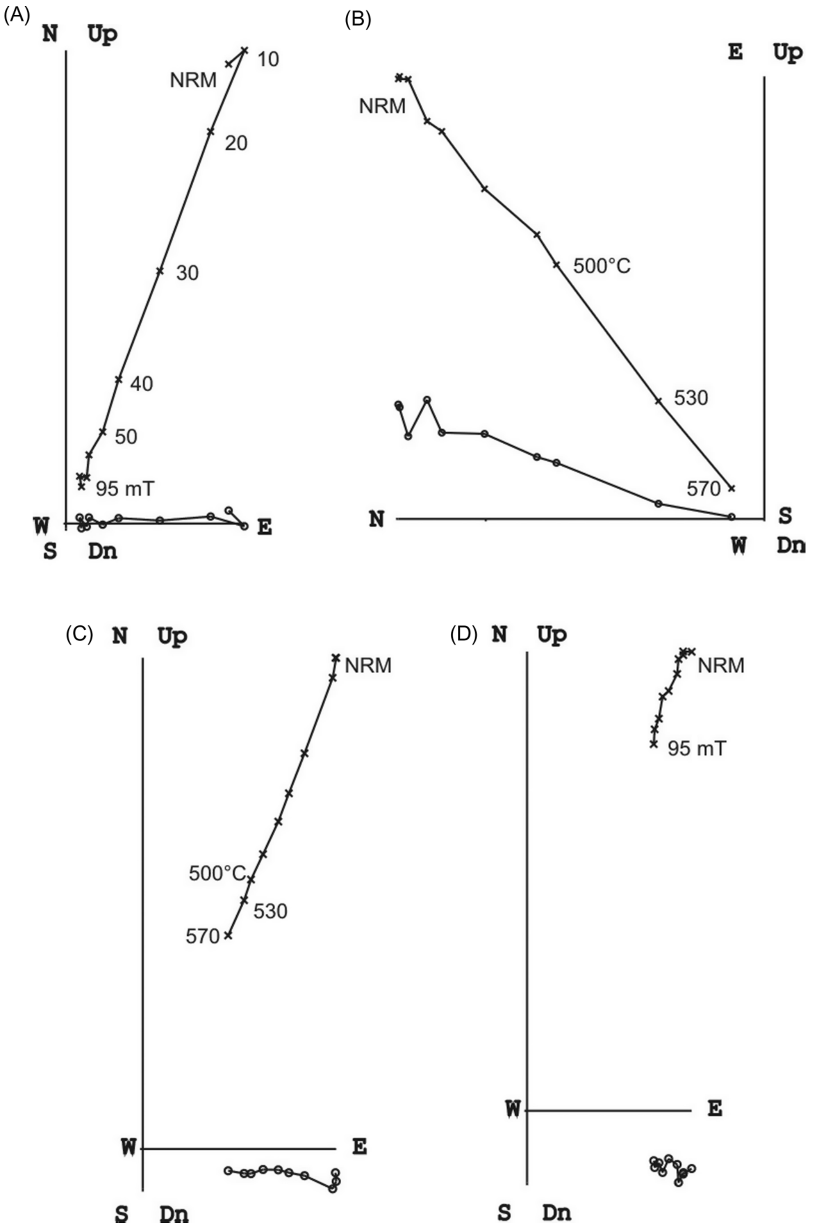

Figure 5. Orthogonal vector plots of stepwise demagnetization of representative samples (stratigraphic coordinates). The numbers refer to the peak alternating fields in mT or temperatures in °C. (A) 09P086A, (B) 09P070A, (C) 09P1364A, and (D) 09P133B.

polarity. Most commonly, virtual geomagnetic pole (VGP) latitudes in the present geographical reference frame are used to delimit the fluctuating field during PSV from the transitional geomagnetic regime. Using this approach, we identified eight transitional VGPs having a latitude of less than ±45° in the present geographical frame as recommended by McElhinny and McFadden (1997) (Figure 7). It should be pointed out that these transitional VGPs are quite precisely determined (Table 1) and must probably have a geomagnetic significance.

Among the 18 VGPs that are kept, two (PY12 and PY14) yielding a rather close location (VGP latitudes in the present geographical frame around 69°) seem to be outliers. However, we believe that there are no strong arguments to reject them from mean pole calculation. The choice of cut-off angle to separate transitional and palaeosecular geomagnetic regimes is still a matter of debate. McElhinny and McFadden (1997) recommend to use a VGP latitude of 45°, whereas Vandamme (1994) proposed a variable VGP cut-off. The VGP latitudes found for PY12 and PY14 exceed even 60° (adopted by some 'most conservative' authors, see Prévot and Camps 1993). The use of Vandamme's (1994) method will keep as well these sites for calculation.

Table 1. Palaeomagnetic results of the studied section.

Site	Latitude (°S)	Longitude (°W)	Altitude	Inc (°)	Dec (°)	α_{95}	*n*	*N*	*k*	PGV lat	PGV long	dp	dm
PY01	24.928	54.942	306	−37.5	5.8	2.3	9	9	562	83.4	359.8	1.6	2.7
PY02	24.676	54.872	274	38.5	175.6	4.9	5	6	188	−85.0	70.7	3.5	5.8
PY03	24.314	54.822	314	−64.8	163.4	4.1	7	7	233	−17.4	113.3	5.3	6.6
PY04	24.194	54.706	317	−32.1	357.7	2.5	7	7	720	82.9	287.3	1.6	2.8
PY05	24.160	54.587	295	39.4	188.2	4.9	7	7	154	−82.2	203.4	3.5	5.9
PY06	24.160	54.587	295	51.4	172.8	3.2	8	8	331	−79.9	342.6	3	4.3
PY07	24.074	54.300	222	49.9	179.2	2.6	8	8	471	−83.3	311.6	2.3	3.5
PY08	24.074	54.300	222	−33.5	358.7	3.9	6	7	297	84.1	293.6	2.5	4.4
PY09	25.508	54.608	150	−45.6	12.7	1.8	10	10	826	78.5	45.9	1.5	2.3
PY10	25.508	54.608	150	−48.7	5.7	3.1	8	8	349	83.5	76.0	2.7	4.1
PY11	25.495	54.694	236	27.2	188.2	2.3	9	9	484	−76.5	161.6	1.4	2.5
PY12	25.778	55.112	248	12.9	173.6	3.3	7	8	330	−69.8	106.2	1.7	3.4
PY13	25.765	55.132	268	48.8	185.3	1.7	9	9	866	−83.9	256.3	1.5	2.2
PY14	25.765	55.132	268	10.4	179.4	4.3	7	8	235	−69.5	123.2	2.2	4.4
PY15	26.045	55.087	217	51.8	193.3	2.3	8	8	558	−76.8	246.9	2.1	3.1
PY16	26.277	55.097	361	−69.4	81.2	3.5	8	8	272	25.9	83.6	5.1	6
PY17	26.277	55.097	361	−66.8	107.4	3.8	9	9	398	9.3	85.9	5.2	6.3
PY18	26.410	55.224	246	−70.5	63.7	3.1	8	8	316	36.3	84.8	4.6	5.4
PY19	26.508	55.222	319	−71.1	88.7	4.8	8	8	143	22.3	87.1	7.3	8.4
PY20	26.671	55.299	170	−44.5	3.8	2.7	7	8	825	86.6	27.1	2.1	3.4
PY21	26.721	55.302	225	−49.1	4.6	7.7	5	8	102	84.8	74.7	6.7	10.2
PY22	26.721	55.338	280	−67.7	76.9	3.9	7	8	198	28.4	80.0	5.4	6.5
PY23	26.795	55.400	244	−46.2	14.2	1.3	8	8	2244	77.4	41.2	1.1	1.7
PY24	26.994	55.559	196	−68.6	51.9	5.5	7	7	121	44.1	81.9	7.9	9.3
PY25	26.927	55.436	167	−70.5	84.8	4.4	7	8	162	24.6	85.3	6.6	7.6
PY26	27.056	55.591		nd	nd	nd	0	8	nd				
PY27	27.083	55.558	134	−38.1	4.2	3.6	7	8	284	83.2	339.3	2.5	4.3
PY28	27.155	55.495		nd	nd	nd	0	8	nd				

Notes: nd, not determined. Dec and Inc are the declination and inclination of the site mean directions; *n* is the number of samples used in site mean calculation; *N* is the total number of specimens demagnetized using either AF or thermal treatments; *k*, α_{95} are Fisher statistical parameters; VGP Long and VGP Lat are longitude and latitude of the VGPs.

An alternative approach to isolate the transitional VGPs is to assume that the mean PP corresponds to the palaeogeographic axis, and thus VGPs having a latitude of less than ±45° in the mean pole reference frame are considered as transitional. Under this assumption, we followed the recommendation of Camps *et al*. (2007) to use an iterative eigenvector analysis, starting with all poles (N–T–R) and removing step by step the furthest VGP until they are all located at an angular distance from the mean axis lower than or equal to 45° (Figure 7). As shown in Table 2, the choice of 18 palaeopoles may be considered as most appropriate and probably reflects the correct estimation of PSV. In case PY12 and PY14 are omitted (Table 3), the value of *K* exceeds 100, a value considered by Prévot *et al*. (2000) as a maximum to faithfully estimate the PSV. To conclude, with this alternative approach, we confirm that the eight VGPs identified as transitional in our first analysis do not have to be included in the mean pole calculation and in the PSV estimate.

In order to calculate the mean PP, VGP locations have been analysed first for both normal and reversed polarities. Nine sites give normal polarity (Figure 6B) and the other nine give reverse polarity (Figure 6C). The mean pole of normal polarity sites gives Lat = 85.2°, Long = 19.9°, and $\alpha_{95} = 4.1°$, whereas reversely magnetized sites give Lat = −86.2°, Long = 150.1°, and $\alpha_{95} = 8.3°$. First, when one of the mean poles is flipped to its antipode, each mean pole lies inside the 95% confidence region of the other. Thus, the reversal test is necessarily positive. Second, this conclusion is strengthened by the reversal test as defined by McFadden and McElhinny (1990), which yields a positive answer corresponding to Type B with $\gamma = 8.7°$ and $\gamma_0 = 3.7$. Thus, the hypothesis of a common mean axis may not be rejected at the 95% level. A positive reversal test ensures that the palaeomagnetic treatment successfully removed the secondary natural remanent magnetization and that the sampling adequately averaged the PSV.

Then, we processed the combined data by reversing the VGPs of reversed polarity to calculate a mean pole. This mean pole obtained from 18 sites (Figure 8) is in the present latitude–longitude grid (*P*long = 359.2°, *P*lat = 86.2°, and $\alpha_{95} = 4.3°$) and differs a little from the reference pole positions for South America given by Besse and Courtillot (2002) for 135 Ma (*P*long = 83.2°, *P*lat = 246.5°, and

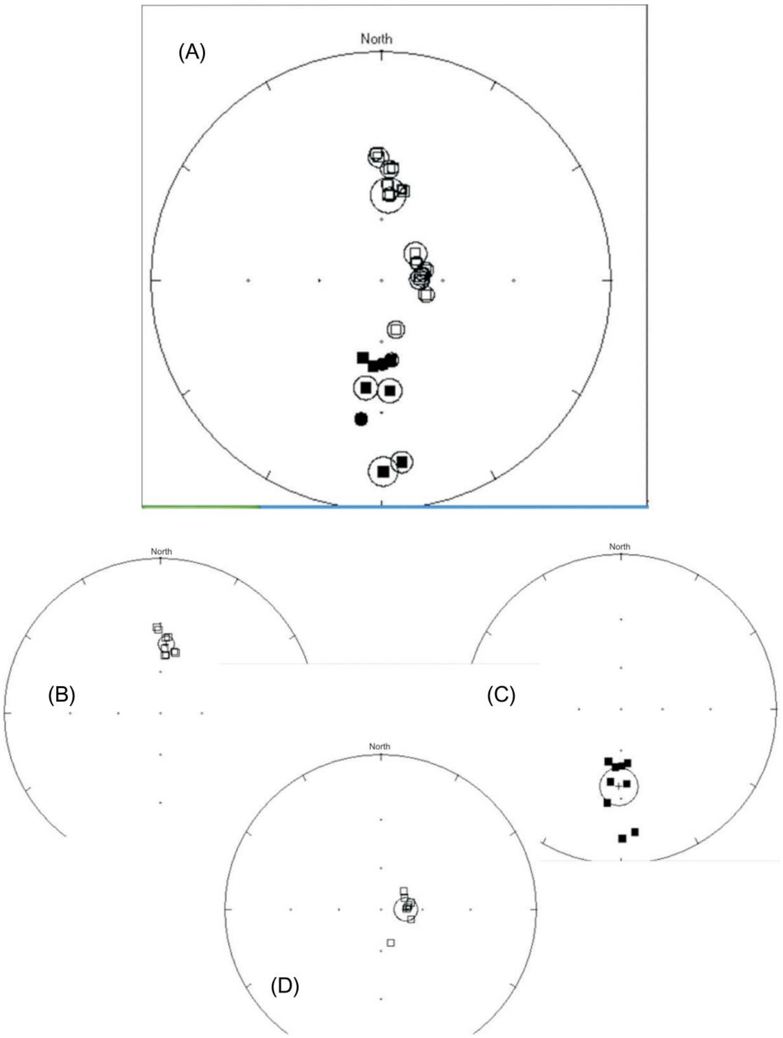

Figure 6. Equal-area projections of the flow mean characteristic palaeodirections for all studied flows (A). Idem for normal (B), reverse (C), and intermediate (D) polarity lava flows.

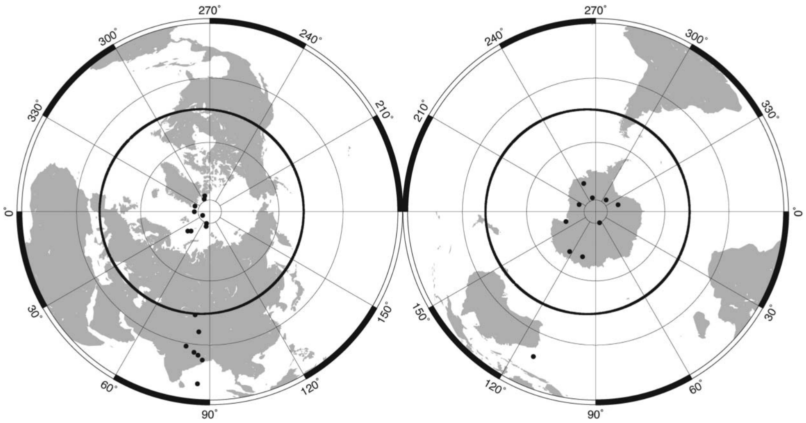

Figure 7. Locations of the VGPs in the present geographical reference frame using the Lambert equal-area projection. The angular distance of 45° from the mean palaeomagnetic axis (north-end *P*long = 359.2°, *P*lat = 86.2°) is represented by bold solid lines.

Table 2. An alternative approach to separate PSV and transitional field (Camps *et al.* 2007; Harrison 2009).

	Mean axis			
N	Longitude (°)	Latitude (°)	Outlier VGPs	Angle (°)
26	65.8	78.6	PY03	80.4
25	67.8	78.1	PY17	69.5
24	65.6	79.3	PY19	57.8
23	61.5	80.8	PY25	57.0
22	56.3	82.2	PY16	57.3
21	49.3	83.6	PY22	56.1
20	39.8	84.8	PY18	50.1
19	23.2	85.7	PY24	45.1
18	359.2	86.2	–	19.5

Notes: First, all directions (N–T–R) are considered for calculating a mean axis. Next, we delete the most departed directions from this axis as shown in the table until we reach a reasonable limit (around 20°). As shown in the table, the choice of 18 directions, including PY12 and PY14, may be considered as the most appropriate and probably reflect the correct estimation of PSV.

Table 3. Calculation of mean palaeodirections.

Mode:	Long (°E)	Lat (°N)	α_{95}	*N*	*k*	Fisherian?
Total $N = 18$ (including PY12 and PY14)						
N	19.9	85.2	4.1	9	156	Yes
R	150.1	−86.4	8.3	9	39	Yes
N + R	359.2	86.2	4.3	18	65	Yes
Total $N = 16$ (PY12 and PY14 are not included)						
N	19.9	85.2	4.1	9	156	Yes
R	241.9	−86.7	7.2	7	72	Yes
N + R	34.1	86.1	3.6	16	106	Yes

Notes: *N* is the number of points used for calculation; *k*, α_{95} are Fisher statistical parameters; Long and Lat are longitude and latitude of PP position.

$\alpha_{95} = 3.4°$). It should be noted that these poles are determined using many more sites. The VGP distribution yields a reasonably good fit with the Fisherian distribution when probability plots as well as formal testing procedures are used (Figure 9). The quantile–quantile (Q–Q) plot for longitudes using the uniform model is approximately linear, passing through the origin with a slope near 45°. The Q–Q co-latitude plot with exponential model is also linear with a slope that gives an estimated $k = 63$. The Q–Q plot for two variables is approximately linear passing through the origin with a slope that gives an estimate of $k = 50$. The fact that estimates of k with co-latitude and two variables tests are in reasonable agreement strengthened the conclusion that the underlying distribution is Fisherian. Employing formal testing procedures, we obtain the following results for the modified statistics of Kolmogorov–Smirnov and Kuiper (D_n^*, V_n^*, $M_\mathrm{U}(V_n)$, $M_\mathrm{E}(D_n)$, and $M_\mathrm{N}(D_n)$; Fisher *et al.* (1987)): longitude test: $D_n^* = 0.655$; $V_n^* = 0.808$; $M_\mathrm{U}(V_n) = 0.736$; co-latitude test: $D_n^* = 0.668$; $V_n^* = 1.024$; $M_\mathrm{E}(D_n) = 0.642$; two-variable test: $D_n^* = 0.607$; $V_n^* = 1.049$; $M_\mathrm{N}(D_n) = 0.613$. The significance probability exceeds 10% for longitude and two-variable statistics, but for the co-latitude test this only happens with D_n^*, whereas V_n^* significance probability exceeds 5% and the $M_\mathrm{E}(D_\mathrm{n})$ statistic lies between the 5% and 1% points, suggesting some very small departure from the Fisher model.

The mean PP of this study is shown in the present geographical reference frame in Figure 8 and listed in Table 4 together with previously published South American poles. In general, the pole obtained in this study agrees reasonably well with other pole positions, in particular with Southern Central Paraná Magmatic Province (CPMP) (Central Paraná), Los Adobes, Misiones, and SAMC poles. However, some other similar age PPs are outliers that may be attributed to local tectonic rotations or insufficient sampling to overcome the PSV. Ernesto *et al*. (1999) argued that PMP poles are somewhat different, indicating unrecognized tectonic disturbances. As a whole, the PMP poles are significantly different from the pole position suggested by hotspot reconstruction (Muller *et al*. 1993), which may be due to TPW or hotspot motion (Cervantes *et al*. 2010). Finally, let us mention that the Alto Paraguay poles obtained in this study slightly differ from the reference poles at 135 Ma for South America given by Besse and Courtillot (2002) based on much larger number of sites.

The formula $S_\mathrm{B}^2 = S_\mathrm{T}^2 - S_\mathrm{W}^2/n$ was used to estimate the PSV, where S_T is the total angular dispersion given by $S_\mathrm{T} = [(1/N - 1)\sum_{i=1}^{N} \delta_i^2]^{1/2}$ (Cox 1969), N is the number of sites used in the calculation, δ_i is the angular distance of the ith VGP from the mean PP, S_W is the within-site dispersion (following McElhinny and McFadden 1997), and n is the average number of samples per site. As shown by Biggin *et al*. (2008), the commonly accepted calculation of the internal dispersion may be affected by some artefacts. We obtained $S_\mathrm{B} = 9.9$ with $S_\mathrm{U} = 13.1$, and $S_\mathrm{L} = 8.0$ (upper and lower limits, respectively), which agrees well with the selected data reported for the CNS. Our data reinforce the hypothesis outlined by Biggin *et al*. (2008) about the different style of secular variation during (and before) the CNS and Plio–Quaternary supporting the link between PSV and reversal frequency.

Because of important palaeo-relief during the extrusion and poor exposure of Paraná basalts, it cannot be ascertained that studied sites follow any stratigraphic order. In any case, three polarity intervals are defined: the lower PFB in Alto Paraguay is normally magnetized, the middle part defined by eight sites yields clearly intermediate polarity, whereas reverse geomagnetic fields typify the top. This polarity sequence is similar to the Misiones section in Argentina studied by Mena *et al*. (2011). However, we found no intermediate lavas. This also agrees with the occurrence of one or two polarity reversals just before the CNS. The age and duration of Paraná volcanism are still a matter of debate: one set of results (Renne *et al*. 1992, 1996a, 1996b, 1997) indicates that the Paraná flood

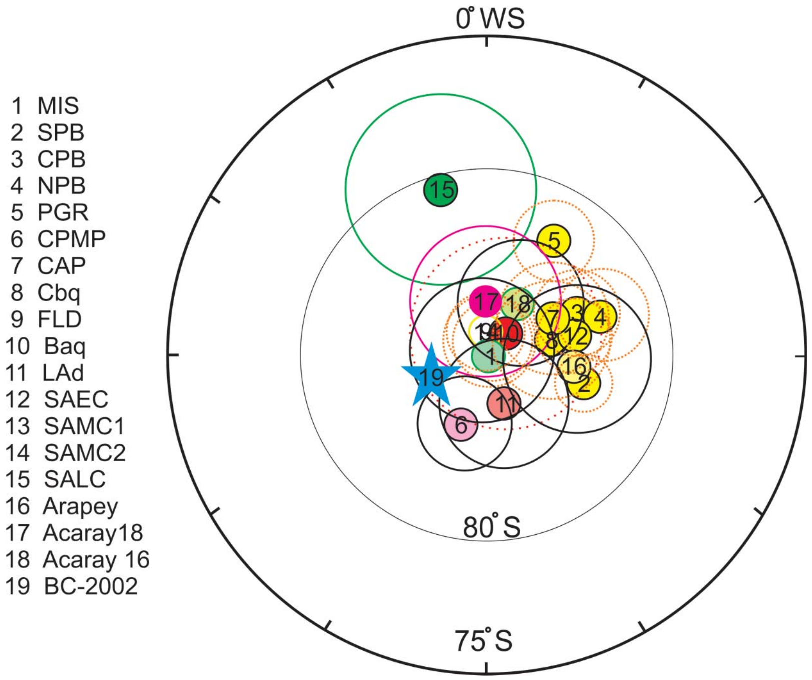

Figure 8. PPs with 95% confidence circles for the Alto Paraguay Formation and the previous Cretaceous PPs listed in Table 4. Also shown is the reference pole position at 135 Ma for South America given by Besse and Courtillot (2002).

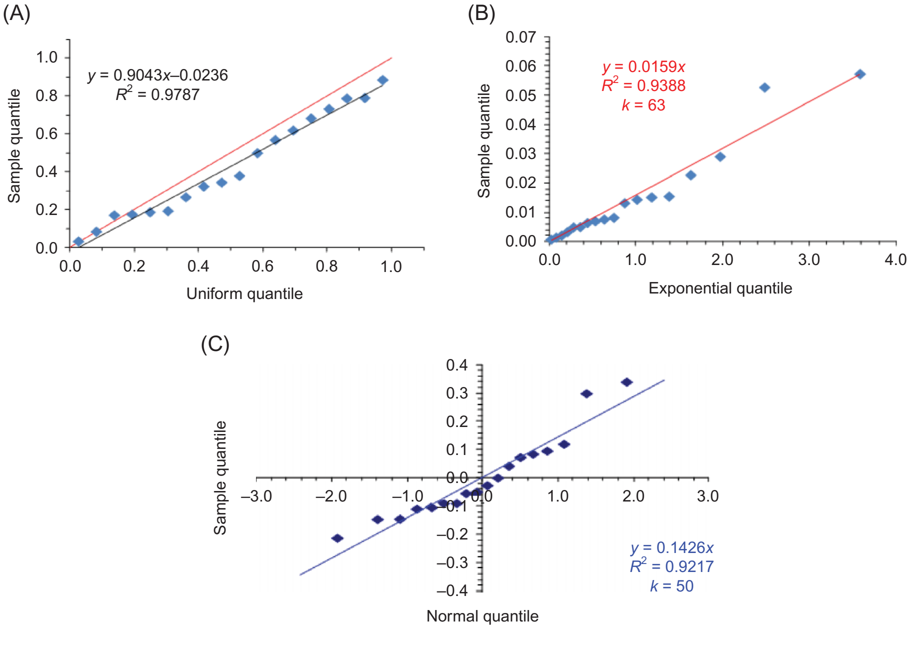

Figure 9. Probability plots to check goodness of fit of the VGPs to the Fisher distribution. (A) Longitude Q–Q plot, (B) colatitude Q–Q plot, and (C) two-variable Q–Q plot.

volcanism began at 134.7 ± 1 Ma and lasted <2 million years. Another set (Turner *et al*. 1994; Stewart *et al*. 1996) indicates an extrusion interval of 11 million years. Thiede and Vasconcelos (2010) re-analysed all previous determinations and reported that new ages are statistically indistinguishable from each other, pointing to a short eruption event (most probably less than 0.6 million years) at 134.7 ± 1 Ma. In this context, our preferred scenario with an N–T–R single transition should be considered as realistic. The intermediate VGPs show a kind of cluster (Figure 7) in the southern hemisphere with a group of seven VGPs located east of India, whereas two other VGPs

Table 4. Selected Cretaceous PPs.

Locality	P	Long (°E)	Lat (°S)	α_{95}	Age (Ma)	References
MIS: Misiones	1	339.1	89.7	4.2	?	Mena *et al*. (2011)
SPB: Southern Paraná Basin	2	106.2	84	1.5	∼133	Raposo and Ernesto (1995)
CPB: Central Paraná Basin	3	64.4	84.1	2.3	∼132	Raposo and Ernesto (1995)
NPB: Northern Paraná Basin	4	71.4	83	2.4	132	Ernesto *et al.* (1999)
PGR: Ponta Grossa dikes (Brazil)	5	30.3	82.4	2	131–129	Raposo and Ernesto (1995)
CPMP: Central Paraná Magmatic Province, Brazil	6	197.9	85.7	2.6	133–132	Alva-Valdivia *et al.* (2003)
CAP: Central Alkaline Province, Paraguay	7	62.3	85.4	3.1	130–127	Ernesto *et al*. (1996)
Cba: Sierras Pampeanas, Córdoba	8	75.9	86	3.3	∼130	Geuna and Vizán (1998)
FLD: Florianopolis dikes, Southern Brazil	9	3.3	89.1	2.7	128–119	Raposo *et al.* (1998)
Baq: Baqueró Group	10	42.7	88.2	5.5	119	Somoza *et al*. (2005)
LAd: Fm. Los adobes	11	159	87	3.8	130–112	Geuna *et al.* (2000)
SAEC: Mean South America Early Cretaceous	12	76.4	84.7	2	135–130	Somoza and Zaffarana (2008)
SAMC1: Mean S.A. Middle Cretaceous	13	33.8	89.1	2.4	125–100	Somoza and Zaffarana (2008)
SAMC2: Mean S.A. Middle Cretaceous	14	354.1	88.7	2.3	125–100	Somoza and Zaffarana (2008)
SALC: Mean S.A. Late Cretaceous	15	345.1	80.6	4.3	85	Somoza and Zaffarana (2008)
UY: Fm. Arapey	16	95.8	84.8	4.2	∼130	Solano *et al*. (2010)
PY: Fm. Alto Paraguay18	17	359.2	86.2	4.3	∼134	This study
PY: Fm Alto Paraguay16	18	34.1	86.1	3.6	∼134	This study
Reference poles at 135 Ma	19	246.5	83.2	5.5	135	Besse and Courtillot (2002)

Notes: P is the number assigned to PP in Figure 8; long (°E), lat (°S), and $\alpha_{95\text{are}}$ are longitude, latitude, and semi-angle of 95% confidence region of the PPs. Also shown is the reference pole position at 135 Ma for South America given by Besse and Courtillot (2002).

are located in the vicinity of Australia. Polarity transitions occur so quickly on a geological timescale that it is difficult to find rocks that have preserved in detail variations of the transitional field. The intermediate directions yielding steep inclinations belong to the same field recorded in very brief periods of time. The occurrence of intermediate palaeomagnetic directions is uncommon for the LIPs. Another example is the Deccan eruption at the *K–T* boundary, yielding C29n–intermediate–C29r transition (Chenet *et al*. 2008, 2009). The VGP positions found in Alto Paraná lavas agree with Hoffman and Fuller's (1978) so-called flooding models, in which reversals originate from a localized region of the core and then progressively propagate into other regions.

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