DRIFT OF SOUTH AMERICAN PLATFORM SINCE EARLY CRETACEOUS: REVIEWING THE APPARENT POLAR WANDER PATH

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ABSTRACT – A review of the available paleomagnetic data based on magmatic rocks of Early Cretaceous to Recent allows the proposition of a new apparent polar wander path (APWP) for South America. As the investigated time span comprises the long normal polarity interval of the Cretaceous (Cretaceous Normal Superchron), the analysis of the magnetization polarity of the rocks allowed some inferences about the relative ages of the igneous complexes when good radiometric control is lacking. Absolute reconstruction of the drift movement of South America was achieved by means of paleomagnetic rotations and longitude control through the sea floor magnetic anomalies. The proposed APWP is a good indicator of paleo-latitude changes of the continent through the considered time interval, which are essential in paleoclimate modeling.
Keywords: Paleomagnetism, APWP, Lower Cretaceous-Recent, South America.

RESUMO – *M. Ernesto – Deriva da Plataforma Sul-Americana desde o Cretáceo Inferior: revendo a trajetória aparente de migração polar*. Uma revisão dos dados paleomagnéticos existentes, baseados em rochas ígneas e com idades do Cretáceo Inferior até o Presente, permite a proposição de uma nova curva de deriva polar aparente (CDPA) para a América do Sul. Como o intervalo investigado compreende o longo período de polaridade normal do Cretáceo (Superchron Normal do Cretáceo), a análise da polaridade da magnetização das rochas permitiu algumas inferências sobre a idade relativa das mesmas, quando o controle radiométrico de idades não era suficientemente bom. Reconstruções absolutas do movimento de deriva da América do Sul foram obtidas através das rotações paleomagnéticas e o controle de longitudes foi dado pelas anomalias magnéticas oceânicas. A CDPA proposta é um bom indicador das mudanças de paleolatitude do continente através do intervalo de idades considerado, as quais são essenciais para a modelagem paleoclimática.
Palavras-chave: Paleomagnetismo, CDPA, Cretáceo Inferior-Recente, América do Sul.

INTRODUCTION

The post-Paleozoic paleomagnetic dataset for South American Platform is still poor, and very few paleomagnetic poles satisfy most of the usually accepted reliability criteria, regarding number of independent sampled sites, field tests and precise radiometric dating. Besides this fact, the available data may be selected and organized in order to draw an apparent polar wander path (APWP) which may describe the plate movements with very reasonable fidelity, although some refinement is still needed. In particular, the definition of mean poles corresponding to 80, 70 and 50 Ma, based on both paleomagnetic and radiometric information so far is not unique (Randall, 1998). Poles of different ages that plot with nearly same coordinates (poles in the range ~80 to ~50 Ma) may lead to the conclusion that the plate displacement was exclusively E-W. However, this may be an effect of the scattering of data when selection does not follow appropriate criteria.

Attempts to explain the origin of magmatic provinces by mantle plume models lead to various arbitrary plate reconstructions, forcing the considered area to be over a supposed hotspot or plume without attempting to better constrained reconstructions. In Northeastern Brazil the Tertiary alkaline basalts (Almeida, 1986) have been attributed both to Santa Helena and/or Ascención hotspot-mantle plume systems, which include the Bahia and Pernambuco seamounts (O’Connor & Le Roex, 1992), or to Fernando de Noronha (Fodor et al., 1998). On the other hand, Courtillot et al. (2003) suggested that Fernando de Noronha could be linked to the Early Jurassic Central Atlantic Magmatic Province (*cf*. Hames et al., 2002). If the above associations, and others found in literature, were true, one should imagine a fixed plate and chaotic hotspot movements occurring underneath with variable velocities.

In this paper it will be reviewed the available paleomagnetic data from Early Cretaceous to Present, and presented an APWP that differs from the one previously presented by Randall (1998). Absolute paleo-reconstructions of the continent will be derived from mean paleomagnetic poles for different ages.

PALEOMAGNETIC POLES AND AGE RELATIONSHIP

Only paleomagnetic poles obtained from igneous rocks were selected in order to avoid problems related to the origin of the magnetic mineralogy or magnetic inclination errors, as frequently reported in literature. Data with no radiometric dating were rejected, as those from active margins which could be affected by uncorrected tilting or rotation.

There are still few paleomagnetic poles for the post-Paleozoic magmatic rocks in South America (Table 1) which satisfy the modern reliability criteria. Early Cretaceous (~140-130 Ma) is by far the better defined part of the APWP with various good paleomagnetic data based on a large number of independent sites, very good age control by $^{40}Ar/^{39}Ar$ dating, and originated from igneous formations from different parts of the continent. On the contrary, Mid to Late Cretaceous still requires some more work, mainly regarding precise dating, and geographic distribution. Most of the existing poles refers to the alkaline provinces surrounding the Paraná Basin (Figure 1), where magmatic activity took place since Triassic, and most concentrated from Campanian to Eocene (87-42 Ma; Almeida et al., 2000). The alkaline magmatism in these areas is quite variable, including ultrabasic rocks, carbonatites and kimberlites. Literature on these rocks is quite abundant (*e.g.*, Almeida, 1983; Comin-Chiaramonti et al., 1997, 1999; Gomes et al., 1990; Thompson et al., 1998). The available paleomagnetic data from Southeastern Brazil belongs to the Alto Paranaíba (Tapira complex; Montes-Lauar, 1993) and Serra do Mar (Poços de Caldas, Itatiaia and Passa Quatro complexes, Santos-Rio de Janeiro dyke swarm, and the São Sebastião necks; Montes-Lauar et al., 1995, unpublished data). The Patagonian plateau basalts is an other good source of paleomagnetic data (Butler et al., 1991) although ages are poorly defined.

TABLE 1. Selected paleomagnetic poles for South America based on igneous rocks.

Formation	Paleomagnetic Pole							
	Code	Age (Ma)	Pol	N	Long. (°E)	Lat. (°S)	α_{95} (°)	REFERENCES
Azufre Volcanics, Argentina	AZ	0-1	N	7	57	87	7.8	*Cañon-Tapia et al. (1994)*
Meseta Visachas Plateau, Patagonia	MV	0-4	M	33	217	89	3.5	*Mejia et al., 2004*
Quixaba Fm., Fernando de Noronha	QX	2-4	M	20	316	87	5.7	*Leonhardt et al (2003)*
El Loa Ignimbrites, Chile	EL	5-12	M	11	304	85	10.0	*Somoza et al. (2004)*
Remedios Fm., Fernando de Noronha	RM	8-12	M	9	17	87	15.3	*Leonhardt et al (2003)*
Fortaleza Province	FO	28.7±2.5	M	7	270	81	19.3	*Schult et al. (1986), recalculated*
Abrolhos	AB	46	M	18	322	80	3.3	*Montes-Lauar (1993), corrected for bedding*
Patagonian Basalts	PB1	42-56	M	15	337	78	6.7	*Butler et al. (1991)*
Asunción alkaline plugs	PP	61-39	M	13	325	79	13.6	*Ernesto et al (1996)*
Patagonian Basalts	PB2	64-79	M	18	358	79	6.3	*Butler et al. (1991)*
Serra do Mar Province, alkaline dykes	SM1	70	R	7	320	75	6.9	*Ernesto et al.(in preparation)*
Itatiaia and Passa Quatro combined	IP	70.5±3.3	M	18	360	80	5.7	*Montes-Lauar et al.(1995)*
Serra do Mar Province, alkaline intrusives	SM2	80	N	26	331	79	4.5	*Ernesto et al. (in preparation)*
Poços de Caldas Alkaline Complex	PC	84	N	36	326	82	3.2	*Montes-Lauar et al.(1995), recalculated*
Tapira Complex	TP	82.9±1.5	R	10	290	71	11.2	*Montes-Lauar (1993)*
Cabo de Santo Agostinho, Brazil	SA	102±1	N	9	315	88	4.5	*Schult & Guerreiro (1980)*
Florianópolis Dikes, SE Brazil	FL	~121	M	65	3	89	2.6	*Raposo et al. (1998)*
Central Alkaline Province, Paraguay	CAP	127-130	M	75	62	85	3.1	*Ernesto et al. (1996)*
Serra do Mar Province, basic dykes	SM3	~130	M	53	44	87	4.6	*Ernesto et al. (in preparation)*
Ponta Grossa Dikes, SE Brazil	PG	129-131	M	115	59	85	2.0	*Ernesto et al. (1999), and reference therein*
Córdoba Province, Argentina	CP	133-115	M	55	75	86	3.3	*Geuna & Vizán (1998)*
Serra Geral Formation	SG	133-132	M	339	90	84	1.2	*Ernesto et al. (1999)*

N= number of sites; Pol= polarity: N= normal, R= reversed, M= mixed; α_{95} = 95% cone of confidence

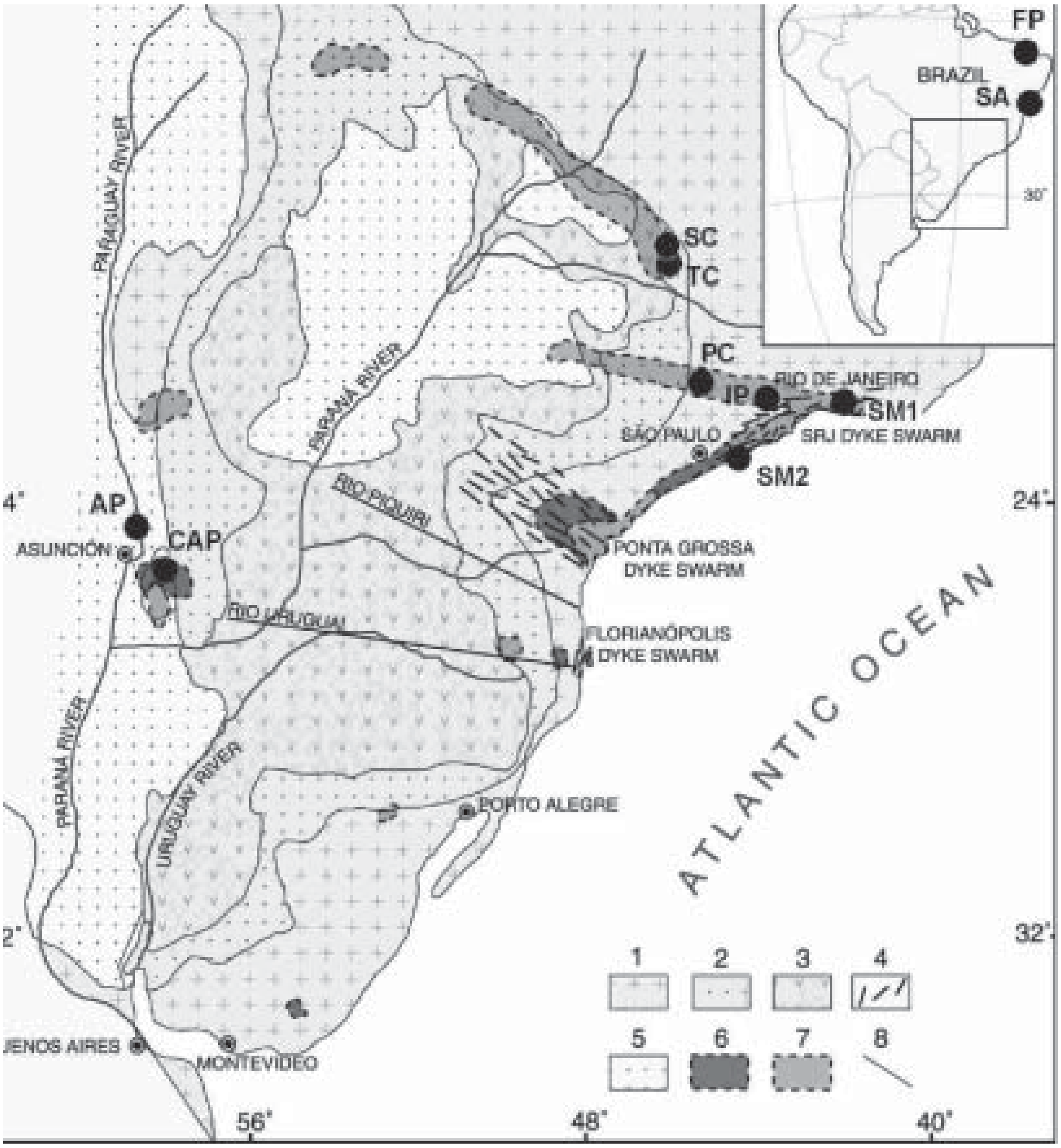

FIGURE 1. Location map showing sites from which paleomagnetic data are available. Codes as in Table 1. Other legends: 1) Pre-Devonian crystalline basement; 2) pre-volcanic sediments; 3) flood volcanics of the Paraná Magmatic Province; 4) dyke swarms; 5) post-volcanic sediments; 6) main areas of Early Cretaceous alkaline rocks; 7) main areas of Late Cretaceous alkaline rocks; 8) tectonic and/or magnetic lineaments.

Northeastern Brazil (Almeida et al., 2000; Ulbrich & Gomes, 1981) was also affected by a magmatic activity that began prior to Early Cretaceous and lasted until Recent (Fodor et al., 1998; Almeida et al., 2000; Ernesto et al., 2002). Paleomagnetic data exist for the Early Cretaceous basic rocks of the Ceará Mirim dyke swarm, combined to the also basic rocks of the Sardinha Formation in the Parnaíba Basin (Ernesto et al., 2002). The Cabo Magmatic Province (CMP) in State of Pernambuco (Nascimento, 2003) gives the only available igneous rocks-based paleomagnetic pole (Schult & Guerreiro, 1980) for Mid Cretaceous, and is very important in tracing the APWP as indicates the way the plate migrated from Early to Late Cretaceous paleopositions. Abundant Tertiary activity occurred inside (Macau Formation; Mizusaki, 1989) or to the south of the Potiguar Basin (Cabugi Magmatism), as well as surrounding the Fortaleza city (Fortaleza Province; Macciotta et al., 1990). Schult et al.(1986) calculated a paleomagnetic pole for the Fortaleza Province based on few sites, but it was included in this data selection as the rocks are well dated (~28Ma; Macciotta et al., 1990), and as the case of Cabo Magmatism, it represents a clue to link Paleogene to Recent latitudes.

The last 10-12 Ma were the objective of numerous paleomagnetic works as recent rocks may represent a good record of geomagnetic variations. These studies concentrate on magmatic rocks of southern South America (Argentina and Chile), but also in Fernando de Noronha (Brazil). In Table 1 only data with a narrow range of radiometric ages, lower paleomagnetic data dispersion and/or at least 5 independent sites were considered.

The Mesozoic-Cenozoic APWP for South America is displayed on Figure 2, based on the paleomagnetic and radiometric data given in Table 1. Although much uncertainties still persist regarding the displacement of the South America plate from ~120 Ma to present due to the scarcity of reference poles (those satisfying the acceptable confidence criteria; *e.g.*, Beck, 1988), and lack of precise radiometric dating in some cases, the available data is sufficient to calculate the amount of drift and rotations that the South America plate underwent during that time interval. It is also possible to draw some inferences about the Brazilian alkaline magmatism ages through a comparative analysis.

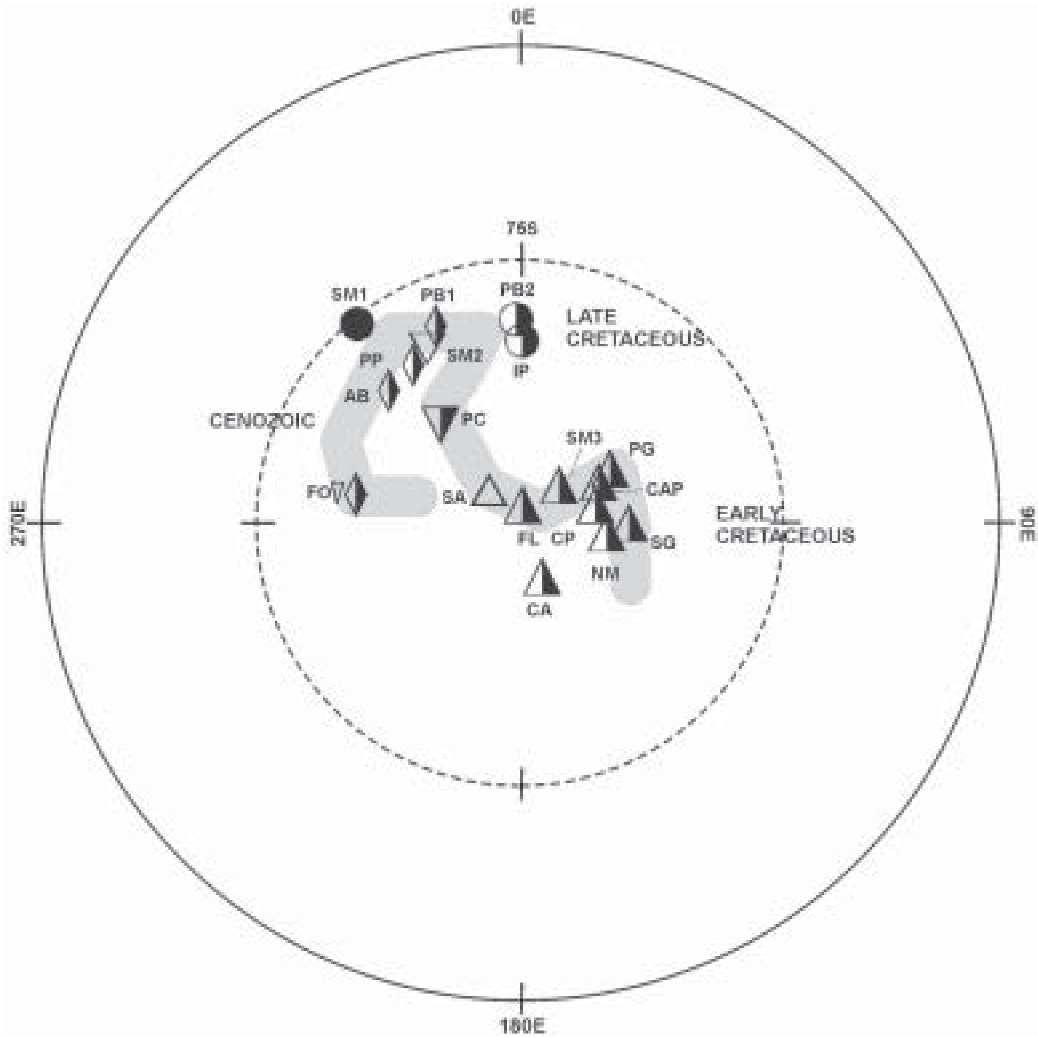

FIGURE 2. Selected paleomagnetic poles (Table 1) for South America and the apparent polar wander path (APWP) proposed in this paper. Symbols are: triangles = Early Cretaceous; inverted triangles = Late Cretaceous (~80Ma); circles = Late Cretaceous (~70-60 Ma); diamonds = Cenozoic. Open, full and half-full symbols represent normal, reversed and mixed magnetic polarity, respectively.

The APWP Early Cretaceous segment is well defined by high quality paleomagnetic poles satisfying rigorous confidence criteria. Of particular interest are the PMP poles (Figure 2), including the tholeiitic extrusive rocks of the Serra Geral Formation (SG: 133-132 Ma; Ernesto et al., 1990; 1999) and the Ponta Grossa dolerites (PG: 129-131 Ma; Renne et al., 1996). The paleomagnetic pole for the Central Alkaline Province (CAP) in Paraguay is in well agreement with the Ponta Grossa pole. K-Ar ages (127-130 Ma; Veláquez et al., 1992) also indicate that the alkaline activity on the western side of the PMP was taking place at the same time as the tholeiitic activity (Ponta Grossa dykes) on the eastern side. The record of the youngest activity in PMP is given by the Florianópolis dykes (FL pole), with $^{40}Ar/^{39}Ar$ ages ranging from ~119 to 128 Ma (preferred age <127 Ma; Raposo et al., 1998) although Deckart et al. (1998) assigned an age of 129 ± 0.3 Ma. However, the FL pole significantly differs from CAP and PG poles, leading to the conclusion that CAP rocks really concentrate on the older, ~130 Ma, ages. To the north, the Cabo Magmatic Province, represented by trachytes, rhyolites, ignimbrites, basalts / trachyandesites, monzonites and alkali-feldspar granite with radiometric age of 102 ± 1 Ma (Nascimento, 2003), was emplaced during the Cretaceous Normal Superchron (CNS of ~121-84 Ma; Gradstein et al., 1994) of normal geomagnetic polarity, as also indicated by the normal polarity magnetizations of those rocks.

The paleomagnetic poles with ages assigned to Late Cretaceous come from the southeastern region (Figure 1): (a) Serra do Mar Province (SM2; Montes-Lauar et al., 1995, Marques et al., 1992, unpublished data) including the stocks and dykes in the São Sebastião Island, and (b) the dykes along the coast between Santos and Rio de Janeiro cities, Poços de Caldas (Montes-Lauar et al., 1995) and Tapira (Montes-Lauar, 1993) complexes, about 80 Ma aged. The Salitre Complex (Montes-Lauar, 1993), from the same region and ~80 Ma aged, did not give a paleomagnetic pole because the data were obtained from unoriented cores, but the mean magnetic inclination of 47° is well in accordance with those obtained from other rocks of same age. Except for SM2 showing only normal polarity, all other poles of this group include reversed polarities. Although very short chrons of reversed polarity are found inside the CNS (Poornachandra Rao & Mallikharjuna Rao, 1996), they often show ages >95 Ma. Therefore, the ages of the reversed polarity rocks may fall between 84 and 81 Ma (Campanian), approximately the limits of the first reversed chron after CNS, according to Gradstein et al. (1994), considering that the majority of the analyzed rocks displayed reversed polarities. The Tapira pole, however, is far from the other two poles, and will not be considered for further interpretations. In fact, as mentioned by Montes-Lauar (1993), this complex is composed by only one plug of 6 km in diameter and shows deep weathering.

In the city of Rio de Janeiro it is frequent to see the dykes of the Serra do Mar Province (normal polarity) being cut by a younger generation of alkaline dykes of reversed polarity. The latter are represented by more evolved lithotypes (Marques et al., 1992), and $^{40}Ar/^{39}Ar$ ages fit 70 Ma (Deckart et al., 1998). The same magnetic and chemical characteristics are shown by other widespread dykes along the coast between Santos and Rio de Janeiro (SRJ dyke swarm in Figure 1). These evidences are strong enough to allow the calculation of two distinct paleomagnetic poles for the Serra do Mar Province: SM1 and SM2 for the reversed and normal polarity rocks, respectively. However, these two poles do not differ significantly on statistical basis, in part due to the low number of sites (only 7) included in SM1. The younger SM1 pole should be closer to the combined Itatiaia-Passa Quatro pole (IP; Montes-Lauar et al., 1995) as the ages are also around 70 Ma, as well as to the pole based on the basaltic rocks from Patagonia (PB1; Butler et al., 1991), although in this case the available K-Ar ages are more scattered (64-79 Ma). However, SM1 pole seems match better the pole group formed by the Asunción plugs (AP; Ernesto et al., 1996), the Patagonian basalts of younger ages (PB1; Butler et al., 1991), and the transitional basalts from Abrolhos Islands (AB; Montes-Lauar, 1993), all of them showing K-Ar data ranging from 39 to 56 Ma. Despite this observation, SM1 pole will be considered along with IP and PB2 for the purpose of calculating a mean pole, as the three poles agree in radiometric ages (~70 Ma). To the other pole group (AP, AB and PB1) a mean age of ~50 Ma will be considered. The only available Oligocene pole for the Brazilian Platform is the one from the Fortaleza plugs in State of Ceará (pole FP; Schult et al., 1986) with an age of about 28 Ma.

PALEOMAGNETIC RECONSTRUCTIONS

Mean paleomagnetic poles for each age group are given in Table 2. Early Cretaceous excepted, the mean poles show large uncertainties, for they are based on few independent results. However, they give good indications of the successive paleolatitudes and rotations of South America since about 130 Ma. The rotation poles derived from the paleomagnetic poles are also given in Table 2. The paleomagnetic reconstructions of South America, considered as a rigid plate, are shown in Figure 3. For reference, the Atlantic islands Fernando de Noronha (FN), Trindade (TR), and Tristão da Cunha (TC) are plotted in the same picture.

Although paleomagnetism is insensitive to longitude variations, absolute paleogeographic reconstructions of the South America plate back to Early Cretaceous are possible if longitude information from sea floor magnetic

TABLE 2. Mean paleomagnetic poles, corresponding rotation poles, and seafloor magnetic anomalies (Nürnberg & Müller, 1991) used in the longitude adjustments.

	Mean Paleomagnetic Poles				Rotation Poles		
Age	N	Long. (°E)	Lat. (°S)	α_{95} (°)	Long. (°E)	Angle (°)	Longitude adjustments
Early Cretaceous (~130 Ma)	5	76.6	85.3	1.5	180.1	5.7	pré-drift (Ernesto et al., 2002)
Late Cretaceous (~80 Ma)	2	328.9	80.6	7.3	73.9	9.7	Anomaly 33R (80.17Ma)
Late Cretaceous (~70 Ma)	3	343.7	78.5	8.1	53.7	11.5	Anomaly 32 (71.37Ma)
Paleoceno (~50 Ma)	3	320.8	79.1	5.7	50.8	10.9	Anomaly AN22 (51.95Ma)
Oligoceno (~28 Ma)	1	269.5	80.8	---	359.5	9.2	Anomaly AN9 (28.15Ma)
Neogene (0-10 Ma)	5	337.8	88.1	2.8	---	---	

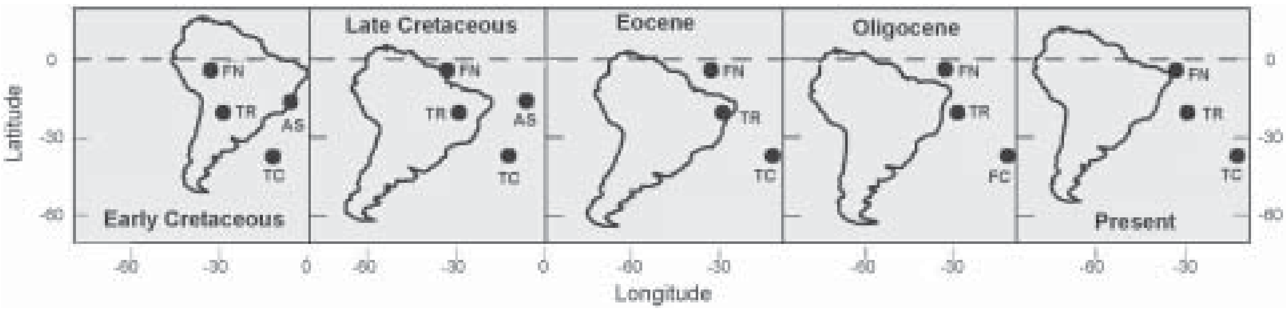

FIGURE 3. The South America displacements from Early Cretaceous to Present. The Tristan da Cunha (TC), Ascención (AS), Trindade (TR), and Fernando de Noronha (FN) islands ("hotspots") are represented in present coordinates.

anomalies are incorporated. In Table 2 the magnetic anomalies corresponding in age to the mean paleomagnetic poles are indicated, as given by Nürnberg & Müller (1991). These authors give Euler poles for each anomaly that may be used to bring South America plate to its former longitudes for each considered age. For Early Cretaceous, when South America and Africa were still in pre-drift configuration, the spreading center of the ocean floor (Mid Atlantic Ridge, MAR) constitutes a very good longitude indicator. At about 130 Ma rifting between the two plates was already taking place at southern latitudes reaching 38°S (Nürnberg & Müller, 1991), and therefore it is reasonable to admit that the eastern border of the South America platform was close to the site where MAR would develop.

From Early Cretaceous to Eocene, South-America plate was rotating clockwise and latitudes varied from slightly lower to slightly greater than the present latitudes (about 3-5°). From Eocene to Oligocene the movement is mainly a counterclockwise rotation almost restoring the plate main axis to its present position. Since Oligocene a slight clockwise rotation can be noticed as the continent is migrating northward. An improvement of the dataset will permit a refinement of the paleo-reconstructions and a better quantification of the displacements.

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