PALEOMAGNETISM OF THE POST-PALEOZOIC ALKALINE MAGMATISM IN THE BRAZILIAN PLATFORM: QUESTIONING THE MANTLE PLUME MODEL

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A review of the available paleomagnetic data on the post-Paleozoic alkaline rocks in the Brazilian Platform and other South America poles of the same age allows the proposition of a new apparent polar wander path, revealing rotations of the plate associated with the emplacement of the alkaline provinces. By means of an analysis of the magnetization polarity of the rocks, some inferences of the relative ages of the igneous complexes are possible, as the investigated time span comprises the long normal polarity interval of the Cretaceous (Cretaceous Normal Superchron). Absolute reconstructions of the drift movement of South America was achieved by means of paleomagnetic rotations and longitude control through the sea-floor magnetic anomalies. By assuming a fixed hotspot reference frame, the relative position of the alleged causative hotspots, in relation to the respective igneous province, is discussed. None of these hotspots was in favorable position when the corresponding magmatic activity occurred. A model based on long-lived deep mantle thermal anomalies, as revealed by geoid heights, is presented as an alternative for the heat source necessary for the magma generation.

INTRODUCTION

The concept of mantle plumes (Morgan, 1971, 1972) gained such strength in geodynamic literature since it has been proposed that all igneous provinces and continental magmatism are tentatively associated with a hotspot, the ultimate expression of the plume activity. However, the identification of the corresponding hotspot in most of the cases has no geological or geophysical basis. It is merely chosen by its proximity to the considered province, and frequently shows a striking feature that may be considered a hotspot track. Consequently, paleo-geographic reconstructions simply force the igneous province into the present hotspot position, even if the paleomagnetism may offer a different interpretation of the plate movement.

In recent years, much has been written (e.g. Sheth, 1999; Smith & Lewis, 1999; King & Ritsema, 2000) against plume model, providing geophysical, geochemical, isotopic and/or numerical modelling evidences that weaken the plume theory. On the other hand, supporters of the theory have presented several alternatives in order to explain the mismatch of the magmatic province and the associated hotspot: 1) when chemical signatures of the rocks are not compatible with plume signature, then the plume contributed with heat, but not with material; 2) if plumes appear displaced from the large igneous provinces, then plumes are not tightly anchored in deep mantle but they move in relation to each other at velocities that may exceed 100 mm/yr. (e.g. Molnar & Stock, 1987; Vandamme & Courtillot, 1990; Duncan, 1990); they are supposed to have generated ~500 mm/yr. fast (Larsen *et al.*, 1999) laterally spreading plumes; plumes would be channeled for a few thousands kilometers to the appropriate position (Thompson *et al.*, 1998); paleomagnetic data may be affected by true polar wander, thus giving wrong plate reconstructions and mislocating the magmatic provinces in relation to the corresponding plumes when the main magmatic phase was occurring (Courtillot *et al.*, 1999).

One of the best examples of a fallacious plume-generated magmatism is the Paraná Magmatic Province (PMP, ~133-132 Ma), one of the largest igneous province in the world, and associated with the Tristan da Cunha (TC) hotspot (e.g. Richards *et al.*, 1989; White & McKenzie, 1989; Milner & Le Roex, 1996; Gibson *et al.*, 1995; Courtillot *et al.*, 1999). The association of the PMP with the TC plume is widely accepted in literature because Walvis Ridge (Fig. 1) has a strong appeal to be taken as a trace left by the Tristan da Cunha hotspot, despite the difficulty of interpreting the expected western symmetrical magmatic chain (i.e. Rio Grande Rise) in terms of a simple mantle plume-hotspot model. As a matter of fact, the Rio Grande Rise (RGR) is composed of two distinct arms (Gamboa & Rabinowitz, 1984): an elevated western portion of elliptical shape (WRGR) and an eastern arm, about 600 km long, trending north-south (ERGR) and parallel to the trend of the present Mid-Atlantic Ridge (MAR).

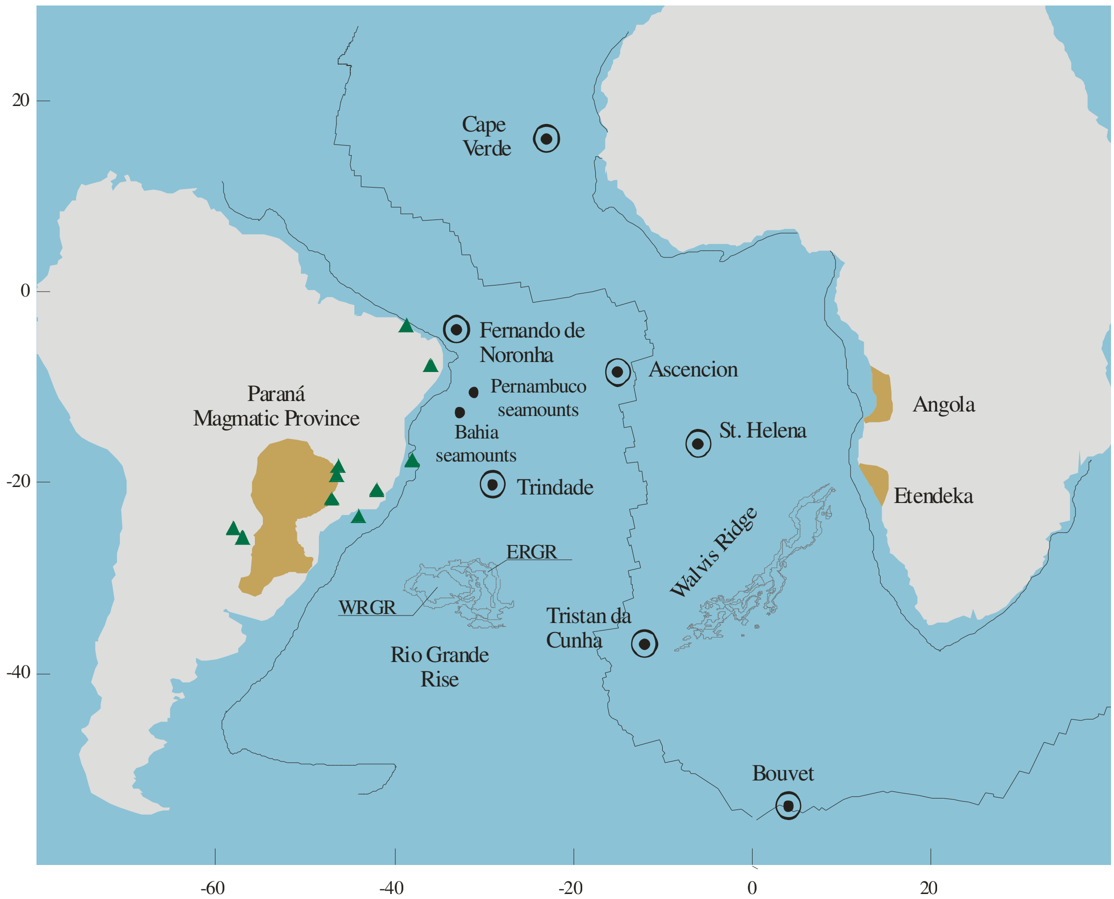

Fig. 1. Distribution of hotspots in Central and South Atlantic in relation to the Paraná Magmatic Province (and its extension into Africa) and the location of some alkaline provinces (triangles) in northeastern and southeastern Brazil.

The quoted authors claim that ERGR, and its conjugate portion of Walvis Ridge, has been formed at the same time by the same processes, and could represent an abandoned spreading center. However, ERGR and WRGR are morphologically different and may have had distinct origins. Le Pichon & Hayes (1971) suggested that WRGR represents a transverse ridge formed along a fracture zone trend, and that the North-South ERGR is due to a modification in the stress field during the opening of the South Atlantic.

Recently, Ernesto *et al.* (2002) demonstrated that PMP could not be generated by TC plume, because TC has never been under the region affected by the Paraná magmatism, and also because does not exist a geochemical plume signature in the Paraná tholeiites, or because the complexity of chemical types and ages distribution in the province does not allow the application of a simple plume model.

The PMP tholeiites are surrounded by alkaline rocks of variable ages. Early Cretaceous (145 Ma) K-alkaline and alkaline-carbonatitic magmatisms (Comin-Chiaramonti *et al.*, 1997, 1999) are found in northwestern PMP (northeastern Paraguay); in the southeastern margins of PMP (Jacupiranga, Juquiá, Anitápolis, and Uruguay) the alkaline rocks are coeval with the tholeiitic magmatism (130-132 Ma); in central Eastern Paraguay more recent activities (i.e. 128-126, 118, 60 Ma) took place (Comin-Chiaramonti & Gomes, 1996).

The alkaline magmatism follows tectonic lineaments (e.g. Ponta Grossa Arch, Rio Uruguay and Rio Pilcomayo), which were also sites of Late Cretaceous (and Tertiary) alkaline magmatism. The latter is also found along other important tectonic lineaments, as the Taiúva-Cabo Frio and Alto Paranaíba-Iporá, and is often attributed to the activity of the Trindade plume (Gibson *et al*, 1995).

In northeastern Brazil, the Tertiary alkaline basalts (Almeida, 1986) have been attributed both to Santa Helena and/or to Ascencion hotspot-mantle plume systems, which include 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).

The distribution of alkaline rocks around PMP and the recurrent magmatic activity in some areas (e.g. western PMP margins, Serra do Mar Province, northeastern Brazil) are also difficult to explain by only one plume model. Furthermore, paleomagnetic data indicate that the plate movement was different from those described by the hypothetical hotspot traces.

In this paper it will be discussed the relationship between mantle plumes and Mesozoic-Cenozoic alkaline magmatism in the Brazilian Platform, by means of plate reconstructions based on paleomagnetic data and sea-floor anomalies.

PALEOMAGNETIC POLES AND AGE RELATIONSHIP

There are few paleomagnetic poles of post-Paleozoic alkaline rocks in the Brazilian Platform (Table 1; Fig. 2). Most of them refer to the alkaline provinces surrounding the Paraná (Brazil) and the Chaco-Paraná (Paraguay) basins (Ernesto *et al.*, 1996), where magmatic activity took place since the Triassic, and they are 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; Gomes *et al.*, 1990; Comin-Chiaramonti *et al.*, 1997, 1999; Thompson *et al.*, 1998); updated papers are presented in this volume. The available paleomagnetic data from southeastern Brazil belongs to the Alto Paranaíba (Tapira and Salitre complexes; 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).

In northeastern Brazil, the Borborema Province (Ulbrich & Gomes, 1981; Almeida *et al.*, 2000) was also affected by an alkaline magmatic activity, ranging from Early Cretaceous to Tertiary times (Fodor *et al.*, 1998; Almeida *et al.*, 2000). The older rocks are best represented by the Cabo Magmatic Province (CMP) in Pernambuco state (Nascimento, 2003), whereas the more abundant Tertiary activity occurs inside (Macau Formation; cf. Mizusaki, 1989) or southwards the Potiguar Basin (Cabugi Magmatism), as well as around Fortaleza city (Macciotta *et al.*, 1990). Paleomagnetic data are only available from CMP (Schult & Guerreiro, 1980), and from the Fortaleza Province (Schult *et al.*, 1986).

In the compilation shown in Table 1, all the existent poles were included, although some of them do not satisfy the commonly accepted reliability criteria. Some other reference poles for the stable South America plate, and some ages of interest for this paper, were included. Poles from the alkaline provinces in Paraguay are considered along with the Brazilian alkaline magmatism, due to the intrinsic geodynamic relationship of these provinces.

The restricted number of poles that are useful to trace the apparent polar wander path (APWP) for South America does not allow a rigorous selection, but poles based on less than five sites were discarded. An exception was made for the Fortaleza Province (only four sites), originally with seven sites (Schult *et al.*, 1986), but recalculated here to lessen scattering.

The Mesozoic-Cenozoic APWP for South America is displayed in Fig. 3, based on the paleomagnetic and radiometric data given in Table 1. It is noticeable the divergence between the APWP proposed by Randall (1998), which combine paleo-magnetic poles from South America and Africa, and the path proposed here. As a matter of fact, Randall's curve does not fit the most reliable poles, mainly for the Paleocene-Eocene epochs.

Although much uncertainties still persist regarding the displacement of the South America plate from ~120 Ma to the present, due to scarcity of reference poles (those satisfying the acceptable reliability 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 by means of a comparative analysis.

The APWP Early Cretaceous segment is best defined by high quality paleomagnetic poles satisfying rigorous reliability criteria. Of particular interest are the PMP poles (Fig. 3), 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 of the Central Alkaline Province (CAP) in Paraguay is in consonance with the Ponta Grossa pole. K-Ar ages (127-130 Ma; Velázquez *et al.*, 1992) also indicate that the alkaline activity on the western side of the PMP have occurred at the same time as the tholeiitic activity (Ponta Grossa dykes) on the eastern side. The record of the most recent 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 the 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 granites 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

Table 1. Selected paleomagnetic poles for stable South America.

Formation	Code	Age (Ma)	Paleomagnetic Pole Pol	N	Long (°E)	Lat (°S)	α_{95} (°)	References
Alkaline rocks in the Brazilian Platform								
Fortaleza Province	FO	$28.7\pm2.5^{*}$	M	4	269.5	80.8	19.3	Schult *et al.* (1986), recalculated
Asunción alkaline plug	PP	$61\text{-}39^{*}$	M	13	325.4	79.4	13.6	Ernesto *et al.* (1996)
Serra do Mar Province	SM1	$70^{\dagger}$	R	7	320.3	75.3	6.9	Ernesto *et al.* (2004); †Deckart *et al.* (1998)
Itatiaia and Passa Quatro combined	IP	$70.5\pm3.3^{*}$	M	18	360.0	79.5	5.7	Montes-Lauar *et al.* (1995)
Serra do Mar Province	SM2	$80^{\dagger}$	N	26	331.3	79.0	4.5	Ernesto *et al.* (2004); †Deckart *et al.* (1998)
Poços de Caldas alkaline complex	PC	$84^{\dagger}$	N	36	325.7	82.2	3.2	Montes-Lauar *et al.* (1995), recalculated
Salitre complex	SC	$82.0\pm2.5^{\#}$	M	8		(47.2)		Montes-Lauar (1993)
Tapira complex	TP	$82.9\pm1.5^{\#}$	R	10	289.8	70.6	11.2	Montes-Lauar (1993)
Cabo de Santo Agostinho	SA	$102\pm1^{\dagger}$	N	9	315.1	87.6	4.5	Schult and Guerreiro (1980); †Nascimento (2003)
Central Alkaline Province, Paraguay	CAP	$127\text{-}130^{*}$	M	75	62.3	85.4	3.1	Ernesto *et al.* (1996)
Related poles for the stable South America Platform								
Abrolhos	AB	46^{*}	M	18	321.8	80.4	3.3	Montes-Lauar (1993), corrected for bedding
Patagonian basalts	PB1	$42\text{-}56^{*}$	M	15	336.5	78.0	6.7	Butler *et al.* (1991)
Patagonian basalts	PB2	$64\text{-}79^{*}$	M	18	358.4	78.7	6.3	Butler *et al.* (1991)
Florianópolis dykes, SE Brazil	FL	$\sim121^{\dagger}$	M	65	3.3	89.1	2.6	Raposo *et al.* (1998)
Serra do Mar Province	SM3	$\sim130^{\dagger}$	M	53	43.9	87.2	4.6	Ernesto *et al.* (2004); †Deckart *et al.* (1998)
Ponta Grossa dykes, SE Brazil	PG	$129\text{-}131^{\dagger}$	M	115	58.5	84.5	2.0	Ernesto *et al.* (1999) and references therein
Serra Geral Formation	SG	$133\text{-}132^{\dagger}$	M	339	90.1	84.3	1.2	Ernesto *et al.* (1999)

N=number of sites; *K-Ar ages; † $^{40}Ar/^{39}Ar$ ages; #Rb-Sr ages; (47.2)=mean inclination

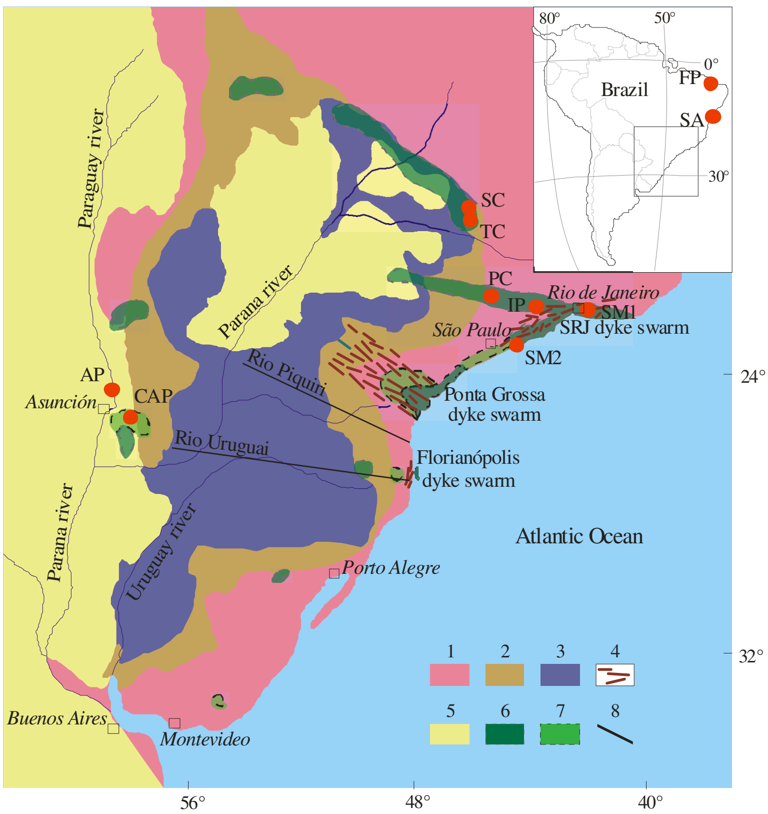

Fig. 2. General map of the Paraná Basin showing the location of the alkaline provinces from which paleomagnetic data are available. Symbols as in Table 1. Other legends: 1) pre-Devonian crystalline basement; 2) pre-volcanic sediments; 3) flood volcanics of the Paraná Magmatic Province; 4) dyke swarms;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

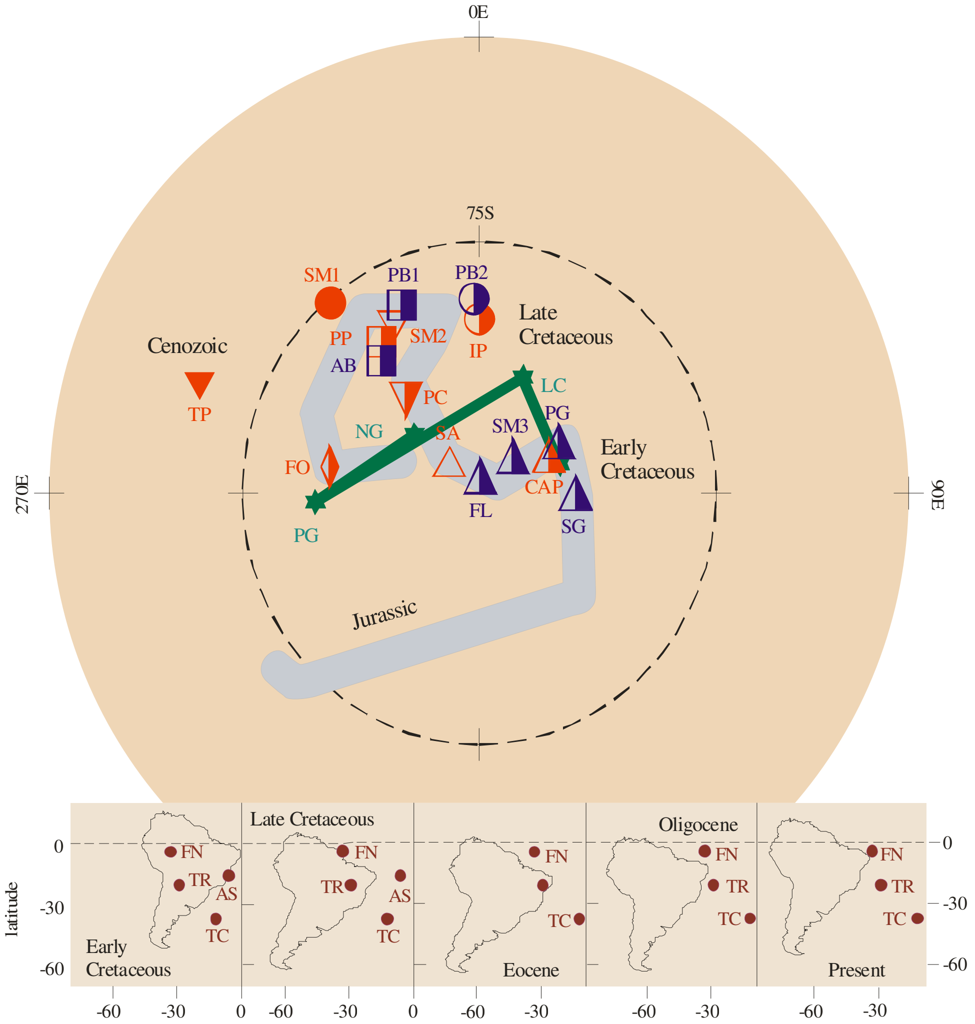

Fig. 3. Paleomagnetic data from post-Paleozoic Brazilian alkaline rocks along with other coeval poles from South America. Triangles: Early Cretaceous; Inverted triangles: Late Cretaceous (~80 Ma); circles: Late Cretaceous (~70 Ma); squares: Eocene (~50 Ma); diamond: Oligocene (~28 Ma). Open, full and half-full symbols represent normal, mixed and reversed polarity, respectively. Green line is the apparent polar wander path (APWP) proposed in this paper. Gray line represents Randall's (1998) APWP combining South American and African poles for Late Cretaceous (LC), Paleogene (PG) and Neogene (NG). Figures bottom: paleomagnetic reconstructions and the relative position of hotspots: Fernando de Noronha (FN), Trindade (TR), Ascension (AS) and Tristan da Cunha (TC).

(Fig. 1): 1) Serra do Mar Province (SM2; Marques *et al.*, 1992; Montes-Lauar *et al.*, 1995; and unpublished data), including the stocks and dykes in the São Sebastião island, and 2) 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 in age. The Salitre complex (Montes-Lauar, 1993), from the same region and ~80 Ma in age, 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, which shows only a 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), if we consider that the majority of the analyzed rocks displayed reversed polarities. The Tapira pole, however, is far away 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 displayed by other widespread dykes along the coast between Santos and Rio de Janeiro (SRJ dyke swarm in Fig. 2). 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). The SM1 pole seems to best fit into 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 Ceará state (pole FP; Schult *et al.*, 1986) with an age of about 28 Ma.

Mean paleomagnetic poles for each age group are given in Table 2. Excepting those from Early Cretaceous, 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 Fig. 3. As reference, the Atlantic islands Fernando de Noronha (FN), Trindade (TR), and Tristan da Cunha (TC) are plotted in the same picture. From Early Cretaceous to Eocene, the South America plate was rotating clockwise and latitudes varied slightly up and down in relation to the present latitudes. From Oligocene to present times, the plate described a counterclockwise rotation, and moved northwards to recover the present position.

Table 2. Paleomagnetic mean poles, rotation poles on the equator used in the reconstructions, and corresponding sea-floor anomalies (Nürnberg & Müller, 1991).

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	pre-drift (Ernesto *et al.*, 2002)
Late Cretaceous (~80 Ma)	2	328.9	80.6	7.3	73.9	9.7	Anomaly 33R (80.17 Ma)
Late Cretaceous (~70 Ma)	3	343.7	78.5	8.1	53.7	11.5	Anomaly 32 (71.37 Ma)
Paleocene (~50 Ma)	3	320.8	79.1	5.7	50.8	10.9	Anomaly AN22 (51.95 Ma)
Oligocene (~28 Ma)	1	269.5	80.8		359.5	9.2	Anomaly AN9 (28.15 Ma)

PALEOMAGNETIC RECONSTRUCTIONS AND THE MANTLE PLUME MODEL

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 anomalies is taken into account. 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 later develop.

Following the same procedures presented by Ernesto *et al.* (2002) to investigating alternative heat sources for the generation of the Paraná Magmatic Province, the reconstructed South America plate (SA) at 130, 80 and 50 Ma is plotted on a map of geoid anomalies, as well as the hotspots of interest in their present coordinates (Fig. 4). Large circles around the hotspots mark the ~1000 km radius, correspondent to the area of the plume head spreading (White & McKenzie, 1989). For each considered age, SA plate is rotated by the Euler pole derived from the sea-floor anomalies after being rotated by the corresponding paleomagnetic rotation poles.

Considering the hotspots anchored in the deep mantle, i.e. they are all fixed in relation to each other, it can be inferred that there is no possible relation between Fernando de Noronha and the

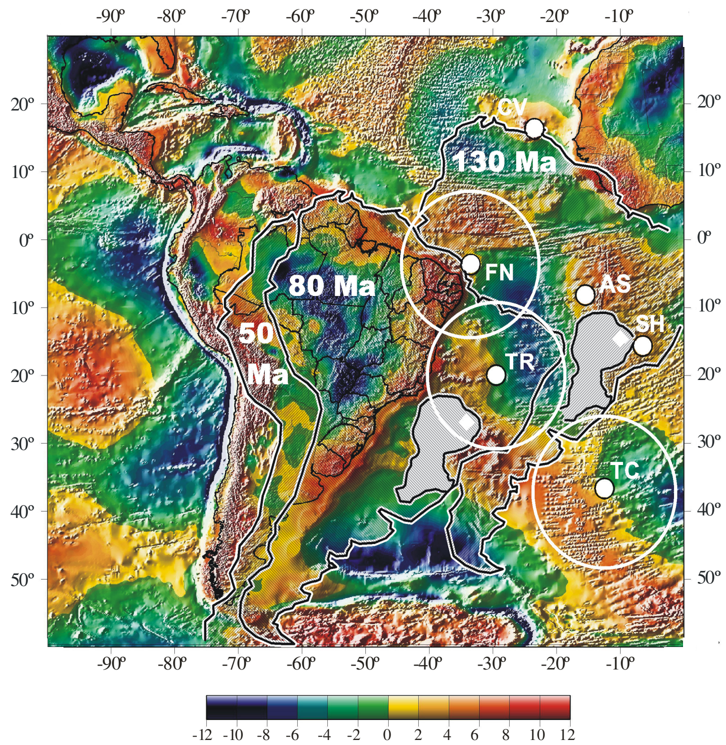

Fig. 4. Geoid anomalies for South Atlantic and South American continental lithosphere (Ernesto et al., 2002). Anomalies in meters. South American plate at 130, 80 and 50 Ma are placed on top of the picture, along with the location of present hotspots and the fossil plume of Van Decar *et al.* (1995).

Tertiary alkaline provinces in Northeastern Brazil as proposed by Fodor *et al.* (1998). Even less chance has Ascencion of having any participation in the northeastern magmatism generation, unless the hypothesis of a hot plume being deflected hundreds of kilometers from the impacted area (Thompson *et al.*, 1998) is taken into consideration. The same may be said of the Late Cretaceous Iporá, Alto Paranaíba and Serra do Mar Provinces and the island of Trindade (Thompson *et al.*, 1998; Gibson *et al.*, 1995).

The hypothesis of mobile plumes is often raised when the hotspot is found away from the magmatic province which it has supposedly generated. This has been so for the case of the Paraná Magmatic Province and Tristan da Cunha hotspot, in order to justify the ~1,000 km offset encountered when paleomagnetic sea-floor spreading reconstruction is used (Ernesto *et al.*, 2002), instead of unconstrained reconstructions (e.g. O'Connor & Duncan, 1990; Turner *et al.*, 1996). However, even in the case of the Paraná-Tristan da Cunha system, for ages from about 80 Ma to the present, the supposed trace of the hotspot (Walvis Ridge) marks the real Africa plate movement. This dichotomy in the hotspot trace-APWP relationship is usually explained as an effect of a true polar wander (TPW) on the paleomagnetic data. TPW corresponds to the differential movement of the mantle reference frame relative to the Earth's spin axes (Andrews, 1985; Gordon & Livermore, 1987). If considerable amounts of TPW are admitted, then paleomagnetic poles are mis-calculated as they are referred to the present rotation axis. Thus, depending on the considered time interval, paleomagnetic data would fall into correctly located large igneous provinces in relation to its correspondent plume head. But calculations of the TPW amount presuppose the concept that the volcanic chains (interpreted as hotspot traces) exactly indicate the movement of the lithospheric plates, and that paleomagnetic APWP deviations reflect TPW. Therefore, these results are not based on an independent source of information, neither from the paleomagnetic data nor from hotspot traces. Furthermore, most of the analyses are restricted to the last 100 Ma, when hotspots are more easily traceable. Although large amounts of TPW have been proposed during Mesozoic, Prévot *et al.* (2000) concluded that no TPW occurred after 80 Ma, and that a single period of shifting existed between 150 and 80 Ma culminating at 110 Ma with an abrupt tilting of 20°.

If TPW cannot be invoked to justify the misfit indicated by paleomagnetic reconstructions between the igneous province and the associated hotspot, then hotspots tracks must be seen as tectonic features reflecting accommodation of stresses in the lithosphere (e.g. LePichon & Hayes, 1971; Ferrari & Riccomini, 1999) rather than continuous magmatic activity induced by mantle plumes beneath the moving lithospheric plates. According to some authors (e.g. Popoff, 1988; Unternehr *et al.*, 1988), the western arm of the Rio Grande Rise represents the accommodation of stresses during the initial opening of the South Atlantic, and its prolongation within South America plate, between the Campos and Pelotas basins, is a dextral deformation. The eastern sector of the Rio Grande Rise is also in accordance with the change of South America movement at about 80 Ma when a north-south drifting component is clear, as already pointed out by LePichon & Hayes (1971). Similar interpretation was given by Ferrari & Riccomini (1999) for the Vitória-Trindade chain, believed to be the Trindade hotspot trace.

From the above discussion it comes out that if plumes have been anchored in the mantle for the last 80 Ma, then TC, TR and FN hotspots have been fixed relatively to the mantle, and therefore could not be under the expected areas in South America plate in order to generate the respective magmatic provinces: PMP and the alkaline provinces on its western and eastern margins (TC; Richards *et al.*, 1989; Courtillot *et al.*, 1999); Iporá, Alto Paranaíba and Serra do Mar provinces (TR; Gibson *et al.*, 1995; Thompson *et al.*, 1998); and the northeastern alkaline provinces (FN; Fodor *et al.* 1998). The Tertiary magmatism in northeastern Brazil has also been associated with the Santa Helena or Ascencion hotspots (O'Connor & Le Roex, 1992), which are even weaker candidates if the above considerations are taken for granted.

MANTLE PLUMES VERSUS MANTLE THERMAL ANOMALIES

Van Decar *et al.* (1995) mapped a low-velocity zone in the mantle in northeastern PMP, which they interpreted as a thermal anomaly corresponding to the "fossil" TC plume that moved with the lithospheric plate. Considering that the lithosphere has a typical time constant of about 60 Ma (McKenzie, 1978; Gallagher & Brown, 1997) for dissipating heat and consequently attenuating topography, it is quite improbable that the heat of a plume that reached the base of the lithosphere more than 130 m.yr. ago could still persist. It would be more acceptable an association of the low-velocity zone with a plume related to the alkaline magmatic provinces nearby, where magmatism younger than 50 m.yr. can be found. However, no geoid anomaly, nor a surface expression of the TC thermal anomaly, is recognized in this region (Molina & Ussami, 1999), except for the Iporá and Alto Paranaíba Late Cretaceous alkaline provinces (Comin-Chiaramonti *et al.*, 1997, and references therein) further to the north.

Geoid anomalies constitute a source of information about the thermal condition of the Earth's interior. They are defined as the difference in geoid height between the measured geoid and some reference model (cf. Anderson, 1989). Positive geoid anomalies (>4 m) extend along the eastern Brazilian coast (Ussami *et al.*, 1999), except onshore the Bahia coast, where they are smaller than 4 m, and between the São Paulo and Curitiba towns in the southeastern area. In the northeastern area (Borborema Province), anomalies as high as 10 m have been calculated. Apatite fission tracks (AFT; Hegarty *et al.*, 1996; Harman *et al.*, 1998) suggest a re-heating of the area (along the Pernambuco lineament) in the Early Tertiary (~60 Ma). Northward the Potiguar basin, at least two rising episodes were identified in the stratigraphy (Campanian and Oligocene; Cremonini, 1993). The later one possibly occurred at about 25 Ma based on the geoid height in the area (Ussami *et al.*, 1999).

In the southeastern side of the São Francisco craton, where a part of the Alto Paranaíba Province and the Serra do Mar Province are located, the geoid anomaly is also expressive and extends towards de Abrolhos islands and Trindade. AFT data (Gallagher *et al.*, 1994; Ribeiro Filho *et al.*, 1995) indicate a Late Cretaceous age for the last thermal event in the area, which coincides with the age of the alkaline rocks (80-50 Ma). When these thermal events were taking place, none of the presumed plumes were under the corresponding lithospheric areas where they are supposed to have impinged, as indicated by the paleomagnetic reconstructions (Fig. 3). For example, during Late Cretaceous (~80 Ma) the Trindade plume was about 1,000 km to the north of the Serra do Mar Province and APIP. Even considering a 1,000 km plume head radius, it is difficult to explain why the main igneous activity would manifest only at the border of the plume. Moreover (cf. Fig. 3), the displacement of South America plate in relation to the fixed hotspot framework would not result in a hotspot track trending ~E-W, as suggested by the oceanic features. Curiously, the same situation has already been observed for the hypothetical system PMP-TC plume (Ernesto *et al.*, 2002), and for TC, located 1,000 km to the south of PMP during the emplacement of the main volcanic event. On its turn, the FN plume had kept away from the Borborema Province in northeastern Brazil until the Oligocene, whereas Trindade was closer to that area since Late Cretaceous.

In view of this scenario, the hypothesis of a mantle plume/hotspot origin for the alkaline provinces must be reviewed, at least regarding the plumes that have had more chances of being active at the right place and time when a specific province is considered. Moreover, geochemical signatures of the magmatic rocks are distinct from those presented by the commonly related plumes. For example, this is the case for TC and PMP (Peate, 1997; Marques *et al.*, 1999), but even for TC and Walvis Ridge-Rio Grande Rise, the alleged hotspot traces. Coring at the basement of WRGR provided tholeiitic basalts of about 85 Ma, but rocks dredged from the escarpments of the guyots, towering over the platform of the rise, indicated the presence of Eocene alkaline basalts (K-Ar date: 47 Ma; Bryan & Duncan, 1983; cf. Fodor *et al.*, 1997). In addition, the geochemical and Sr-Nd-Pb isotope data are different from those of Walvis Ridge basalts. All the geochemical data (Piccirillo & Melfi, 1988; Marques *et al.*, 1999) indicate that the genesis of the PMP tholeiites mainly reflects melting of heterogeneous lithospheric mantle reservoirs (cf. Comin-Chiaramonti *et al.*, 1997, 1999). Furthermore, the geochemical and isotope signatures of Walvis Ridge and RGR basalts may be explained by the detached continental lithospheric mantle left behind during the continental break-up processes (e.g. Hawkesworth *et al.*, 1986; Peate *et al.*, 1999).

It is also important to stress that the mantle heterogeneity, involved in the Paraná magmatism, is not confined to the tholeiites, but also to the PMP Early (and Late) Cretaceous alkaline magmatism. Even the carbonatites have on the whole a Sr-Nd-Pb isotope imprinting close to that of the related alkaline rocks and the spatially associated tholeiites (Comin-Chiaramonti *et al.*, 1997, 1999, and in this volume; Alberti *et al.*, 1999; Peate *et al.*, 1999; Marques *et al.*, 1999), indicating similar mantle components in their genesis.

In conclusion, the simplistic model of mantle plumes is not satisfactory for explaining most of the continental flood basalts and the recurrent intraplate magmatism; therefore, following Ernesto *et al.* (2002), alternative thermal sources can be found in the mantle with no implication of material transfer from the lower mantle to the lithosphere. Besides the indications from geoid anomalies, the existence of long-living thermal anomalies in the mantle have already been demonstrated by velocity distribution models based on seismic tomography techniques, using both P- and S-waves (e.g. Zhang & Tanimoto, 1992; Zhou, 1996; Li & Romanowicz, 1996; Van der Hilst *et al.*, 1997).

In Fig. 4, the residual geoid anomalies for the South Atlantic, including the continental lithosphere of the South America map, are overlaid by a shaded relief map of the 5'x5' digital topography/bathymetry (cf. Ernesto *et al.*, 2002). The most important residual geoid anomalies clearly correlate with major lithospheric scale features, such as a belt of subtle positive anomalies along the mid-ocean ridges, negative anomalies along deep oceanic basins, thick cratons and, above all, along the Paraná Province.

Two conspicuous intermediate wavelength positive anomalies are observed along the South Atlantic. The first one starts in the equatorial fault system which separates the Central and South Atlantic, then obliquely cross-cuts the ridge axis, and continues along the Ascencion and Santa Helena hotspots, as well as along the Walvis Ridge. The second one extends from southern Brazil, continues along the Rio Grande Rise and get linked to the Antarctic Ridge System. The extent of these anomalies indicates that their source must lie within the mantle. In fact, these two large positive anomalies correlate with a low-velocity zone mapped within the mantle, extending from 165-210 km to 660-710 km (Zhou, 1996). Below this depth, the low-velocity zones almost disappear. For the first 150 km upper mantle interval, Tanimoto & Zhang (1992) proposed a S-wave seismic tomographic model, which shows that the mid-ocean ridges are characterized by a focussed and shallow (~100 km) depth interval of low-velocity distribution. This may explain why geoid anomalies are also not very strong over these features, except in those places where an extra deep seated mantle thermal anomaly is present, as it is the case of those two plate scale positive geoid anomalies. Anderson *et al.* (1992) also observed that the upper mantle is characterized by vast domains of high temperatures rather than by small regions surrounding hotspots, and that low-velocity anomalies record previous positions of migrating ridges, or, in Tanimoto & Zhang's (1992) view, it marks the place where the Western Gondwana break-up occurred. Whatever the interpretation, this is a clear indication that this anomaly persisted for over 100 Ma, and the existence of long-living deep mantle thermal anomalies is very likely.

When the South America plate is represented (Fig. 4) in the geoid anomaly map, in its paleopositions at approximately 130 Ma (pink contour), as calculated in the previous section and displayed in Fig. 3, it comes out that the Paraná Province and the surrounding alkaline provinces plot over the NW-SE geoid/mantle thermal anomaly that contains also Ascencion and Santa Helena hotspots. Most of the alkaline activity concentrates in the 90-50 Ma interval. At 80 Ma (blue contour) the plate moves slightly southwards placing the area correspondent to the Alto Paranaíba and Serra do Mar provinces under the strong geoid anomaly that is now located over the Rio Grande Rise, and continues along the mid-ocean ridge. The same anomaly continues toward the South America eastern continental margin describing a path that nearly coincides with the plate drift path itself. Therefore, the alkaline magmatism that developed in the time interval of 90-70 Ma bordering the Paraná Province does not necessarily need an associated plume to be explained, because, as in the case of PMP, all the affected region was (and part of it still is) over a mantle thermal anomaly.

Paleomagnetic data indicate that drifting velocity was relatively high, and varied from about 23 mm/yr. in the 130-80 Ma interval, to about 7 mm/yr. in the 80-50 Ma interval. However, the path described by the South America plate as seen in Figs. 3 and 4, was such that the areas where the alkaline igneous provinces developed were kept under important mantle thermal anomalies for a time interval long enough for the lithosphere to incorporate the necessary heat. For example, as stressed by Ernesto *et al.* (2002) the area occupied by the PMP was kept under the thermal anomaly for at least ~50 Ma since the Jurassic. If sufficient heat is incorporated to the lithosphere, then magmatism will occur when adequate tectonic conditions take place, and this could mean stress accommodations (Ferrari & Riccomini, 1999) to the plate successive rotations.

The same can be said in relation to the Borborema Province, which moved from a mild anomaly close to the Trindade island to an area of stronger geoid/thermal anomaly near Fernando de Noronha, from 50 Ma to the present.

CONCLUDING REMARKS

The paleomagnetic data for the post-Paleozoic alkaline rocks in the Brazilian 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. The same can be said for the whole paleomagnetic database for the same age interval. Besides this fact, the available data suggest that APWP describes the South America 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. The group of poles, mixing up rocks of ages in the range from ~80 to ~50 Ma, could also indicate that in this time span the plate displacement was exclusively E-W, and consequently without latitude variation for the paleomagnetic method to detect plate movements.

Changes in the APWP, which account for this alternative drifting scenario, will not change the relative position of the magmatic provinces and the presumed causative hotspot shown in Figs. 3 and 4. This remark reinforces the observed inconsistency between igneous provinces and plate reconstructions

(Heller *et al.*, 1996). In fact, plate reconstructions, usually used to check out the correspondence between igneous provinces and hotspots, are 1) all based on the hotspot frame itself (e.g. O'Connor & Duncan, 1990), and 2) considered to be indicator of absolute plate motions. Therefore, these attempts of reconstruction constitute a vicious proposition.

Paleomagnetic data represent an independent source of information which suggests a very different relationship. If some of the oceanic islands do represent hotspots or the final stage of a mantle plume, then Santa Helena rather than Tristan da Cunha should be associated with the Paraná Igneous Province, as well as Trindade, and not Fernando de Noronha, would be responsible for the Tertiary magmatism in northeastern Brazil.

Courtillot *et al*. (2003) recognized that not all hotspots have deep mantle origin as to characterize mantle plumes, as envisaged by Morgan (1972). Among the hotspots of interest in this paper, only Tristan da Cunha meets the necessary conditions to be classified as deep or primary plume in those authors' view. All the others, i.e. TR, FN, AS and SH, were considered to be a passive response to the lithosphere break-up, with origin in the asthenosphere, as already pointed out by Anderson (2000).

ACKNOWLEDGMENTS

This work was supported by the Brazilian funding agencies FAPESP and CNPq. Thanks are due to P. Comin-Chiaramonti, L.S. Marques, N. Ussami, E.C. Molina and E.M. Piccirillo, who collaborated to this paper in many different ways.

ACRONIMOUS LIST QUOTED IN THE TEXT

AS	Ascension island
AB	Abrolhos islands
AFT	Apatite fission tracks
AP	Asunción plugs
APWP	Apparent polar wander path
CAP	Central Alkaline Province, Paraguay
CMP	Cabo Magmatic Province
CNS	Cretaceous Normal Superchron
ERGR	Eastern Rio Grande Rise
FL	Florianópolis
FN	Fernando de Noronha islands
FP	Fortaleza plug
IP	Itatiaia-Passa Quatro
MAR	Mid Atlantic Ridge
PB	Patagonia basalts
PG	Ponta Grossa Arch
PMP	Paraná Magmatic Province
RGR	Rio Grande Rise
SA	South America plate
SG	Serra Geral Formation
SM	Serra do Mar Province
SRJ	Santos-Rio de Janeiro
TPW	True polar wander
TC	Tristan da Cunha island
TR	Trindade island
WRGR	Western Rio Grande Rise

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Mesozoic to Cenozoic Alkaline Magmatism in the Brazilian Platform
Comin-Chiaramonti, P. & Gomes, C.B. (eds.)
Edusp/Fapesp, São Paulo, pp. 689-705, 2005