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The Late Cretaceous alkaline magmatism in the SE Brazilian coast: new paleomagnetic data and age constraints

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Abstract

Alkaline dikes from the Santos-Rio de Janeiro coast, SE Brazil, mainly from São Sebastião and Búzios islands, yielded a Late Cretaceous paleomagnetic pole (SR) located at 319.7°E 81.2°S (N = 44, A_{95} = 3.0°, k = 44). This pole includes some sites of alkaline stocks from São Sebastião Island of the same age and supersedes the previous pole for this island. To match the available radiometric ages and the prevailing normal polarity remanence of the rocks with the geomagnetic polarity time scale, the SR pole is placed at 84 Myr. Another group of alkaline rocks, dikes located mainly in Rio de Janeiro, was assigned an age of less than 70 Myr. The ages of the Poços de Caldas, Itatiaia, and Passa Quatro paleomagnetic poles are also discussed based on available radiometric data. Assuming a rigid plate, the SR pole indicates the southward movement of about 7° with virtually no rotation between 100 and 84 Myr. From approximately 84 to 70 Myr, a clockwise rotation of 8° is postulated, with slight variation in latitude.

KEYWORDS: Paleomagnetism; alkaline rocks; Upper Cretaceous; SE Brazil.

INTRODUCTION

Alkaline intrusive rocks bordering the Paraná Magmatic Province (PMP) in southern Brazil have ages ranging from the Lower Cretaceous to the Eocene (Geraldes *et al.* 2013). They are particularly abundant in the northeast area, forming large alkaline provinces. Between Santos and Rio de Janeiro cities (parallels 20°–24°S), dike swarms trending mainly NE intrude the Proterozoic-to-Cambrian crystalline basement along the coast. They followed the old structures of the South American platform reactivated during the South Atlantic opening (Almeida 1986). Most dikes are tholeiitic with similar ages to those of the PMP (Deckart *et al.* 1998). The alkaline dikes are of Late Cretaceous to Tertiary ages (Deckart *et al.* 1998, Guedes *et al.* 2005, Giraldo-Arroyave *et al.* 2021). They are mainly related to the alkaline complexes located on São Sebastião Island and neighboring areas (Fig. 1).

For more than five decades, radiometric ages for this alkaline magmatism have been collected (e.g., Giraldo-Arroyave *et al.* 2021). Despite the significant age collection, there still needs to be more consistency among ages of the same alkaline occurrence. The older ages coincide with the Cretaceous Normal Superchron (CNS, 120–83 Myr, Ogg 2020) time interval in which the geomagnetic field was stable at a single polarity and then resumed high-rate polarity reversal behavior. Therefore, paleomagnetic data from the alkaline rocks may help to constrain the age intervals.

Paleomagnetic data are available from the Itatiaia-Passa Quatro, Tapira, and Poços de Caldas complexes, and a few sites from the São Sebastião island, including stocks and alkaline dikes (Montes-Lauar 1993, Montes-Lauar *et al.* 1995). Among those, the Poços de Caldas paleomagnetic pole is the more reliable, based on extensive sampling. All studied sites are of reverse magnetization, placing the magmatism outside the CNS, although ages obtained by various methods are in the range of 89–76 Myr (Vlach *et al.* 2018).

This study presents paleomagnetic results from the alkaline dikes along the coastal area between Santos and Rio de Janeiro cities and São Sebastião and Búzios islands. Field relationship and a confrontation of the radiometric ages with the geomagnetic polarity timescale will define possible age groups for the studied rocks. The ages of the alkaline complexes for which paleomagnetic data are available will also be discussed in light of the magnetic polarities. A new paleomagnetic pole computed in this study will help to constrain the plate movements during the opening of the South Atlantic.

Since the Jurassic, the South American plate underwent displacements with slight variations in latitude or rotation of its central axis, two conditions for discriminating efficiently between paleomagnetic pole positions. Since the Jurassic, the South American plate underwent displacements with slight variations in latitude or rotation of its central axis, two conditions that produce differences in the paleomagnetic pole positions. Therefore, the inconsistency of the radiometric ages prevents the time ordering of the paleomagnetic poles.

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GEOLOGICAL SETTINGS

The Early Cretaceous PMP is surrounded by abundant alkaline magmatism, mainly from the Late Cretaceous ages post-dating the Western Gondwana breakup (Geraldes *et al.* 2013). Most of the alkaline activity concentrates in the north-northeast sectors of the PMP and is referred to as the Alto Paranaíba and the Serra do Mar Provinces (SMP; Geraldes *et al.* 2013). The latter occupies the coastal area extending to the near-shore islands. The area experienced pulses of uplift from the Coniacian to the Santonian, which increased the sedimentary supply to the adjacent Santos Basin (Hackspacher *et al.* 2004). Some sedimentary basins developed in the highlands of the Serra do Mar area as a consequence of the tectonism that took place from the Upper Cretaceous to the Eocene (Ricomini *et al.* 2004).

The SMP comprises large alkaline complexes such as Poços de Caldas, Itatiaia-Passa Quatro, and other smaller complexes, with large syenitic stocks in the São Sebastião Island (Enrich *et al.* 2005) and a NE-trending dike swarm of tholeiitic and alkaline nature. The tholeiitic dikes are similar in age and chemical composition to the flood basalts of the PMP (Deckart *et al.* 1998). On the other hand, the alkaline dikes are younger, Upper Cretaceous-Tertiary in age, sometimes cutting the alkaline complexes (Brotzu *et al.* 2005).

The tholeiitic dikes occupy the highlands up to the Paraiba Valley and are similar to the flood basalts of the north of the PMP (Valente 1997), with ages ranging from 133 to 129 Myr (Turner *et al.* 1994, Deckart *et al.* 1998). The alkaline dikes crop out on the coast, mainly in the islands (Comin-Chiaramonti *et al.* 1983, Garda *et al.* 1995, Garda and Schorscher 1996, Brotzu *et al.* 2005), and rarely in the highlands. The alkaline dikes are generally thin, varying from a few centimeters to a few meters thick, with a general tendency to the NE directions.

Chemical and petrological studies of the alkaline dikes from the SMP were performed by various authors (Comin-Chiaramonti *et al.* 1983, Bellieni *et al.* 1990, Marques and Ernesto 1992, Brotzu *et al.* 2005). They found a wide compositional variation from the medium (alkali-basalts, trachybasalts, and latibasalts) to the strong (nephelinites, tephrites, phonotephrites, and phonolites) alkaline affinity. In addition, Brotzu *et al.* (2005) observed cross-cutting dikes with different compositions and multiple intrusions along the coast. The same behavior was observed in the Rio de Janeiro quarries.

On São Sebastião Island, the dikes have a thickness of 0.5–3 m. They are a few meters long, cutting across the Upper Cretaceous São Sebastião, Serraria, and Mirante stocks (Fig. 2) or the basement rocks of the Neoproterozoic Costeiro Complex (Almeida 1983). Whole-rock K-Ar ages of 78 ± 8 to 83 ± 6 Ma were reported by Sonoki and Garda (1988) for the alkaline dikes. High-precision $^{40}Ar/^{39}Ar$ dating yielded ages of 88–86 Ma for the entire alkaline magmatism on the island (Giraldo-Arroyave *et al.* 2021). In the neighboring Búzios Island, the alkaline dikes cut the ~80 Ma syenitic rocks (Gomes *et al.* 2017).

In Rio de Janeiro, the intrusive activity is represented mainly by dikes cutting the pre-Cambrian granites and gneisses. Their thickness varies from a few centimeters to 2 m. The thinner dikes are frequently seen in Bangú and Baixada de Guaratiba quarries, which appear with irregular directions. Crosscutting dikes are frequent, and multiple intrusions also exist.

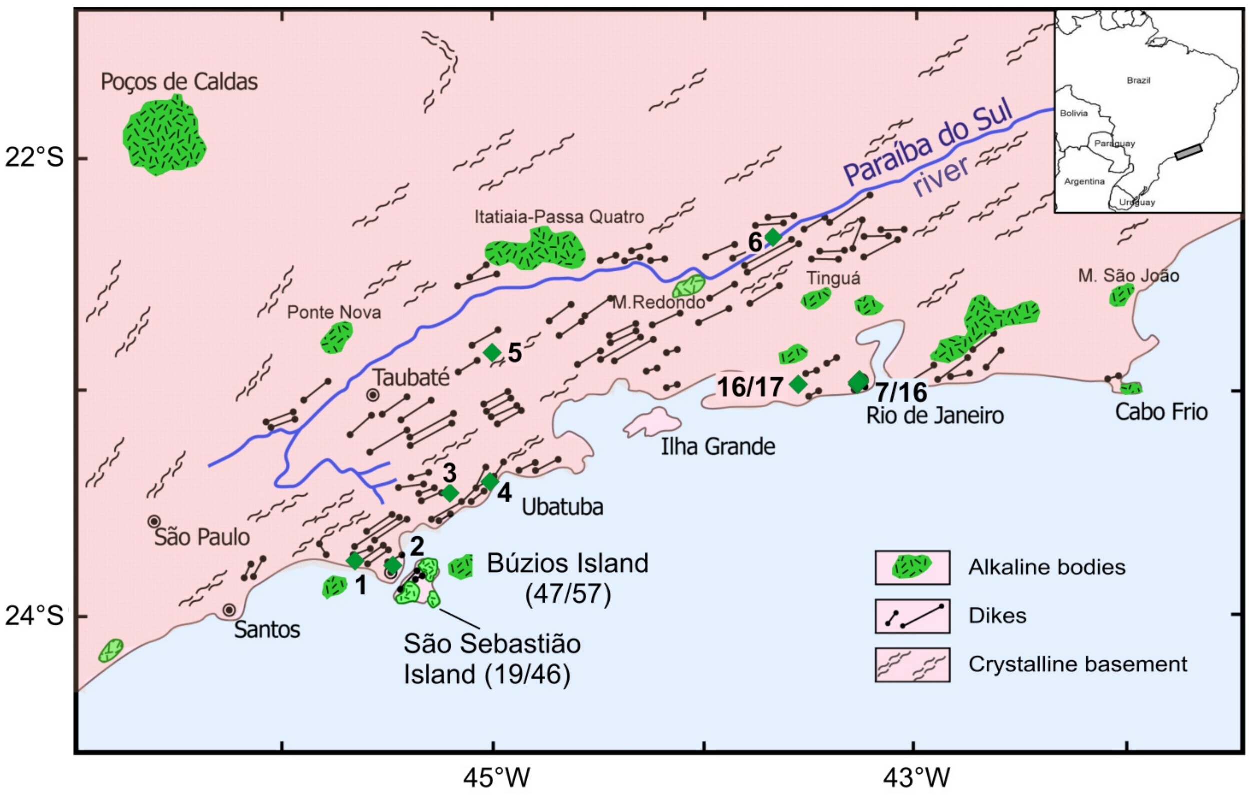

Figure 1. General view of the Santos-Rio de Janeiro coast area, indicating the sampling site locations and the main alkaline complexes in the area.

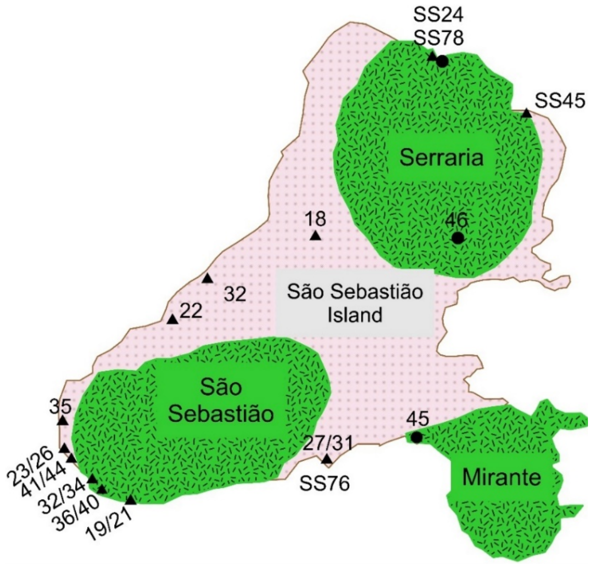

Figure 2. Sampling sites in São Sebastião Island. Sites coded SS are from Montes-Lauar *et al.* (1995).

EXPERIMENTAL PROCEDURES AND RESULTS

Sampling and natural remanent magnetization analysis

A total of 44 alkaline dikes were sampled along the Santos-Rio de Janeiro coast. Most of them are located on São Sebastião Island, where two sites of the alkaline stocks were also sampled (Fig. 1). The dikes are vertical, trending N30-60°E (rarely in the NW or E-W direction), with a thickness of a few meters to tens of meters. Detailed information on the sampled dikes in São Sebastião Island is given by Raposo (2020). In Rio de Janeiro, sampling was carried out in four quarries (Bangu, Sigra, Emasa, and Sulacap; from now on, referred to as RJ quarries), where the dikes are thinner and sometimes twisted. Samples for the paleomagnetic work were collected with a portable, gasoline-powered drill or hand samples. Orientation was performed by both magnetic and sun compasses whenever

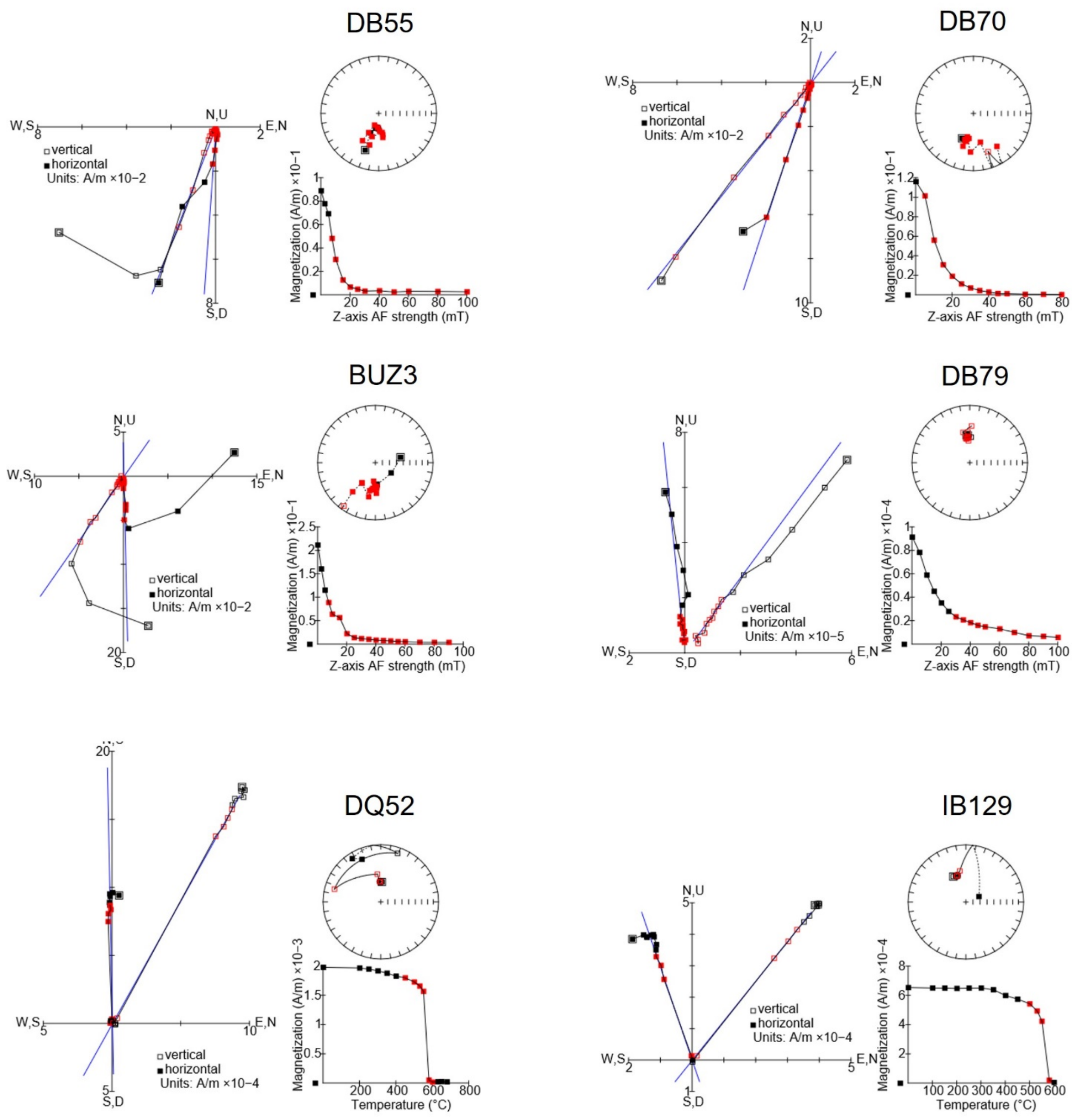

Figure 3. Orthogonal diagrams, stereographic projections, and the variation of the magnetization intensity during the demagnetization procedures. Blue lines are the adjusted magnetization components through the selected points (red dots). Plots are created using the PuffinPlot software (Lurcock and Wilson 2012).

possible. In addition, a sample collection from Búzios Island, already available at the Department of Geophysics (IAG/USP), was reanalyzed, and the new data were also included in this work. The sampling in Búzios followed the same procedures described for the present sampling.

The sample preparation and the paleomagnetic measurements were carried out in the Universidade de São Paulo laboratories. Analyses of the São Sebastião Island samples were performed at the Instituto de Geociências (IGc); all the other samples were analyzed at the Instituto de Astronomia, Geofísica and Ciências Atmosféricas (IAG).

Remanent magnetizations were measured with Agico JR-6A spinner magnetometers. Alternating magnetic fields (AFs) and thermal procedures were used for the sample magnetic cleaning. In general, samples were subjected to AF demagnetizations up to 100 mT at 12–20 steps. The thermal demagnetization was performed at temperatures up to 700°C for at least one specimen from each sampling site. Remanent components were identified and calculated using the orthogonal diagrams (Zijderveld 1967) and the principal component analysis method (Kirschvink 1980). The remanent magnetization was stable in most rocks and up to 50–60 mT (Fig. 3). A soft secondary magnetization component was removed at fields not greater than 20 mT. The thermal demagnetization erased the remanence at around 600°C, indicating that the primary magnetic carriers are oxidized magnetites.

Contact tests were possible on São Sebastião Island and helped to confirm the magnetization stability. Two normal-polarity dikes cut the basement metamorphic complex (Fig. 4A), meaning that the dikes kept their original magnetization. A dike of reversed polarity cuts the syenitic stock (Fig. 4B). These field relationships indicate that the magnetizations were not reset by any intense regional thermo-tectonic event.

The identified characteristic magnetizations and the corresponding virtual geomagnetic poles (VGPs) for each site are displayed in Fig. 5 and Table 1. Most sampling sites are of normal polarity, but dikes of reversed polarity appeared mainly in the RJ quarries, where they sometimes cut normal-polarity dikes. In Fig. 5, the remanence directions are tightly grouped and indistinguishable from place to place. The mean magnetization of the normal and reversed sites is antipodal in statistical terms, as seen in Table 1. The mean inclination of the normal site places the investigated area at about 31°S, roughly 7° south to the present position, considering the current mean latitude of the studied sites and preserving the ~N-S position of South America's central axis.

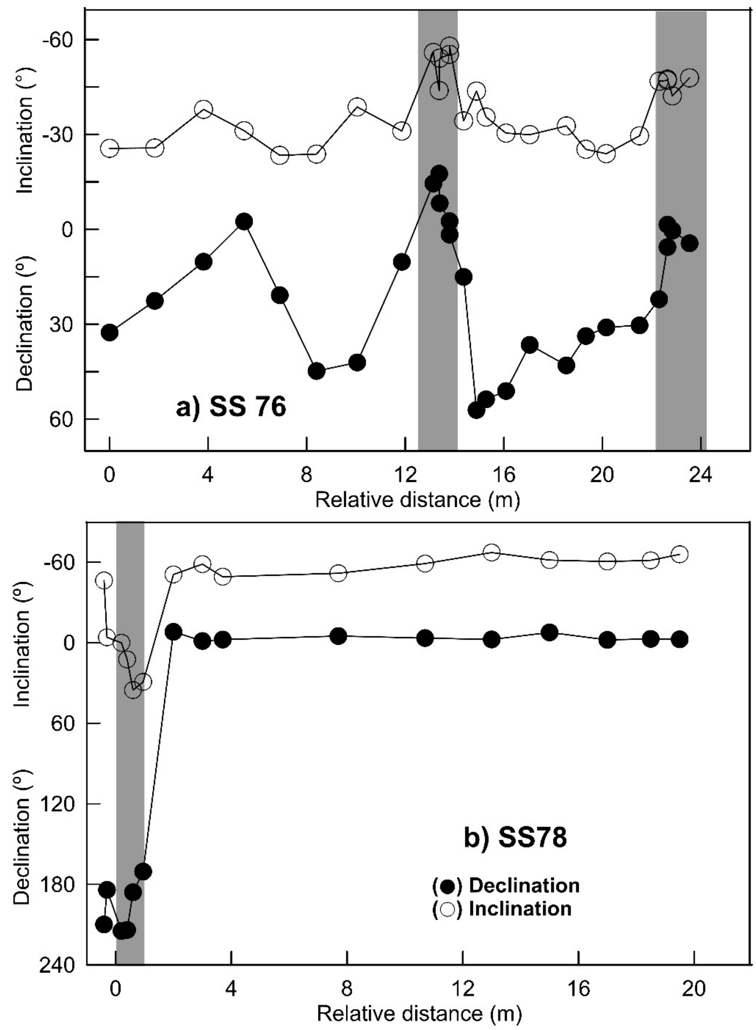

Figure 4. Contact tests between the host rocks and the alkaline dikes. (A) In site SS76, two normal polarity dikes (gray stripes) cut the metamorphic Costeiro Complex. (B) In site SS78, one reversed polarity dike cut the alkaline Serraria stock, which is also of Late Cretaceous age.

Table 1. Paleomagnetic results and radiometric ages for the Santos-Rio de Janeiro alkaline dikes and stocks.

Site #	Samples	Long (°W)	Lat. (°S)	Location	Age	n/N	Dec. (°)	Inc. (°)	α_{95} (°)	k	Pol.	Plong (°E)	Plat (°S)
1	DQ4,5,6	45.65	23.80	S. Sebastião		12/12	1.1	-51.3	3.8	132	N	307.8	-81.7
2	DQ7,8,9	45.47	23.82	Ubatuba		12/12	356.9	-63.4	3.0	207	N	320.6	-68.7
3	DQ45	45.20	23.50	Ubatuba		15/12	186.6	52.2	6.8	42	R	284.2	-79.0
4	DB31	45.01	23.45	Ubatuba		5/3	350.0	-61.6	14.8	70	N	335.7	-69.0
5	DB22	45.00	22.88	Angra dos Reis		6/6	355.7	-52.1	5.7	141	N	335.0	-79.4
6	DB55,56	43.67	22.37	Juparanã	69.6 ± 0.2[a]	6/5	184.2	62.7	6.1	156	R	308.3	-68.0
7	DB72,73,76	43.27	23.01	Emasa quarry		9/9	359.4	-44.4	1.5	1076	N	326.7	-86.9
8	DB78,79	43.26	23.00	Emasa quarry	72.5 ± 0.5[a]	6/6	354.1	-53.7	4.8	193	N	340.1	-77.6
9	DB70,71	43.27	23.02	Emasa quarry		6/6	189.4	52.9	5.9	127	R	280.5	-76.7
10	DB75	43.27	23.02	Emasa quarry	58.2 ± 1.6[b]	5/3	184.7	51.8	4.2	853	R	293.9	-79.7
11	DB77	43.27	23.02	Emasa quarry	66.9 ± 1.9[b]	5/3	182.9	55.3	2.5	2373	R	306.2	-76.9
12	DB80	43.26	23.01	Bangu quarry	97.6 ± 3.5[b]	6/3	11.4	-44.5	3.2	1445	N	245.9	-79.2
13	DB81	43.27	23.01	Bangu quarry		6/3	5.7	-54.1	2.5	2471	N	294.8	-77.3
14*	DB82,85	43.26	23.01	Sulacap quarry		6/5	338.7	-34.2	10.5	54	N	54.8	-69.7
15	DB86,87	43.27	23.01	Sulacap quarry	82.3 ± 1.9[b]	6/6	8.1	-51.2	3.7	314	N	279.4	-78.6
16	DB96,98	43.55	23.02	Sigra quarry		6/6	334.4	-34.1	7.8	74	N	231.8	65.7
17	DB99	43.55	23.02	Sigra quarry	53.8 ± 1.3[b]	5/5	178.5	52.8	10.4	55	R	323.4	-79.6
18	DQ41	45.30	23.80	S. Sebastião		14/14	13.3	-57.7	3.7	115	N	279.7	-71.6
19	DQ42	45.41	23.94	S. Sebastião		17/12	15.9	-51.2	4.2	105	N	257.6	-73.9
20	DQ43	45.40	23.90	S. Sebastião		26/9	358.7	-67.4	6.7	59	N	316.4	-63.7
21	DQ47	45.40	23.90	S. Sebastião		24/9	349.7	-47.9	6.3	68	N	13.7	-79.5
22	DQ52	45.40	23.90	S. Sebastião		9/9	353.5	-53.4	3.2	264	N	342.6	-78.4
23	IB92	45.44	23.93	S. Sebastião		11/9	353.3	-50.2	4.2	153	N	353.1	-80.8
24	IB100	45.50	23.90	S. Sebastião		12/10	8.1	-55.0	5.1	91	N	285.3	-76.4
25	IB101	45.50	23.90	S. Sebastião		11/11	20.4	-49.3	3.2	201	N	248.1	-70.8
26	IB104	45.50	23.90	S. Sebastião		12/12	350.2	-63.6	2.1	412	N	332.6	-67.2
27	IB122	45.34	23.92	S. Sebastião		11/10	353.2	-51.9	4.2	131	N	348.0	-79.5
28	IB123	45.34	23.92	S. Sebastião		10/10	359.7	-48.8	2.7	312	N	317.1	-84.2
29	IB124	45.34	23.92	S. Sebastião		15/13	0.1	-48.4	2.6	247	N	314.1	-84.5
30	IB128	45.34	23.92	S. Sebastião		11/11	348.0	-51.9	3.2	202	N	2.8	-76.4
31	IB129	45.34	23.92	S. Sebastião		10/10	352.4	-49.4	3.6	184	N	0.2	-80.7
32	IB22	45.39	23.83	S. Sebastião		10/10	1.9	-54.7	2.0	559	N	306.6	-78.5
33	IB44	45.40	23.90	S. Sebastião		25/16	3.7	-38.1	4.9	57	N	188.8	-85.8
34	IB46	45.40	23.90	S. Sebastião		19/14	4.7	-50.6	2.3	300	N	286.4	-81.5
35	IB80	45.46	23.90	S. Sebastião		10/10	359.6	-49.5	4.3	125	N	318.0	-83.6
36	IB83	45.40	23.90	S. Sebastião		11/11	2.2	-47.7	2.9	252	N	292.9	-84.7
37	IB84	45.40	23.90	S. Sebastião		19/12	353.8	-34.6	4.4	97	N	83.5	-82.4
38	IB85	45.40	23.90	S. Sebastião		11/11	353.2	-42.7	3.7	150	N	35.4	-83.7
39	IB86	45.40	23.90	S. Sebastião		11/12	348.9	-47.8	3.9	141	N	15.9	-78.9
40	IB87	45.40	23.90	S. Sebastião		12/10	354.1	-45.2	2.6	337	N	16.0	-84.0
41	IB93	45.50	23.90	S. Sebastião	84–85[a]	15/13	353.7	-41.2	3.5	140	N	46.2	-84.3
42	IB95	45.50	23.90	S. Sebastião		11/11	15.1	-53.4	3.5	168	N	265.2	-73.4
43	IB96	45.50	23.90	S. Sebastião		11/12	20.1	-50.4	3.7	157	N	251.1	-70.8
44	IB48	45.50	23.90	S. Sebastião		15/9	186.5	40.1	4.2	150	R	215.2	-83.9
45	IB131	45.29	23.91	Serraria stock		21/18	6.0	-37.2	2.1	262	N	196.5	-82.6
46	IB137	45.29	23.84	Mirante stock		13/13	354.7	-53.0	3.7	126	N	338.9	-79.3
47	SS1	43.42	23.82	Serraria stock		3/3[#]	345.2	-47.8	8.9	195	N	20.4	-75.7
48	SS6	43.42	23.83	Serraria stock		3/3[#]	347.1	-54.7	11.8	110	N	356.4	-74.1
49	SS7	43.42	23.83	Serraria stock		3/3[#]	9.2	-58.7	10.9	147	N	290.6	-72.5
50	SS14	43.42	23.83	Serraria stock		3/3[#]	6.0	-52.2	8.8	199	N	105.9	-79.5
51	SS78	45.30	23.70	Serraria stock		9/9	356.7	-59.4	3.8	186	N	323.5	-73.3
51	BUZ2	45.14	23.81	Búzios		3/3[#]	6.7	-39.8	23.1	29	N	215.3	-83.7
52	BUZ3	45.14	23.81	Búzios		3/3[#]	164.7	57.6	10.8	132	R	353.4	-70.6
53	BUZ5	45.14	23.81	Búzios		3/3[#]	352.5	-54.4	6.9	321	N	343.5	-77.1
54	BUZ6	45.14	23.81	Búzios		3/3[#]	359.5	-51.5	8.8	198	N	317.8	-81.6
55	BUZ8	45.14	23.81	Búzios		3/3[#]	355.6	-71.4	6.9	317	N	319.5	-57.6
Mean magnetization – normal polarity sites						N = 48	358.6	-51.0	2.6	63			
Mean magnetization – reversed polarity sites						N = 8	182.6	53.4	5.4	108			

Long. and Lat.: site coordinates; n: number of specimens analyzed; N: number of specimens in the means; Dec. and Inc.: declination and inclination; α_{95} and k: Fisher's (1953) statistical parameters; Pol.: polarity (N: normal; R: reversed); [a]Ar^{39}/Ar^{40}; [b]K/Ar ages; [#]Hand-blocks; *Excluded from the pole calculation.

Magnetic mineralogy

The low- and high-temperature thermomagnetic curves (Fig. 6) were obtained in a CS3-L apparatus coupled to the Agico KLY-3 bridge equipment in an Argon atmosphere. The high-T susceptibility (K) curves show the Hopkinson peak characteristic of magnetite. Curie temperatures are generally around 600°C, probably due to oxidation at high temperatures. The curves' inflection at 300–400°C indicates the presence of some maghemite. This general behavior was also reported by Raposo (2020).

The isothermal remanent magnetization (IRM; Fig. 7) curves indicate that the primary magnetic carrier in most dikes has low coercivity and saturates at fields of 100–200 mT. This behavior is compatible with magnetite. However, some samples have higher coercivities and saturate up to 300 mT. This behavior may reflect the presence of smaller magnetic grains or a higher oxidation state and is generally associated with the more evolved alkaline types.

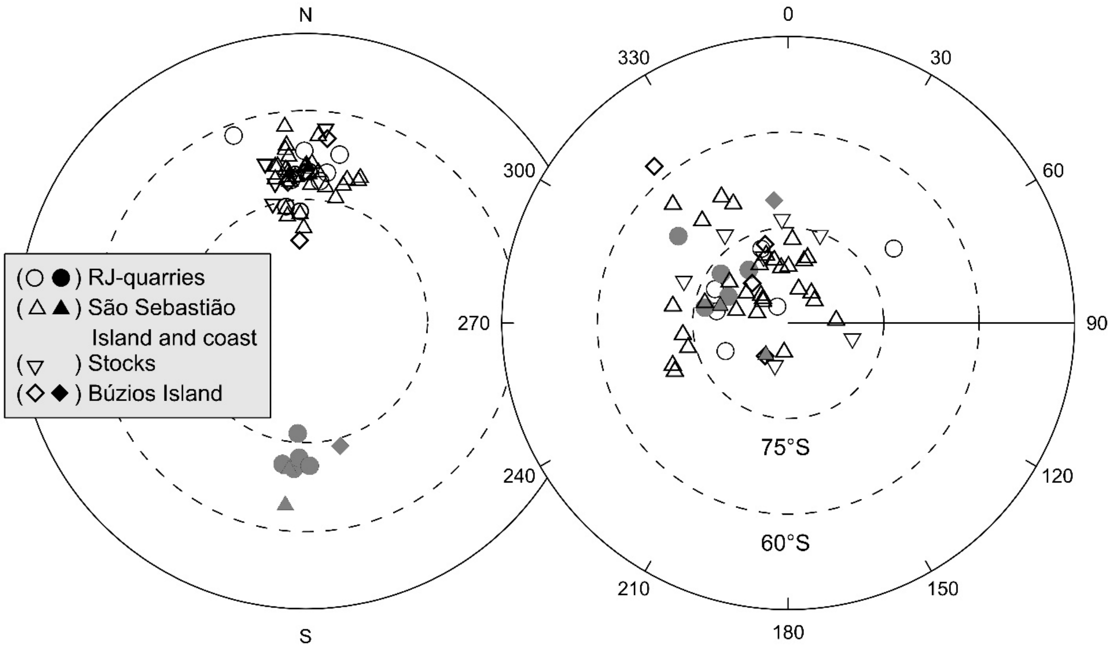

Figure 5. The paleomagnetic directions (left; Wulff projection) and the corresponding south VGPs (right; equal area plot) of the alkaline dikes and available results from the São Sebastião syenitic stocks. Full symbols represent the VGPs from sites of reversed polarity.

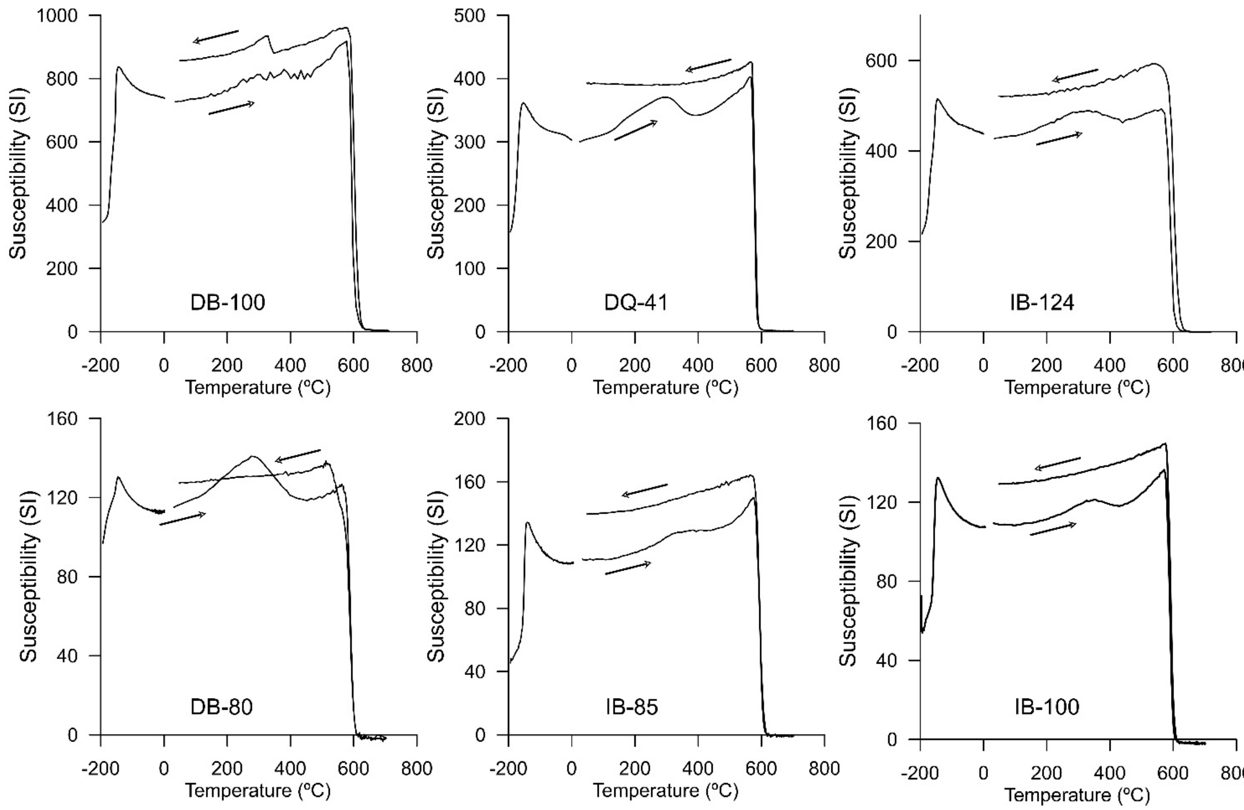

Figure 6. Thermomagnetic curves at low and high temperatures for different types of rocks and polarities. Arrows indicate the heating and cooling curves.

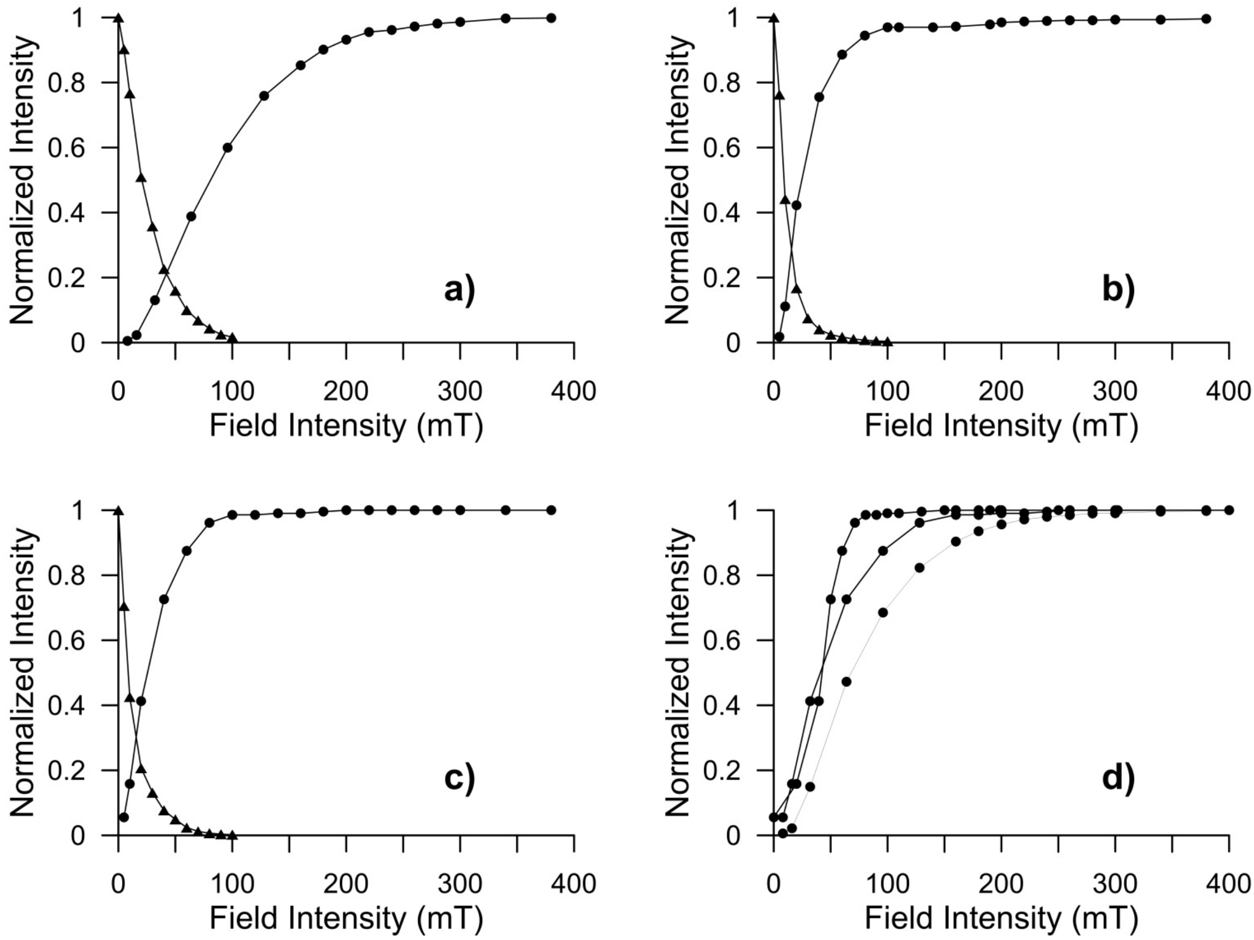

Figure 7. (A, B, C) IRM curves and AF demagnetization of the saturation IRM and (D) other IRM curves are representatives of the various rock types.

CHEMICAL CLASSIFICATION

The studied dikes are of wide compositional variation, as seen in the TAS diagram (Fig. 8). Two groups can be distinguished, one of strongly alkaline affinity, represented by nephelinites, tephrites, fonotephrites, and phonolites. Alkaline basalts, trachybasalts, and trachyandesites represent the other set with medium alkaline to transitional affinity. This group tends to concentrate on the continental areas. Petrographically, the dikes have subaphyric to porphyritic textures, except for the trachyandesites with aphyric texture. In general, the strongly alkaline dikes have phenocrysts of pyroxene (augite), nepheline, biotite, and rare feldspars in a microcrystalline to vitreous matrix (pyroxene, biotite, opaque, nepheline, and feldspar). The porphyritic dikes of lower alkaline affinity have phenocrysts of plagioclase, alkaline feldspar, olivine, hornblende, and kaersutite dispersed in a matrix with a trachytic to fluidal texture composed generally of plagioclase, pyroxene, opaques, and biotite (accessory).

The mineralogical constitution of dikes with aphanitic texture is plagioclase, augite, opaque, and biotite (accessory). Carbonates are present in practically all the studied dikes. In the thicker dikes, contact and central parts show no significant differences that could indicate in situ differentiation processes (Marques and Ernesto 1992). These dikes show similar characteristics to those already described for those occurring along the Santos-Rio de Janeiro coast and São Sebastião Island (Comin-Chiaramonti *et al.* 1983, Bellieni *et al.* 1990).

In the Rio de Janeiro quarries, the dikes displaying reversed magnetization tend to be of more evolved lithotypes (phonolites and tephrites), and they are frequently seen cutting the normal polarity dikes (Marques and Ernesto 1992).

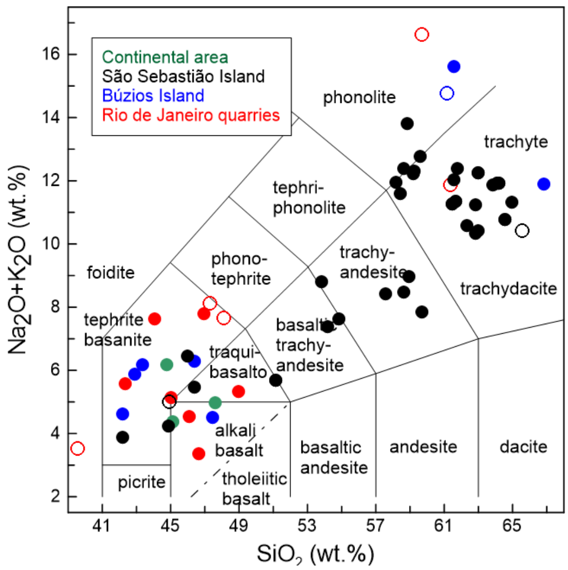

Figure 8. Chemical classification using the total alkali versus silica (TAS) diagram. Full (open) circles correspond to the normal (reversed) polarity dikes. Samples from São Sebastião Island were obtained at IGc/USP and Búzios Island at the University of Trieste (Montes-Lauar; unpublished). Data for the continental dikes are from Comin-Chiaramonti *et al.* (1983) and Marques and Ernesto (1992).

DISCUSSION

Although the paleomagnetic results presented in this study indicate no significant differences among the various alkaline occurrences, it is important to consider that in a scenario of a purely E-W movement of the South American plate, paleomagnetism would be unable to detect the plate drift. The field relationship and the available radiometric ages suggest that at least two generations of dikes may be considered. In São Sebastião Island, Giraldo-Arroyave *et al.* (2021) found high-precision $^{40}Ar/^{39}Ar$ ages in the range 88–85 ± 0.6 Myr for the alkaline rocks (stocks). One normal polarity dike (IB93) from this work gave an age of ~84 Myr (M.H. Bezerra, personal communication). Montes-Lauar *et al.* (1995) also dated the São Sebastião rocks obtaining 84 ± 2.2 Myr (K-Ar) and 80.8 ± 3.1 (Rb-Sr) for the stocks and K-Ar ages of ~76–83 Myr for the dikes. Guedes *et al.* (2005) also reported ENE ages of about 82 Myr for lamprophyre dikes (lamprophyres) but also younger ages of ~70 Myr for syenites and a younger group of 64–59 Myr in the area of Volta Redonda and Rezende. The last area is at the margin of Paraíba river and close to Juparanã, where a dike of reversed polarity exists (Table 1), with a $^{40}Ar/^{39}Ar$ age of 69.6 ± 0.2 Myr (Deckart *et al.* 1998). Three K-Ar determinations (Misuzaki, personal communication) of reversed dikes from Rio de Janeiro gave ages of 66.9 ± 1.9, 58.2 ± 1.6, and 53.8 ± 1.3 Myr, and 72–97 Myr for the normal polarity dikes in the same quarries (Table 1; Deckart *et al.* 1998).

Considering the relatively large ranges of age variation, it is worth checking how the available radiometric ages and magnetic polarities fit the Geomagnetic Polarity Time Scale (GPTS; Gradstein 2012). The long CNS lasted ~37 Myr, ending at about 83 Myr (He *et al.* 2012). Some brief reversed polarity intervals may exist at the end of the CNS but have yet to be confirmed worldwide (Yoshimura 2022).

In Fig. 9, the floating bar graph associates the radiometric ages and the magnetic polarities. The bar lengths consider the uncertainties in the determination of the radiometric age. The Búzios and São Sebastião rocks are in the same age range, which partly agrees with the GPTS. Considering the few existing dikes of reversed polarity in both areas (only 4), we suggest that the better age for the dikes and stocks is ~84 Myr at the end of the CNS interval. For the dikes from the quarries and the highland area near the Paraíba do Sul river (sites 6–17 in Table 1), the widespread ages point to a mean age < 70 Myr, close to both normal and reversed polarity intervals in the GPTS. Therefore, two paleomagnetic poles will result from the paleomagnetic data.

Given the concordance of the geochronological and paleomagnetic data (Table 2) and the fact that the number of stock sites is insufficient for a reliable pole, results from the continental area and the islands are combined to calculate a unique paleomagnetic pole (SR; Table 2) of mixed polarity. This pole supersedes the existing São Sebastião pole (Montes-Lauar *et al.* 1995) for the alkaline rocks from the island, and the other poles for the Serra do Mar alkaline dikes (Ernesto *et al.* 1996). The SR pole (Fig. 10) plots at 319.7°E 81.2°S (N = 44, A_{95} = 3.0°, k = 44).

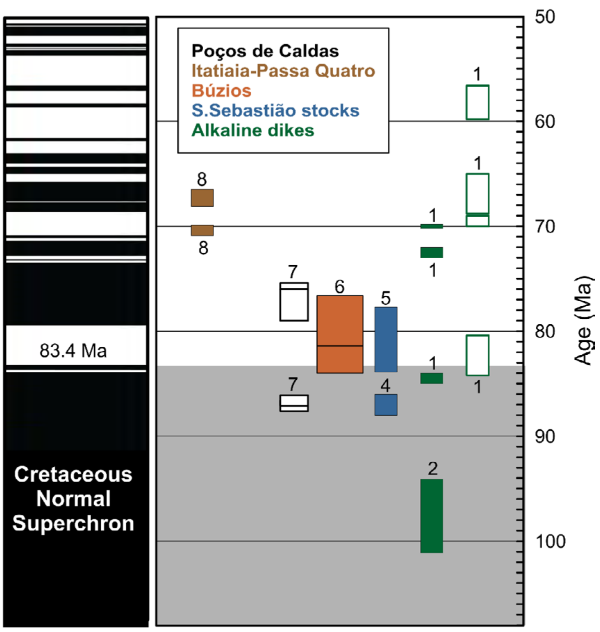

Figure 9. Floating bar graph of radiometric ages for the alkaline occurrences in the northern border of the PMP and respective magnetic polarity. The colored bars represent normal polarity, and the white-filled bars correspond to reversed polarity. The polarity time scale (left column) is from Gradstein (2012), and the CNS radiometric age is from He *et al.* (2012). Data source: 1: this work; 2: Deckart *et al.* (1998); 3: Misuzaki (personal communication); 4: Giraldo-Arroyave *et al.* (2021); 5: Montes-Lauar *et al.* (1995); 6: Gomes *et al.* (2017); 7: Vlach *et al.* (2018); 8: Rosa (2017).

Table 2. Mid to Upper Cretaceous paleomagnetic poles from South American igneous rocks.

Formation	Age (Myr)	Long. (°E)	Lat. (°S)	Polarity	N	k	A_{95} (°)	References
Cabo Magmatic Province (CMP)[1]	102[2]	335.9	87.9	Normal	24	138	2.5	[1]Font *et al.* (2009) [2]Nascimento *et al.* (2002)
SR - alkaline dikes and stocks	~84	319.7	81.2	Mixed	44	54	3.0	This work
RJ - alkaline dikes (sites 6–17 in Table 1)	70–53[1,2]	297.2	80.7	Mixed	12	45	6.5	This work [1] Deckart *et al.* (1998) [2] Misuzaki (unpublished)
Poços de Caldas (PC)[1] (recalculated)	87–76[2]	329.2	82.4	Reversed	31	71	3.2	[1]Montes-Lauar *et al.* (1995) [2]Vlach *et al.* (2018)
Patagonia basalts	80–65	358.4	78.7	Mixed	18	32	6.3	Butler *et al.* (1991)
Itatiaia and Passa Quatro (IPQ)[1]	71–67[2]	359.1	78.1	Normal	16	35	6.3	[1]Montes-Lauar *et al.* (1995) [2]Rosa (2017)

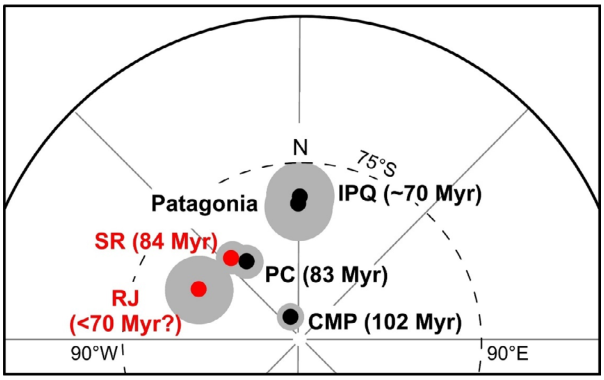

Figure 10. South America mid to Late Cretaceous paleomagnetic poles based on igneous rocks. The SR and RJ poles are highlighted in red. Gray circles are the A_{95} confidence limits.

An independent and less reliable pole was calculated for the other dikes (RJ; Table 2) based on sites 6–17 in Table 1, for which ages 70–53 Myr are attributed.

The SR pole plots (Fig. 10) close to the Poços de Caldas pole. However, in Poços de Caldas, all sites have reversed polarity except for the pyroclastic rocks (3 out of 47 sites) with ill-determined remanences that could be of secondary origin. It is worth mentioning that Montes-Lauar *et al.* (1995) identified magnetite as the magnetic carrier in the Poços de Caldas' rocks. The remanence in magnetites is blocked slightly below 580°C. At about 510°C, fine magnetite grains have a relaxation time of about 10^3 Myr (Butler 1992), ensuring that the Cretaceous rocks can preserve the trustworthiness of the acquired magnetization. Therefore, the 89–76 Myr age interval (Vlach *et al.* 2018) based on various methods must be restricted to an 83–76 Myr interval to represent the magnetization polarity better. Ulbrich *et al.* (2002) argued that the best estimation for this massif is about 79 Myr. Considering the proximity of the Poços de Caldas and the SR poles, an age of about 83 Myr would satisfy all conditions and the GPTS.

The paleomagnetic pole for the Itatiaia-Passa Quatro complexes is of normal polarity. Therefore, the age interval of 71–67 Myr, defined by the U-Pb (Rosa 2017) and Ar/Ar (Mota *et al.* 2011) dating, is compatible with the GPTS mixed polarity interval. This pole has a relatively large confidence circle (A_{95}) but plots next to the Patagonia basalts pole (Butler *et al.* 1991) of 80–65 Myr and mixed polarities. In this study, an age of 70 Myr will be adopted for both poles.

From the above considerations, an apparent polar wander path segment from 102 to ~70 Myr can be envisaged, although it still needs confirmation with more paleomagnetic data and precision dating. From 102 to 84 Myr, the South American plate moved southward (~7°) with practically no rotation, but then, it would rotate about 8° clockwise until ~70 Myr. If the RJ pole is reliable, it would indicate a recovery of South America's present axis position.

CONCLUDING REMARKS

- Alkaline rocks from the Santos-Rio de Janeiro coast yielded a paleomagnetic pole (SR) based on 44 sites, for which an age of 84 Myr is assigned. The sampling sites are mostly dikes, but some stock sites from São Sebastião Island were included;
- The RJ dikes are younger with ages in the interval of 70–55 Myr. However, the paleomagnetic pole is based on a few sites, maybe encompassing different ages, and does not represent a reference pole;
- Considering a rigid plate, the SR pole indicates a southward plate movement since ~100 Myr (age of the Cabo Magmatic Province pole, Fig. 10) of about 7° with practically no rotation. From 84 to 70 Myr, the plate underwent an 8° clockwise rotation with slight latitude variation if an age of ~70 Myr is attributed to the Itatiaia-Passa Quatro and Patagonia poles. However, much more paleomagnetic work is necessary to confirm the plate kinematics.

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