PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Studies on Rock Formations from Northeast Brazil

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II. STUDIES ON ROCK FORMATIONS FROM NORTHEAST BRAZIL

CONTENTS

Devonian, Carboniferous and Triassic formations from Piaui and Maranhão States in the northeast of Brazil have been studied and palaeomagnetic pole positions deduced. During the Devonian and Carboniferous the south pole appears to have moved away from S. America in a southeasterly direction from the vicinity of Rio de Janeiro: in the Triassic it was situated near the present position of the south pole relative to S. America. These results are in good agreement with those from other formations of the same age from other parts of the continent.

Thermal cleaning has been carried out. The Devonian formations were almost completely remagnetized by the Mesozoic or Tertiary geomagnetic fields and the primary magnetization is very weak. Polar wander of 40 to 50° appears to have occurred during the time interval under investigation, i.e. M. Devonian to Triassic.

1. Introduction

The area studied lies between the 3 and 8° S parallels of latitude and between the 40 and 44° W meridians and is situated in the states of Maranhão, Piaui and Ceará in northeast Brazil. It is shown in the geological sketch map of figure 1 where the sampling sites are indicated. The stratigraphy is given in table 1. From the Devonian, The Pimenteiras and Cabeças formations have been studied and the results grouped together. From the Carboniferous the Piaui formation has been well sampled and some samples, possibly of the Poti formation, were also collected. The data are presented together. The Triassic and Permian have also been studied.

Rock formations from this area, particularly the Devonian formations which initially contained much less ferromagnetic material than the upper Carboniferous, Permian and Triassic formations, were severely remagnetized in the Mesozoic and Tertiary approximately in either the normal or reserved direction of a dipole geomagnetic field alined along the present geographic axis.

2. Geology

As may be seen in the geological sketch map (figure 1) and section (figure 2), the beds of the Maranhão basin (sometimes referred to as the Parnaiba basin) dip gently to the east so that the Devonian is exposed along a strip running north–south in the east and the Mesozoic is exposed in a similar strip in the west with the Carboniferous between.

The Devonian and younger formations are usually concordant and both overlie the Pre-Cambrian diastrophism with angular discordance.

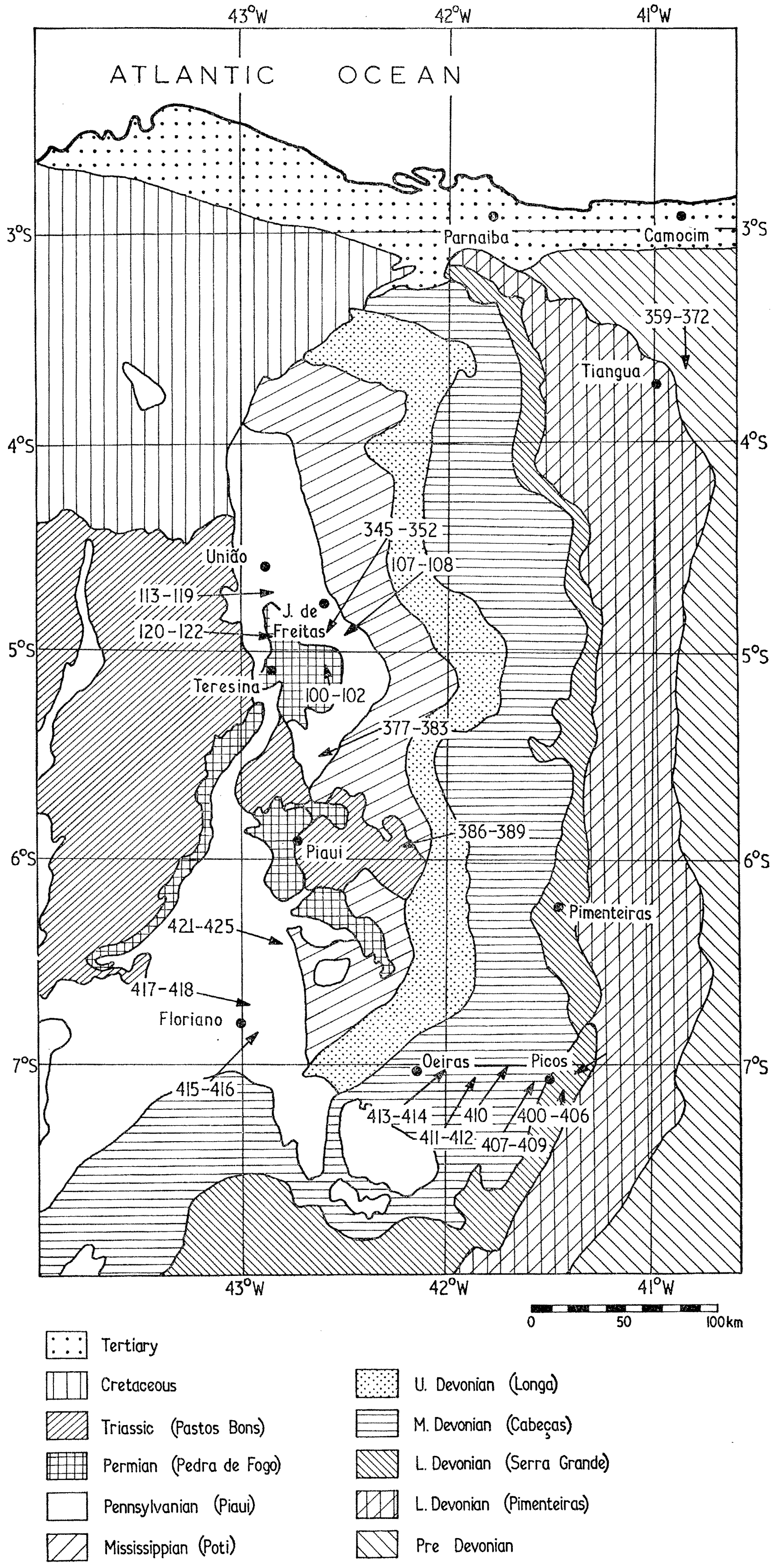

FIGURE 1. Geological sketch map of the Maranhão basin.

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TABLE 1. STRATIGRAPHIC TABLE—NORTHEAST BRAZIL (AFTER W. KEGEL)

era	period		formation	rock types		facies
Cainozoic	Tertiary		Eocene to Pliocene	chalk, sands, sandstone		continental and marine
Mesozoic	Cretaceous		Maestricht	chalk (anhydrite), sandstone, argillaceous shale		marine and continental
	Jurassic		Corda	sandstone		continental
			—	basalt		—
	Triassic		Sambaiba	sandstone		continental
			Pastos Bons	shale (sandstone)		not marine
			Motuca	sandstone, shale		
Palaeozoic	Permian		Pedro de Fogo	shale, chalk, sandstone	anhydrite	—
	Carboniferous	U	Piaui	mocambo-chalk, sandstone red shale		
		L	Poti			
	Devonian	U	Longa	sandstone, shale		continental, marine
		M	Cabeças	dark banded shale		marine
		L	Pimenteiras	sandstone, shale		marine
	Lower Palaeozoic		Serra Grande	shale, sandstone		marine
				conglomerate, sandstone		(marine), continental
			Trombador	sandstone, shale		? marine
			Bambui	alum shale, chalk, sandstone, argillaceous shale		marine

2.1. *Devonian*

700 to 1200 m of Devonian sediments dip at less than 1° towards the middle of the basin. While they are predominantly of marine facies, continental and deltaic facies are important at the base of the middle Devonian.

The formation at the base of the Devonian is the Serra Grande (see table 1). It is represented by from 50 to 700 m of light grey to white coarse grained, feldspathic sandstones. Conglomerates occur locally. Equivalence with the Furnas sandstone of Paranà State in S. Brazil has been suggested.

It is followed by the Pimenteiras formation (see table 1) which contains two members. The lower (Itaim) is a variegated sandstone of finer grain size than the underlying Serra Grande formation: it is very micaceous and there are intercalations of siltstone and shale. The upper member (Picos) is composed of beds of yellow and purplish sandstones and interbeds of siltstone and shale. The fauna indicate an early Devonian age.

The Cabeças formation consists generally of sandstones. There are three members of which the lower (Passagem) consists of beds of light grey sandstones up to 30 m thick and of siltstones. The Oeiras member consists of thick, locally cross-bedded non-fossiliferous grey sandstones. The upper member (Ipiranga) consists of light grey sandstones distinguished from the Oeiras by their finer grain. Locally it is represented by siltstones.

The Upper Devonian is represented by the Longa formation which consists of between 150 and 500 m of dark grey and black banded siltstones and shales. It is succeeded by the lower Carboniferous Poti formation.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

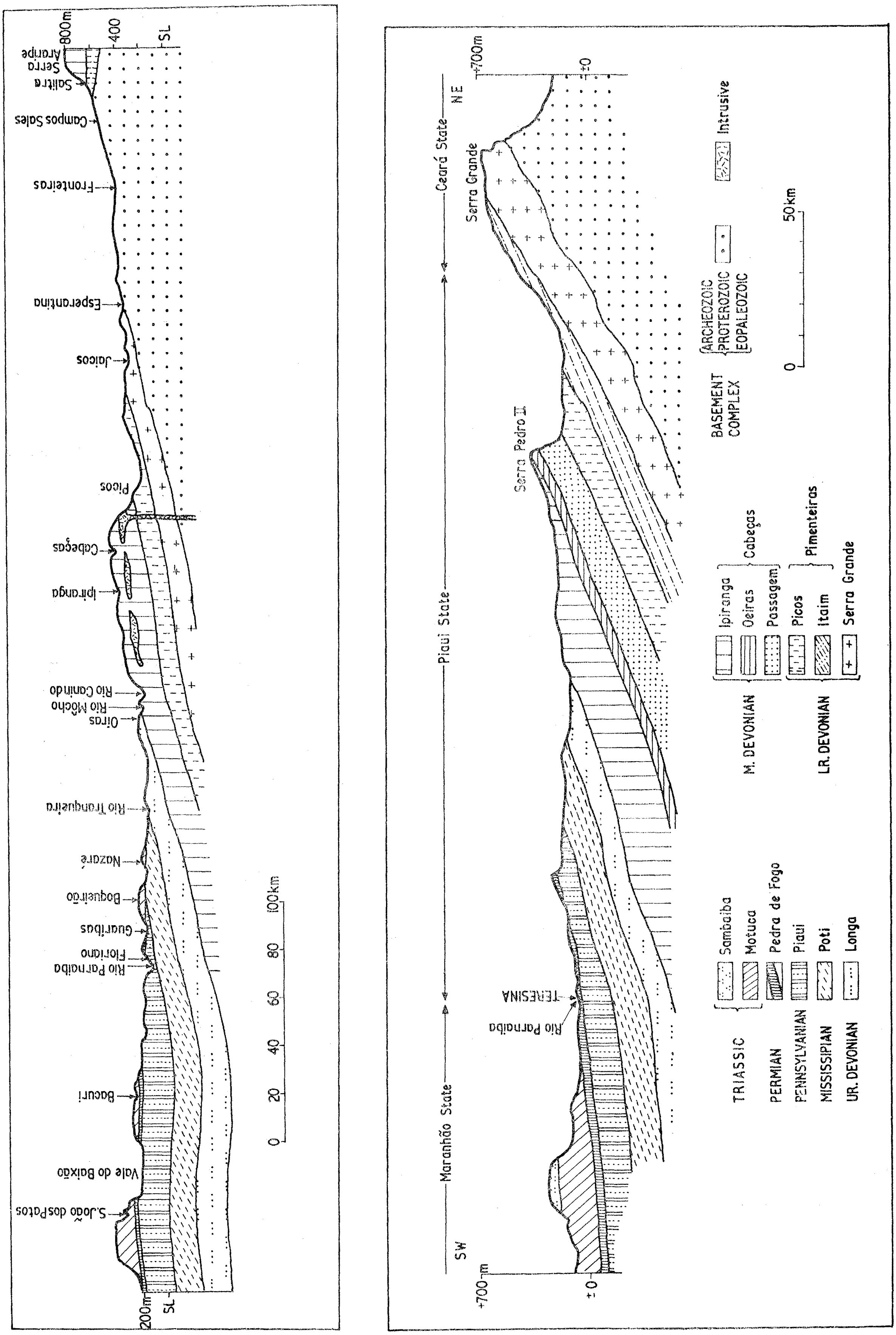


FIGURE 2. Geological sections across the Maranhão basin: (a) NE–SW from Teresina to Serra Grande and (b) W–E from São João through Floriano, Oeiras, Picos and Fronteiras to the Serra Araripe.

2.2. *Carboniferous*

During the Carboniferous, the Devonian shales of Maranhão and Piaui States were covered by continental and marine sediments and then by the strongly continental Permian deposits. The lower Carboniferous is represented by the partly marine, partly continental Poti formation of which the lower part consists of yellow or white sandstones and the upper part of dark grey sandstones. It is typically about 200 m thick, but thins out to a few metres in some places. Thin beds of coal are found.

It is followed by the Piaui formation which may thin out or be absent in some areas. It consists of grey, yellowish somewhat limey sandstones and purplish siltstone and shales. Its age is probably lower–middle Pennsylvanian, and its red or purple colour is doubtless primary. It is the oldest formation in the area to contain primary red or purple beds: surface outcrops of many of Devonian Formations are stained red, but we can be reasonably sure that this coloration is secondary because these formations are invariably pale coloured when encountered at depth in boreholes.

2.3. *Permian*

The Pedro de Fogo formation usually rests directly on the Piaui, but sometimes on the Poti formation, indicating that there was an erosion interval after the deposition of the Piaui. It is composed of a friable light grey feldspathic sandstone and is overlain by thin layers of shale, siltstone and sandstone, which were not lithologically suitable for collection. Its age is fixed as Permian because it underlies fossiliferous Triassic beds.

2.4. *Triassic*

The Motuca formation was originally described as Jurassic–Cretaceous but has since been shown to be older by the discovery of fossil fishes near Floriano. The lower part is composed of a large thickness of red shales and sandstones and is known as the Caxias member. An upper member, the Pastos Bons, is sometimes described as a formation (table 1) and is sandier than the Caxias.

The Sambaiba formation overlies the Pastos Bons and contains red and reddish brown sandstones with intercalated diabase traps. It is sometimes described as a member of the Enxu formation which includes as its upper member the red-grey, medium grained Grajaú Sandstone.

The diabases of southern Brazil have been dated radiometrically as Cretaceous and it was thought possible that those of northeast Brazil were also of that age. If this is so, the Sambaiba and Grajaú sandstones may be younger than their usually quoted Triassic age. But Schult (1969) finds that diabase cores from boreholes in the Amazon basin have Permian palaeomagnetic inclinations.

For a fuller account of the geology reference should be made to de Oliveira (1956) and to Guimarães (1964) and Kegel (1964).

3. Palaeomagnetic results

Samples were collected from the Picos member of the Pimenteira formation and from the Passagem member of the Cabeças formation. The sampling sites are briefly described in table 2. The Piaui formation was sampled in 1958 and again in 1963 and the sample numbers

Table 2. Devonian: Picos Series (392–406) and Passagem Series (407–414)

sample no.	location	dip of beds	colour	code no.	lithology
392–394	From hill on right of road 7 km from Picos on the road to Fronteiras	flat lying	—	—	—
395–396	7 km from Picos on the road to Jaico	flat lying	light brown	5YR–6/4	siltstone
397–399	2.7 km from Picos Bridge on the road to Fronteiras	about 5° at 115°	moderate orange pink pale red	5YR–8/4 5R–6/2	v.f.g. sandstone v.f.g. sandstone
400–402	1.8 km from Picos Bridge on the road to Fronteiras	about 10° at 330°	pale red moderate orange pink	5R–6/2 10R–7/4	f.g. sandstone f.g. sandstone
403–404	0.7 km from the petrol station at Picos on the road to Oeiras	about 5° at 195°	greyish red streaks of moderate red	5R–4/2 5R–5/4	m. to f.g. sandstone
405	1.5 km from Picos on the road to Oeiras	flat lying	—	—	—
406	1.9 km from Picos on the road to Oeiras	flat lying	—	—	—
407–409	5 km from Picos on the road to Oeiras	flat lying	moderate reddish brown	10R–4/6	f.g. sandstone
410	15.2 km from Picos on the road to Oeiras	flat lying	brownish grey	5YR–4/1	m.g. sandstone
411–2	41 km from Picos on the road to Oeiras	flat lying	moderate orange pink pale red	10R–7/4 10R–6/2	f.g. sandstone f.g. sandstone

v.f.g., very fine; f.g., fine; m, medium grained. Colour code no: refer to G.S.A. rock colour chart (1963).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Table 3. Carboniferous: Piaui Formation and possibly Poti Formation (421–425)

sample no.	location	dips of beds	colour	code no.	lithology
345–346	34 km from Terezina on the road to José de Freitas: road cut. From a purple bed below a 1 m sandstone bed which is white inside	flat lying	moderate reddish orange	10R–6/6	siltstone, mudstone
347–348	36 km from Terezina on the road to José de Freitas	10° at 290°	moderate reddish orange	10R–6/6	siltstone
349–350	37 km from Terezina on the road to José de Freitas, road cut	flat lying	pale reddish brown moderate reddish orange	10R–9/4 10R–6/6	siltstone siltstone
351–352	40.5 km from Terezina on the road to José de Freitas, road cut	flat lying	pale reddish brown	10R–5/4	siltstone
353	42.5 km from Terezina on the road to José de Freitas, road cut	8° at 270°	—	—	—
354–355	from top of hill at José de Freitas	flat lying	pale reddish brown	10R–5/4	v.f.g. sandstone, siltstone
380–383	2.2 km beyond km post 40 on the road from Terezina to Picos	flat lying flat lying flat lying	pale red to pale red purple light red	5R–6/2 5RP–6/2 5R–6/6	saltstone — soft v.f.g. sandstone
415–416	12 km from Floriano on the road from Oeiras	flat lying flat lying	pale yellowish brown to dark yellowish brown	10YR–6/2 to 10YR–5/2	v.f.g. sandstone
421–423	at km 139.2 from Terezina on the road from Floriano	flat lying	pale red	10R–6/2	—
424–425	at km 137.1 from Terezina on the road from Floriano	flat lying	pale reddish brown	10R–5/4	—
YY 103	Terezina–Altos road, 5 km from Altos (at 565 km post—from Fortaleza)	flat lying	reddish purple (primary colour yellow?)	—	friable sandstone
YY 104–106	Terezina–Altos road, at 566 km post	flat lying	whitish	—	f. to m.g. sandstone
YY 107–108	Terezina–Altos road, about 10 km from Altos, at 540.5 km from Fortaleza	flat lying	—	—	—
YY 111–112	from top of hill at José de Freitas	flat lying	purple	—	hard sandstone
YY 113–116	44 km from Terezina on the road to São Raimundo	5° at 240°	—	—	marly clay
YY 117–120	40 km from Terezina on the road to São Raimundo	flat lying	117–8 purple weathering to paler colour 119–20 red green	—	marl marl
YY 121–122	35.5 km from Terezina on the road to São Raimundo		—	—	—
YY 123	34 km from Terezina on the road to São Raimundo	flat lying	red purple	—	friable marl

v.f.g., very fine; f.g., fine; m, medium grained. Colour code no: refer to G.S.A. rock colour chart (1963).

Table 4. Triassic: Motuca Formation

sample no.	location	dip of beds	colour	code no.	lithology
386–387	74.8 km from Terezina on the road to Picos, pale brick red poorly cemented siltstones	3° at 90°	pale reddish brown	10R–5/4	f.g. sandstone
			moderate reddish orange	10R–6/6	f.g. sandstone
388–389	79.2 km from Terezina on the road to Picos, rock types as 386–387	flat lying	moderate reddish orange	10R–6/6	f.g. sandstone
417–418	8 km from Floriano on the road to Terezina, red-purple marly siltstones, from isolated Triassic outcrop overlying Piaui formation	flat lying	pale reddish brown	10R–5/4	muddy sandstone
419–420	10 km from Floriano on the road to Terezina, red-purple siltstone, from same Triassic outcrop overlying Piaui formation	flat lying	greyish red	5R–4/2	v.f.g. sandstone
			moderate red	5R–5/4	v.f.g. sandstone

v.f.g., very fine grained; f.g., fine grained; m.g., medium grained. Colour code numbers: refer to G.S.A. rock colour chart (1963).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

and sites are listed in table 3. A list of sample numbers and sites in the Triassic formations is given in table 4. The palaeomagnetic results for the Devonian, Carboniferous and Triassic periods are described below.

3.1. *Devonian results*

Mean directions of the n.r.m. of the several disks cut from each hand sample were calculated and these are given in table 5 and illustrated in figure 3. The n.r.m. directions are approximately parallel or antiparallel to the present axial dipole field direction.

TABLE 5. N.R.M. DIRECTIONS OF DEVONIAN FORMATIONS FROM NORTHEAST BRAZIL

rock series	sample no.	number of disks	directions of n.r.m./degree				polarity N or R
			D	*I*	δ	δ_m	
Picos	396	9	14	−19	18	6	N
	397	6	4	−8	22	9	N
	398	5	88	−6	78	35	N
	399	3	247	−27	12	7	R
	400	5	321	+10	43	20	N
	401	9	120	−6	20	7	R
	403	5	126	−41	10	5	R
	404	1	333	+2	—	—	N
	405	3	196	+15	12	7	R
Passagem	408	2	74	−20	52	37	N
	409	4	184	+39	26	13	R
	411	4	182	+5	13	7	R
	412	2	221	+10	30	21	R
	413	8	355	−11	10	4	N
	414	5	146	+14	25	11	R
normal mean	—	7†	12	−10	48	18	—
reversed mean	—	8†	179	+1	49	17	—
axial dipole field	—	—	0	−14	—	—	—
present field	—	—	343	+10	—	—	—

Note: (1) N.r.m. directions are referred to the present horizontal. (2) † refers to number of samples, *not* disks.

After thermal demagnetization at progressively higher temperatures, a population of directions at optimum demagnetization temperatures selected from the trends in direction and intensity of r.m. during cleaning was formed. The latter are listed in tables 6 and 7. After cleaning, the directions fall into two groups which have been classified as normal or reversed in table 7.

In figure 4 the successive directions of r.m. at the various stages of thermal cleaning are illustrated and the angular change induced varies from 10° for sample 403 up to 330° for sample 398. Two samples show angular changes of more than 180°, three between 90 and 180° and six less than 90°. Three samples were not demagnetized. Twelve of the fifteen samples studied form the group from which the population of cleaned directions was formed.

In order to form a statistically viable population of directions, the north ends of the reversed remanent magnetization vectors and the south ends of the normal magnetization vectors were treated together. They are illustrated in figure 5 where the mean and the standard deviation and standard error circles are shown. The grouping appears poor when compared with that usually obtained for more strongly magnetized formations with little secondary magnetization. But when the extent of the secondary magnetization present in these rocks is taken into account it is better than might be expected: although the standard deviation is large, the c.s.d. circle contains 6 out of 12 of the unit vectors, i.e. 50 % of them as compared with 63 % required of a Fisherian distribution. Five of the remaining 6 unit vectors lie just outside the c.s.d. circle.

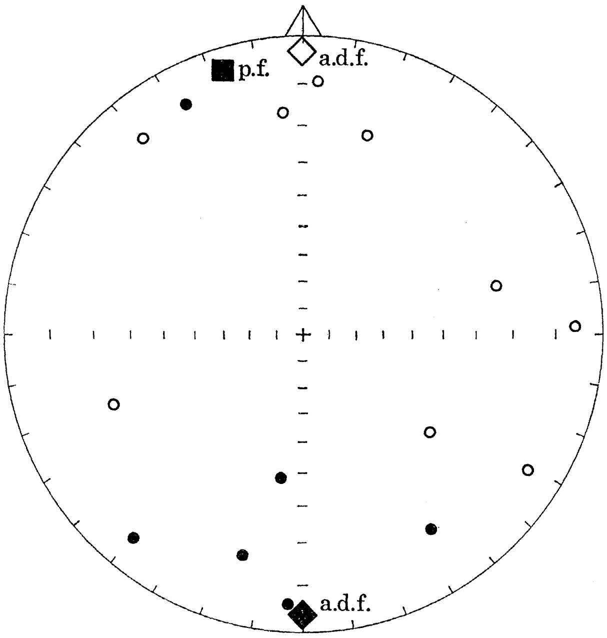


FIGURE 3

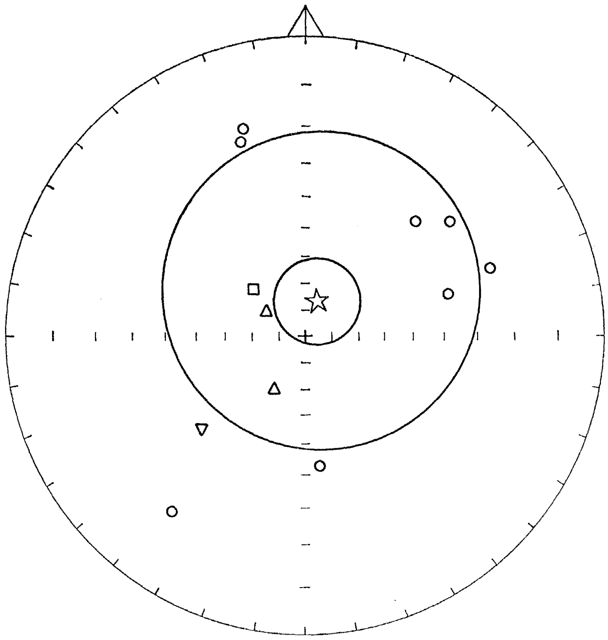
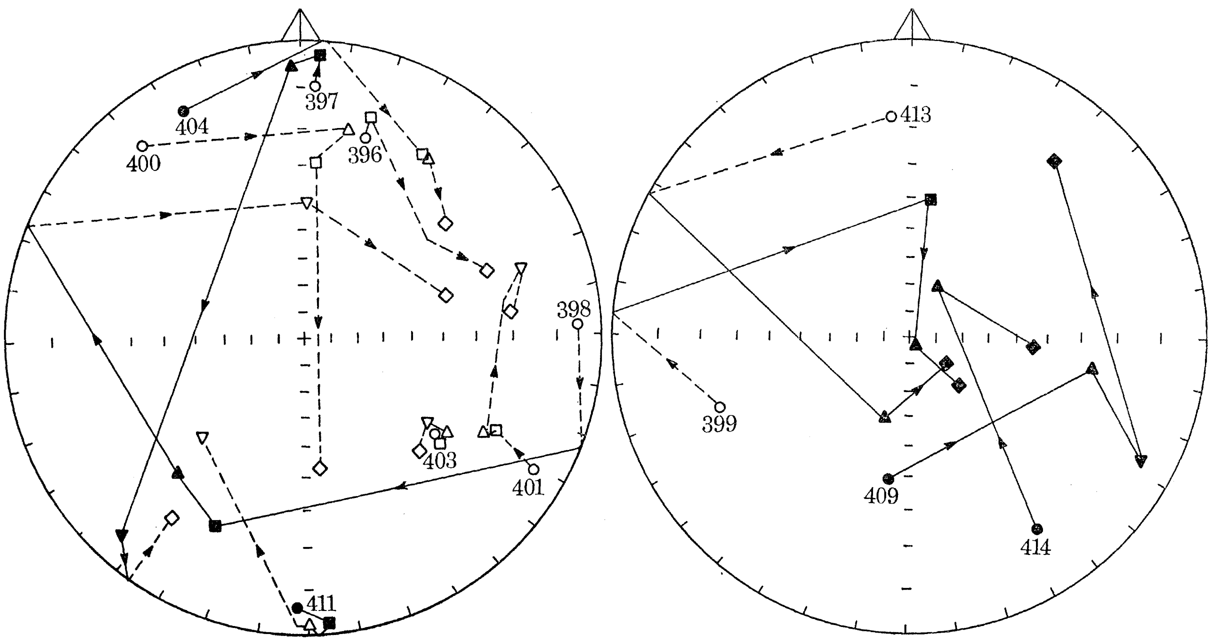


FIGURE 5

FIGURE 3. N.r.m. directions of samples from the Picos and Passagem Series (Devonian). Present field (p.f.) and axial dipole field (a.d.f.) directions shown.

FIGURE 5. Cleaned r.m. sample-mean directions of Picos and Passagem Series. Standard error and standard deviation circles shown.

cleaning temperature	600 °C	530 °C
north-seeking pole	○	▽
south-seeking pole	□	△



●n.r.m. ■400 °C ▲530 ▼590 ◆600

FIGURE 4. Trends of change of r.m. directions of r.m. directions of samples from the Picos and Passagem Series during thermal cleaning.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE 6. G.M. INTENSITIES OF DEVONIAN ROCKS FROM NORTHEAST BRAZIL DURING THERMAL DEMAGNETIZATION

°C	N	$M/\mu G$	lg M	s.d.	s.e.
n.r.m.	14†	8.13	0.910	0.782	0.209
	78	11.01	1.042	0.785	0.089
400	11†	6.40	0.806	1.048	0.316
	31	6.04	0.781	1.024	0.184
530	10†	4.42	0.645	1.160	0.367
	38	6.53	0.815	1.100	0.178
590	7†	3.40	0.532	0.553	0.209
	24	4.03	0.605	0.780	0.159
600	8†	1.87	0.271	0.701	0.248
	28	1.70	0.230	0.773	0.146

† Sample-means given unit weight: otherwise disks.

TABLE 7. CLEANED R.M. DIRECTIONS OF DEVONIAN FORMATIONS FROM NORTHEAST BRAZIL

rock series	sample no.	temperature of cleaning	number of disks	direction of r.m./degree				polarity (N or R)
				D	I	δ	δ_m	
Picos	396	600	1	69	−25	—	—	N
	397	600	2	216	−14	47	33	N
	398	600	2	73	−38	58	41	N
	399	600	1	133	+62	—	—	R
	400	600	3	172	−44	49	28	N
	401	600	5	83	−19	38	17	N
	403	600	3	136	−34	48	28	N
	404	600	1	51	−26	—	—	N
Passagem	409	530	3	85	+22	17	10	R
	411	590	1	226	−39	—	—	N
	413	530	4	136	+73	50	25	R
	414	530	2	19	+69	75	53	R
mean†			12‡	20	−76	55	16	
			28	356	−66	60	11	

† Mean formed from population comprising directions given above for R samples and of their opposites for N samples.
‡ Refers to number of samples.

TABLE 8. SOUTH PALAEOMAGNETIC POLE OF R.M. OF DEVONIAN FORMATIONS

treatment	number of		south palaeomagnetic pole			
	disks	samples	lat.	long.	δ	δ_m
cleaned thermally at 530–600 °C	—	12	30° S	47° W	64°	18°
	28	—	45° S	39° W	67°	13°

The mean south palaeomagnetic pole and statistical parameters of this population of cleaned directions are listed in table 8 and illustrated in figure 11. Although the standard deviation of the distribution of sample-mean poles is large the position of the mean is consistent with south palaeomagnetic pole positions obtained from other South American rock formations whose ages range from Cambrian to Devonian (pp. 496, 510 and 514). There is now considerable evidence that the south pole was situated near the northeast coast of Brazil in the early Palaeozoic.

3.2. *Carboniferous results*

Collections were first made from the Piaui formation in 1958 (samples 345 to 355, 380 to 383 and 415 to 425) and then in 1963 (samples YY 103 to 123). The sites are listed in table 3 and shown in figure 1.

Samples 345 to 355, which were collected from the environs of José de Freitas were studied in more detail than the others. They were demagnetized in steps at 150, 300, 400, 500, 550 and 630 °C. The resulting sequence of changes in direction of r.m. and the corresponding south virtual geomagnetic poles are listed in table 9. The distribution of intensities both of disks and of hand sample means is logarithmic-normal. The geometric means with their standard errors at each demagnetization stage are shown in figure 6.

TABLE 9. THERMAL DEMAGNETIZATION OF PIAUI FORMATION (JOSÉ DE FREITAS SITES)

demagnetizing temperature/°C	number of samples	mean direction of r.m./degree				south virtual pole			
		D	I	δ	δ_m	lat.	long.	δ	δ_m
n.r.m.	9	130	+58	48	16	34° S	5° E	52	17
150	9	130	+52	57	19	38° S	10° E	57	19
300	9	147	+38	60	20	53° S	16° E	58	19
400	9	144	+36	58	19	52° S	21° E	57	19
500	9	140	+37	58	19	50° S	23° E	57	19
550	9	142	+41	63	21	48° S	18° E	62	21
630	9	146	+32	69	23	55° S	32° E	65	22

See table 12 for circular standard deviations and errors computed for the populations of disk directions corresponding to the above.

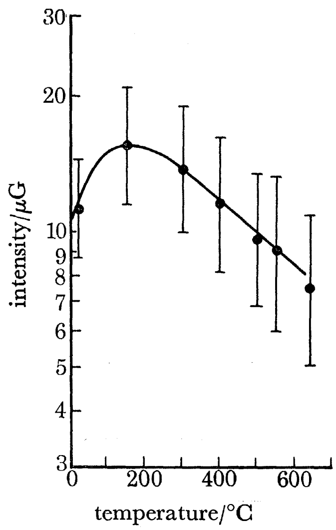


FIGURE 6. Thermal decay curve of mean r.m. of the samples from the José de Freitas sites in the Piaui formation The geomagnetic site mean intensity with its standard error at each successive stage of demagnetization is shown.

The other samples from the 1958 collection were thermally treated at 550 °C only and the results were combined with those from José de Freitas at 550 °C. The populations of r.m. directions are illustrated in figures 7 and 8 before and after thermal cleaning. The mean directions of r.m. and corresponding south palaeomagnetic poles are listed in table 10, (i) for the whole 1958 collection, and (ii) for the samples from sites other than José de Freitas (i.e. those not included in table 9). In computing the statistical parameters, the data from samples 422 and 423 have been omitted because their r.m. directions do not belong to the main population in figures 7 and 8 (open symbols). This may be because their intensities are so weak: that of sample 422 was only 0.3 μG and that of sample 423 only 0.4 μG as compared with 8.9 and 7.1 μG respectively for samples 424 and 425.

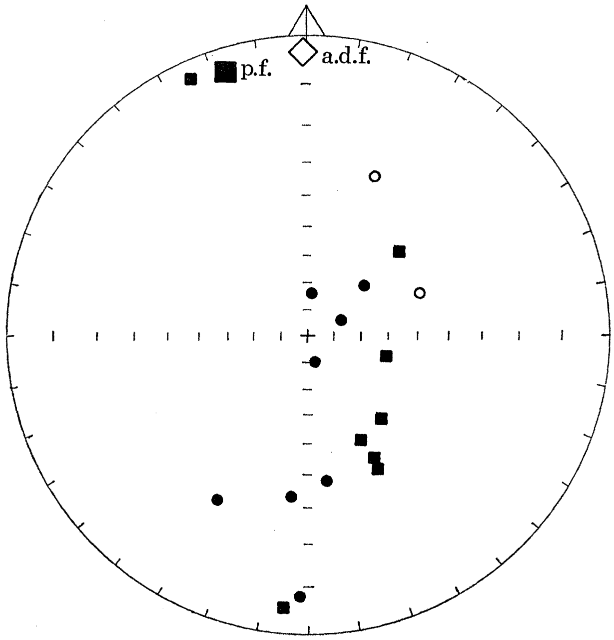


Figure 7

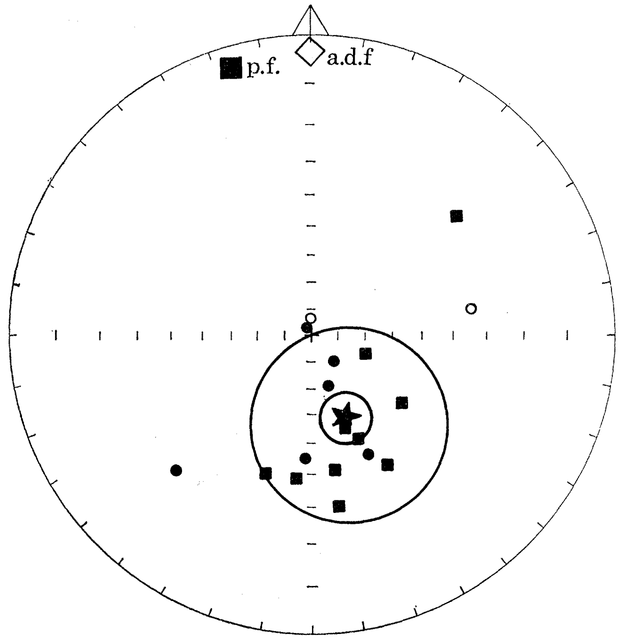


Figure 8

Figure 7. Sample-mean n.r.m. directions for the 1958 collection from the Piaui formation. Directions of samples from the José de Freitas sites plotted as squares: those from the other sites as circles. Present field (p.f.) and axial dipole field (a.d.f.) directions shown.

Figure 8. R.m. sample-mean directions after thermal cleaning of Piaui formation at 550 °C. Standard error and standard deviation circles shown. Key as for figure 7.

Table 10. R.m. directions and south palaeopoles of Piaui formation

		number of		mean directions of r.m./degree				South pole			
population	treatment	samples	disks	D	I	δ	δ_m	lat.	long.	δ	δ_m
(i)	n.r.m.	17	—	151	+63	44	11	36° S	13° W	52	13
		—	64	153	+62	43	5	40° S	15° W	50	6
(i)	550 °C	15	—	158	+57	31	8	50° S	15° W	36	9
		—	44	160	+52	35	5	55° S	12° W†	39	6
(ii)	n.r.m.	8	—	177	+63	42	15	38° S	34° W	52	19
		—	28	181	+66	37	7	36° S	40° W	46	9
(ii)	550 °C	6	—	181	+62	30	12	47° S	40° W	37	15
		—	17	176	+59	35	9	50° S	34° W	42	10
(iii)	n.r.m.	7	—	155	+44	29	11	57° S	1° W	33	12
		—	47	162	+44	43	6	61° S	9° W	74	7

Population: (i) whole 1958 collection; (ii) 1958 collection except José de Freitas sites (table 9); (iii) 1963 collection.

† This pole is plotted in figure 11 and listed on p. 553.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

In 1963, a second collection (YY series) was made. The n.r.m. directions of some samples indicate partial remagnetization in the Quaternary or Tertiary normal geomagnetic field as shown in figure 9. The mean direction and mean south virtual pole for the group of samples in the southeast quadrant of the stereogram are listed in entry (iii) of table 10. Some of the disks from the partially remagnetized samples which lie in the northwest quadrant of the stereogram (figure 9) were subjected to alternating field demagnetization, but only in fields of up to 1600 Oe which produced no significant change (table 11). Thermal demagnetization is a more effective method of isolating the primary r.m.

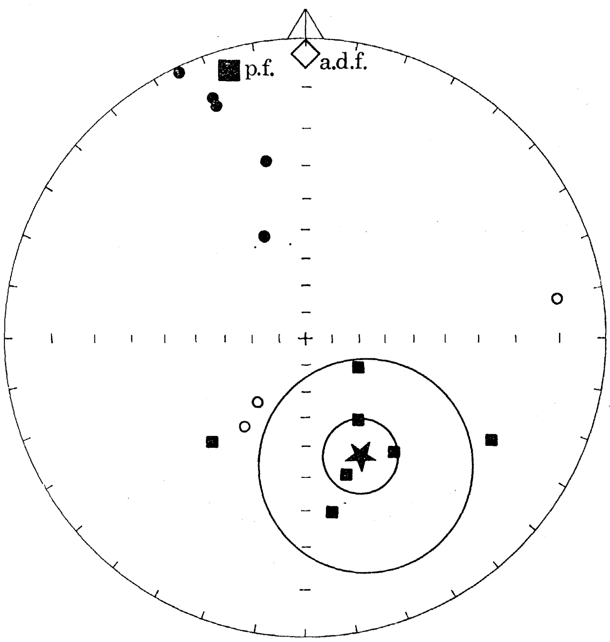


FIGURE 9

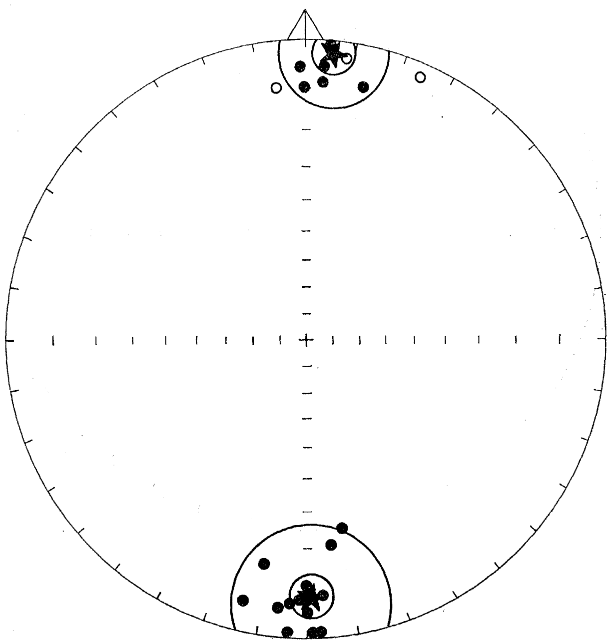


FIGURE 10

FIGURE 9. N.r.m. sample-mean directions for 1963 collection from the Piaui formation. The stable group of samples are plotted as squares: their mean direction with standard error and standard deviation circles are shown.

FIGURE 10. Sample-mean directions of n.r.m. of the Motuca formation (Triassic). The mean direction, standard error and standard deviation circles are shown.

The homogeneity of r.m. in the Piaui formation is such that the standard deviation of a population of disk directions (total N_d) is not significantly different from that of the population of sample-mean directions formed from the same disk measurements (total N_s) see table 12. The corresponding standard errors are smaller when disks are used as units since N_d is always larger than N_s. These smaller c.s.e. (or α_{95} values) are thought to be more realistic than those computed from sample means for the data presented here (though this is not always so).

The palaeomagnetic pole at 55 °S 12 °W accepted here for the Piaui (line 4 of table 10) is derived from thermally cleaned r.m. and differs from that at 38 °S 9 °W originally obtained from n.r.m. measurements (Creer 1964*a*), or at 40 °S 15 °W (line 2, table 10). During progressive thermal cleaning, the mean r.m. vector moves to shallower inclinations (see table 9). This result is consistent with a Kiaman magnetic age: the r.m. is exclusively of reversed polarity.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

TABLE 11. PILOT A.F. DEMAGNETIZATION OF PIAUI FORMATION

demagnetizing field/Oe	number of disks	direction of r.m./degree D	I	δ_m
0	4	6	+14	17
300	4	351	+9	6
650	4	346	+10	6
1000	4	348	+10	6
1250	4	349	+9	5
1600	4	348	+12	11

One disk taken from each of four samples whose n.r.m. was about 90° from the thermally cleaned formation-mean direction.

TABLE 12. COMPARISON OF STATISTICS OF DISTRIBUTIONS WITH (*a*) SAMPLE-MEAN DATA AND (*b*) DISK DATA AS UNITS

temperature of demagnetization/°C	standard deviations: directions/deg (*a*)	(*b*)	intensities/μG (*a*)	(*b*)	standard errors: directions/deg (*a*)	(*b*)	intensities/μG (*a*)	(*b*)
20	48	45	0.71	0.70	16	7	0.24	0.11
150	52	52	0.72	0.74	19	10	0.24	0.13
300	60	53	0.74	0.73	20	10	0.25	0.14
400	58	53	0.78	0.76	19	10	0.26	0.15
500	58	56	0.78	0.76	19	11	0.26	0.15
550	63	59	0.87	0.86	21	11	0.29	0.17
630	69	65	0.81	0.80	23	13	0.27	0.16

Notes: (1) Populations formed from José de Freitas group of samples. (2) Columns (*a*): sample-means, (*b*) disk measurements used as statistical units. (3) Standard deviations and errors of the distribution of logarithms of intensity are given (the distribution of intensities is log-normal). Intensities in μG.

3.3. *Triassic results*

The sampling sites are located in figure 1 and briefly described in table 4. The n.r.m. directions are plotted in figure 10. It was observed that three of the four samples from the first two sites (386, 388 and 389) had normal polarity while sample 387 was reversed. The third and fourth sites (about 125 km southwest of the first two) yielded samples with reversed polarity (417, 419 and 420). Sample 418 broke in transit and was therefore not studied.

Specimens from all samples were then thermally demagnetized at 400, 530 and 600 °C. The mean directions of the normal and reversed sites at the successive demagnetization stages are listed in table 13

The mean direction of the normally magnetized group of specimens is almost antiparallel to that of the reversely magnetized specimens. Hence a single population was formed, by inverting one of these groups of directions and combining it with the other. The c.s.d. progressively increased during thermal demagnetization so the combined normal+reversed population of n.r.m. directions was used at first to compute a pole (given in table 13). However the pole computed from the average of the N and R means after cleaning at 600 °C (at 81 °S 64 °W) is accepted as a better estimate of the Triassic palaeomagnetic pole position and supersedes that given in table 1 of Creer *et al.* (1970).

Specimens rather than hand samples have been assigned unit weight because the standard deviation of the distribution of disk directions within each hand sample is as large as or larger than that of the distribution of sample-mean directions, indicating that the small scale (order of a few centimetres) inhomogeneities of magnetization are as great as the larger scale inhomogeneities over distances between samples.

Table 13. Directions of r.m. of the Triassic Motuca formation

population	treatment	number of disks	directions of r.m./degree D	I	δ	δ_m
normal polarity	n.r.m.	9	9	+3	11	4
	400 °C	5	356	−26	23	10
	530 °C	4	356	−16	19	10
	600 °C	4	356	−22	22	11
reversed polarity	n.r.m.	15	179	+9	17	5
	400 °C	8	188	−5	33	12
	530 °C	9	175	−4	58	19
	600 °C	15	190	+32	54	14
all (see §3.3)	n.r.m.	24	9	0	40	8

The last entry has been used to compute the following Triassic palaeomagnetic pole: lat. 78° S, long. 169° W, c.s.d. = 40°, c.s.e. = 8°. However, that obtained from the average of the directions listed in lines 4 and 8 is accepted as a better estimate of the Triassic palaeomagnetic pole position (81° S 64° W).

4. Discussion of results

4.1. *Palaeomagnetic latitudes*

The Devonian formations studied (§3.1) have been almost completely remagnetized approximately in the normal or reversed senses of the present axial dipole field. Nevertheless, a weak relic of what is believed to be a primary magnetization dating from pre-Carboniferous times has been detected. The palaeomagnetic pole corresponding to this remanence falls in the region of Rio de Janeiro, to the south of those (off northeast Brazil) computed from the r.m. of Lower Palaeozoic (Cambrian and Ordovician) rock formations from Argentina (part III below) and Ordovician and Lower Devonian formations from Bolivia (part IV), and to the northwest of the Carboniferous poles computed for the Piaui formation (this part), for red beds from La Rioja (part III) and for the Taiguati formation (part IV). Thus, throughout the Palaeozoic, Brazil must have occupied very high, almost polar latitudes.

It could be argued that the result obtained from the Picos and Passagem series (§3.1) is not suitable for interpretation in terms of palaeolatitudes because of its large standard deviation and standard error resulting from very weak r.m. intensity and the severe cleaning applied. However, it is consistent with the other palaeomagnetic data from formations of similar geological age from S. America, and also from Africa (Creer 1964*b*, 1968). The results presented here should be considered together with the others obtained from similar studies on Palaeozoic rock formations from Argentina and Bolivia. Palaeolatitudes for the Lower Palaeozoic are poorly established by traditional geological methods.

4.2. *Agreement with other geological evidence*

There is considerable evidence of glaciation in S. America in the late Palaeozoic, between the early Carboniferous and the early Permian in northwest Argentina and Bolivia, and between the Carboniferous and the Permian in Paraná State in southeast Brazil. This has been the subject of a recent article by Frakes & Crowell (1969).

Evidence of earlier glaciation is not so strong, though the palaeomagnetic latitudes (§4.1) suggest that we should look for it in northeast Brazil rather than in the southern states. De Oliveira (1956) in his chapter on Brazil in the G.S.A. memoir on the geology of S. America, mentions that there are scattered vestiges of glaciation extending 1200 km from central Bahia to northeast Paraná in the Cambrian, but that it is not known whether they are the result of alpine or continental glaciers. He suggests that there seems to be a correlation between this

Figure 11. Palaeomagnetic pole positions deduced from this work. Standard error circles shown. Equal area (Schmidt) projection. D, Devonian (tables 7 and 8); P, Piaui (Ur Carboniferous) (table 10); Ꞧ, Triassic (table 13).

glaciation and others noted in various parts of Africa, in India, China, Australia, Europe, and N. America in the Algonkian or Eo-Cambrian. On this evidence it is not easy to define climatic zones and it appears that perhaps the whole globe underwent a cold spell at the same time. Termier (1969) concluded that climates and seasons were not well differentiated in the late pre-Cambrian and early Cambrian and that climatic belts became well established only by the Silurian, but the evidence is sparse at present. It seems unreasonable to expect that the poles have always been covered by ice-gaps during geological time and the absence of indisputable evidence of glaciation in northeast Brazil in the Devonian when the palaeolatitudes deduced from rock magnetic studies are high may thus be an important feature of the palaeoclimatology of early Phanarozoic time.

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The following maps cover the area sampled: Carta do Brasil, 1:500000. Sheet SA–24–SO, Fortaleza, S.O. Sheet SB–23–NE, Terezina, N.E. Sheet SB–23–SE, Terezina, S.E. Sheet SB–24–SO, Jaguariba, S.O.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES