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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Palaeomagnetic Studies on Rock Formations from Northwest Argentina

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III. PALAEOMAGNETIC STUDIES ON ROCK FORMATIONS FROM NORTHWEST ARGENTINA

CONTENTS

Cambrian, Cambro-Ordovician and Ordovician formations of red sandstones and siltstones from the sub-Andean regions of the Provinces of Salta and Jujuy have been studied. The grouping of n.r.m. directions suggests partial remagnetization after folding in the Tertiary or Quaternary geomagnetic field. Thermal cleaning at 300 °C and higher temperatures destroys this secondary magnetization leaving a magnetization which is accepted as representing the lower Palaeozoic geomagnetic field. Palaeomagnetic south pole positions have been computed and lie in the Atlantic Ocean to the NNE of Brazil.

The period between the Carboniferous and Triassic is covered by the Paganzo formation which is exposed in La Rioja Province. The older part (Paganzo II) is reversely magnetized with a south p.m. pole in the South Atlantic, while the upper part (Paganzo III) is normally magnetized with a south palaeomagnetic pole in the vicinity of poles obtained for Triassic rock formations from elsewhere in S. America.

Formations of red beds from Salta province regarded as Upper Palaeozoic or Mesozoic yield a south palaeomagnetic pole in the South Atlantic corresponding to a Triassic age.

Ore microscope and thermal decay curves suggest that the remanent magnetism is due to haematite.

1. Introduction

Palaeozoic rocks are found in Argentina principally in the northwestern provinces of Salta and Jujuy and also in the Sierra de la Ventana in the south of the province of Buenos Aires. The latter have been found to be too weakly magnetized to warrant detailed studies. The former consist of red sandstones and siltstones and are highly suitable for palaeomagnetic investigations. In fact it was from these formations that the first reliable estimates of the lower Palaeozoic poles for S. America were obtained and these have been quoted in review papers (Creer 1964, 1965, 1968).

2. Geology

The stratigraphy of northwest Argentina is summarized in table 1.

2.1. *Pre-Cambrian*

In the Pre-Cordillera, the Pre-Cambrian is represented by phyllites, quartzites and crystalline limestones exposed a little to the northwest of Mendoza where they are intruded by gabbros

Table 1. Stratigraphic table, Jujuy

Cenozoic	Quaternary	Recent and Present			sands, clays and pebbles
			discordance		
		Lower			conglomerates, sandstones, etc.
			discordance		
			Huachichocana fm		andesite (hornblende)
			discordance		
	Tertiary	Pliocene	Chaco fm		sandstones and red clays
			discordance		
Mesozoic	Cretaceous		Yacoraite fm		limestones, oolitic limestones
			discordance		
Palaeozoic	Ordovician	Arenigian	Huantes	Cienaguillas fm	lutites and clay-sandstones
		Ur Tremadocian	Group	Coquena fm	sandstones, limestones and lutite
			discordance		
	Cambrian		Meson	Chalhualmayoc fm	
					ortho quartzites
			Group	Campanario fm Lizoite fm	
			discordance		
Pre-Cambrian			Puncoviscana fm		slates, greywackes and quartzites

and serpentinized periodotites. In the north of Salta Province and in the puna of Jujuy Province green and violet phyllites and greywackes are exposed at the base of the Cambrian over a large area. They are only weakly metamorphosed.

2.2. *Cambrian*

The geological map of the area makes no distinction between Cambrian and Ordovician formations.

Unfossiliferous Cambrian deposits are known in the eastern Cordilleras of northern Argentina where they rest with strong angular unconformity on highly folded Pre-Cambrian rocks and are covered, with angular unconformity, by the lowermost Ordovician beds. The group attains a maximum thickness of 1500 m and is formed of brightly coloured sandstones and shales. The middle part of the sequence contains frequent intercalations of reddish and green shales and thin quartzitic layers packed with Skolithos tubes.

2.3. *Ordovician*

The Ordovician has been mapped with the Cambrian in northern Argentina and with the rest of the Palaeozoic in western Argentina. These rocks attain great total thickness and regional extent. They form many subparallel bands of general north–south trend. The Tremadocian is well developed in the eastern Cordilleras of Salta and Jujuy provinces where it attains a maximum thickness of 2400 m. In the western border of the outcrops (Quebrada del Toro, Salta Province) the basal conglomerate grades upward into a green shale and light coloured quartzite with intercalations of glacio-marine conglomerate. These are succeeded by green shales with thin lenticular masses of blue limestone.

In the central outcrops (Quebrada de Humahuaca, Jujuy Province) the lower part of the sequence is formed of black shales, succeeded by sandy limestones and green shales.

In the eastern border (Rio Santa Victoria, Salta Province), the whole sequence is formed of dark grey shale.

Grey-green shales alternating with yellowish sandstones constitute the Arenig in Cerro San Bernado near Salta City.

In the Famatina range of northwest Argentina, the Llanvirnian, consists of 700 m of green and blue shales with dark-grey sandstones capped by 80 to 100 m of reddish shaly sandstone. The beds are unconformably overlain by Mississippian continental strata. The reddish sandstones have yielded fossils. In the western part of the Cordillera, between Calingasta and the Pampa de Yalgueraz, the Caradocian is represented by 800 m of dark greenish greywackes and shales, capped by 200 to 300 m of purple and green phyllitic shales.

2.4. *Silurian*

In north and west Argentina, Silurian rocks are not differentiated from the rest of the Palaeozoic. In the southern hills of Buenos Aires province they have been grouped with the Devonian.

In the Pre-Cordillera, the Silurian is exposed between Jachal and the San Juan river where it consists of dark greenish grey shales and intercalations of shaly limestone. These beds contain two thick intercalations of highly haematitic layers near the base and rest with slight regional unconformity on the Caradoc.

2.5. *Devonian*

Devonian rocks are exposed in the sub-Andean ranges of Salta and Jujuy Provinces. The sequence rests with slight unconformity on Silurian strata and attains 800 m. It is formed of dark grey shales with intercalations of grey and pink quartzitic sandstones.

2·6. *Carboniferous to Triassic*

In the Pampean Ranges at the eastern border of the Precordillera, Mississippian beds rest on peneplained Pre-Cambrian rocks. In the Famatina Range they consist of 1200 m of red, yellow, green, blue and grey sandstones, partly glacial conglomerates, and siltstones and shales (Paganzo I) overlain unconformably by exclusively continental (Paganzo II) beds consisting of yellowish, green, grey and reddish sandstones, shales, and conglomerates which are again in part of glacial origin. The latter are Pennsylvanian and may be up to 700 mm thick.

They are overlain with slight erosional unconformity, in northern La Rioja Province by the Patquia formation (Paganzo III formation), 1500 m of typical red beds which begin with pink or whitish conglomerates of Permo-Triassic age.

Permian and Triassic beds also occur in the sub-Andean ranges of Salta and Jujuy where they begin with tillites which rest unconformably on the lower Devonian, followed by interbedded green and red shales and 700 m of varicoloured sandstones and shales.

3. Paleomagnetic results

A sketch map of the area sampled in Salta and Jujuy provinces is shown in figure 1.

3.1. *Cambrian and Cambro-Ordovician*

Localities and brief descriptions of these samples are listed in tables 2 and 3. Recent geological work allows the outcrops from which samples were collected to be classified as Cambrian or Cambro-Ordovician.

The n.r.m. directions have been plotted on stereographic projections in figure 2 with respect to the present horizontal and in figure 3 with respect to the bedding planes, i.e. the palaeo-horizontal. A brief inspection of figure 2 indicates these rocks have been remagnetized in recent geological time.

A representative group (A) of samples whose n.r.m. directions are shown in figure 4 were demagnetized thermally, with results as illustrated in figure 5. These groups of directions both referred to the bedding (i.e. the palaeo-horizontal) show a pronounced improvement after cleaning. The data plotted in figure 5 consist of a population of directions chosen after demagnetization at the optimum temperature for each sample, these temperatures having been chosen by studying the trend in changes of direction and intensity of remanence during cleaning. The sample-mean directions at each demagnetization step are listed in table 4 and the corresponding mean intensities of r.m. are listed in table 5. The optimum demagnetization temperatures are indicated by the entries in italics. Of the 16 samples studied, 478, 550 and 565 were excluded since they appear to be normal while the main group, $N = 13$, are reversed (population A, table 6).

Another set of specimens from these samples was demagnetized in steps. The results are given in table 6 (population B) and the successive mean directions illustrated in figure 7 are seen to be in excellent agreement with the earlier result. The secondary component appears to have blockage temperatures less than 300 °C because the cleaned directions at 300, 500 and 560 °C are closely grouped (figure 7). The palaeomagnetic pole after cleaning at 500 °C has been taken as representative of the primary magnetization of this formation.

The distribution of intensities is log-normal and therefore geometric-mean values have been computed with their appropriate standard deviations and standard errors. The standard errors are illustrated in the thermal decay curve (figure 6), a logarithmic plot having been used in this figure because this makes the error bars symmetrical about the mean values. The blockage temperature of the main component of remanence is distributed over the whole range of temperatures shown: at 500 °C only about 15 % of the natural magnetization remains: between 600 and 660 °C, just over 10 % is left. The remanence measured after cleaning above 570 °C must certainly be due to ferric oxide. That existing below this temperature could be due to either fine grained ferric oxide such that the blockage temperature is less than the Curie temperature or titanomagnetite. The red colour of the beds and ore microscope observations described in §4 indicate that ferric oxide is the most likely carrier of remanence in these rocks.

The directions of r.m. of populations A and B after cleaning do not differ significantly at the 95 % probability level, equivalent to twice the standard error (δ_m) circle.

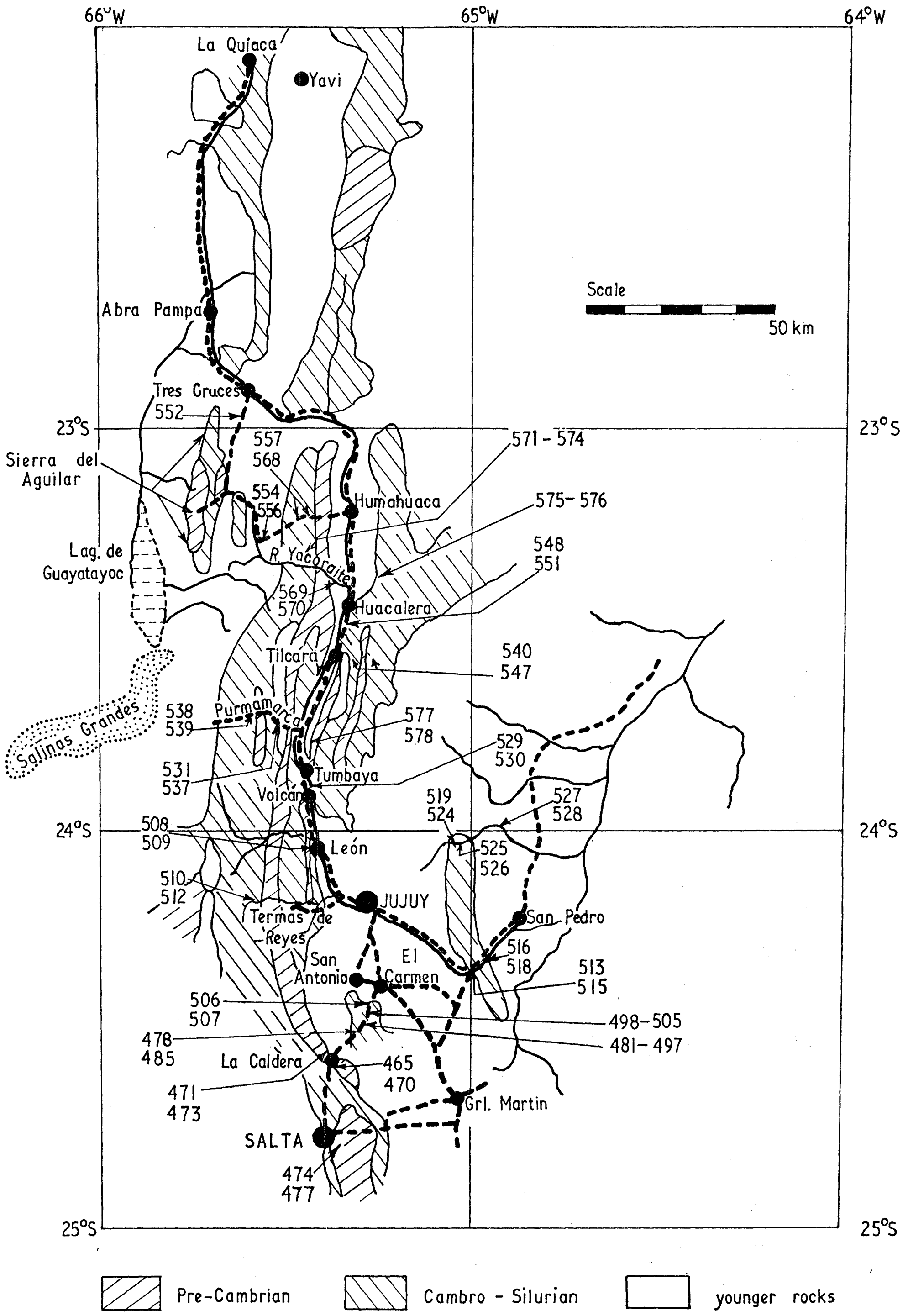

Figure 1. Sketch map and sampling sites in Salta and Jujuy Provinces.

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Table 2. Cambrian sample descriptions from Salta and Jujuy Provinces

site no.	sample nos.	location	dip of beds	description	colour	code no.
(A) Between Salta and Jujuy cities						
1	478, 479, 480	'Pedrera' road, 18–19 km	40° at 260°	v.f.g. sandstone	pale reddish brown greyish red	10R–5/4 10R–4/2
2	498–501	'Cornisa' road 28 km, north of Salta	18° at 0°	—	greyish red	10R–4/2
3	502, 503	'Cornisa' road, 36.5 km north of Salta	20° at 270°	—	pale brown pale red	5YR–5/2 5R–6/2
4	504, 505	'Cornisa' road, 38 km north of Salta	15° at 240°	—	dark reddish brown moderate red	10R–3/4 5R–5/4
5	508	Yala-Las Lagunas road	25° at 335°	—		
(B) North of Jujuy city						
6	540, 541	Tilcara: 'garganta del diablo' road, 4 km	40° at 280°	massive hard m.g. sandstone	pale red pale red	10R–6/2 5R–6/2
7	542–543	as site 6 at 4.8 km, older than site 6	25° at 285°	massive f.g. sandstone	greyish red moderate red dark reddish brown	5R–4/2 5R–5/4 10R–3/4
8	544–545	as site 6 at 5.9 km, (Lower Cambrian?)	95° at 285°	sheared siltstone	greyish red greyish red dusky brown	5R–4/2 10R–4/2 5YR—2/2
9	546–547	as site 6 at 6 km, across the fault	30° at 115°	v.f.g. sandstone	greyish red very dusky red	5R–4/2 10R–2/2
10	548–551	Perchel	45° at 275°	f.g. sandstone	moderate red pale red dusky red	5R–5/4 5R–6/2 5R–3/4

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Table 3. Cambro-Ordovician sample descriptions from Jujuy Province

site no.	sample nos.	location	dip of beds	description	colour	code no.
1	506, 507	'Cornisa' road between Salta and Jujuy, 200 m inside Jujuy province	70° at 90°		moderate red	5R–5/4
2	538, 539	Quebrada Purma Marca	95° at 250°	massive siltstones	greyish red very dusky red	5R–4/2 10R–2/2
3	557–560	El Aguila-Humahuaca road, 27 km from Humahuaca	30° at 280°	massive f. to m.g. sandstone	pale red purple pale red light brownish grey very dusky red	5RP–6/2 5R–6/2 5YR–6/1 10R–2/2
4	561–562	as site 3, 25.4 km from Humahuaca	30° at 240°	massive f. to m.g. sandstone	greyish red	5R–4/2
5	563–564	as site 3, 23.3 km from Humahuaca	40° at 80°	f.g. sandstone	olive grey greyish red	5Y–4/2 10R–4/2
6	565–566	as site 3, 20.5 km from Humahuaca	30° at 80°	f.g. sandstone	greyish red	5R–4/2
7	567–568	as site 3, 17.2 km from Humahuaca	35° at 135°	f.g. sandstone	dark greenish grey	5GY–4/1
8	577, 578	Tumbaya	49° at 290°	massive, pisolitic sandstones	—	—

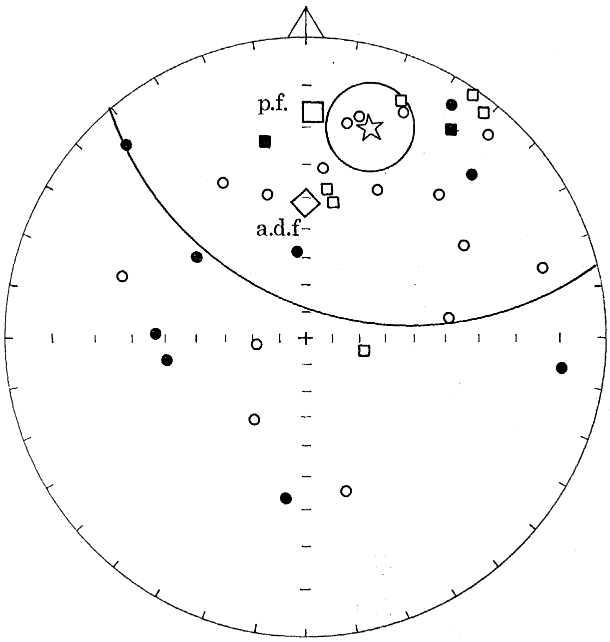

Figure 2

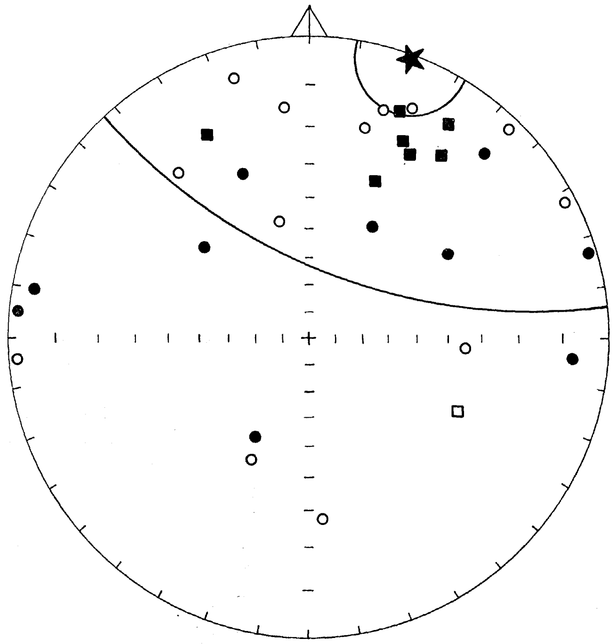

Figure 3

Figure 2. N.r.m. directions of whole collection of Cambrian (circles) and Cambro-Ordovician (squares) samples referred to the present horizontal. The mean direction is indicated by the star and the standard error and standard deviation circles are shown. The present field (p.f.) and axial dipole field (a.d.f.) directions are also plotted. Open symbols represent upward inclinations and solid black symbols represent downward inclinations.

Figure 3. N.r.m. directions referred to the bedding, i.e. to the palaeohorizontal for the same population of samples as in figure 2.

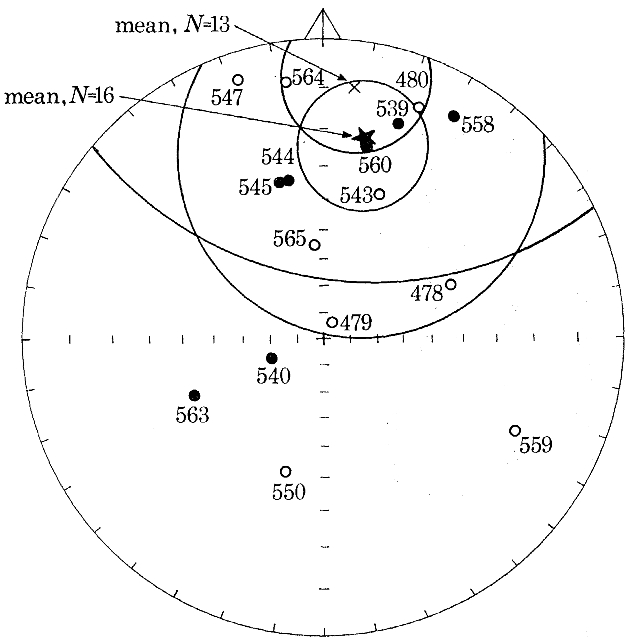

Figure 4

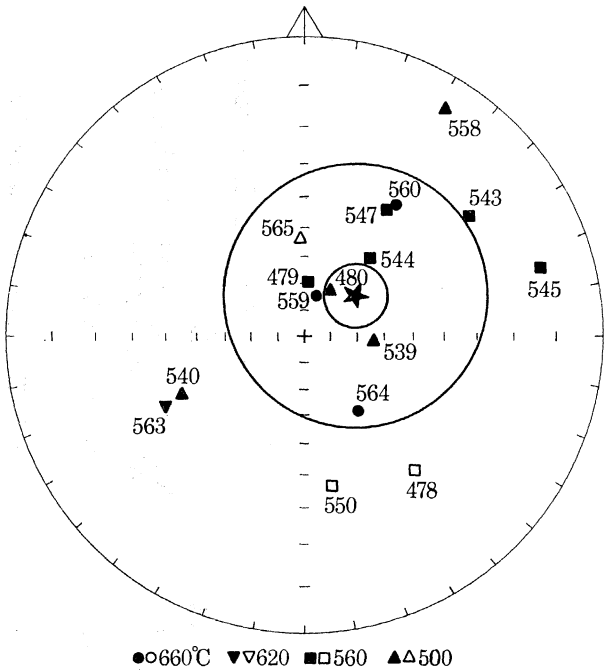

Figure 5

Figure 4. N.r.m. directions referred to the bedding of Cambrian samples selected for thermal cleaning. Sample numbers shown.

Figure 5. Cleaned directions of r.m. with mean and standard error and standard deviation circles for the population of Cambrian samples of figure 4. Temperature of cleaning indicated by symbol.

TABLE 4. THERMAL DEMAGNETIZATION OF CAMBRIAN AND CAMBRO-ORDOVICIAN SAMPLES

sample no.	age	directions of r.m./degrees after thermal demagnetization at 20 °C		150 °C		300 °C		400 °C		500 °C		560 °C		620 °C		660 °C	
478	Ꞓ	68	−40	99	+24	139	+41	171	+31	123	+9	*140*	*−29*	96	−2	—	—
479	Ꞓ	33	−83	41	−80	28	+41	11	−15	3	+81	*3*	*+70*	272	+25	331	−27
480	Ꞓ	23	−10	38	−89	52	+66	52	+43	*26*	*+71*	—	—	265	−22	355	−58
539	Ꞓ/O	20	+15	18	+60	145	+74	34	+41	*94*	*+65*	314	+64	263	−9	343	+35
540	Ꞓ	247	+69	248	+40	247	+42	*251*	*+30*	246	+40	239	+43	217	+53	162	+8
543	Ꞓ	22	−35	15	−52	9	+1	139	−64	—	—	*52*	*+22*	99	−1	—	—
544	Ꞓ	348	+33	338	+52	356	+62	27	+47	13	+58	*36*	*+53*	288	−4	178	+35
545	Ꞓ	345	+33	354	+28	24	+21	79	+9	83	−3	*73*	*+12*	108	+2	123	+49
547	Ꞓ	342	−6	342	−1	61	+48	31	+26	26	+37	*30*	*+37*	117	+6	309	+74
550	Ꞓ	195	−41	196	−45	177	−42	187	−4	185	−32	*171*	*−39*	172	−66	43	+53
558	Ꞓ/O	30	+8	28	+15	27	+27	29	+14	*32*	*+7*	28	−37	348	+27	1	−56
559	Ꞓ/O	114	−13	97	−44	98	−15	72	−25	79	−19	73	−44	320	+1	*20*	*+73*
560	Ꞓ/O	14	+23	10	+10	13	+9	10	+6	12	+6	11	+12	12	+8	*34*	*+44*
563	Ꞓ/O	246	+40	240	+38	—	—	248	+30	308	+43	—	—	*244*	*+35*	—	—
564	Ꞓ/O	352	−8	351	−13	—	—	351	−16	347	−21	—	—	342	+38	*142*	*+57*
565	Ꞓ/O	356	−55	358	−48	—	—	353	−56	*357*	*−53*	—	—	62	−34	279	+17

3.2. *Ordovician*

The sampling sites are illustrated in figure 1 and brief descriptions of the samples are given in table 7. These samples were taken from formations near the top of the Ordovician according to C. M. Turner (1967, personal communication), although in some review and summary articles (Creer 1962, 1964, 1965, 1968) they have been mistakenly quoted as being Devonian, this information having been provided during the field work.

TABLE 5. THERMAL DEMAGNETIZATION OF CAMBRIAN AND CAMBRO-ORDOVICIAN SAMPLES

sample		intensity of r.m./μG after thermal demagnetization at							
no.	age	20 °C	150 °C	300 °C	400 °C	500 °C	560 °C	620 °C	680 °C
478	Ɛ	2.5	1.1	1.4	1.1	0.8	*0.7*	10.6	—
479	Ɛ	2.7	0.7	1.8	0.2	0.2	*0.1*	3.4	0.1
480	Ɛ	2.5	50.1	2.1	0.7	*1.0*		9.9	0.1
539	Ɛ/O	14.4	5.1	—	2.4	*0.5*	0.1	49.9	10.8
540	Ɛ	18.3	20.2	13.5	6.6	*5.1*	11.8	1.9	0.4
543	Ɛ	2.2	1.6	1.9	0.8	—	*0.3*	5.4	—
544	Ɛ	17.1	12.3	4.2	1.9	0.9	*0.6*	15.8	3.5
545	Ɛ	10.8	4.4	1.6	1.4	1.3	*1.0*	42.0	3.8
547	Ɛ	19.3	9.7	4.9	1.9	1.8	*1.7*	30.8	6.4
550	Ɛ	3.4	2.7	1.5	0.9	0.7	*0.6*	3.8	0.3
558	Ɛ/O	6.3	5.4	3.9	1.9	*1.1*	0.4	16.0	0.4
559	Ɛ/O	2.1	2.4	1.7	1.0	0.6	0.7	0.9	*0.3*
560	Ɛ/O	95.1	85.1	75.0	44.3	36.9	33.7	17.6	*1.1*
563	Ɛ/O	124.6	102.7	—	16.7	50.1	—	*2.3*	—
564	Ɛ/O	18.1	17.1	—	5.4	7.1	—	6.0	*0.4*
565	Ɛ/O	8.1	7.5	—	4.3	*3.0*	—	10.9	0.4

TABLE 6. THERMAL DEMAGNETIZATION OF CAMBRIAN AND CAMBRO-ORDOVICIAN

			direction of r.m./degree				south palaeopole			
population	treatment	number of samples	D	I	δ	δ_m	lat.	long.	δ	δ_m
A	n.r.m.	13	7	+10	58	16	61° N	57° W	57	16
(see figures 4, 5)	thermally cleaned	13	42	+64	43	12	8° N	40° W	52	14
B	n.r.m.	19	15	+10	68	15	57° N	35° W	65	15
(see figure 7)	150 °C	19	14	+4	73	17	63° N	26° W	71	16
	300 °C	13	48	+43	66	18	19° N	22° W	68	19
	500 °C	18	51	+41	68	16	15° N	22° W	66	16
	560 °C	14	59	+43	67	18	8° N	20° W	67	18

Thermal demagnetization of the r.m. was carried out by Chamalaun (1963). The directions of n.r.m. when referred to the present horizontal (figure 8) are scattered, mainly in the northeast quadrant with upward inclinations, the distribution of directions being elongate and trending towards the present axial dipole field direction. The n.r.m. directions when referred to the palaeohorizontal still fall in the northeast quadrant but have predominantly downward inclinations (figure 9).

The directions of r.m. after thermal demagnetization at 300 °C are shown relative to the present horizontal in figure 10 and relative to the palaeohorizontal (i.e. to the bedding planes) in figure 11. The former group of directions are more scattered (c.s.d. = 52°) than before cleaning (c.s.d. = 46°) and the mean has moved away from the present geomagnetic field

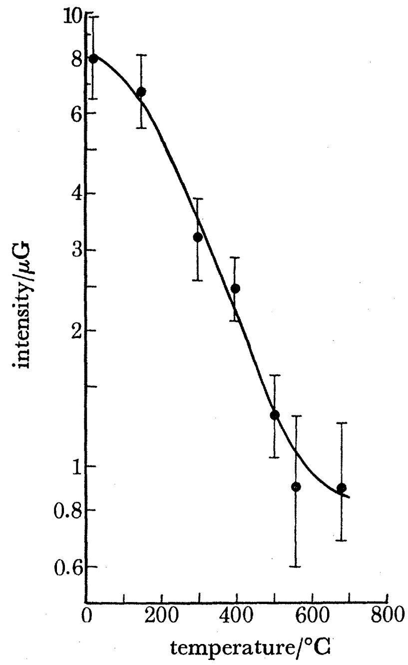

FIGURE 6. Thermal decay of r.m. of Cambrian and Cambro-Ordovician samples. Geometric mean intensity with its standard error at each stage of cleaning plotted on logarithmic scale against temperature.

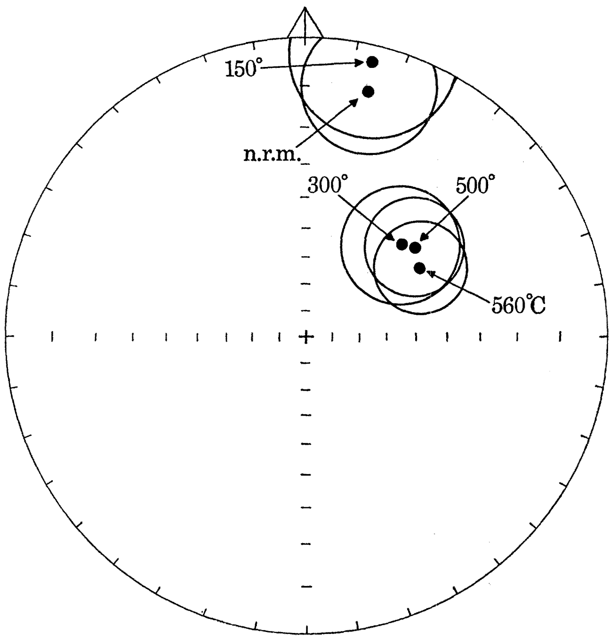

FIGURE 7

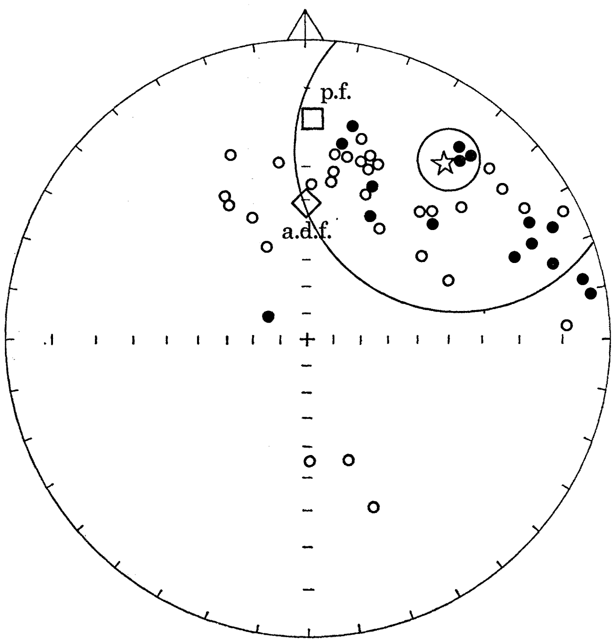

FIGURE 8

FIGURE 7. Mean direction and standard error circles of r.m. of the second group of Cambrian and Cambro-Ordovician samples subjected to thermal cleaning, shown at each stage.

FIGURE 8. Ordovician samples from Salta and Jujuy. Disk n.r.m. directions plotted with respect to present horizontal. Present field (p.f.) and axial dipole field (a.d.f.) directions are indicated. The mean (star) with standard error and standard deviation circles are also given. One or two disks per sample, 26 samples.

TABLE 7. ORDOVICIAN SAMPLE DESCRIPTIONS FROM JUJUY PROVINCE

site no.	sample nos.	location	dip of beds	description	colour	code no.
1	509	Yala–Las Lagunas road	43° at 290°		pale red	5R–6/2
2	510–512	Termes de Cordon	60° at 276°	massive, medium grained sandstone	dark reddish brown greyish red	10R–3/4 10R–4/2
3	513–514	At Las Lajitas	30° at 300°	laminated, medium-coarse grained sandstone	greyish red	10R–4/2
4	516–518	by Rio Grande, between sites 3 and 5	25° at 245°	massive, medium grained, sandstone	greyish red	5R–4/2
5	519–524	Rio Capillas†	40–60° at 275°	massive mudstone	greyish red	5R–4/2
6	529–530	Volcan–Tumbaya road (road no. 9)	35° at 90° (or 145° at 270°?)	massive, fine grained, sandstone		
7	531–537	Quebrada Purmamarca	60° at 295°	massive, fine to very fine grained sandstones	greyish red greyish red	10R–4/2 5R–4/2
8	525–526	Arrojo el Potrero‡	25° at 270°	massive, very fine grained sandstone	very dusky red dark reddish brown	10R–2/2 10R–3/4

† See Capillas sheet (no. 2566), scale 1:50 000, ref. 406 (N) 900 (E).
‡ See Capillas sheet (no. 2566), scale 1:50 000, ref. 374 (N) 894 (E).

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irecti on (compare figure 10 with figure 8). The grouping of directions referred to the bedding is slightly improved by cleaning (c.s.d. = 28° after cleaning as compared with 32° before) as may be seen in figures 11 and 9. The mean directions and relevant statistical parameters of the four populations of directions are given in table 8.

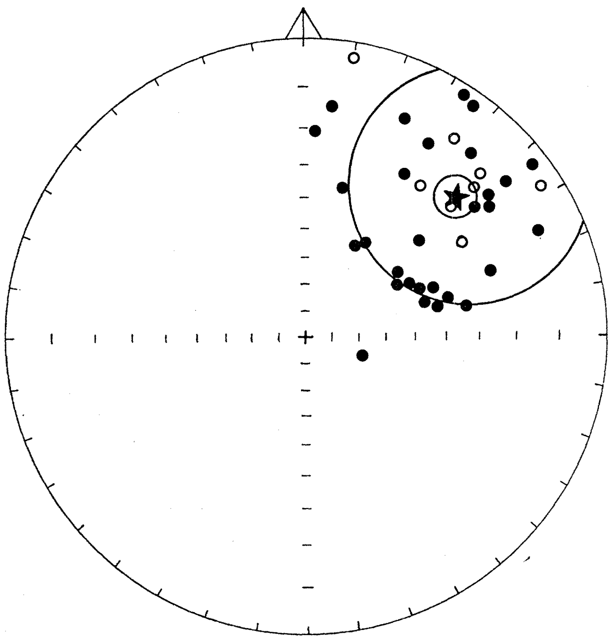

FIGURE 9

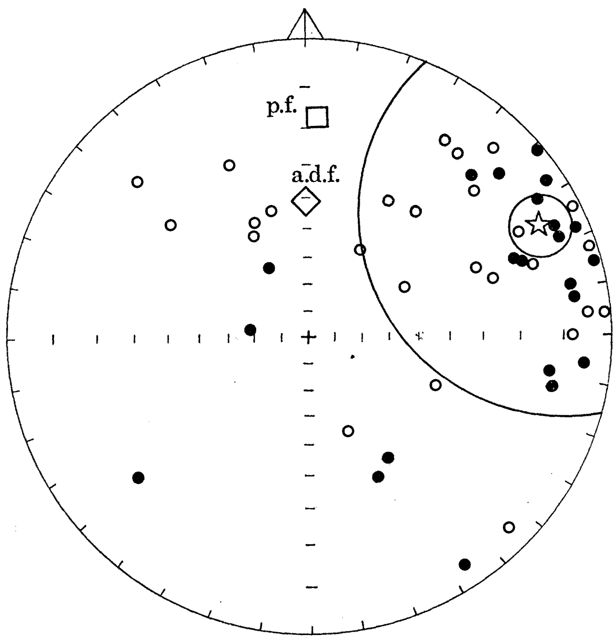

FIGURE 10

FIGURE 9. Disk n.r.m. directions for the same population of samples as figure 8 plotted with respect to the bedding.

FIGURE 10. Disk r.m. directions referred to present horizontal after thermal cleaning at 300 °C. Same population of samples as figure 8.

TABLE 8. STATISTICAL ANALYSIS OF R.M. OF ORDOVICIAN

plane of reference	treatment	number of disks	direction of r.m./degree			
			D	I	δ	δ_m
present horizontal	n.r.m.	47	37	−17	46	6.5
	300 °C	50	63	−7	52	7.5
palaeohorizontal	n.r.m.	42	46	+22	32	5
	300 °C	42	52	+53	28	4.5

One or two disks taken from each of 26 samples.

Chamalaun (1963) computed the directions of the low-temperature components which were removed by thermal demagnetization. These may be seen to be alined approximately along the present or axial dipole field directions in figure 12.

Three typical thermal decay curves are shown in figure 13, one for an 'unstable' sample, i.e. one whose r.m. direction changes appreciably during thermal demagnetization and two for 'stable' samples (samples whose magnetization vectors show only a small change). The secondary component in the first sample is removed by treatment below 300 °C, and that is why this temperature was chosen for the bulk demagnetization of the samples.

The south palaeomagnetic pole and relevant statistics are illustrated in figure 18 and table 14.

3.3. *Carboniferous–Permian–Triassic*

The Paganzo formation was sampled in La Rioja Province at sites shown in figure 14. Particulars about the samples are given in table 10 where they have been classified as Permo-Carboniferous or Permo-Triassic according as to whether they come from the bottom part or the top part of the succession.

N.r.m. measurements only have been made, but the more stable samples have been selected by using the criterion that the within-sample circular standard deviation of disk directions should be less than 15°.

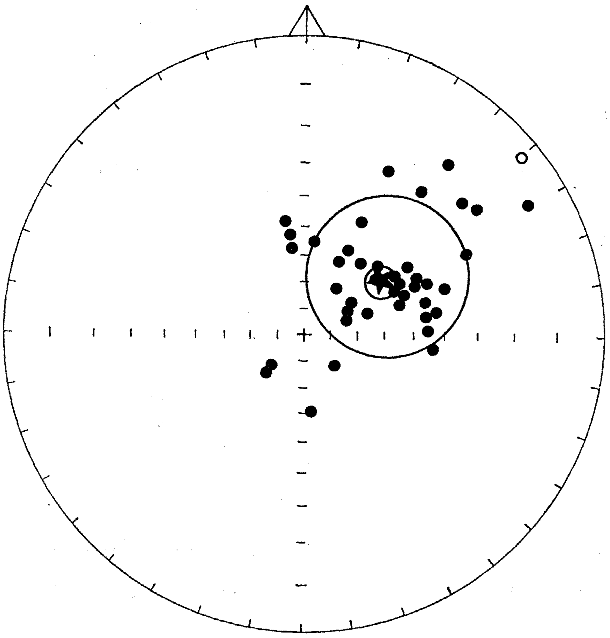

FIGURE 11

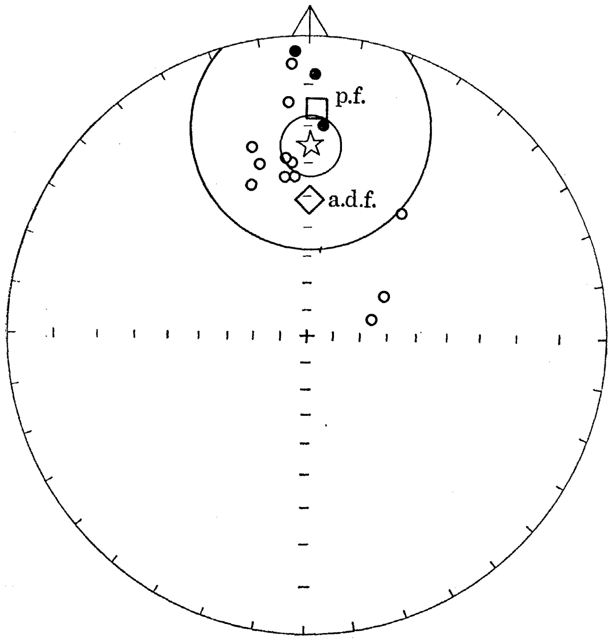

FIGURE 12

FIGURE 11. Disk r.m. directions referred to bedding after thermal cleaning at 300° C. Same population of samples as figure 8.

FIGURE 12. Directions of the low-temperature components of r.m. removed by thermal cleaning at 300° C of Ordovician disks for Salta and Jujuy referred to the present horizontal. One disk per sample.

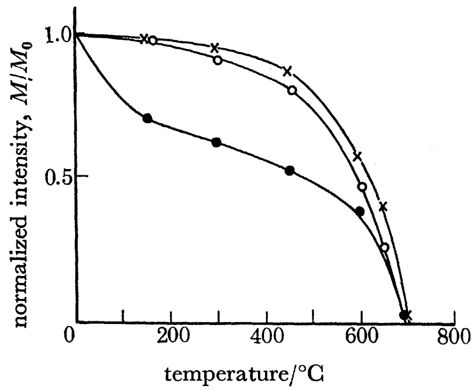

FIGURE 13. Thermal decay curves for Ordovician samples from Salta and Jujuy. The curve showing a sharp decrease below 200 °C is typical of those samples whose r.m. direction changes markedly during cleaning. The other two curves are typical of samples whose r.m. directions show only small changes.

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Table 10. Descriptions of samples and site localities of the La Rioja collection

age	sample nos.	locality	dip of beds	lithology	colour
Permo-Carboniferous	579–581	Dique los sauces	34° at 250°	muddy and c.g. sandstones	pale red 5R–6/2: pale reddish brown 10R–6/6
	582–586	Los Colorados	12° at 240°	muddy and c.g. sandstones	moderate reddish brown 10R–5/4: pale reddish brown 10R–4/6
	589–593	West Huaco	40° to 60° at 240° to 260°	muddy sandstones	pale red 5R–6/2
	594–598	East Huaco	80° to 110° at 80°	muddy sandstones	pale reddish brown 10R–5/4
Permo-Triassic	599	Zanja de la Vivda	35° at 130°	marly sandstone	pale red 10R–6/2
	600–601	3 km E. of Puerto Alegre (29° 27′ S, 67° 55′ W)	12° at 220°	m.–c.g. sandstone	pale reddish brown 10R–5/4: moderate red 5R–5/4
	603	at approx. km 524	17° at 200°	soft m.g. sandstone	pale reddish brown 10R–5/4
	604	km 525	10° at 190°	soft m.g. sandstone	pale reddish brown 10R–5/4
	605–606	km 528.5	14° at 185°	muddy sandstone	pale reddish brown 10R–5/4: greyish red 10R–4/2
	607	km 535	2° at 100°	muddy sandstone	moderate reddish brown 10R–4/6
	608	km 540	10° at 340°	soft m.g. sandstone	moderate reddish brown 10R–4/6
	609	km 548	17° at 350°	soft m.g. sandstone	greyish red 10R–4/2
	610	km 551	36° at 0°	soft m.g. sandstone	greyish red 10R–4/2

All sites are on r.n. 40 which is shown in figure 14 and which runs north from San Juan to Chilecito. See sheet 3381 ‘San Juan’, scale 1:1000000 published by the Instituto Geografico Militar (1957), Buenos Aires.

Kilometre references for samples 603–610 are to km posts registering the distance from Mendoza City, Miranda being at km 364.

Table 11. Mean data for La Rioja samples

age	sample nos.	number of disks	direction of n.r.m./degree				south palaeopole position			
			D	I	δ	δ_m	lat.	long.	δ	δ_m
Permo-Triassic	599–610	22	14	−37	36	8	76° S	157° W	36	8
Permo-Carboniferous	579–598	15	164	+67	16	4	65° S	44° W	25	6

TABLE 12. PERMO-CARBONIFEROUS SALTA PROVINCE SAMPLE DESCRIPTIONS AND SITES

sample no.	locality	dip of beds	lithology	colour	code no.
527	Arrojo del Potrero	60° at 260°	soft, friable f.g. sandstone	moderate reddish orange	10R–6/6
554–555	48 km from Humahuaca on road to el Aguila	60° at 60°	m.g. sandstone	greyish red	10R–4/2
				pale red	10R–6/2
556	46 km from Humahuaca on road to el Aguila	15° at 230°	m.g. sandstone	pale red	10R–6/2
				pale red	5R–6/2
569	Quebrada Yacoraite	30° at 340°	soft, m.-f.g. sandstone	moderate pink	5R–7/4
575–576	Quebrada de Juella	60° at 290°	f.-m.g. sandstone	moderate pink	5R–7/4
				light red	5R–5/4

TABLE 13. MEAN DATA FOR MESOZOIC FORMATIONS FROM SALTA PROVINCE

number of disks	direction of n.r.m./degree				south palaeomagnetic pole			
	D	I	δ	δ_m	lat.	long.	δ	δ_m
17	198	+59	20	5	67° S	105° W	24	6

TABLE 14. SUMMARY OF SOUTH PALAEOMAGNETIC POLES DEDUCED FROM THIS STUDY

	province	period	number of measurements	south palaeopole			
				lat.	long.	δ	δ_m
1	Salta and Jujuy	Cambrian and Cambro-Ordovician	13†	8° N	40° W	60	14
2	Salta and Jujuy	Cambrian and Cambro-Ordovician	18‡	15° N	22° W	66	16
3	Salta and Jujuy	Ordovician	42§	11° N	27° W	34	5
4	La Rioja	Permo-Carboniferous	22§	65° S	44° W	25	6
5	La Rioja	Permo-Triassic	15§	76° S	157° W	36	8
6	Salta and Jujuy	Permo-Triassic	17§	67° S	105° W	24	6

† These samples were all thermally cleaned at 560 °C.
‡ These samples were thermally demagnetized at temperatures indicated in tables 5 and 6.
§ Disks, not samples.

The Permo-Carboniferous samples are reversely magnetized with a fairly steep inclination, the directions of specimen disks being shown in figure 15. Disk directions from different samples are mixed up, i.e. they do not form clusters about sample-mean directions and this is why they have been plotted rather than sample mean directions.

TABLE 9. COMPONENT OF R.M. DESTROYED BY THERMAL DEMAGNETIZATION COMPARED WITH PRESENT GEOMAGNETIC FIELD (ORDOVICIAN, §3.2)

r.m. or field	number of disks	direction of r.m./degree			
		D	I	δ	δ_m
low temperature component of r.m. referred to present horizontal	15	0	−26	31	8
present geomagnetic field direction	—	2	−16	—	—
axial dipole field direction	—	0	−42	—	—

The Permo-Triassic samples are normally magnetized at rather weaker intensities (the geometric mean intensity is 2.1 μG as compared with 7.5 μG for the older samples). Disk directions have again been plotted (figure 16).

Mean directions of upper and middle parts (III and II) of the Paganzo formation are given in table 11 with statistical parameters computed using disks and also sample-means as statistical units.

Permo-Triassic formations from the sub-Andean ranges of Jujuy Province have also been studied. The sampling sites are listed in table 12.

The samples with more stable n.r.m. were selected as described for the Paganzo formation. Disk directions are illustrated in figure 17 and the statistics concerning the measurements given in table 13. The palaeomagnetic pole is close to that obtained from the measurements on part III of the Paganzo formation.

South palaeomagnetic pole positions are given in table 14 and have been plotted in figure 18.

4. DISCUSSION OF RESULTS

4.1. *Carrier of remanence*

Ore microscope observations have been made on many of the samples studied. All show a finely divided red pigment situated interstitially between quartz and feldspar grains or coating them. After heating in air to 600 °C as is required in thermal demagnetization experiments the pigment in some specimens turns a bluish colour when viewed in reflected light, indicating that the ferric oxides and oxyhydroxides tend to be reduced on heating. In some rocks small cavities (10 to 30 μm in diameter) appear to be filled with red pigment. Specularite grains typically of 10 to 20 μm in diameter are observed in most specimens and also in some very small red haematite platelets about 1 μm in diameter.

Magnetite grains were not observed, although some of the specularite grains appeared to be pseudomorphs of spinel.

The abundance of ferric oxides is consistent with the thermal decay of intensity during demagnetization by cooling in zero magnetic field. The remanent magnetization is not destroyed by heating to 600 °C. Unstable components of remanence are considered to reside in haematite of fine grain size and low blockage temperatures.

4.2. *Relevant palaeoclimatic evidence*

The evidence concerning upper Palaeozoic glaciations has been recently discussed in a paper by Frakes & Crowell (1969).

It has already been mentioned in § 2, that evidence of glaciation has been found in rocks of Mississippian and Pennsylvanian age in northwest Argentina. The palaeomagnetic south pole was only 10°–20° away from this region in the Lower Carboniferous. By the Upper Carboniferous, it was some 40°–50° away (in Kiaman time) and by the Triassic some 60° away. The palaeomagnetic latitudes for the Permo-Carboniferous and Permo-Triassic are consistent with the production of red beds then. The persistence of some indications of glaciation into the Upper Carboniferous may be attributed to Alpine type rather than a polar ice cap.

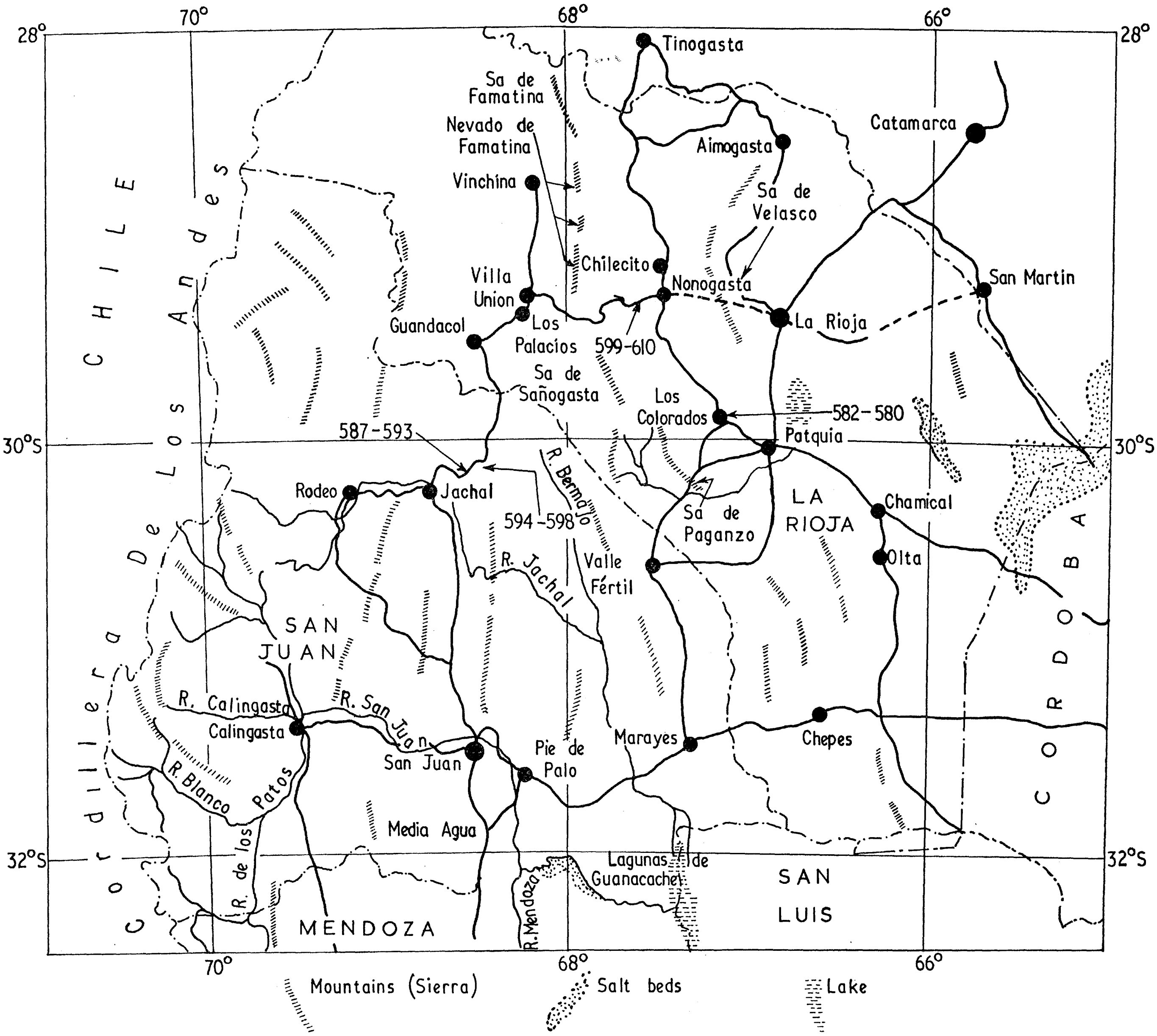

FIGURE 14. Sketch map of area of collection in La Rioja Province. The sampling sites are marked.

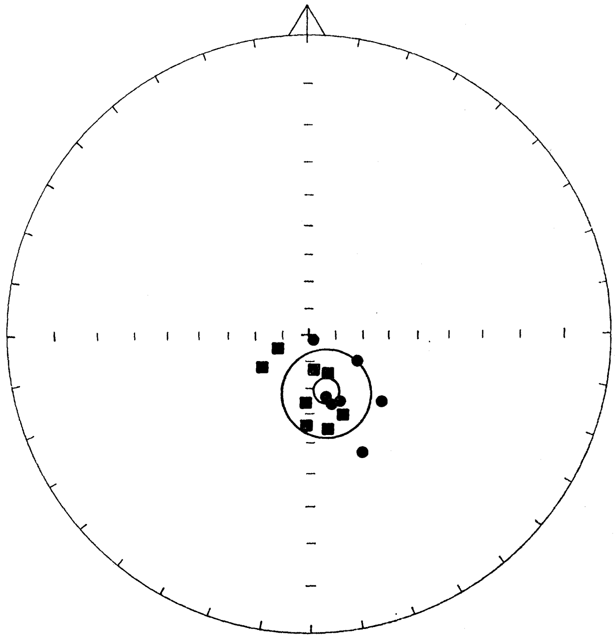

FIGURE 15

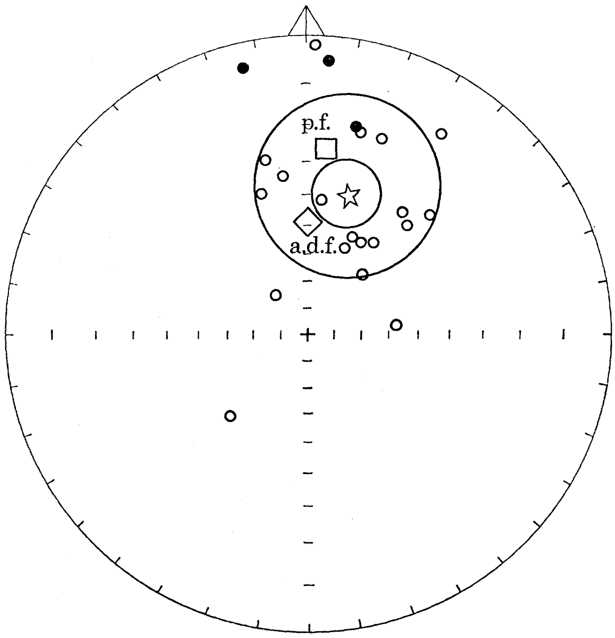

FIGURE 16

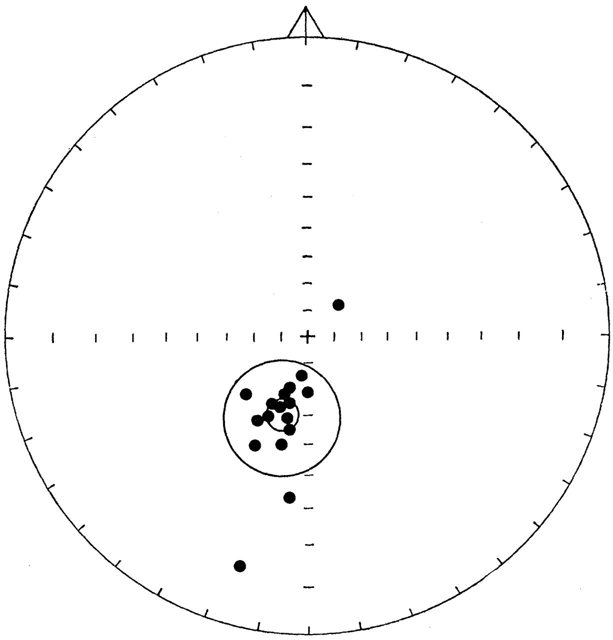

FIGURE 17

FIGURE 15. N.r.m. directions of specimen disks from Permo-Carboniferous samples from La Rioja Province showing small internal scatter (c.s.d. less than 15°). Mean direction, standard error and standard deviation circles shown. The plane of projection is the palaeo-horizontal. ■, From east and west Huaco; ●, from los Colorados and Dique los Sauces.

FIGURE 16. N.r.m. directions of specimen disks from Permo-Triassic samples showing small internal scatter (c.s.d. less than 15°) mean direction, standard error and standard deviation circles shown. The plane of reference is the palaeo-horizontal.

FIGURE 17. N.r.m. directions of specimen disks from Permo-Triassic samples from Jujuy Province showing small internal scatter (c.s.d. less than 15°). Mean direction, standard error and standard deviation circles shown. Plane of reference is the palaeo-horizontal.

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FIGURE 18. South palaeomagnetic pole positions with standard error circles for the formations studied. Є, ЄO = Cambrian and Cambro-Ordovician; O = Ordovician; PC = Permo-Carboniferous, PTR = Permo-Triassic. Subscripts refer to entries in table 14, p. 496.

4.3. *Consistency with other Palaeozoic palaeomagnetic data from S. America*

Palaeomagnetic studies on Bolivian and Brazilian Palaeozoic rock formations lead to the conclusion drawn from the present work that the south palaeomagnetic pole lay to the northeast of Brazil in the lower Palaeozoic and that it moved southwards down the eastern side of S. America to a position in the S. Atlantic east of the River Plate approximately in the Upper Palaeozoic.

5. Acknowledgements

The field work was carried out with the help of geologists from the Comision Nacional de Energia Atomica of the Republic of Argentina, with vehicles provided by this organization. Wholehearted thanks are expressed to the Director, to Dr Anibal Pozzo, head of the Salta division and to Ingenieros Enrique Lerida, Krilo Malinkef, Jorge Gamba and Luis de la Fuente who accompanied the author in the field in Salta and Jujuy and also to Dr Luis Alberto Barrionuevo, head of the La Rioja division and Ingenieros Raul Lopez and Luis Azamor who helped in La Rioja Province.

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Thermal demagnetization work on the Cambrian and Cambro-Ordovician samples was carried out partly by Dr A. Stephenson and on the Ordovician samples by Dr F. H. Chamalaun

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as part of their Ph.D. projects. The Upper Palaeozoic collection has since been incorporated into a new and much larger collection made in 1968–9 by Ing. D. Valencio, Mr F. Vilas, Mr B. J. J. Embleton and myself and which is being studied by B.J.J.E. as part of his Ph.D. research project.

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