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

Palaeomagnetic Studies on Palaeozoic Rocks from Bolivia

K. M. Creer

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IV. PALAEOMAGNETIC STUDIES ON PALAEOZOIC ROCKS FROM BOLIVIA

CONTENTS

The palaeomagnetism of Ordovician and Devonian and Carboniferous sedimentary rock formations exposed in Bolivia has been studied. It is deduced that the south palaeomagnetic pole was situated in the Guianas in the Middle Palaeozoic, and in the south Atlantic, about half way between the present positions of Buenos Aires and Cape Town in the Carboniferous.

1. Introduction

Bolivia occupies an area of about 5×10^6 km². It consists of (1) a region of high cordilleras in the west in which the mining centres of Oruro and Potosi are situated; (2) a high plateau (the Altiplano) farther west where the capital La Paz is situated and where other mining centres have been developed; (3) further east and towards the centre the fertile valleys of Cochabamba; and (4) in the east a flat low lying plain (the extensive Chaco–Beniana plain) extending from Santa Cruz to the River Paraguay which is the boundary with Brazil.

The country may be divided into nine morpho-structural regions, one of which, the eastern and central cordilleras is an extensive block located between the altiplano to the west and the sub-Andean zone on the east. At the northern border of Bolivia, this block is 100 km wide and elongated from Peru in a southeasterly direction. At latitude about 18° S it bends, extending southwards into Argentina. It is cut by numerous deep river valleys and the several parts have been given different names such as the Cordillera Real and Cordillera de Muñecas.

Between Oruro and east of Cochabamba cities is a high block of Palaeozoic rocks. Samples of Ordovician and Devonian rocks were collected in this region from the vicinity of the Oruro–Cochabamba–Santa Cruz highways (see sketch map, figure 1). Carboniferous rocks were collected from the east of this region in Santa Cruz Province.

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2. Geology

2.1. *Cambrian*

Sediments of certain Cambrian age are known only in the extreme south of Bolivia, to the west of Tarija. There, they form two parallel anticlines which constitute the most uplifted parts of the Tascara Range in the east and the Yunchara Range in the west. These two chains unite to form the Victoria Range near the frontier with Argentina. To the north, the axes of the anticlines pitch beneath the Ordovician. These sediments have been named the Sama formation. They are unfossiliferous quartzitic sandstones and contain grey and red patches which show undulating lineation in the stratification planes. A thickness of 600 m has been observed (Ahlfield & Branisa 1960).

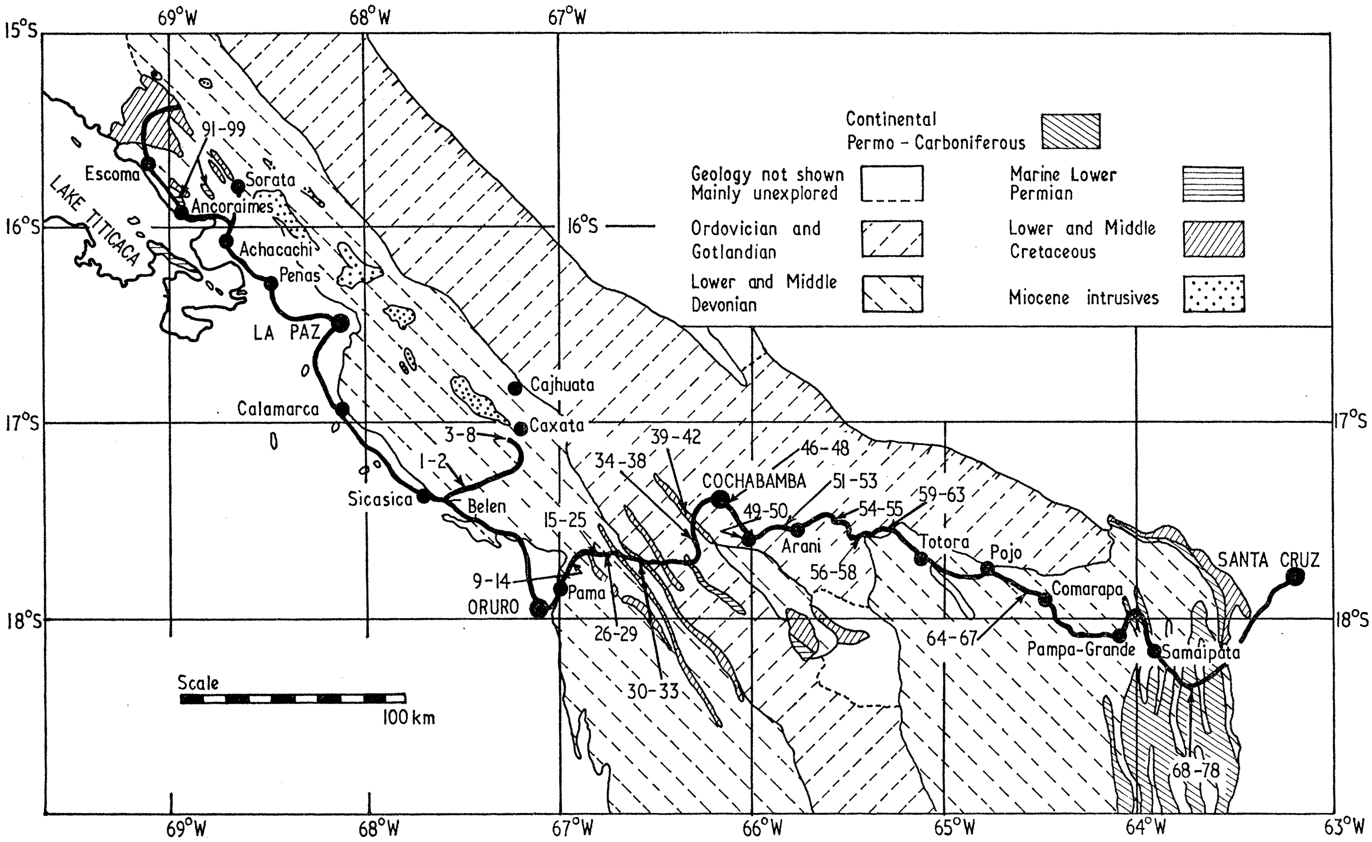

Figure 1. Sketch map of Oruro, Cochabamba, Santa Cruz region.

2.2. *Ordovician*

Ordovician sediments occupy a 100 km wide uninterrupted belt extending from the region of Huanuco in central Peru, through Bolivia into the province of Salta in northern Argentina. They are exposed over about two-thirds of the eastern and central cordilleras, but the boundary with the Devonian is tentative.

A belt of Ordovician rocks, 50 to 60 km wide, enters northern Bolivia from Peru and constitutes the central cordillera almost entirely as far as Pojo. A thin Ordovician belt, the Cosincho quartzites, is exposed on the eastern border of the Andean system between Ixiamas and

Rurrenabaque. The Ordovician block extends to the eastern foot of the Andes between the Rivers Isiboro and Ichilo. Between Cochabamba and Sucre, Ordovician rocks occur only in belts which constitute the cores of anticlines. South of 19° 30′ latitude, Ordovician sediments occupy nearly all the Puna block which is 220 km wide, Devonian rocks being exposed in a thin belt at the east.

The lower Ordovician rocks contain many fossils, the Tremadoc, Arenig and Llanvirnian being well represented. However, the Caradoc although present over a wide area does not contain a significant quantity of fossils. Also, the Llandeilo and Ashgillian are generally present as non-fossiliferous facies.

2.3. *Silurian*

Gotlandian sediments have been mapped in all southern and central parts of Bolivia, especially in the regions of Tarija, Tarabuco and Cochabamba. The base of the Gotlandian consists of 'the glacial horizon of Zapla', an important marker bed extending from northern Argentina as far as Cochabamba. It consists of unstratified clay grits of thickness between 1 and 70 m. These tillites may be distinguished from the Gondwana tillites because they contain inclusions of pale yellow and green granite pebbles, whereas those in the Gondwana tillites are generally red. Possibly they were carried from the south where there is a pre-Cambrian granite intrusion. Striated and triangular pebbles are not very common.

Sandy shales with dark grey siltstones, stratified in thick banks and containing small pebbles, believed to be fluvio-glacial occur around Pojo and are also exposed to the north of Cochabamba.

2.4. *Devonian*

The Bolivian Devonian is rich in fossils and therefore has been used to form the basis of the South American classification. Devonian rocks are exposed in the east and west parts of the central and eastern cordilleran block and also in synclines within the block. There are three stratigraphic units, namely: (i) slates of the Cordillera Real, (ii) the Icla series, and (iii) the Sicasica series. Samples were collected from both the Icla and Sicasica series which belong to the lower and middle Devonian respectively, principally from the vicinity of Sicasica and between Cochabamba and Santa Cruz where mainly lower Devonian rocks are exposed.

They are mainly sandstones and quartzites with a few greywackes, siltstones and mudstones. It has been suggested that the climate was quite cold because of lack of coral reefs. When we consider the relative quantities of sandstones and clays, we must distinguish between the geosynclinal zone where there are 80% clays and the zone of epicontinental seas where the proportion of sandstones is higher. In Tarija (near the Argentine border), the proportion of sands to clays is 2:1, while in the region of Cochabamba, Oruro and La Paz the proportion of clays is higher. In many places there is evidence of rhythmic sedimentation.

The fauna is marine and exhibits many similarities with that of Brazil, Argentina and South Africa, but few similarities with that of Europe and N. America (Ahlfield & Branisa 1960).

2.5. *Carboniferous and Permian*

A thick sequence of continental sediments is found above the Devonian, and it is known as the Gondwana series. It is exposed in a block of width 140 km with general north–south strike, extending from Argentina as far north as Santa Cruz to the north of which exposures are rudimentary. The stratigraphy is illustrated in table 1.

A few samples were collected from the Violaceo formation which occurs disconformably above the middle Devonian. This angular disconformance is regional and although the overlying younger rocks have been assigned to the upper Carboniferous (Ahlfield & Branisa 1960), a lower Carboniferous age cannot be disputed. The Tupambi formation is exposed in all the subandean sierras from Bermejo in the south to Santa Cruz, and contains lenses of very fine grained sandstone which sometimes bear petroleum when encountered at depth.

Table 1. Middle and upper palaeozoic stratigraphy

Permian (Upper Gondwana)	San Telmo fm Escarpment fm	
Upper Carboniferous (Lower Gondwana)	Taiguati fm Tarija fm Tupambi fm Violaceo fm	
unconformity		
Middle Devonian Lower Devonian	Iquiri fm Los Monus fm	(Sicasica series) (Icla series)
Silurian	Santa Rosa sandstones	

Above the Tupambi, the Tarija formation lies concordantly. It is characterized by an abundance of clay grits thought to be of glacial origin. Banks of tillites alternating with interglacial sediments have been observed. These sediments contain striated pebbles of red granite. The thickness of the Tarija formation is between 400 and 700 m.

The upper part of the Gondwana series is known as the Mandiyuti group. It has been subdivided into three formations, namely the Taiguati, the Escarpment and the San Telmo.

The Taiguati formation was well sampled with good results palaeomagnetically. It is composed of an assemblage of clays, tillites and sandstones. The Escarpment formation was so-called because of its tendency to form vertical walls, canyons and waterfalls. It is about 400 m thick. Well bedded grey mudstones are followed by compact red, grey and green coloured sandstones and coloured mudstones with glacial horizons above. The San Telmo formation is divided into the Taguacua, Chimco and Caiguami members. The first consists of red clay and clay grits, the second of coarse compact sandstones and the last by the latest glacial unit of the Gondwana series consisting of clay grits, shaly sandstones and clays. It is between 500 and 600 m thick.

In the southern section the Gondwana series may total 1200 to 1900 m of clastic sediments such as sandstones, clays, conglomerates, siltstones and tillites.

The glacial deposits in the south of Brazil have been generally considered to be upper Carboniferous. It has been accepted provisionally that those found in Bolivia are of the same age but they lack the coal beds so characteristic of the Brazilian glacial and interglacial deposits.

3. Palaeomagnetic results

3.1. *Ordovician*

A brief description of the Ordovician samples collected is given in table 2 and the sites are shown in figure 1. The directions of n.r.m. averaged for each of the 17 hand samples are shown in figure 2 referred to the present horizontals and in figure 3 referred to the bedding, i.e. to the ancient horizontal. The grouping is very slightly better in the former case. There are indications

TABLE 2. DESCRIPTION OF ORDOVICIAN ROCK SAMPLES

sample no.	locality	dip of beds	description: rock type	description: texture	description: colour
XY 34–35	63 km from Cochabamba†	30–40° at 230°	v.f.g. quartzitic sandstone	laminated	yellow tint/grey
XY 36–38	63 km from Cochabamba†	40–50° at 40°	hard f.g. sandstone	thin bedded, micaceous	yellow tint/grey
XY 46–48	10 km from Cochabamba†	10° at 330°	siltstone	massive	grey/grey
XY 49–50	22 km from Cochabamba†	30° at 205°	hard f.g. sandstone	thick bedded, jointed	grey/grey
XY 60	km 184‡	42° at 45°	siltstone	discontinuous thin black lamellae	grey/grey-greenish
XY 61–2	km 297‡	60° at 5°	siltstone	thin bedded, micaceous	grey/grey-greenish
XY 63	km 310‡	20° at 24°	silty shale	thin bedded, micaceous	grey/grey-greenish
XY 64–65	km 435‡	5° at 250°	siltstone	hard, thin bedded micaceous	grey
XY 66–67	km 413‡	15° at 280°	v.f.g. sandstone	hard, thin bedded micaceous	light purple
XY 26–29	89 km from Cochabamba on road from Oruro	10° to 25° at 215° to 235°	m.g. sandstone	hard, thin bedded, micaceous, some cross bedding	light purple
XY 30–33	80 km from Cochabamba (Sayari)	35° at 50°	m.g. sandstone	subangular, micaceous, thin bedded	light grey mottled
XY 34–36	63 km from Cochabamba	30° at 240°	f.g. quartzitic sandstone	subangular, micaceous, thin bedded	whitish
XY 37–38	63 km from Cochabamba	40° at 225°	f.g. sandstone	hard, thin bedded	light brown
XY 46–48	10 km from Cochabamba on road to Santa Cruz	10° at 330°	siltstone	hard, thick bedded	grey
XY 49–50	22 km from Cochabamba	35° at 205°	quartzitic f.g. sandstone	hard, thick bedded	light grey
XY 51–53	48 km from Cochabamba	25° at 245°	siltstone	hard, thick bedded	grey
XY 54–55	92 km from Cochabamba	50° at 350°	quartzitic sandstone	hard, thin bedded	light grey
XY 59–60	184 km from Cochabamba	35° at 10°	v.f.g. sandy shale	hard, thin bedded	greenish
XY 61–62	297 km from Cochabamba	60° at 5°	siltstone	hard, thin bedded	grey/greenish
XY 63	310 km from Cochabamba	20° at 25°	silty shale	soft, micaceous, thin bedded	brown

† km from Cochabamba on Oruro–Cochabamba road.
‡ km from Cochabamba on Cochabamba–Santa Cruz road

of magnetization in both normal and reverse senses of the present axial dipole field. The mean direction referred to the present horizontal of the data illustrated in figure 2 is $D = 19°$, $I = -7°$ (table 3).

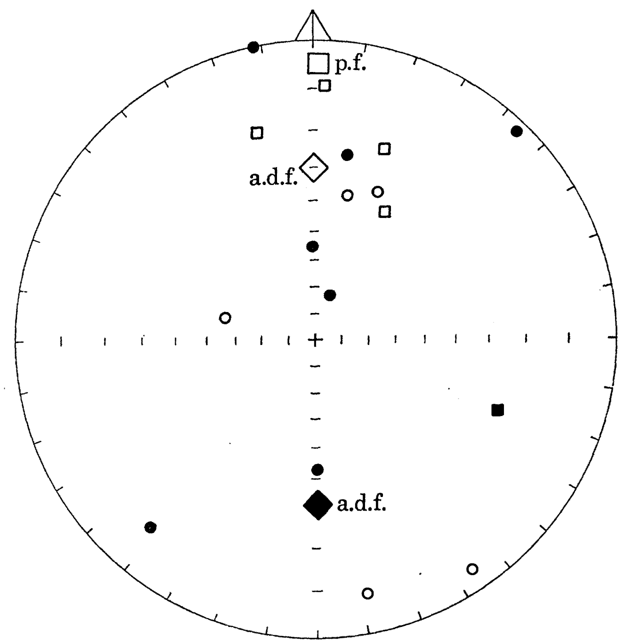

FIGURE 2

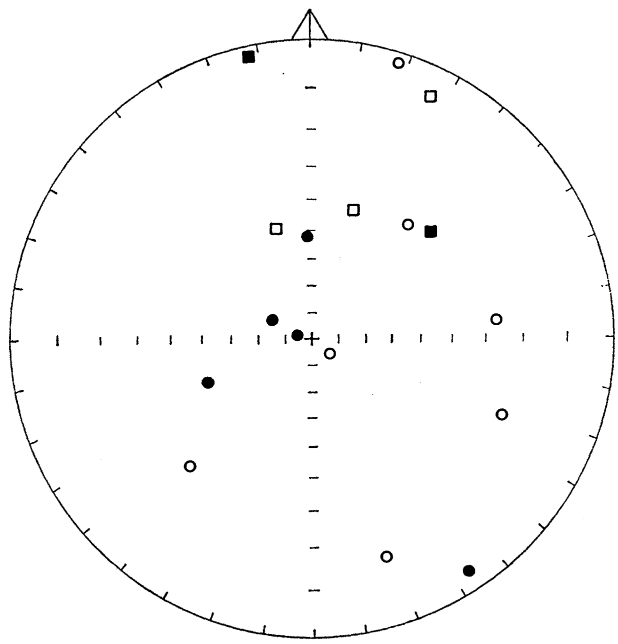

FIGURE 3

FIGURE 2. N.r.m. sample-mean directions of Ordovician rocks referred to the present horizontal; p.f., present field and a.d.f., axial dipole field direction.

FIGURE 3. N.r.m. sample-mean directions of Ordovician rocks referred to the bedding.

TABLE 3. ORDOVICIAN SEDIMENTS

plane of reference	temperature of demagnetization/°C	number of samples	direction of r.m./degree			
			D	I	δ	δ_m
palaeo-horizontal (bedding)	n.r.m.	17 (all)	51	+11	81	20
	n.r.m.	12 (major group)	74	−13	82	24
	530	12 (major group)	284	+83	42	12
	600	12 (major group)	42	+84	39	11
present horizontal	n.r.m.	17 (all)	19	−7	75	18
	n.r.m.	12 (major group)	64	−16	83	24
	530	12 (major group)	202	+57	61	18
	600	12 (major group)	139	+68	66	19
present field	—	—	0	−6	—	—
axial dipole field	—	—	0	−32	—	—

Specimens were subjected to thermal demagnetization by heating to progressively higher temperatures and cooling in zero field. Demagnetization temperatures of 530 and 600 °C were applied. The directions measured at 600 °C are illustrated in the stereographic projections of figure 4 (referred to the palaeo-horizontal). Even after cleaning, the scatter remains quite high, partly because the intensities of remanence are very low. The intensity of n.r.m. was only of the order of 1 μG in most samples, but ranged over two orders, from 0·2 to 17 μG. The geometric-mean intensity of n.r.m. was 0.85 and that of the remanence left after demagnetization of components with blockage temperatures below 600 °C was not significantly different, 0.88 μG.

The statistics are given in table 4. Note that in this table both specimen disk intensities and mean hand-sample intensities (found by finding the geometric mean of the disks within a hand sample) have been used as statistical units. The standard deviations of the distributions of disk unit and sample-unit data are about the same. This indicates that we are not making full use

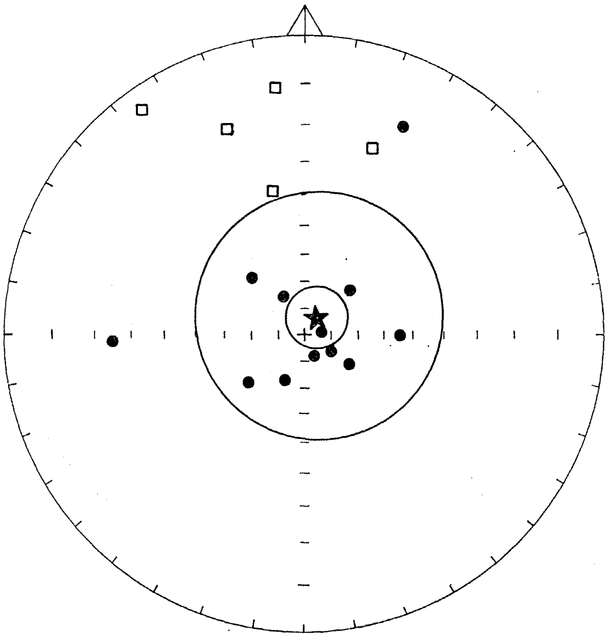

FIGURE 4

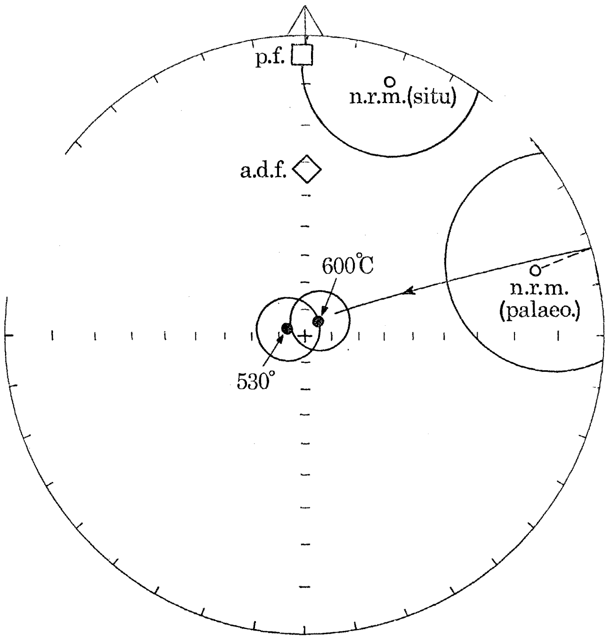

FIGURE 5

FIGURE 4. Cleaned sample-mean directions of r.m. after cleaning at 600 °C. The 12 samples with downward inclinations comprise the 'major' group of table 3. C.s.d. and c.s.e. circles shown.

FIGURE 5. Mean r.m. direction referred to the palaeo-horizontal of group of Ordovician samples subjected to thermal demagnetization at different stages of the experiment. Standard error circles are shown. The n.r.m. direction is illustrated with respect to the palaeohorizontal and also with respect to the present horizontal. Present (p.f.) and axial dipole field (a.d.f.) directions are shown for comparison with the latter.

TABLE 4. ORDOVICIAN SEDIMENTS GEOMETRIC MEAN INTENSITY, M DURING THERMAL DEMAGNETIZATION

temperature of demagnetization	number of disks	number of samples	M	lg M	s.d.	s.e.
n.r.m.	—	18	0.79	−0.10	0.60	0.14
	107	—	0.85	−0.07	0.63	0.06
530 °C	—	19	0.68	−0.165	0.50	0.11
	97	—	0.57	−0.24	0.66	0.07
600 °C	—	20	1.05	+0.02	0.53	0.12
	101	—	0.88	−0.06	0.56	0.06

of the available data when we use sample means rather than disk means as statistical units in this case, in that the reliability of the mean is better than described by the standard error obtained in this way and is better described by the smaller standard error computed using individual disk intensities as statistical units. In both cases, the distributions of intensity were log-normal as far as could be assessed from the amount of data available: they were certainly not normal. Hence geometric means rather than arithmetic means have been used.

The data were analysed following three different methods. In the 600 °C stereogram (figure 4) 12 of the samples (those with positive inclinations) have been formed into a group. The statistics of this population of directions of remanence, measured after thermal demagnetization at 530 °C and also at 600 °C were computed, see table 3. The standard deviation falls to 39° when the directions are referred to the ancient horizontal (i.e. to the bedding) but only to 66° when referred to the present horizontal. This indicates that the remanence left after cleaning was acquired before folding. Note that sample-mean directions have been used as statistical units rather than the directions individually measured for each disk. As for intensities, the standard deviations of the population of sample-mean directions is about equal to that of the corresponding population of disk directions. In the latter case the standard error (s.d. of the mean) is smaller, and judging from the consistency of the results obtained from this formation with those for other S. American Lower Palaeozoic formations it may be considered a truer estimate of the reliability of the mean direction (and the corresponding mean pole) than those given in tables 3 and 4 based on sample means as statistical units.

Some of the mean directions are illustrated in figure 5. First the mean n.r.m. direction referred to the present horizontal is shown as point 'n.r.m. (situ)' and compared with the present geomagnetic field and the axial dipole field directions. Secondly, the mean n.r.m. direction and the directions of n.r.m. after cleaning at 530 and 600 °C with their standard error circles (c.s.e.) are plotted (note that the c.s.e. is about half as large as the α_{95} circle).

The other method of analysis was as follows. Samples which responded well to thermal treatment were selected in two ways; first by studying the trend in direction of remanence during thermal demagnetization, and secondly by studying the trend in intensity. The difficulty with thermal demagnetization of weakly magnetized rocks is that they sometimes acquire a new component of magnetization on cooling in the residual (error from non-zero) field during cooling. Such effects may be recognized by anomalous changes in direction of remanence at the various stages of treatment. With (*a*) direction changes and (*b*) intensity changes used as criteria, optimum temperatures of thermal demagnetization were selected for some samples and results from other samples were rejected completely.

Because of the weak intensities of remanence, both before and during cleaning, it was feared that the cleaned directions might have been induced as a t.r.m. during cleaning, perhaps due to the existence of a weak geomagnetic field with steep positive (i.e. downward) inclination in the apparatus. Although this possibility was carefully checked, no such field could be detected. Nevertheless, to make sure, a further step of thermal demagnetization was carried out at a slightly higher temperature, namely 620 °C under different experimental conditions. For this purpose the palaeomagnetic laboratory of Bergen University was kindly placed at our disposal by Dr Gjellestad and Dr Storetvedt. The measurements were carried out by Mr B. Embleton and the earlier results described above were confirmed.

In figure 6 is shown a population of sample-mean directions of remanence selected on the criterion of trend in direction during cleaning, some sample-mean directions having been selected at 600 °C and others at 620 °C. It was thought reasonable to suppose that the four samples with negative (upward) inclinations were magnetized in the reversed sense of the other fourteen samples. So the former four directions were reversed to form a single population of eighteen unit directions.

South palaeomagnetic poles were then computed for the population groups defined by (*a*) the 12 of the 17 samples which formed a compact group after treatment at 600 °C, (*b*) the population of directions selected on the basis of direction trends during thermal demagnetization selected at 600 °C (see previous paragraph), and (*c*) the population of directions selected in the basis of trends in intensity of remanence. The statistics of these groups are listed in table 5 and plotted in figure 14. The estimates of the south palaeomagnetic pole position obtained by the different methods are mutually consistent.

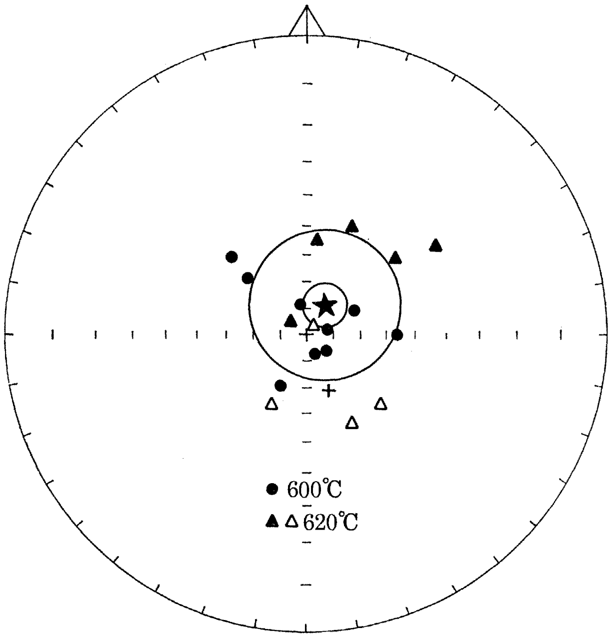

FIGURE 6

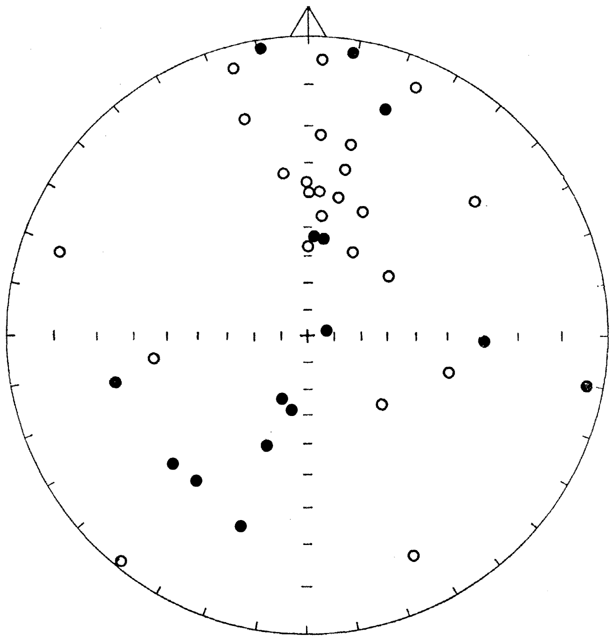

FIGURE 7

FIGURE 6. Cleaned r.m. sample-mean directions of another population of samples. Optimum temperatures of cleaning as described in the text.

FIGURE 7. N.r.m. sample-mean directions of Devonian rocks referred to the present horizontal. The present field (p.f.) and axial dipole field (a.d.f.) directions are shown.

TABLE 5. ESTIMATES OF POSITION OF SOUTH PALAEOMAGNETIC POLE FROM R.M. OF ORDOVICIAN ROCKS

			south palaeopole			
key	population of samples	number of samples	lat.	long.	δ	δ_m
1	major group 600 °C	12	12° S	59° W	52	15
2	direction trend	18	4° N	58° W	35	8
3	intensity trend	9	2° N	59° W	56	19

These poles are plotted in figure 14.

3.2. *Devonian*

A list of samples with brief descriptions of them is given in table 6. The sites are shown in figure 1.

The directions of n.r.m. are plotted on stereographic projections with the bedding planes as primitive (figure 8), and with the present horizontal as primitive (figure 7). The n.r.m. directions, although scattered, show a tendency to be grouped around either the normal or the reversed direction of the axial dipole field of Tertiary and Quaternary times in figure 7. (Note that Creer & Valencio (1969) have shown that there has been little polar movement relative to S. America

TABLE 6. DESCRIPTION OF DEVONIAN SAMPLES

sample no.	locality	dip of beds	description: rock type	description: texture	description: colour
XY 1–2	Belen, quebrada Chilucucho	95° at 75°	sandy shale	hard, fine, thin bedded	grey
XY 3–6	about 7 km from Caxata, on road to Viloco	30° at 55–65°	f.g. sandstone	hard, thin bedded	purple/grey
XY 7–8	about 4 km from Caxata, on road to Viloco	50° at 140°	f.g. sandstone	hard, laminated, micaceous	pale purple/light grey
XY 9–10	81 km from Oruro on road to Cochabamba	25–30° at 220°	f.g. sandstone	medium bedded, micaceous, laminated	reddish brown/ reddish purple
XY 11–12	82 km from Oruro	40–45° at 270°	f.g. sandstone	medium bedded, micaceous, laminated	reddish brown/ reddish purple
XY 13–14	88 km from Oruro	55° at 240°	m.-f.g. sandstone	medium bedded, micaceous, laminated	red/grey
XY 15–16	111.5 km from Oruro	40° at 250°	m.-f.g. sandstone	thin bedded, micaceous, laminated	light purple
XY 17–19	114 km from Oruro	35–50° at 230° to 270°	m.-f.g. sandstone	thin bedded, micaceous, laminated	light purple/grey
XY 20–21	115 km from Oruro	30–40° at 235°	m.-f.g. sandstone	sub-angular, micaceous hard, thin bedded	light purple/grey
XY 22–23	121 km from Oruro	20° at 270°	m.-f.g. sandstone	sub-angular, micaceous hard, thin bedded	light purple/grey
XY 24–25	121 km from Oruro	20° at 230°	m.g. sandstone	hard, thin bedded, micaceous, some cross bedding	light purple

in those periods, apart from reversals.) Thus it is concluded that these rocks were given a secondary magnetization in Tertiary and Quaternary times. We would expect this secondary component to have a chemical origin (Hedley 1968), the reactions having occurred in some samples while the geomagnetic field was of normal polarity and in other samples while it was of reversed polarity.

Of the sample-mean directions referred to the present horizontal and shown in figure 7, 20 may be classified as normal and 14 as reversed. The statistics of these two groups are given in table 7 with the geometric mean intensity. The mean direction of the normal group $D = 357°$, $I = -37°$, $\delta_m = 10°$ is close to the axial dipole field direction, $D = 0$, $I = -32°$, while that of the reversed group differs significantly from that of the reversed axial dipole field (the level of significance adopted is twice the c.s.e., i.e. very nearly the same as the 95 % circle of confidence). The high inclinations of the reversed samples suggest that their n.r.m. is being pulled round into the normal geomagnetic field direction.

Table 7. Devonian sediments: thermal demagnetization

group	temperature of demagnetization/°C	number of samples	directions of r.m. referred to present horizon/degree D	I	δ	δ_m
normal	n.r.m.	20	357	−37	46	10
	400	20	334	−14	51	11.5
	530	20	351	−5	56	12.5
	600	20	12	+1	73	16
reversed	n.r.m.	14	142	+63	49	13
	400	14	146	+68	48	13
	530	14	136	+69	55	15
	600	14	79	+59	56	15
present field	—	—	0	−6	—	—
axial dipole field	—	—	0	−32	—	—

The poor grouping may be explained by either (*a*) incomplete remagnetization in which case there exists a possibility of recovering the primary component, or (*b*) experimental errors in measuring the weak n.r.m. intensities which are of the order of microgauss. However, the scatter is rather high to be explained by the second cause.

Thermal demagnetization was carried out at 400, 530 and 600 °C. Sample-mean directions after cleaning at 600 °C are plotted in figure 9 with respect to the bedding and it will be observed that there has been a tendency for them to acquire a positive inclination. The samples have been assigned to subgroups which will be referred to as 'major' and 'minor' according as to whether their directions lie on the hemisphere centred on the major group of representative points with downward inclinations in the 600 °C stereogram (figure 9) or in the opposite hemisphere. Thus 26 samples have been assigned to the 'major' group and five to the 'minor' group. The statistics of these groups have been computed for the 400, 530 and 600 °C stages of thermal demagnetization and also for the n.r.m. directions. These data are given in table 8 where it is seen that, in response to thermal treatment the circular standard deviation decreases from 82 to 54°. The geometric mean intensities of all the samples studied are listed in table 9. There is a slight increase in intensity from 2.0 to 2.8 μG and this is probably explained by the loss of a secondary component orientated more or less in opposition to the primary. The same argument outlined in §3.1 as to whether disk intensities or sample-mean intensities should be used as units applies here.

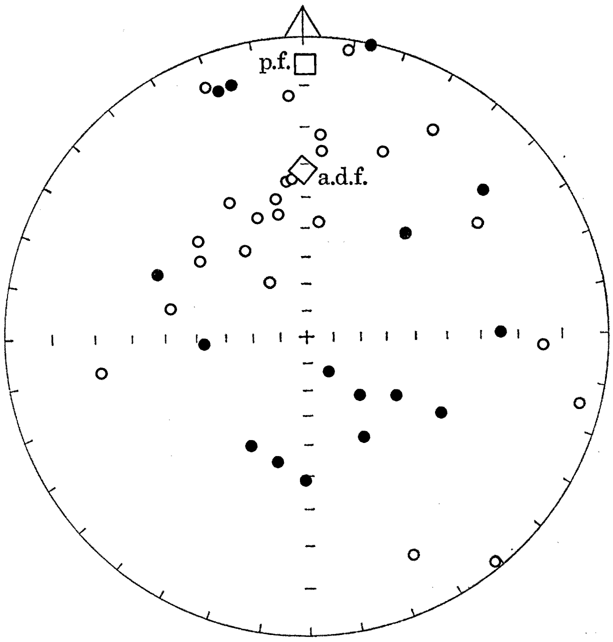

FIGURE 8

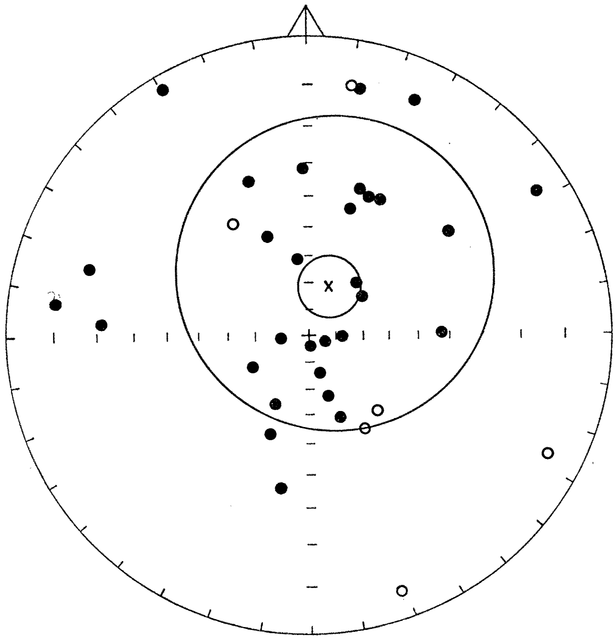

FIGURE 9

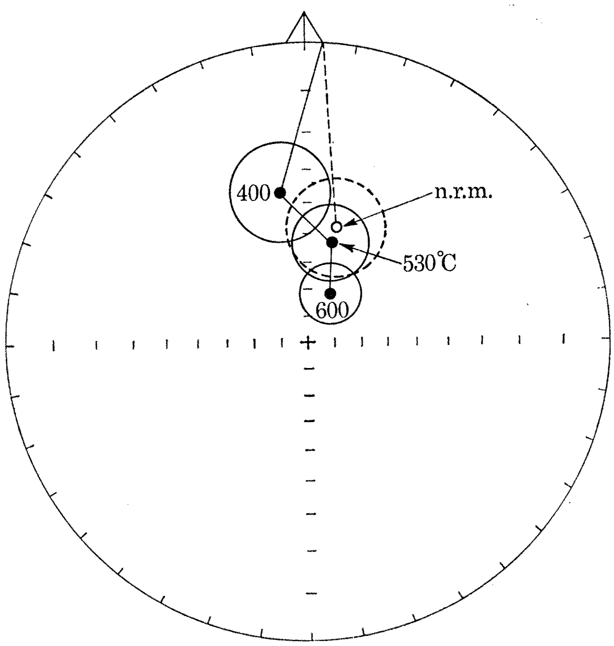

FIGURE 10

FIGURE 8. N.r.m. sample-mean directions of Devonian rocks referred to the palaeohorizontal.

FIGURE 9. Population of sample-mean directions of cleaned r.m. of a group of samples to which thermal demagnetization was applied. Cleaning temperature of the illustrated directions was 600 °C. The mean direction is marked by a cross and its standard error and standard deviation circles are shown.

FIGURE 10. Mean r.m. direction of the group of Devonian samples subjected to thermal demagnetization. The mean directions with standard error and standard deviation circles are shown for each step.

Although statistics for the 'minor' group are also given, these are not considered to be a sufficiently large population to yield a reliable result, in fact the circular standard deviation increases during thermal treatment so that it is likely that these samples were strongly re-magnetized in the present geomagnetic field (note the n.r.m. mean direction is $D = 8°$, $I = -20°$).

Table 8. Devonian sediments: thermal demagnetization

group	temperature of demagnetization/°C	number of samples	directions of r.m. referred to palaeo-horizontal/degree D	I	δ	δ_m
major (normal)	n.r.m.	26	14	−48	82	16
	400	26	350	+37	74	14.5
	530	26	10	+49	69	13.5
	600	26	25	+70	54	11
minor (reversed)	n.r.m.	5	8	−20	21	9
	400	5	5	−16	48	21
	530	5	4	−7	51	23
	600	5	114	−70	65	28

Table 9. Devonian sediments: thermal demagnetization variation of geometric mean intensity, M, of major group (table 8)

temperature of demagnetization/°C	number of disks	number of samples	M	lg M	s.d.	s.e.
n.r.m.	—	39	1.81	0.26	0.62	0.10
	236	—	1.98	0.30	0.68	0.04
400	—	34	2.26	0.35	0.85	0.15
	74	—	2.44	0.39	0.87	0.10
530	—	39	2.43	0.38	0.85	0.14
	191	—	2.57	0.41	0.91	0.07
600	—	27	2.90	0.46	0.93	0.18
	94	—	2.79	0.45	1.00	0.10

We now refer back to table 7 and note that the circular standard deviation of the normal group of sample-mean directions referred to the present horizontal increases from 46 to 73° during thermal treatment while that of the reversed group increases from 49 to 56°. This confirms the conclusion drawn from the fact that the c.s.d. of the major group decreases during thermal demagnetization (table 8) that the cleaned remanence predates the folding. The mean directions with c.s.d. and c.s.e. circles for the major group with downward inclinations are shown of n.r.m. and after cleaning at 400, 530 and 600 °C in figure 10 and the trend away from the present field direction is clearly seen.

The south palaeomagnetic poles computed for the major group of directions after the 600 °C stage of cleaning is illustrated in figure 14 together with the other poles deduced in this paper. It is situated at latitude 7° N, longitude 53° W with c.s.d. = 62° and c.s.e. = 12°, $N = 26$.

3.3. *Carboniferous*

Samples were collected from the Violaceo, Tupambi and Taiguati formations from sites along the Cochabamba–Santa Cruz highway. Particulars about sample numbers and lithology are given in table 10.

The Tupambi and Violaceo formations are magnetized approximately in the normal

TABLE 10. SITE LOCATIONS AND BRIEF DESCRIPTIONS OF CARBONIFEROUS SAMPLES

age	formation	sample nos.	location/km	dip of beds	colour	colour code no.	grain size
Upper Carboniferous	Taiguati	ZY 58–63	370	69° towards 258° E	moderate red	5R–5/4	very fine and medium
		ZY 64–65	369	71° towards 281° E	moderate red	5R–5/4	very fine and medium
		ZY 66–69	367.5	60° towards 260° E	samples lost in transit		
Lower Carboniferous	Tupambi	ZY 25–28	425	80° towards 220° E	pale red	5R–6/2	medium to fine
		ZY 29–33	418	55° towards 90° E	pale red	5R–6/2	medium to fine
		ZY 52–54	375	15° towards 285° E	moderate reddish brown	10R–4/6	medium
		ZY 70–73	310	10° towards 100° E	pale red	5R–6/2	medium to fine
Lower Carboniferous	Violaceo	ZY 34–39	414	20° towards 290° E	pale red	10R–6/2	fine
		ZY 47–51	376	30° towards 270° E	greyish-red	10R–4/2	fine
					dark reddish brown	10R–3/4	coarse to medium
		ZY 74–77	386	10° towards 100° E	pale reddish brown	10R–5/4	coarse to medium
		ZY 78–81	387	12° towards 215° E	pale red	5R–6/2	fine
					dark reddish brown	10R–3/4	coarse to medium

Colour code numbers: refer to G.S.A. rock-colour chart (1963).
Locations: reference is made to the kilometre posts on the main Cochabamba–Santa Cruz highway.

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direction of a dipole field symmetrical about the present axis of rotation. For both formations the scatter of n.r.m. directions is slightly smaller when they are referred to the bedding rather than to the present horizontal, hence magnetization must have occurred before folding. N.r.m. directions for the Violaceo formation are shown in figure 11 and for the Tupambi formation in figure 12. The formation-mean n.r.m. directions and relevant statistical parameters are listed in table 11. In this table the c.s.d. for each of the two populations of disk magnetization directions

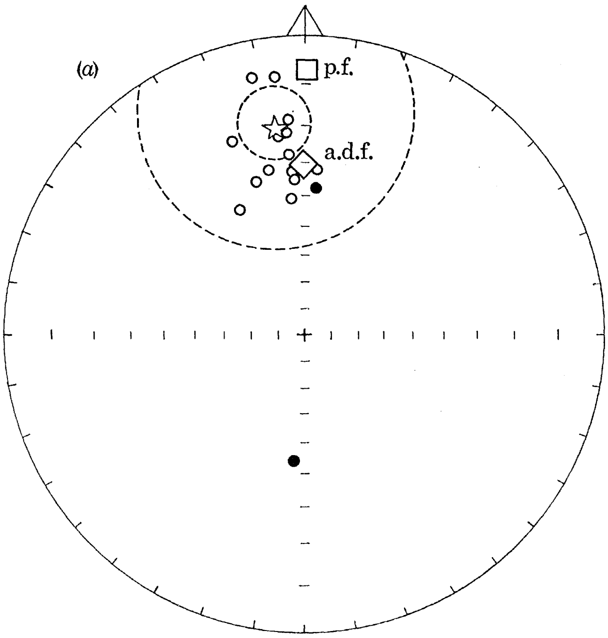

Figure 11. N.r.m. of sample-mean directions for the Violaceo formation plotted (*a*) with respect to the present horizontal, and (*b*) with respect to the palaeohorizontal.

Table 11. N.r.m. directions of Tupambi and Violaceo formations

		directions of n.r.m./degree							
		referred to bedding				referred to present horizontal			
formation	number of specimens	*D*	*I*	δ	δ_m	*D*	*I*	δ	δ_m
Tupambi	63	2	−23	13	2	340	−41	33	4
Violaceo	78	359	−20	37	4	353	−20	37	4
present field	—	358	−20	—	—	—	—	—	—
axial dipole field	—	0	−31	—	—	—	—	—	—

is given. They are very close indeed to those computed for the distributions of sample-mean directions (13.4° as compared with 12.6° for the Tupambi and 37° as compared with 35° for the Violaceo formation). Hence accuracy of the formation-mean direction in each of these cases is better described by the standard error of the population of disk directions rather than by that computed using the sample-means as units. The same is true for the intensity distributions which are shown in table 12, the statistics listed there having been computed from disk intensities as statistical units. The samples from these formations have not been thermally cleaned.

The direction of the palaeogeomagnetic field in South America has remained close to the present axial dipole field (normal or reversed) since the Triassic. Before the Triassic the geomagnetic field directions were quite different. We have already seen that these formations were magnetized before folding. We can now add the rider that they must have been magnetized during or after the Triassic.

Hence we can conclude from the palaeomagnetism of these formations: (*a*) that the n.r.m. must have a chemical and not a detrital origin, and (*b*) that the folding must be post-Triassic. The latter conclusion is reasonable because it is known that the Andes were uplifted during the Cretaceous and Tertiary.

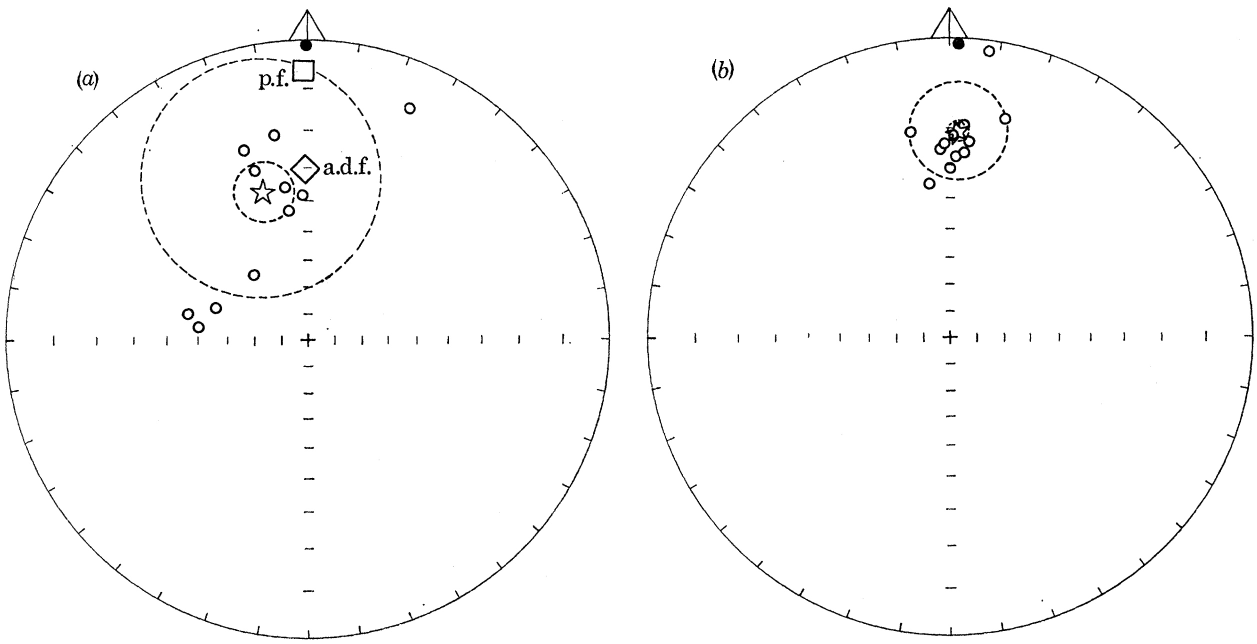

FIGURE 12. N.r.m. sample-mean directions for the Tupambi formation plotted (*a*) with respect to the present horizontal and (*b*) with respect to the palaeohorizontal.

TABLE 12. N.R.M. INTENSITIES (μG)

formation	polarity	number of specimens	geometric mean intensity, *M*			
			M	lg *M*	s.d.	s.e.
Taiguati	normal (N)	20	11.5	1.06	0.23	0.05
	reversed (R)	22	20.2	1.30	0.25	0.05
	N and R	42	15.4	1.19	0.27	0.04
Tupambi	normal	63	5.1	0.71	0.35	0.04
Violaceo	normal	74	7.3	0.86	0.56	0.07

South palaeomagnetic poles computed from the n.r.m. directions of these two formations are given in table 13. These poles correspond to those of the field acting on the rocks before folding at the time they acquired their remanence. Their angular separation from the present geographic pole of 5 and 7° may be compared with twice the c.s.e. (the normally accepted level of significance) of 4 and 8°. They are both closer to the Cretaceous pole computed from 30 sites in the Serra Geral fm (entry 20, table 1, p. 553) at latitude 78° S, longitude 54° E, with $\delta = 17°$, $\delta_m = 3°$ than to the mean Triassic pole computed from seven different formations in S. America at latitude 80° S, longitude 122° W, $\delta = 32°$, $\delta_m = 10°$.

The Taiguati formation, although younger than either the Violaceo or Tupambi (see table 1), possesses an n.r.m. whose direction is strongly oblique to the present field. Two groups of directions exist.

The mean directions with statistical parameters are given in table 14, where they are referred to the present horizontal and in table 15 where they have been referred to the palaeohorizontal. The latter group of directions are illustrated in figure 13. The scatter of the reversed group is

Table 13. South palaeomagnetic poles for Tupambi and Violaceo formations

formation	number of specimens	south palaeomagnetic pole: lat.	long.	δ	δ_m
Tupambi	63	85° S	135° E	10	2
Violaceo	78	83° S	112° E	34	4

Note. These poles are computed from the n.r.m. direction referred to the palaeo-horizontal and are therefore the poles of the magnetizing field which acted before folding occurred.

Table 14. Taiguati formation

polarity	number of specimens	directions of n.r.m. referred to present horizontal/degree: D	I	δ	δ_m
normal	14	271	−5	14	4
reversed	21	115	3	12	2.5
present field	—	358	−20	—	—
axial dipole field	—	0	−31	—	—

Table 15. N.r.m. directions and palaeomagnetic poles computed for the Taiguati formation

	polarity	number of specimens	directions of n.r.m.: D	I	δ	δ_m	south palaeomagnetic pole: lat.	long.	δ	δ_m
1	Normal (N)	14	301	−68	14	4	31° S	24° W	22	6
2	Reversed (R)	21	147	+57	9	2	54° S	15° W	13	3
3	N+R	35	319	−62	14	2	45° S	20° W	20	3

N.r.m. directions are referred to the bedding (palaeo-horizontal).

slightly improved when referred to the palaeo-horizontal rather than to the present horizontal (c.s.d. = 9° as compared with 12°) but that of the normal group (c.s.d. = 14°) is the same in both cases, so it is not possible, on this criterion, to decide whether or not the magnetization predates the folding which occurred in the Cretaceous or Tertiary. However, since the directions of n.r.m. referred to the present horizontal correspond to no known Mesozoic geomagnetic field for S. America (e.g. see p. 553) it is concluded that magnetization must surely have occurred before folding.

The inexact opposition of the means of the normal and reversed groups of directions could be due to a small secondary component in which case we could deduce the direction of the larger primary one by forming a population comprising the normal directions as they stand together with the reversed directions turned through 180° (see entry 3 in table 15).

However, the normally magnetized samples all come from km 370 (see table 10) while the reversely magnetized samples were collected at km 369 approx. Thus, if there is no faulting between the two sites they could be separated stratigraphically by about 950 m of sediment, the

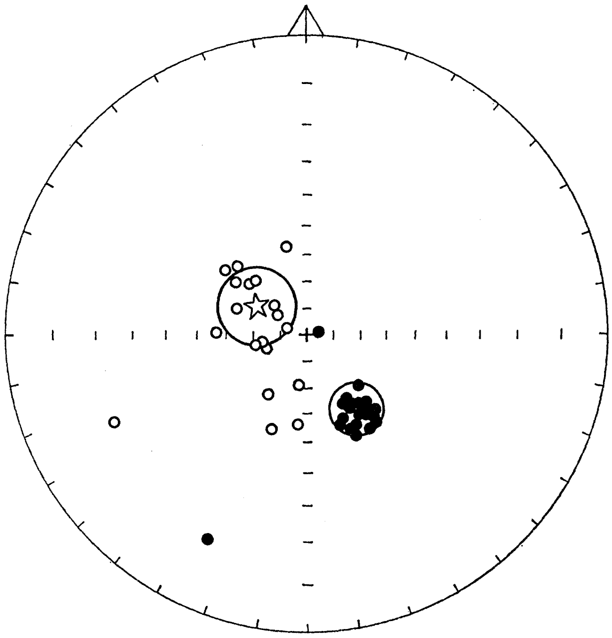

FIGURE 13. N.r.m. directions of specimen disks from samples of the Taiguati formation plotted with respect to the palaeo-horizontal. Mean directions and standard deviation circles of the normal and reversed groups.

FIGURE 14. South palaeomagnetic pole positions for the formations studied in this work. O1, O2, O3, Ordovician poles (see table 5); *D*, Devonian (see §3.2) and *T*, Taiguati formation (Carboniferous) see table 14.

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normally magnetized samples being the older. This interpretation is preferred to the one given above because the two palaeomagnetic poles (entries 1 and 2 in tables 10 and T_L and T_U in figure 14) correspond to lower-middle Carboniferous and Permo-Carboniferous pole positions respectively for S. America. In particular the upper Taiguati pole agrees very well indeed with the Permo-Carboniferous poles obtained for the Piaui formation from northeast Brazil and the Paganzo formation from northwest Argentina (parts II and III above). The position of the Taiguati pole previously reported (see, for example, Creer 1964) is close to that of the lower Taiguati pole computed here and is correlated with the Dwyka varves from S. Africa and the lower Kutting lavas and Yawal stage basalts from Australia (Creer *et al.* 1969).

The Taiguati formation is stated to be Permian in the chapter on Bolivian geology in the *Handbook of S. American geology* (G.S.A. memoir no. 75, 1956) and also by Ahlfield & Branisa (1960), but some Bolivian geologists now consider it to be Pennsylvanian (J. Davila 1968, personal communication). These palaeomagnetic results suggest that its age may span the middle Carboniferous to Permo-Carboniferous (Kiaman) interval.

4. Discussion of results

4.1. *Carrier of remanence*

The r.m. of the Ordovician (§3.1) and Devonian (§3.2) samples have blockage temperatures above 600 °C (tables 4 and 9) and this strongly suggests that the remanence resides in haematite and not in a magnetite or titanomagnetite.

The Carboniferous samples were not thermally demagnetized. However, Collinson (1966) has investigated the magnetic properties of the Taiguati formation, his experiments having been carried out on the actual samples reported on in the present paper. Iron oxides are present both in the red pigment and as black specularite particles, but the former is the dominant form. It was concluded that the natural remanence was acquired by chemical magnetization of the red pigment during its formation in situ in the rocks. This need not, however, have taken place during deposition.

4.2. *Evidences of glaciation*

There is some geological evidence of weak glaciation and of a cold climate during the lower and middle Palaeozoic in Bolivia. As mentioned in §2, tillites occur in the Silurian (the glacial beds of Zapla). Also the absence of coral reefs in the Devonian succession has led to the suggestion that the climate was cold.

The palaeomagnetic results reported in this paper indicate palaeolatitudes of 60 to 80° in the Ordovician and about 55° in the Devonian. If the poles were covered with ice-caps as large as exist at the present time, these palaeomagnetic results would lead us to expect to find abundant evidence of glaciation in the Ordovician. However, the size of the polar ice caps have varied considerably throughout geological time. Taken together, the palaeomagnetic and geological evidence suggest light glaciation and high latitudes in the Ordovician and Devonian.

The Taiguati formation yields a palaeolatitude of 45 to 50°, which must almost certainly be that of the environment in which these beds became red, since the remanence is probably of chemical origin (§4.1). Such latitudes are rather higher than those at which red beds are today formed, and this is suggestive of an overall warmer global climate than the present one.

However, the Tarija formation (table 1), which is stratigraphically older than the Taiguati, contains an abundance of glacial clay grits, banks of tillites and interglacial sediments (see §2).

The magnetic remanence (if any) present in samples from this formation was too weak to measure. Glacial horizons have also been found in formations lying stratigraphically higher than the Taiguati. The youngest glacial unit being found in the San Telmo formation, said to be Permian (table 1).

Hence it is tentatively concluded that during the interval of geological time between the Ordovician and Permian the overall global temperature fluctuated, the south pole sometimes being covered with ice caps and at other times being free of ice caps, though probably these cycles had considerably longer time constants than the glacial-interglacial Pleistocene cycles. Evidence of glaciation in S. America is strongest in upper Carboniferous formations and in Australia in the Permo-Carboniferous, so it would appear that the cold cycles became more frequent and severe as time advanced during the considered interval (i.e. Ordovician–Permian). The Ordovician, Devonian and Carboniferous rocks whose remanence could be measured and for which the palaeomagnetic data are described in §3 must have acquired their magnetization when chemical processes (dehydration and oxidation) occurred in the iron oxides and oxyhydroxides they contained during the warmer cycles.

4.3. *Comparison with other palaeomagnetic data from other parts of S. America*

The palaeomagnetic data described in this paper are broadly consistent with other similar data representative of the same geological time interval from Brazil and Argentina (parts II and III, this volume; Creer *et al.* 1969), and also with palaeomagnetic data for Africa (Creer 1968), provided the existence of Gondwanaland is accepted.

5. Acknowledgements

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