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

# Palaeomagnetism of Rock Formations from Peru

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# V. PALAEOMAGNETISM OF ROCK FORMATIONS FROM PERU

CONTENTS



The Pennsylvanian Ambo Group and the Permo–Triassic Mitu Group from the central cordillera of Peru, appear to have been originally magnetized when they were formed and then partly remagnetized after folding during the Tertiary or Recent epochs. Tertiary sediments from the eastern flank of the cordillera appear to have escaped remagnetization after folding although they dip steeply. Some provisional data are presented for the Cretaceous.

## 1. Geology

A geological sketch map of the region from which samples were collected is presented in figure 1. It runs across the Peruvian Andes in a NNE direction from Lima, through the mining towns of La Oroya and Cerro de Pasco on the altiplano and then on to Huanuco and down to Tingo Maria on the River Huellaga which runs into the Amazon.

The sampling sites are marked in figure 1 and described in §3 where information about their lithology and colour and of the amount and direction of dip of the strata are tabulated.

The oldest formations studied belong to the Ambo group which consists of continental type strata containing some coal beds and which is mapped as undifferentiated Carboniferous. Massive beds of tuff were collected from the top of the type section at Ambo and are considered to be Pennsylvanian.

The larger part of the collection was taken from the Mitu group which consists of a series of continental red beds and volcanics of Permian age (Newell, Chronic & Roberts 1953). The volcanics have been associated with a well defined orogeny probably centred in the western Cordillera in the Permian. Marine strata are interbedded in places. The Mitu formation unconformably overlies lower Permian beds in Southern Peru and Middle Pennsylvanian in Central Peru.

Cretaceous sediments and volcanics were sampled in the vicinity of Vinchos and Moracoche in the altiplano.

Finally a section spanning the Jurassic to Tertiary was sampled in the vicinity of Boqueron near Tingo Maria.

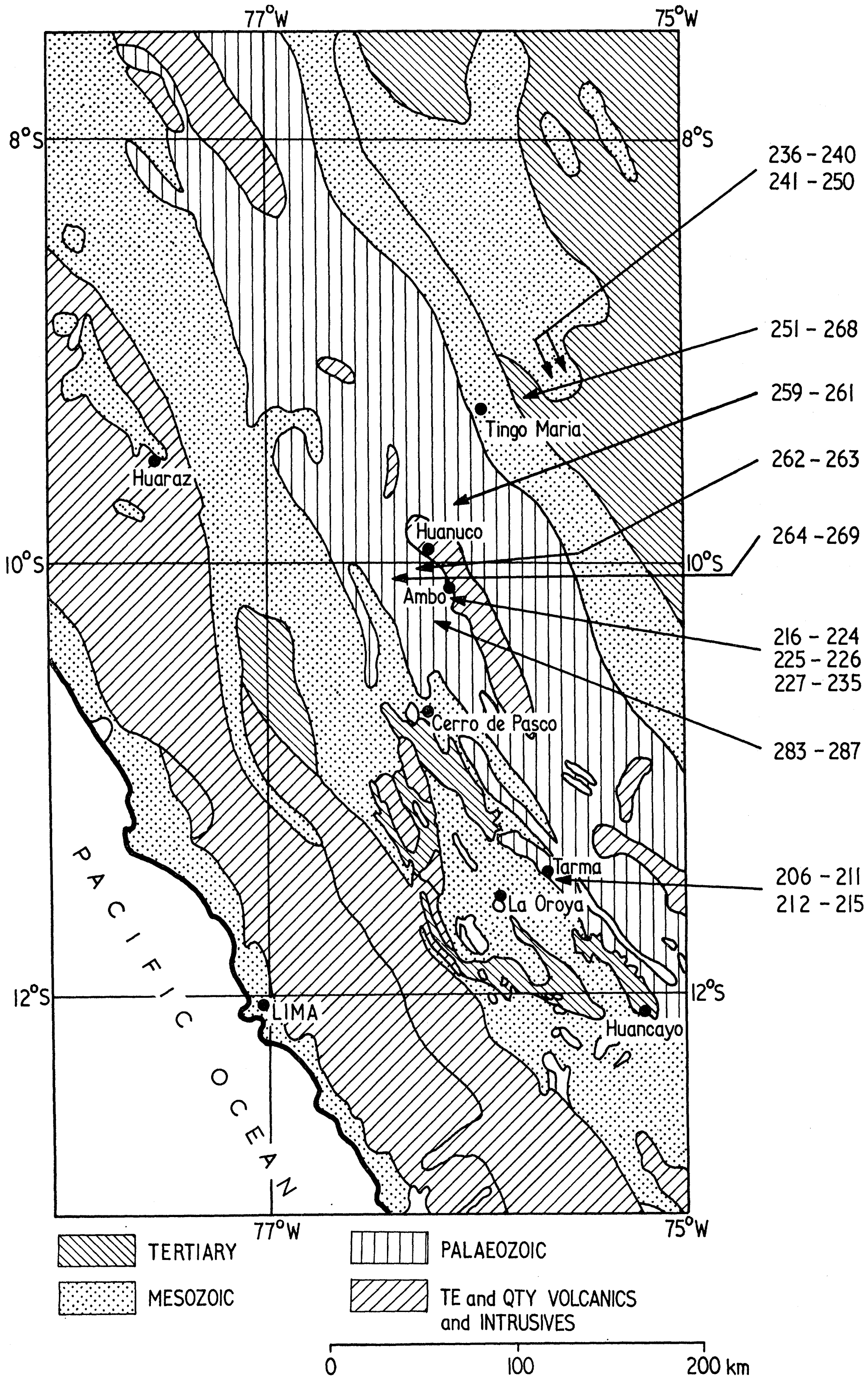


Figure 1. Geological sketch map of area from which samples were collected.




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## 2. Results

The Mitu formation has been sampled fairly thoroughly (see table 1) and the collection has been thermally cleaned. Only n.r.m. measurements have been made on the Pennsylvanian from Ambo (table 2), and on the Cretaceous sediments and lavas. The Tertiary sediments from Boqueron have been thermally cleaned. The results for the Mitu formation are discussed first and then those for the other formations starting with the oldest.

Table 1. Descriptions of collection from Mitu formation

| sample nos. | locality | lithology | dip of beds | colour |
|---|---|---|---|---|
| 212–213 | I road cutting near Tarma, above Pennsylvanian | f.g. sandstone | 35° at 100° | greyish red 5R–4/2 |
| 214–215 | II stratigraphically higher than previous site | f.-m.g. sandstone | 45° at 50° | blackish red 5R–2/2 |
| 227–231 | III from hill S.W. of Ambo, above Pennsylvaniana | f.g. sandstone | 85° to 90° at 80° | greyish red 5R–4/2 blackish red 5R–2/2 |
| 232–235 | IV ½ km south of Ambo | f.g. sandstone | 80° at 90° | dark reddish brown 10R–3/4 |
| 264–269 | V on the Goyllarioquisca–Tusi road | m.g. sandstone f.g. muddy sandstone | 35° at 210° | pale brown 5YR–5/2 |
| 283–287 | VI road to Vinchos | m.g. sandstone m.-c.g. sandstone | 30° at 220° 30° at 230° | greyish red 5R–4/2 |
| 299–300 | VII km 134 on Cachuamayo–Ulcumayo road | m.-c.g. sandstone | 70° at 240° | greyish red 10R–4/2 |

Table 2. Ambo group (Pennsylvanian)

| sample nos. | locality | rock type | dip of beds | colour |
|---|---|---|---|---|
| 216–224 | type section, near river, 216 is at top of succession | tuffs | 80–85° at 70–90° | olive grey 5Y–3/2 |
| 225–226 | south of Ambo | f.g. muddy sandstone | 80° at 80° | dark yellowish brown 10YR–4/2 |

### 2.1. *The Mitu group*

Sample-mean directions of n.r.m. referred to the bedding planes, are illustrated in figure 2. These may be classified into two groups of oppositely polarized directions of which the larger group is directed downwards mainly in the southwest quadrant: its mean direction is represented by the star and the c.s.d. circle of the population is also shown. The statistical parameters of the two populations are presented in table 3. Two observations are made: (*a*) that both mean directions referred to the present horizontal, are oblique to the axial dipole field direction ($D = 0°$, $I = -24°$), and (*b*) the c.s.d. angles are smaller when the populations of directions are referred to the palaeo-horizontal rather than to the present horizontal, suggesting that at least part of the remanence predates the folding.

These data were among the first obtained from the continent of S. America for the lower Mesozoic and were at first thought representative of the geomagnetic field of that epoch for the two reasons mentioned in the previous paragraph and also because of the presence of the two groups of opposed directions (Creer 1962*a*). However when more palaeomagnetic data were obtained it was realized that this result from the Mitu formation was anomalous (Creer 1964*a*, *b*).

Later, when the collection was thermally cleaned, optimum grouping was achieved at 530 °C (the sample-mean directions are illustrated in figure 3), although some r.m. was retained above 600 °C (see figure 4) indicating that the carrier of remanence is haematite rather than a titanomagnetite. The mean direction of the southwest and positive group represented by a

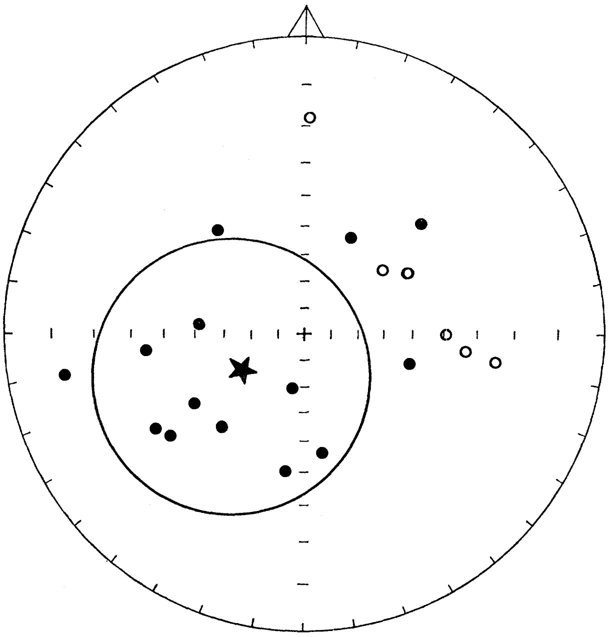

Figure 2

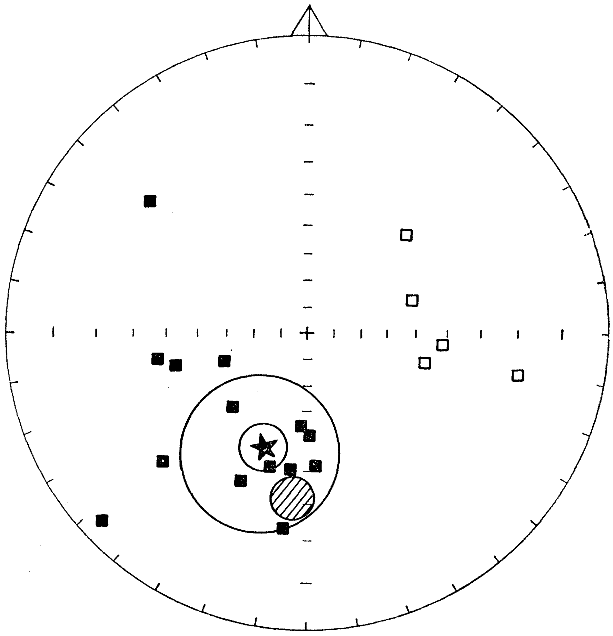

Figure 3

Figure 2. N.r.m. directions of samples collected from the Mitu formation (table 2). The mean of the southwest and positive group of directions is plotted as a star. Note the northeast and negative group of directions nearly opposed to the former. Solid symbols represent vectors in the lower hemisphere and open symbols represent vectors in the upper hemisphere. The c.s.d. circle is shown.

Figure 3. R.m. directions of samples for the Mitu formation after thermal cleaning. Mean direction represented by the star. C.s.e. and c.s.d. circles shown. The shaded area represents the estimated direction of the primary palaeogeomagnetic field.

Table 3. N.r.m. of Mitu group

| | | direction of n.r.m./degree | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | palaeo-horizontal | | | | present horizontal | | | |
| population | number of samples | $D$ | $I$ | $\delta$ | $\delta_m$ | $D$ | $I$ | $\delta$ | $\delta_m$ |
| S.W. and + | 14 | 239 | +63 | 46 | 12 | 258 | +27 | 64 | 17 |
| N.E. and − | 5 | 70 | −38 | 36 | 16 | 70 | +19 | 56 | 25 |

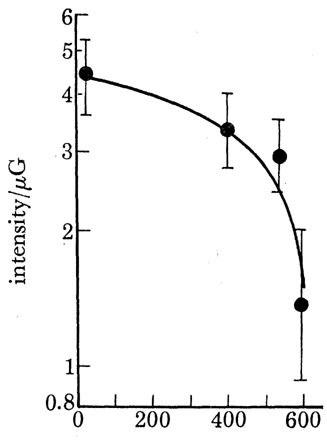


Figure 4. Thermal decay curve of r.m. of Mitu formation (southwest and positive group of directions). Geometric mean intensities (μG) with standard error bars plotted on logarithmic scale against temperature.

star has migrated in a counter clockwise sense towards the direction of the Triassic geomagnetic field whose c.s.e. is represented by the shaded circle. (The Triassic field for this region of Peru has been calculated from the Triassic palaeomagnetic pole for S. America described by Creer, Embleton & Valencio (1970).) The northeast and negative group of directions did not migrate appreciably and further cleaning at higher temperatures produced no further migration of the southwest and positive group.

Let us suppose that we have failed to isolate the primary remanence by thermal cleaning and in particular test the hypothesis that the cleaned remanence is composite, being the vector sum

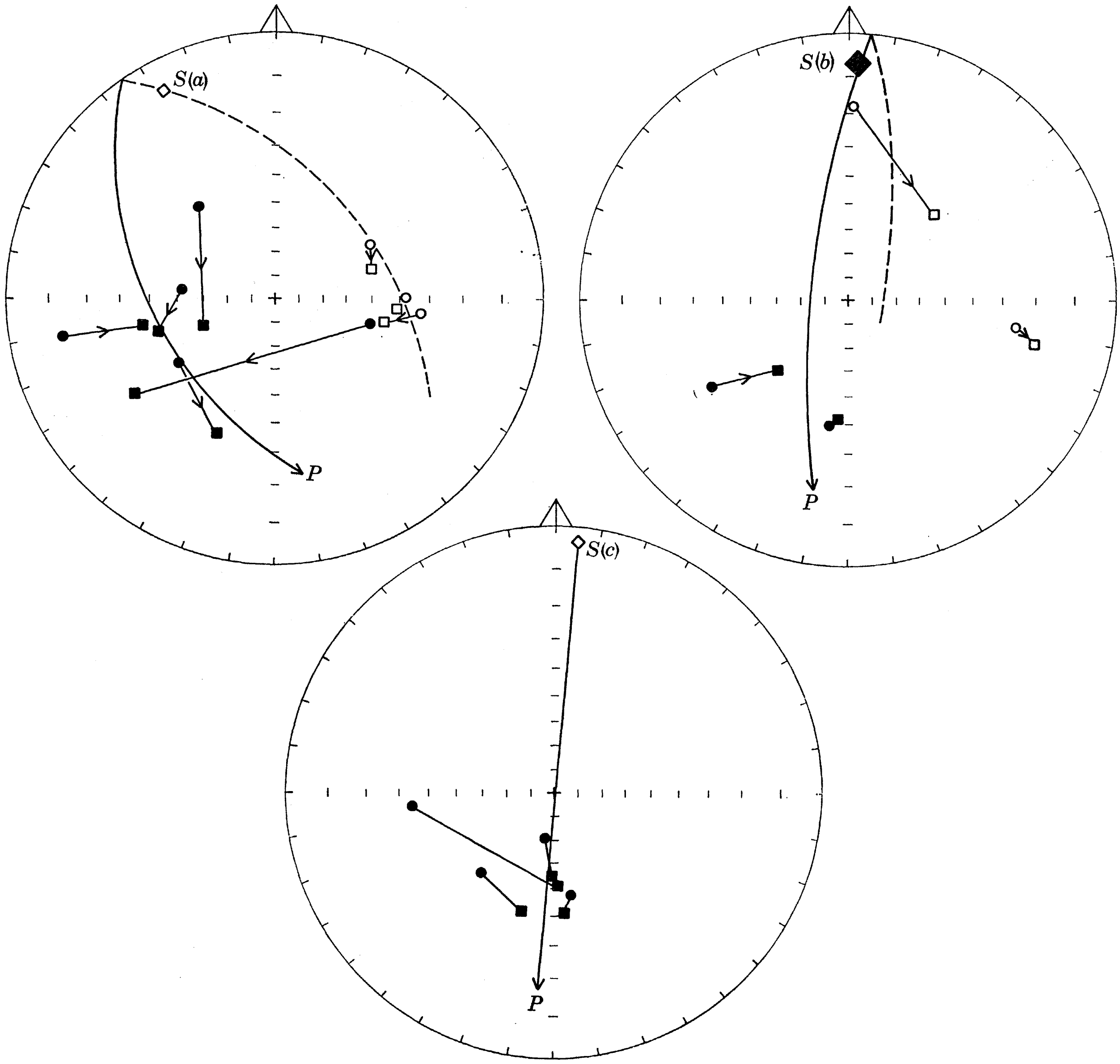


FIGURE 5. Great circles of remagnetization (*a*) for sites III and IV (see table 2); (*b*) for site VII and (*c*) for sites V and VI. *S* represents the present axial dipole field as seen from the bedding planes and *P* the primary remanence (given by the points of intersection of the great circles (*a*), (*b*) and (*c*). The measured n.r.m. directions are represented by round symbols and the cleaned r.m. directions by square symbols.



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of an unknown (to be determined) primary component, *P*, and a secondary component *S*, acquired in the present axial dipole field after folding. In figure 5*a* sample-mean directions of n.r.m. and of cleaned r.m. for sites III and IV (table 1) are seen to lie close to the great circle connecting the mean of the cleaned r.m. directions of the southwest and positive group and the present axial dipole field direction, *S*, as seen from the bedding planes. Considering now this group of directions only, we conclude that the primary direction, *P*, must lie somewhere along this great circle, beyond the measured r.m. directions. The northeast and negative group of directions have possibly been pulled around in the opposite sense in the plane represented by this great circle. A similar situation is illustrated in figure 5*b* for site VII and in figure 5*c* for sites V and VI. In the former, one sample does not lie near the great circle (shown by the broken line) in the upper hemisphere while in the latter there are no samples belonging to the northeast and negative group, so the above argument applies most strongly to the southwest and positive group, which however, is the principal one.

We have thus defined three planes in which the primary remanence, i.e. that acquired before folding, must lie, and the three lines of intersection of pairs of these planes are represented by the points of intersection of their representative great circles. The mean of these three points is situated at $D = 188°$, $I = +25°$ and agrees well with the field direction calculated for the Permo-Triassic palaeomagnetic pole at 82° S, 154° W, c.s.d. = 4° (Creer *et al.* 1970) as shown in figure 6. (This pole incorporates new data not included in entry *E*, table 2, p. 554.)

Thus the palaeomagnetism of the Mitu formation is consistent with its having been magnetized first in the Triassic, before folding, and later, after folding, in a field whose orientation was similar to that of the present axial dipole field.

### 2.2. *The Ambo group*

The samples collected were mainly of tuffs. The directions of n.r.m. have positive inclinations and almost westerly declinations. The intensities were rather weak, of the order of a few microgauss, and thermal cleaning produced unpromising results in that the scatter increased while the mean direction did not migrate significantly.

The mean n.r.m. direction is represented by the star in figure 7. Its virtual geomagnetic pole is situated at 15° N, 25° E, with c.s.d. = 26° and c.s.e. = 8°. This does not correspond to any well-established palaeomagnetic pole for the Carboniferous, Permian, Mesozoic or Tertiary and hence the possibility of remagnetization is tested by the method described in the previous section (2.1). Two secondary fields have been tested. *S* (a.d.f.) in figure 7 represents the present axial dipole field as seen in the bedding planes and $S(T)$ similarly represents the normal sense of the Tertiary geomagnetic field as deduced from palaeomagnetic studies on Tertiary rocks from Boqueron (see §2.4).

The grouping of n.r.m. directions is consistent with the presence of two components of magnetization and in this respect two conclusions may be drawn tentatively, namely (i) that the post-folding component may have been acquired in the Tertiary rather than the recent geomagnetic field since the great circle constructed through the point $S(T)$ fits the points representing the n.r.m. directions better than that constructed through the point *S* (a.d.f.) and (ii) that the prefolding component may have been acquired in the Permo-Carboniferous rather than in the Middle Carboniferous or Triassic because both the great circles pass closer to the point PC which represents the direction of the Permo-Carboniferous geomagnetic field at Ambo, calculated from the palaeomagnetic pole relative to S. America for that period

Creer *et al.* (1969), than to the points C or Ŧ which respectively represent the other two field directions considered similarly calculated. Furthermore, the Kiaman field (point PC) was almost exclusively reversed.

This conclusion is compatible with the geology. First, the estimated direction of remanence acquired before folding agrees with the stratigraphic age. Secondly, the post-folding component may well have been acquired during the Tertiary at moderately elevated temperatures, when the Andes were built, rather than more recently.

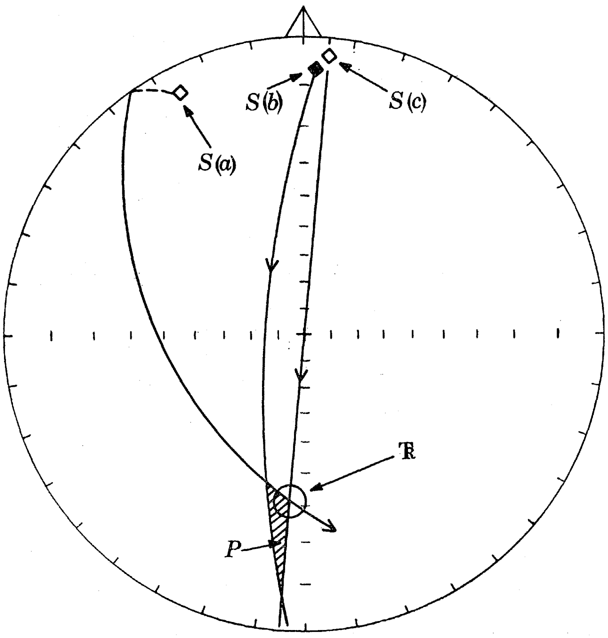


FIGURE 6

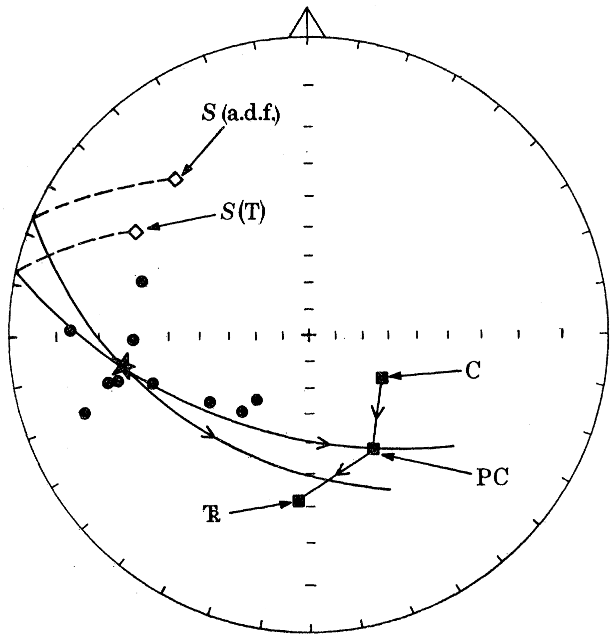


FIGURE 7

FIGURE 6. Illustrating the points of intersection of the three great circles constructed in figure 5. The direction of the Triassic geomagnetic field, calculated for the sampling sites from the mean of seven S. American formations (Creer *et al.* 1970) is shown by the circle whose radius represents the c.s.e. with which the mean direction was determined.

FIGURE 7. Directions of n.r.m. of disks cut from samples listed in table 1 from tuffs from the type section of the Ambo group. The plane of projection is the bedding plane. The points plotted as diamonds, namely *S* (a.d.f.) and *S* (*T*) represent respectively the present axial dipole field and the Tertiary field (see § 2.5) referred to the bedding. The points plotted as squares represent the middle Carboniferous (C), the Permo-Carboniferous and the Triassic (Ŧ) palaeo-geomagnetic field directions respectively. The mean direction of n.r.m. is represented by the star and the great circles suggest that the primary remanence of reversed polarity was acquired in the Permo-Carboniferous (Kiaman).

### 2.3. *Cretaceous formations*

A variety of sediments and volcanics were collected as indicated in table 4. However, neither a.f. nor thermal cleaning have been carried out and the results are reported here in order to illustrate that further work on these formations would be worth while.

The dikes at Herradura near Lima exhibit magnetization with both polarities. The n.r.m. directions are illustrated in figure 8: (*a*) with respect to the present horizontal, and (*b*) with respect to the bedding. These populations of directions are provisionally accepted as representative of the Cretaceous geomagnetic field because the mean directions make an angle of more than the 95 % circle of confidence (about twice the c.s.e. given in table 5) with the a.d.f. direction.

TABLE 4. CRETACEOUS SEDIMENTS AND VOLCANICS

| sample nos. | locality | rock type | dip of beds | colour |
|---|---|---|---|---|
| 274–276 | road to Vinchos | sediments | 40–45° at 240–250° | greyish brown 5YR–3/2 |
| 279–282 | road to Vinchos | volcanics | 55–60° at 240° | greyish olive 10Y–4/2 |
| 303–304 | km 134, near Moracoche | porphyry | 90–100° at 160° | olive-black 5Y–2/1 |
| 305–307 | km 134, near Moracoche | f.g. sandstone | 85–95° at 95° | brownish grey 5YR–4/1 |
| 193–201 | Herradura, near Miraflores, Lima | dikes | 10–20° at 200–240° | grey |

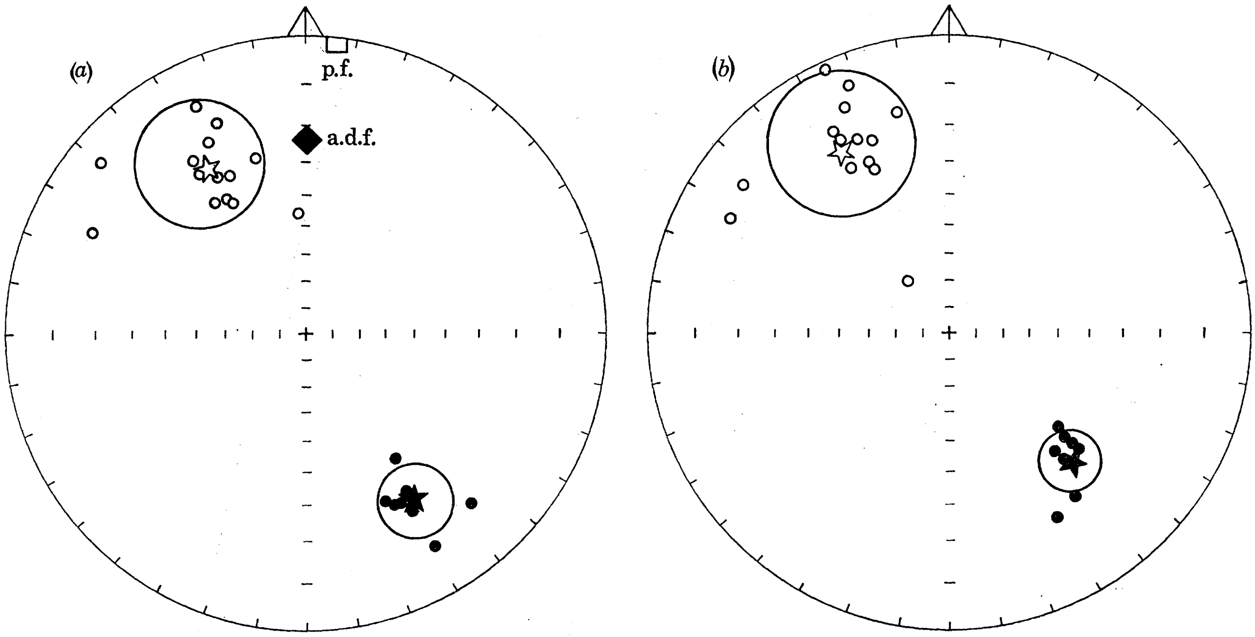


FIGURE 8. N.r.m. directions of specimens from the dikes at Herradura, near Lima, (*a*) plotted with respect to the present horizontal (a.d.f., axial dipole field direction; p.f., present field) and (*b*) with respect to the palaeohorizontal. The c.s.d. of the two groups are shown.

TABLE 5. CRETACEOUS FORMATIONS

| locality | sample nos. | number of disks | directions of n.r.m./degree: palaeo-horizontal D | I | $\delta$ | $\delta_m$ | present horizontal D | I | $\delta$ | $\delta_m$ | acceptability† |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Herradura (dike) | 195–8 | 14 | 330 | −20 | 18 | 5 | 329 | −26 | 18 | 5 | yes |
| | 193–4 200–1 | 8 | 137 | +30 | 9 | 3 | 149 | +23 | 10 | 4 | yes |
| 2. Vinchos (sediments) | 274–6 | 9 | 350 | −9 | 44 | 15 | 340 | −15 | 44 | 15 | yes |
| 3. Vinchos (volcanics) | 279–82 | 6 | 170 | +65 | 26 | 10 | 94 | +36 | 23 | 9 | no (*b*) |
| 4. Moracoche (porphyry) | 303–4 | 5 | 133 | −18 | 47 | 21 | 28 | −54 | 40 | 18 | no (*b*) |
| 5. Moracoche | 305–7 | 9 | 351 | +35 | 15 | 5 | 333 | −17 | 15 | 5 | yes |

† Result accepted provisionally if (*a*) c.s.d. of population referred to the palaeo-horizontal is less than or equal to that of the same population of n.r.m. directions referred to the present horizontal, and (*b*) if the mean direction referred to the present horizontal makes more than the c.s.e. angle with either of the a.d.f. directions.



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Particulars of the n.r.m. of the other Cretaceous formations studied are given in table 5. Data are provisionally accepted if (*a*) the c.s.d. of the population of directions referred to the palaeo-horizontal is less than or equal to that of the same population referred to the present horizontal, and if (*b*) the mean direction makes an angle of more than the c.s.e. with the a.d.f. (63 % probability level as opposed to 95 % above). It is stressed that these criteria of acceptance are provisional and should merely be taken as a guide as to whether the formations are suitable for further palaeomagnetic study.

A population of virtual south geomagnetic poles corresponding to the accepted data was formed and its mean falls at 63° S, 30° E with c.s.d. = 23° and c.s.e. = 4°. This should be

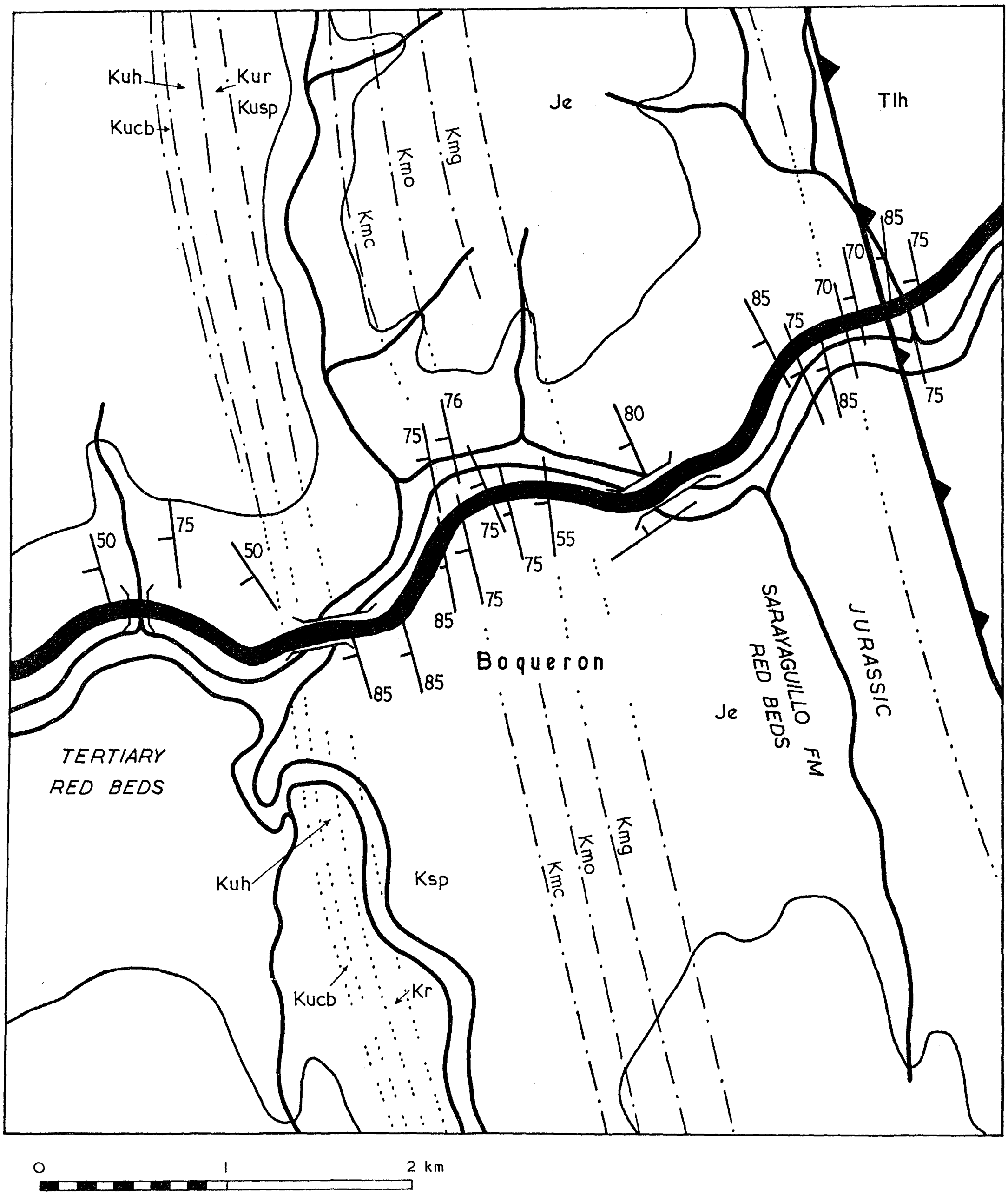


FIGURE 9. Geological sketch map of the section at Boqueron.

compared with the well-established Cretaceous (120 Ma) palaeomagnetic pole deduced from studies of the Serra Geral formation (Creer 1962*b*) at 78° S, 54° E with c.s.d. = 17° and c.s.e. = 3°.

### 2.4. *Tertiary formations*

Tertiary sediments were collected from the section at Boqueron (sketch map in figure 9) and are described in table 6. (The Cretaceous–Jurassic samples from this locality had a mean intensity of only 1.5 $\mu$G and did not yield sensible results.)

The n.r.m. directions are illustrated in figure 10 where it is seen that when referred to the present horizontal, those from the normally magnetized group are scattered and not far from the axial dipole field direction while the reversely magnetized group of directions are more tightly grouped (figure 10*a*). In figure 10*b* these directions have been referred to the bedding. The remanence of the reversely magnetized specimens proved stable to thermal cleaning up to

Table 6. Samples of Tertiary-Jurassic age from Boqueron

| age | sample no. | locality | lithology | dip of beds | colour |
|---|---|---|---|---|---|
| Tertiary | 251–2 | 20 m from bridge near Boqueron on Tingo Maria side | hard poorly bedded mudstone | 70–80° at 260° | brownish black 5YR–2/1 |
| | 253–6 | just upstream from junction of rivers | m.-f.g. sandstone | 70–80° at 260° | greyish red 5R–4/2 to blackish red 5R–2/2 |
| | 257–8 | from quarry on left side of road, looking downstream | compact mudstone | 70° at 270° | pale red 5R–6/2 |
| Jurassic-Cretaceous | 241–244 | on left hand side of river (K) | f.-m.g. sandstone | 70–80° at 260–270° | pale red 5R–6/2 |
| | 245–249 | just before bridge (J) | f.-m.g. sandstone | 70–80° at 260–270° | greyish orange pink 5YR–7/2 |
| | 250 | just over bridge (J) | f.-m.g. sandstone | 70–80° at 260–270° | pale red 5R–6/2 |

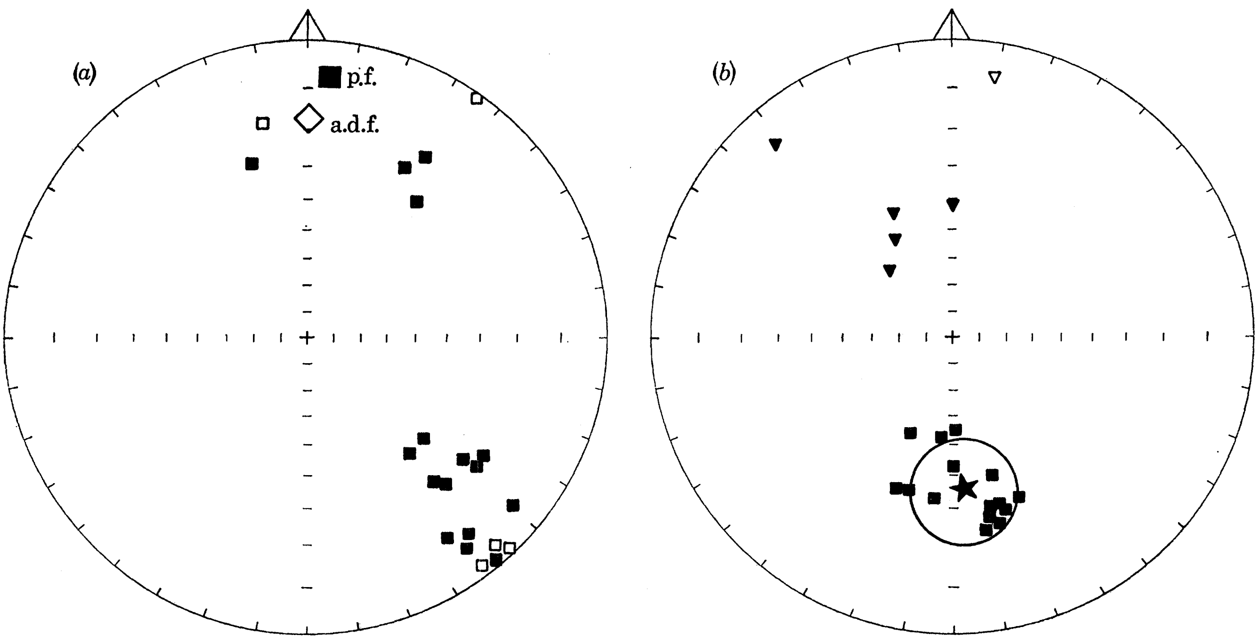


Figure 10. N.r.m. directions of Tertiary sediments from Boqueron (*a*) referred to the present horizontal and (*b*) to the bedding planes.

600 °C while that of the normally magnetized samples migrated into the reversed group as shown in figure 11. However, the best estimate of the Tertiary field is considered to be that given by the n.r.m. of the reversely magnetized specimens (figure 10*b*), because its mean does not migrate significantly during cleaning while the c.s.d. increases. The mean direction and south virtual geomagnetic pole for this formation is given in table 7.

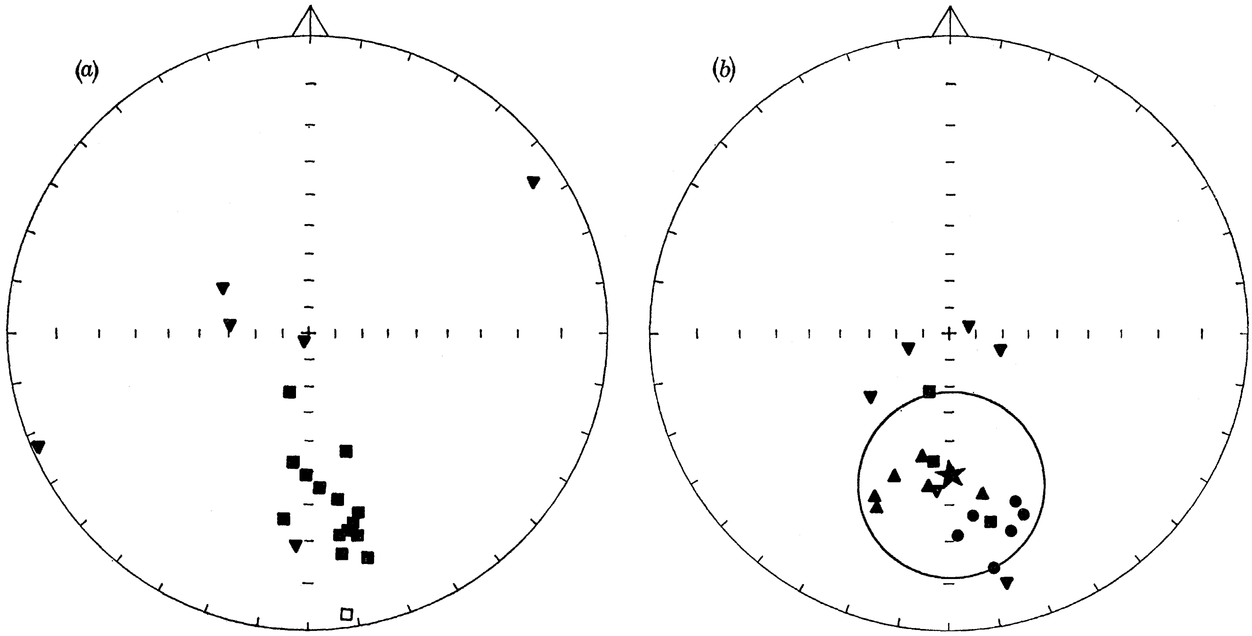


FIGURE 11. Cleaned r.m. directions of the Tertiary sediments from Boqueron, (*a*) and (*b*) as for figure 10.

TABLE 7. TERTIARY AT BOQUERON

| group of specimens | number of specimens | direction of r.m./degree *D* | *I* | $\delta$ | $\delta_m$ | south virtual pole lat. | long. | $\delta$ | $\delta_m$ |
|---|---|---|---|---|---|---|---|---|---|
| n.r.m. of reversed (stable) group | 15 | 176 | +36 | 16 | 4 | 79° S | 58° W | 14 | 6 |
| selected, cleaned (figure 11*b*) | 21 | 179 | +39 | 28 | 6 | 75° S | 74° W | 31 | 7 |

## 3. CONCLUSIONS

The Tertiary mountain building movements which created the Andean cordillera have made the palaeomagnetic record in most of the rock formations studied quite complex. Thus the Pennsylvanian Ambo group appear to have been originally magnetized in the Permo-Carboniferous geomagnetic field as deduced from palaeomagnetic studies on rock formations from outside the cordillera (table 1, p. 553), and then partly remagnetized after folding in the Tertiary geomagnetic field. Similarly, the Mitu group appears to have been magnetized originally in the Triassic and then partly remagnetized after folding.

Various Cretaceous formations yield palaeomagnetic data which warrant further study. Tertiary sediments from Boqueron yield good palaeomagnetic data for that period and appear to have been magnetized before folding. It is noted that they were collected from the eastern flank of the cordillera at low altitude and this may explain why they appear to have escaped remagnetization which the rocks collected from the central cordillera underwent.

## 4. Acknowledgements

The geological field work was planned after extensive discussions with Dr J. A. Broggi, who at that time was Chairman of the International Geophysical Year Committee for Peru, and also with Dr V. Benavides. A Landrover was provided by the I.G.Y. organization and driven by Dr Broggi's son. Thanks are also expressed to the mining companies at Cerro de Pasco and La Oroya who allowed us to use company accommodation during the field work.

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