

Palaeomagnetism and K-Ar Ages of the South-west African Basalts and their Bearing on the Time of Initial Rifting of the South Atlantic Ocean

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(Received 1975 January 15)‡

Summary

Palaeomagnetic and isotopic results from the Kaoko lavas, Hoachanas basalts and dolerite sills of South-West Africa indicate that the Upper Triassic–Lower Jurassic Stormberg flows of South Africa may have extended into SW-Africa and that younger igneous events of Lower Cretaceous age were simultaneous with the Serra Geral volcanism in Brazil. Five analyses on three samples of the Keetmanshoop sills gave K-Ar ages between 178 ± 4 and 199 ± 4 Ma, four analyses of two samples of the Hoachanas basalts gave ages between 161 ± 3 and 173 ± 2 Ma and eight analyses of five samples of Kaoko basalt gave ages between 110 ± 4 and 128 ± 2 Ma.

The components of remanent magnetization (RM) used to compute palaeomagnetic pole positions for the Kaoko lavas (48° N, 93° W, $A95 = 3^\circ$) and for the Hoachanas basalts (61° N, 106° W, $A95 = 7^\circ$) are stable to alternating field (AF) and thermal demagnetization.

Correlation on a pre-drift map and on a map reconstructed for 112 Ma BP (before present) between the palaeomagnetic poles from the Kaoko and Serra Geral lavas suggests that the South Atlantic had not opened appreciably by 112 Ma BP. Cretaceous pole positions for S. America and Africa on a map reconstructed for 80 Ma BP are also discussed.

1. Introduction

The Mesozoic lava fields in South-West Africa, which comprise the Kaoko lavas in the north and the Hoachanas lavas in the south, were originally correlated with the Triassic Stormberg lavas of the Karroo system. Siedner & Miller (1968) however obtained a major peak of potassium–argon ages between 114 and 136 Ma for the Kaoko lavas and dolerites in the northern part of South-West Africa (Fig. 1). This is about 50 Ma younger than the Karroo lavas and dolerites exposed in the south-east of Africa (McDougall 1963; Snelling 1966; Snelling & Rex 1967; Manton 1968).

The Kaoko basalts of the Etendeka plateau are flat-lying and the absence of erosion horizons has been taken to infer that they were poured out rapidly without significant interruption (Haughton 1969). Melfi (1967) made the same observation

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‡ Received in original form 1974 October 11.

regarding the Serra Geral basalts from the Parana Basin, Brazil, and Amaral *et al.* (1966) found a steady increase in activity with time starting at about 140 Ma ago, reaching a peak at 120 Ma and then sharply declining after 115 Ma. This correlation in age of the Kaoko with the Serra Geral basalts is of interest because the sites of these two lava fields must have been adjacent before the South Atlantic was opened out and this might imply that originally they formed parts of the same lava field. How the Hoachanas basalts fit into the picture is not known.

Hence it was decided to study the palaeomagnetism and geochronology of the South-West African basalts and dolerites to compare the directions obtained with palaeomagnetic directions from the Serra Geral Formation (Creer 1962) in order to further contribute to our knowledge of the early stages of drifting apart of South America and Africa.

2. Geological environment of palaeomagnetic sites

Palaeozoic and Mesozoic strata of South-West Africa consist mainly of rocks that have been correlated with the Karroo system in the Republic of South Africa. The Permo-Carboniferous glacial and fluvio-glacial Dwyka beds in northern South West Africa occur as infillings in pre-Dwyka valleys and in the southern Kaokoveld are unconformably overlain by the aeolian Etjo Sandstone (Martin 1972). These in turn underlay the thick pile of Kaoko lavas that form the Etendeka plateau. A very hard and massive rhyolite constitutes the highest preserved rock, but most of the remaining flows either have an andesitic or basaltic composition. These rarely exceed 50 m in thickness and commonly contain amygdalae at the top or base. Fig. 1 shows the location of 49 sites collected from the Kaoko lavas of the Etendeka plateau. A total of 118 hand-samples, 99 short-cores and 9 deep-cores were collected. 'Short-cores' were drilled with a McCulloch hand-drill and 'deep-cores' with the drill equipment belonging to the Bernard Price Institute of Geophysical Research (Graham & Keiller 1960), the latter rig being capable of obtaining oriented cores down to 1 m depth in solid rock.

The Dwyka beds occurring in the southern part of South-West Africa have a glacio-marine origin having accumulated in an embayment which was open to the west (Martin & Wilczewski 1970; Martin, Walliser & Wilczewsia 1970). In the Kub-Hoachanas basin they are overlain by the Hoachanas lavas (Fig. 2) which have been eroded down to a flat landscape in contrast with the Kaoko lavas. The lava flows (a thickness of 360 m has been penetrated by a bore hole) overlie different units of the Dwyka Series with a pronounced regional disconformity. Subsidence has been accompanied by some faulting along north-south striking faults in the vicinity of the Fish River and to the east of Hoachanas (Martin, private communication). The Hoachanas basalts were sampled at 3 sites (95, 96 and 97, Fig. 2) all located in road cuttings respectively 19, 26 and 27 km north of Mariental. Two deep-cores and one or two hand-samples were collected from each site.

In the Keetmanshoop area the Dwyka beds are intruded by probably not more than two dolerite sills which appear at different stratigraphic levels (Martin, private communication). Sites 90 and 91 are situated respectively 42 and 8 km north of Keetmanshoop, while sites 92 and 93 lie along the road to Koes respectively 16 and 51 km NE of Keetmanshoop (Fig. 2). A sampling scheme similar to that for the Hoachanas lavas was adopted.

3. Remanent magnetization

One-inch cylindrical specimens were cut from the samples collected in the field and the natural remanent magnetization (NRM) measured initially with an astatic

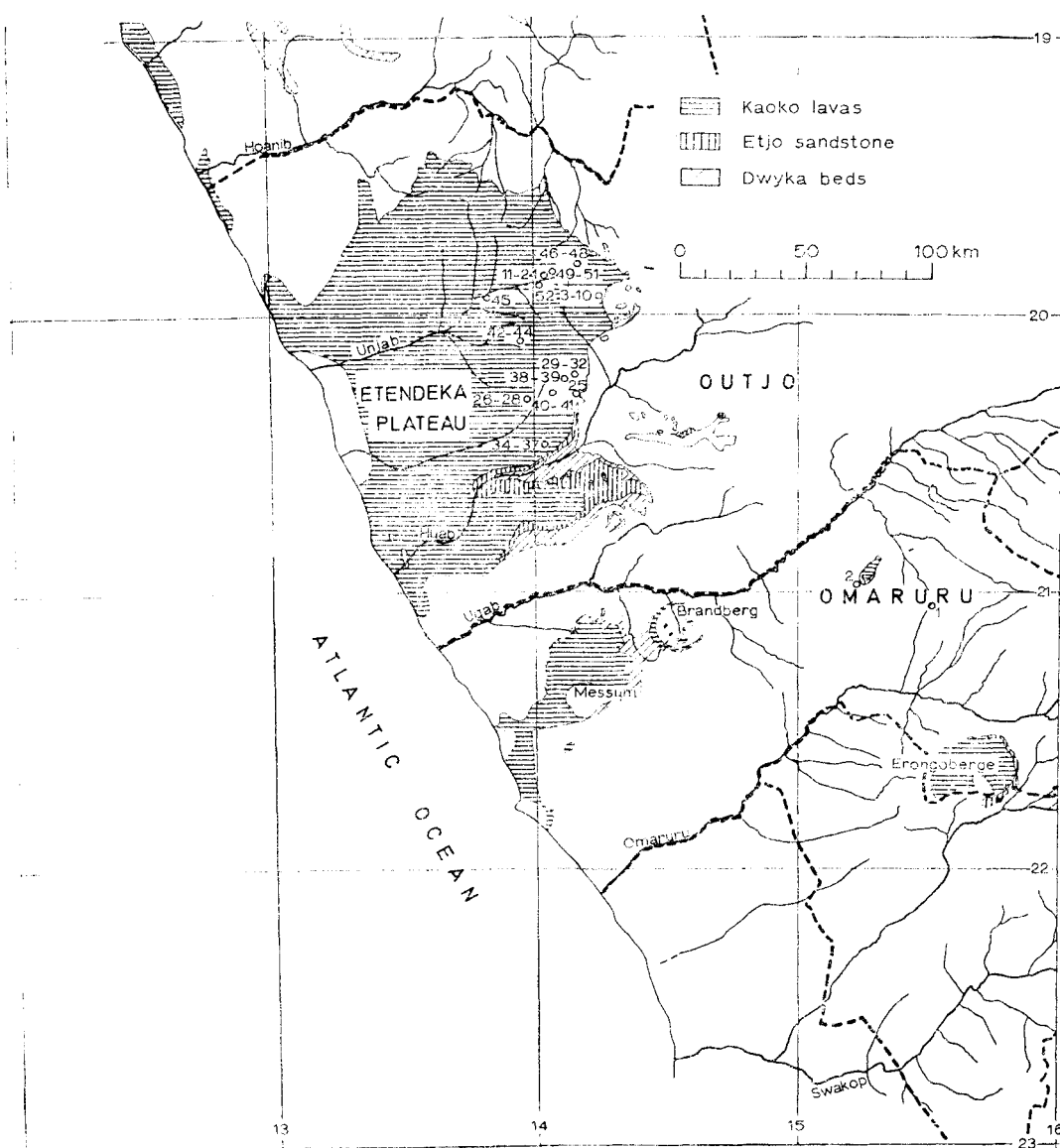


FIG. 1. Location of sites collected from the Kaoko Lavas of the Etendeka plateau.

magnetometer and subsequently with a 'Digico' fluxgate magnetometer. The specimens were then subjected to either alternating field or thermal demagnetization. We shall deal with the results from the Kaokoveld, and Hoachanas and Keetmanshoop areas separately.

3.1 *Kaoko Lavas*

Detailed demagnetization was carried out on different groups of pilot specimens. One set of thirty-nine specimens, all cut from hand-samples, were progressively cleaned in a series of steps up to 850 Oe for the magnetically hardest rocks. In the initial stages

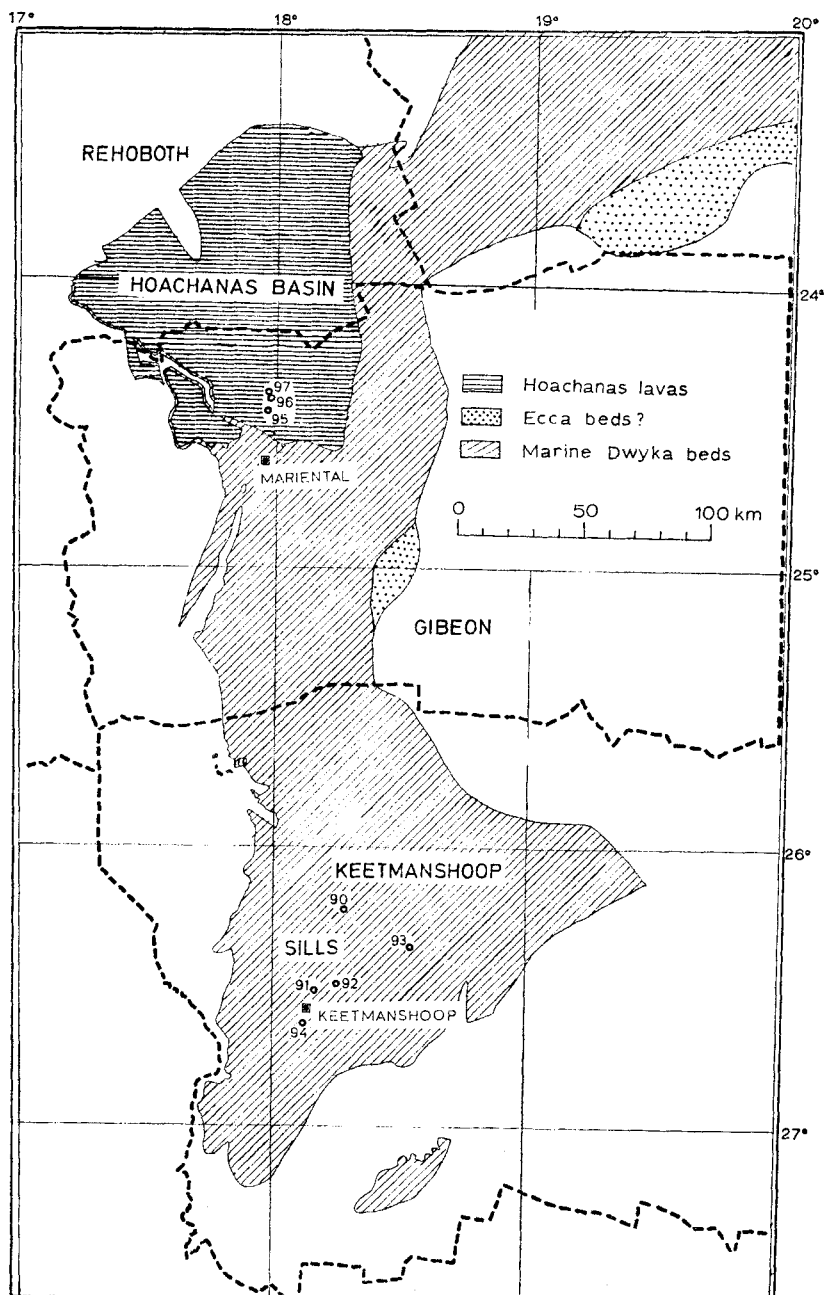


FIG. 2. Location of the sites sampled from the Hoachanas Basalts and Keetmanshoop Sills.

50 Oe steps were used, but larger steps were applied for higher field strengths. A 'Digico' spinner magnetometer was used to measure the treated remanent magnetization. Computer graphics, examples of which are given in Figs 3 and 4, were

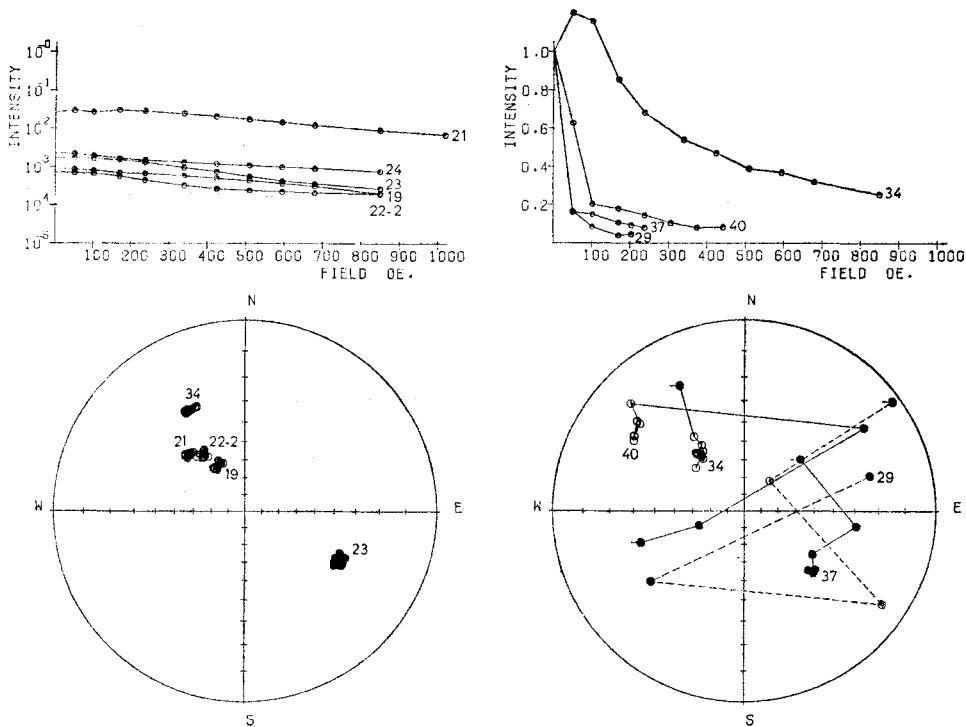


FIG. 3. AF demagnetization results for specimens with stable magnetization. Intensity (in gauss) plotted on a logarithmic scale. Labels refer to sites in Fig. 1.

FIG. 4. AF demagnetization results for specimens with a component of soft magnetization. Normalized intensity plotted. (—) marks NRM direction. Labels refer to sites in Fig. 1.

produced for each specimen (Gidskehaug 1975a). The plots obtained suggested that the specimens could be divided into 3 groups on the basis of directional behaviour: (a) no change, (22 specimens); (b) shift towards a fixed axis, (15 specimens) and (c) random changes, (2 specimens).

Two indices of stability were computed: (i) the sum of the angular deviations; and (ii) the sum of the RM vector differences between successive demagnetization steps. The former showed no correlation with NRM intensity (correlation coefficient, $R = -0.03$) while the latter was highly correlated ($R = +0.99$). On the other hand the former parameter was strongly correlated with the absolute value of the initial slope of the normalized AF demagnetization curve ($R = +0.64$). The latter is immediately apparent from the figures. For the stable specimens of group (a), the change in intensity rarely amounted to more than 10 per cent after the first demagnetization step (50 Oe), while those placed in groups (b) and (c) had shown changes in intensity up to 80 per cent. This behaviour was confirmed by experiments on specimens from 42 'short' cores, cleaned in eight steps up to 500 Oe. Hence the first demagnetization step provides a good indication of a specimen's response to further magnetic cleaning or of how to continue the stability test.

Most specimens of Kaoko lava remained stable to thermal demagnetization up to 500 °C, though above 550 °C RM directions generally changed randomly. A few specimens exhibited a marked drop in intensity at steps below 200 °C. Examples of thermal demagnetization curves are shown in Figs 5 and 6. A positive correlation was

again noted between the initial slope of the demagnetization curve and the sum of the vector differences produced by each step in another population of thirty-nine specimens subjected to stepwise thermal demagnetization.

After cleaning, 84 per cent of the stable specimens of Kaoko lava were found to have *normal* magnetization. Mean directions computed for the populations of specimens with normal and reversed polarity were almost anti-parallel. Computer graphics of the cleaned RM directions at specimen, sample and site levels are shown in Fig. 7. Reversed sample-mean and site-mean directions have been rotated into the normal sense in these plots. Statistical parameters for the data of Fig. 7 are shown in Table 1. The distributions were shown to be Fisherian by goodness-of-fit tests. The palaeomagnetic south pole is positioned within a few degrees of 48° S 87° E and the palaeolatitude of the Etendeka Plateau is 26° S as compared to the present geographical latitude of about 20° S.

A two-tier analysis (Watson & Irving 1957) yielded a between-site dispersion $KB = 77.4$ and circular standard deviation $S63 = 9.2^\circ$. The test variable F conforms to an F -distribution if the different sites have the same precision parameter $KW = 72.8$, $S63 = 9.5^\circ$ and the value of $F(= 3.77)$ for 78 (between sites) and 156 (within sites) degrees of freedom suggests that a between-site effect really exists. Palaeosecular variation is likely to be the main cause because the lava beds are remarkably horizontal and tectonic tilting can therefore be ruled out.

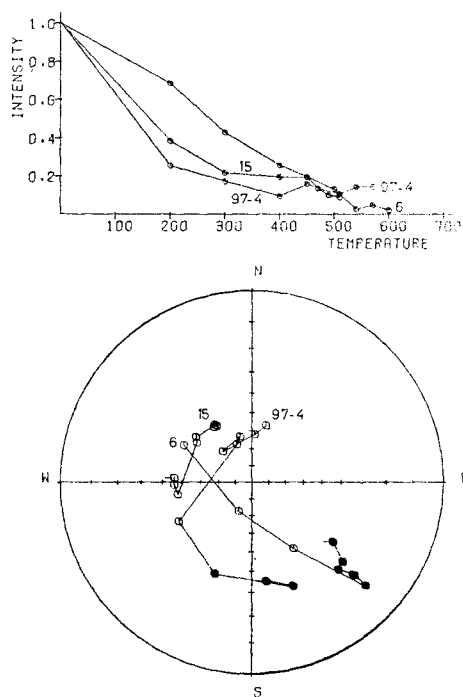
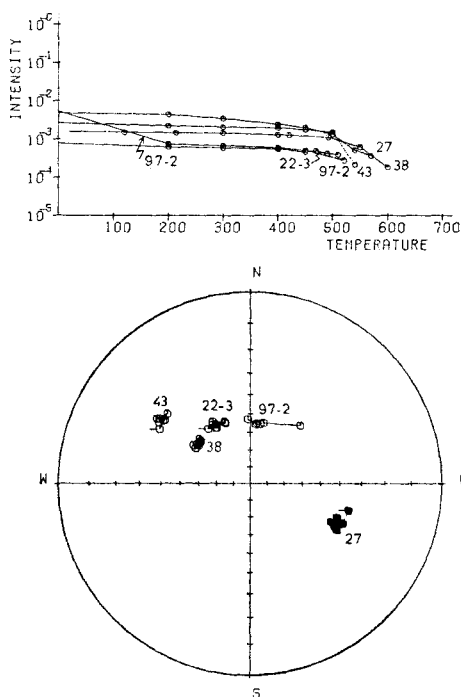


FIG. 5. Thermal demagnetization results for specimens with stable RM. Intensity (in gauss) plotted on a logarithmic scale. (—) marks NRM directions. Labels refer to site localities in Fig. 1.

FIG. 6. Thermal demagnetization results for specimens with unstable RM. Normalized intensity plotted. (—) marks NRM directions. Labels refer to site localities in Figs 1 and 2.

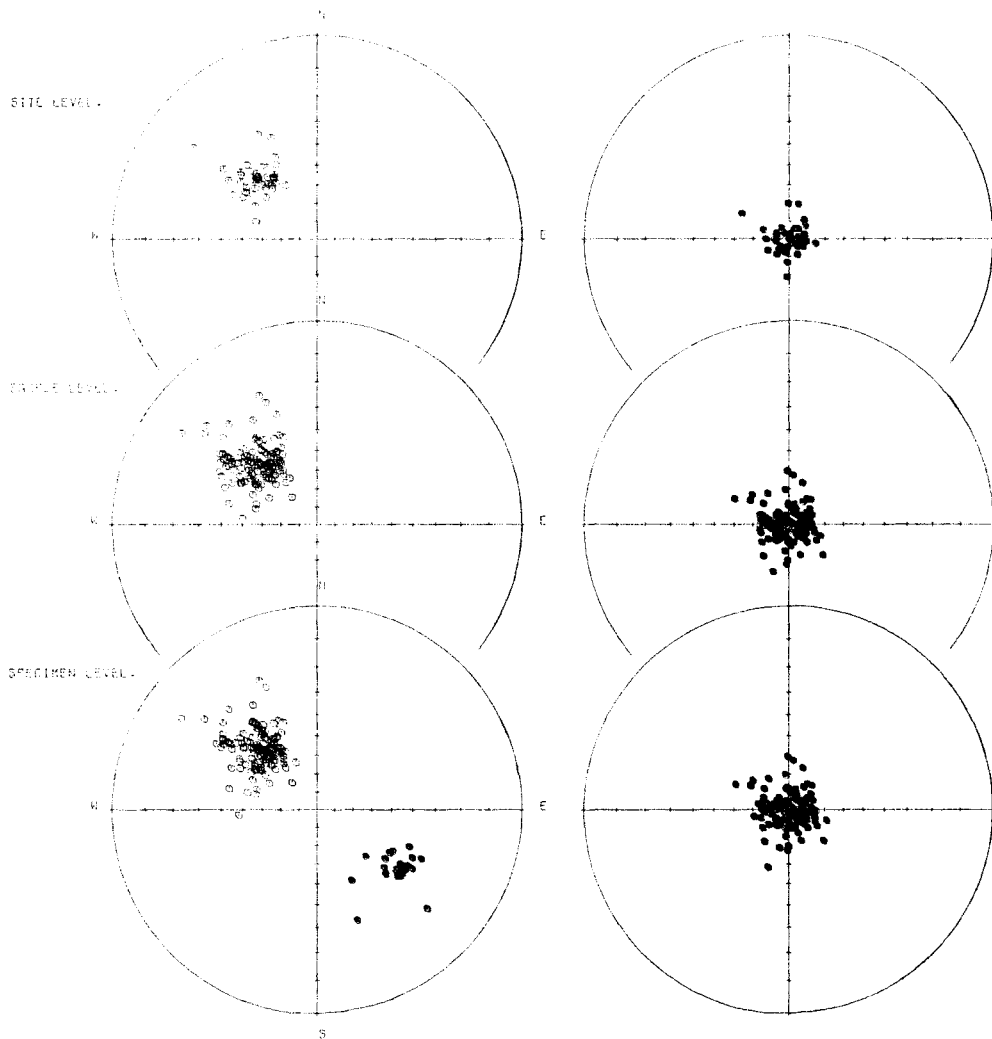


FIG. 7. Computer graphics of the distribution of directions of magnetization of the Kaoko Lavas. Reversed site-mean and sample-mean directions have been rotated into the normal sense so as to show the shape of the populations more clearly. The stereograms on the right are centred on the mean direction of each population.

3.2 Hoachanas Basalt and Keetmanshoop Sills

Forty-six specimens of Hoachanas basalts and Keetmanshoop sills, mainly from deep cores, were AF demagnetized in steps up to 450 Oe.

The directions of all the specimens from site 95 (Fig. 2) remained stable within a tight group toward which the cleaned directions for sites 96 and 97 converged. The cleaned directions obtained from hand-samples agreed well with those obtained from deep cores. At high demagnetizing field strengths, RM directions of specimens from site 96 changed erratically.

Thermal cleaning caused a reduction in intensity to 20 per cent of the natural value after heating to 400 °C for sites 95 and 96 and after heating to 200 °C for site 97.

Table 1
Statistics of the observed distribution of RM directions and VGP's obtained from the Kaoko Lavas

| <i>N</i> | <i>R</i> | <i>K</i> | <i>S</i> 63 (°) | <i>A</i> 95 (°) | <i>D</i> M (°E) | <i>I</i> M (°) | <i>P</i> LAT (°S) | <i>L</i> at. (°N) | <i>L</i> ong. (°E) | <i>V</i> GP Long. (°E) | <i>E</i> P (°) | <i>E</i> M (°) |
|-----------------------|------------|----------|--------------------|--------------------|--------------------|-------------------|----------------------|----------------------|-----------------------|------------------------------|-------------------|-------------------|
| 143 specimen D & I | 139·261400 | 38·0 | 13·1 | 1·9 | 314·4 | -43·7 | 25·5 | 47·8 | 267·5 | 1·5 | 1·5 | 2·4 |
| 118 sample-mean D & I | 114·912829 | 37·9 | 13·1 | 2·1 | 314·8 | -44·0 | 25·8 | 48·2 | 267·2 | 1·7 | 1·7 | 2·7 |
| 40 site-mean D & I | 39·267676 | 53·3 | 11·1 | 3·1 | 315·0 | -44·5 | 26·2 | 48·3 | 266·6 | 2·5 | 2·5 | 3·9 |
| 143 specimen VGP's | 139·109962 | 36·5 | 13·4 | 2·0 | — | — | — | 47·9 | 266·7 | — | — | — |

N = number of unit vectors; *R* = length of resultant; $K = (N-1)/(N-R)$ = precision parameter; *S*63 = circular standard deviation; *A*95 = radius of circle of confidence at 5 per cent significance level; *D*M, *I*M = declination and inclination of mean vector; *P*LAT = palaeolatitude; *E*P, *E*M = semi-minor and semi-major axes of VGP oval of confidence at 5 per cent significance level.

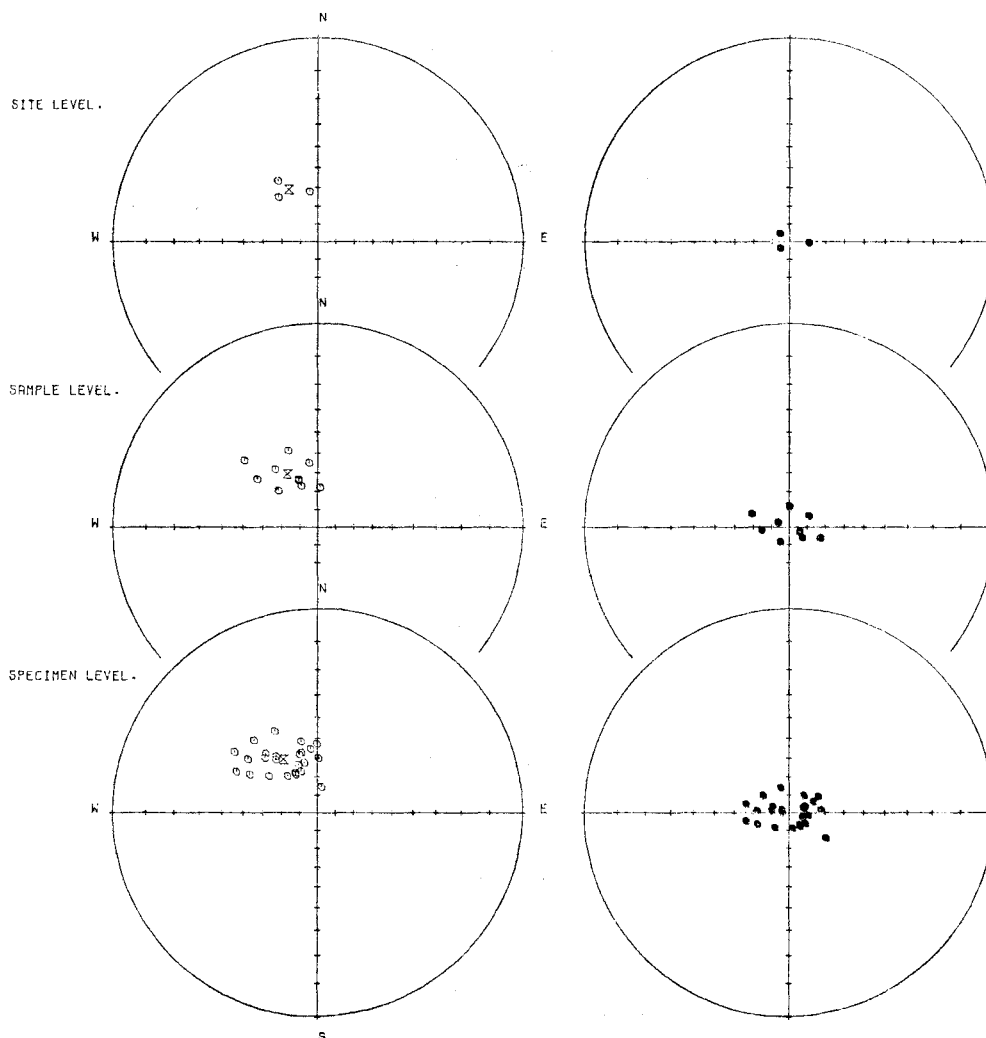


FIG. 8. Computer graphics of the distribution of magnetization of the Hoachanas Basalts. The stereograms on the right are centred on the mean direction of each population.

The directions converged towards the group obtained by AF cleaning where they remained stable at temperatures up to at least 450 °C.

Computer graphics at specimen, sample and site levels are shown in Fig. 8. The corresponding statistical data are given in Table 2. The palaeomagnetic south pole is near 61° S, 74° E and the palaeolatitude of the Hoachanas Basin at 36° S, as compared with the present latitude of about 24° S. An *F*-test indicates that no physical significance (at 1 or 5 per cent levels) can be attached to estimates of between and within site scatter.

No consistent results were obtained for the Keetmanshoop sills.

4. K-Ar age determination

Ten of the freshest hand-samples were selected for potassium-argon age determina-

Table 2
Statistics of the observed distribution of RM directions and VGPs obtained from the Hoachanas Basalts. Estimate of overall distribution with unit weight on respectively, specimens, samples and sites

| <i>N</i> | <i>R</i> | <i>K</i> | <i>S63</i> (°) | <i>A95</i> (°) | <i>DM</i> (°E) | <i>IM</i> (°) | <i>PALAT</i> (°S) | <i>VGP</i> | | | <i>EM</i> (°) |
|----------------------|----------|-----------|-------------------|-------------------|-------------------|------------------|----------------------|------------|------|------|------------------|
| | | | | | | | | (°E) | (°N) | (°) | |
| Specimen D & I | 24 | 23·234375 | 30·0 | 5·5 | 327·9 | −55·8 | −36·3 | 257·0 | 60·0 | 5·6 | 7·9 |
| Sample-mean D & I | 10 | 9·745746 | 35·4 | 8·2 | 330·6 | −56·9 | −37·4 | 253·5 | 61·8 | 8·7 | 12·0 |
| Site-mean D & I | 3 | 2·967855 | 62·2 | 15·8 | 331·0 | −57·5 | −38·1 | 251·9 | 61·9 | 16·9 | 23·1 |
| Mean values of poles | | | | | | | | | | | |
| Specimen VGPs | 24 | 22·794251 | 19·0 | 7·0 | — | — | — | 254·3 | 60·6 | — | — |

Key as for Table 1.

tions: five from Etendeka, two from Hoachanas and three from the Keetmanshoop sill. The ages obtained are presented in Table 3 and fall within the range of ages found by Siedner & Miller (1968). Potassium was determined by flame photometry and argon by isotope dilution using an Omegatron mass spectrometer. The average of the ages obtained for the Kaoko lavas from the Etendeka plateau is 118 ± 4 Ma. A sill associated with these lava flows gave significantly younger ages than the flows and younger than any of the ages estimated by Siedner & Miller (1968). However, alkaline intrusions of this age are found near the Brazilian coast (Amaral *et al.* (1967)).

The average age of the lavas of the Hoachanas Basin is 168 ± 5 Ma and that of the Keetmanshoop sills 185 ± 5 Ma. These ages correspond to those of the igneous activity in the south east part of southern Africa and are of importance for the discussion of the palaeomagnetic results.

Thus K–Ar dating confirmed the Early Cretaceous age for the Kaoko lavas, while the Hoachanas lavas and Keetmanshoop sills gave an Early Jurassic age. Accordingly the Mesozoic lavas in SW Africa appear to belong to two different successions which can be correlated with the Karroo and Serra Geral basalts, respectively. The view may therefore come into force again that vast lava piles of Stormberg age were emplaced in all of southern Africa and that remnants of this field have been preserved from erosion in the Kub–Hoachanas Basin. Dolerite dykes in the Damara igneous province of Late Triassic–Early Jurassic age seem to support this idea (Siedner & Miller 1968).

5. Opaque and magnetic mineralogy

5.1 Ore microscopy

One or more polished sections from each site were examined under the ore microscope. The main ore content of the rock comprises titanomagnetite and free ilmenite grains to the extent of a few per cent. Most of the larger titanomagnetite grains contain ilmenite granules of sandwich, internal or external type as defined by Buddington & Lindsley (1964). The co-existing α and β phases were microprobed. An equilibrium temperature of between 600 °C and 800 °C and an oxygen fugacity of between 10^{-16} and 10^{-12} atmospheres were obtained for the granular texture. A fuller description of the ore mineralogy will be given by Gidskehaug (1975b).

Thermomagnetic analyses were made on samples representative of all sites. A histogram of the Curie points measured on the heating curves is given in Fig. 9. The three thermomagnetic curves shown in Fig. 10 are for site 21 where samples labelled 1, 2 and 3 were taken in that order from what at first appeared to be a single lava flow in a dry river bed. Sample 1 contained 1- to 10- μ m diameter titanomagnetite grains, sample 2 contained devitrified glass but no visible ore grains and sample 3, while similar to sample 1, contained some larger grains up to 30- μ m diameter. The curves for samples 1 and 3 show some characteristic properties of the Kaoko basalt: (i) the Curie points on heating are somewhat higher than 575 °C while those measured on cooling are significantly lower, and (ii) the room-temperature saturation magnetization is lowered as a result of the heating. These two observations suggest that an initially oxidized titanomagnetite phase breaks down into haematite and another (possibly oxidized) titanomagnetite richer in titanium than the parent phase. Sample 2 has a lower Curie point on heating than samples 1 and 3 but that on cooling is about the same while the room-temperature saturation magnetization after heating is greater than the natural value. Some heating curves show an inflexion or a knee at about 400 °C which disappears on heating at a fixed temperature of 260 °C for a few hours. A possible explanation is that an initial (possibly slightly oxidized) titanium-rich spinel phase becomes more oxidized on heating.

Table 3
Potassium-argon ages measured in this study

| Place | | Sample No. | K ₂ O% | V/M | A.C. | Age Ma |
|----------------------|------|------------|----------------------------|--|--------------|--------------------|
| Etendeka plateau: | lava | AG 11-2 | 1.57, 1.56 Mean 1.57 | (6.28 ± 0.10)10 ⁻³ (6.12 ± 0.11)10 ⁻³ | 35.8 42.9 | 117 ± 2 114 ± 2 |
| | lava | AG 12-2 | 1.86, 1.86 Mean 1.86 | (7.73 ± 0.08)10 ⁻³ (7.92 ± 0.10)10 ⁻³ | 22.5 22.0 | 122 ± 2 125 ± 2 |
| | lava | AG 38-6 | 1.495, 1.485 Mean 1.49 | (5.55 ± 0.17)10 ⁻³ (5.45 ± 0.25)10 ⁻³ | 68.5 80.5 | 110 ± 4 107 ± 4 |
| | lava | AG 38-4 | 7.75, 7.76 Mean 7.76 | (3.39 ± 0.05)10 ⁻² (3.15 ± 0.05)10 ⁻² | 11.7 7.9 | 128 ± 2 119 ± 2 |
| | sill | AG 13-2 | 0.736, 0.728 Mean 0.732 | (2.33 ± 0.03)10 ⁻³ (2.31 ± 0.05)10 ⁻³ | 53.0 51.1 | 94 ± 2 93 ± 3 |
| Hoachanas: | | 96-4 | 0.792, 0.812 Mean 0.802 | (4.67 ± 0.08)10 ⁻³ (4.80 ± 0.06)10 ⁻³ | 39.7 27.7 | 168 ± 3 173 ± 2 |
| | | 97-4 | 0.809, 0.792 Mean 0.801 | (4.45 ± 0.07)10 ⁻³ (4.76 ± 0.06)10 ⁻³ | 32.9 31.9 | 161 ± 3 171 ± 0 |
| Keetmanshoop: | | AG 91-3 | 0.663 | (4.09 ± 0.07)10 ⁻³ (4.19 ± 0.07)10 ⁻³ | 45.5 45.9 | 178 ± 4 182 ± 4 |
| | | AG 92-3 | 0.654, 0.640 Mean 0.647 | (4.13 ± 0.05)10 ⁻³ (4.50 ± 0.07)10 ⁻³ | 35.0 33.7 | 184 ± 3 199 ± 4 |
| | | AG 93-3 | 0.570, 0.573 | (3.64 ± 0.05)10 ⁻³ | 49.4 | 183 ± 3 |

V/M is the radiogenic argon-40 content of the sample in mm³ l⁻¹ at NTP per gram.
AC is the atmospheric contamination.

Constants: $\lambda_\beta = 4.72 \cdot 10^{-10} \text{ yr}^{-1}$
 $\lambda_\alpha = 0.585 \cdot 10^{-10} \text{ yr}^{-1}$
 $^{40}\text{K}/\text{K} = 1.19 \cdot 10^{-2} \text{ atom per cent.}$

Samples from the Keetmanshoop sills typically give thermomagnetic curves similar to that of sample 2 above.

6. Relevance of this result to the time of opening of the South Atlantic

Geological and geophysical evidence relating to the time of opening of the South Atlantic may be summarized as follows.

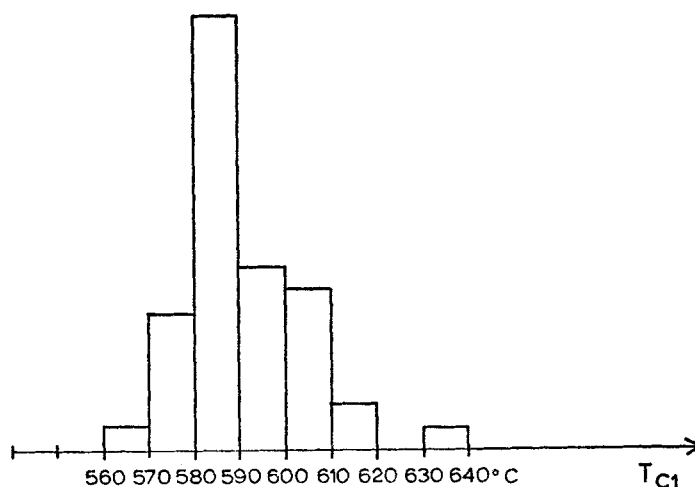


FIG. 9. Histogram of Curie temperatures obtained on heating specimens of Kaoko Lava.

(i) A sequence of north-west trending magnetic anomalies in the Cape Basin indicates that sea floor spreading occurred from 127 to 110 Ma BP at a rate of 1.6 cm yr^{-1} . They may be correlated with anomalies identified in the Argentine Basin (Larson & Ladd 1973).

(ii) Previously, Larson & Pitman (1972), who had not recognized the Cape Basin anomalies had concluded that spreading started at 110 Ma BP and proceeded at a rate of 5 cm yr^{-1} until 85 Ma BP. Larson & Ladd (1973) have amended this rapid spreading rate to 4.5 cm yr^{-1} .

(iii) The oldest magnetic lineations (127 Ma BP) are in agreement with the ages of the Serra Geral and Kaoko basalts.

(iv) A widespread marine transgression recorded in the Valanginian (127–124 Ma BP) in the southern parts of Africa, Argentina and Chile may be taken to mark the time when drifting started (Rayment & Tait 1972a). Larson & Ladd (1973) suggest that this was a consequence of the pattern of early drifting.

(v) Biostratigraphic studies of Lower Cretaceous formations have led Rayment & Tait (1972b) to conclude that only a narrow sea-way caused by occasional inundations separated Africa from South America in the Upper Albian.

Against this background, we should expect to find that the palaeomagnetic poles for (a) the Chon Aike Formation and Hoachanas basalts, and (b) the Serra Geral Formation and the Kaoko basalts should respectively coincide when plotted on a pre-drift map. That this is in fact so is illustrated in Fig. 11 where the data presented in Table 4 are plotted. The pole for the Hoachanas basalts (#1) is separated from that for the Chon Aike Formation (#2) by only 5° which is less than A95, the radius of the 95 per cent circle of confidence, of either. These poles are situated some 20° away from the poles for the Kaoko basalts (#3), the Serra Geral (#4) and Cerro Colorado Formations (#5). The angular separation of pole #3 from #4 is about 10° . These two poles may be brought into closer proximity by using a reconstruction made for 112 Ma BP by Le Pichon & Hayes (1971) whose rotation of -4.6° about a pole at $21.5^\circ \text{ N } 14^\circ \text{ W}$ has been used to draw Fig. 12. Our new palaeomagnetic result for the

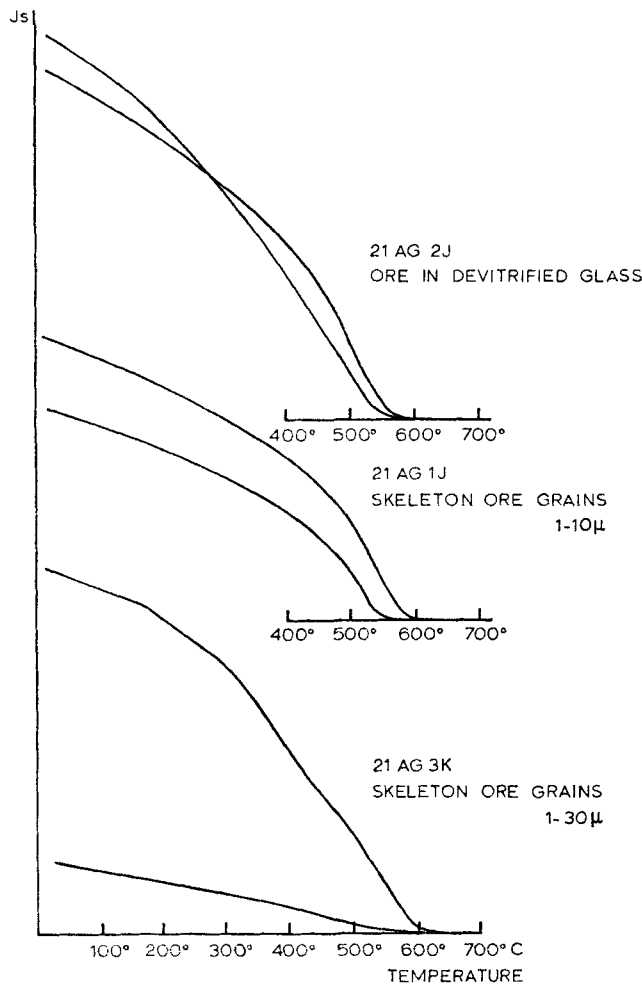


FIG. 10. Examples of thermomagnetic curves. Samples are all from site 21. Specimens 1J, 2J and 3K are referred to as #1, 2 and 3, respectively, in the text.

Kaoko lavas thus suggests that a little relative movement between South America and Africa had taken place in the direction of the initial sea-floor spreading at the time of emplacement which is, however, slightly earlier than the suggested date of the reconstruction (112 Ma BP).

A problem arises, however, when we consider the position of the palaeomagnetic poles for the Lower Cretaceous Lupata Volcanics and Mlanje Massif. These poles (Table 4) are located within a few degrees of one another and the relevant data may be combined to yield the single pole, #8 which we note is situated some 16° distant from pole #3 for the Kaoko basalts, also Early Cretaceous in both Fig. 11 (pre-drift) and Fig. 12 (112 Ma BP). This problem is resolved if we suppose that pole #8 is younger than pole #3. The difficulty about this concerns one of the two K-Ar ages (116 ± 6 and 128 ± 6 Ma) assigned to the Mlanje Massif palaeomagnetic samples by Briden (1967), but we note that the older of these was measured on a sample collected some 19 km east of the Lauderdale Crater where the palaeomagnetic samples were

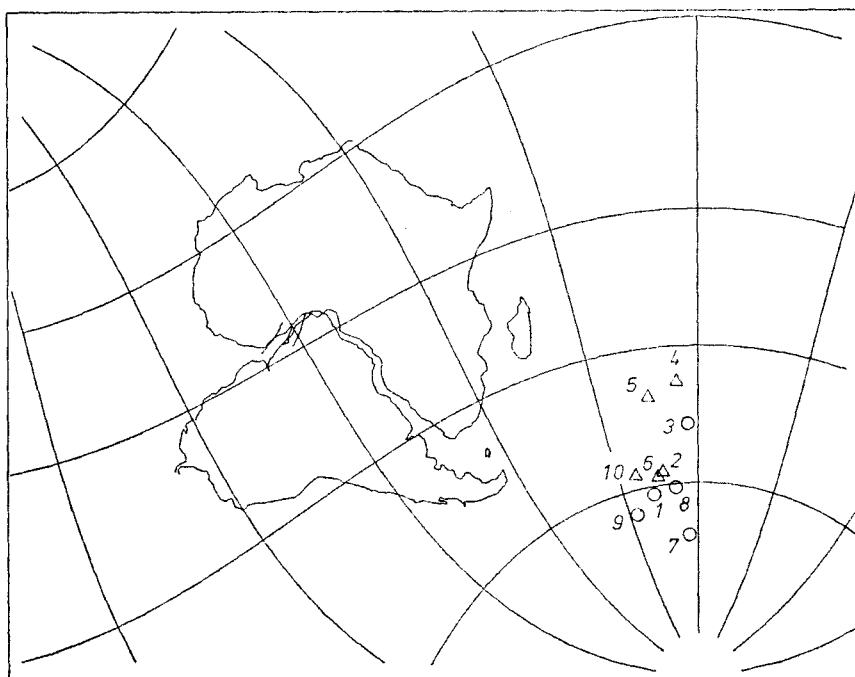


FIG. 11. Comparison between African and South American Jurassic and Cretaceous palaeomagnetic poles illustrated on the pre-drift map with Africa occupying its present geographic position. Key: pole #1 = Hoachanas, #2 = Chon Aike, #3 = Kaoko, #4 = Serra Geral, #5 = Cerro Colorado, #6 = Pocos de Caldos, #7 = Karroo, #8 = Lupata and Mlanje, #9 and #10 = Mean Triassic poles for Africa and S. America respectively. Fuller details are given in Table 4. (Rotation of S. America = -57° about pole at 44° N 30.6° W).

collected and we are therefore not convinced that the radiometric age applies to the palaeomagnetic data. Hence we feel justified in proceeding with supposition that pole #8 is in fact slightly younger than pole #3.

Thus, the apparent polar wander curve relative to Africa may exhibit an excursion to the north (relative to the grids of Figs 11 and 12) which occurred at an as yet undetermined rate at some time between 160 and 130 Ma BP approximately (i.e. after the time of emplacement of Hoachanas and Chon Aike lavas and prior to that of the Kaoko, Serra Geral and Cerro Colorado formations, returning to the area occupied through the Triassic and Jurassic within a brief interval between the time of emplacement of the Kaoko basalts and the Lupata volcanics, circa 110 to 115 Ma BP. Pole #7, for the Karroo dolerites and Stormberg lavas and pole #9, a mean for African Triassic formations, are also shown in Fig 11. We do not yet have a sufficiently good time coverage to answer the question as to whether the apparent polar wander path relative to South America exhibits a similar excursion in the same time interval. The northward shift is evident between poles #2 and #4. But what of the return southward shift? The position of pole #6 for the Pocos de Caldas Formation indicates that it had occurred by 80 Ma BP but by this time the South Atlantic had attained an appreciable width so that the reconstruction of Fig. 12 is no longer valid.

Poles for the Cretaceous are plotted on a reconstruction for 80 Ma BP (about

Table 4
Jurassic and Cretaceous palaeomagnetic poles for South America and Africa

| Label | Age | Formation | Site location | | Lat. | Pole position | | Rotated pole position | | Polarity | Ref. |
|-------|---|------------------------|---------------|-------|------|---------------|-------|-----------------------|------|----------|------|
| | | | Lat. | Long. | | Lat. | Long. | A95 | Lat. | | |
| | (Ma) | | (°S) | (°E) | (°S) | (°E) | (°) | (°S) | (°E) | | |
| (A) | South-West Africa and Eastern South America | | | | | | | | | | |
| 1. | 161-173 | Hoachanas (SWA) | 24 | 18 | 62 | 72 | 7 | — | — | N | 1 |
| 2. | 157-173 | Chon Aike (Arg.) | 45 | 294 | 82 | 231 | 12 | 58 | 77 | M | 2 |
| 3. | 110-128 | Kaoko (SWA) | 20 | 14 | 48 | 87 | 2 | — | — | M | 1 |
| 4. | 115-130 | Serra Geral (Brz.) | 25 | 310 | 78 | 54 | 4, 7 | 46 | 85 | M | 3 |
| 5. | 118 ± 6 | Cerro Colorado (Arg.) | 32 | 296 | 81 | 14 | 13 | 42 | 75 | R | 4 |
| 6. | 63-80 | Pocos de Caldas (Brz.) | 22 | 313 | 81 | 233 | 8, 13 | 58 | 76 | M | 5 |
| (B) | South-eastern part of Africa | | | | | | | | | | |
| 7. | 154-190 | Karoo (Rho., RSA) | 25 | 30 | 69 | 83 | 8 | — | — | M | 6 |
| | | Stromberg (RSA) | 30 | 29 | 71 | 89 | 15 | — | — | M | 7 |
| 8. | 106-111 | Lupata (Moz.) | 17 | 34 | 62 | 80 | 3, 5 | — | — | N | 8 |
| | 116-128 | Mlanje (Mal.) | 16 | 36 | 60 | 82 | 12 | — | — | N | 9 |
| 9. | Triassic | Africa | — | — | 65 | 63 | — | — | — | — | — |
| 10. | Means | S. America | — | — | 79 | 260 | — | 57 | 66 | — | 10 |

Footnote to Table 4

Key to references:

Key to country of origin: 1 = this paper; 2 = Creer *et al.* (1972), Valencio & Vilas (1970); 3 = Creer (1962); 4 = Valencio (1972); 5 = Opdyke & MacDonald (1973); 6 = entry 051, and 7 = entry 050 in Hicken *et al.* (1972); 8 = Gough & Opdyke (1963); 9 = Briden (1967); 10 = Creer *et al.* (1970). SWA = South-West Africa; Arg. = Argentina; Brz. = Brazil; RSA = Republic of South Africa; Rho. = Rhodesia; Moz. = Mozambique; Mal. = Malawi.

Polarity: N = normal, R = reversed, M = mixed.

Additional notes: Values given are to nearest degree, site location co-ordinates are those of centre of region sampled.

Rotation parameters:

- (i) From present to pre-drift position: rotate through -57° about a pole at 44° N 30.6° W (Bullard *et al.* 1965).
(ii) From the pre-drift configuration to that estimated for 112 Ma BP: rotate through -4.6° about a pole at 21.5° N 14° W (Larson & Ladd 1973).

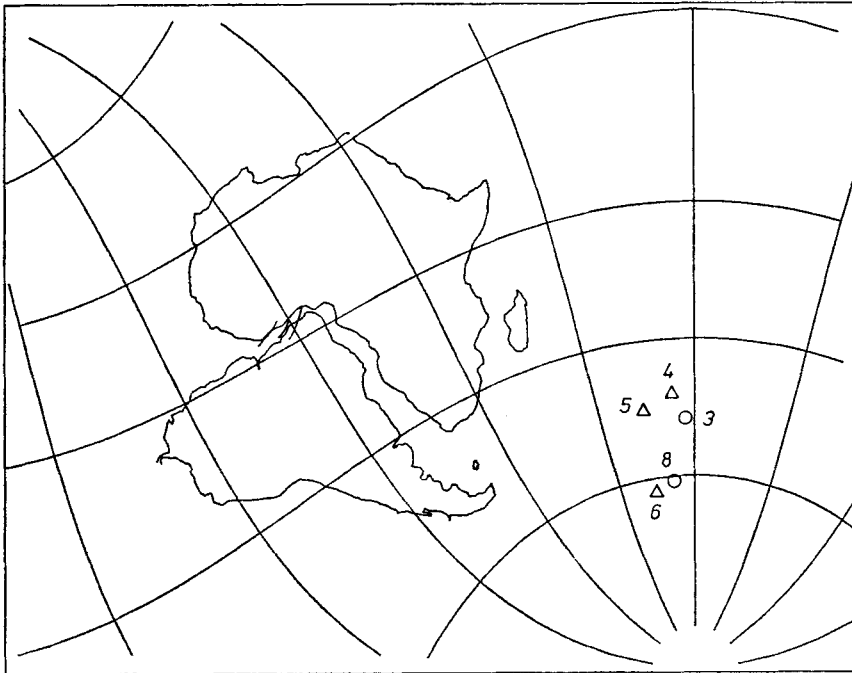


FIG. 12. Comparison of African and South American Cretaceous palaeomagnetic poles on map reconstructed for 112 Ma BP. Key as in Fig. 11 and Table 4. Africa in its present position. Rotation of S. America = -4.6° about pole at 21.5° N 1.4° W from pre-drift position relative to Africa.

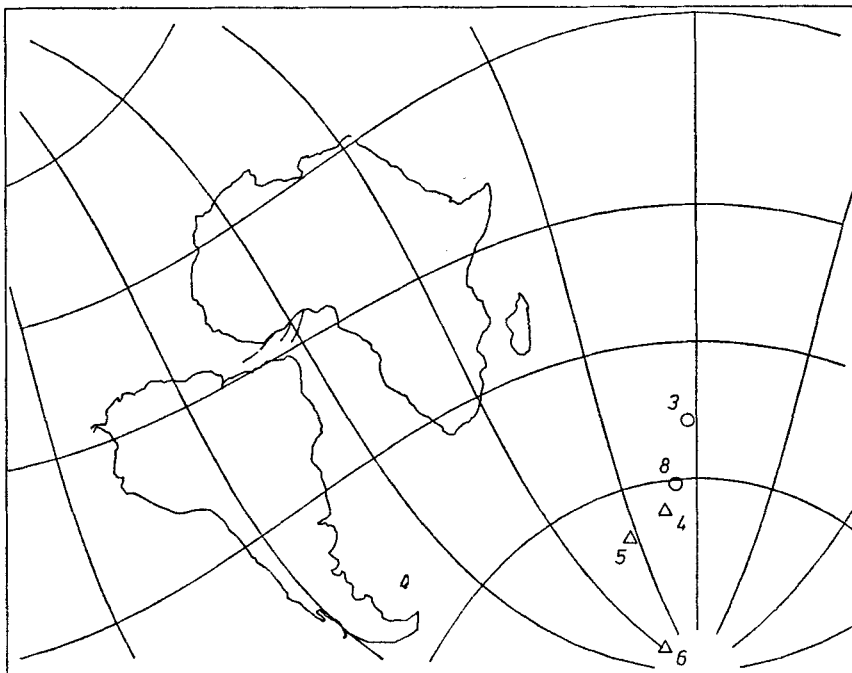


FIG. 13. Comparison of Africa and South American Cretaceous palaeomagnetic poles on map reconstructed for 80 Ma BP. Key as in Fig. 11 and Table 4. Africa in its present position. Rotations of S. America = -32.8° about a pole at 67.3° N, 39.5° W.

a pole situated at 67.3° N, 39° W, Francheteau 1970) in Fig. 13. The older pole #3 (for S.W. Africa) is now seen to be displaced from poles #4 and #5 (for S. America) as one would expect. No palaeomagnetic poles have as yet been obtained for the top of the Upper Cretaceous for Africa. The closest to that age is pole #8 for the Lupata Volcanics (106 Ma BP). For South America we have pole #6 for the Pocos de Caldas Formation (63–80 Ma BP). Assuming the validity of the reconstruction of Fig. 13, the 80 Ma BP pole for Africa should lie in the vicinity of pole #6 in this figure, a general inspection of which gives one a feeling for the time-density of palaeomagnetic data necessary to make an independent check of the sequence of sea-floor spreading reconstructions that can be made through the Late Mesozoic and Tertiary.

Acknowledgments

The field work was carried out in cooperation with the Bernard Price Institute of Geophysical Research, University of the Witwatersrand, Johannesburg. The research was funded in part by the UK Natural Environment Research Council (NERC) and Dr Louis Nicolaysen of BPI kindly authorized Dr Hugh Bergh and a field assistant to take part in the project and for us to use the BPI drilling equipment. The Geological Survey of South Africa provided a vehicle and a geologist and field assistant to help and advise with the field work. Mr A. Gidskehaug received grants from the Royal Society of London and later from the Norwegian Research Council for Science and the Humanities which enabled him spend two years at the University of Newcastle where much of the work was carried out. The final stages of data processing were undertaken at the University of Bergen. The financial, professional and technical help provided by the above organizations and institutes is gratefully acknowledged. Part of the collection made during the field trip is being studied by Dr Hugh Bergh who will publish the results later.

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