Geophysical Interpretation of Palaeomagnetic Directions from Great Britain

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VI. GEOPHYSICAL INTERPRETATION OF PALAEOMAGNETIC DIRECTIONS FROM GREAT BRITAIN

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The relation of this survey of the palaeomagnetism of the geological column in Great Britain to the problems of polar wandering and continental drift is discussed. Reference is made to similar results in the U.S.A. which show that the hypothesis of polar wandering explains the results obtained. There is also evidence for a relative movement of 1000 miles between America and Europe since Triassic times. The results also provide further evidence for reversals of the geomagnetic field.

CONTENTS

1. Introduction

In the preceding papers it has been shown that magnetically stable rocks of several geological formations in Great Britain possess uniform directions of remanent magnetization. These directions persist over great distances and stratigraphical thicknesses in rocks of the same geological period, but vary in different parts of the geological column.

Local magnetic anomalies, or, in the special case of sediments, stream directions and wave action through tides or prevailing winds, may possibly occasionally influence magnetization. However, magnetic anomalies which cause appreciable field distortion of the order of 10° are rare because ferromagnetic minerals account for only a fraction of 1 % of the earth's crust. Similarly, mechanical orientation is effective only on those iron oxide grains which are elongated or discoidal. Especially in sandstones, such grains represent only a small fraction of those responsible for the magnetization. Since such local causes are not likely to be consistent in direction over considerable distances and times, it is concluded that the natural magnetizations are due to the main geomagnetic field.

2. Computation of pole positions

A mean position of the magnetic axis, relative to the site, is calculated for each geological period. The mean direction of magnetization for each sampling site is found as described in the preceding papers, thus eliminating errors due to the incorrect alinement of direction of the magnetization along the original field direction as well as those arising in the experimental measurements. Directions representing opposed fields are separated. The meaned site directions for a given period are then assigned unit weight and the mean taken. The latter is the mean palaeomagnetic direction for that geological period and the geomagnetic secular change is presumed to have been smoothed out. Errors in direction due to tectonic movements are eliminated by correcting for geological dip and by sampling from a large number of sites from a wide area. Errors due to the secondary components of magnetization are reduced if sites are taken where the rocks dip in different directions. By these methods polar wandering occurring during a geological period is also smoothed out, but with the present density of sampling it is not advisable to divide geological time into smaller units.

It is postulated that the mean magnetic field for each period is a geocentric dipole field. The pole position (θ, ϕ) for that period using present geographical co-ordinates is given by

$$\cos\theta = \cos\theta' \cos\psi + \sin\theta' \sin\psi \cos D, \tag{2·1}$$

$$\sin(\phi - \phi') = \sin D \sin\psi / \sin\theta, \tag{2·2}$$

where (θ', ϕ') is the site position. ψ, the magnetic colatitude, is the angular distance along the great circle from the site to the north magnetic pole and is given by

$$\cot\psi = \tfrac{1}{2}\tan I. \tag{2·3}$$

3. Precision of computed pole positions

Corresponding to directions within the cone of confidence described about the mean palaeomagnetic direction is a roughly oval area on the globe in which the true pole position lies with a 95 % probability. The semi-axes $(d\psi, d\chi)$ of this area along and perpendicular respectively to the meridian joining the site to the pole position may easily be calculated:

$$d\chi = \alpha \sin\psi / \cos I, \tag{2·4}$$

$$d\psi = \alpha \sin^2\psi / 2\cos^2 I = \tfrac{1}{2}\alpha(1 + 3\cos^2\psi). \tag{2·5}$$

This area, considered as the accuracy of the pole position determined, may be artificially small, if the rocks sampled represent only a small interval of time. This appears to account for the smallness of the areas for the Pre-Cambrian and Silurian based on the American measurements.

4. Hypothesis of polar wandering

Pole positions have been calculated from the results of the preceding papers for a number of geological periods from the Pre-Cambrian to the Triassic with respect to Great Britain and preliminary values were given by Creer, Irving & Runcorn (1954). Measurements from sites in the U.S.A., mainly on the Colorado plateau, by Runcorn (1955*b*, 1956*a*) Doell (1955) and Graham (1949, 1955) provide independent determinations of the pole positions, in many cases for the same geological periods. This comparison is shown in tables 1 and 2 and in figure 1, which is a polar stereographic projection of the northern hemisphere. Results from the work of others have also been used, the sources being indicated in the footnotes. The agreement is sufficiently good to prove that a movement of the magnetic pole over the earth's surface has occurred steadily since Pre-Cambrian times, although it appears probable that relative motion of the continents of North America and Europe has also occurred.

Table 1. Palaeomagnetic data for British rocks

period	formation	key to figure 1	direction of magnetization D_m	direction of magnetization I_m	α_m	κ_m	no. of sites	pole positions latitude	pole positions longitude	oval of confidence semi-major axis	oval of confidence semi-minor axis
Tertiary	Icelandic basalts (Miocene)	*M*	N 2° E	+78°	5°	57	5	89° N	5° E	10°	10°
	N. Ireland basalts (Eocene)	*E*	N 14° E	+60°	5°	—	—	74° N	133° E	8°	6°
Triassic*	Keuper sandstones	*Ʀ*	N 33° E	+26°	12°	18	9	43° N	131° E	12°	7°
Permian	Exeter Volcanic Series	*P*	S 9° W	−9°	20°	15	5	43° N	164° E	20°	10°
Carboniferous†	Coal Measures (Derbyshire)	*C*	N 26° E	+37°	—	—	—	48° N	138° E	—	—
Devonian	O.R.S. Lower and Upper	*D*	S 16° W	−5°	5°	19	35	30° N	159° E	5°	3°
Cambrian	Caerbwdy sandstone	*Є*	S 7° W	+39°	8°	32	10	15° N	173° E	10°	8°
Pre-Cambrian	Upper Torridonian sandstones	Pre-Є^3	N 57° W	−44°	5°	12	81	6° S	137° W	6°	4°
	Longmyndian	Pre-Є^4	N 66° W	−29°	12°	5	12	2° N	120° W	13°	7°
	Lower Torridonian sandstones	Pre-Є^2	N 53° W	+34°	7°	40	13	35° N	112° W	8°	5°

* Calculated from results of Clegg *et al.* (1954).

† Results obtained by J. C. Belshé to be published shortly (quoted by Runcorn 1955*a*).

Table 2. Palaeomagnetic data for American rocks*

period	formation	key to figure 1	direction of magnetization D_m	direction of magnetization I_m	α_m	κ_m	no. of sites	pole positions latitude	pole positions longitude	oval of confidence semi-major axis	oval of confidence semi-minor axis
Tertiary (1)	Columbia River lavas	*M*	N 6° E	+65°	9°	29	7	86° N	53° E	5°	4°
Cretaceous	Dakota sandstones	*K*	S 16° E	−62°	—	—	1	77° N	127° E	11°	9°
Triassic	Springdale sandstones	*Ʀ*	N 22° W	+16°	—	—	1	55° N	107° E	—	—
Permian	Supai shales‡ Doell(2)	*P*^{1}	S 34° E	+8°	7°	—	—	39° N	115° E	—	—
	Supai shales‡ Runcorn	*P*^{2}	S 47° E	+23°	8°	16	1	26° N	121° E	9°	5°
Carboniferous—Pennsylvanian	Naco sandstones	C_p	S 30° E	−3°	4°	40	1	41° N	120° E	4°	4°
Silurian (3)	Rose Hill, Maryland	*S*	N 38° W	−39°	5°	27	5	19° N	138° E	6°	4°
Pre-Cambrian	Hakatai shales Doell(2)	*A*^{1}	S 35° W	+76°	18°	—	1	21° N	130° W	—	—
	Hakatai shales Runcorn	*A*^{2}	S 88° W†	+73°†	5°	22	1	31° N	150° W	10°	9°
Pre-Cambrian (4)	Diabase dykes (Michigan)	Pre-Є	S 82° W	+86°	1°	82	2	45° N	99° W	2°	2°

(1) Campbell & Runcorn (1956)
(2) Doell (1955), but Hakatai shales result corrected for geological dip.
(3) Calculated from results of Graham (1949)
(4) Calculated from results of Graham (1953).

* Cambrian pole for America given by Day & Runcorn (1955) was based on inadequate data and is omitted here.

† Doell (1955) incorrectly states that these values are not corrected for geological dip.

‡ The results of Graham (1956) on the Permian of the western states of the U.S.A. are in reasonable agreement with these but cannot be treated by exact statistical methods as he does not give values of declination and inclination except on stereograms which are too small for the purpose.

Because the magnetic poles reverse, there are two possible positions for the north geographical pole for any geological period. Consequently the path of the pole of rotation is not unambiguous, but working back from its present position it is more reasonable to suppose that the north geographical pole moved into the north-west Pacific in Mesozoic times rather than into the south Atlantic. The path of this pole has been reconstructed in this way and is shown in figure 1. It is possible that between Torridonian and Cambrian times the pole may have moved into the west Pacific from East Africa rather than from the east Pacific; however, this will not be certain until the geological column has been sampled more closely.

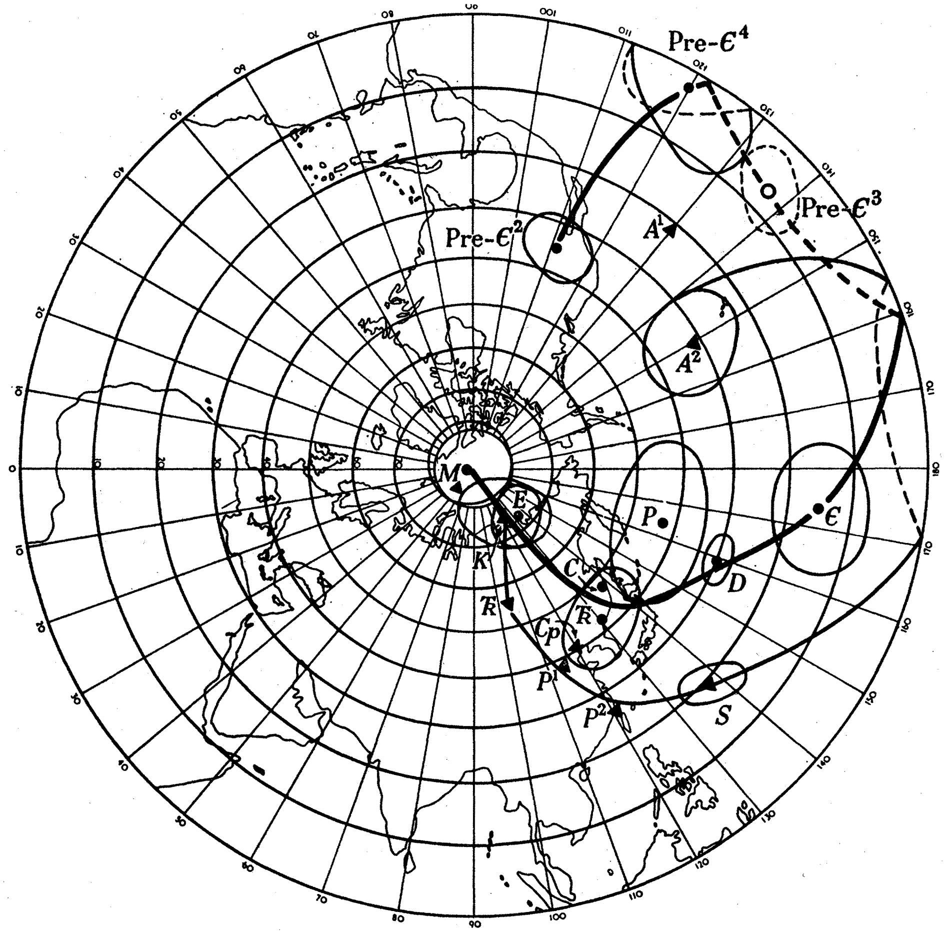


FIGURE 1. Pole positions and approximate path of north pole. ——●——, inferred from British rocks, plotted in northern hemisphere; — — ○ —, in southern hemisphere; ——▲——, inferred from American rocks, plotted in northern hemisphere; ----, in southern hemisphere.

Because the drift of the earth's magnetic axis is apparently slow, whereas reversals of polarity of the field are frequent in those parts of the geological column where they occur, it is reasonable to suppose that they arise from two distinct physical causes. Creer *et al.* (1954) proposed that the slow movement of the mean geomagnetic axis reflects a change of the axis of rotation with respect to the earth's surface. It is taken for granted that, apart from precession, the axis of rotation remains fixed in space. The coincidence of the mean magnetic and rotational axes is thought by Runcorn (1954, 1955*a*) to result from the dominance of the Coriolis force in the hydrodynamics of the earth's core. Another argument however, can be used to show that the assumption of this coincidence over geological time is reasonable. The earth's core, in which the magnetic field observed at the surface is generated, is known to be rotating more slowly than the mantle. At the present rate the core will make one retrograde revolution with respect to the mantle in about 2000 years. The coupling between the core and mantle is weak and appears to be largely electromagnetic. It cannot have changed by orders of magnitude in geological time, as rock magnetism data gives little suggestion of large changes in the intensity of the geomagnetic field. Consequently, even if a component of the field, which is not symmetrical about the axis of rotation, could be generated in the core for long periods, its effect at the earth's surface would be smoothed out in times of the order of many thousands of years by the relative rotation of mantle and core, for the integral around a line of latitude of any non-axial harmonic of the magnetic field is zero. This argument would of course have no force if any appreciable proportion of the geomagnetic field arose in the earth's mantle.

There seems, however, to be no theoretical reason to dismiss the possibility that over considerable periods of geological time the mean geomagnetic field might be an axial multipole orientated along the axis of rotation. In the case of a quadrupole field, the pole position relative to the site would be obtained using the formulae (2·1) and (2·2) with the following expression in place of (2·3):

$$\tan I = \cot \theta - \tfrac{1}{2} \tan \theta.$$

Such a quadrupole field would have steep angles of dip near the equator as well as the poles and over greater areas of the earth's surface than the dipole field. The reason for discounting this possibility is that there is no evidence for a quadrupole field in Tertiary times; which is many thousand times longer than the time constant of free decay of the geomagnetic field and the time of rotation of the fluid eddies in the core. During this time the mechanism of the production of the field, despite many reversals of its polarity, succeeds in maintaining an axial dipole field. It is therefore reasonable to suppose that this has been the situation for much of the earth's history. Moreover, an axial quadrupole field gives $D = 0$, so that this hypothesis alone does not help to explain the palaeomagnetic data.

In postulating the existence of extensive polar wandering, Creer *et al.* (1954) were aware that continental drift might be an alternative explanation of the results of palaeomagnetic surveys. Their view, however, was that polar wandering was the simpler hypothesis, involving fewer degrees of freedom than continental drift, and the one easier to reconcile with our present model of the earth. Since then discussions of the dynamics of polar wandering have been given by Gold (1955), Runcorn (1955*a*) and Munk (1956), who show that such wandering is not at variance with geophysical theory as had often been tacitly assumed. Kuiper (1943) and Vening Meinesz (1948) had earlier considered polar wandering to be dynamically possible. Continental drift, on the other hand, implies motion of the continents relative to the crust. This motion will involve flow in the upper parts of the basaltic substratum beneath the continental layer. The palaeomagnetic measurements primarily determine the colatitude of the site and its rotation relative to the axis of rotation. Thus it would be possible for the palaeomagnetic results in Great Britain to represent a drift and a rotation of Great Britain relative to the substratum. A similar drift and rotation would be necessary to explain the palaeomagnetic evidence from North America. It is, however, unlikely that the rate of continental drift of these two widely separated land areas would keep in step. The hypothesis of polar wandering is therefore a more satisfactory explanation. The rate at which this occurs, calculated from the American and British results, is shown in table 5 to be remarkably constant with time. This series of papers, therefore, is held to demonstrate the existence of polar wandering.

It is at the present uncertain whether the polar movement indicated in figure 1 is continuous or discontinuous, but the following points support the latter possibility. First, the change in magnetic direction at the top of the Diabaig group of the Torridonian, which has been referred to in a previous paper of this series, occurs quickly compared with the time of duration of the NW+ and NW−/SE+ directions below and above: the polar movement corresponding to this change is 48° (cf. figure 1), which appears to have occurred in a short time geologically speaking. Secondly, within any rock formation, such as say the Old Red Sandstone, there is no systematic variation in direction, the directions from different stratigraphical levels within the rock formation being arranged in what appears to be a random manner around the mean direction. This evidence is consistent with a discontinuous polar movement; that is, the pole has occupied a series of relatively stable positions, the movement from one stable position to another occurring comparatively rapidly.

5. Discrepancy between pole positions given by British and American rocks

Figure 1 shows that there exist certain discrepancies between the pole positions inferred from the permanent magnetization of British and American strata. Runcorn (1956*b*) and Irving (1956) have shown that the poles deduced from the American measurements are systematically to the west of those from the British measurements. Table 3 shows this most clearly. Four possible reasons for such a discrepancy will now be examined.

Table 3. Mean westward displacement of poles inferred from American strata from those inferred from British strata for corresponding geological periods

geological period	British formation	American formation	difference in longitude
Triassic	Keuper sandstones	Springdale sandstones	24°
Permian	Exeter volcanic traps	Supai shales	46°
Carboniferous	Millstone grit and coal measures	Naco sandstone	18°
Silurian	*	Rose Hill	25°
late Pre-Cambrian	Torridonian and Longmyndian	Hakatai shales	24°

* British value obtained by interpolation between Cambrian and Devonian results.

(*a*) *Error in angle of inclination*

During sedimentation elongated or discoidal ferromagnetic particles will tend to settle horizontally rather than along the field direction. As these particles will tend to be magnetized along their long axes this will result in the angle of inclination (I) of the remanent magnetization being less than the angle of inclination of the field by a small angle $\mathrm{d}I$. If the field is horizontal or vertical there should be no discrepancy. King (1956) has demonstrated this effect by redepositing varve clays in different fields in the laboratory and has given a formula for the effect. Runcorn (1955*a*) has given a similar formula based on very general assumptions which will also apply to the case of compaction. If f is a factor depending on the fraction of flattened grains and the likelihood of their assuming a horizontal position, then

$$\tan I = f \tan(I + \mathrm{d}I), \tag{4·1}$$

or

$$\tan \mathrm{d}I = (1/f - 1)/[\cot I + (1/f) \tan I]. \tag{4·2}$$

Such a discrepancy may exist if the natural magnetization is depositional in character and will be revealed if lavas and sediments of similar age are available for measurement. Our experience is that it is not large for fine-grained sandstones.

The effect of these deviations on the calculated pole positions is easily seen. An error $\mathrm{d}I$ in the angle of inclination gives rise to an angular error in the pole position of $(\sin^2 \psi/2 \cos^2 I)\, \mathrm{d}I$ along the great circle joining the site and the pole position. Correction for this effect involves moving the geomagnetic equator, determined from the mean palaeomagnetic direction, away from the site.

Because the measurements are largely based on sediments of similar lithology, it is reasonable to assume that any systematic errors between the palaeomagnetic directions and the geomagnetic fields at the time of magnetization due to errors in inclination can be determined from equation (4·2) using the same value of f. Runcorn (1956*b*) shows that these displacements do not remove the discrepancy between the poles based on results from the two continents.

(*b*) *Secondary component of magnetization*

A stable secondary component may arise by the remagnetization of any low Curie point constituents after heating, due perhaps to deep burial, or through chemical magnetization during diagenesis. The high Curie points and unaltered state of the rocks chosen has probably made this unlikely. Of more importance is the component of isothermal remanent magnetization (i.r.m.) acquired along the direction of the mean field during Quaternary times since the last geomagnetic reversal. This component will be along that of a dipole field orientated along the present axis of rotation, but in any rock series all the specimens may not be affected to the same degree. Consequently the directions of remanent magnetization lie in a plane containing the direction of the original magnetization and the present dipole direction, the distribution of the representative points of the directions of magnetization on the projection showing a tail. This is explained in detail by Creer in the preceding paper and examples are also given in the second paper of this series and by Runcorn (1956*a*).

As dipole fields add vectorially, the effect of secondary magnetization is to move the computed pole along the great circle joining the pole of the original magnetic field and the pole of the field corresponding to the secondary magnetization. Thus inadequate allowance for i.r.m. causes an error in the latitude of the computed pole but not in its longitude. Correction for the effect of i.r.m. consists therefore in moving the north magnetic pole, determined from the mean palaeomagnetic direction, away from the present north geographical pole.

Since the first palaeomagnetic collection from Arizona was made, the results of which have been described by Runcorn (1955*b*, 1956*a*), the Supai formation has been examined independently by Doell (1955) and by Graham (1955). These three sets of results are compared in table 4. The longitudes of the pole positions inferred for the same rock series by the different authors agree more closely than the latitudes, as is shown in figure 1, thus demonstrating the result of an isothermal remanent magnetization by the present dipole field.

Table 4. Comparison of palaeomagnetic measurements in Arizona

author	formation	D	I	α	pole position	
Runcorn	Supai shales	S 47° E	+23°	8°	26° N	121° E
Doell	Supai shales	S 34° E	+8°	7°	39° N	121° E
Graham*	Supai shales	—	—	—	41° N	117° E

* Mean of poles from six sites plotted in figure 6 of Graham (1955)

Where such a component is large, the mean direction of magnetization cannot be used to determine the ancient pole position. But where laboratory experiments of the kind described by Creer in the preceding paper show such a component to be fairly small compared with the primary one, the pole position has been calculated. The above difficulty only arises in a rock series having one polarity. If both occur then a correction is unnecessary. As the components of such an i.r.m. in the one group is compensated by those in the other, the effect is eliminated when the mean axis of magnetization is determined.

(*c*) *Differences in age and correlated formation*

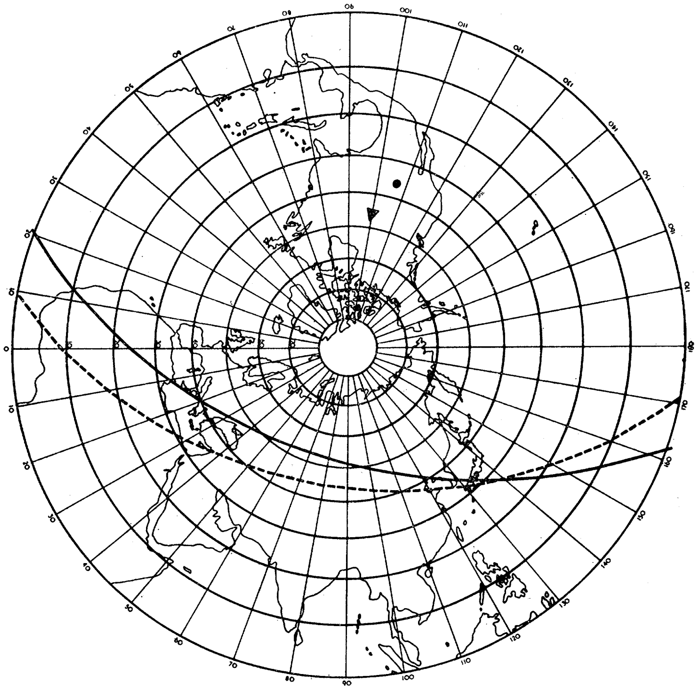
The discrepancies could be due to polar wandering alone if the path of the pole has not been a smooth curve and if it moved through about 20° within one geological period. It cannot be supposed that the correlations are correct to better than 20 million years in post-Cambrian times and 100 million in Pre-Cambrian times. However, this would suppose that the American strata sampled each happened to represent a time when the pole was on a westward swing. This seems unlikely. On the other hand, random differences in pole positions for rocks from corresponding geological periods could be so explained. The large discrepancy found in the Permian rocks may result from this cause.

(*d*) *Continental displacement*

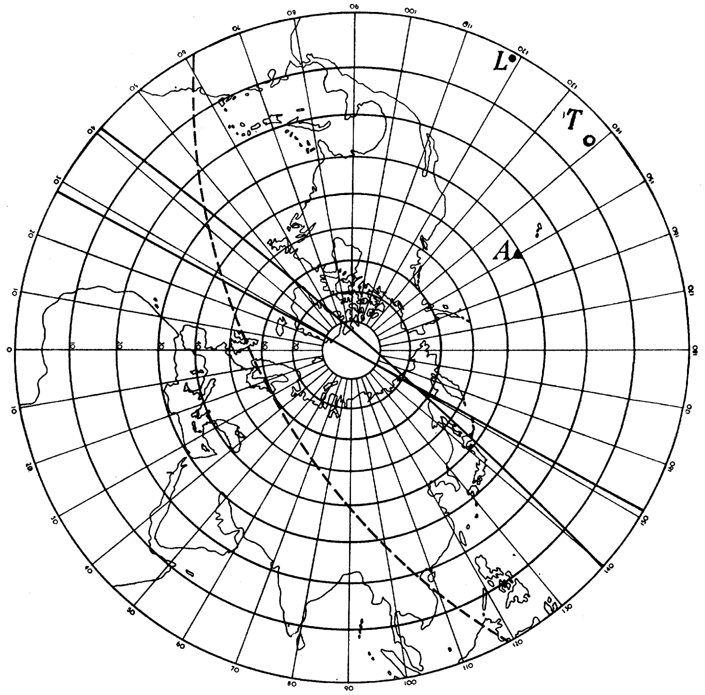
The discrepancy may mean that in pre-Jurassic times Europe and North America were several thousand miles closer than they are to-day. Such a displacement is considerably larger than those which are thought to have occurred in a single land mass during mountain building processes and is described in the literature as continental displacement or drift. In view of the unsatisfactory nature of the other explanations it is postulated that in Palaeozoic and early Mesozoic times Europe and North America were very much closer together, and at some time prior to the mid-Tertiary they moved apart to their present positions.

6. COMPARISON OF PALAEOMAGNETIC AND GEOLOGICAL EVIDENCE RELATING TO POLAR WANDERING AND CONTINENTAL DISPLACEMENT

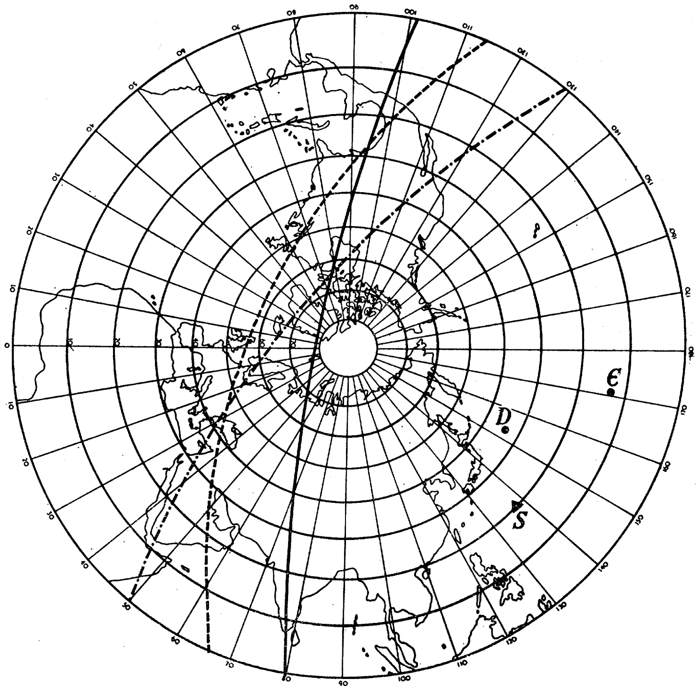
Some geologists have long entertained the possibilities of the hypotheses by which we explain the results of these palaeomagnetic surveys. Köppen (1940) and Bain (1953) postulated polar wandering to explain the fact that in certain geological periods, notably the



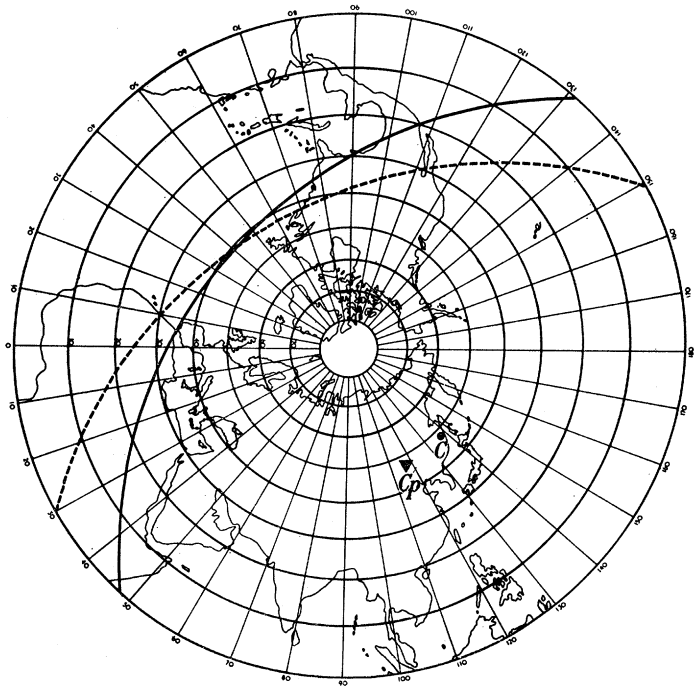
(*a*) Earlier Pre-Cambrian



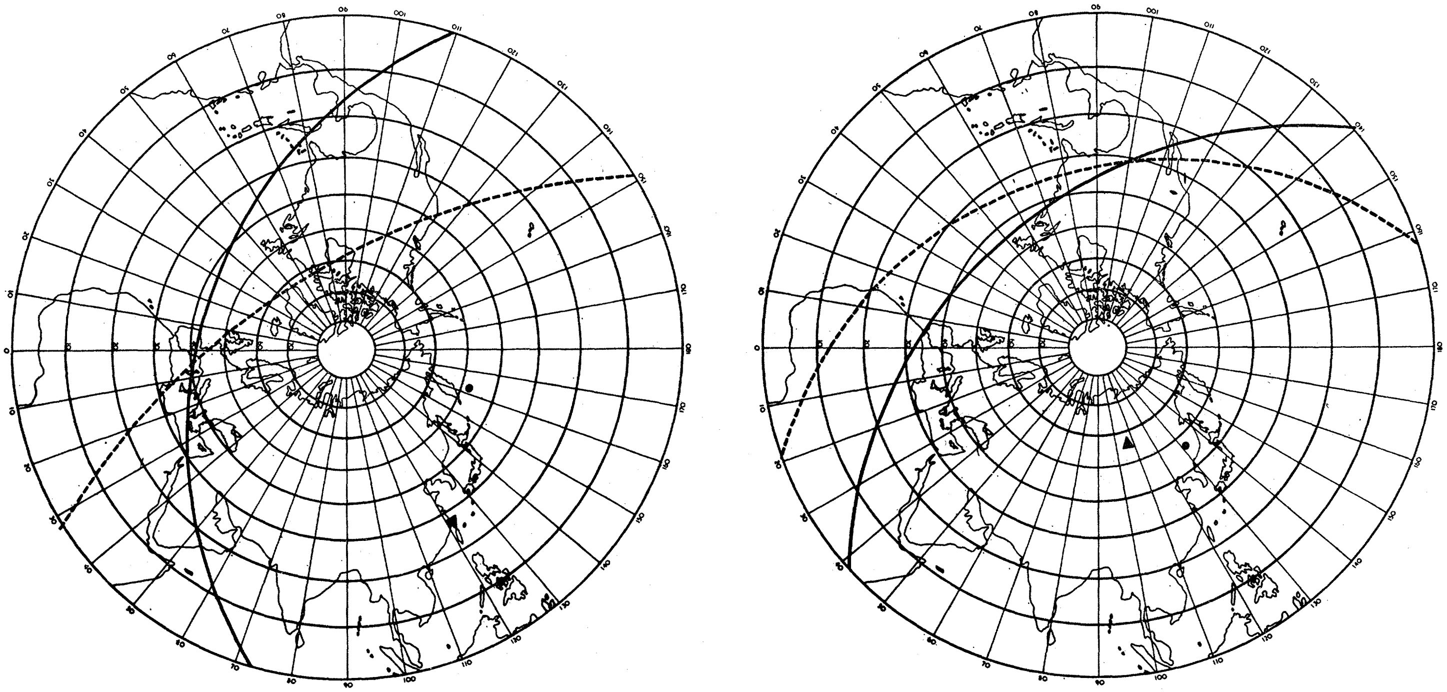
(*b*) Late Pre-Cambrian (*L*, Longmyndian; *T*, Torridonian)



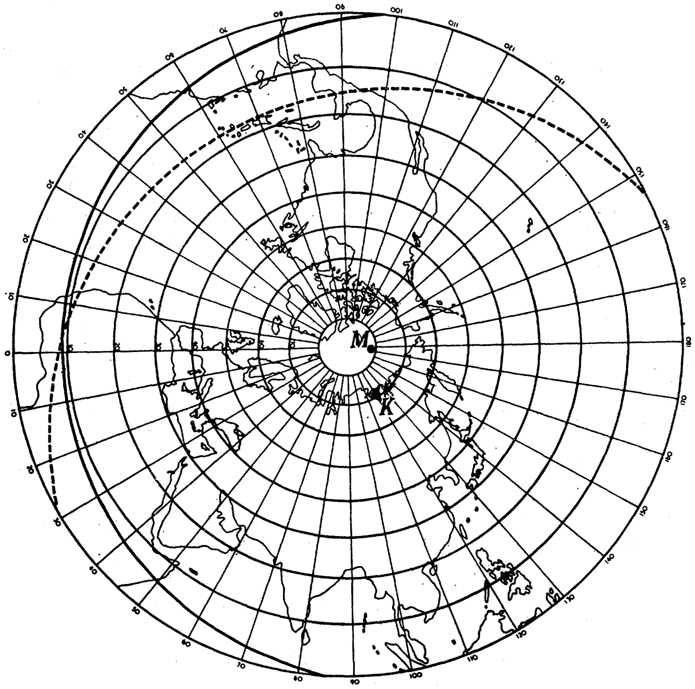
(*c*) Lower and middle Palaeozoic



(*d*) Carboniferous



(*e*) Permian (*f*) Triassic



(*g*) Tertiary and Cretaceous

FIGURE 2. Equators and north pole positions in present northern hemisphere. ●, inferred from British rocks; ▲, inferred from American rocks.

Pre-Cambrian and the late Palaeozoic, extensive glaciations occurred in regions, at present equatorial or near equatorial, without there being evidence that similarly cold climates were experienced over the whole globe. Wegener (1929) and du Toit (1937) postulated continental drift to explain certain geographical, palaeontological and tectonic similarities of coast-lines now separated by thousands of miles of ocean. The geological considerations relating to these two hypotheses are not decisive, but it is interesting to compare them with the results of this paper. Du Toit (1937) assumes that considerable continental displacements of India, Australia, South Africa and South America relative to Europe and North America occurred. Du Toit places the Devonian pole relative to Africa at 40° N, 160° W, but Nairn (1956) shows, from palaeomagnetic measurements, that Africa moved about 29° northwards and 76° eastwards relative to Europe after the Jurassic. This possible movement is similar to that postulated by Wegener and du Toit and must be borne in mind in comparing du Toit's Devonian pole with the corresponding palaeomagnetic one; the agreement may then be reasonable. Köppen places the Cretaceous pole at 49° N, 140° W, the Jurassic at 48° N, 132° W, the Permian at 35° N, 112° W and the Carboniferous at 31° N 145° W. Bain places the pole for Cretaceous–Jurassic times at 42° N, 179° E and for Permian times at 5° N, 164° W. These are in very poor agreement with the palaeomagnetic results. In figure 2, which comprises seven parts, are shown corresponding north pole positions and equators with respect to Great Britain and to North America as they would be in the present northern hemisphere. Irving (1956) and Runcorn (1956*c*) show that the positions of these equators do not conflict with the evidence of the climates in the rocks of the corresponding epochs in Europe and North America but they point out that there is a very clear conflict in the present southern hemisphere. Therefore the case for large continent displacements there appears to be very strong.

7. Reversals of the geomagnetic field

Reference has been made to the opposed directions of magnetization found in the Torridonian sandstones and in the Longmyndian of the Pre-Cambrian, a phenomenon similar to that found in Tertiary lava flows except for the different axis. Clegg, Almond & Stubbs (1954) also found opposed magnetizations in the Keuper sandstones of Triassic age. On the other hand, Creer in the preceding paper shows that a rather careful sampling gives no evidence of a direction other than a southward magnetization in the upper and lower Old Red Sandstones. The other periods listed in tables 1 and 2 have also single polarities, but have been sampled insufficiently to exclude the possibility of reversals.

If these results are interpreted as representing reversals of the geomagnetic field, then we conclude that reversals have taken place at very irregular intervals. In discussing the phenomena in Tertiary times use is made of the terms 'normal' and 'reversed'. In pre-Tertiary times this is confusing because of the slow drift of the magnetic axis. Consequently Runcorn (1956*a*) has suggested that dipole fields with the same sense, relative to the axis of rotation, as the present field, be termed negative and fields opposed to these positive. In table 5 the number of reversals of the polarity of the field which have been found in the different periods from both British and American rocks are shown.

As explained by Runcorn (1955*a*), the reversal of the polarity of the geomagnetic field is not at variance with any of those theories which attribute it to the generation of electric currents by motions in the core. Changes in the pattern of fluid flow might bring about reversal without any other important geophysical consequences and in a time very short on a geological scale. Such a possibility has been investigated by Runcorn (1955*c*) and appears to be inherent in the dynamo theories discussed by Bullard & Gellman (1954) and by Elsasser (1956). There appears to be no reason why reversals should occur at regular intervals, but one sign of field should not, over the whole of the earth's history, be preferred to the other.

TABLE 5. RATE OF POLAR WANDERING AND NUMBERS OF REVERSALS IN THE GEOMAGNETIC FIELD IN THE GEOLOGICAL COLUMN

geological period	time duration (million years) (Holmes 1944)	approximate rate of polar wandering (degrees per million years)	sign of field	minimum number of reversals inferred in each period
Quaternary	1	0·3	+ and −	1
Tertiary	70			8
Cretaceous	50		+	0
Jurassic	30	0·3	no results	
Triassic	40	0·3	+ and −	
		0·7		
Permian	30		+	0
		0·4		
Carboniferous	60		+ and −	1
		0·5		
Devonian	40		+	0
Silurian	30		−	0
Ordovician	50	0·2	no results	
Cambrian	100		+	0
		0·5-1·0		
late Pre-Cambrian	100 (?)		+ and −	10

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