Palaeomagnetic Comparisons between Europe and North America

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Phil. Trans. R. Soc. Lond. A 1965 **258**, 1-11
doi: 10.1098/rsta.1965.0016

A. CONTINENTAL RECONSTRUCTIONS

I. Palaeomagnetic comparisons between Europe and North America

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Much of the current interest in continental drift arose from the discovery of large divergences between the polar wandering curves determined from the palaeomagnetic directions in different continents. The geological lines of evidence for continental drift, each indecisive yet as a whole striking, were thus supported in a remarkable way by quantitative evidence from an entirely separate branch of geophysics. The palaeomagnetic evidence from Europe and North America is of particular interest as almost all geological periods have been sampled in these continents back to 1200 My. A systematic westward displacement, of the order of 20° to 30°, of the polar wandering path from American rocks from that determined from European rocks has been demonstrated.

That the mean geomagnetic field is axially symmetrical seems a secure deduction from the mechanics of the mantle-core system. The possibility that the discrepancy could be due to the field having had an axial but non-dipole character during these periods can be dismissed on palaeoclimatic grounds. The palaeomagnetic data can therefore be used to reconstruct the northern hemisphere in pre-Triassic times: Europe and North America were closer together and in low latitudes.

Comparison between the Precambrian of the western United States and the Keweenawan system appears to provide evidence of displacements within North America before the world-wide orogenic epoch of 1000 My ago.

1. Introduction

At first sight it seems rather strange that the study of the ancient geomagnetic field has any connexion with the problem of continental drift. In considering why palaeomagnetism has proved to be a decisive factor in establishing continental drift as a geophysical theory two points need emphasis.

The remanent magnetization of rocks provides a record of the changes which have occurred in the Earth's magnetic field through the geological past. The uniqueness of palaeomagnetism among quantitative geophysical measurements is that it is the only one not restricted to the present day but available for times from a few thousand to a thousand million years ago. By contrast, no method of measuring the gravitational acceleration in the past is known. A possible way of doing so would be to measure the angle of repose of sand in the past, preserved in aeolian sandstones; but the effect of g on this angle is only of second order. However, two new developments are worth noting. From aeolian sandstones palaeowind directions can be inferred (Opdyke & Runcorn 1960), but they are restricted in occurrence, and information is limited to a few geological periods in three continents. Wells (1963) has shown how the angular velocity of the Earth can be determined from the annual and daily growth rings on the epitheca of corals, but this study has only just begun. Because no other palaeogeophysical record is comparable in scope, palaeomagnetic surveys in the different continents have led to important conclusions about the Earth's evolution.

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* Elected F.R.S. 18 March 1965.

The second point is that palaeomagnetism can be used to locate positions on the globe. Observation and theory both lead to the conclusion that the geomagnetic field, when averaged over some thousands of years, is a geocentric dipole parallel to the axis of rotation. This leads to a simple relation between the latitude λ and the angle of inclination I of the mean geomagnetic field:

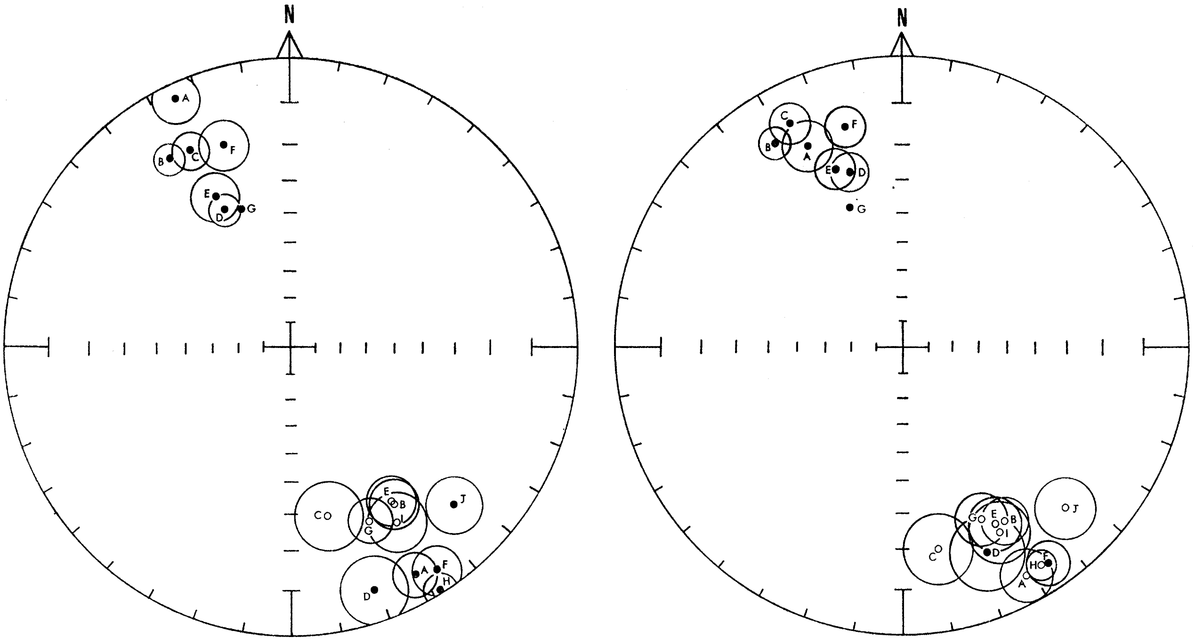
$$\tan I = 2 \tan \lambda. \tag{1}$$

At the present time, and over any time short compared with the secular variation time scale, the Earth's magnetic field does not obey this relation exactly. Thus the axis of the best fitting dipole is now inclined at about 11° to the geographical axis. This has seemed to many geologists a possible fallacy in the magnetic method, for why should the axes not have been inclined at a greater angle in the past? However, physical theory predicts that the geomagnetic field generated in the fluid, electrically conducting, core should be alined in the long run along its axis of rotation. The time scale over which this will be true is given by the velocity in the core divided into the eddy length scale. Thus the axial character of the mean field is an assumption in rock magnetism which the physicist finds easier to accept than the geologist. A simple theoretical argument in support will be developed later.

2. The palaeomagnetic method

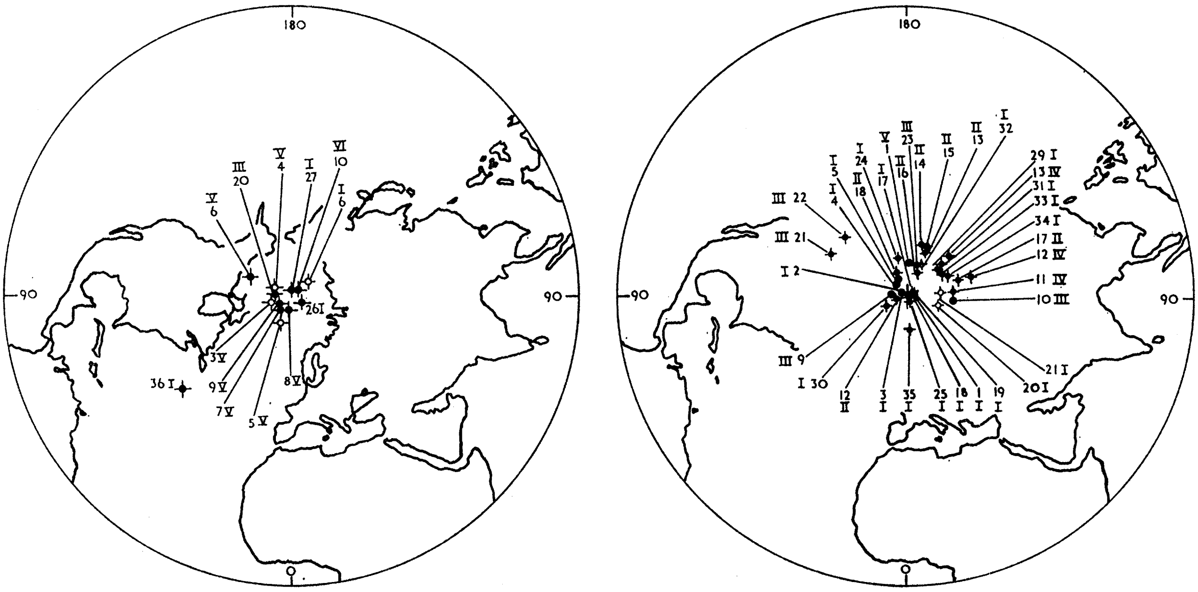
Early in the development of palaeomagnetism it was found that red sandstones and lavas had a strong remanent magnetization not easily affected by laboratory treatment. In many cases, comparison of samples of one geological age over a considerable area within one continent gave consistent magnetization directions. It was often found that proof could be obtained that the magnetization was stable, i.e. that it had not changed since at least the early history of the rock. This is well illustrated by figure 1 (*a*, *b*) which shows the mean directions obtained at various localities of the Chugwater formation of Triassic age in widely separated parts of Wyoming. Comparison of the two plots shows that the points are closer after correction is made for geological dip. This provides evidence that the remanent magnetism has been essentially unchanged since the Rocky Mountain orogenies which tilted these strata. This is a simple illustration of an argument, first proposed by Graham (1949), which is the most convincing test of stability.

Having obtained the mean direction of magnetization of a formation of a certain geological period, corrected for geological dip, a useful way of presenting the results, first introduced by Creer, Irving & Runcorn (1954), is to calculate a pole position. This fixes the axis of a geocentric dipole, the field of which coincides in direction at the site with the mean palaeomagnetic one. The consistency of palaeomagnetic directions at sites more than a few hundred kilometres apart may thus be compared by testing whether the pole positions coincide within the statistical limits. Figure 2 shows that the positions of poles for rocks of Cenozoic age (the last 60 My) from different continents support the hypothesis that the mean geomagnetic field is a geocentric dipole along the present geographic axis. It seems likely that the dipole is more accurately alined along the present axis of rotation for the later rather than the earlier part of the Cenozoic. It is also found that the more extensively sampled the formation, the more exactly does the pole agree with the present axis of rotation, e.g. the Victoria lavas of Australia (Irving & Green 1957), the Icelandic avas (Hospers 1954), the Columbia River basalts (Campbell & Runcorn 1956). Even f experimental errors and deviations of the remanent magnetization of a lava flow rom the field in which it cools were absent, palaeomagnetic results from a lava series will



(*a*) (*b*)

FIGURE 1. Directions from Chugwater Formation (Triassic) of Wyoming (*a*) before and (*b*) after correction for geological dip. ●, Lower hemisphere; ○, upper hemisphere of stereographic projection. Circles are 95% cones of confidence.



(*a*) (*b*)

○, Quaternary; ●, Tertiary.

●, Quaternary; -✦-, Tertiary; ○, Tertiary (Pliocene) to Quaternary (Pleistocene).

FIGURE 2. Cenozoic poles for (*a*) North America and (*b*) Europe.

be scattered owing to the secular variation of the field. The directions of magnetization of successive lavas in such series are spot readings of the field over a time perhaps of the order of millions of years. This is very long compared with the time constant of free decay of the geomagnetic field and also with the period of rotation of the non-axial part of the geomagnetic field relative to the Earth's surface. Thus the scatter of the individual measurements on a stereogram can convey to the casual reader an impression that the palaeomagnetic method is lacking in accuracy. The use of a statistical treatment of the data, such as Fisher (1953) provided, enables the full potential of the method to be used through an exact estimate of the mean and its confidence limits.

3. Palaeomagnetic surveys of Europe and North America

Creer, Irving & Runcorn (1954, 1957), using formations from Europe, and Runcorn (1956*a*) and Collinson & Runcorn (1960), using those from America, found that the pole positions for both continents formed a serial progression with time. This strongly indicated that the explanation of the varying palaeomagnetic directions was likely to be found in some planetary phenomenon rather than in local causes, for example, if the remanent magnetization directions had been determined by water currents during the deposition of the rocks. Figure 3 shows the polar wandering paths from these publications, with dates of publication. In Runcorn (1956*a*) an attempt was made to represent both American and British results by a single path. However, Runcorn (1956*b*) showed that the American path was systematically west of the European one, that this was statistically significant and that it was not likely to be an effect of later magnetization.

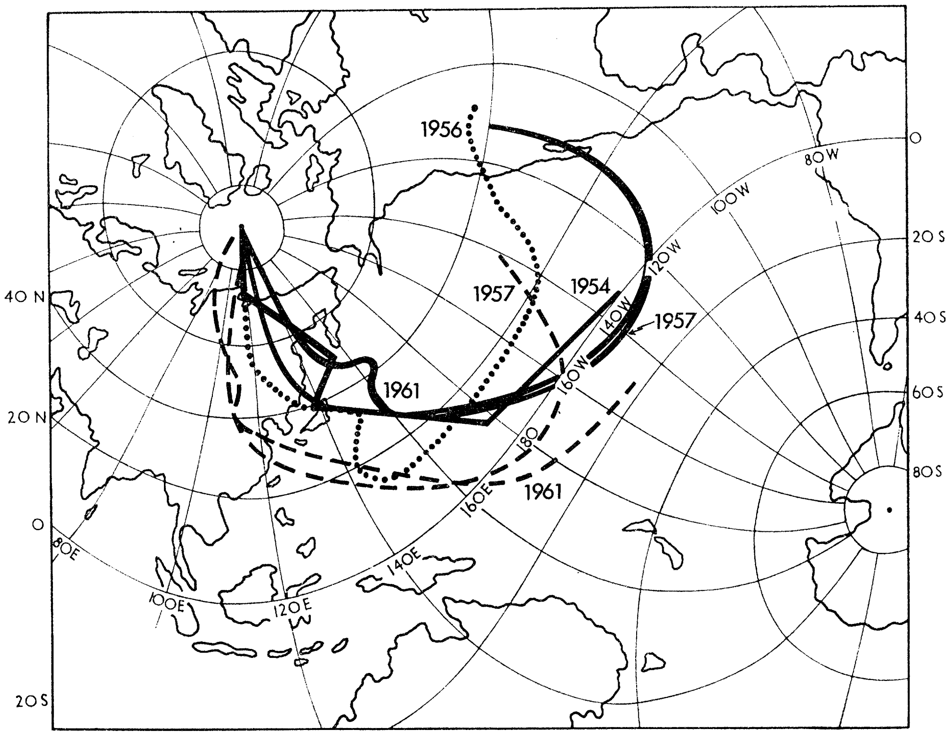


FIGURE 3. Polar wandering paths published at various dates for Europe and North America. ▬, British; — —, American; •••, all points.

Figures 5 to 10 show the pole positions for Europe and North America in the Mesozoic, the Palaeozoic and late Precambrian, taken from tables by Irving (1959–63) listing all published data. Strong grouping of pole positions occurs for all periods, except the Jurassic from Europe and the Precambrian for North America. The accuracies of the determinations of the poles cannot really be compared, as the number of samples taken,

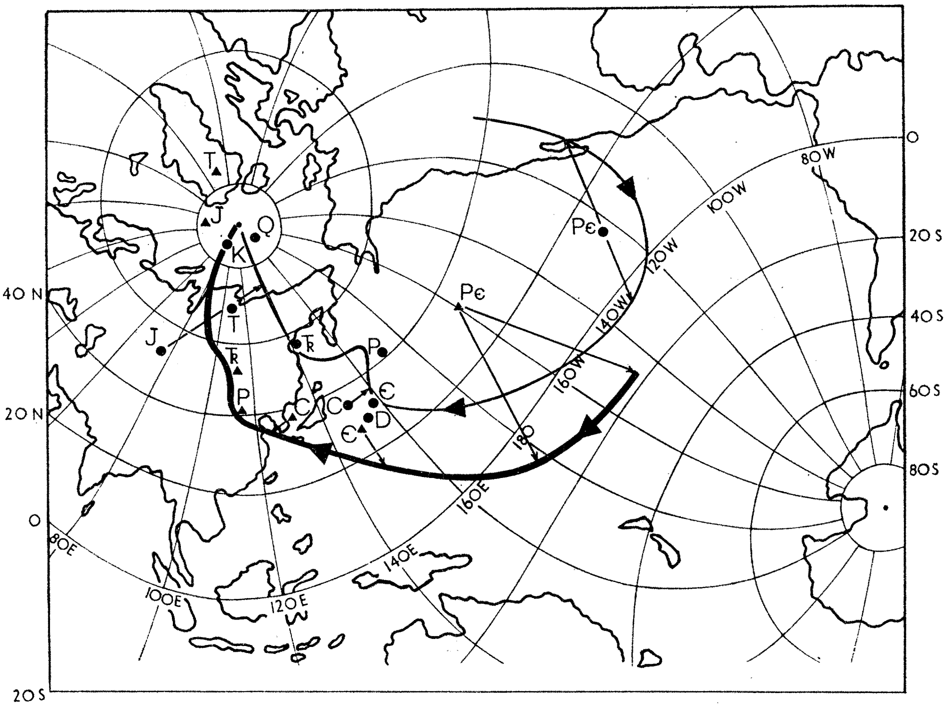
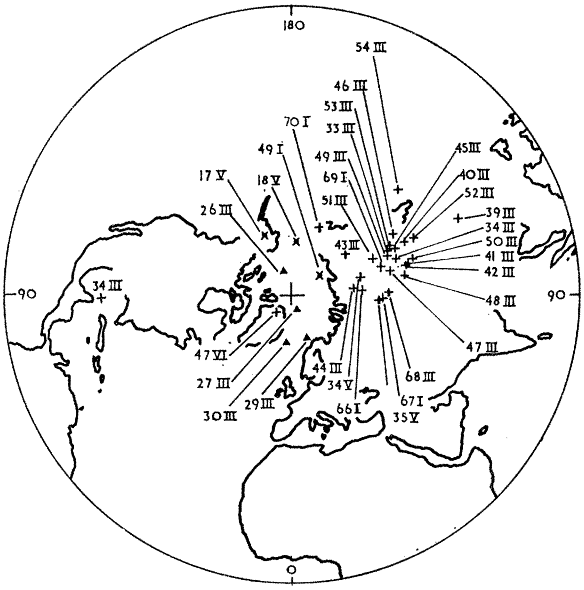
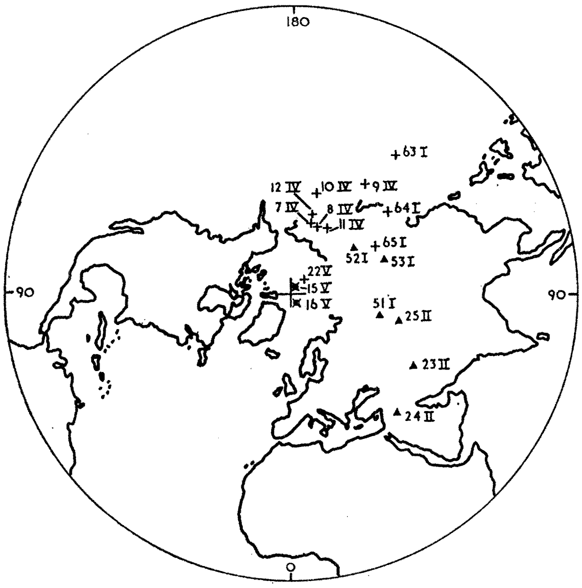


Figure 4. Polar wandering paths for Europe and North America derived from the mean poles. ▲, American rocks; ●, European rocks.



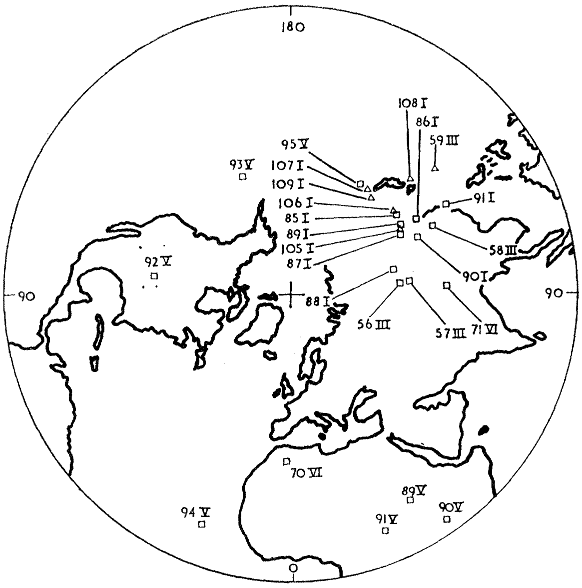


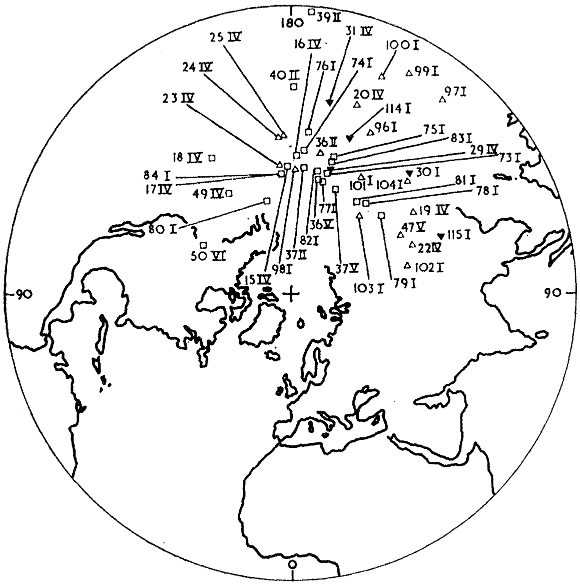
×, Cretaceous; ▲, Jurassic; +, Triassic.

Figure 5. Palaeomagnetic poles for Mesozoic rocks of North America.

Figure 6. Palaeomagnetic poles for Mesozoic rocks of Europe.

the thickness and extent of the formation sampled and the experimental techniques used are very varied. Further, the formations sampled in any period are not of exactly the same age. Nevertheless, it is instructive to take the vector mean of all the pole positions, for a geological period, giving each equal weight and compare it with the polar wandering paths of Creer *et al.* (1957) for Europe, and Collinson & Runcorn (1960) for the United States. Figure 4 shows these comparisons. The first polar wandering paths for Europe

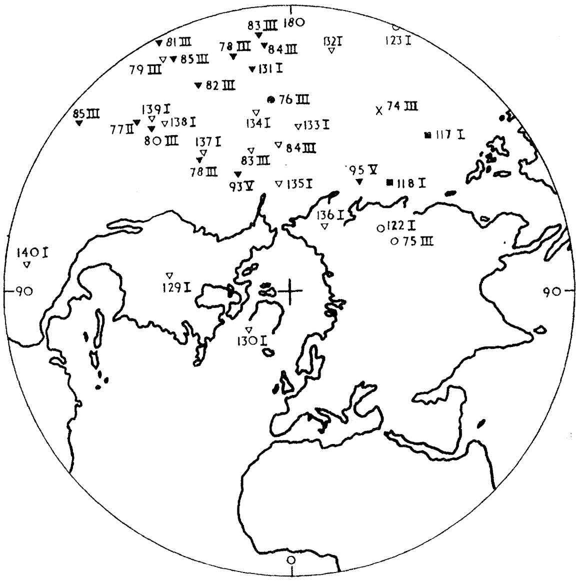




□, Permian; △, Carboniferous; ▼, Devonian.

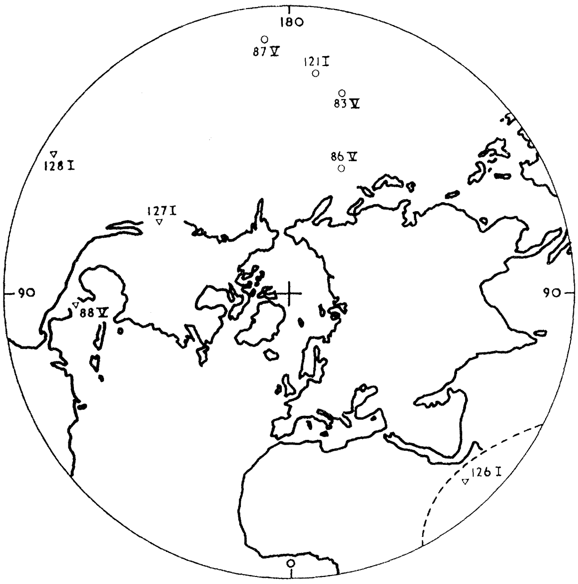
FIGURE 7. Palaeomagnetic poles for Palaeozoic rocks of North America.

FIGURE 8. Palaeomagnetic poles for Palaeozoic rocks of Europe.



□, Silurian; ×, Ordovician; ○, Cambrian;
▽, ▼, upper and lower Precambrian.

FIGURE 9. Palaeomagnetic poles for Precambrian and early Palaeozoic rocks from North America.



○, Cambrian; ▽, Precambrian.

FIGURE 10. Palaeomagnetic poles for Precambrian and early Palaeozoic rocks from Europe.

(1954) and for the United States (1956), as is seen from figure 3, are not too dissimilar from the later ones which, of course, are based on many more data. The mean Cambrian, Carboniferous, Permian and Triassic poles for North America are all west of those for Europe. The Precambrian, as might be expected, because of the long time span, presents a more complicated picture, as shown in figures 9 and 10. The main discrepancy is between the poles for the Keweenawan and those for the Precambrian of the western

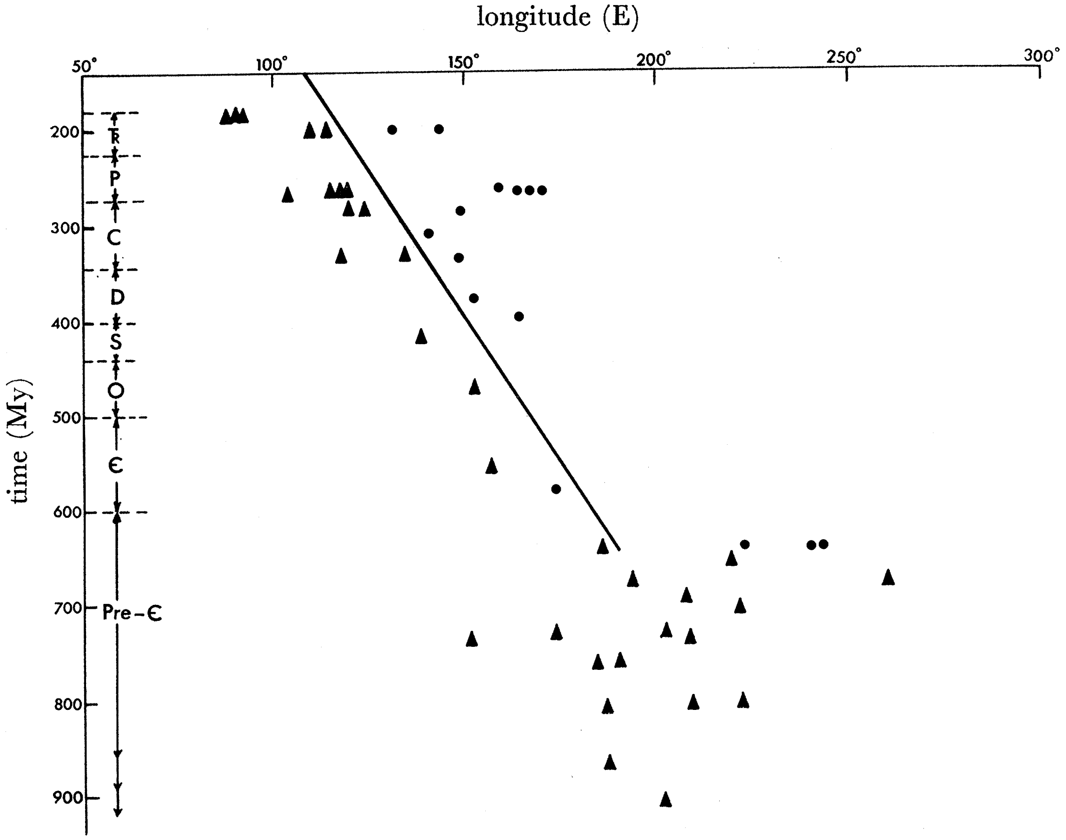


Figure 11. Plot of longitude of palaeomagnetic pole positions of Europe and America against the age of the formations concerned. ●, European rocks; ▲, American rocks.

United States. Runcorn (1964) discusses this problem and concludes that either the two groups are not contemporaneous or else relative movement between different parts of one continent must be considered for results of this age. From figure 6 the Jurassic poles are seen to be scattered over the whole of Asia and thus the mean pole is not significant. However, if the original directions of magnetization of the formations sampled are examined it will be seen that they do not give the well grouped directions common in other periods. The difficulty appears to be the lack of strongly magnetized red beds in Europe for this geological period.

As palaeomagnetic surveys developed in different continents, systematic differences between the polar wandering paths from them emerged. Figure 11 shows that, if the longitudes of the poles from American rocks and those from Europe are plotted against time, the westward displacement of the former is very clear. Such a discrepancy might merely have shown that the magnetizations of the rocks from one continent have been altered very slightly by processes occurring since their formation. It is possible to conceive that there could be a systematic effect of this kind due perhaps to the different climates causing more weathering in rocks from one continent than another.

Runcorn (1956*a*), however, had obtained clear examples of rocks which had acquired a secondary magnetization since their formation. Figure 12 shows a striking example of this. Instead of the directions from one site forming a circular group, they are distributed about a plane, represented on the stereogram by the arc of a circle. These rocks have evidently been remagnetized to varying degrees. In figure 12 the vector mean of these directions is calculated and is joined by a great circle to the present dipole field direction for Arizona, that is the direction that the field would have if it was due to a dipole along the present axis of rotation. The directions lie near to this great circle: the samples have acquired varying degrees of magnetization along the present field, in which they have been exposed at the surface for the last few thousand years. Runcorn (1956*b*) proves that this secondary magnetization along the present dipole field does not explain the discrepancy between the North American and European polar wandering curves. The pole position computed from the vector mean of the planar distributions differs from that corresponding to the original direction of magnetization in *latitude* only. The palaeomagnetic pole has been displaced towards the present north pole by the secondary component of magnetization. The possibility of a secondary magnetization component, not along the present dipole field, is small as the relative intensity of secondary to primary magnetization would have to be the same in every specimen in order to produce no scatter. That this discrepancy in the position of the poles for the different continents is due to rapid polar wandering coupled with the fact that the rocks studied are only roughly contemporaneous, is most improbable. The westward displacement of the American poles

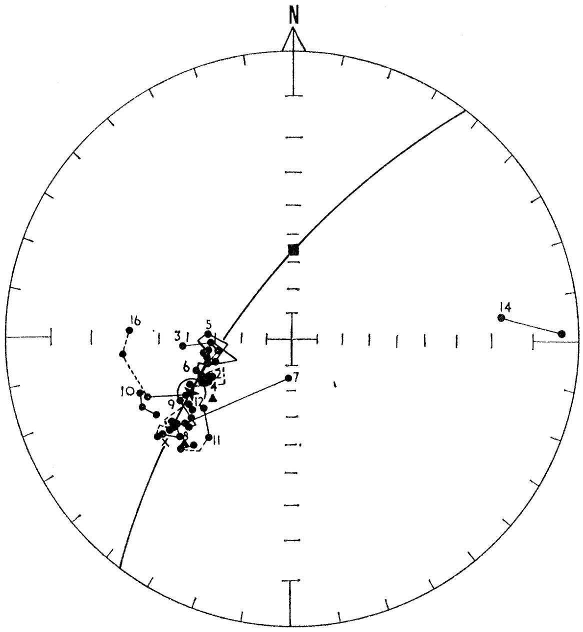


FIGURE 12. Palaeomagnetic directions in the Bass limestone (Precambrian) of Arizona showing secondary magnetization along the present field.

from the Cambrian to the Triassic appears to be systematic and therefore cannot be ascribed to this cause. Differences between the paths before this time are on the present data difficult to interpret.

4. Axial, non-dipole field models

It can be postulated that for each geological period before the Cenozoic, the geomagnetic field has had a distribution more complicated than that of a dipole field, even though this is proved by Cenozoic palaeomagnetic results to have existed over the last 50 My. However, speculation is limited because it can be shown that the *average* field must always have been alined along the axis of rotation. The argument rests on the relative rotation of the core and the mantle. The observation that the non-axial parts of the geomagnetic field are moving westwards at about $\frac{1}{5}°$ per year provides evidence of this rotation. In large scale, hydromagnetic phenomena the magnetic lines of force tend to remain fixed relative to a good conductor such as the core. At present the core is rotating more slowly than the mantle by about 1 part in 10^8. As the Earth's mantle has a rather low electrical conductivity, the electromechanical coupling between the core and mantle is weak. Further the torque always varies because the geomagnetic secular variation will induce varying electric currents in the lower mantle. The fluctuations of the rate of rotation of the mantle which result are measurable by astronomical methods. These irregular changes in the length of the day, though known for fifty years, were only accounted for by the recent development of geomagnetic theory. It may be confidently supposed that there have been slight fluctuations in the rate of rotation of the core with respect to the mantle throughout the Earth's history. The consequence of this is very interesting. If the field at any point on the Earth's surface is observed for some thousands of years the

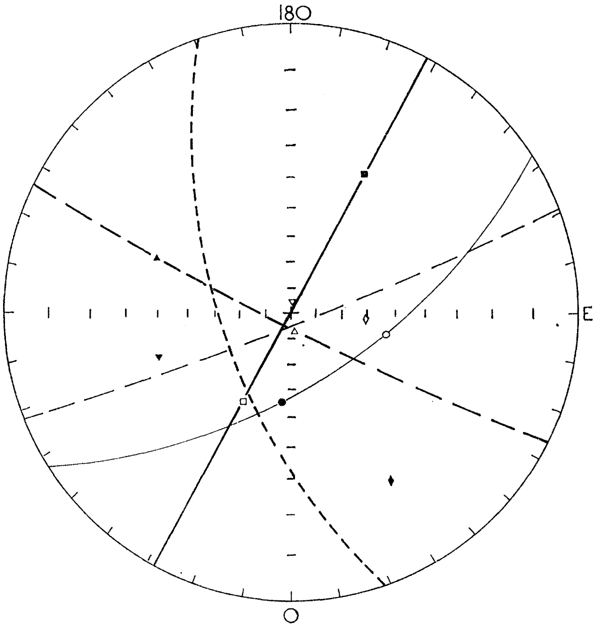


Figure 13. Meridians for the different continents from palaeomagnetic observations of Jurassic rocks.

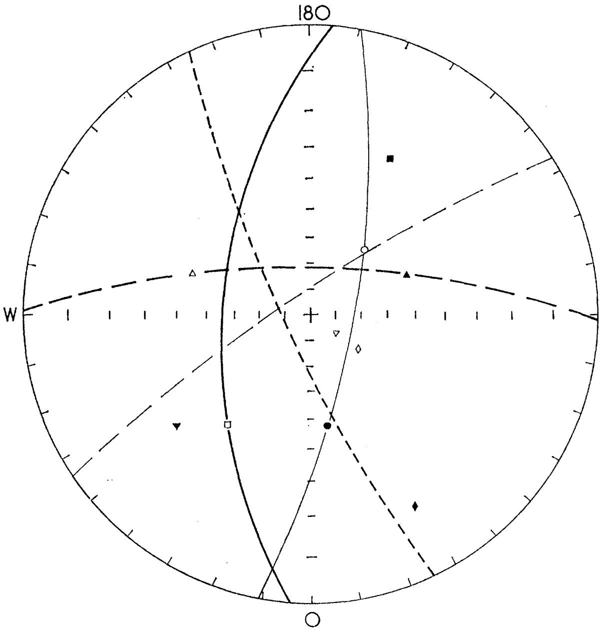


Figure 14. Meridians for the different continents from palaeomagnetic observations of Triassic rocks.

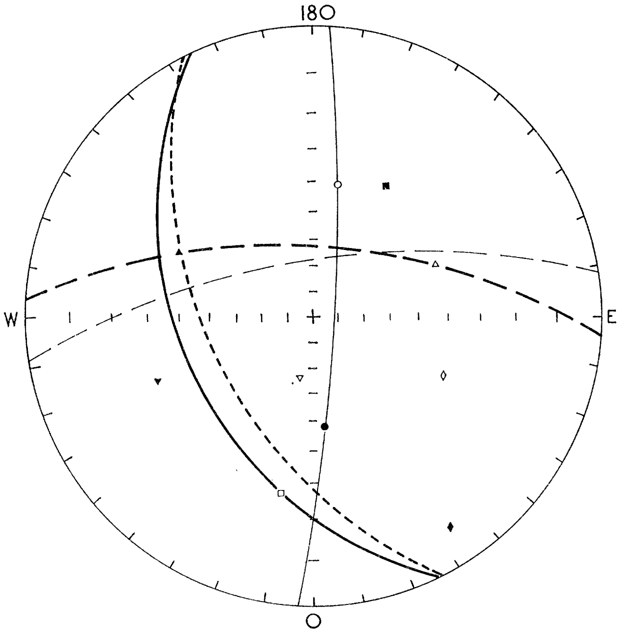


Figure 15. Meridians for the different continents from palaeomagnetic observations of Permian rocks.

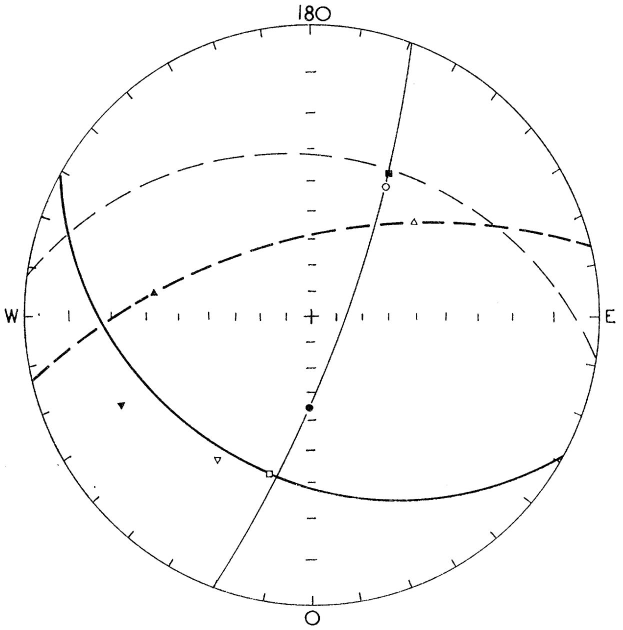


Figure 16. Meridians for the different continents from palaeomagnetic observations of Carboniferous.

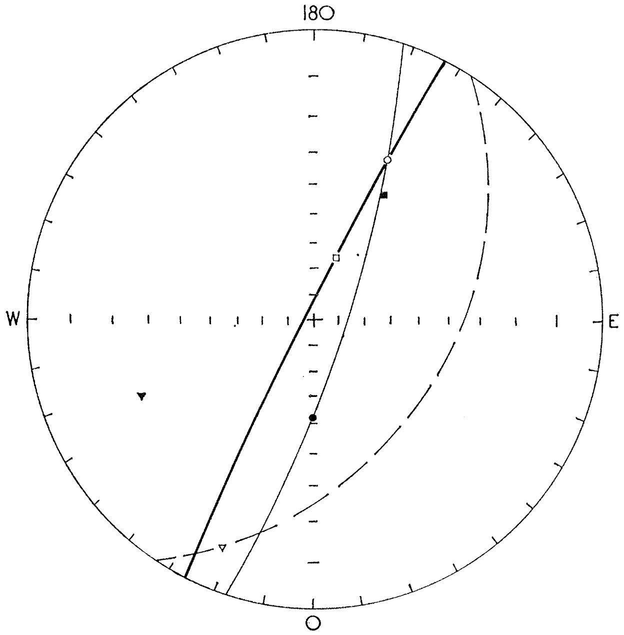


Figure 17. Meridians for the different continents from palaeomagnetic observations of Devonian rocks.

Key to figures 13 to 17:

pole	meridian	site	
■	———	□	Australia
○	········	●	Europe
△	— —	▲	America
▽	— —	▼	South America
◇	- - - - -	◆	Africa

non-axial parts of the geomagnetic field drift past. Runcorn (1959*a*) shows that, when averages over long periods of time are taken, which in geology is unavoidable, the mean field so obtained is symmetrical about the axis of the Earth's rotation.

Thus if, in the geological past, there have been times when the mean geomagnetic field, although axial, departed from the simple dipole configuration, equation (1) would no longer be valid and discrepancies between the polar wandering paths could occur even without continental drift.

To test the possibility that the mean geomagnetic field was for hundreds of millions of years in the past an axial multipole or combination of axial multipoles, one can proceed by the method of Runcorn (1959*b*). Because the mean field is axial, the palaeomagnetic declination gives the direction from the site to the pole. Thus the ancient meridian can be found. If the continents have not changed their positions since the geological period being considered, meridians determined from different continents should intersect together in one point. Figures 13 to 17 show the meridians for different ages from the different continents. In general they fail to meet. Even if one allows for the uncertainties in the data there is no possibility that a single pole will fit the data. At the first test, therefore the non-dipole hypothesis fails to explain the discrepancies found in palaeomagnetic measurements from the various continents. The hypothesis of continental drift is supported as being much preferable in view of the concurrence of palaeomagnetic, palaeoclimatic and geological evidence.

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