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

A Comparison of Geomagnetic Secular Variation as Recorded by Historical, Archaeomagnetic and Palaeomagnetic Measurements

R. Thompson

Phil. Trans. R. Soc. Lond. A 1982 **306**, 103-112
doi: 10.1098/rsta.1982.0070

Phil. Trans. R. Soc. Lond. A **306**, 103–112 (1982) [103]
Printed in Great Britain

A comparison of geomagnetic secular variation as recorded by historical, archaeomagnetic and palaeomagnetic measurements

By R. Thompson
Department of Geophysics, University of Edinburgh, King's Buildings, Edinburgh EH9 3JZ, U.K.

Palaeomagnetic methods can extend the documentary record of changes in the Earth's magnetic field far into the past. Tolerable agreement is found between various methods, demonstrating the geophysical value of palaeomagnetic experiments. Combining results from the different approaches of investigating secular change can lead to a better perspective and to superior models of geomagnetic field behaviour. Lake sediments have recently been found to hold remarkably detailed signatures of past field changes. A mathematical approach to formulating an empirical description of global geomagnetic field behaviour is proposed and applied to palaeomagnetic data spanning the last 10 ka.

1. Introduction

The geomagnetic field varies on all measurable timescales. At one extreme of the geomagnetic spectrum are abrupt impulsive changes or transients with periods of a fraction of a second. At the other extreme are changes in polarity reversal frequency with periods in excess of 100 Ma. The transient magnetic variations which include micropulsations, magnetic storms and diurnal variations have their origin outside the Earth, being due to a variety of solar–terrestrial phenomena including the flow of tidally induced electrical currents in the ionosphere and hydromagnetic waves generated by the solar wind. The main geomagnetic field, in contrast, is of internal origin and exhibits both intermediate and long period changes. It is generally believed to be caused by motions in the Earth's fluid electrically conducting core generating a self-sustaining dynamo. Magnetic field variations occurring on timescales ranging from years to thousands of years are known as the geomagnetic secular variation.

2. Experimental basis of secular variation studies

Our record of the geomagnetic field naturally becomes more vague as we consider progressively earlier times. Satellite observations now provide a very detailed coverage of the global geomagnetic field. During the early twentieth century ground-based observations of all three components of the magnetic field were made at permanent magnetic obervatories. These data can be used to produce quite detailed secular variation and main field models. Before A.D. 1833 only directional measurements of the field were made. Models of the shape of the geomagnetic field can be calculated back to A.D. 1600 based on these angular data, although observations of magnetic dip were scarce before A.D. 1700. Palaeomagnetic measurements of the remanent magnetization of well-dated natural objects and artefacts can usefully complement historical field observations made in the sixteenth to nineteenth centuries and in particular they can extend the geomagnetic record to earlier epochs.

Figure 1 illustrates results obtained by using the main experimental methods of investigating secular change. Figure 1*a* shows the motion of the magnetic field vector at London since A.D. 1580 (after Malin & Bullard 1981). Similar, but less detailed, curves have been calculated for the whole world by Thompson & Barraclough (1982) from historical data. The field motion in France for 1500 years before A.D. 1580 as deduced from archaeomagnetic investigations (after Thellier 1981) is also plotted in figure 1*a*. Magnetic direction changes recorded in British lake sediments deposited between 4.0 and 3.8 ka B.P. and in Hawaiian lava flows erupted during a noisy magnetic period about 5 Ma ago are shown in figure 1*b* and *c* respectively. Estimates of ancient field intensities can be obtained in addition to directional information, from lavas and archaeological materials.

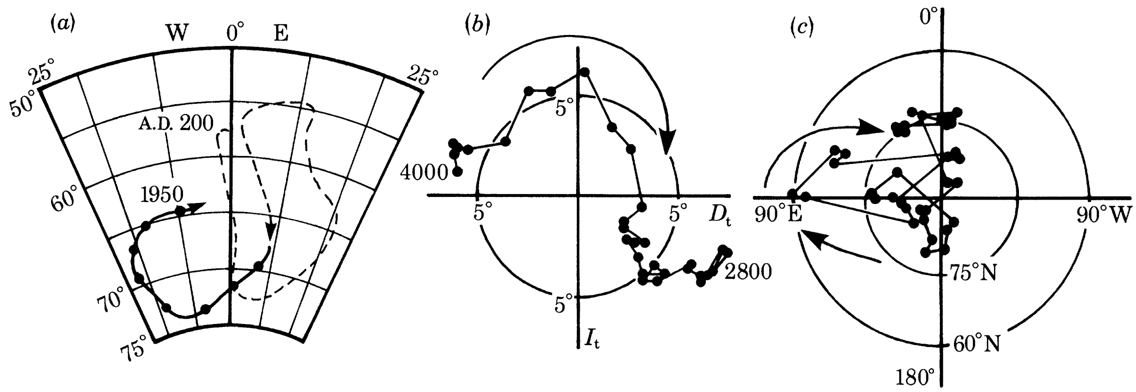

FIGURE 1. (*a*) Examples of secular variation records of changes in direction of the geomagnetic field. The dashed line shows the direction at Paris as derived from archaeomagnetic data (after Thellier 1981). The solid line shows the direction at London based on historical observations of declination and dip (after Malin & Bullard 1981). Note the anticlockwise sense of motion between A.D. 750 and 1400, which is followed by a clockwise motion. (*b*) The variation in field direction in Britain between 4.0 and 2.8 ka B.P. as recorded by the average palaeomagnetic vector of 10 lake sediment cores (after Turner & Thompson 1981). The points, plotted at intervals of 40 years, show the variation relative to the mean direction of all 10 cores. A period of quiet secular change before 4.0 ka B.P. is followed by a more rapid clockwise movement of the field vector. (*c*) Palaeomagnetic field directions recorded in lava flows on Hawaii during a magnetically noisy time (after Doell 1972). The record begins with a clockwise loop.

Dating probably currently presents the greatest problems in palaeomagnetic secular variation studies. Interpretation of dating information can be crucial in all palaeomagnetic methods of studying secular variation. Fortunately in the case of sediment and lava sequences the chronological order of the samples is not in doubt. Radiocarbon dating is invaluable in investigations covering the last few thousand or tens of thousands of years. Laboratory precisions of 50 or 100 years are generally achieved for ^{14}C age determinations. Unfortunately, this precision often has little bearing on the true accuracy of the date of the palaeomagnetic signature. Differences between laboratory precision and dating accuracy partly result from time lags in palaeomagnetic recording processes but are mainly due to natural contamination effects, which can introduce errors of several hundred years.

Nevertheless, detailed patterns of secular variation such as those shown in figure 1 have been established. Agreement between the various methods lends credibility to their geophysical reliability. Thellier (1981) has shown a clear correspondence between the remanent magnetic inclination of bricks and tiles in France and historical field measurements at Paris. Mackereth (1971) demonstrated that lake sediments had recorded the historically documented A.D. 1815 westerly declination maximum, and Turner & Thompson (1981) have shown that lake sediments have also recorded the historically observed A.D. 1700 inclination maximum in addition to the major declination and inclination feature of Thellier's (1981) archaeomagnetic record of figure 1*a*. Doell & Cox (1965) have evaluated the accuracy of the palaeomagnetic method when using historical lava flows as being around 4°.

3. The geomagnetic dipole

The dipole is the dominant term in the spherical harmonic representation of the present Earth's magnetic field. Palaeomagnetic measurements suggest that the geomagnetic field, although frequently reversing its polarity, has been predominantly of a dipolar shape for over 1 Ga. Furthermore, palaeoclimatic evidence suggests that the dipole axis has, on the time average, remained close to that of the Earth's spin. Historical observations show that the moment of the geomagnetic dipole has decreased at an average rate of 16 nT per year during the last 150 years. The rate of decrease has not been linear; indeed the dipole moment almost stopped decreasing between A.D. 1940 and 1950 (Bullard 1953; Hodder 1981). The direction of the dipole axis has also changed during the last few hundred years. It has moved slowly westwards and southwards at average annual rates of 0.1° and 0.03° respectively. The rates of dipole movement can also vary, as is illustrated by the southward drift's having effectively ceased during the last 100 years. Barbetti (1977) has interpreted the direction of remanent magnetization in archaeological materials from four regions around the world to indicate that a rapid shift in direction of the dipole axis over 15° took place around A.D. 1500.

Palaeointensity measurements on archaeological materials and igneous rocks demonstrate that the dipole moment has changed by a factor of at least two during the last 10 ka. A maximum dipole moment at around 2.5 ka ago succeeded a broad minimum about 6.5 ka B.P. (McElhinny & Senanayake 1982). Yukutake (1971) has suggested that palaeointensity measurements indicated that the dipole moment increased during the sixteenth and seventeenth centuries to pass through a pronounced maximum around A.D. 1770. However, more recently obtained palaeointensity data do not confirm this proposed pattern of field behaviour. They indicate higher dipole moments in the fifteenth and sixteenth centuries, closer to Barraclough's (1974) linear extrapolation (figure 2). Walton (1979) and Games (1980) have suggested, on the basis of archaeomagnetic investigations in Greece and Egypt, that the intensity of the ancient magnetic field has changed very rapidly. They report changes in magnetic field intensity by a factor of two or three over a period of a few hundred years. Such local rapid intensity changes could reflect changes in moment of the geomagnetic dipole or possibly changes in intensity of the non-dipole field, although it would have to have been stronger than it is today.

4. The non-dipole field and its variation with time

Although the root mean square strength of the non-dipole field is only about 10% of that of the dipole, present field changes are dominated by non-dipole field variations. Active centres of non-dipole change are of regional rather than planetary importance, covering areas of continental extent. These centres tend to migrate slowly westwards, as does the non-dipole

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

field itself. Bullard *et al.* (1950) demonstrated the westward drift to be a global phenomenon and calculated the average annual drift rate of the non-dipole field in the early twentieth century to have been 0.18°. The drift rate can be shown to have varied. Hodder (1981) for example, has calculated a change in annual drift rate from 0.21° to 0.13° between A.D. 1950.5 and 1970.5.

While certain features of secular change are measured in decades, Yukutake & Tachinaka (1969) and Cox & Doell (1964) have presented evidence to suggest that some features of the present non-dipole field may have persisted for very long periods. Yukutake & Tachinaka interpreted the non-dipole field of the last 400 years to have been composed of both drifting and stationary anomalies. They claim that most of the conspicuous anomalies of the non-dipole part of the Earth's magnetic field are standing and suggest that these anomalies have a separate origin from that of the drifting anomalies. Cox & Doell obtained palaeomagnetic results from Pacific lavas that led them to suggest that the present low rate of secular changes in the Pacific had persisted or been predominant there for several million years.

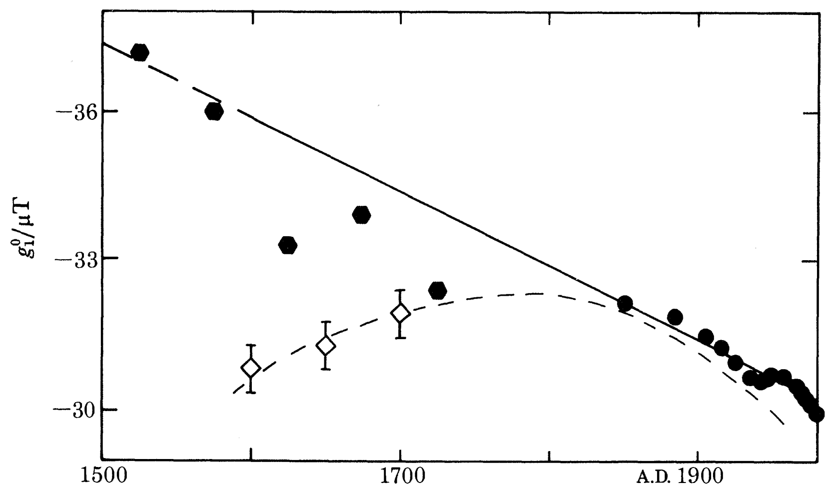

FIGURE 2. Time variation of the axial dipole magnitude g_1^0. The circles show values deduced from sixth-order spherical harmonic analyses since A.D. 1885. The straight line shows Barraclough's (1974) linear extrapolation of such analyses. The dashed curve shows Yukutake's (1971) estimate of g_1^0 based on archaeomagnetic data. Medians of a recent compilation of fifteenth to eighteenth century palaeointensity data are shown as hexagons.

The largest of Yukutake & Tachinaka's standing anomalies of the vertical component of the non-dipole field occurs in the South Atlantic. It is suggested that the persistence of an anomaly in this region is in fact due to two short-lived anomalies happening to have grown up close to one another. Series of contour maps of the non-dipole field based on Thompson & Barraclough's (1982) spherical harmonic coefficients show a new anomaly growing up 40° to the east of an older westward drifting anomaly, to become the dominant anomaly in the South Atlantic around A.D. 1950. Such replacement of non-dipole field anomalies appears to be able to account for another two of Yukutake & Tachinaka's four major standing anomalies. These new observations indicate that Yukutake & Tachinaka's standing field simply represents a 400 year time average of part of the non-dipole field and that it does not have any long-term physical significance. Further unpublished analyses by G. Smith indicate that the typical lifetime of a non-dipole vertical field anomaly is about 500 years (figure 3) and that as described by Yukutake & Tachinaka (1968), anomalies can exhibit significant latitudinal movement in addition to their more pronounced longitudinal motions. Other points that arise from analyses of historical records are that the present region of low secular variation in the Pacific appears to have only been in existence for 150 years, that the axial quadrupole changed sign in the mid-nineteenth century and that the balance of energy between the dipole and higher-order coefficients noted by McDonald & Gunst (1968) does not appear to have held during the seventeenth and eighteenth centuries.

At most localities around the world the magnetic vector has, during the last few hundred years, rotated clockwise (*sensu* Bauer 1896) although Thompson & Barraclough (1982) have noted a possible region of sustained anticlockwise motion centred on the Indian Ocean. This global average clockwise motion has been accounted for by Runcorn (1969) as being a consequence of the westward drift of a non-dipole field with significant sectorial harmonics.

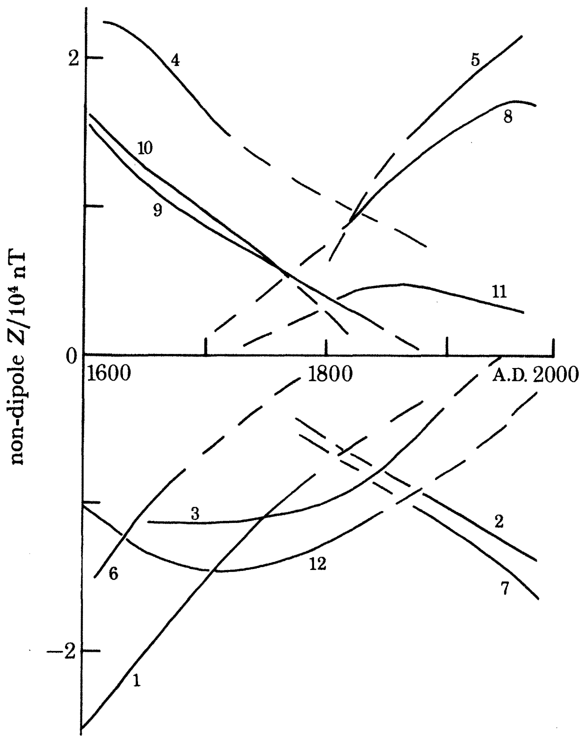

FIGURE 3. Time variation of the intensity of isoporic foci of the vertical component of the non-dipole field. Location and longitudinal yearly drift rate of foci: 1, Southern Ocean 0.05 °E; 2, Australia 0.1 °W; 3, S Pacific 0.1 °W; 4, S Atlantic I 0.15 °W; 5, S Atlantic II 0.2 °W; 6, India 0.2 °W; 7, Africa 0.2 °W; 8, Mongolia 0.05 °W; 9, C. Pacific 0.05 °W; 10, N.E. Pacific 0.1 °W; 11, N America 0.1 °E then W; 12, Greenland 0.05 °E.

5. Empirical description of Holocene secular variation

The full dynamo problem, starting from electrodynamic and hydrodynamic equations such as those of Maxwell, Ohm and Navier-Stokes and incorporating geophysical boundary conditions, is highly complicated. Not surprisingly, theoretical geomagnetic models do not yet duplicate details of observed field changes and so unfortunately cannot be used for collating and examining palaeomagnetic data. Instead we have to be content with mere geometrical models with simple mathematical formulations.

McNish (1940) for example, succeeded in modelling the non-dipole field in terms of 14 radial dipoles. By moving a few radial dipoles westward with time a simple secular variation model is produced. This rather appealingly simple type of model can be employed very successfully to imitate past magnetic field changes. However, Alldredge & Stearns (1969) found that they needed 34 radial dipoles to form a global model and that the positions of the satellite dipoles are quite different when different numbers of dipoles are used. In addition, to build up a global model that also permits the growth and decay of non-dipole sources, many more parameters have to be determined. There are not sufficient palaeomagnetic data available to allow all the necessary parameters to be calculated, so any particular satellite dipole model that is chosen to

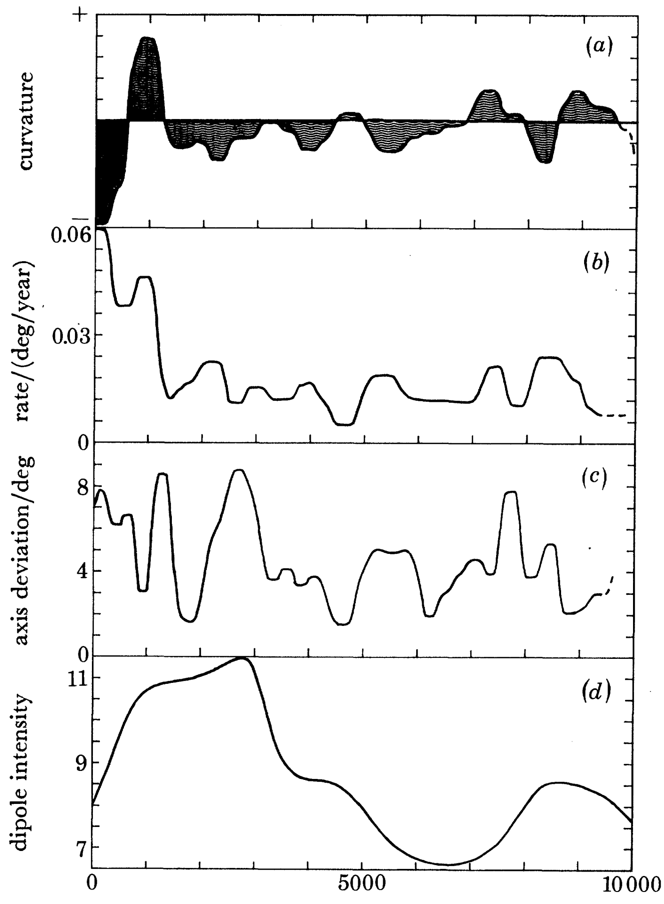

FIGURE 4. Holocene averages from six regions. (*a*) Global average of rate of movement of virtual pole position where positive rates correspond to anticlockwise curvature and negative rates correspond to clockwise curvature. For most movements of physically plausible geomagnetic sources these curvatures correspond to eastward and westward drift of the geomagnetic field respectively. Averaging was performed by taking medians every 50 years followed by Tukey's 7RSSH7RSSH7, twice median smoothing procedure (Tukey 1977). (*b*) Global average of magnitude of rate of movement of virtual pole positions over the last 10 ka. Averaging as in (*a*). (*c*) Global average of deviation of virtual pole positions from their mean direction. Note that lake sediment cores are not orientated so the mean direction only approximates to the geographic pole position. Averaging as in (*a*). (*d*) Dipole intensity; global average. Smooth fit based on McElhinny & Senanayake's (1982) world archaeomagnetic intensity mean values.

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

explain Holocene secular variation is just one of scores that could be employed. Similarly, abundant, precise, well distributed data are needed for spherical harmonic calculations, and available Holocene palaeomagnetic data do not satisfy any of these conditions. Correlation schemes can be produced to match Holocene secular variation records from different localities. Again, however, so many parameters need to be introduced to stretch and squeeze the time-scales and to account geometrically for the lack of precise correlations that many geomagnetic models can be invoked, so an alternative empirical approach has been developed in an attempt to sidestep such 'over-parametrization' problems.

In my empirical approach towards estimating the past behaviour of the Holocene geomagnetic field, palaeomagnetic records have been subjected to closely defined mathematical procedures. Four particular aspects of Holocene geomagnetic field behaviour have been chosen for study. Firstly, longitudinal drift has been assessed by examining the sense of looping of the field vector. Secondly, quiet periods of secular variation, as opposed to disturbed periods, have been investigated by examining the rate of change of position of virtual geomagnetic poles. Thirdly, movement of the main dipole axis has been assessed by calculating the average path of the virtual poles. Finally, the global average moment of the geomagnetic dipole, as derived from palaeointensity studies (McElhinny & Senanayake 1982) provides a fourth feature in the empirical geomagnetic description (figures 4 and 5). The first three geomagnetic field properties have been investigated by analysing lake sediment records from six regions of the world.

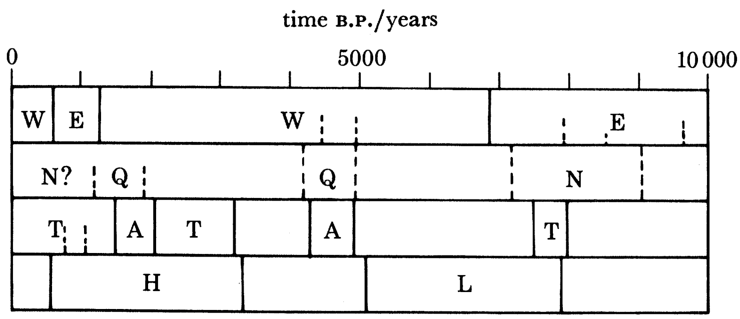

FIGURE 5. Summary of Holocene global averages. (*a*) E, W, eastward and westward drift; (*b*) Q, N, quiet and noisy secular variation; (*c*) A, T, axial and tilted dipole orientation; (*d*) H, L, high and low dipole intensity.

The mathematical procedures used in these analyses briefly involved (i) choosing type limnomagnetic records by using reliability criteria, (ii) linearly detrending the paired declination and inclination measurements to take into account any twisting or warping of core tubes during coring, (iii) allowing for random noise in the palaeomagnetic records by smoothing the data with robust, weighted, least squares, cubic spline functions in conjunction with a cross validation technique (Thompson & Clark 1981), (iv) transforming the depth scales into a tree-ring-calibrated ^{14}C timescale (Clark 1975), (v) converting the resulting declination and inclination information into virtual pole positions at intervals of 50 years, and finally (vi) averaging the virtual pole position records and intrinsic equations of the spline curves by using Tukey's (1977) robust running median method.

Turning our attention to the figures summarizing the empirical model, the average curves of figure 4*a*, *b* have been based on the intrinsic equations of the polar paths. Figure 4*b* uses the rate of change of the polar path as calculated by using the gradient of the spline functions fitted to the polar paths. Figure 4*a* also uses the gradient of the spline functions but in addition it takes into account the sign of the curvature of the polar paths. Curvature has been calculated directly from polar paths for the first time by combining the gradient and acceleration of their spline functions according to the usual geometric formula (see, for example, Thomas 1960). A positive curvature corresponds to anticlockwise looping of the geomagnetic vector. The curve of figure 4*c* illustrating axial tilt is based on the solid angle departure of the virtual poles from their average value. The summary dipole intensity curve of figure 4*d* is a smooth curve based on McElhinny & Senanayake's 1000 and 500 year disjoint means. The marked differences in the declinations, inclinations and virtual geomagnetic poles of the six regional secular variation records used in these analyses point to the importance of non-dipole fields in the production of angular magnetic changes during the last 10 ka.

The most important feature of figure 4*a* is the change in sign of the average curvature. It is suggested (figure 5) that the clear changes in sign of curvature correspond to reversals in the sense of average global geomagnetic longitudinal drift. The proposed change from eastward to westward drift during the last 1 ka based on the lake sediment records is particularly interesting because it corresponds well with the change in sense of looping in European archaeomagnetic records (Aitken *et al.* 1964). The most noticeable feature in figure 4*b* is the rapid increase in rate of polar movement during the last 2 ka. A large part of this increase undoubtedly reflects poor memory effects in the palaeomagnetic recording process rather than the behaviour of the geomagnetic field, as some lake-sediment palaeomagnetic records have been smoothed or degraded in their older sections. Nevertheless, it is suggested that quiet field times can be

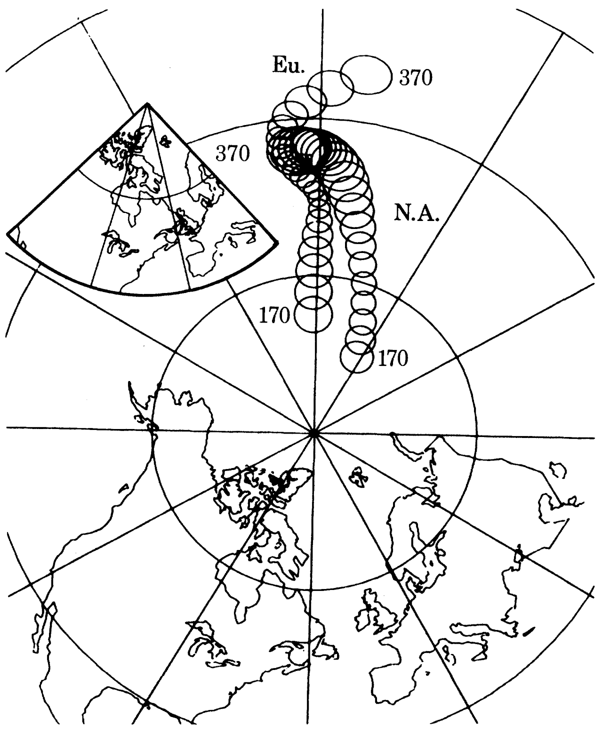

FIGURE 6. Apparent polar wander paths for North America and Europe between 350 and 170 Ma plotted on the continental reconstruction by Bullard *et al.* (1965), with America held stationary. The ellipses form 95% confidence bands for the paths at 10 Ma intervals. The best fit of the two paths is found for a North Atlantic reconstruction involving a rotation of 47° about 84 °N 170 °E, which results in a discrepancy in matching the continental edges of over 500 km (inset). The differences between the paths resemble the palaeomagnetic effects to be expected from long-term non-dipole field components.

detected by the polar movement method (figure 5). Furthermore, there are indications in figure 4*c* that it is possible to distinguish periods when the dipole axis was close to the rotation axis. It is interesting to note in figure 5 that these proposed periods of axial alignment of the field occurred at similar times to those of quiet field behaviour.

6. Geological perspective

Geomagnetic secular variation and long-term non-dipole field components can be investigated by measuring the remanent magnetization of geological samples. Irving & Pullaiah (1976) have suggested that long-term trends in the magnitude of palaeosecular variation can be recognized and, in particular, that secular variation was smaller during the long-lived polarity intervals of the Lower Cretaceous and Permo-Carboniferous. Wilson (1970) and Cox (1975) have described the persistence of a small but significant axial quadrupole term over the last few million years that reverses when the main dipole field reverses polarity. Even longer persistent non-dipole field components may be revealed in the regional departures of polar wander paths (figure 6) from a time-average geocentric dipole field model.

7. Conclusions

Geomagnetic palaeosecular variation during the last few thousand years has been established at several localities. It has been determined sufficiently accurately to be used for magnetostratigraphic dating and to help fill the gap in the spectrum of geomagnetic field behaviour between polarity reversals and changes on time scales of years or decades.

References (Thompson)

Aitken, M. J., Harold, M. R. & Weaver, G. H. 1964 *Nature, Lond.* **201**, 659–660.
Alldredge, L. R. & Stearns, C. O. 1969 *J. geophys. Res.* **74**, 6583–6593.
Barbetti, M. 1977 *Earth planet. Sci. Lett.* **36**, 207–218.
Barraclough, D. R. 1974 *Geophys. Jl R. astr. Soc.* **36**, 497–513.
Barraclough, D. R. 1978 *Bull. Inst. geol. Sci. Geomagn.* **8**, 1–66.
Bauer, L. A. 1896 *Phys. Rev.* **3**, 34–48.
Bullard, E. C. 1953 *J. geophys. Res.* **58**, 277.
Bullard, E. C., Everett, J. E. & Smith, A. G. 1965 *Phil. Trans. R. Soc. Lond.* A **258**, 41–51.
Bullard, E. C., Freedman, C., Gellmann, H. & Nixon, J. 1950 *Phil. Trans. R. Soc. Lond.* A **243**, 67–92.
Clark, R. M. 1975 *Antiquity* **49**, 251–266.
Cox, A. 1975 *Rev. Geophys. Space Phys.* **13**, 35–51.
Cox, A. & Doell, R. R. 1964 *Bull. seism. Soc. Am.* **54**, 2243–2270.
Doell, R. R. 1972 *J. geophys. Res.* **77**, 862–876.
Doell, R. R. & Cox, A. 1965 *J. geophys. Res.* **70**, 3377–3405.
Games, K. P. 1980 *Geophys. Jl R. astr. Soc.* **63**, 45–56.
Hodder, B. M. 1981 *Geophys. Jl R. astr. Soc.* **65**, 763–776.
Irving, E. & Pullaiah, G. 1976 *Earth Sci. Rev.* **12**, 35–64.
McDonald, K. L. & Gunst, R. H. 1968 *J. geophys. Res.* **73**, 2057–2067.
Mackereth, F. J. H. 1971 *Earth planet. Sci. Lett.* **12**, 332–338.
McElhinny, M. W. & Senanayake, W. E. 1982 *J. Geomagn. Geoelect., Kyoto.* (In the press.)
McNish, A. G. 1940 *Trans. Am. geophys. Un.* **21**, 287–291.
Malin, S. R. C. & Bullard, E. C. 1981 *Phil. Trans. R. Soc. Lond.* A **299**, 357–423.
Runcorn, S. K. 1959 *Annls Geophys.* **15**, 87–92.
Thellier, E. 1981 *Phys. Earth planet. Inter.* **24**, 89–132.
Thomas, G. B. 1960 *Calculus and analytic geometry*, 3rd edn. Reading: Addison-Wesley.
Thompson, R. & Barraclough, D. R. 1982 *J. Geomagn. Geoelect., Kyoto.* (In the press.)

Thompson, R. & Clark, R. M. 1981 *Phys. Earth planet. Inter.* **27**, 1–7.
Tukey, J. W. 1977 *Exploratory data analysis.* Reading: Addison-Wesley.
Turner, G. M. & Thompson, R. 1981 *Geophys. Jl R. astr. Soc.* **65**, 703–725.
Walton, D. 1979 *Nature, Lond.* **272**, 643–644.
Wilson, R. L. 1970 *Geophys. Jl R. astr. Soc.* **19**, 417–437.
Yukutake, T. 1971 *J. Geomagn. Geoelect., Kyoto* **23**, 11–31.
Yukutake, T. & Tachinaka, H. 1968 *Bull Earthq. Res. Inst. Tokyo Univ.* **46**, 1027–1074.
Yukutake, T. & Tachinaka, H. 1969 *Bull Earthq. Res. Inst. Tokyo Univ.* **47**, 65–97.

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