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Secular Variation as Recorded in Lake Sediments: A Discussion of North American and European Results

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Secular variation as recorded in lake sediments: a discussion of North American and European results

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Type-curves depicting secular variations in declination and inclination through Holocene time have been constructed by stacking data from individual cores of lake sediment from east-central North America and the U.K. There is a strong *positive* correlation in declination with zero phase shift from 0 to 4500 ^{14}C years b.p. but from 4500 to 8500 ^{14}C years b.p. the correlation is strongly *negative*, which we interpret in terms of fluctuations in intensity of standing geomagnetic sources. A source located under the Atlantic Ocean appears to have been dominant before *ca.* 4500 ^{14}C years b.p., and then another similar source located either to the east or to the west of both observation areas gained dominance. However, the inclination type-curves show optimum positive correlation for a phase shift of *ca.* 400 years, suggesting that the geomagnetic sources that caused them were drifting westward at *ca.* 0.2 degrees a year. There is no way of adjusting the timescales so as to obviate this apparent paradox. Secular variations of the total geomagnetic vector have been investigated by noting the sense (clockwise, anticlockwise) of looping of the v.g.p. paths, though this cannot be interpreted uniquely in terms of westward or eastward drifting sources in the core, as demonstrated by specific radial dipole models.

1. Introduction

(*a*) *Background*

It is now possible to obtain from lake sediments continuous palaeomagnetic records of sufficient resolution to study geomagnetic secular variations. In the decade since the first pioneer study was made by Mackereth (1971) many data have been accumulated, particularly for western Europe (Creer *et al.* 1979, 1980, 1981; Thompson & Stober 1977; Turner & Thompson 1981), for N America (Creer *et al.* 1976*a*, *b*; Vitorello & Van der Voo 1977; Banerjee *et al.* 1979; Lund & Banerjee 1979; Mothersill 1979, 1981) and for Australia (Barton & McElhinny 1981). The reader is referred to these papers for information about methods and techniques and for details of the consistency of the results obtained within each region.

Palaeomagnetic records from parallel cores taken from the same lake may be correlated on the basis of their lithological and magnetic susceptibility logs. In this way all the records from a given lake may be plotted on a common depth scale and if this is done even minor features of the recorded inclination and declination variations are observed to line up most impressively. At the between-lake and higher levels, correlation demands accurate dating of the sediment cores. Although the radiocarbon method can provide absolute ages (though not in calendar years) they should be supplemented if possible by palynological studies because the presence of fossil organic carbon in many sediments causes the determined ^{14}C ages to be systematically too old and it is not possible to correct for this rigorously. Transformation from the depth scale to a reliable timescale constitutes one of the most difficult problems encountered in the construction of palaeomagnetic secular variation records.

The validity of lake sediments as reliable recorders of past geomagnetic secular variations is substantiated by the agreement of palaeomagnetic results from Greece covering the last three to four millennia with parallel results derived from archaeological material such as pottery and kiln walls (Creer *et al.* 1981; Kovacheva 1980). Similar agreement has been established for the U.K. palaeomagnetic data with archaeomagnetic† and historic data for northwest Europe, though over a shorter time interval.

An important advantage of lake sediment palaeomagnetic records over archaeomagnetic records is that data from different lakes can be assembled to provide a *continuous* record for a given region. Furthermore, the archaeomagnetic method can only be applied to the few geographical regions where ancient civilizations flourished and it cannot be extended much before *ca.* 6000 years ago when techniques of baking pottery in kilns were invented. As yet, however, it has not proved possible to develop a satisfactory method of obtaining palaeo-intensities from sedimentary rocks, although the determination of ancient field intensities rather than directions has comprised the major achievement of archaeomagnetic research.

(*b*) *The magnetization process*

In nearly all of the lacustrine sediments yet studied the natural remanent magnetization (n.r.m.) is carried by detrital magnetite grains of less than *ca.* 50 μm diameter (see, for example, Papamarinopoulos *et al.* 1982). It can be acquired in two different ways. First, depositional remanent magnetization (d.r.m.) may be acquired in calm water when the individual magnetic moments of the carrier grains become preferentially aligned along the direction of the ambient geomagnetic field as they fall through the water. Second, a post-depositional remanent magnetization (p.d.r.m.) may be acquired if the carrier grains are free to rotate in the voids of the sediment matrix as they attempt to follow secular variations of the geomagnetic field that occurred after deposition. The p.d.r.m. process has been studied experimentally in several laboratories during recent years (see, for example, Tucker 1979, 1980, 1981; Otofuji & Sasajima 1981) and for this reason is now generally accepted as being the more important of the two. In particular, Tucker (1980) has shown that the efficiency of the magnetization process depends on the relative diameters of the carrier and bulk matrix grains, being most effective when the carrier grains are smaller than the matrix grains. The size of the voids decreases progressively as a consequence of compaction, which occurs in the natural environment due to the deposition of more and more sediment as time goes by. Thus the ability of the carrier grains to rotate towards the geomagnetic field direction is progressively impeded and decreases sharply at a critical value of porosity. Tucker found that p.d.r.m. ceased to grow when the water content decreased below *ca.* 70%, which he estimated would occur at a depth of about 17 cm in his synthetic sediment. The essential conclusion is that there is a rather critical depth that will vary with the physical properties of the sediment at which the p.d.r.m. becomes 'blocked in'. Thus a most important property of p.d.r.m. is that it is acquired over a finite interval of time, the duration of which depends on the rate of sediment deposition. For lacustrine sediments with

† The prefixes *archaeo-* and *palaeo-* both come from the Greek. The former is derived from *arche* meaning 'beginning' or 'the earliest', while *palaeo-* means 'ancient'. Thus in geological usage, quite correctly, the name Archaean is given to the oldest known rocks ($\gtrsim$2500 Ma old) while the name Palaeozoic is given to the first era in the Phanerozoic aeon (230–570 Ma ago). Unfortunately, the name archaeomagnetism has been given to studies of the magnetism of archaeological materials (i.e. human artifacts), which are in fact quite young on the geological timescale, while the name palaeomagnetism has been given to studies of the magnetism of much older naturally occurring rocks, the age of which may range from Recent through Phanerozoic and Proterozoic to Archaean.

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typical rates of deposition of *ca.* 1 mm/year, the 'window' through which the geomagnetic secular variations are recorded is *ca.* 200 years. For deep ocean sediments, typical deposition rates are about one-hundredth of this, so that we should expect the recorded palaeomagnetic signal to be smoothed over intervals of 20000 years. The results of laboratory experiments also show that for field strengths of the order of the Earth's, the intensity of p.d.r.m. is proportional to the strength of the applied magnetic field and to the logarithm of the time over which it is applied, other conditions remaining steady.

(*c*) *Objectives*

Thus lake sediments are particularly well suited for recording secular variations with periods *ca.* 10^3 to 10^4 years. Taking a deposition rate of 1 mm/year, the whole of the Holocene would be sampled by a 10 m core. A typical sample size used for palaeomagnetic measurements is *ca.* 2 cm, in which case, with continuous sub-sampling of the core, the geomagnetic secular variations would be sampled at intervals of 20 years. However, the resolution of the recorded signal is not as good as this because of the smoothing associated with the p.d.r.m. recording process (see § 1 *b*).

Techniques of collecting sediment cores without unduly disturbing the sediment and methods of measuring the remanent magnetization have now been developed to the extent that a comprehensive global study of Holocene lake sediments is a thoroughly practicable proposition. Particularly important would be a comparative study of lake sediments from sites located along a baseline within a specific band of latitudes, e.g. across Europe and Asia or across North America. This would yield valuable data about the long-term persistence of geomagnetic drift and the lifetimes of non-dipole foci. In this paper we take a first step towards the realization of this objective by describing and discussing the relation between North American and west European palaeomagnetic declination and inclination records. The possibility of obtaining secular variation records from a large number of globally well distributed sites to permit spherical harmonic analyses at a number of epochs through the Holocene is a realistic though potentially costly long-term objective.

For pre-Holocene time, independent dating control becomes progressively less precise, and a unique correlation of features with characteristic times *ca.* 10^3 year recorded palaeomagnetically becomes virtually impossible beyond Late Glacial time.

2. Establishment of regional type-curves

(*a*) *Method*

We shall describe and compare regional type-curves of secular variations in inclination and declination for east-central North America and for the U.K. Our method of constructing these type-curves was to examine critically all the available data for each region and to select only those that we considered to be of the best quality and for which there was good independent dating control. The data points for each record were then recomputed at equal (40 year) time increments. Next, because sediment cores are hardly ever oriented in azimuth and we can never be sure that the corer penetrated the bottom sediments absolutely vertically, it is necessary to make some adjustments to the measured palaeomagnetic directions before individual core data can be combined. The mean of the population of unit vectors for each core for the interval 0–8000 years b.p. was calculated, and together with all the unit vectors, it was rotated into the direction of the axial dipole field for the region. Thus the mean declination, D_m, was set to 0° and the mean inclination, I_m, was set to the axial dipole field value. This procedure will not orient the palaeomagnetic records perfectly because it is unlikely that the secular variations average themselves out over 8000 years but any error introduced will be systematic for a given region. Finally, the amplitudes of the individual records were normalized to correct for variations in the efficiency of the magnetization process (see §1*b*). These adjusted and normalized data points were then stacked. Standard errors at each time horizon were computed by using Fisherian statistics.

We adopted the procedure of stacking with the objectives of removing spurious features exhibited by some of the individual records and to enhance the signal:noise ratio. These objectives are invariably achieved when *instrumental* records are stacked, essentially because the time parameter has been measured very accurately. In contrast, the 'clock' used to transform palaeomagnetic secular variation records from depth to time scales assumes uniform rates of sediment deposition between the depths of adjacent 'time-checks' (radiocarbon ages or the principal palaeomagnetic features used for correlation), which is not true, and furthermore each radiocarbon age determination is subject to experimental error of a small percentage. Thus stacked core records are often found to show less fine detail than some of the better individual records comprising the stack.

(*b*) *North American type-curves*

The type-curves illustrating secular variations of declination and inclination for east-central North America (43–48° N, 82–98° W) illustrated in figure 1 have already been described by Creer & Tucholka (1982), who combined palaeomagnetic records from Lakes St Croix and Kylen in Minnesota, which are well dated by numerous radiocarbon age determinations (Banerjee *et al.* 1979; Lund & Banerjee 1979) with less well dated records from Lake Superior (Mothersill 1979) and Lake Huron (Mothersill 1981). The pattern of the secular variations recorded by the Minnesota lake sediments is not very well defined before about 6000 years b.p., while that recorded by the Great Lakes sediments shows well formed features that are repeatable from core to core. Creer & Tucholka (1982) showed that it was possible to define a unique correlation between Great Lakes and the Minnesota records on the basis of several characteristic features exhibited by the inclination variations, and so they were able to combine the best qualities of both sets of data.

Both curves shown in figure 1 have been centred around the declination and inclination values for the axial dipole field, namely 0° and 65°, as described in §2*a*. Scale divisions in figure 1 are in tens of degrees. The amplitude of the recorded declination variations is about ±30° and the inclination variations range between about 55° and 75°. The major features characterizing the variations are labelled with letters from the Latin alphabet A to I (declination) and a to o (inclination). If we neglect, for the time being, the four apparently minor inclination swings labelled b, c, g and h, it will be noticed that the inclination and declination swings correspond roughly one to one. In particular, (i) inclination highs e, i and l occurred at times when declination was changing from easterly to westerly values with advancing time, and (ii) inclination lows f/h, k and m occurred at times when the declination was changing from west to east. These observations can be explained most simply though not exclusively in terms of radial dipole sources in the Earth's core drifting westwards under the region with the north-seeking pole pointing (i) upwards and (ii) downwards as proposed by Creer (1981) to explain

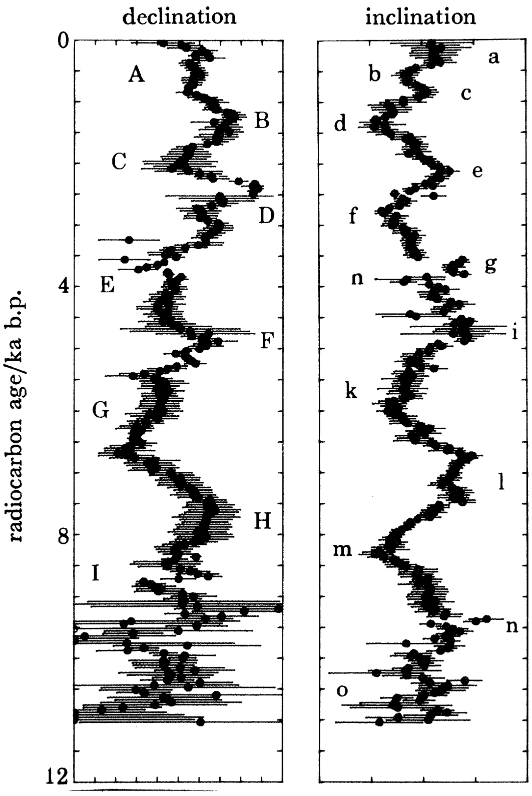

FIGURE 1. Type-curves of geomagnetic secular variations recorded by lake sediments from east-central North America (43–48° N, 82–98° W). Curves from individual cores have been stacked at 40 year intervals and standard error bars are shown at each level. The scale divisions of declination and inclination represent 10°. The timescale, as in later figures, is in uncalibrated radiocarbon years before present (b.p.).

the relation between west European and North American palaeomagnetic secular variation inclination data for Holocene times.

(*c*) *European type-curves*

Palaeomagnetic results from Holocene lake sediments are available for many parts of Europe, ranging from Greece (Creer *et al.* 1981) northwards through Poland (Creer *et al.* 1979) to Finland (Thompson & Stober 1977) and westwards through Switzerland (Creer *et al.* 1980) to the U.K. (Thompson & Turner 1979; Turner & Thompson 1981). Considering the scale of the spatial variations in the geomagnetic field for any given historical epoch, it would not be sensible to construct a single pair of type-curves for the whole of this area.

Of all the European data, those from Lake Windermere and Loch Lomond in the U.K. (*ca.* 55° N, *ca.* 4° W) are the most comprehensive and have the tightest dating control. Therefore we have used these to produce the type-curves shown in figure 2. The combined records from Loch Lomond and Lake Windermere have been used to construct our type-curves shown in figure 2 back to *ca.* 5000 years b.p., beyond which only Lake Windermere records are available. Individual core records, already transformed to a 'preferred' timescale and computed at equal 40 year time increments were made available to us by G. M. Turner. We rotated the directions and normalized the amplitudes as described in §2*a* before stacking them and computing standard error bars at each time-horizon. There are some important differences between the type-curves shown in figure 2 and those presented in figure 5 of Turner & Thompson (1981): first, those authors rotated their coordinate system so as to set both the mean inclination and the mean declination equal to zero while in ours the mean inclination is set at the axial dipole field value *ca.* 70°; second, they included results from Lake Geirionydd as well as from Loch Lomond and Lake Windermere; third, their timescale is in calendar years while we have used ^{14}C years.

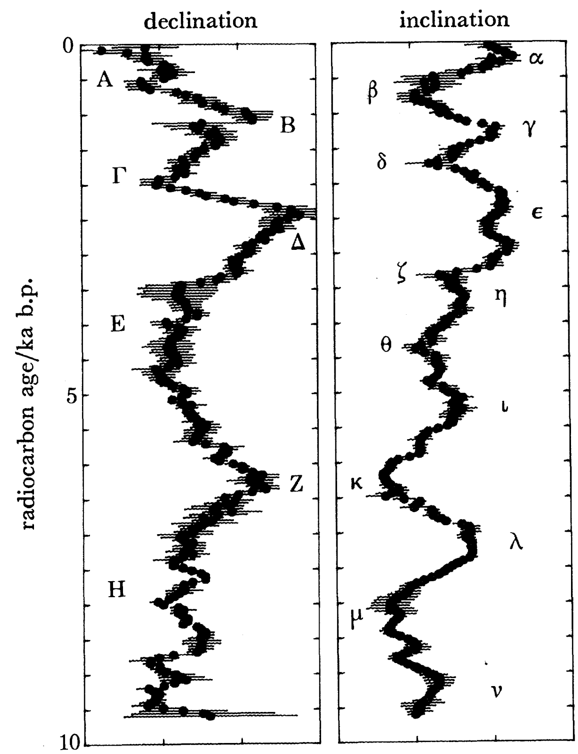

FIGURE 2. Type-curves of geomagnetic secular variations recorded by lake sediments from Lake Windermere and Loch Lomond, U.K. (*ca.* 55° N 4° W). Curves from individual cores have been stacked at 40 year intervals and standard error bars are shown at each level. The scale divisions of declination and inclination represent 10°.

The type-curves of figure 2 show that declination and inclination vary with amplitudes of about ± 10° (the scale divisions denote increments of 10°). These amplitudes are less than those recorded along the North American curve, and we attributed this to systematic differences in the physical properties and in the rates of deposition of the respective sediments (see §1*b*).

The principal features of the recorded secular variations are labelled with capital Greek letters A to H (declination) and lower case Greek letters α to ν (inclination). The same patterns can be recognized along palaeosecular variation records obtained for Greece and Poland (both of which extend back to 6000 years b.p.) and also for Switzerland (extending beyond the U.K. record, to *ca.* 14000 years b.p.), though the dating control is not as good for these regions.

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3. Virtual geomagnetic pole plots

(a) V.g.p. and Bauer plots

It is instructive to study the pattern of movement of the geomagnetic vector with time. This may be done conveniently either by constructing Bauer plots of declination, D, against inclination, I, or by plotting virtual geomagnetic pole (v.g.p.) paths.

Runcorn (1959) showed that a moving magnetic source in the Earth's core will cause the north pole of the magnetic vector, if viewed towards its north-seeking end at a fixed point on the surface, to rotate clockwise (anticlockwise) for a westward (eastward) motion of the source (see, for example, Skiles 1970). The same rule applies to the motion of the north v.g.p.

However, it is important to stress that the converse of this rule will not normally be true: that is to say clockwise (anticlockwise) looping of v.g.p. paths or Bauer plots cannot be interpreted uniquely in terms of westward (eastward) drifting sources. For example, it is shown in §5 that simple non-drifting but oscillating sources can also cause looping of the geomagnetic vector in both senses.

(b) Description of North American and European v.g.p. paths

V.g.p. paths smoothed over 400 year moving windows have been constructed for the palaeomagnetic directions shown in figures 1 and 2. From about 600 years b.p. to the present, both plots show clockwise motion (figure 3*a*). The U.K. curve shows an anticlockwise loop between *ca.* 1750 and *ca.* 750 years b.p., in agreement with archaeomagnetic results (Aitken 1970), but the corresponding part of the North American curve follows a very narrow loop, almost linear, between *ca.* 3750 and *ca.* 2000 years b.p. Both paths show open clockwise looping and both show a more or less linear excursion at about 3000 years b.p., which is of shorter duration as viewed from North America (figure 3*b*). From *ca.* 5500 to *ca.* 4000 years b.p. the North American curve follows an open clockwise loop whereas the corresponding U.K. loop is elongated. The amplitude of v.g.p. motion recorded in both curves is relatively small (figure 3*c*). In figure 3*d*, which covers *ca.* 9000 to *ca.* 5500 years b.p., the North American curve follows a broad open clockwise loop whereas the U.K. curve follows an elongated loop between *ca.* 6750 and *ca.* 5750 years b.p. preceded by a small narrow anticlockwise loop from *ca.* 8000 to *ca.* 6750 years b.p., which in turn is preceded by two small anticlockwise loops. Thus the sense of movement along the v.g.p. curves is almost exclusively clockwise and open for North America and mainly anticlockwise and elongated for the U.K. The North American path for *ca.* 10900 to 9000 years b.p. and the European path constructed from the results from Lac de Joux (Creer *et al.* 1980) (not illustrated here) show essentially anticlockwise motion with an open loop running to *ca.* 9000 from *ca.* 10200 and from *ca.* 12750 b.p. respectively, preceded in the Lac de Joux curve by an open clockwise loop.

(c) Discussion

The North American v.g.p. path shows open looping in a clockwise sense for the last 9000 years except a short period between *ca.* 1800 and *ca.* 800 years b.p., but the character of the U.K. path is more variable. The sense of looping of the v.g.p. paths may be represented by plots of its curvature as a function of time, as shown in figure 4.

The sense of looping of v.g.p. paths or Bauer plots caused by geomagnetic secular variations has very often been interpreted in the literature in terms of the direction of drift of the sources in the Earth's core. The results of computer model experiments described in §5 clearly show that such interpretations should not be regarded as unique.

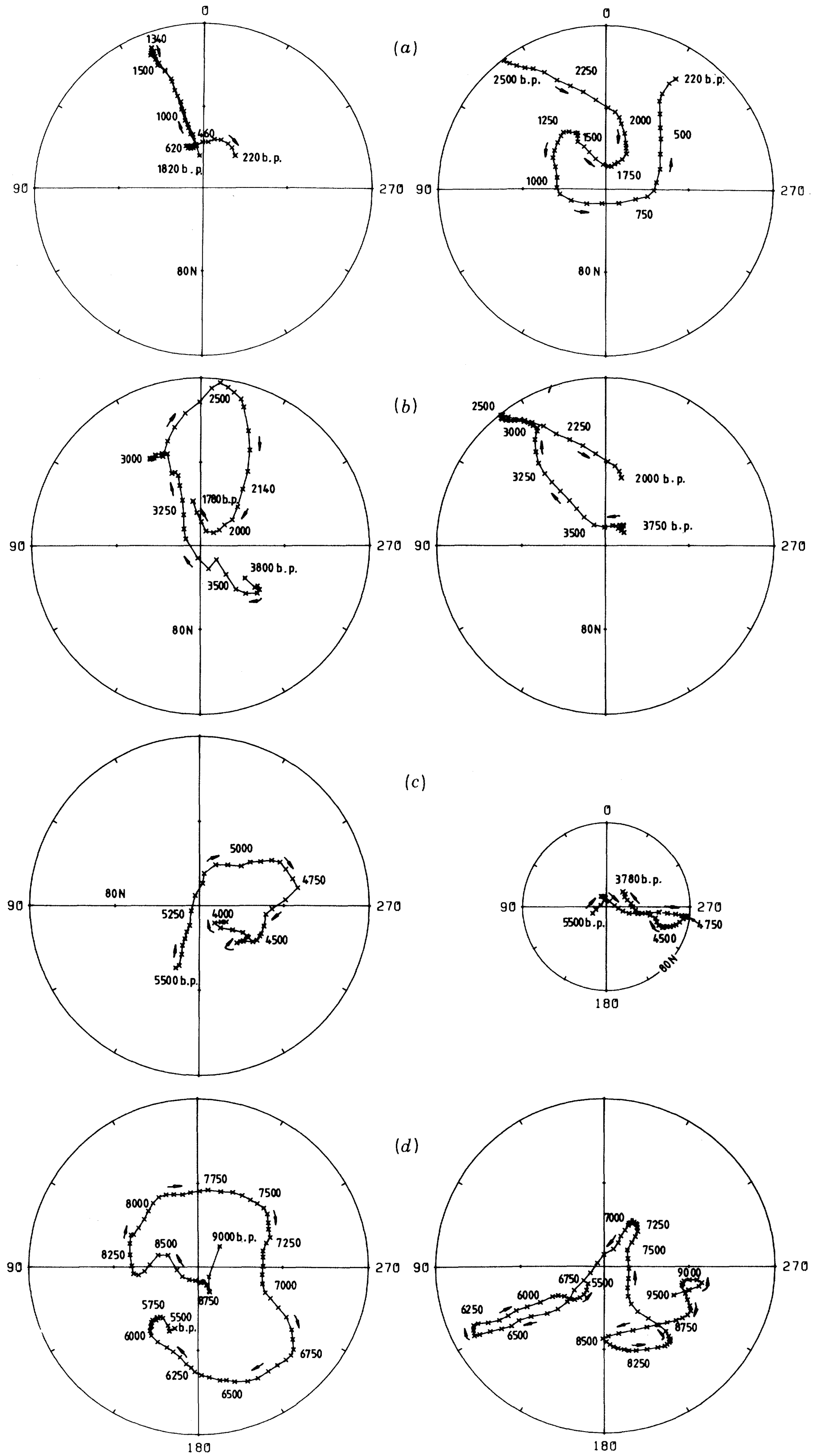

FIGURE 3. Plots of v.g.p. paths for North American (left) and U.K. (right) secular variation type-curves: (*a*) 0–2000 years b.p.; (*b*) 2000–3750 years b.p.; (*c*) 4000–5500 years b.p.; (*d*) 5500–9000 years b.p.

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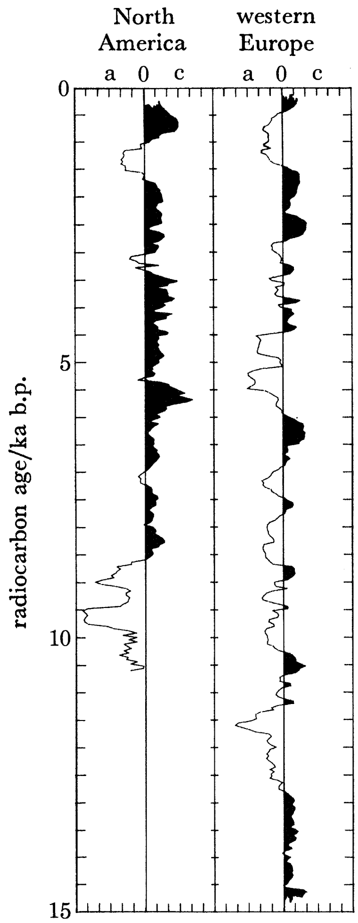

FIGURE 4. Plot illustrating curvature of North American and U.K. v.g.p. paths through Late Glacial and Holocene time: c, clockwise curvature; a, anticlockwise curvature.

4. COMPARISON BETWEEN THE EUROPEAN AND NORTH AMERICAN TYPE-CURVES

(*a*) *Introduction*

To facilitate comparisons between the curves, we first removed the long-term trends though we shall not attempt to interpret these in this presentation. We then normalized the amplitudes of the variations recorded by the straightened curves by setting the root mean square of the deviations from the mean value at each level equal for declination and inclination respectively. This necessitated multiplying the U.K. declinations by a factor 3.28 and the inclinations by a factor 1.03. The use of different factors must be related to the geomagnetic source/observation point geometry because a systematic difference in the magnetic recording process would require the same factor to be used for declination and inclination.

(*b*) *Comparison of the inclination type-curves*

The straightened curves are shown in figure 5. Our preferred correlation is illustrated by 14 tie-lines. Though other correlations are possible our approach was to choose the one involving the minimum phase shift. Our starting point was to note the marked similarity between the shapes of features k and l with κ and λ. On this basis the ages of each correlated pair of features as observed in North America are generally younger than the European ages. An exception is the short interval between *ca.* 7000 and 8000 years b.p. The shifts of the tie-lines from 0 to 7000 years b.p. average 374 ± 65 years. This may be interpreted in terms of an overall average annual westward drift of *ca.* 0.24°, which is consistent with the sense of looping of the North American v.g.p. paths in terms of Runcorn's rule but not for the U.K. paths (see figure 3).

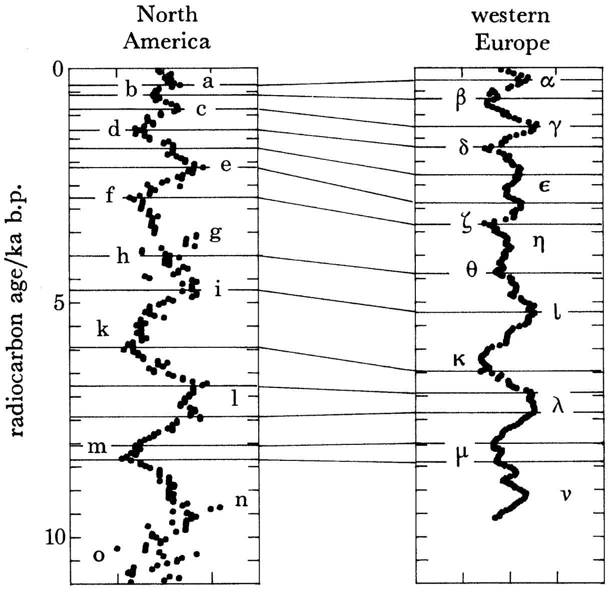

FIGURE 5. Illustrating the correlation drawn between the North American and U.K. type-curves of secular variations in inclination. The type-curves of figures 1 and 2 have been normalized and the long-term trends subtracted.

(*c*) *Comparison of the declination type-curves*

The modified declination type-curves, shown in figure 6, exhibit some strikingly similar features and also some other features that at first sight appear very different. From 0 to 4500 years b.p., good detailed correlation can be made as illustrated by the 10 solid tie-lines of figure 6. These average shift is -25 ± 36 years, which is not significantly different from zero (a negative sign indicates that a European age is younger than the corresponding North American one). From *ca.* 4500 to 8500 years b.p. the variations recorded in North America appear to be almost a mirror image of those recorded in Europe. This is illustrated in figure 6 by the series of six dashed tie-lines. The average phase shift is -390 ± 70 years.

Such reversed patterns of secular variations in declination could be reproduced by changes in intensity of a radial dipole situated somewhere under the North Atlantic. However, the secular variations so produced would be exactly out of phase in the two continents. We suspect that the phase shift that we have observed may arise from systematic errors in the timescales constructed respectively for the North American and U.K. data. This is quite possible because systematic errors can occur in radiocarbon dating sediments due, for example, to the presence of 'old' carbon. It is desirable to reconcile the negative correlation discussed above with the good positive correlation for 0 to *ca.* 4500 years. An oscillating radial dipole located either to the east or to the west of both sites would cause declination variations of the same sign at each site. One possibility is that the proposed source was drifting very slowly in longitude and passed under one of the sites *ca.* 4500 years ago so causing a reversal in the east–west component.

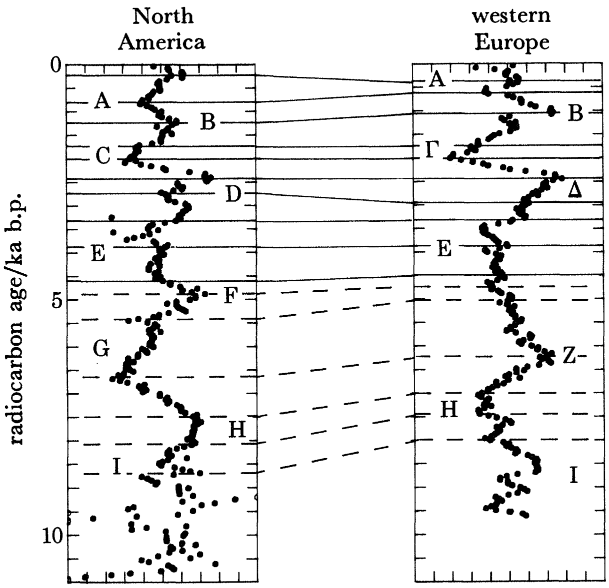

FIGURE 6. Illustrating the correlation inferred between the North American and U.K. type-curves of declination. The curves of figures 1 and 2 have been normalized and the long-term trends subtracted. Note that there appears to be a positive correlation from 0 to *ca.* 4500 years b.p. (solid tie-lines) and a negative correlation for before *ca.* 4500 years b.p. (dashed tie-lines).

Alternatively, the Atlantic source may have died out *ca.* 4500 years ago, at which time another new source became dominant.

(*d*) *Correlation coefficients*

We have computed linear regression coefficients as a function of phase shift for the inclination and declination type-curves illustrated in figures 5 and 6. For 0–4500 years b.p. (figure 7*a*) the correlation coefficient for declination peaks at $\rho = +0.67$ for a phase shift of *ca.* 30 years. The correlation for inclination is not as good: $\rho \approx +0.20$ for phase shifts ranging between *ca.* 350 and 750 years. For 4500–8500 years b.p. (figure 7*b*) there is a strong correlation between the U.K. and the inverted North American declination, reaching a maximum of $\rho = 0.87$ for a phase shift of -390 years. The correlation between inclination reaches a peak for a phase shift of $+360$ years ($\rho = +0.6$). Figure 7*c* illustrates the overall correlation coefficients for the whole of the curves, 0–8500 years b.p. The correlation coefficient for declination reaches a peak at $\rho = +0.63$ and that for inclination at $\rho = +0.39$.

Thus the correlation between the declination patterns is substantially stronger than that between inclinations, though the latter is markedly better for the lower part of the curves, as is evident from a visual inspection of figure 5. We are at present studying the problem of evaluation of significance levels.

5. Properties of specific non-dipole sources

(*a*) *Radial dipoles*

Radial dipoles have sometimes been preferred over spherical harmonics to model the spatial variations of the geomagnetic field at a given epoch (see, for example, Alldrege & Hurwitz (1964) or Harrison & Carle, this symposium). Radial dipoles also may be used to model

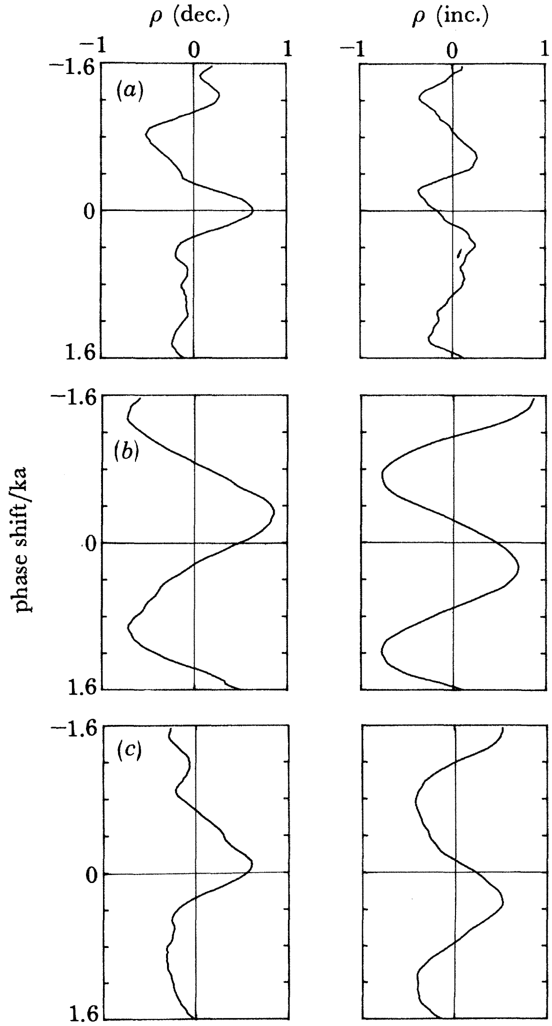

FIGURE 7. Correlation coefficients plotted against phase shift for the declination (on left) and inclination (on right) curves of figures 5 and 6: (*a*) 0–4500 years b.p.; (*b*) 4500–8500 years b.p., North American declinations inverted; (*c*) 0–8500 years b.p., North American declinations inverted before 4500 years b.p.

secular variations by allowing them to drift in the core relative to the Earth's surface or to fluctuate in intensity (see, for example, Creer 1977, 1981).

(*b*) *Drifting radial dipoles of fixed intensity*

Let us consider a specific model of two radial dipoles, at $r = 1750$ km, initially at 45 °N 0° E and 45° N 180° E, drifting westwards at an annual rate of 0.072°. Let the ratio of the intensities of radial and central dipoles be 0.28. (These parameters were chosen on the basis of the Alldredge & Hurwitz (1964) model.) Figure 8*a* illustrates the secular variations produced on the Earth's surface at 45° N 0° E. Note that the shape of the tangent function causes the inclination minima produced by r.d. no. 1 to be more pronounced than the maxima caused by r.d. no. 2 (figure 8*b*) The v.g.p. path corresponding to these secular variations in direction takes the form of an open loop and the motion around the loop is in a clockwise sense (figure 8*c*). Similar model calculations show that Runcorn's rule is obeyed at all geographic sites for radial dipoles at any latitude.

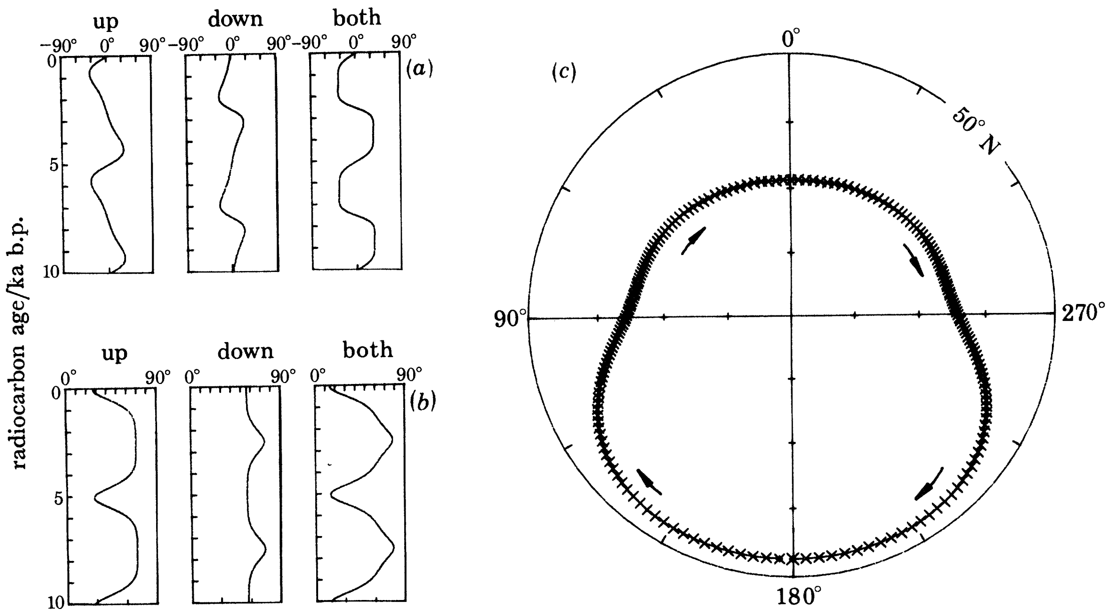

FIGURE 8. Variations in (*a*) declination and (*b*) inclination produced by two radial dipoles (r.d.s) of opposite sign drifting westwards round latitude 45° N. The observer is situated at 45° N 0° E. The upward-pointing r.d. (no. 1) starts at 0° E and the downward-pointing r.d. (no. 2) starts at 180° E. Rate of drift is 0.072° a year westwards; $m/M = 0.20$; $r/R = 0.28$. (*c*) The corresponding v.g.p. path.

(*c*) *Standing and oscillating radial dipoles*

Let us now consider the form of the secular variations that would be produced by two radial dipoles oscillating with the same frequency. Let the observer be at 45° N 0° E and two radial dipoles as specified in § 5*b* located in the outer core under 45° N 30° E and 45° N 30° W. Let them both oscillate with the same frequency. The v.g.p. path for the variations due to each of the radial dipoles separately or for both radial dipoles together if they are oscillating in phase will be a straight line, as shown in figure 9*a*, *b*. However, if there is a phase difference, the v.g.p. path will be in general elliptical as shown in figure 9*c*, *d*, with either clockwise or anticlockwise motion depending upon the sign of the phase difference.

(*d*) *A drifting and oscillating equatorial dipole*

The secular variations in declination and inclination that would be observed at 45° N 0° E and at 45° N 90° W due to a single radial dipole oscillating with a period, *T*, of 2000 years and drifting westwards at 0.072° a year (taking 10000 years to make one complete revolution relative to the surface) is shown in figure 10*a*. We have set the moment, *m*, to be zero at $t = 0$ and the record illustrated spans 10000 years. The variations in declination will be seen to be of opposite sign (as the North American and U.K. declination variations are before 4500 years b.p.) when the source is situated between the two sites. The corresponding v.g.p. path consists of a series of petals round which the v.g.p. moves in a clockwise direction.

(*e*) *General comments*

The form of the contours of the non-dipole field through historic epochs is such that the foci can be represented by electric current loop sources located in the outer core. For modelling purposes it is convenient to represent these current loops by radial dipoles located at rather greater depths.

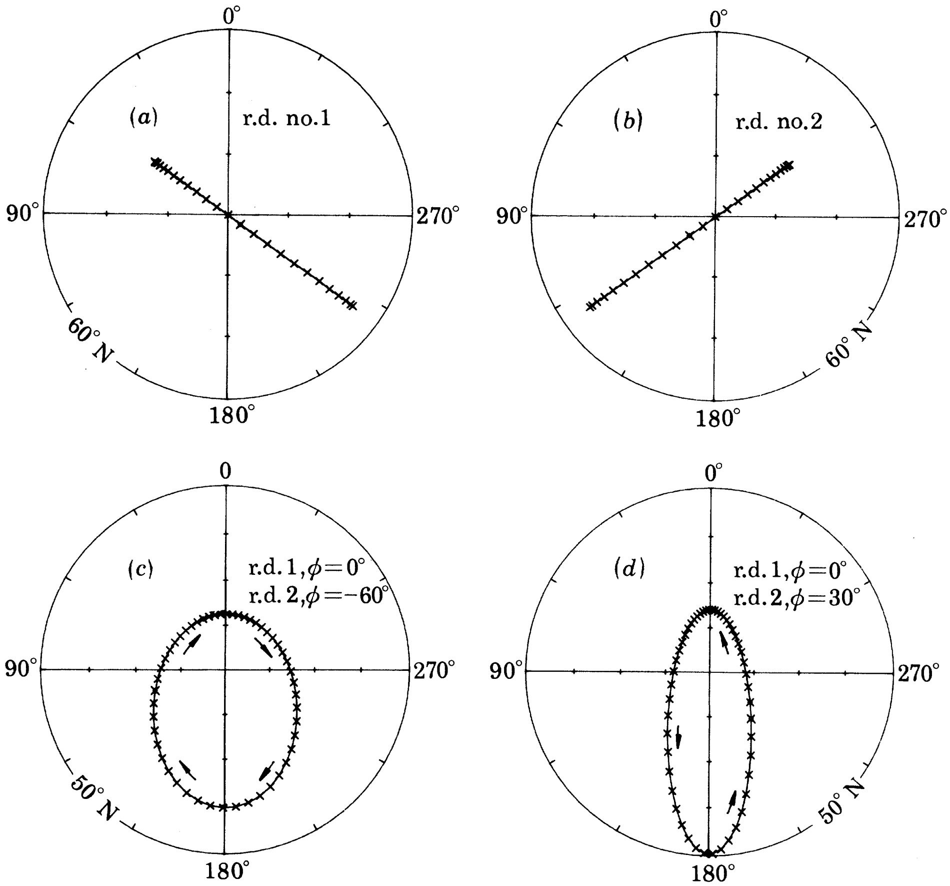

Figure 9. V.g.p. path corresponding to secular variations in geomagnetic field produced at 45° N 0° E by a single oscillating radial dipole (T = 2000 years) located at (*a*) 45° N 30° W and (*b*) 45° N 30° E. For both radial dipoles acting together, the magnetic vector will trace out an elliptical path with either (*c*) clockwise or (*d*) anticlockwise motion depending on the phase difference. $m_0/M = 0.17$; $r/R = 0.28$.

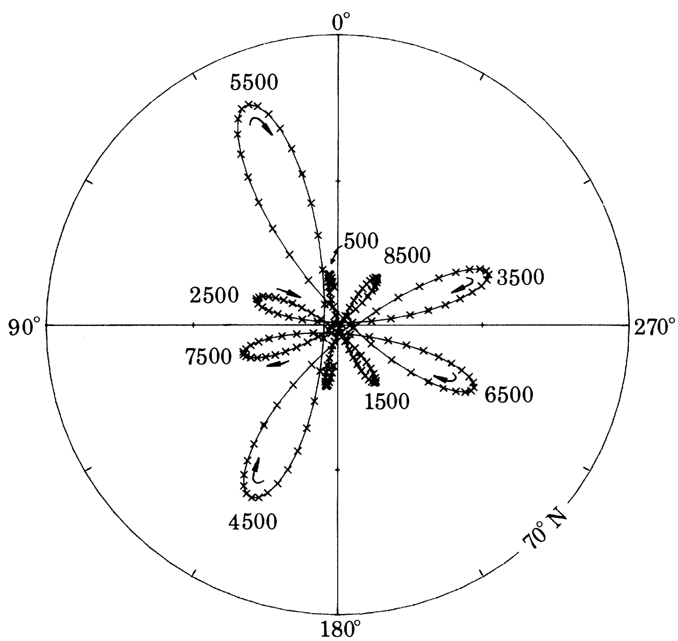

Figure 10. V.g.p. path produced by a radial dipole at r = 1750 km drifting westwards around the equator at 0.072° a year. Its intensity varies as $m = m_0 \sin(2\pi t/T)$, where T = 2000 years; $m_0/M = 0.17$, where M is the strength of the axial dipole, which is supposed constant. The observer is at 45° N 0° E and the r.d. starts at 180° E at t = 0. Numbers on the curves are radiocarbon years before present.

Drifting geomagnetic sources of fixed intensity produce Bauer or v.g.p. plots with characteristically open loops, as shown in figure 8. In general, however, for historic epochs, the intensities of non-dipole foci have been observed to change while they drifted and the timescale of the intensity changes would appear to have been shorter than that of drift. It would therefore seem to be appropriate to consider models of the type discussed in § 5*d*. If a particular geomagnetic source had a rather short lifetime during which it grew to a maximum in intensity and then decayed to zero as it drifted, the Bauer or v.g.p. plot would trace out one petal of a pattern like that illustrated in figure 10. Narrow loops occur along the v.g.p. paths of figure 3, particularly the U.K. one, and the sense of motion is sometimes clockwise, e.g. at *ca.* 6250 years b.p. An interpretation in terms of a single westward drifting source would thus be valid though not unique.

It would not be unique because, as shown in § 5*c*, a pair of standing geomagnetic sources that vary in intensity will produce v.g.p. paths for which the looping is equally likely to be clockwise or anticlockwise. The shape of such loops can range from circular through elliptical to linear depending on the relative phase of the sources. In general more than one geomagnetic source should be expected to contribute to the secular variations as observed at any place, so this kind of model is a realistic one. A pair of standing sources that waxed and waned in intensity only once would cause the geomagnetic vector to trace out only a limited portion of an ellipse.

If, when new data are obtained, clockwise and anticlockwise looping are found to occur equally frequently, it would seem reasonable to interpret the loops in terms of a mechanism of the type described in § 5*c* rather than to infer repeated changes in the sense of drift. On the other hand, any strong bias to one particular sense of looping may be taken as suggestive of drifting sources.

6. Conclusions

Type-curves illustrating geomagnetic secular variations for the last 10000 years have been constructed for east-central North America and northwest Europe. While lake sediments are clearly inferior to instruments as recorders of the higher geomagnetic frequencies, their strength is that they provide completely new information about the lower frequency part of the spectrum that must always remain inaccessible to instrumental observation.

On the historical timescale geomagnetic secular change is a highly complex phenomenon. It is therefore not surprising to find that no simple relation exists between the lake sediment records obtained from either side of the North Altantic. In particular, we are faced with the paradox that the declination variations appear to be dominated by standing geomagnetic sources, whereas the inclination variations are dominated by different, drifting sources. This paradox cannot be overcome by adjustment of the timescales.

It would be particularly useful if similar studies could be carried out at sites occupying a wider range of longitudes at mid-northern latitudes as recognized by resolution no. 7 adopted by I.A.G.A. at the Canberra Assembly in 1979.

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