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Long Period European Geomagnetic Secular Variation Confirmed

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Summary

The periodicity of geomagnetic secular declination changes for the last 10 000 yr, first observed from sediments in Lake Windermere, is verified by radiocarbon age determinations from Blelham and Ennerdale lakes in north-west England. No clear correlation of the British records can be made with Continental European data, suggesting that a complex, rather than simple, geographic pattern of long-period secular changes has existed. Geomagnetic declination variations, with several restrictive factors, can be used to date Flandrian sediments. It has recently been suggested that geomagnetic inclination and NRM intensity of the Lake Windermere record can be used for dating with an accuracy approaching ±200 years. Palaeomagnetic measurements on additional cores from Lakes Ennerdale and Blelham, north-west England and Lough Neagh, Northern Ireland, chemical and mineral magnetism analyses and basic geological principles show that these two magnetic parameters cannot reliably supply dates of the accuracy which can be derived from geomagnetic declination variations.

Introduction

Geomagnetic secular variation during the last 10 000 years has been recorded in most detail and accuracy by the remanent magnetization of lake sediments. Radiocarbon dating of the organic sediments produces an accurate time scale. In comparison with lacustrine deposits deep-sea cores, although providing extensive information about reversals of the magnetic field, have not accumulated sufficiently rapidly to record detailed secular changes of the geomagnetic field. Basic lava flows have been erupted too intermittently and cannot be dated with an accuracy which could establish continuous geomagnetic secular variation. Archaeomagnetic studies provide information about secular changes often more detailed than that which has been obtained from lake sediments, but are limited by the sporadic rise and fall of past Civilizations.

The lake sediments used for palaeomagnetic analyses were collected using pneumatically operated, 6-m long, piston corers designed by Mackereth (1958). Occasional laminations in the sediments show that the cored material is undisturbed, except close to the walls of the core tube. The top (~30 cm) of a 6m core may be disturbed due to (i) ' pumping in ' the corer anchor chamber, or (ii) the extremely high water content (>80 per cent) of the surface sediment. Mackereth (1969) designed a 1-m long ' mini ' corer to collect the uppermost sediments undisturbed.

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The Post-Glacial lacustrine sediments investigated are gyttja (allochthonous, nekron mud with a carbon–nitrogen ratio lower than 10). Mackereth (1966) has examined in detail the chemical composition of Post-Glacial gyttja from several lakes in north-west England. He relates the changing chemical composition of the Post-Glacial gyttja to the rates of erosion within drainage basins, which may be strongly influenced by climatic change.

Secular variations of the Earth's magnetic field, like reversals of the field, can be a useful dating tool. In this instance they can be applied to Flandrian climatic, vegetational and sedimentological studies. The method was first used by Thompson (1973) in comparing sedimentation rates in Lough Neagh, N. Ireland with those in Lake Windermere, N.W. England. Magnetic declination changes alone were correlated and confirmed by pollen zonation (O'Sullivan, Oldfield & Battarbee 1973). Creer & Kopper (1974) have recently proposed a correlation of the Windermere palaeomagnetic record with a cave deposit in Spain using magnetic inclination and intensity, in addition to declination, changes.

Established palaeomagnetic declination records of lake sediments now permit determination of sections of the record which are real (reproducible) and those which are simply noise (non-reproducible from lake to lake). In particular, radiocarbon analyses are now available for Flandrian sediments from three British lakes in which palaeomagnetic and radiocarbon studies have been made on the same cores.

Lake Windermere

The Lake Windermere dated sequence covers the longest period of time extending from the Oldest Dryas through Late-Glacial and Post-Glacial sediments to the present, and has been discussed in detail by Mackereth (1971). Palaeomagnetic measurements were first carried out by Mackereth on 2 cm thick discs of sediment. When the complete palaeomagnetic profile had been deduced, subsamples (comprising from four to seven discs according to organic carbon content) recording all of the extreme westerly and easterly oscillations of the magnetic field were grouped together by Mackereth, and their radiocarbon age determined (lab sample nos W 2267–2276) by M. Rubin of the U.S. Geological Survey. The oscillations in declination were found to have a periodicity of 2700 years using calibrated radiocarbon age determinations. Palaeomagnetic declination measurements have been repeated on four other cores from the South basin of Lake Windermere and extended to include inclination (Creer *et al.* 1972; Thompson 1973) but no additional radiocarbon age determinations have been made. One significant oscillation of magnetic inclination was found when inclination was high around 2000 years BP. This high in inclination was also reported by Thompson (1973) in cores from Lough Neagh and is the only oscillation in inclination which has been found to be repeatable in Holocene sediments from Britain. The systematic shallower inclinations reported from one core from Lake Windermere (Creer *et al.* 1972) are probably not a true record of geomagnetic field inclination but due to either the method of extrusion of the palaeomagnetic samples from the core tube, which has now been superseded, or to non vertical penetration of the corer (Thompson 1972).

Blelham Tarn

The Blelham sequence of organic gyttja, spans the period 10 000 yr BP to the present day. Two 6-m cores were collected. Core 73(1) was broken near the top. Core 73(1) (Fig. 1(a)) penetrates to the base of the Post-Glacial gyttja and is very similar in stratigraphy to that described with a full pollen diagram in Pennington (1965) (W. Tutin 1974, private communication). Core 73(2) (Fig. 1(b)) does not reach the base of the Post-Glacial gyttja. Deposition rates ranging from typically about

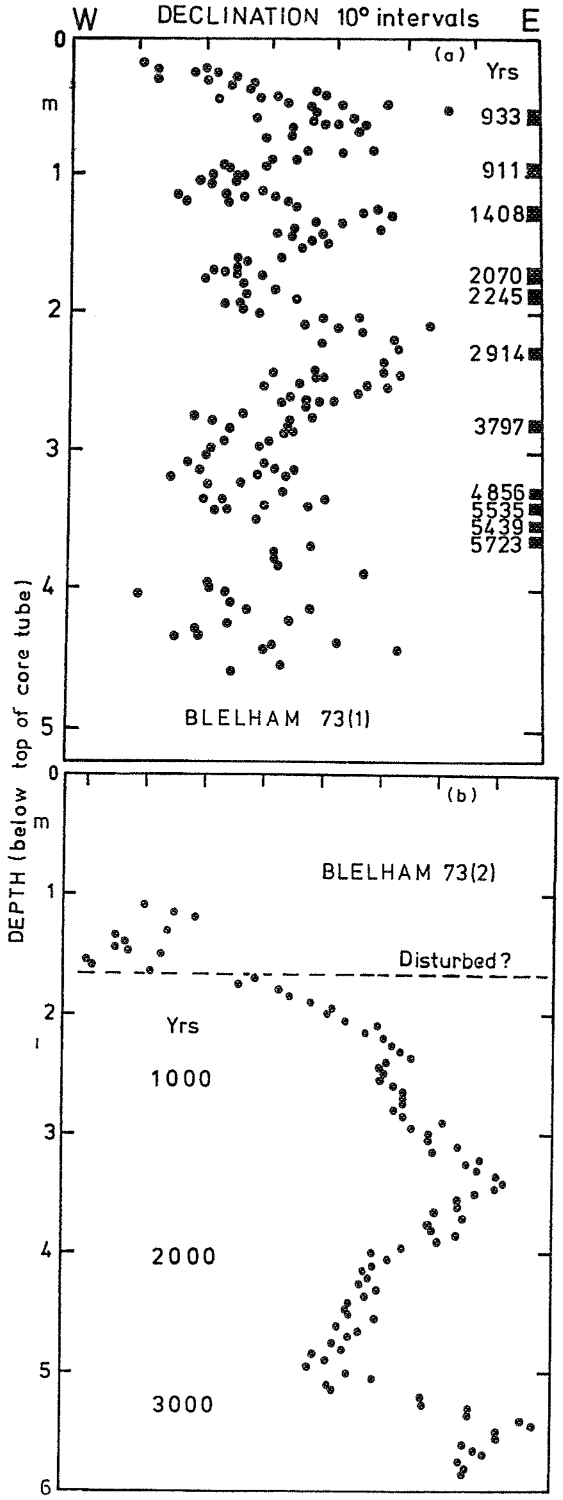

Fig. 1(a). Plot of declination *vs* depth in core Blelham 73(1). Blocks at right indicate material used for radiocarbon analyses. Conventional C^{14} age determinations listed.

(b) Plot of declination *vs* depth in core Blelham 73(2). Probable ages shown.

0·6 mm per year in the upper part (Pennington *et al.* 1976) to 0·2 mm per year in the lower part of the sequence are found in core 73(1). Hence geomagnetic changes preserved in the core vary in detail with depth (Fig. 1(a)). Eleven radiocarbon age determinations have been made by Harkness & Wilson (1975) at the Scottish Research Reactor centre on the 6-m long core 73(1) from Blelham. Palaeomagnetic declination and susceptibility measurements had previously been made on the whole of this core using non-destructive techniques developed by Molyneux *et al.* (1972) Molyneux & Thompson (1973). The radiocarbon age determinations apart from the two youngest (note inversion of ages) and the three concentrated near 350 cm around the (palynological) Elm decline (~5100 year BP) can be related to the long-period oscillation maxima of geomagnetic declination or else to the finer detail and are plotted in Fig. 5.

Apparent initial susceptibility has been measured on five mini cores collected along the length of the lake at roughly 100-m intervals. The cores are numbered 7, 4, 1, 11 and 9, where 9 is closest to the outflow and 7 furthest away. Mini core 1 and the 6-m core 73(1) are from the same locality, as are mini core 4 and core 73(2). Varying depths of susceptibility maxima and minima in the mini cores (Fig. 2) are due to different rates of deposition within the lake basin. Apparent susceptibility of the 6-m core 73(1) shows a minimum at 50 cm depth and an increase at 15 cm whereas mini core 1 from the same locality shows a minimum at 70 cm depth, an increase around 40 cm and a maximum at 20 cm depth (Fig. 2). It would seem that some 30 cm is missing from the top of core 73(1). The palaeomagnetic declination records from mini cores from Blelham are very poor but many do show a weak westerly maximum near 50–60 cm depth. This swing probably corresponds to the 1802 AD westerly excursion of the horizontal component of the geomagnetic field recorded in the sediments of Lake Windermere near 30 cm depth (Mackereth 1971) and should occur near the top of core 73(1). This palaeomagnetic interpretation is in good agreement with C-14, Cs-137 and

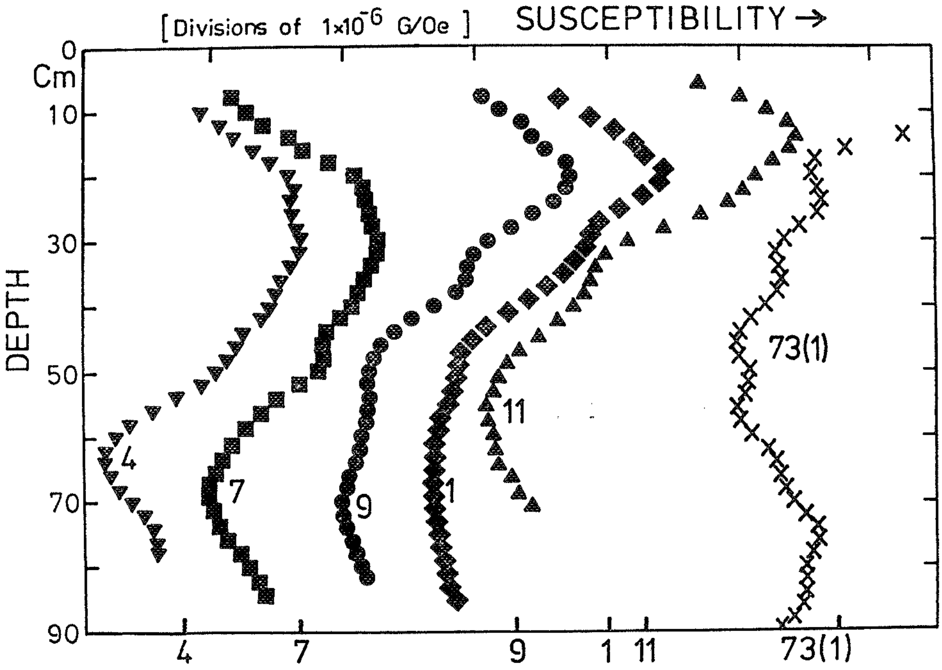

FIG. 2. Magnetic susceptibility (increasing to the right) *vs* depth in five 1-m cores and the top 90 cm of the 6-m core 73(1) from Blelham. Magnetic susceptibility of 3 G/Oe, for each core, is indicated by a short vertical line on the lower axis.

Pb-210 dates from the Blelham mini cores (W. Tutin 1975, private communication). The easterly maximum declination at 135 cm depth lies just below the radiocarbon age determination of 1408 ± 47 years at 120–130 cm and hence corresponds to the youngest easterly maximum recorded in the Windermere record. The westerly swing at 180 cm depth lies between the radiocarbon age determinations of 2070 ± 52 and 2245 ± 47 years BP at 164–174 cm and 181–191 cm. The easterly swing at 225 cm depth corresponds to the radiocarbon age of 2914 ± 52 years BP (222–230 cm). The westerly swing near 315 cm depth lies slightly above the radiocarbon date of 4856 ± 57 years BP from 323–329 cm depth and there is an indication of a subsidiary westerly maximum, near the top of the large swing, dated at 3797 ± 48 years BP (273–280 cm) which is also seen in the Ennerdale record. It is not possible to place accurately the Elm decline dates ($\sim$5100 years BP) on the magnetic declination record of Blelham because of the slow rate of deposition. Near the top of core 73(1) there are clear easterly and westerly swings which are taken to reflect finer detail of the geomagnetic field between 1400 and 130 years BP (O, BP = 1950 AD) and possibly can be correlated with the Lough Gall (Molyneux *et al.* 1972) or archaeomagnetic (Aitken 1970) declination variations. The oldest gyttja at 440 cm depth conformably overlies Late-Glacial clay

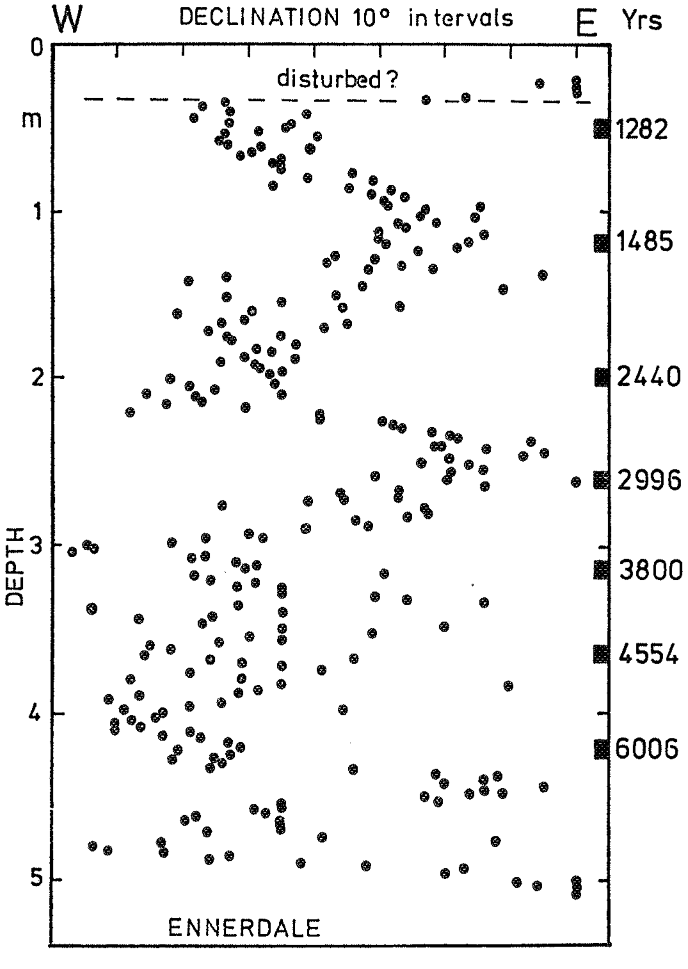

Fig. 3. Plot of declination *vs* depth in a 6-m core from Ennerdale lake. (Data of late F. J. H. Mackereth). Blocks at right indicate material used for radiocarbon analyses. Conventional C^{14} age determinations listed on the far right.

(~10 000 years BP) (Pennington & Bonny 1970) and although the rate of deposition of the gyttja is very slow there is some resolution in the magnetic record (i.e. easterly swing at 370–390 cm and westerly 400–430 cm) to lend confirmation to the two oldest swings of declination of the Windermere record not yet substantiated by any other radiocarbon age determinations.

Ennerdale lake

Palaeomagnetic measurements of the Ennerdale cores were made by Mackereth on orientated slices which were grouped for radiocarbon analyses at extremes of geomagnetic westerly and easterly oscillations. Seven radiocarbon age determinations (Nos SRR 178–184) have been made and published by Harkness & Wilson (1974). Mackereth's palaeomagnetic declination results are plotted in Fig. 3 and with the radiocarbon analyses, summarized in Fig. 5. The uppermost palaeomagnetic results are probably disturbed due to the coring process of the 6-m corer. The lower maxima of declination at approximately 120, 200 and 255 cm depth are dated as 14856±0, 2440±60 and 2996±55 years BP by radiocarbon and when plotted in Fig. 5 show good

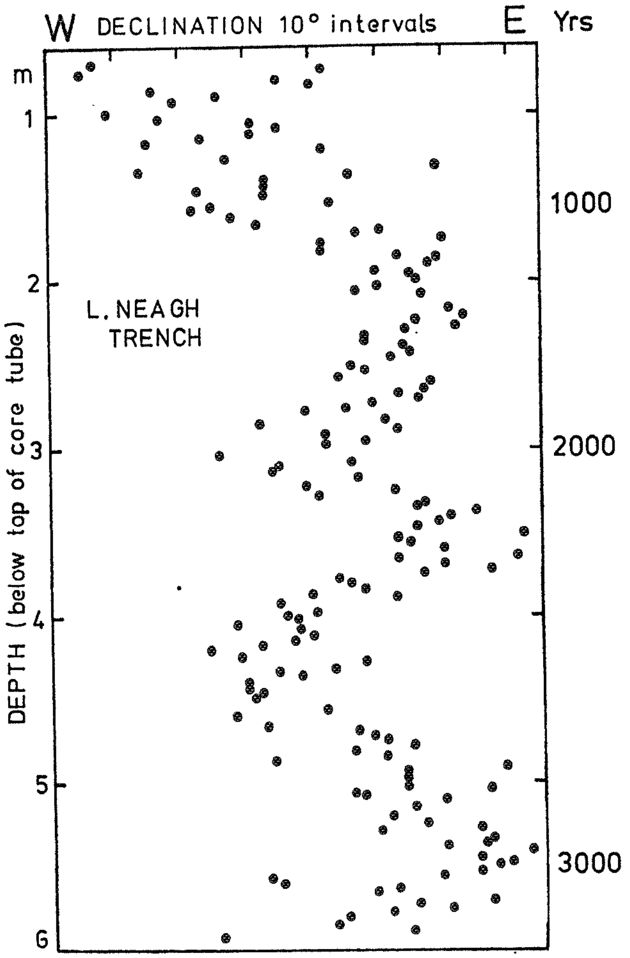

Fig. 4. Plot of declination *vs* depth in a 6-m core from the deepest part of Lough Neagh. (Top of core tube 25 cm above estimated sediment/water interface.) Probable ages listed on the far right.

agreement with the Windermere and Blelham results. Mackereth thought there might have been an eastward swing (in the 2700 year cycle) recorded at around 360 cm depth. However, radiocarbon age determinations from the westward swings at 310 cm and 420 cm are 3800±60 and 6006±75 years BP and from the intermediate easterly direction 4554±60 years BP. If these magnetic swings are instead interpreted as being finer detail on the long periodic swings then the Ennerdale radiocarbon results match with the Windermere and Blelham records. No radiocarbon age determinations have been made below 420 cm on this core so it is not possible to assign ages to the magnetic changes in the bottom metre of the core.

Lough Neagh

A core from the deepest part of Lough Neagh (Northern Ireland) shows very clear swings in magnetic declination (Fig. 4). Pollen assemblage zones (F. Oldfield 1974, private communication) show that the base of the core lies above the Elm decline and hence is younger than the base of the 3-m cores LN (AB 3, 4 and 9) from Antrim Bay (AB) in Lough Neagh on which natural remanent magnetic measurements have been made (Thompson 1973). Oldfield considers the base of the 6-m core corresponds to about 225 cm in core LN (AB 9). The easterly swing at 550 cm (Fig. 4) thus corresponds to the swing at about 3000 years BP (uncorrected age) of core LN (AB 9). Apparent initial magnetic susceptibility of the trench core peaks at 125 cm and by comparison with core LN (AB 9) suggests the easterly swing at 210 cm (Fig. 4) corresponds to the youngest easterly swing in the Windermere record. There is thus, in the

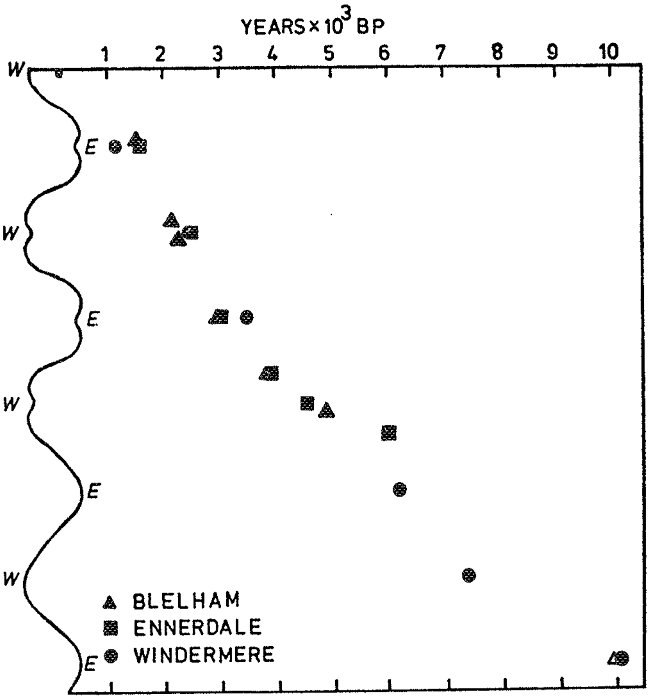

FIG. 5. Oscillations of magnetic declination *vs* conventional radiocarbon years for lakes Blelham, Ennerdale and Windermere. W. (West) and E. (East) indicate the major period swings. In cores with high deposition rates additional shorter period fluctuations have been determined and are indicated as single fluctuations within the major swings. Small circle 1820 westerly maximum. Open symbol lithological dating.

Trench core, an easterly maximum at about 360 cm depth and two westerly maxima falling between the two ages of 1500 and 3000 years BP. It would therefore seem that deposition in the trench had been much more rapid than in Antrim Bay at least between 1500 and 3000 years BP. The easterly swing at 360 cm depth is thus the small oscillation (which can be seen in cores LN (AB 3 and 11) in Fig. 3 of Thompson 1973) extended to reveal more detail.

This magnetic record illustrates the difficulties of dating cores on their magnetic record alone even when the magnetic trace is clearly defined, but also shows the detail of geomagnetic variations which can be deduced from lacustrine sites.

Resolution of detailed structure

Observatory records of the geomagnetic field during the last few hundred years have established in detail how the field varies on a time scale of 10's to 100's of years. These secular changes in direction are of an equivalent magnitude to the long-period variations first noted in Lake Windermere but are obscured in the older part of the Windermere record because of the slow rate of deposition (averaging about 0·3 mm per year). However when deposition rate is faster in a lacustrine sequence these more rapid variations begin to be resolved and complicate the palaeomagnetic record. In the most recent sediments these more rapid changes can be confirmed by comparison with the archaeomagnetic curve for Great Britain (Aitken 1970), (e.g. the uppermost metre of sediments from Lake Windermere or Lough Gall (Molyneux *et al.* 1972)). The more detailed record is discernible in parts of the Blelham and Ennerdale radiocarbon dated cores; and also in cores from Lough Neagh and Lake Ullswater, on which pollen assemblage zone dating only is available. The details are perturbations within certain major swings of declination and have been included in Fig. 5 as fluctuations superimposed on the long-periodic oscillation of declination.

Mean inclination

Although cores from lakes are generally unorientated it has been possible to estimate the mean inclination of the geomagnetic field by taking the average of mean inclinations from several cores. Thus in Lough Neagh seven cores which span the last 6000 years have an average inclination of 68·7° and a standard error of 2·3° in comparison to the inclination of the geocentric axial dipole field in Northern Ireland of 70·5°. Declination and inclination results from three of these cores have been published, (Fig. 3(a), (b), and (c) in Thompson 1973). Although the sense and amount of inclination deviation agree with the 'far-sided' effect noted by Wilson (1970) and Wilson & McElhinny (1974), for the Tertiary, over periods of about 10^6 years, the Lough Neagh mean inclination is not significantly different from the inclination of the geocentric axial dipole field at 54·7° North. Unfortunately no information about the average declination of the European geomagnetic field has yet been gained from lacustrine sediments as they are unorientated. Orientated sediments have now been collected from lakes using a Russian peat sampler (Jowsey 1966) to determine the local absolute directions of the magnetic field through the Late Weichselian and Flandrian.

Intensity changes

In deep-sea cores striking correlations of decrease in intensity of remanence at reversals of the geomagnetic field have been documented (Ninkovich *et al.* 1966). It is considered that the sediment is recording a variation in field rather than (a) changes in content of magnetic minerals, or (b) overlapping influence of normal and reversed fields on sediment taking several hundred years to acquire a stable remanence

(Opdyke 1972). Thus the modified Koenigsberger ratio NRM:x (natural remanent magnetization intensity divided by initial susceptibility) is often used in deep-sea sediments to reflect changes in intensity of the geomagnetic field (Harrison 1966; Opdyke 1972). Intensity changes from two Aegean deep-sea cores, spanning the last 27 000 yr reflect lithological variations in the sediment (Opdyke *et al.* 1972); but by eliminating sections containing volcanic ash and sapropel the pattern of changing intensity with time matches the trends established from archaeomagnetic investigations (Bucha *et al.* 1970), and Opdyke has suggested that the intensity changes represent the change in intensity of the Earth's magnetic field over the last 28 000 yr (Opdyke 1972).

For lacustrine sediments deposited during the last 10 000 yr which show no lithological changes it could thus be expected that intensity changes would reflect field intensity changes. Normalization of intensity changes by either apparent initial reversible susceptibility or saturation magnetization (J_{RS}) would then give an even closer monitoring of field intensity changes. Magnetic declination and inclination changes in lacustrine sediments were shown to be a true record of the geomagnetic field by comparison with Observatory records since 1580 AD (Creer *et al.* 1972). Similarly, if lacustrine sediments hold a record of past magnetic field intensity changes we should be able to confirm this by comparison with Observatory data since 1800 AD (Veinberg & Shibaer 1969). Modified Koenigsberger ratios (Q_n) from a Lake Windermere 1-m core decrease as the sediment becomes younger (Fig. 6), as would be expected from the Observatory records, if Q_n was primarily controlled by the geomagnetic field intensity. During the last 10 000 yr, however, Q_n from Lake Windermere has a maximum at about 5000 yr BP and no minima (Fig. 6) in contrast to archaeomagnetically derived geomagnetic intensities of a maximum at 1500 yr BP and a maximum at 550 yr BP (e.g. Cox 1968). Furthermore Q_n does not correlate between lakes or in certain cases within lakes. In a core from the deepest part of Lough Neagh. Q_n shows a broad double-peak about 2000 yr BP (Fig. 7). In contrast a gradual fall in Q_n from 6000 yr to the present is observed in cores from the shallower north-east part of Lough Neagh

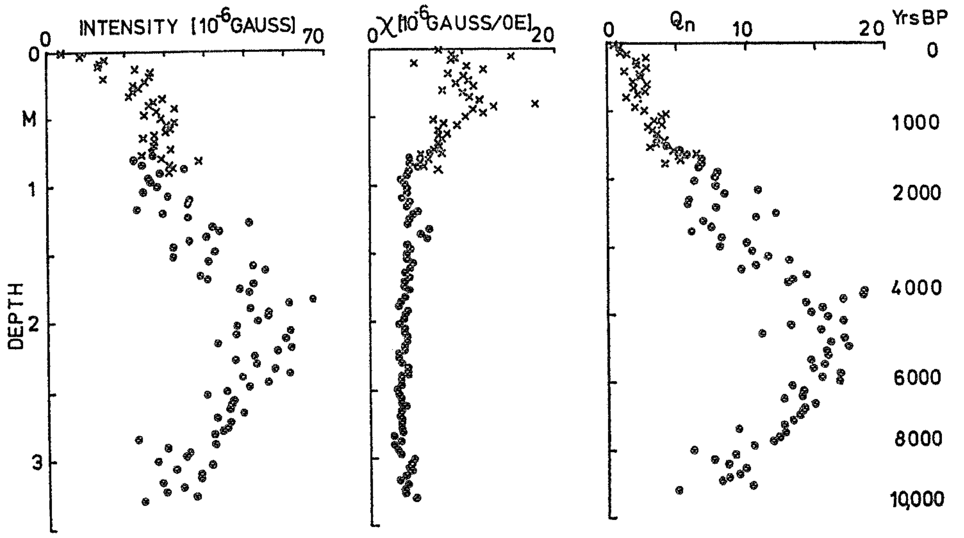

FIG. 6. Down core variation in magnetic intensity, initial susceptibility and modified Koenigsberger ratio in Lake Windermere. Crosses, data from a 'mini' core. Dots, data from a 6-m core. Ages indicated on right by correlation of magnetic declination and intensity with radiocarbon age determinations from Lake Windermere plotted in Fig. 5.

(Thompson 1972). Many lake sediment cores reveal a fall of Q_n in the last few hundred years. This fall is probably due to increasing importance of agriculture and ploughing around the lakes, leading to higher proportions of detrital magnetic minerals in the sediments and hence higher susceptibilities. The opposite trends of NRM and χ in the topmost 70 cm of Lake Windermere emphasize the difference in their controlling factors (Fig. 6). The remanence has been shown to be at least partly caused by haematite whereas initial susceptibility is mainly related to the magnetite content. Thus in Lake Windermere and Lough Neagh and many other British lakes neither NRM intensity nor Q_n are primarily controlled by field intensity. In apparently uniform lake sediments and possibly also in deep sea cores it is thus important to have shown that NRM intensity and χ or J_{RS} are due to the same magnetic minerals before using normalized intensities as indicators of ancient field intensities.

Magnetic investigations such as Curie point determinations, X-ray cell size determination of the magnetic extract, *J–H* curves and growth of IRM curves fail even to detect haematite in lacustrine sediments where magnetite is the dominant mineral. In an attempt to make some estimate of the variation of haematite of Post-Glacial organic gyttja in order to normalize the intensity variations, chemical analyses were carried out. Total iron and 'free' or 'active' iron were determined by atomic absorption. A sodium dithionite citrate process similar to that of Oades & Townsend (1963) was used to extract 'free' iron. Neither total nor 'free' iron showed any correlation with NRM, χ or J_{RS} through minor lithological changes. A more promising

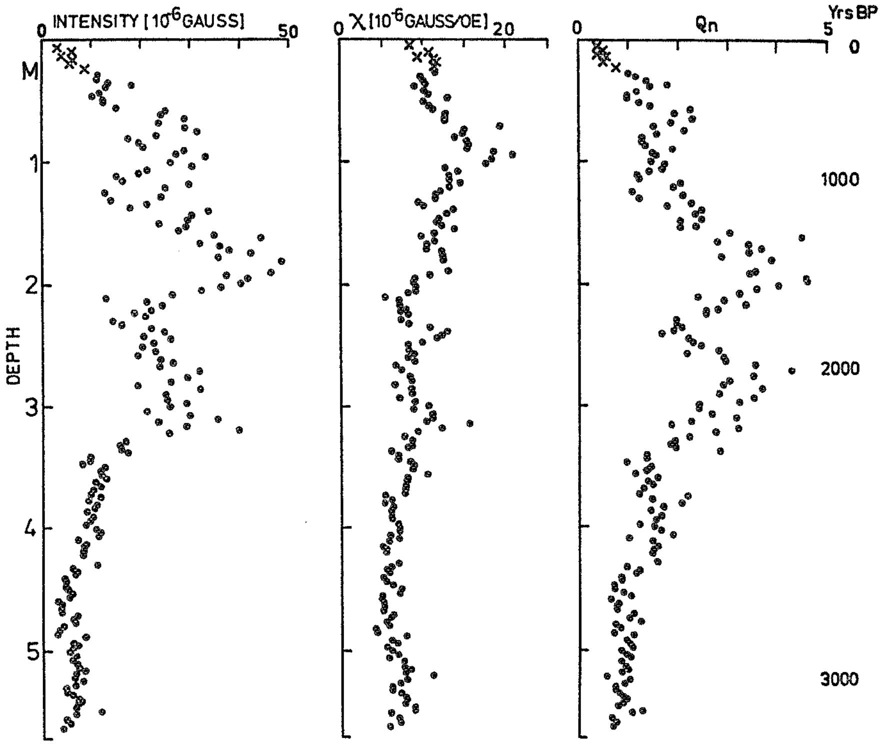

FIG. 7. Down core variation in magnetic intensity, initial susceptibility and modified Koenigsberger ratio in the deepest reach of Lough Neagh. Crosses, data from top of a 'mini' core. Dots, data from a core. Declinations of 6-m core plotted in Fig. 4. Ages indicated on right by correlation of Fig. 4 and Fig. 5.

method of determining abundance of iron minerals in lake sediments is to combine Mössbauer and standard X-ray methods of analysis with chemical analyses (Coey 1975).

Conclusions

(a) *Geomagnetic*

Considering Fig. 5 our main conclusion is that the long-period (~2700 yr) oscillations of declination discovered by Mackereth are clearly substantiated while more rapid variations are present when cores with higher deposition rates are investigated. The cause of the long-period oscillations remains unknown. The oscillations could, for example, be due to main field wobble, westward or eastward drift of non-dipole sources, fluctuation in intensity of stationary non-dipole sources, or combinations of each. These various mechanisms would, however, produce different secular changes in geographically separated localities.

Flandrian palaeomagnetic records from Switzerland (Thompson & Kelts 1974), the Aegean Sea (Opdyke *et al.* 1972) and the Black Sea (Creer 1974) show characteristic patterns so different from each other and from Britain's that it is extremely difficult to correlate between them. For example inclination changes from the south-easterly localities are much more pronounced than in Britain and inclination oscillations from the Aegean Sea have a period of 6000 yr, whereas the oscillations from the Black Sea have a period of 2800 yr, the same as the declination swings in Britain. It is clear then that long-period geomagnetic secular variation has been markedly different during the last 10^4 yr within Europe between sites. More data from new regions between existing sites are needed to determine over what distances the long-period variations can be correlated, and hence used as a dating tool, and to determine whether variations over the whole of Europe can be explained by a single simple oscillating or drifting dipole source, or how complex a model is required. Quaternary sediments from Greece, Finland and Sweden have been collected and are presently being investigated to help solve the above problems.

(b) *Geological*

Recent sediments can be dated in North-West Europe by comparing their palaeomagnetic declination record with the diagrammatic master curve of secular variation in Fig. 5. There are, however, several restrictions:

(i) The NRM must be stable: many shallow lakes in Scotland, England, Ireland, Wales, Sweden and Finland consistently have gyttja with a weak or unstable magnetic remanence whereas large deep lakes from the above countries contain gyttja with a stable, strong magnetic remanence.

(ii) The age of at least one horizon of the core must be known because of the repetitive nature of the master curve. This horizon is normally the top of the core, but if the uppermost sediments are missing from the record for example due to 20th century lake lowering, a single-pollen assemblage boundary or lithological boundary is sufficient.

(iii) The sequence to be dated must be long enough and of known relative orientation to have significant variations which can be matched to the master curve.

The method's precision can be gauged from the closeness of fit of the points in Fig. 5 to a smooth curve (or straight line if calibrated radiocarbon ages are used and the major swings truly periodic). The accuracy naturally also depends on errors involved in radiocarbon age determinations.

Palaeomagnetic inclination variations are so small in the British Flandrian that only one oscillation has been found to be reproducible within and between localities. Thus it is unlikely that the minor fluctuations apparent in the magnetic inclination record of Lake Windermere (Creer *et al.* 1972) can at present be used as a master curve for dating other sequences.

The parameter of magnetic intensity of gyttja is not primarily controlled by the past intensity of the geomagnetic field but by the physico-chemical environment in which it was deposited (Thompson 1973). Although similar sequences of changes of intensity of remanence may be found in Holocene sediments from different latitudes, the changes must be diachronous and hence magnetic intensity alone also cannot be used for accurate dating. The modified Koenigsberger ratio NRM:χ (natural remanent magnetization intensity divided by initial susceptibility) which in deep-sea sediments often reflects changes in intensity of the geomagnetic field is unlikely to provide a simple method of estimating field intensities in lacustrine deposits, unless conditions of deposition have been exceptionally uniform. Various magnetic parameters such as initial susceptibility, NRM intensity and saturation magnetization can, however, be extremely useful for correlating ages between cores within a single drainage basin, or when ash layers are common to different drainage basins.

The periodic oscillations of magnetic declination plotted in Fig. 5 are thus the only presently viable method of assigning magnetic ages to Holocene sediments in North-Western Europe. In other regions for example the Eastern Mediterranean where magnetic inclination and declination have varied significantly and probably periodically (Creer 1974), both parameters can be used for assigning magnetic ages.

Acknowledgments

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