Stratigraphic consequences of palaeomagnetic studies of Pleistocene and Recent sediments

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SUMMARY

Polarity reversals, excursions and secular variation of the geomagnetic field are examined as magnetostratigraphic tools in recent sediments. Polarity reversals and some excursions are recognizable worldwide, whereas secular variation occurs on a more local scale. The reliability of palaeomagnetic directions in recent sediments, as a record of the ancient geomagnetic field, varies widely. The necessity of acceptability criteria for using palaeomagnetic data in chronological studies is emphasized. Low temperature partial demagnetization of Recent sediments is described to illustrate its use, in conjunction with more conventional magnetic and geochemical techniques, in establishing the mode and duration of origin of the natural remanent magnetization.

THE FIRST PART of this paper discusses the applications of three geomagnetic phenomena—reversals, excursions and secular variation, to stratigraphic investigations of Pleistocene sediments with particular reference to Europe. The second part discusses two approaches to resolving the geomagnetic signal in the palaeomagnetic record of Recent sediments.

1. European Pleistocene sediments

(A) POLARITY REVERSALS OF THE GEOMAGNETIC FIELD

A polarity event is a chronological unit characterized by a single geomagnetic polarity which lasted between 10^4 and 10^5 years, while a polarity epoch lasted between 10^5 and 10^6 years. The polarity reversal history of the Pleistocene is well defined as a consequence of palaeomagnetic studies combined with K-Ar dating of continental basalts (Dalrymple 1972). The Pleistocene in Europe spans part of three polarity epochs, namely the Gauss (normal), Matuyama (reversed) and Brunhes (normal). At least two polarity events in the Matuyama are observed (van Montfrans 1971). A tool for resolving many Pleistocene stratigraphic, palaeontological and palaeoclimatic problems is thus available.

In Britain reversely magnetized Pleistocene sediments are found very infrequently. By contrast in the Netherlands, only 300 km away, reversely magnetized sediments are of similar abundance to normally magnetized sediments and furthermore the sequence of polarity changes can be matched with the known polarity reversal history for the last 2·5 Ma. The palaeomagnetic direction data combined with pollen analysis have led Zagwijn (1975) to suggest that Quaternary sedimentation in Britain is characterized by long *hiati* as shown in Fig. 1. Thus even the lack of reversely magnetized horizons is a powerful stratigraphic tool in the British Pleistocene.

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(B) GEOMAGNETIC EXCURSIONS

A polarity excursion is defined as a sequence of virtual geomagnetic poles which extend beyond 45° of latitude from the pole and return to the original polarity after a short period of time. Such excursions are clearly of high potential value in detailed stratigraphic studies.

European Brunhes geomagnetic excursions are a point of controversy. They are not as well determined as in other parts of the world, e.g. Australia (Barbetti & McElhinny 1972) and North America (Creer *et al.* 1976). Although there are a number of palaeomagnetically well documented excursions, e.g. Laschamp (Bonhommet & Zahvinger 1969), they are not closely defined in time. Standard sections, where the age is well controlled, could be expected to clarify these dating problems. However, they have, to date, presented problems involving distinguishing the geomagnetic signal in the palaeomagnetic record from sedimentologically controlled disturbances.

About 12 500 years BP has been suggested as the time of a geomagnetic excursion. The length of time of this excursion has been estimated to be as short as 50 years by Morner (1976) and about 300 years by Noel & Tarling (1975) and Noel (1975). In certain sites this excursion is based on the palaeomagnetic direction of one sample. The possibility of spurious data must in these circumstances be carefully assessed. Watkins (1971) has presented strong arguments for very critical evaluation of data when inferring short geomagnetic events from sediment cores. It is obvious that his warnings must be followed in this example. Watkins further has drawn attention to "The Reinforcement Syndrome" problem of interpreting such data. Unfortunately this aspect of analysing data is already involved in the assessment of European Brunhes excursions. For example dissimilar palaeomagnetic behaviour around 12 500 years ago at Windermere (Thompson 1973) (large declination swings, minor inclination fluctuations) and Gothenberg (Morner *et al.* 1971) (reversal of inclination, low change in declination) have been correlated by other research workers (e.g. Clark & Kennett 1973, Noel & Tarling 1975) to reinforce the evidence for a worldwide geomagnetic excursion at this time.

In this type of investigation stringent quantitative criteria for the acceptability of palaeomagnetic measurements are clearly necessary. They should include: (i) consistency of directions between individually orientated samples, (ii) restriction to lithologies known to provide reliable results, (iii) laboratory stability tests, (iv) rejection of data possibly biased by 'bedding error', post-depositional movement or weathering. An excellent example of this approach are the six criteria of van Montfrans (1971). In the author's experience the two most important requirements are that the palaeomagnetic directions should have been observed in two separate cores from the same locality and in sediment of clay or silt grade.

(C) GEOMAGNETIC SECULAR VARIATION

Secular variation with periodicity between 5×10^2 and 5×10^3 years is better established in Europe than on any other continent. The palaeomagnetic data have been principally derived from fine detritus gyttja from lake sites in North

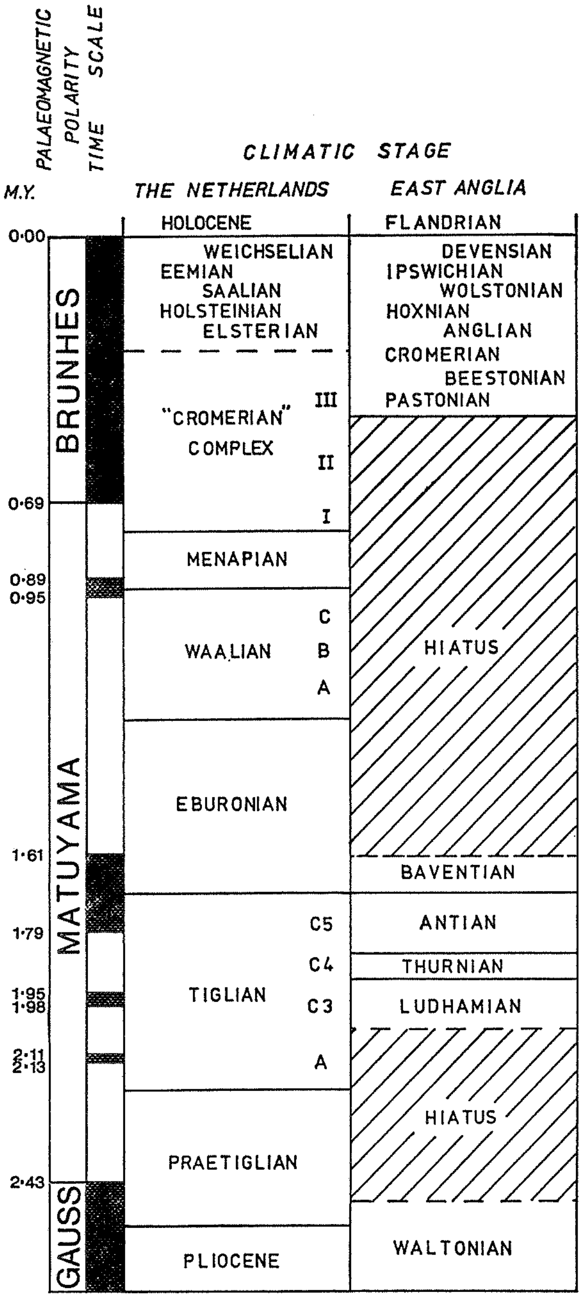

FIG. I
Polarity time scale (solid bars normal polarity, open bars reversed polarity) and stratigraphic subdivision of the Quaternary in the Netherlands and East Anglia (modified from Zagwijn 1975).

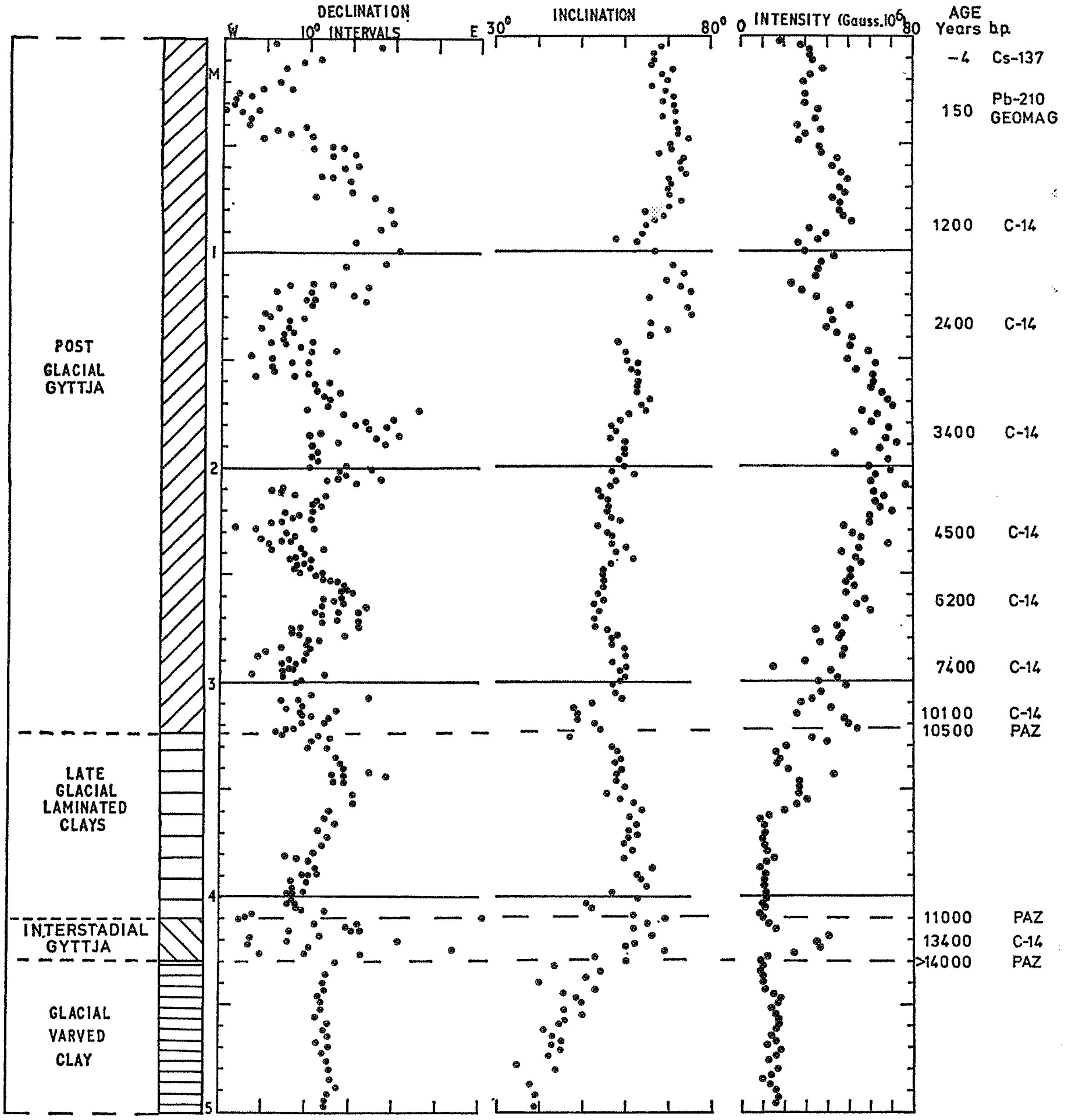

FIG. 2. Lake Windermere palaeomagnetic data 14 000 BP to present. Record built up from data from several cores. Dating from ^{14}C (conventional ages), ^{210}Pb, ^{137}Cs, pollen assemblage zones (PAZ) and 1820 westerly maxima in Magnetic Observatory records (Geomag).

Britain. The fluctuations of magnetic declination are greater than those in inclination (Fig. 2). Both these parameters are regarded as directly recording the past behaviour of the geomagnetic field whereas palaeomagnetic intensity, as in all palaeomagnetic studies, is a function of the proportion and type of magnetic grains carrying the magnetic remanence as well as the past strength of the geomagnetic field. In Fig. 2 we see that variation of declination is thus most likely to be of the most stratigraphic importance. Similar declination oscillations have been measured and dated by the ^{14}C technique in other lakes. These results are summarized in Fig. 3 which can be used as a master curve to date declination oscillations recorded in sediments deposited at a rate of around 1 mm/yr. The accuracy of this type of magnetic age dating is controlled by: (i) the quality of match between the new declination data and the master curve and, additionally, (ii) the accuracy of the ^{14}C dating of the sediments of the master curve. The areal extent over which this master curve is valid is not yet determined. Shorter period secular changes have similar forms over regions of continental extent and we can expect the longer period changes to follow the same areal pattern.

Difficulties will arise in attempting to date sediments in which the rate of sedimentation has changed markedly, for the following reason. Geomagnetic secular direction changes cover a wide frequency spectrum and different parts

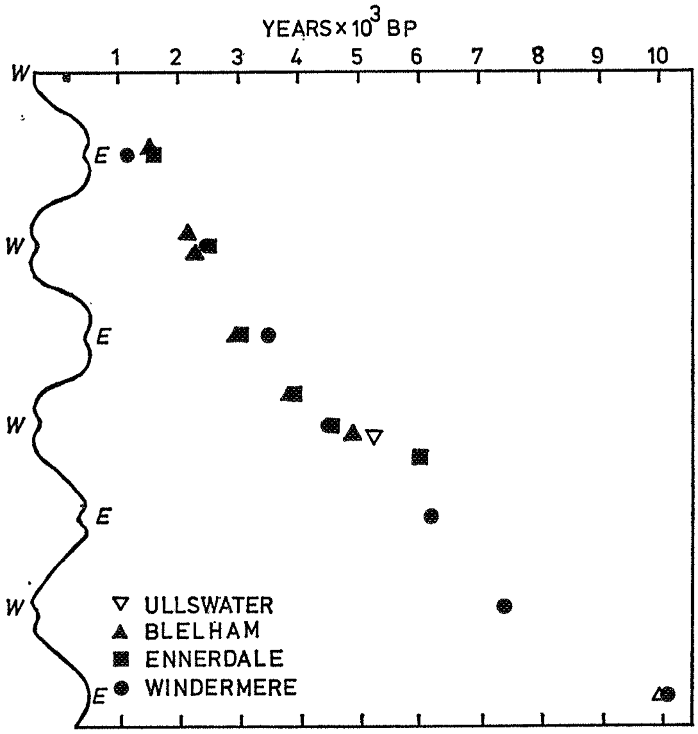

FIG. 3. Master declination curve for Northern Britain vs. conventional ^{14}C ages. Solid symbols, ^{14}C dating on same cores as palaeomagnetic measurements. Open symbols, pollen and lithological dating.

of the spectrum will dominate the geomagnetic signal recorded in sediments of different deposition rates. This effect will be particularly noticeable when the remanence is of a chemical origin and smoothing of the geomagnetic fluctuations occurs. The time over which the remanence is acquired, and hence the amount of smoothing can be dependent on rate of sedimentation. Without careful assessment of the rates of deposition involved the various geomagnetic oscillations could be confused because of their similarity in amplitude and apparent cyclicity.

The great practical advantage of this type of magnetic age dating is that it is very rapid and can be carried out while the sediment core remains undisturbed within its liner tube. Many limnic, estuarine, marine and even cave deposits have been found suitable for these studies, but it must be noted that certain Recent sediments have not retained a stable magnetic remanence formed in the geomagnetic field direction close to the time of deposition.

2. Recent sediments

(A) MAGNETIC INITIAL SUSCEPTIBILITY

Magnetic susceptibility provides a method of rapidly cross-correlating macroscopically homogeneous sediment cores and determining relative changes in rate of deposition (Thompson *et al.* 1975). Subtle changes in rate of accumulation can be seen reflected in the susceptibility traces from Lough Neagh in Northern Ireland (Fig. 4). Diatom analyses have confirmed that the susceptibility changes are synchronous in different regions of the lake. Chemical and pollen data show that the susceptibility peaks are registering an increased proportion of sediment of detrital, as opposed to organic, input into the lake. Susceptibility measurements

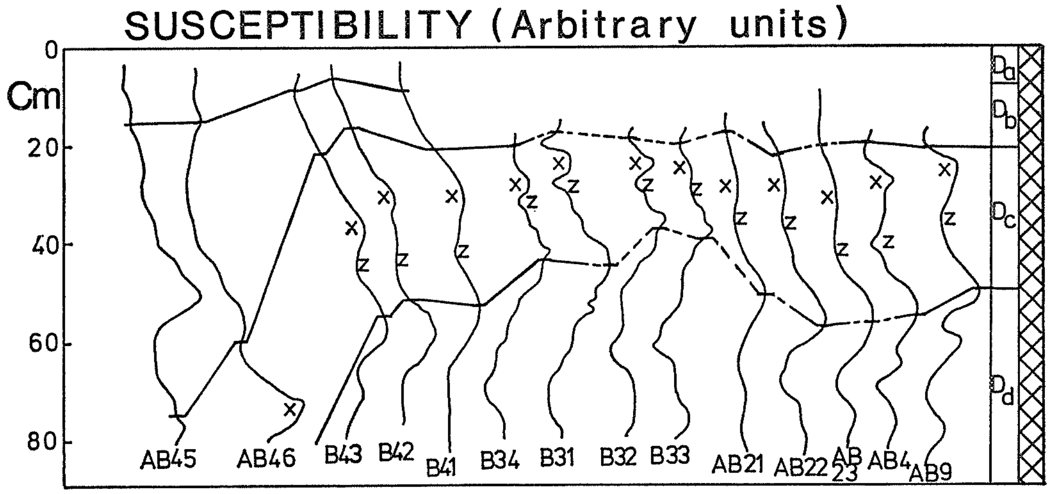

FIG. 4. Magnetic susceptibility and diatom boundary zones vs. depth in 14 cores from three sites in Lough Neagh.

can be made on the whole core. Deconvolution of the signal with the instrument response may be made in real time. Susceptibility peaks separated by about half the core diameter (typically 3 cm) can be resolved and a 10 m long core analysed in about 10 minutes. Present studies are investigating the possibility of using magnetic susceptibility as a quantitative measure of detrital components within a lake.

(B) GEOMAGNETIC SIGNAL VS. SEDIMENTOLOGICAL NOISE

Two simple but unsuccessful methods of producing best fitting curves to secular variation data are running means, or sliding averages, and polynomial fitting. It is widely recognized that the first approach passes spurious high frequency oscillations of no physical significance. Polynomial fitting generally is unsuccessful at picking out rapid changes or sharp kinks, which have physical significance, and appears to overemphasise the long period changes. Fourier smoothing combined with a cubic spline has been used to overcome the above problems (Thompson & Kelts 1975). However, a new approach using cross validation with a smoothing cubic spline has been developed by Dr Clark of Monash University (*pers. comm.*). It promises to have several advantages over previous methods. As well as giving the best estimate of the unknown function (the geomagnetic signal) by minimizing the error of predicting individual data points using the remaining data set, Clarke's method also calculates confidence limits of the geomagnetic signal.

The method gives a standard deviation of about 5° about the best fitting curve for the Windermere declination data of Fig. 2. If we assume that instrumental errors of measuring the declination data are 1° and orientation errors are 3° then the remaining 4° error (combined square of errors: $1^2 + 3^2 + 4^2 \approx 5^2$) is due to deposition processes or sedimentological disturbances such as microslumping or differential compaction. The confidence limits about the fitted signal will allow us statistically to compare functions from different cores and check their repeatability. Clark's adaption of the cross validation method has the possibility of being as beneficial to palaeomagnetic secular variation studies as Fisher's 95% probability cones of confidence have been in helping establish palaeomagnetic polar wander paths.

(C) MINERAL MAGNETISM EXPERIMENTS AND TIME OF ACQUISITION OF REMANENCE

As many of the Recent sediments mentioned in the investigations above are still being deposited at the present time, they can be studied in detail to determine the carrier and mode of acquisition of remanent magnetization.

Low temperature demagnetization of the natural remanent magnetization (NRM) of limnic sediments has proved to be considerably more critical than the coercivity spectrum of NRM in identification of the carriers of magnetization. In Fig. 5 low temperature demagnetization reveals up to three components carrying the NRM in different sediments. The sediment from Hjortsjön has 40% of NRM carried by pure hematite with a grain size of about 10 μm, 40% carried by multidomain magnetite and 20% by a third unknown component. The Lake

Windermere sediment has about 50% of the NRM carried by pure hematite, while at Björkeröds Mosse pure hematite carries none of the NRM. These three sediments and their various carriers of remanence all have mean destructive fields between 300 and 500 Oe. In Lake Windermere the hematite remanence is greatest at times of proportionally low detrital input. This suggests the hematite is authigenic and that its stable magnetization is due to chemical growth through the blocking volume. The time over which this chemical remanence is acquired can be deduced by examination of the palaeomagnetic record of sediments deposited during historic times, particularly since the 18th century when direct measurements of geomagnetic secular variation began. Comparison of NRM direction in most Recent sediments deposited at a rate of about 3 mm/yr with observatory data shows that fluctuations of both declination and inclination over 500 years can be easily distinguished although the fluctuations appear reduced in amplitude by a factor of around 25% in the palaeomagnetic record. This suggests that the remanence became stabilized in less than about 100 or 200 years after deposition. There are indications that greater smoothing of the geomagnetic signal has occurred at times of lower deposition rate. Aitken's (1975) comparison of archaeomagnetic data with the Windermere record of Fig. 2 shows little repeatability in inclination although declination matches well. Part of the discrepancy may be in the age correlation of the two records. When sediments of a higher deposition rate, e.g. Lough Neagh (Thompson 1973, fig. 3), are compared with Thellier's (1971) archaeomagnetic inclination data the high frequency components (period 200 years) are found to be smoothed out but oscillations with a characteristic period of 800 years (maximum about 1200 BP, minimum about 800 BP) can be recognized with amplitude reduced from about 15° to 10°.

Mineral magnetism experiments, especially low temperature and alternating field demagnetization, provide information on the mode and duration of origin

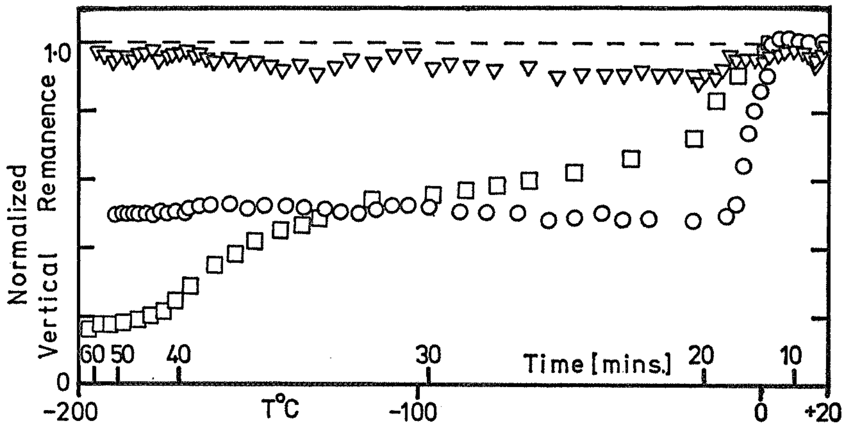

FIG. 5. Low temperature demagnetization of sediment from Lake Windermere (circles), Björkeröds Mosse (triangles) and Hjortsjön (squares). Morin transition (of hematite) occurs near −10°C, K_1 transition (of magnetite) near −140°C. On warming no memory effect is observed.

of NRM. Thus criteria of a more quantitative nature can be used to select sediments retaining a straight-forward record of past magnetic field changes. Statistical analysis (e.g. cross validation) of these records will delimit the consistent fluctuations which can then be used for constructing source models of the geomagnetic field, and for stratigraphic correlations.

3. References

Aitken, M. J. 1974. *Physics and Archaeology*, 2nd Ed. Clarendon, Oxford.

Barbetti, M. & McElhinny, M. 1972. Evidence of a geomagnetic excursion 30,000 yr. B.P. *Nature, Lond.* **239**, 327–30.

Bonhommét, N. & Zähringer. J. 1969. Palaeomagnetism and potassium argon age determinations of the Laschamp geomagnetic polarity event. *Earth Planet. Sci. Lett.* **6**, 43–6.

Clark, H. C. & Kennet, J. P. 1973. Palaeomagnetic excursion recorded in latest Pleistocene deep sea sediments, Gulf of Mexico. *Earth Planet. Sci. Lett.* **19**, 267–74.

Creer, K. M., Anderson, T. W. & Lewis, C. F. M. 1976. Late Quaternary geomagnetic stratigraphy recorded in Lake Erie sediments. *Earth Planet. Sci. Lett.* **31**, 37–47.

Cox, A. 1969. Geomagnetic reversals. *Science* **163**, 237–45.

Dalrymple, G. B. 1972. Potassium-argon dating of geomagnetic reversals and North American glaciations. *In* Bishop W. W. & Miller, J. A. (eds.), *Calibration of hominid evolutions*, Scottish Academic Press, Edinburgh.

Montfrans, H. M. van 1971. *Palaeomagnetic dating in the North Sea Basin.* Thesis, Amsterdam, 113 pp.

Morner, N-A. 1976. Palaeomagnetism and the relation between the Bredakra delta and the Fjaras Stadial and the Gothenburg magnetic excursion. *Geol. För. Stockh. Förh.* **97**, 294–7.

——, Lanser, J. P. & Hospers, J. 1971. Late Weichselian palaeomagnetic reversal. *Nature Lond.* **234**, 173–4.

Noel, M., 1975. The palaeomagnetism of varved clays from Blekinge, southern Sweden. *Geol. För. Stockh. Förh.* **97**, 357–67.

——, & Tarling, D. H. 1975. The Laschamp geomagnetic 'event' *Nature, Phys. Sci.* **253**, 705–6.

Thellier, E. 1971. Geophysique, Encyclopedie de la Pleiade, 235–376.

Thompson, R. 1973. Palaeolimnology and Palaeomagnetism. *Nature, Phys. Sci.* **242**, 182–4.

—— 1974. Palaeomagnetism. *Sci. Prog. Lond.* **61**, 349–73.

—— & Kelts, K. 1974. Holocene sediments and magnetic stratigraphy from Lakes Zug and Zurich, Switzerland. *Sedimentology* **21**, 577–96.

——, Oldfield, F., Battarbee, R. W. & O'Sullivan, P. E. 1975. Magnetic susceptibility of lake sediments. *Limnol. Oceanogr.* **20**, 687–98.

Watkins, N. D. 1971. Geomagnetic Polarity events and the problem of "The Reinforcement Syndrome" *Comments Earth Sci.: Geophys.* **2**, 36–42.

Zagwijn, W. H. 1975. Variations in climate as shown by pollen analysis, especially in the Lower Pleistocene of Europe. *In* Wright, A. E. & Moseley, F. (eds.) *Ice Ages: Ancient and Modern*, 137–52. Seel House Press, Liverpool.

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