[14]

Secular variation magnetostratigraphy

Among the great geophysical enigmas, whose unravelling promises to unlock many another of natures secrets . . . the cause of the secular variations of terrestrial magnetism plays a prominent part.

L. A. Bauer 1895

14.1 Introduction

This chapter concentrates on secular variation magnetostratigraphic dating applications within the past 10 000 years. It describes collection and measurement techniques which have been found useful in investigating lake sediments and presents type palaeomagnetic secular variation records of both declination and inclination, from seven regions of the world. These patterns of secular change can be used as master curves for dating newly acquired palaeomagnetic records.

Current interest in the use of sedimentary secular variation records as a dating tool largely derives from Mackereth's (1971) studies in the English Lake District. Mackereth demonstrated that repeatable palaeomagnetic declination records were held by the sediments of Lake Windermere and that the uppermost sediments revealed secular changes which could be matched with the known historical declination fluctuations of London. The first studies of the remanence of recent sediments were carried out in North America by McNish and Johnson (1938) and Johnson *et al.* (1948) on varved clays from New England and in Europe by Ising (1943) on late-Glacial varved sediments from Sweden. These early investigations were followed up in the 1950s by further studies of Swedish varved clays by Granar (1958) and Griffiths *et al.* (1960). Such varved sediments did not turn out to be ideal materials for palaeomagnetic work, as a number of quite complicated sedimentological effects such as inclination error, bedding error and the effects of bottom water currents, were associated with the remanence acquisition process of the varves (Section 13.2.2). These processes needed to be taken in account before a geomagnetic field signature could be discerned. It remained for Mackereth (1971) using his pneumatic corer (Mackereth 1958) to demonstrate the more reproducible, more straightforward secular variation records of organic-rich lake sediments and to open up the subject of secular variation magnetostratigraphy. The potential value of palaeomagnetic declination correlations within a lake can be clearly seen in Mackereth's results. The speed of whole core measurements (Molyneux *et al.* 1972) makes such correlations extremely attractive, first, as a reinforcement for the more traditional approaches to core correlations and, secondly, as a potential dating tool. Within- and between-lake palaeomagnetic declination and inclination correlations were presented by Thompson (1973) on sediments being investigated as

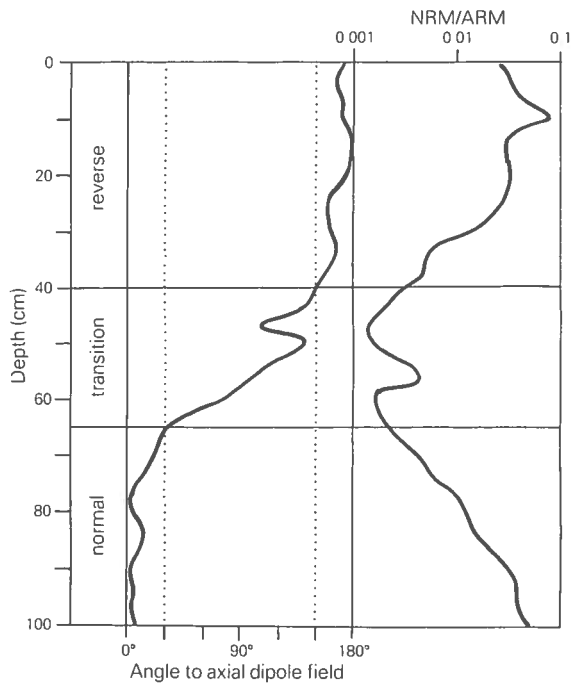

Figure 13.9 Diagrammatic representation of a polarity transition captured by the remanence of steadily accumulating sediments. Transitional directions are defined as vectors which deviate from the local axial dipole field directions by more than 30°. Low NRM/ARM ratios largely indicate times of low geomagnetic field intensity, but may also reflect low NRM intensities caused by unresolved dual component remanences.

in sediments it has often been stated that such field intensity changes persist for a longer time than the field direction changes. More recent palaeointensity data on lavas, however, suggest that the direction and intensity change more or less synchronously (Coe *et al.* 1983) and the early drop and late recovery of intensity commonly observed in sediment transition records is more likely to be a remagnetisation effect. Palaeomagnetic records of certain polarity transitions have now been obtained from different parts of the world. These records show that the predominantly dipole nature of the stable geomagnetic field is not preserved during the transitions. Two approaches to modelling the more complicated field structure during polarity changes are (a) by axial quadrupole and octupole field configurations and (b) by transitions through standing non-dipole fields. More observations of polarity transitions are needed to evaluate the applicability of each model and in particular more transition records from the southern hemisphere are needed to distinguish between transition fields dominated by quadrupole terms and those dominated by higher order axisymmetric terms (Fuller *et al.* 1979).

13.5 Summary

Since the first polarity timescales were constructed in the early 1960s, reversal magnetostratigraphy has developed into an important surrogate dating technique. Use of the polarity timescale played a key rôle in the discovery of sea-floor spreading and the development of plate tectonics. Probably all polarity intervals younger than 150 million years which lasted for longer than 0.1 million years have been discovered. Additional shorter polarity intervals are continually being found as more detailed geological records of particular time periods are discovered and investigated. The most recent firmly established global polarity reversal was the Matuyama to Brunhes transition which took place 700 000 years ago.

Geomagnetic reversal sequences are recorded in the thermal remanent magnetisation of igneous rocks, the chemical remanence of red beds and loess, and the detrital remanence of fine-grained sediments such as clays and limestones. This broad range of remanence and rock types makes reversal magnetostratigraphy a widespread chronological and correlation tool.

Details of geomagnetic behaviour during the reversal process are beginning to be unravelled. The characteristics of individual reversal transitions can be seen to be varied. Some reversal transitions display exceedingly complex changes with pronounced non-dipole, non-axisymmetric behaviour, while other transitions have performed simpler more axisymmetric switches between polarity states.

part of a wider environmental study of Lough Neagh in Northern Ireland (O'Sullivan *et al.* 1973). Diatom (Battarbee 1978), pollen (O'Sullivan *et al.* 1973) and magnetic susceptibility (Thompson *et al.* 1975) correlations demonstrated the quality of the within-lake remanent direction correlations and the potential of secular variation magnetostratigraphy for lakes such as Lough Neagh with severe ^{14}C dating problems. Older Quaternary sediments, recovered from dried-out lake basins, have also been subjected to palaeomagnetic study (Denham & Cox 1971, Liddicoat & Coe 1979, Verosub *et al.* 1980, Negrini *et al.* 1984). The pattern of geomagnetic changes at the time of deposition of these sediments has proved somewhat difficult to elucidate, but the original site at Mono Lake, studied by Denham and Cox, still provides some of the best evidence available for unusually large secular change. The Mono sequence contains palaeomagnetic direction changes of over 30° which are thought to have lasted some 500 years and to date from 25 000 years BP. Even older Pleistocene sediments contain palaeomagnetic direction fluctuations reminiscent of geomagnetic secular changes (Opdyke *et al.* 1972, Thompson *et al.* 1974, Kent & Opdyke 1977, Doh and Steele 1983), but in terms of magnetic dating the most widely used geomagnetic phenomena in the Pleistocene are the polarity reversals discussed in Chapter 13 which provide a remarkable global magnetostratigraphy.

14.2 Experimental methods

CORE COLLECTION AND WHOLE CORE MEASUREMENT

Standard palaeomagnetic methods can be used in magnetostratigraphic secular variation studies. However, as the palaeomagnetic signals under investigation have amplitudes of only a few degrees rather than the one hundred and eighty degrees found in polarity reversal studies, particular care needs to be taken at the sediment coring and sampling stages. Fortunately, for magnetostratigraphic purposes absolute sample orientation is not mandatory. A knowledge of the way up of sediment samples is sufficient for relative changes in remanence direction to be investigated. Constancy of azimuth permits relative declination to be used in addition to inclination. With this relative declination method the average palaeomagnetic declination is used as an estimate of the north direction.

A most convenient magnetostratigraphic technique has been found to be that of collecting long (>3 m) sediment columns using pneumatic (Mackereth 1958) or gravity corers and then measuring the natural remanence of the sediment while it remains undisturbed in its core liner. This technique permits the remanence direction changes to be logged quickly and avoids the sometimes severe problems of aligning short, overlapping core sections. The resolution of whole core measurements is almost as good as that of subsamples taken every 3–4 cm. In principle the best whole core measuring method is that of the three-axis open-ended cryogenic magnetometer. In practice, however, the instrument most commonly used for whole core remanence measurements is the fluxgate magnetometer, although it cannot provide whole core inclination data. This means that when using fluxgate instrumentation subsamples have to be taken to yield full palaeomagnetic direction data. Two palaeomagnetic coring problems which repeatedly arise are core twist and core warp. If the coring system in use cannot be modified to remove twist and warp then their effect can be partly taken into account by mathematically detrending the palaeomagnetic data. If there is a choice of sediments to be investigated in any study then sites more likely to provide good material for magnetic work can be selected. Research to date supports a preference for lakes that have (a) a minerogenic input with a magnetite component derived from either basic igneous material in the bedrock/drift or from enhanced top soil, (b) flat (slopes <2°), current-free sites below the level of wave action (>8 m depth), and (c) stiff, moderately organic-rich sediments.

SUB-SAMPLING

Thin-walled cuboid plastic boxes of around 10 ml volume are handy for extracting and holding subsamples and they fit easily into magnetometers. Commercial boxes are available with an arrow, to show orientation, a small hole, to allow air escape during subsampling and thin walls, to minimise sediment sampling disturbance. Duplicate subsamples can be very useful for assessing palaeomagnetic reproducibility, although much more information is to be gained by examining duplicate cores. An efficient sampling scheme is to subsample contiguously at least two cores, while occasionally (e.g. every metre) taking duplicate subsamples to check within-horizon reproducibility. No palaeomagnetic secular variation data from sediments

should be trusted unless reproducibility has been clearly demonstrated. Remanence should be measured while the sediment is still fresh, i.e. before it has dried out. Freezing of samples is likely to distort remanence directions.

STABILITY TESTING

An important weapon in the armoury of the general palaeomagnetic worker is that of partial demagnetisation. In the great majority of palaeomagnetic studies of older rocks, partial demagnetisation studies of multicomponent remanences play a most crucial rôle. Stability tests are also of great importance in reversal magnetostratigraphy studies. However, for very recent sediments, with their comparatively short, quiet histories, such stability studies turn out to be of lesser importance. Alternating field cleaning can be helpful in removing viscous remanence components, often acquired through drying during prolonged horizontal core storage, as illustrated in Figure 14.1. However, as only one significant stable remanent component is invariably found in fresh Holocene sediment, partial demagnetisation studies can, somewhat perversely, degrade rather than improve natural remanences. Such impairment arises from occasional small false remanences produced during the partial demagnetisation experiments. Zero field storage can be a very effective alternative method of removing small viscous drying components and many published Holocene palaeomagnetic results are of natural remanence measured after a period of zero field storage. Resistance to alternating magnetic fields is often used to boost claims of unusual Holocene and Weichselian remanence directions being reliable reflections of the ancient geomagnetic field. However, the magnetic stability of recent sediment holding a detrital or post-depositional remanence mainly reflects the stability of primary source minerals and not the propensity of the sediment to record faithfully the geomagnetic field. If sediment can be analysed while still fresh, before any significant drying out has begun, then secular variation magnetostratigraphic studies can be quite adequately performed with the portable fluxgate magnetometer (described in Section 6.3.2) and a mu-metal shield for zero field storage.

The intensity of the natural remanence of lake sediments is found to decrease on cooling. This phenomenon was originally interpreted as being due to the effect of the Morin transition occurring at –10 °C in haematite (Section 3.2.2) (Creer *et al.* 1972, Barton 1978). It is now recognised to be due to the randomising effects of grain rotations associated with the growth of ice crystals (Stober & Thompson 1979).

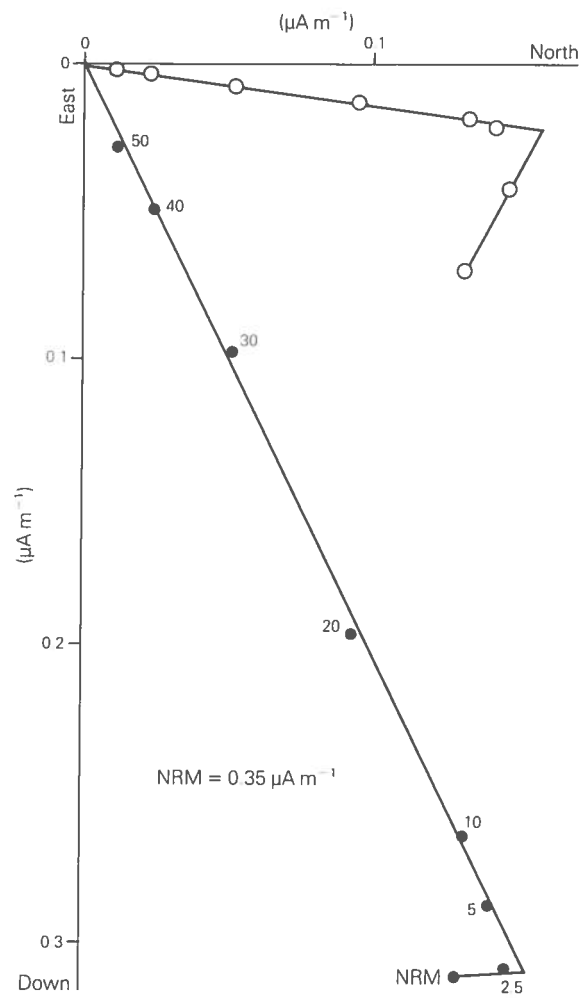

Figure 14.1 Orthogonal plot of alternating field demagnetisation of the natural remanence of sediment 6000 years old from Gass Lake, Wisconsin (sampled by S. Webb). Open and solid circles mark remanence changes projected on the horizontal and north/down planes respectively with partial demagnetisation in fields up to 50 mT. Two remanence components are seen. The high coercivity component points 8° east of north with a dip of 63° and is taken to be an original remanence, marking the direction of the ancient field. The low coercivity component is taken to be a 'viscous' drying remanence formed during 18 months' core storage. These preliminary results suggest that fresh Gass Lake sediments would have high potential for secular variation magnetostratigraphic work.

SEDIMENTOLOGICAL INVESTIGATIONS

The only sedimentological analyses commonly used in palaeomagnetic secular variation studies are estimates of particle size. Such granulometry studies are valuable, as it is widely recognised that coarse sediments make poorer geomagnetic recorders than fine sediments. Reconstitution and more rarely redeposition experiments, in beakers and tubes respectively, have been tried in connection with estimating palaeointensities (Section 13.2.2). Unfortunately, despite considerable effort, little progress has been made towards establishing a practicable palaeointensity method for lake sediments. However, reconstitution experiments at least show that lake sediments are capable of acquiring a post-depositional remanence (Section 13.2.2) in the ambient field direction. Fabric measurements, particularly through the use of anisotropy of susceptibility instrumentation (Section 6.3.3), are relatively easy and rapid to perform. Again, however, they are infrequently used in magnetostratigraphic studies as the magnitude of the anisotropy of most recent lake sediments is extremely low, well below instrumental noise levels. Laboratory procedures based on such fabric, granulometry or reconstitution experiments are badly needed to help distinguish those sediments capable of accurately recording the ancient field from those in which sedimentological effects have masked or surreptitiously mimicked geomagnetic fluctuations.

STATISTICAL AND TRIGONOMETRICAL METHODS

The two main trigonometric manipulations used by palaeomagnetic workers are (a) rotation on the sphere and (b) conversion of field directions to pole positions. Both calculations are straightforward, but they are quite time consuming without the aid of a computer. Descriptions of the manipulations are to be found in standard texts such as Mardia (1972) and McElhinny (1973). Two common frames of reference used in presenting palaeomagnetic directional data are with respect to (a) the vertical direction and (b) the local direction of a geocentric axial dipole field.

The chief palaeomagnetic statistical methods were formulated by Fisher (1953). They are based on his spherical distribution, which can be thought of as the equivalent of a Gaussian distribution on the sphere. Fisher (1953) gives the relevant formula for calculating the mean, its standard error, the variance and other useful statistics of palaeomagnetic data. Watson (1970) has been prominent in the further development of statistical aspects of palaeomagnetic data. Mardia (1972) summarises the wealth of statistical literature dealing with circularly and spherically distributed data. Computer programs for carrying out such trigonometric rotations and statistical calculations are widely available.

Hyodo (1984) has suggested that deconvolution using a digital filter can improve secular variation records in marine cores by correcting for amplitude attenuation and phase shifts occurring during the post depositional defrital remanence acquisition process.

14.3 Magnetic dating and magnetostratigraphy

THE HISTORICAL PERIOD

Sediment sequences spanning the past 400 years can be dated directly from their magnetic remanences by matching their palaeomagnetic secular variation signature with historically documented geomagnetic field fluctuations. Three examples of such field changes, observed over the last few hundred years, are shown in Figure 5.5 for London (Malin & Bullard 1981), Rome and Boston. The earliest known written record of the value of the local geomagnetic field comes from Hartmann's report concerning the 4° difference in magnetic declination between Nurnberg and Rome in 1510 AD as found in connection with the use of portable sun dials (Mitchell-Crichton 1939). The direction of magnetic declination appears to have been inscribed onto some sun dials and this permits the historical declination record to be extended back at least to 1492 AD when sun dials manufactured in Nurnberg and Augsburg by master craftsmen were marked with a declination of 11° to the east of north. Compass maps unfortunately do not appear to be of sufficient accuracy to be of use in establishing even earlier ancient field changes. Navigators' declination observations made since the sixteenth century provide the earliest geomagnetic field measurements in many parts of the world and have been collected together, most notably by Sabine (see Malin & Bullard 1981) and Veinberg (Veinberg & Shibaev 1969). Inclination measurements began in London in AD 1576 with the work of Norman (1581), while intensity measurements had to await the genius of Gauss (1833). All these historical records have been combined using spherical harmonic analysis with a few archaeomagnetic measurements to produce Figure 14.2 which

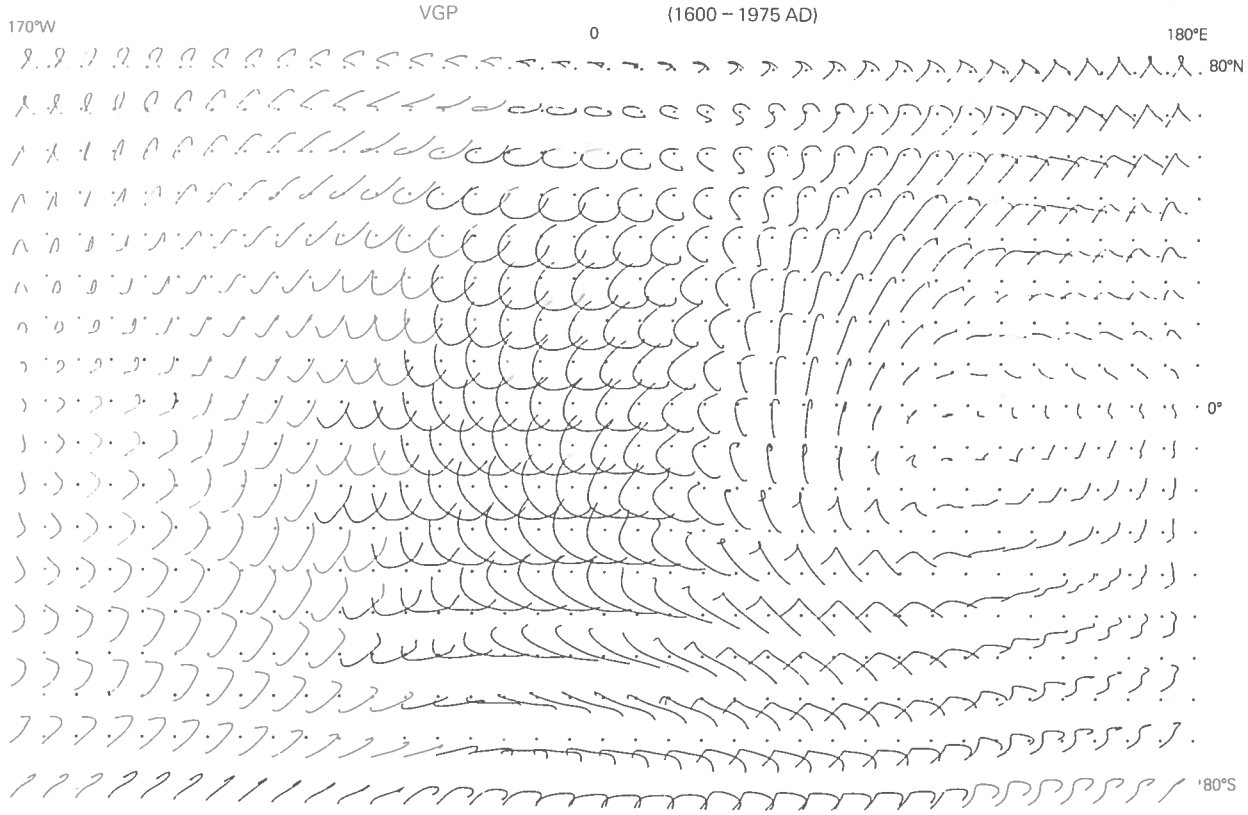

Figure 14.2 Historical virtual geomagnetic pole plots on a 10° latitude and longitude grid. Each curve charts the motion of the local virtual geomagnetic pole from 1600 AD to 1975 AD. The sense of motion is clockwise except in the region of the Indian ocean. Note the large geomagnetic direction changes that have occurred over Africa and Europe compared with the low geomagnetic changes of the Pacific region.

is a plot of the local changes in declination and inclination over the whole world on a 10° by 10° grid (Thompson & Barraclough 1982). The direction changes of Figure 14.2 form the basis of the magnetic dating method. The rather complex global pattern of Figure 14.2 is described mathematically by 120 parameters (24 two-piece cubic splines). The easiest historical field features to recognise in palaeomagnetic secular variation logs are the declination and inclination turning points. For examples the 1810 AD westerly declination maximum and 1710 AD inclination maximum observed at London (Fig. 5.5) can be seen in the recent sediment record from Loch Lomond (Fig. 5.8). Note in the grid of Figure 14.2 how the direction turning points occur at different times in various parts of the world and how the amplitudes of the features also vary from place to place. The most promising localities for historical magnetic dating are those with rapid high amplitude secular changes and clear turning points.

THE PAST 10 000 YEARS

Magnetic age determinations are necessarily indirect for sediments older than 400 years. The approach followed is one of correlating a new palaeomagnetic remanence log with that of a nearby type sequence which has been dated independently, for example by ^{14}C. The palaeomagnetic records of seven such special type sequences are shown in Figure 14.3 and the ages of their turning points are tabulated in Table 14.1. These seven type records (Thompson 1983) are almost exclusively dependent on the radiometric ^{14}C method for their dating. Radiometric dating of the carbon content of lake sediments is more problematical than the dating of the carbon of many other materials such as charcoal, bone, ombrotrophic peat

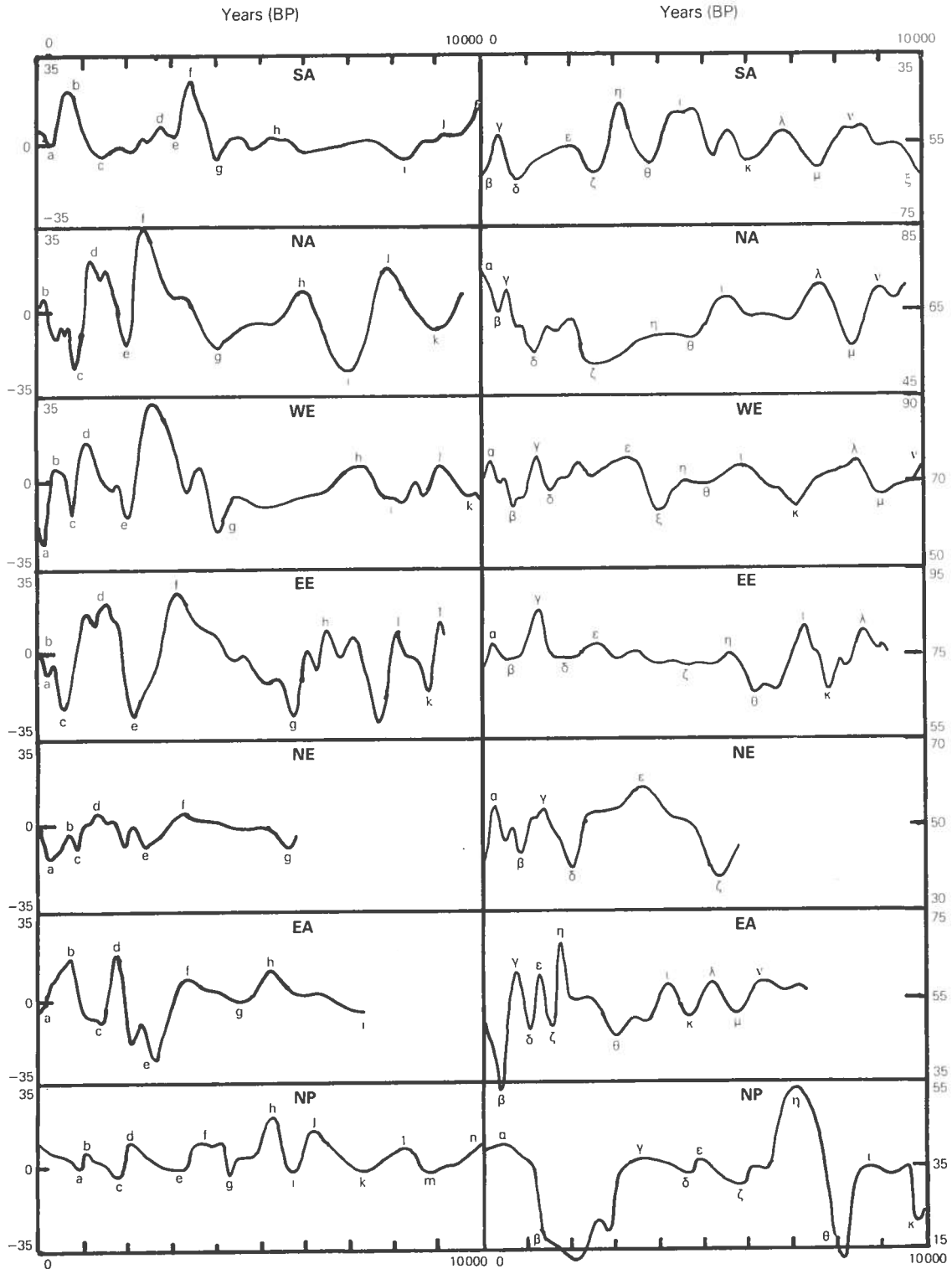

Figure 14.3 Regional Holocene declination and inclination master curves for South Australia, SA; North America, NA; western Europe, WE; eastern Europe, EE; Near East, NE; East Asia, EA and North Pacific, NP. Tree ring timescale calibrated in calendar years BP. Curves based on data from Barton and McElhinny (1981), Banerjee *et al.* (1979), Mackereth (1971), Turner and Thompson (1979), Huttunen and Stober (1980), Tolonen *et al.* (1975), Thompson *et al.* (1985), Horie *et al.* (1980) and McWilliams *et al.* (1982).

Table 14.1 Ages of magnetostratigraphic features.

	SA*	NA	WE	EE	NE	EA	NP
Declination							
a†	300	—	140	160	220	0	900
b	680	100	450	300	700	700	1100
c	1300	750	600	600	850	1200	1800
d	2000	1200	1000	1400	1300	1650	2150
e	2800	2000	2000	2200	1900	2200	3200
f	3500	2400	2600	3100	2100	3100	3900
g	4500	4000	4900	5700	2400	4400	4400
h	5500	5900	7100	6500	3200	5100	5300
i	8300	7000	8300	7600	5600	7300	5600
j	9000	7900	9100	8000	—	—	6000
k	—	9000	10000	8700	—	—	8350
l	—	—	—	9000	—	—	8900
Inclination							
α	—	50	240	300	300	—	200
β	—	420	650	600	550	400	2150
γ	400	750	1150	1300	700	760	3500
δ	900	1200	1650	1900	900	1000	4700
ε	1900	2300	3100	2600	1400	1300	5100
ζ	2600	2900	3800	4600	2000	1550	5800
η	3200	3700	4300	5500	3600	1750	7000
θ	3600	4400	5000	6400	5300	2800	8200
ι	4600	5300	6000	7200	—	4100	8950
κ	6000	6600	7100	7800	—	4600	9800
λ	6800	7700	8300	8600	—	5100	—
μ	7900	8400	8800	—	—	5600	—
ν	8600	9600	9700	—	—	6600	—
ξ	10000	—	—	—	—	—	—

* SA South Australia (35°S 140°E) based on Barton and McElhinny (1981).
NA North America (45°N 90°W) based on Banerjee *et al.* (1979).
WE Western Europe (55°N 05°W) based on Turner and Thompson (1981).
EE Eastern Europe (60°N 30°E) based on Huttunen and Stober (1980).
NE Near East (30°N 35°E) based on Thompson *et al.* (1985).
EA Eastern Asia (35°N 140°E) based on Horie *et al.* (1980).
NP North Pacific (20°N 155°W) based on McWilliams *et al.* (1982).

† a to l declination turning points. α to ξ inclination turning points. Ages tabulated in calibrated ^{14}C years BP. The EA ages are rather poorly known, based here on a linear interpolation between the basal tephra layer and the archaeomagnetic features preserved in the upper sediments. Errors in ^{14}C ages at all the sites possibly amount to several hundred years. Labelling of the palaeomagnetic features is purely for convenience of reference. Any likenesses in ages or in shapes of similarly labelled features are probably chance occurrences, unlikely to be duplicated in other parts of the World.

and wood. The recent sediment isotopic difficulties are rather subtle involving natural contamination and hard-water effects (Olsson 1974). The main problem is that the recent sediment carbon being dated is often older than its stratigraphic position, which results in erroneously old radiocarbon ages. Kidson (1982) notes that 'Despite caveats in the literature . . . many authors still appear to believe that the age of a sample lies within one standard deviation given by the dating laboratory . . . No allowance is made for non-counting errors. Many potential inaccuracies widen the possibility that the true date lies outside the one sigma limits'. The problem of old carbon contamination due to stable organic residues, such as mor humus or peat, and geologic carbon, such as graphite, being washed into lake sediments from eroding soils in their catchments is a widespread dating difficulty. Additional dating methods such as tephra chronologies, pollen zoning and lamination counts are consequently highly desirable for enhancing the reliability of the chronology of type palaeomagnetic sequences. The geographic range over which palaeomagnetic types records can be used is still under investigation. They can certainly be used without significant loss of

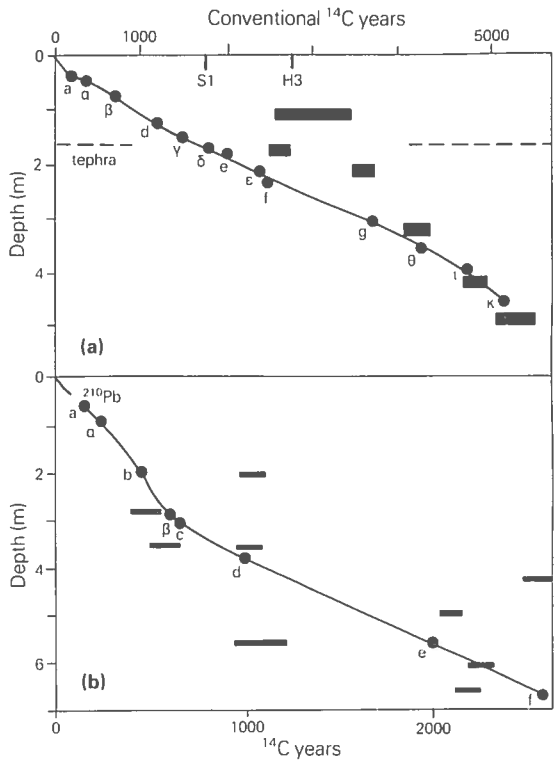

Figure 14.4 Time–depth curves comparing ^{14}C and magnetic chronologies for: (a) Vatnsdalsvatn, north-west Iceland and (b) Rostherne Mere, England. Horizontal bars mark ^{14}C age determinations and their laboratory counting precision. Solid circles mark magnetic turning points dated by correlation with the WE master curves of Figure 14.3. Additional dating information comes from the tephra at 1.7 m depth in Vatnsdalsvatn and ^{210}Pb dating of the uppermost Rostherne sediments. Rostherne data after Nelmes (1983).

accuracy over distances of tens and even hundreds of kilometres. The upper practical limit for Holocene palaeomagnetic pattern matching seems to be working out at around 2000 km.

Figures 14.4a and b illustrate two examples of the use of secular variation magnetostratigraphy in helping to tie down the chronology of recent lake sediments. The first example shows a series of six radiocarbon age determinations from Lake Vatnsdalsvatn (Lochglenlochy) in northwest Iceland. The radiocarbon dates, drawn as solid bars in Figure 14.4a, appear to be internally fairly consistent. The tephra at 1.7 m depth appears to have an age of around 3000 years BP, quite close to the 2900 years BP age of the Hekla-3 eruption. Also there appears on the basis of the ^{14}C ages to have been a dramatic fall in sediment accumulation rate in recent years. The palaeomagnetic direction changes repeat well from core to core and show some similarities to the British master sequence of Figures 5.8 and 14.3, 1500 km distant. If the Icelandic and British magnetic features are correlated by matching their turning points then a quite different time–depth curve from that of the radiocarbon age determinations is found (Fig. 14.4a). The magnetostratigraphic dating method indicates that the lower Vatnsdalsvatn ^{14}C dates are reliable but that the upper dates have been contaminated by old carbon. Furthermore, the magnetostratigraphy suggests that the Vatnsdalsvatn tephra layer is only 1700 years old, presumably originating from the other nearby explosive volcano Snaefells and that by and large the sediment accumulation rate has remained constant over the last 6000 years.

The second example compares the ^{14}C and palaeomagnetic chronologies of Rostherne Mere, England. Figure 14.4b plots nine radiocarbon ages as bars and the palaeomagnetic turning points as a time–depth profile labelled a to f. The radiocarbon age determinations were made as part of a detailed diatom study (Nelmes 1983) in order to provide estimates of accumulation rate. Such a need for accumulation rate data rather than just the ages of isolated horizons is common in many palaeolimnological studies. The investigator faced only by the isotopic ages, (i.e. the solid bars, of Fig. 14.4b) would be hard pressed to calculate useful accumulation rates for any part of the 7 m sequence. The Rostherne Mere palaeomagnetic record showed many similarities to that of the Western Europe type record (see Fig. 14.3) allowing the turning-point profile to be constructed as far back in time as declination turning point WE f of around 2600 years BP. This Rostherne Mere palaeomagnetic time–depth relationship fits in well with the short-lived ^{210}Pb isotopic information and can be seen to provide a basis on which diatom accumulation rates can be calculated. The magnetic results suggest that the Rostherne Mere sediments are most unsuitable for conventional ^{14}C dating having both excessively young and excessively old radiocarbon ages.

It must be made clear that by no means all lake sediments are suitable for palaeomagnetic studies. During the past 20 years the sediments of over 100 lakes in Europe have been analysed magnetically and less than one in five have yielded useful results (in the sense that both the declination and inclination data were repeatable in two or more cores).

One statistical approach to analysing the scattered palaeomagnetic data of secular variation logs is to fit

them with a smooth curve. The idea is to estimate the proportion of the scatter that can be adequately explained by random orientation and measurement errors and the proportion of the palaeomagnetic signal likely to have been caused by geomagnetic fluctuations. Several smoothing methods have been tried, of varying degrees of mathematical complexity. The simplest methods tend to produce ill-fitting jagged curves containing spurious high frequency components. The most complicated methods can be very time consuming in their application. A routine method employed to calculate the curves of Figure 14.3 is that of fitting least squares cubic splines on the sphere (Thompson & Clark 1981). The method uses a robust biweighting procedure (Mosteller & Tukey 1977) in order to remove outliers (the cause of much high frequency contamination) and a cross-validation procedure (Clark & Thompson 1978) in order to assess the appropriate degree of smoothing. Such least squares methods permit confidence bands to be placed about the smooth best fitting curves. An alternative approach to investigating secular variation logs is to assess the scatter by calculating a single statistic. A particularly simple but handy statistic is the median solid angular difference (ξ) between adjacent declination and inclination measurements. Good quality lake sediments have ξ values below 6°. The high quality Loch Lomond data of Figure 5.8 have an ξ value of 2.5°. Epp *et al.* (1971) discuss a more comprehensive statistic based on this approach to assessing data consistency.

Core correlation methods using palaeomagnetic secular variation data have been suggested by Denham (1981) and Clark and Thompson (1979). Other more general correlation methods (e.g. Rudman & Blakely 1976, Gordon 1973, 1982) have also been applied to secular variation data. In practice, however, none of these procedures has proved to be workable and subjective trial and error methods are still used for the magnetostratigraphic task of matching a palaeomagnetic log to its nearest master curve. Averaging of logs by stacking is a very useful approach in helping to confirm the reliability of palaeomagnetic fluctuations, a good example being provided by Barton and McElhinny's (1981) work on three South Australian lakes.

14.4 Origin of palaeolimnomagnetic secular variation

Spectral analyses of palaeolimnomagnetic logs (Thompson 1973, Denham 1975, Turner & Thompson 1981) reveal a concentration of power at periods of around 2000 to 3000 years. This dominant thousand year timescale of the palaeomagnetic direction fluctuations can be clearly seen as the major oscillations in the raw data plotted in Figure 5.8 and can be seen in all the spline plots of Figure 14.3. The concentration of spectral power at thousand year periods does not of course mean that the data are periodic nor does it mean that the same signal is being recorded at all the sampling sites. From a uniformitarian point of view the geomagnetic *processes* operating at present are likely to have been operating in the past and so present geomagnetic secular change is likely to be a useful first guide to gaining an understanding of ancient secular variation and palaeolimnomagnetic logs.

As described in Section 5.1.2 the present features of the Earth's non-dipole field are varying on timescales of tens and hundred years. Hide and Roberts (1956) put the average timescale of secular variation at round 40 years on the basis of kinematic changes of the secular variation field. Thompson (1982) found an average lifetime of around 500 years for the major non-dipole field foci (Fig. 5.4) which have evolved since 1600 AD through a global analysis of historical field observations and archaeomagnetic data (Thompson & Barraclough 1982). Despite the great difference in the characteristic timescale of non-dipole field change (100 years) and the characteristic timescale of palaeolimnomagnetic secular variation features (2000–3000 years), it has been suggested (Thompson 1983) that the dominant geomagnetic cause of the lake sediment secular variation features is the growth and decay of non-dipole foci that we can see taking place at the present day. The thousand year palaeolimnomagnetic fluctuations are viewed as resulting from chance successions of several non-dipole foci with 500 year lifetimes evolving almost contemporaneously near the sampling sites and producing apparently persistent geomagnetic features. Higher frequency components of geomagnetic change are viewed as having been lost from the palaeolimnomagnetic records through (a) the averaging effects of post-depositional remanence acquisition, (b) the slow viscous degradation effects of particle realignment and (c) the introduction of sedimentological noise by processes such as bioturbation and micro-slumping. On this uniformitarian model the differences between long period secular variation patterns of various continents (Fig. 14.3) are explained as arising from the effects of local,

short-lived geomagnetic sources, while the few similarities which are to be found between such widely spaced secular variation records are thought to have little geomagnetic significance and to have arisen by chance, as would be expected for such a comparison of field patterns generated by local magnetohydrodynamic processes.

Holocene palaeomagnetic secular variation records can be mimicked well by random processes such as random walk or autoregressive processes (author's unpublished calculations). Historical main field spherical harmonic coefficients can be used through their autocovariance functions to judge the order and variance of the autoregressive processes while the ratio of the present day main field to secular change coefficients allows the remaining parameters of the autoregressive processes to be calculated for spherical harmonic degree two to six. With some smoothing, to imitate signal attenuation associated with remanence acquisition effects, declination and inclination time series indistinguishable from those presented in Figure 14.3 can be generated by such autoregressive random processes based around historic field data.

The lack of reliable palaeointensity records from lake sediments means that only angular magnetic information is available from palaeolimnomagnetic studies. This fundamental drawback severely limits the chances that specific Holocene geomagnetic models of lasting value can be constructed with present data. As an alternative approach to that of geomagnetic modelling, an empirical description of Holocene secular change records has been built up in order to try to answer certain questions about Holocene field behaviour (Thompson 1982, 1983). Such an empirical description can potentially demonstrate periods of quiet and noisy secular changes, times of tilted as opposed to axial dipole fields, and times of average eastward or westward longitudinal drift. Figure 14.5 summarises an attempt at obtaining these features from the seven secular variation records plotted in Figure 14.3. The mathematical procedures followed in establishing the empirical description are described by Thompson (1982, 1983). In particular a quantitative method of assessing the average global sense of longitudinal drift, through the use of the curvature of the spline functions fitted to secular variation records, has been developed; Halley's (1692) approach of timing the longitudinal drift rate of geomagnetic features, which worked so well for 17th and 18th century changes, is unfortunately not appropriate with lake sediment

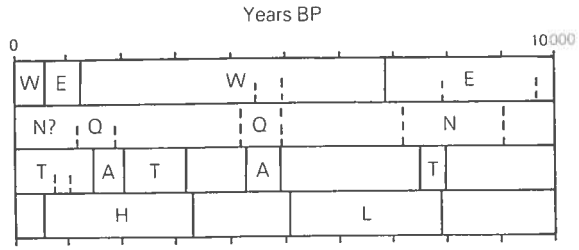

Figure 14.5 Summary of Holocene global averages: (a) E, W, eastward and westward drift; (b) Q, N, quiet and noisy secular variations; (c) A, T, axial and tilted dipole orientation; (d) H, L, high and low dipole intensity.

records, as Denham (1974) has pointed out, since ^{14}C dating is not sufficiently accurate to date the rate of movement of short-lived geomagnetic foci. The main features indicated by Figure 14.5 are that during the past 10^4 years (a) there were periods of both westward and eastward drift (b) that quiet periods of low secular change occurred and (c) that these were times when the dipole axis was more closely aligned with the spin axis than during the last 400 years.

14.5 Palaeomagnetic pitfalls

The magnetic dating method outlined above requires careful interpretation of the palaeomagnetic record. A serious stumbling block in magnetostratigraphy is the confusion of sedimentologically induced palaeomagnetic signals with geomagnetic signatures and the consequent proposal of quite mistaken correlations and chronologies. Sedimentological influences, particularly the well documented 'inclination error', make many sediment types unsuitable for magnetostratigraphic investigations. Two guidelines we have found particularly useful in differentiating between valuable geomagnetic records and stratigraphically worthless sedimentological influences are (a) the repeatability between sequences of both palaeomagnetic declination and inclination and (b) the lithological independence of palaeomagnetic direction data.

A palaeomagnetic difficulty of some philosophical interest concerns the 'reinforcement syndrome'. In 1971 Watkins discussed many aspects of the reinforcement syndrome and its connection with the misinterpretation of short geomagnetic polarity events. He summarised how the first published

description of a geomagnetic phenomenon can have great influence over future studies as 'it enables workers pondering their own "curious" data to realize its real(?) meaning', and he pointed out that 'a substantial trap will have been laid . . . if the behaviour described in the initial publication is in fact erroneous' as it will lead to the generation of spurious data. An important human element can serve to reinforce an initial (erroneous) discovery for, as pointed out by Watkins, 'it is far more reasonable to generate both the energy and belief (faith?) required for publication of data confirming a discovery than to publish much negative data of a pedestrian nature'. He concluded that 'the case for super critical evaluation of data pertaining to polarity events is both obvious and strong'. Secular changes are naturally also ripe for abuse through the action of the reinforcement syndrome. A likely example can be found in the approach of correlating secular variation features having little or no dating control with previously published features several thousand kilometres distant, and then of concluding that the correlations show that similar geomagnetic field behaviour has occurred over large regions.

14.6 Excursions and the reinforcement syndrome

Geomagnetic excursions are taken to represent magnetic field behaviour intermediate between that of polarity reversals and large secular change. They may be unsuccessful or aborted reversals and as such possibly expected to be at least as common as successful reversals and could be of global extent (Verusob 1982). Naturally they are of great potential magnetostratigraphic significance (Denham 1976). Recent igneous rocks carrying unusual remanence directions which have been taken to be records of geomagnetic excursions have been found in France (Bonhommet & Babkine 1967), Iceland (Peirce & Clark 1978, Kristjansson & Gudmundsson 1980) and Indonesia (Sasajima *et al.* 1984). Unfortunately the development of the subject of excursions within the Brunhes normal polarity chron has led to a very confused situation and the likelihood of Brunhes excursions being able to play a major rôle in Quaternary magnetostratigraphy is receding.

The most debated recent excursions are the Gothenburg (Morner *et al.* 1971, Noel & Tarling 1975) in Europe and its North American equivalent the Erieau (Creer *et al.* 1976). Both excursions are claimed to be of late-Weichselian age and to provide detailed information about the pronounced changes in direction of the late-Weichselian geomagnetic field. Following the original proposals, numerous reports of excursions or unusual geomagnetic field behaviour have been made. The sediments involved have included those from lake (Nakajima *et al.* 1973, Noltimier & Colinvaux 1976, Anderson *et al.* 1976, Vitorello & Van der Voo 1977), cave (Kopper & Creer 1976), loess (Bucha 1973), till (Stupavsky *et al.* 1979), shallow marine (Vilks *et al.* 1977, Abrahamsen & Knudsen 1979, Abrahamsen & Readman 1980, Stoker *et al.* 1983) and deep-sea (Clark & Kennett 1973, Freed & Healy 1974) environments. These reports should not necessarily be taken at face value as they could well have been encouraged by the snowballing action of the reinforcement syndrome. Our interpretation of most of these unusual Brunhes palaeomagnetic directions is that they have been strongly influenced by sedimentological effects in high energy environments, such as the action of water currents or by slumping or by the inclination error of deposition remanence (Thompson & Berglund 1976).

It is interesting to reflect that an important observation used in the original identification of the late-Weichselian excursions was that the Laschamp/Olby lava flows of the Auvergne district, France had been found to have approximately reversed palaeomagnetic directions (Bonhommet & Babkine 1967) and to have an age which could conceivably have been late Weichselian. Since the initial dating studies the ages of these lavas have been revised and they are now taken to have been erupted between 35 000 and 45 000 years ago. Also it has since been discovered (Heller 1980) that the lavas self-reverse (Section 13.2.1) their remanence on reheating and cooling in the laboratory. The self-reversal is caused by the intimate association of different magnetic phases produced by both high and low temperature titanomagnetite oxidation. Although the laboratory self-reversal of many of the Laschamp/Olby lavas cannot be taken to prove unequivocally that the Laschamp geomagnetic event did not occur, these new findings coupled with the revised Laschamp ages destroy the crucial original observation used in justifying a late-Weichselian excursion and emphasise the need for an understanding of the rôle of the reinforcement syndrome in prompting the publication of spurious palaeomagnetic data.

14.7 Summary

Secular changes of the geomagnetic field can be used for correlating and dating some kinds of recent sediment. The geomagnetic field continually changes, producing an irregular but characteristic magnetic pattern which can form the basis of a magnetostratigraphic core correlation method. Magnetic direction fluctuations have been dominated by local magnetohydrodynamic effects in the Earth's fluid core. These processes give rise to a regional distribution of geomagnetic changes at the Earth's surface.

The secular variation magnetostratigraphic method is straightforward in principle, involving matching the palaeomagnetic remanence record of a new sediment sequence with a nearby, previously dated type palaeomagnetic section. The accuracy of the secular variation magnetostratigraphic method largely depends on the accuracy of the dating of the type palaeomagnetic record. At best the dating of the type records is probably only good to within one or two hundred years. However, this uncertainty does not prevent secular variation magnetostratigraphy from competing with alternative dating methods.

[15]
Biomagnetism

My mind is in a state of philosophical doubt as to the origin of animal magnetism.

Coleridge 1830

15.1 Introduction

The study of the weak magnetic fields originating in biological systems has been made possible by the production of cryogenic magnetometers (Section 6.2.4) and high quality magnetic shielding (Section 6.6.3). The subject of biomagnetism can be subdivided into three main topics according to the origin of the biomagnetic fields (Williamson & Kaufman 1981). These three topics of (a) magnetic precipitates formed through biochemically controlled processes, (b) magnetic contaminants and (c) electric currents arising from ion flow in various organs such as the heart and the brain are all discussed below.

Biochemically precipitated magnetite has been found in the body tissues of organisms as diverse as bacteria, algae, insects, birds and mammals; indeed magnetite is probably the fourth most common biochemically precipitated mineral. In many of the magnetic organisms the magnetite precipitates can be used for detecting the Earth's magnetic field and hence can be used for orientation and navigation. Recent advances in biomedical aspects of biomagnetic fields and magnetic contaminants have been summarised in the excellent review article of Williamson and Kaufman (1981).

15.2 Magnetic navigation

The clearest demonstration of magnetic navigation by living organisms is Blakemore's (1975) discovery of a diverse group of bacteria which orientate in the Earth's magnetic field and swim along its magnetic field lines. These magnetotactic bacteria possess a biomagnetic compass in the form of a chain of magnetite particles which they have synthesised from soluble iron. Many organisms, besides bacteria, have also been found with magnetite precipitates. The list of organisms includes pigeons, bees, algae, chitons, turtles, tuna, dolphins and butterflies. The quite extraordinary navigational and homing abilities of many of these organisms are well known and it has often been suggested that the geomagnetic field may play a rôle in aiding their perception of direction. Unambiguous demonstration of the use of a biomagnetic compass in higher organisms is rather difficult as it must involve both behavioural and physiological experiments. Nevertheless laboratory experiments on the location, mineralogy and mineral magnetic properties of the biochemically synthesised magnetic particles provide a wealth of information about the likely sensitivity, value and possible biophysical methods of geomagnetic field sensing.

MAGNETOTACTIC BACTERIA

The response of magnetotactic bacteria to a magnetic field is easily demonstrated by observation of the bacteria under low power magnification. Viewed under one hundred times magnification magnetotactic bacteria, in a droplet of clean water, appear as moving points of light. They naturally swim along the geomagnetic meridian, accumulating at the edge of

the water droplet. Their direction of swimming can be readily changed by approaching the droplet with a bar magnet. Bacteria collected in the Northern Hemisphere swim consistently to the geomagnetic north whereas those collected in the Southern Hemisphere swim to the south (Blakemore & Frankel 1981). This difference in behaviour of northern and southern hemisphere bacteria was predicted on the supposition that a likely biological survival advantage of magnetotaxis was that bacteria would use the inclination of the geomagnetic field in order to direct themselves downwards so keeping themselves near the substrate, well away from surface waters.

Magnetotactic bacteria are anaerobic or microaerophilic, occurring in concentrations of around 100 or 1000 per millilitre in a wide range of environments (Moench & Konetzka 1978). They are typically about 3–5 μm in length and have been found in salt and freshwater peat bogs, marshes, sewage treatment plants, and lake, estuarine and marine surface sediments. They appear to be ubiquitously distributed in aquatic sediments with pH values in the range 6–8, although only rarely occurring in the overlying water columns. Moreover, the relative importance of their contribution to soil and to lake sediment magnetism remains unevaluated (Chs 8 & 10).

Transmission electron micrographs of magnetotactic bacteria reveal striking chains or clusters of opaque iron-rich particles in the cytoplasm of the cells. Mossbauer absorption spectra of freeze-dried cells demonstrate that the iron is primarily in the form of magnetite. Some other compounds, presumably precursors of magnetite in its biochemical pathway, are also found in the precipitates or magnetosomes. Magnetosomes are produced in bacteria cultured in media with soluble iron concentrations in excess of 1 mg l^{-1}. They are not produced if the iron concentrations fall much below this level. The magnetite particles have lengths of around 0.05–0.1 μm, axial ratios (width/length) ranging from 0.6 to 0.9 and shapes varying from cubic or octahedral to sharply pointed forms. Clumps of magnetite particles are found outside the bacteria cells suggesting that the particles are released after death and can accumulate in the substrate. The size of the particles produced by the magnetotactic bacteria falls neatly in the range 0.04–0.2 μm which ensures that they are single domain (Kirschvink & Gould 1981). This condition assures efficient use of the magnetite in its rôle as a compass. Larger multidomain particles would have a lower specific remanent magnetisation and smaller superparamagnetic particles would have a lower fluctuating moment, which again would result in a much reduced effective magnetic moment. The configuration of the magnetic particles in chains is an enterprising biochemical arrangement designed to exploit magnetic interactions which serve to align the magnetic moments of all the particles along the length of the chain and hence to form a most efficient magnetic disposition.

Of course the magnetic particles do not cause a magnetic force which can pull the bacteria along the geomagnetic field lines. The torque produced by the Earth's magnetic field acting on the chain of magnetised magnetite particles only serves to point the bacteria: they have to swim along the field lines using their flagellae. This orientational rôle is clearly demonstrated by the observation that dead bacteria do not move along magnetic field lines, but only align with the field direction. The usual number of a few tens of magnetite particles in natural magnetotactic bacteria seems to be controlled by the magnetic moment needed to produce a useful torque.

A novel experiment (Kalmijn & Blakemore 1978) can be performed in order to (a) demonstrate that the bacteria do indeed possess a magnetic remanence which is used to sense the geomagnetic field and (b) at the same time to determine the coercivity of the biomagnetic remanence. The procedure of this neat experiment is first to align the bacteria in a weak magnetic field and then to hit them with a short one-shot magnetic field pulse antiparallel to the weak aligning field. Production of a sufficiently strong magnetic field pulse reverses the biomagnetic remanence and instantly causes the bacteria to turn around and swim in the opposite direction. The strength of the field required to produce this change in behaviour reflects the coercivity of remanence of the magnetite particles. It varies from species to species ranging from at least 35 to 55 mT. Exposure of a population of magnetotactic bacteria to an alternating field demagnetising coil also produces a change in behaviour. After magnetic cleaning half of the population swims to the north and half to the south. This result is that expected for a chain of magnetite particles as their magnetic moments cannot be destroyed, they can only be switched from one easy direction to another. Natural populations of mixtures of both north- and south-seeking bacteria are found near the magnetic equator. Magnetotaxis is presumably useful there in preventing harmful upward excursions.

The evolution of bacterial communities when subjected to changing magnetic field conditions has also been studied (Blakemore 1982). Such investigations permit speculation about shifts in magnetotactic bacterial population densities and their magnetic characteristics during geomagnetic field changes (Kirschvink 1982a). On culturing a natural population of normal polarity bacteria in a reversed field a significant change in bacterial polarity is found after only a few days and almost complete population reversal takes place in a month. These types of response to magnetic field change clearly must occupy a few generations of bacteria. The polarity of a bacterium with a chain of magnetic particles is conserved in its daughters by the act of partitioning of the magnetic chain during cell division. Any particles later synthesised by the daughters become magnetised in the chain polarity, i.e. the polarity of the parent. Although such an ability to synthesise magnetic particles can be genetically encoded, the polarity of the particles cannot be encoded. So if a bacterium without magnetosomes begins to manufacture them it can be either north or south seeking. In every generation a few bacteria can end up with the wrong polarity. These few can proliferate under a change of field conditions.

A decrease in geomagnetic field intensity can be expected to lead to an increase in the number of magnetosomes, in order to produce an equivalent magnetic torque to that of modern day natural bacteria. A fall in field intensity below a critical limit however is likely to halt the production of magnetosomes altogether, as the synthesis of additional magnetosomes becomes too much of a burden. If magnetotactic bacteria were making a significant contribution to the total magnetic mineral content of a substrate then geomagnetic field intensity fluctuations could be imagined as being reflected in mineral magnetic concentration variations.

In summary, magnetotactic bacteria are bottom-dwelling, swimming organisms that are passively steered by the torque of the Earth's magnetic field on their biomagnetic compass. Being anaerobic or microaerophilic they swim downwards in order to avoid the toxic effect of greater oxygen concentrations in surface waters. They are able to control the size of their precipitated magnetite crystals, synthesising chains of single-domain particles from soluble iron in their environment. Concentrations of around 1000 magnetotactic bacteria per millilitre in many surface sediments are quite sufficient to indicate that magnetosomes might be an important part of the mineral magnetic component of some sediment and soil samples.

A SENSE OF MAGNETISM

The most convincing evidence that certain higher animals can use the geomagnetic field as a navigational aid is provided by studies of homing pigeons (Keeton 1971). Pigeons need both a map and compass-sense to be able to return home after being released at an unfamiliar site. A number of controlled experiments on pigeon homing have indicated that magnetic field information is used to aid orientation. For example, pigeons have been found to navigate poorly on cloudy days if small magnets or current-carrying coils are affixed near their heads (Keeton 1971, Walcott & Green 1974). In older experienced pigeons the sun is the preferred compass. The use of the sun as a compass to aid navigation on sunny days is well established since clock-shift experiments (in which the internal clocks of homing pigeons have been phase shifted by several hours) deflect departure bearings of pigeons from their release locations.

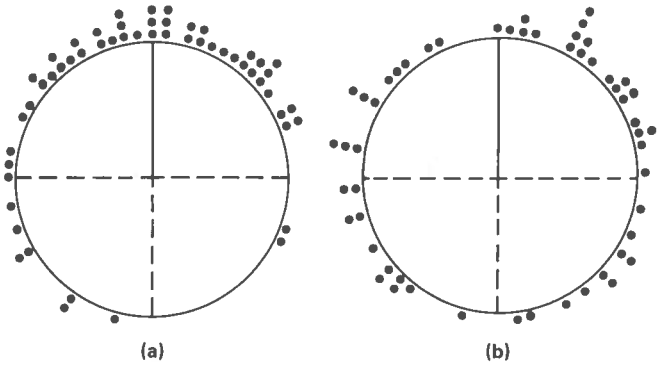

Figure 15.1 The influence of magnetic fields on the departure bearings of pigeons. Clock-shifted pigeons (i.e. ones that had never seen the sun before noon) neverthe-less were homeward (solid line) orientated on morning release (a) but were disorientated (b) when carrying magnets. Dots mark the vanishing bearings of individual birds. Data from Wiltschko *et al.* (1981).

However, on cloudy days released, clock-shifted pigeons depart directly homeward, presumably navigating by the geomagnetic field. The predominant use of the geomagnetic field compass even on sunny days is illustrated in Figure 15.1 for young pigeons which have no previous use of the sun as a compass. Figure 15.1 plots out the well orientated homeward departure direction of control pigeons and the random departure directions of birds carrying small bar magnets.

The ability of pigeons to sense magnetic fields is presumably related to the magnetite particles which have been found between their brain and skull in a small (0.5 ml) region of tissue which also contains nerve fibres (Walcott *et al.* 1979). The remanent magnetic moments of pigeons range from 10^{-4} to 10^{-3} A m^2. Magnetite is thought to be the dominant magnetic mineral in pigeons' heads because the magnetic particles have yielded Curie temperatures of 575 °C. The magnetite is thought to be largely single domain, but the domains of individual particles are not well aligned as an isothermal remanence about ten times the magnitude of the natural remanence can be produced by a 0.2 T field.

Bees also apparently orientate in the geomagnetic field (Kirschvink 1982b). Their dances, used to communicate the direction of a food source (with respect to the sun), make small regular errors. Cancellation of the ambient magnetic field causes these errors to disappear. Another indication that bees have a sense of magnetism is that the orientation of combs constructed by swarms otherwise deprived of orientation cues are reported to be in the same magnetic direction as that of the parent hive. Many bees have been found to possess a magnetic remanence of about 10^{-3} A m^2. The remanence tends to lie in their horizontal plane and to have its source almost exclusively in the anterior part of the abdomen. Again magnetite is indicated to be the main magnetic mineral by a 580 °C Curie temperature. Cooling experiments, however, point to the presence of a large proportion of superparamagnetic magnetite particles. In addition to bees, five other invertebrate species have been found to have magnetic moments approaching 10^{-3} A m^2.

Magnetic minerals have even been isolated from the heads of dolphins (Zoeger *et al.* 1981). These magnetic minerals, which are in part magnetite, have a low natural magnetic moment of 2×10^{-8} A m^2. The weakness of their natural remanence is mainly due to an exceedingly low stability as revealed by a median destructive field of 2 mT in alternating field demagnetisation. The magnetic tissue is located near the roof of the skull of the dolphin, apparently associated with nerve fibres. If magnetite is used by dolphins as part of a biomagnetic geomagnetic field detection system, then a torque on the induced moment of the multidomain magnetite is a likely receptor mechanism.

The ability of humans to navigate by means of sensing a magnetic field has been examined, but the experimental trials have yielded conflicting results (Gould & Able 1981). Some navigation and orientation tests have led to different aptitudes being recorded for subjects wearing magnets and subjects wearing equivalent dummy weights. These experimental results suggested that man may unknowingly use a magnetic sense. However, attempts to replicate the experiments have failed. So it now appears that any human ability to sense the Earth's magnetic field is at most marginal and is unlikely to match that of our conventional senses.

Biogenic magnetite is clearly produced by many organisms and can be used as a magnetic compass. An interesting question concerns the time in the geological past when biogenic minerals were first produced and whether biomagnetic precipitates have been preserved in the geological record. At present the magnetite of chitons' teeth (used as a strengthening material) probably makes the largest contribution to the biomagnetic mineral content of any sediments (Kirschvink & Lowenstam 1979). A rough calculation of the chiton teeth magnetite input to continental shelf sediments, assuming that all the biomagnetite is preserved, shows that it could account for average magnetite concentrationssuming that all the biomagnetite is preserved, shows that it could account for average magnetite concentrations of up to one part in 10^5 (Kirschvink & Lowenstam 1979), which is comparable with typical shallow marine total magnetite concentrations. Bacteria with natural population densities of 1000 cells per millilitre would only account for magnetite concentrations of one part in 10^{10}, but this amount could be increased to perhaps one part in 10^5 through the accumulation of successive generations of dead bacteria. Distinguishing between biogenic, volcanic and pedogenic magnetite is not an easy task as the size ranges, shapes and magnetic properties of all these magnetite types overlap. The possibilities of bacterial biomagnetic mineral concentration changes reflecting geomagnetic field intensity fluctuations merit careful study, although

recent sediment mineralogy records do not obviously track or mirror the well established Holocene geomagnetic 6500 year BP intensity minimum and the 2500 year BP maximum of Figure 5.9.

15.3 Pneumomagnetism

One of the first practical medical applications of biomagnetism concerned the measurement of the remanent magnetic field of magnetic contaminants in the lung (Cohen 1973). Cohen showed that it was possible to estimate the amount of magnetic dust (cf. Ch. 11) in a person's lungs by magnetising the dust and then by measuring the newly created magnetic field at the subject's chest.

Such pneumomagnetic techniques have found application in both research and occupational health areas. A particularly helpful aspect of magnetic techniques in studying the hazards from respired particles is that they are non-invasive. Magnetic methods are also potentially very useful for studying contaminant clearance rates. For example they have suggested that smokers may have distinctly lower clearance rates than non-smokers (Cohen *et al.* 1979). Occupational exposure to airborne particles can lead to large numbers of particles being inhaled. In certain cases an appreciable fraction of the particles is magnetic and the smaller particles (>2 μm) will be carried into the lung and may be deposited on the large alveolar surface. This is an unhealthy situation as it is known that iron oxides retained in the lungs are responsible for the development of pulmonary sideosis.

The non-invasive pneumomagnetic method basically consists of magnetising the contaminant particles by standing the subject for about 5 minutes between a pair of Helmholtz coils giving a magnetising field of some 0.02 T and then of mapping the remanent field parallel to the applied field (i.e. normal to the skin). Measuring times using a superconducting magnetometer capable of sensing fields as low as 10^{-5} nT are around 5 minutes. The average error, as deduced from measurements on control groups, works out to be 0.02 nT with the largest error signals from the abdominal area – presumably related to ingested food (Kalliomaki *et al.* 1976, 1981). Some of the strongest signals have come from the right lungs of welders (Fig. 15.2). Their magnetic contaminants produced remanent fields of several hundred nanotesla, several orders of magnitude above those of the control subjects. The magnetic technique turns out in many instances to be more sensitive than others, such as radiography, in assessing lung contamination. The threshold of radiographs corresponds to a remanent field of around 1 nT which in turn is equivalent to about 100 mg of dust. At this and higher concentrations good correlations have been found between magnetic measurements and radiographic findings.

After magnetisation the remanent field of the lung shows characteristic decay with time (Cohen 1973) dropping to a small fraction of the original in around one hour. These changes in remanence are thought to relate to movement of the magnetised particles in the lung tissue rather than to viscous mineral magnetic behaviour properties of the contaminants. Variations in relaxation rate may be related to pulmonary diseases which can change the mechanical properties of pulmonary tissue.

Magnetopneumography has thus been successfully applied to meet the needs of many workers including arc welders, coal miners and shipyard and foundry workers by assessing particle deposition in the lung (Kalliomaki *et al.* 1981). Being a non-invasive method of characterising particulate burden it can play an important rôle in both research and occupational

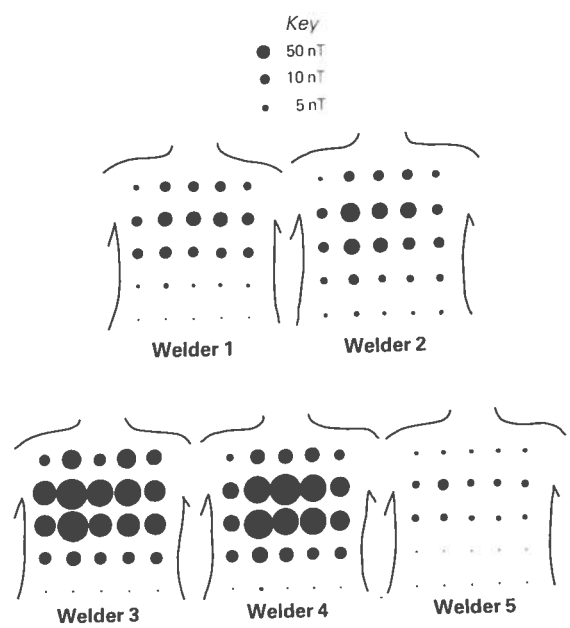

Figure 15.2 The remanent fields of five welders (after Kalliomaki *et al.* 1976).

health. A weakness of the magnetic technique is that high remanent fields might derive from a relatively small number of dust particles with strong individual magnetisations rather than from many particles caught on the lungs as a result of a long exposure to dust that is magnetically weaker. However, such disadvantages are countered by a number of extra research potentials such as the possibility of guiding particles towards regions of the lung of special interest through the use of magnetic field gradients.

15.4 Cardiomagnetism

One of the most studied and indeed one of the strongest biomagnetic phenomena is the magnetocardiogram (Williamson & Kaufman 1981). Magnetic fields of 50 pT corresponding to magnetic moments of 0.1 μA m² are produced by the electric currents of the cardiac cycle. A normal magnetocardiogram is shown in Figure 15.3. Clinical applications of the magnetocardiogram include (a) a convenient, rapid screening method for large numbers of people, (b) a complementary research approach to the electrocardiogram in investigations of the nature of electrical activity in the heart and (c) a method of characterising abnormal electrocardiograms. Most of the current interest in cardiomagnetism is involved with its diagnostic applications as a supplement to the electrocardiogram.

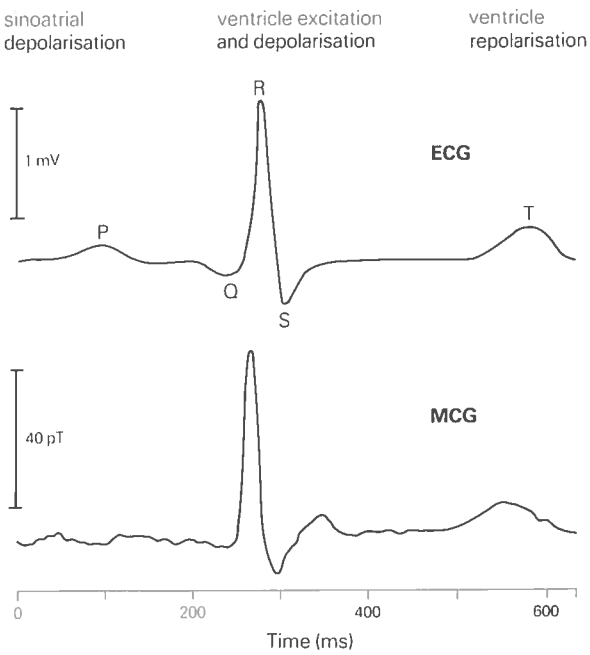

Figure 15.3 An electrocardiogram (ECG) and a magnetocardiogram (MCG) recorded in a hospital (after Williamson & Kaufman 1981).

Early measurements of the heart's magnetic field were made by induction coils (Baule & McFee 1963) but superconducting magnetometers now provide better spatial resolution, lower noise levels and a better frequency range. In practice it is useful to demagnetise any magnetic contaminant particles found lodged in the body by the application of a magnetic recording tape eraser before measuring the magnetocardiogram. Contributions from the susceptibility of the changing volume of blood in the heart need to be taken into account in detailed research studies but are unnecessary for clinical applications. Magnetocardiograms can be displayed in a number of ways many of which closely resemble methods used in palaeomagnetic and geomagnetic studies. They may be represented as a set of time series; alternatively they may be modelled as a dipole heart vector and the locus of the vector traced on orthogonal plots. In another approach higher order heart terms are modelled using spherical harmonic analyses, and the variations of the multipole coefficients are plotted against time.

15.5 Neuromagnetism

Magnetic signals from the nerves have been studied in attempts to bridge the gap between psychological and psychophysical aspects of behaviour and perception, and the functioning of individual neurons (Williamson & Kaufman 1981). A possible advantage of studying magnetic signals over electric signals is that they are less affected by dispersion through intervening tissue. This observation suggests that a magnetoencephalogram recorded outside the head should be able to resolve the site of neural activity more accurately than can an electroencephalogram. The two main lines of neuromagnetic research which have been pursued are first, analysis of spontaneous brain activity, such as the alpha rhythm, and secondly, investigation of activity evoked by sensory stimuli. Neuromagnetic signals can be extremely weak ranging from amplitudes of a few picotesla down to a few femtotesla. Well balanced SQUID gradiometers (Fig. 6.4a) or particularly well shielded rooms are needed for these remarkably sensitive measurements.

The most common spontaneous neuromagnetic activity is the theta brain rhythm with a frequency of around 6 Hz. Magnetic and electrical activity of the brain at this frequency are often similar although correlation is lost during sleep. Magnetic activity as a response to sensory stimuli includes (a) visual cortex fields of a few 100 fT evoked by light flashes, (b) somatically evoked field responses such as from stimuli to the wrist and finally, (c) fields near the auditory cortex produced by click stimuli or prolonged sounds. The sources of some of these evoked fields have been located within the head to an accuracy of around 1 cm. Signal processing has been used to extract somatically evoked magnetic activity of below 50 fT in strength (Okada *et al.* 1982). This type of neuromagnetic experimentation represents one of the finest, most sensitive magnetic detection systems yet realised.

15.6 Summary

The long-held belief that magnetic fields can influence the behaviour of certain animals and organisms has been strikingly confirmed in recent years through the detection of magnetised iron oxides in bacteria, pigeons, dolphins and a host of other animals. Iron oxides, particularly magnetite, are now recognised as being produced biochemically by many phyla.

The recognition of biochemical magnetite in sediments and soils is hampered by its similarity to authigenic or volcanic magnetite. Consequently, the importance of biochemical magnetite in environmental studies remains enigmatic. The profusion of magnetotactic bacteria in many present day aquatic environments suggests that the possible presence of biochemical magnetite crystals must be carefully considered in interpreting the magnetic properties of environmental samples, particularly those with low concentrations.

Airborne iron oxide dusts can be trapped in our lungs; thus non-invasive magnetic methods can be used to investigate the health hazards to people such as welders, shipyard workers and miners who are particularly prone to pulmonary problems. Sensitive cryogenic magnetometers are also contributing to cardiological and neurological work by measuring the very weak but diagnostic magnetic signals emanating from the heart and the nervous system.