^{14}C DATING AND MAGNETOSTRATIGRAPHY

ROY THOMPSON

Department of Geophysics
University of Edinburgh
James Clerk Maxwell Building
Mayfield Road, Edinburgh EH9 3JZ
Scotland

ABSTRACT. The history of the earth's magnetic field is pre-
served in the fossil magnetism of archaeologic specimens,
natural rocks and sediments. Samples such as lava flows and
baked sherds that acquired a thermoremanent magnetization on
cooling can be used to estimate ancient geomagnetic field
intensities and directions. Paleofield directions can also
be obtained from fine-grained sediments that acquired detrital
magnetic remanence when deposited. Study of the earth's
magnetic field over the last few tens of thousands of years
yields information on geomagnetic dynamo theories, causes of
fluctuations in cosmic-ray activity, and the formulation of
a new regional chronologic tool.

INTRODUCTION

Both the intensity and shape of the geomagnetic field
change with time. Over 1000 paleo-intensity determinations
have been made on materials covering the last 10,000 years.
These determinations show that the global mean dipole moment
during this time was 9 x 10^{22} Am^2 and that it varied from a
broad minimum of 6.5 x 10^{22} Am^2 ca 6500 years BP to a maximum
of 11.5 x 10^{22} Am^2 near 2700 years BP (McElhinny and Senanay-
ake, in press). Superimposed on this overall trend are more
rapid intensity fluctuations, such as those observed in the
last century. Since AD 1850 the axial dipole has been de-
creasing at an average rate of 5% per century, the rate
dropping for a few years ca AD 1950 to almost zero. Vari-
ations of even higher frequency have recently been observed.
In AD 1970 the earth's magnetic field underwent a jerk (Malin
and Hodder, 1982) which noticeably altered the rate of secular
variation at many localities of the world. Sustained intens-
ity changes causing the local field to vary by a factor of 2
or 3 in 100 years were suggested on the basis of a sequence
of archaeomagnetic results from Greece (Walton, 1979). The
general pattern of field intensity changes summarized above
largely confirms that discussed by Smith (1966) and Bucha
(1970) and reinforces the possibility of important global in-
tensity changes occurring in only a few hundred years.

Detailed information about the evolution of the shape of
the geomagnetic field over the last 10,000 years recently be-
came available through paleomagnetic studies of lake sediment
cores (Mackereth, 1971) from different regions of the world.
Two key advances made the acquisition of global paleolimno-
magnetic data possible. The first advance was the development
of piston corers, such as Mackereth's (1958) pneumatic 6m
corer which allowed multiple, long, undisturbed sediment
cores to be collected from a lake during one day's fieldwork.
The second advance was the computerization of fluxgate and
cryogenic magnetometers which permitted the magnetic reman-
ence of hundreds of fragile, weakly magnetized samples to be
measured during one day's laboratory work. Following these
technical developments, much of the paleomagnetic data syn-
thesized below were collected from lake deposits. In Europe,
e g, well over 50,000 samples from tens of lakes have been
subjected to paleomagnetic measurements.

DATA QUALITY

PALEOMAGNETIC DATA. As most natural materials do not hold a
reliable paleomagnetic record of ancient geomagnetic field
changes, it is very important to demonstrate the credibility
of the data before accepting them for magnetostratigraphic or
geophysical work. The standard approach for such an assess-
ment is to use minimum reliability criteria. In this approach
practical quantitative criteria are used in order to reject
results that are unlikely to be reliable indicators of the
paleomagnetic field. In paleolimnomagnetic studies the most
important criteria concern 1) reproducibility between
samples, cores and lakes, and 2) independence from sediment
lithology. Unusual paleomagnetic results from only one sedi-
ment sampling site should be viewed with great caution.

^{14}C DATA. Most paleolimnomagnetic records have been dated
directly by the ^{14}C method. A limited number of key magnetic
records have also been dated using a pollen biostratigraphy or
tephra chronology, tied to the ^{14}C time scale. Sediments
dated by yearly laminations are now beginning to yield re-
liable paleomagnetic records.

Contamination of lake sediments by old carbon (Olsson,
1979) is a recurrent problem in dating lake sediments. Nat-
ural carbon contamination due to either erosion of materials
such as graphite, coal, or old soils in the catchment, or to
the redeposition of old sediments cannot, at present, be dealt
with satisfactorily by either laboratory pretreatment or
modelling procedures. Particularly pronounced natural con-
tamination can lead to out-of-sequence dates. Such highly

aberrant ages can of course be easily discarded. More common-
ly, however, natural contamination leads to subtle systematic
errors that can be difficult to detect unless the ^{14}C dates
from lake sediments can be compared with dates from materials
such as peat and charcoal.

A second problem concerns hard-water corrections. In
regions of carbonate-rich bedrock or glacial deposits, ages
can again be systematically old. The usual method of corr-
ecting hard-water errors is to extrapolate the ^{14}C age/depth
relationship to the mud/water interface in order to estimate
the present day hard-water error. This error is then assumed
constant and all the ^{14}C ages are then reduced by the amount
of the present hard-water error. Constant hard-water correct-
ion errors of several 100 years have had to be applied to the
South Australian, North American, and Near Eastern master sed-
iments. The need for duplicate dating techniques such as
tephra or pollen zonation combined with ^{14}C dates is apparent.
In this paper all ^{14}C dates were calibrated to calendar dates
using Clark's (1975) tree-ring curve. Dates older than 6500
years (the limit of Clark's curve) were modified using an ex-
tension to Clark's calibration curve that decreases smoothly
to zero correction at 10,000 years BP.

REGIONAL GEOMAGNETIC MASTER CURVES

Regional master curves (fig 1) were derived by analyzing
high quality paleomagnetic results from lake sediments. The
curves plot the variation of declination and inclination with
calibrated ^{14}C age. All the directional records were confirm-
ed by stacking results from more than one lake or from multi-
ple samples. Stacking, however, was not used in constructing
the master curves because of signal attenuation. Each curve
consists of a cubic spline fitted to the sequential direction-
al data of a type section. The type lakes and cores selected
for the six regions are: South Australia, Bullenmerri core BC
extended by Keilambete core KF (Barton and McElhinny, in
press); North America, St Croix core 75 (Banerjee, Lund and
Levi, 1979); western Europe, Lomond core LLRPI extended by
Windermere core W3 (Thompson and Turner, 1979); eastern Europe,
Paajarvi core P4 (Huttonen and Stober, 1980) extended by Lovo-
jarvi core D (Tolonen, Siiriainen and Thompson, 1975); Near
East, Kinneret core K8 (Thompson and Stiller, ms in preparat-
ion); East Asia, Kizaki core K3 (Horie et al, 1981). The
North Pacific curve of fig 1 is based on the paleomagnetic
results from ^{14}C dated lava flows of McWilliams, Holcomb and
Champion (1982).

SECULAR VARIATION MAGNETOSTRATIGRAPHY

The regional master curves form a basis for dating Holo-

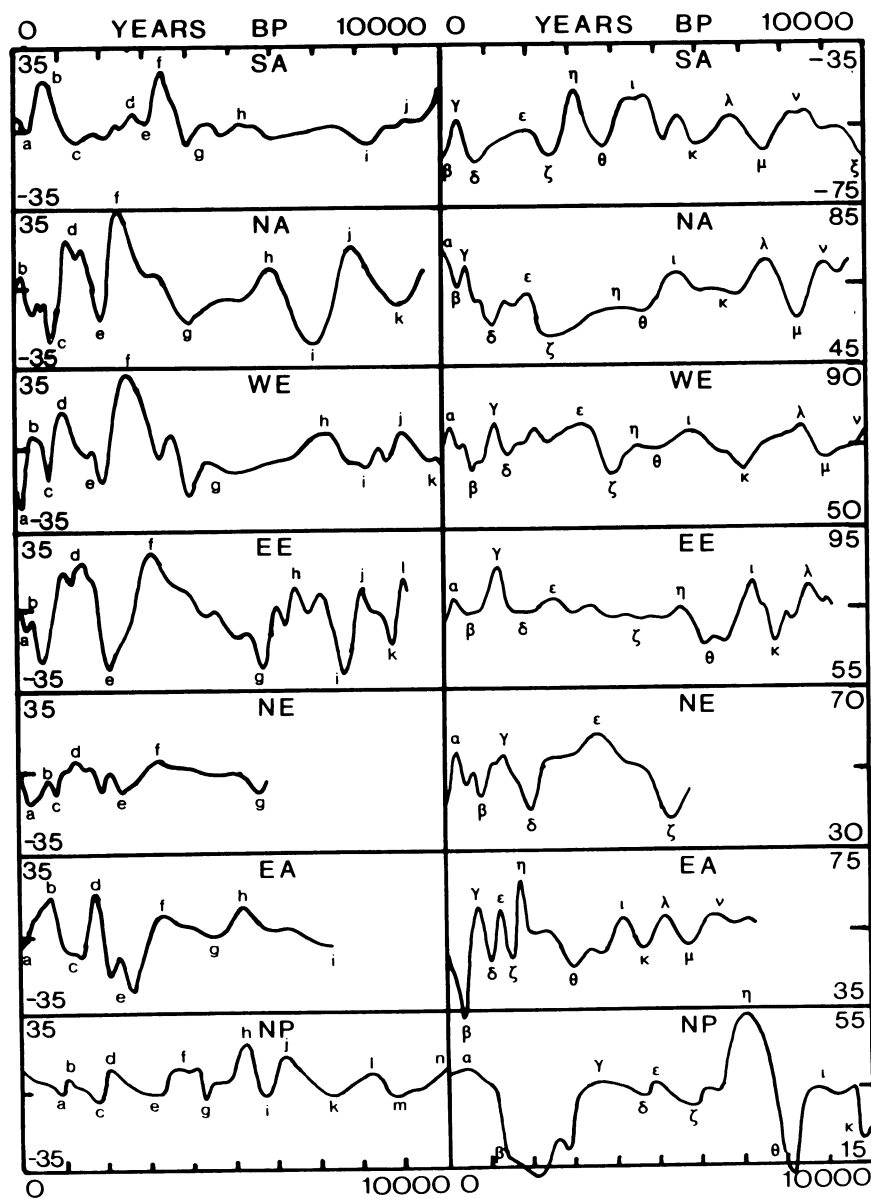O   YEARS   BP   10000 O   YEARS   BP   10000

Fig 1. Regional declination (left) and inclination (right)
master curves for South Australia, SA; North America, NA;
West Europe, WE; East Europe, EE; Near East, NE; East Asia,
EA; North Pacific, NP. Tree ring calibrated time scale in
calendar years BP (O BP = AD 1950).

cene sediments. By matching paleomagnetic features from new
sedimentary sequences with those of the curves, dates can be
transferred to the new materials under investigation. Turn-
ing points of the direction variations prove to be the clear-
est features to recognize; thus, they are labelled (Fig 1).
Some turning points are poorly developed; others, eg, WEe and
WEg, have double peaks. Both of these are difficult to label.
Bearing in mind difficulties discussed above, the typical un-
certainty in the estimated ages of the secular variation feat-
ures (Table 1) is probably ca 5%. Dominant errors relate to
natural carbon contamination problems and not to paleomagnetic
or isotopic laboratory experimental precision limitations.
Geographic areas over which the regional magnetostratigraphy
master curves will apply can best be judged from a study of
the historic magnetic field.

Table 2 summarizes global Holocene geomagnetic field
changes. The main geomagnetic variation is the fluctuation
of the axial dipole intensity (g_1^0). The magnitude and tim-
ing of these variations can be used to account for a large
proportion of the changes in ^{14}C production through a shield-
ing modulation of the flux of galactic cosmic rays. Spheri-
cal harmonic analyses of the paleomagnetic data plotted in
Figure 1 reveal slow changes in the axis of the geomagnetic
dipole about the earth's spin axis (Table 2). The analyses
indicate that the dipole axis was markedly tilted away from
the rotation axis around 7500 and 2500 years ago as well as
during the last few hundred years. An estimate of the relat-
ive importance of the non-dipole field has been made through
the residual errors (RSS) to the best fitting dipole (Table
2). The non-dipole field appears to have been relatively
strong around 7500 years BP and relatively weak around 5000
years BP.

THE HISTORICAL FIELD

Spherical harmonic analyses of historic and archaeomag-
netic data provide a consistent set of harmonic coefficients
at 50-year intervals since AD 1600 (Thompson and Barraclough,
in press). By taking differences between these coefficients,
global maps of magnetic field changes can be constructed. Two
maps are shown in Figure 2A and B for the North Atlantic reg-
ion. These illustrate the change in position of the westerly
declination maxima WEa (Fig 1) and the inclination maxima WEα
(Fig 1) between AD 1625 and 1975. The maps were prepared by
calculating and contouring the zero isopores of the rate of
change of declination (D) and inclination (I). The zero iso-
pores, in common with many features of the non-dipole field,
exhibit a general westward drift. Their drift rate varied
markedly from place to place, eg, compare the AD 1675 and 1875

Table 1. Ages of magnetostratigraphic features

Declination

Turning points	SA	NA	WE	EE	NE	EA	NP
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	–	–	7300
l	–	–	–	9000	–	–	8350
m	–	–	–	–	–	–	8900

Inclination

Turning points	SA	NA	WE	EE	NE	EA	NP
α	–	50	240	300	300	–	200
β	0	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)   NE Near East   (30°N 35°E)
NA North America   (45°N 90°W)   EA Eastern Asia (35°N 140°E)
WE Western Europe (55°N 05°W)   NP North Pacific (20°N 155°W)
EE Eastern Europe (60°N 30°E)

Ages tabulated in calibrated ^{14}C years BP. The pre-2000 BP EA magnetostratigraphic features are taken from Horie et al (1981). The EA ages are rather poorly known, based here on a linear interpolation between the basal tephra layer and the archaeomagnetic features in the upper sediments. The NP turning points are based on the ^{14}C dated lava flow palaeomagnetic data of McWilliams et al (1982).

Table 2   Geomagnetic coefficients and parameters

Epoch BP	g_1^o μT	λ_c	ϕ_c	g_2^o/g_1^o	RSS	Regions
Present	−30.5	79°N	070°W	+0.05	−	>100
0	−30.5	81	087 W	+0.02	0.011	7
500	−37.6	83	086 W	−0.02	0.009	7
1000	−40.9	89	041 W	+0.04	0.014	7
1500	−41.8	85	163 E	+0.03	0.008	7
2000	−42.0	87	165 W	+0.07	0.018	7
2500	−44.0	80	155 E	+0.04	0.019	7
3000	−40.2	85	121 E	+0.02	0.011	7
3500	−33.9	89	110 W	−0.04	0.023	7
4000	−32.5	88	001 E	+0.00	0.015	7
4500	−32.6	88	008 E	−0.01	0.004	7
5000	−30.0	86	020 W	−0.02	0.003	7
5500	−26.9	84	080 W	−0.02	0.004	7
6000	−25.4	86	090 W	−0.01	0.008	6
6500	−25.2	86	015 W	+0.02	0.005	6
7000	−25.5	82	004 W	−0.06	0.019	6
7500	−27.1	80	054 W	+0.13	0.036	5
8000	−30.2	87	155 W	−0.01	0.004	5
8500	−32.8	88	113 E	−0.09	0.011	5
9000	−33.0	88	023 W	−0.04	0.011	5

g_1^o is the strength of the axial dipole. This is the dominant term in the spherical harmonic expansion of the earth's internal magnetic field and is the main parameter to be considered in assessing the influence of geomagnetic field variations on ^{14}C production. λ_c is the latitude of the north magnetic pole. ϕ_c is the longitude of the north magnetic pole. g_2^o/g_1^o is the ratio of the axial quadrupole to the axial dipole and is an important geomagnetic parameter in assessing asymmetry between the northern and southern hemispheres. RSS is the mean residual sum of squares, here presented as a proportion of the axial dipole (i e, with g_1^o = 1.0), to the palaeolimnomagnetic direction data when fitted by a 'tilted' geocentric dipole. RSS is a measure of the non-dipole field. Large values indicate times of high non-dipole to dipole field ratio. The right hand column notes the number of regions used in the calculations. The data used are shown in Fig 1. The effect of data distribution can be judged by comparing the 0 BP parameters with those of the present field. The small number of regions available for analysis and the lack of absolute orientation of the palaeomagnetic records can lead to systematic errors in spherical harmonic analyses.
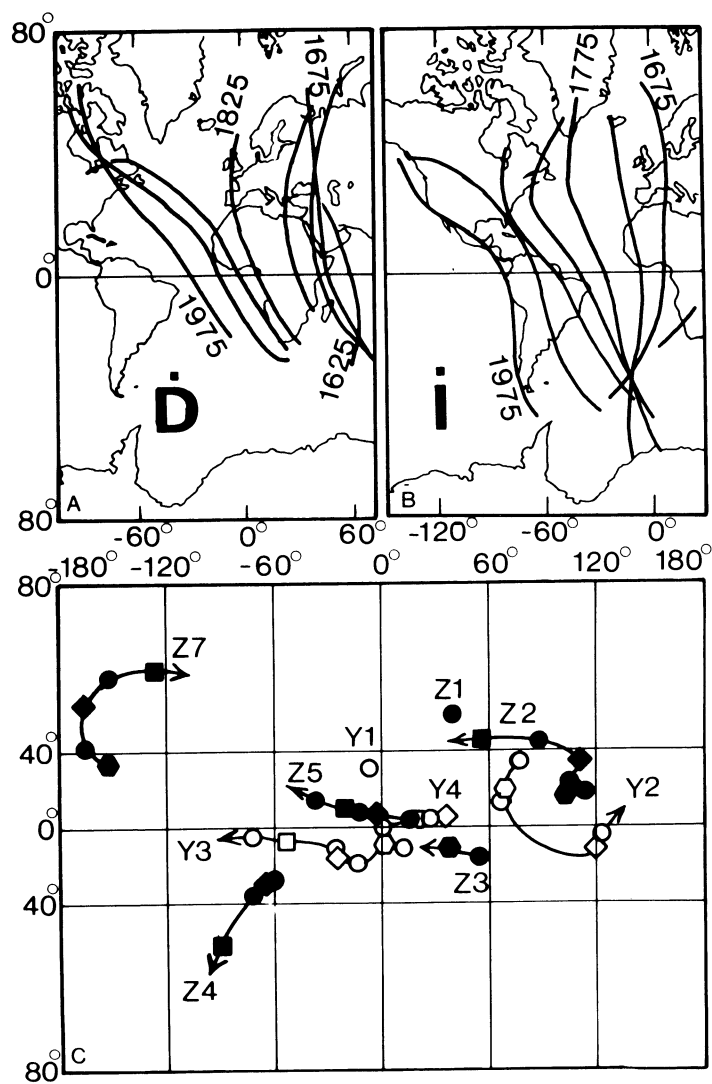
Fig 2. Examples of geomagnetic changes between AD 1625 and
1975. A. Location of the isopore D = 0. B. Location of the
isopore I = 0. C. Major foci of changes in Y (open symbols)
and Z (closed symbols) at 50-year intervals. Positive
anomalies have even codes (eg, Y2), negative anomalies have
odd codes. Hexagons, diamonds, and squares correspond to
epochs AD 1725, 1825 and 1925, respectively.

positions of the zero D isopore at the equator and at the latitude of Britain in Figure 2A. These differences and the overall changes can be understood in terms of the growth, movement, and decay of local centers of secular change. Figure 2C shows the location of isoporic foci of the field elements Y and Z calculated from Thompson and Barraclough's coefficients. Changes in the easterly horizontal element (Y) and the vertical element (Z) are closely related to changes in declination and inclination, respectively. The 17th century pattern of North Atlantic declination changes was dominated by the foci Y1 and Y2. The change in location of the westerly declination turning point WEa (ie zero D isopore) has been controlled partly by the establishment of the new foci Y3 and Y4 and partly by the movement of all four foci. The change in position of the zero I isopore (WEα) was controlled by the evolution and movement of the minimum focus Z5 gradually replacing the foci Z1 and Z3, (Fig 2C).

SUMMARY

Holocene field intensities have varied by a factor of 2 or 3 due to fluctuations in the geomagnetic dipole moment, whereas field direction changes have been dominated by the turbulent evolution of the non-dipole field with short-lived foci of secular change. The foci have combined, largely at random, to produce the field variations of Figure 1. Analysis of historic field variations reveals regions of similar field changes several thousand kilometers in extent. The boundaries between such regions undoubtedly alter along with the field changes; nevertheless, the regional master curves (Fig 1) are likely to be useful over distances of several hundred kilometers and possibly a few thousand kilometers. The age differences of turning points, due to source drift, across such distances is only ca 100 years. When dating older Holocene sediments, such differences are not of critical importance, and for younger historic materials, the turning point chronology has now been mapped (Fig 2A, B).

ACKNOWLEDGMENTS

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