[RADIOCARBON, VOL 22, No. 2, 1980, P 192-199]

GEOMAGNETIC STRENGTH OVER THE LAST 50,000 YEARS AND CHANGES IN ATMOSPHERIC ^{14}C CONCENTRATION: EMERGING TRENDS

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ABSTRACT. Palaeomagnetic field strength measurements for the last 50,000 years are summarized. The period before ~12,000 yr bp** is characterized by low dipole moments, but high values are associated with the Lake Mungo polarity excursion between ~32,000 and ~28,000 yr bp. The variation since 12,000 yr bp, based on new results from Australia and published data from the Northern Hemisphere has a quasi-cyclic appearance with maxima at ~10,000 and ~3500 yr bp. The geomagnetic record is used to predict variations in atmospheric ^{14}C concentration, and the results are compared with independent comparisons between ^{14}C and other dating methods. Long-term variations in the ^{14}C time-scale are readily explained by known geomagnetic changes.

INTRODUCTION

It has long been recognized that variations in geomagnetic strength affect the cosmic ray flux reaching the earth and, hence, the production rate of all cosmogenic isotopes (eg, Elsasser, Ney, and Winkler, 1956; Wada and Inoue, 1966; Lingenfelter and Ramaty, 1970). Many authors have performed model calculations for variations of ^{14}C, using either summaries of contemporary palaeomagnetic data or sinusoidal approximations to it (see Olsson, 1970; Rafter and Grant-Taylor, 1972; Berger and Suess, 1979). In this paper, a considerable amount of new palaeomagnetic field strength data is summarized. Some broad trends in ^{14}C concentration are predicted. Independent comparisons between ^{14}C and other dating methods are also summarized.

Palaeomagnetic data

Estimates of dipole moment for the late Pleistocene (50,000-10,000 yr bp) were reviewed recently by Barbetti and Flude (1979), and their conclusion that the geomagnetic field was weaker than it is today for much of that period is supported by further data from Japan (Tanaka, 1978). The late Pleistocene data do not exhibit the quasi-sinusoidal variation observed in Holocene times.

Holocene data from the Northern Hemisphere have also been reviewed recently (Barton, Merill, and Barbetti, 1979) and, as has been found previously from reviews of smaller but similar data sets (Cox, 1969), the variation appears roughly periodic with a minimum at 5500 yr bp and maxima at 8500 and 1500 yr bp. However, new data from Greece (Walton, 1979), Peru (Gunn and Murray, in press) and Australia (Barbetti and others, ms in preparation) indicate a broad maximum beginning at ~3500 yr bp, together with clear evidence for shorter-period fluctuations between then and the present day.

A summary of the probable values of geomagnetic dipole moment and 95 percent confidence limits is given in table 1. Only long-term

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** Note that bp denotes conventional ^{14}C ages, and BP, absolute ages, in this paper changes are expressed in curve A, but the wide confidence limits allow for the possibility of shorter-period or smaller amplitude fluctuations.

Predicted atmospheric ^{14}C concentrations

The probable effects of geomagnetic variation on ^{14}C concentration have been calculated in an approximate manner, using the Lingenfelter and Ramaty (1970) relationship between dipole moment and ^{14}C production (with no long-term changes in solar activity). It has been assumed that the concentration at 32,000 yr bp was between the limits 1.75 and 0.9 times standard with a probable value of 1.25; these values correspond to exponentially-averaged dipole moments of 2, 10 and 5 $\times$ 10^{22} Am^2, respectively, for times before 32,000 yr bp, as suggested by Barbetti and Flude (1979). Changes since then were derived using curves A, B and C in table 1, and assuming that changes in the ^{14}C production rate are attenuated with coefficient 0.33 and a lag of ~1000 years because of reservoir storage (Houtermans, Suess, and Oeschger, 1973). The method, even though fairly crude, produced curves that agreed very well with the long-term trends in tree-ring data. Results are illustrated in figure 1. No allowance was made for the possible effects of climatic changes or variations in the cosmic ray flux due to other causes.

^{14}C concentrations from other dating methods

Comparisons between ^{14}C and absolute dates provide estimates of atmospheric ^{14}C concentrations quite independently of predictions based on geomagnetic variation. A summary of all results known to me is given

TABLE 1

Geomagnetic strength over the last 40,000 years

Time	Dipole		Moment	
(yr bp)	(10^{22} Am^2)			
	Palaeomagnetic limits	Curve A	Curve B	Curve C
0	8	8	8	8
1500	6-13	8½	8½	8½
3500	7-14	11	12	12
6000	4-7	6	7	4
10,000	5-12	10	12	8
14,000	4-9	7	7	9
17,000	4-8	6	5	8
21,000	4-7	5½	4	7
25,000	2½-6½	4	2½	6½
28,000	3-8	6	3	8
29,500	10-50	30	10	50
32,000	2-10	5	2	10

Estimates are based on data from Europe, Australia and Hawaii (reviewed by Barbetti and Flude, 1979), preliminary data from Japan (Tanaka, 1978), averages of published data from the Northern Hemisphere (Barton, Merrill, and Barbetti, 1979) and new data from Australia (Barbetti and others, ms in preparation). Palaeomagnetic limits enclose 95 percent confidence intervals for most of the data, and curve A gives probable values of dipole moment. Curves B and C are hypothetical extremes used to predict limits for atmospheric ^{14}C concentration over the last 40,000 years. The present day dipole moment is 8×10^{22} Am^2.

https://doi.org/10.1017/S0033822200009450 Published online by Cambridge University Press

TABLE 2

Summary of ¹⁴C and comparative thermoluminescent

Absolute age			Conventional ^{14}C age			Age difference	Atmospheric concentration	Symbol
Lab No.	(yr B.P.)	Ref	Lab no.	(yr B P)	Ref	(yr)		
Thermoluminescent:								
BOR-6	11,290±1470	1	Ly-858	11,150±220	2	140	0.98±0.19	◆
OxTL 133a1	13,970±1850	3	Gak-949	12,400±350	3	1570	1.16±0.30	■
			Ly-859	13,510±220	2			
			Ly-860	13,840±210	"			
BOR-7	14,500±1890	1	*W Mean*:	13,680±150		820	1.05±0.27	◆
OxTL 174F51	16,900±5000	4	ANU-668	19,420±360	5	-2520	0.69±0.57	▲
OxTL 174F6	21,800±3700	6	ANU-667	26,270±470	"	-4470	0.53±0.30	▲
			GrN-2092	28,300±300	7			
			GrN-2598	29,000±200	"			
OxTL 117	33,000±3000	7	*W Mean*:	28,800±170		4200	1.50±0.66	●
OxTL 174F7	35,300±5600	6	ANU-680	30,780±520	5			
" "	29,500±4100	"	"	" "	"			
" "	31,300±5600	"	"	" "	"			
" 174F8	37,900±6400	"	ANU-681	28,310±410	"			
" 174F9	32,000±5700	"	ANU-682	27,530±340	"			
" "	32,300±5800	"	"	" "	"			
" 174F12	38,600±7700	"	ANU-683	28,000±410	"			
Mean:	33,500±4300	"	*Mean*:	29,100±700		4400	1.54±1.07	▲
$^{230}Th/^{234}U$:								
				13,860±220	8			
				13,600±220	"			
	17,000±800	9	*W Mean*:	13,730±200		3270	1.42±0.15	¤
L-773Q	13,100	10		12,100	10			
L-772GA	16,200	"		16,800	"			
L-774B	16,700	"		15,000	"			
L-772I	15,400	"		17,600	"			
L-775J	18,000	"		15,300	"			
L-774I	17,300	"		17,600	"			
L-774R	17,000	"		18,000	"			
L-773O	12,800	"		11,500	"			
L-364CQA	19,900	"		16,500	"			
L-772K	16,100	"		17,900	"			
L-772HB	24,400	"		18,400	"			
L-364CQB	20,000	"		16,800	"			
L-722A	21,600	"		17,100	"			
L-672B	21,400	"		17,100	"			
Mean:	17,850±880		*Mean*:	16,265±570		1585	1.14±0.15	○
			GrN-4837	15,150±110	11			
			GrN-4838	16,100±150	"			
35D	20,000±2000	12	*W Mean*:	15,480±90		4520	1.64±0.45	□

References and Notes

1. Schvoerer, Lamarque, and Rouanet (1974); uncertainty assumed to be 13% of age.
2. Evin, Marien, and Pachiaudi (1976).
3. Fleming and Stoneham (1973).
4. Huxtable, J and Aitken, M, pers commun (see also Barbetti and Flude, 1979).
5. Barbetti and Polach (1973).
6. Huxtable and Aitken (1977).
7. Zimmerman and Huxtable (1971).

Lab No.		Absolute age (yr B.P.)	Ref	Conventional ¹⁴C age Lab no.	(yr B P)	Ref	Age difference (yr)	Atmospheric concentration	Symbol
Thermoluminescent:									
21C		24,000±3000	12	21C-C	25,000±1000	12	-1000	0.81±0.38	□
		23,800	13						
		24,800	"						
		24,800	"						
S7	*Mean:*	24,500±1400			22,900±300	13	1600	1.12±0.21	△
		24,200	13						
		27,000	"						
		23,700	"						
		25,300	"						
S6	*Mean:*	25,100±1400			24,700±300	13	400	0.96±0.18	△
		25,800	13						
		23,000	"						
S5	*Mean:*	24,400±1400			27,400±300	13	-3000	0.63±0.12	△
		26,200	13						
		26,200	"						
S4	*Mean:*	26,200±1400			27,900±400	13	-1700	0.74±0.14	△
S3		29,300±1500	13		29,400±400		-100	0.89±0.18	△
				GrN-4841	29,000±380	11			
				GrN-4842	29,900±530	"			
35B		30,500±2500	12	*W Mean:*	29,310±310		1190	1.04±0.37	□
		31,000±2500	9		28,500±600	9	2500	1.22±0.45	⌑
		31,800	13						
		30,200	"						
S2	*Mean:*	31,000±1500			29,400±400	13	1600	1.09±0.23	△
		33,000	13						
		33,000	"						
		30,100	"						
S1	*Mean:*	32,000±1500			31,800±300	13	200	0.92±0.19	△
TF-907		34,000±2000	14		27,800±1500	14			
TF-1063		33,100±1000	"		35,100±5600	"			
	W Mean:	33,300±1000		*W Mean:*	28,300±1500		5000	1.66±0.40	◇
		40,000±3000	9		35,600±1500	9	4400	1.50±0.75	⌑

8. Veeh and Veevers (1970).
9. Chappell and Veeh (1978).
10. Kaufman and Broecker (1965); results from table 5, excluding ostracods and samples showing distinctly abnormal Ra^{226} and U^{234} concentrations.
11. Vogel and Waterbolk (1972). See note 12.
12. Kaufman (1971). Note that sample 36 was contaminated; dates for this sample are therefore omitted from table.
13. Peng, Goddard, and Broecker (1978); ^{14}C ages interpolated from results of Stuiver (1964), Stuiver and Smith (1979).
14. Gupta (1973); results cited by Peng, Goddard, and Broecker (1978).

Ages are those given in the references indicated, and all ^{14}C ages are based on a 5568 yr half-life. Errors are standard errors. Mean ages (simple or weighted inversely by variance, as indicated) are given for appropriate groups of results. Age differences (absolute–^{14}C) and corresponding atmospheric ^{14}C concentrations (calculated using a 5730 yr half-life) are also listed. Symbols are those used in figure 1.

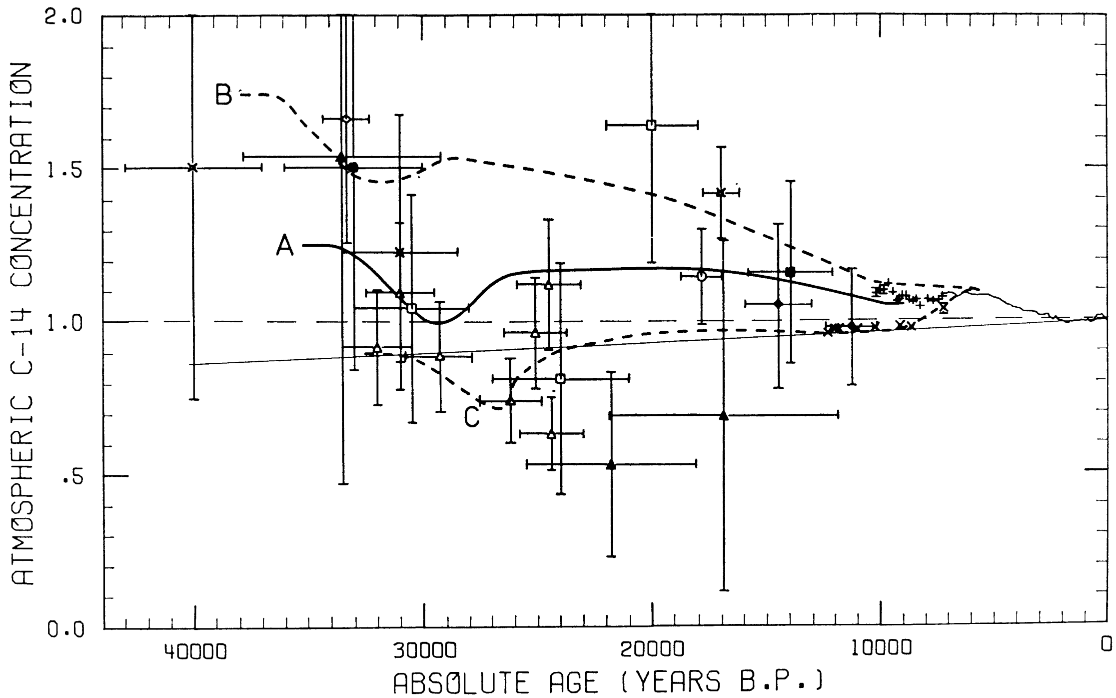

Fig 1. Atmospheric ^{14}C concentration over the last 40,000 years. The dashed horizontal line marks the standard concentration (0.95 times that of NBS oxalic acid) used for calculating radiocarbon ages, and the thin exponential line beneath it the hypothetical concentration variation which would make conventional ^{14}C ages identical to absolute ages. Points with large standard errors are derived from comparisons between ^{14}C and thermoluminescent or uranium series ages; values and symbols are given in table 2. Other points are derived from comparisons between ^{14}C and varve ages in Scandinavia (×, Tauber, 1970) and the USA (+, Stuiver, 1971); standard errors are about the size of the points. The curve for the last 7400 yr is obtained from comparisons between tree-ring and ^{14}C ages, using the compilation of Clark (1975). Curve A is the probable variation, predicted using known variations in geomagnetic strength (curve A, table 1). Curves B and C are limits obtained using extreme values for geomagnetic strength before ~20,000 yr bp and values after that which make the limits converge on the tree-ring curve at ~6000 yr BP.

https://doi.org/10.1017/S0033822200009450 Published online by Cambridge University Press

in table 2. Appropriate mean values, age differences and concentrations (C_A) are also given; the latter were obtained using the expression

$$C_A = exp \left[\left(\frac{T_a}{5730} - \frac{T_c}{5568} \right) ln\ 2 \right]$$

where T_a is the absolute age and T_c the conventional ^{14}C age. Atmospheric concentrations estimated in this manner have very large uncertainties, because the precision of the other dating methods is generally much less than that of radiocarbon. Nevertheless, they do suggest a decrease between ~35,000 and ~25,000 yr BP and subsequent increase, which accords well with the trend predicted on geomagnetic evidence (and the suggestion by Ottaway and Ottaway, 1974 from frequency analyses of ^{14}C dates).

CONCLUSION

Atmospheric concentrations above unity are indicated for most of the late Pleistocene, with a large fluctuation at around ~30,000 yr BP. The prediction from geomagnetic data (curve A, figure 1) matches the varve data of Stuiver (1971) fairly well. The varve data of Tauber (1970), however, are near the lower limit permitted by known geomagnetic variations. There is considerable scope for future refinement of the curves presented here, using new palaeomagnetic data as they become available, and improved methods of calculation.

ACKNOWLEDGMENTS

It is a pleasure to thank M W McElhinny, H A Polach, M J Aitken, and J R Prescott for guidance and encouragement through a decade of research in palaeomagnetism and radiocarbon dating. I also thank Iain Davidson for drawing my attention to the work of Schvoerer, Lamarque, and Rouanet (1974), Ann McLean for typing the manuscript, and Judy Laing for help with the figure. This work was supported by the Australian Research Grants Committee. Copies of the computer program are available from the author.

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DISCUSSION

Damon: Dr Barbetti's analysis places the geomagnetic dipole field intensity maximum prior to the beginning of the Christian era. This agreed with our modeling of the geomagnetic forcing function on ^{14}C production (Damon, 1970; Sternberg and Damon, 1979).

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Barbetti: The Barton, Merrill, and Barbetti (1979) re-analysis of northern hemisphere geomagnetic strength data gives results fairly similar to those of Cox (1969), and the most recent peak still appears at 1500 yr bp. The Australian data are important for reconstructing *global* variations because the southern hemisphere is hardly represented in existing analyses. The field in Australia reached a high value at 3500 yr bp. New evidence from Peru (Gunn and Murray, in press) and Greece (Walton, 1979) also suggest a high field somewhat earlier than the currently-accepted time of 1500 yr bp.

Tauber: The Swedish varve chronologists are increasingly uncertain about the absolute scale precision of the Late Glacial Swedish varve chronology. The varve dates quoted in my paper (1970) therefore, are considerably more uncertain than believed in 1970.

Lal: The large dipole moment excursion around 30,000 yr bp is very interesting. A factor of 5 higher dipole moment corresponds to a vertical cut-off rigidity of about 50-60 GeV at the equator—the global production rate will be depressed quite a bit and it should be possible to check on this by studying calcareous oozes.

Barbetti: ^{14}C data for that period would be very interesting. However, there are also uncertainties in the *effective* dipole moment around 29,500 yr bp. The geomagnetic field was probably not dipolar during the Lake Mungo excursion; possible source configurations are discussed by Coe (1977). Most likely the geomagnetic shielding against cosmic rays would be equivalent to a dipole with strength higher than the present-day. The limits given here ($1 - 5 \times 10^{23}$ Am^2) cover the most plausible interpretations.

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