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IMPLICATIONS OF DIPOLE MOMENT SECULAR VARIATION FROM 50,000-10,000 YEARS FOR THE RADIOCARBON RECORD

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ABSTRACT. Sparse paleointensity data from 10-50 ka suggest that the average dipole moment (DM) was 50-75% of the average of 8.67×10^{22} A m^2 for the past 5 Ma, and 8.75×10^{22} for the past 12 ka. A linear ramp function, increasing the DM from 4 to 8.75×10^{22} A m^2 between 50-10 ka BP, generates a total ^{14}C inventory of 126 dpm/cm_e^2, agreeing very well with an inventory assay of 128 dpm/cm_e^2, which includes ^{14}C in sediments. With the Lingenfelter and Ramaty (1970) production function and a model DC gain of about 100, this DM function would give a $\Delta^{14}C$ of 500‰ at 20 ka BP, consistent with the Barbados coral record, and also gives a good match to the Holocene record. A Laschamp geomagnetic event at about 45 ka BP, with a DM of 25% of its average value and lasting 5 ka, would only increase the present inventory by 0.3-1.2 dpm/cm_e^2, and would probably have only a small effect on $\Delta^{14}C$ at 20 ka BP, but could produce a short-lived ^{14}C spike of over 500‰.

INTRODUCTION

Until recently, discussion of radiocarbon activity fluctuations (Olsson 1970; Damon, Lerman & Long 1978) has focused on the Holocene (Stuiver & Kra 1986). In general, the "long-term" fluctuation with a quasi-periodicity of 10 ka has been attributed to changes in the geomagnetic dipole moment (DM) and the resulting modulation of ^{14}C production (Damon & Sonett 1991; Sternberg 1992; Stuiver *et al.* 1991). Shorter-term fluctuations are attributed to changes in solar activity and its modulation of ^{14}C production (Damon, Cheng & Linick 1989; Stuiver *et al.* 1991).

The research of Bard *et al.* (1990a, b) has revived interest in the late Pleistocene ^{14}C record. Their initial ^{14}C and mass spectrometric U-Th ages on Barbados corals suggested that $\Delta^{14}C$ may have been as high as 500‰ at 20 ka BP (Bard *et al.* 1990a). Subsequent analysis of these coral samples with AMS ^{14}C dates on leached samples suggest that $\Delta^{14}C$ was about 350‰ at 20 ka BP (Bard *et al.* 1990b). Bard *et al.* (1991) further report that corals from French Polynesia also indicate a $\Delta^{14}C$ of 340‰ at 17.6 ka BP. If we accept these results, atmospheric activity was considerably higher than in the tree-ring record. Phillips, Sharma and Wigand (1991) found corroborative evidence in high $^{36}Cl/Cl$ ratios in fossil packrat urine from western Nevada: 410‰ and 280‰ (relative to a sample from 3 ka BP) at 21 ka and 12 ka, respectively. The question naturally arises as to a cause, and one possibility is geomagnetic modulation of ^{14}C production.

We examine here the relationship between the ^{14}C record and DM behavior in the Late Pleistocene. We assume that the long-term ^{14}C fluctuations are primarily due to geomagnetic modulation. Our analysis consists of three components. First, we look at the ^{14}C inventory, which integrates Q over time, and is independent of the details of the geochemical system. Second, we model atmospheric activity fluctuations. Third, we consider the effects that a "Laschamp" event would have had on ^{14}C activities. We hope to demonstrate that the high activities suggested by the Barbados coral records are consistent with geomagnetic modulation of ^{14}C production by a low DM in the Late Pleistocene.

INVENTORY

Method of Calculation

We use the term, "inventory," as the total amount of ^{14}C in all geochemical reservoirs combined. The equation for inventory is

$$I = \frac{\int_0^{\infty} Q(t)e^{-\lambda t}dt}{\int_0^{\infty} e^{-\lambda t}dt} \qquad (1)$$

$$= \lambda \int_0^{\infty} Q(t)e^{-\lambda t}dt \qquad (2)$$

where I is the inventory in dpm/cm_e^2, t is time in years BP, Q is the production in atoms/cm_e^2/min, and λ is the ^{14}C decay constant (Elsasser, Ney & Winckler 1956; Houtermans 1966; Libby 1967; Ramaty 1967; Lingenfelter & Ramaty 1970; Sternberg & Damon 1979; Damon & Sternberg 1989). We get the present inventory by integrating Q back in time. Inventory is a useful parameter for geomagnetic history, because it depends only on Q, and is independent of the ^{14}C geochemical system.

We have calculated the inventory for a number of DM models and production functions. Figure 1 shows our "standard" DM model and corresponding "standard" Q function. The DM model for the last 12 ka is based on the compilation of McElhinny & Senanayake (1982), using their 0.5 ka global averages back to 2 ka BC, and 1 ka averages from 2–10 ka BC. The standard DM model for the period before 12 ka BP is based on data from McElhinny and Senanayake (1982: Fig. 5). We let the DM linearly decrease from 8.36×10^{22} A m^2 at 11.5 ka BP (midpoint for the last 1 ka average) to 4.0×10^{22} A m^2 at 20 ka BP, and remain constant at that value farther into the past.

The standard production function uses the relationship

$$\frac{Q}{Q_0} = \left(\frac{M}{M_0}\right)^{-0.5} \qquad (3)$$

where M is the DM, and Q_0 and M_0 are corresponding reference values of the production and DM (Elsasser, Ney & Winckler 1956; Wada & Inoue 1966; Ramaty 1967; Lingenfelter & Ramaty 1970; O'Brien 1979; Blinov 1988; Lal 1988). For reference values, we used Q_0 = 132 atoms/cm_e^2/min, averaged over three recent solar cycles (Lingenfelter & Ramaty 1970), for the present DM of 8.0 $\times 10^{22}$ A m^2.

Inventory Assay

The calculated value for inventory is compared with an estimate for the ^{14}C contained in all geochemical reservoirs. We take our estimate of 142 ± 19 (2σ) dpm/cm_e^2 from Damon and Stern-

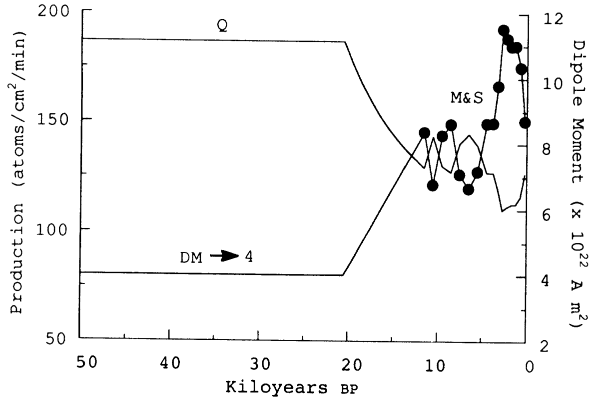

Fig. 1. The standard DM model and corresponding ^{14}C production function. M&S = McElhinny & Senanyake (1982)

berg (1989). We estimated that 10% of this amount is produced by solar flares, which will not be subject to the same rules of geomagnetic modulation; thus, we estimate that geomagnetically modulated production is responsible for 128 ± 17 (2σ) dpm/cm$_e^2$.

Results of Inventory Calculations

Figure 2 shows the results of the inventory calculation for the standard DM and Q functions. Integration is from the present to 50 ka BP, so the inventory value shown at that time is actually the present inventory. The result is 126 dpm/cm$_e^2$, almost exactly the same as the geomagnetically modulated inventory value given above.

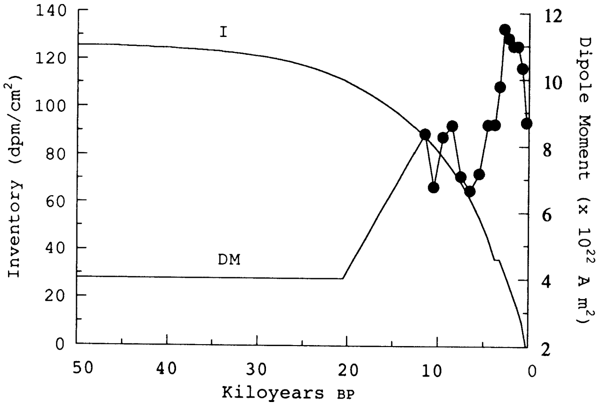

Fig. 2. The standard DM model and the resulting global ^{14}C inventory, calculated by integrating back in time, so the value at 50 ka BP is actually the present inventory

Table 1 presents inventory calculations for other cases. The standard (std) DM model represents a "slow" drop spanning 8 ka to the lower DM at 20 ka BP (Case 1); in contrast, the "fast" drop lasts just 1 ka (Case 2). Paleointensities for Hawaii (Coe, Grommé & Mankinen 1978), the western USA (Champion 1980), Iceland (Schweitzer & Soffel 1980), Europe (Salis, Bonhommet & Levi 1989), and Japan (Tanaka 1990) suggest that the DM could have been as low as 5–6 × 10^{22} A m^2 by 11–12 ka BP.

The next two cases (3 and 4) in Table 1 increase and decrease, respectively, all values in the standard DM model by 1 σ, using the standard deviation values given by McElhinny and Senanayake (1982) back to 12 ka BP, and then relative standard deviations of 17.5%, representative of

TABLE 1. Global ^{14}C Inventory Calculations

Case	DM*	Production**	Inventory (dpm/cm_e^2)
1	M&S to 4, slow (std)	L&R	126
2	M&S to 4, fast	L&R	132
3	M&S + 1 σ to 4, slow	L&R	114
4	M&S - 1 σ to 4, slow	L&R	143
5	M&S to 8.67	L&R	118
6	Std	OBr	104
7	Std	C&L	146
8	Std + "Laschamp"	L&R	127

*DM model for the past 12 ka based on: M&S = McElhinny & Senanayake (1982). See text for additional details.

**Production functions from: L&R = Lingenfelter & Ramaty (1970); OBr = O'Brien (1979); C&L = Castagnoli & Lal (1980).

the present field (McElhinny & Senanayake 1982), for earlier values. These generate inventories of 114 and 143 dpm/cm_e^2, respectively, which are both within 1σ of the assay value.

We have considered a DM model (Table 1, Case 5) that switches from the McElhinny and Senanayake (1982) data to a value of 8.67×10^{22} A m^2, which is the average DM during the past 5 Ma, according to McFadden and McElhinny (1982). The resulting inventory is 118 dpm/cm_e^2.

We also tried different production functions (Damon 1988; Damon & Sternberg 1989) with the standard DM model. The lowest production function is O'Brien's (1979), which is 26% lower than that of Lingenfelter and Ramaty (1970). Consequently, this gives a low inventory of 104 dpm/cm_e^2 (Case 6), which is not consistent with the assay value. The highest production function of Castagnoli and Lal (1980) gives an inventory of 146 dpm/cm_e^2 (Case 7), still within the error of the assay.

Finally, we considered the effects of a "Laschamp" (in quotes because of the inconclusive evidence regarding this event) event on the inventory. Bonhommet and Babkine (1967) first detected anomalous paleomagnetic directions in the Laschamp flows. Marshall, Chauvin and Bonhommet (1988), Roperch, Bonhommet and Levi (1988) and Levi *et al.* (1990) have correlated anomalous paleomagnetic directions at Laschamp and Iceland that have similar dates of 45 ka BP and paleointensities about 15% of the present field strength. The Laschamp event was not originally observed in the high-fidelity sedimentary paleomagnetic record of Lac du Bouchet (Thouveny, Creer & Blunk 1990), very close to the type locality for the Laschamp lavas. More recently, Thouveny and Creer (1991) observed low relative paleointensities in Lac du Bouchet from 28–60 ka BP, with a minimum at 33 ka (Thouveny & Creer 1991). On the other hand, anomalous magnetic directions have not been observed in all paleomagnetic records during the time of Laschamp. Heller and Petersen (1982) have even suggested that the rocks of Laschamp may be self-reversing.

To calculate the inventory, we modeled an extreme case for the Laschamp event, with a DM decreasing to 1.0×10^{22} A m^2, about 12% of the present value, from 40-50 ka BP (Table 1, Case 7). Although production doubles to 373 $atoms/cm_e^2/min$, this is old enough to add only a negligible 1 dpm/cm_e^2 to the inventory calculation.

We have not considered the relative paleointensity data derived from marine sediments by Tauxe and Valet (1989), as was done by Stuiver *et al.* (1991). This is an intriguing data set, in that it tends to corroborate the general pattern in the McElhinny and Senanayake (1982) compilation. However, these paleointensities are only relative, not absolute, and coming from a single locality, would include a non-dipole as well as a dipole component.

Our conclusions from the inventory analysis are: 1) the standard DM model, including low DM prior to 20 ka BP, yields an inventory concordant with the assayed value; 2) O'Brien's production function appears to be too low; 3) a Laschamp event is not ruled out, although it is certainly not necessary.

FLUCTUATIONS

We next examine the effects of late Pleistocene DM behavior on atmospheric ^{14}C activity. Barbetti and Flude (1979) and Barbetti (1980) used simpler modeling in previous research. Although the Barbados coral record was not yet available, it is noteworthy that Barbetti (1980: Fig. 1) inferred the possibility of such high activities from the low DM during the late Pleistocene.

The Model

To model atmospheric fluctuations, we used a three-box first-order exchange model with a sedimentary sink. We did our modeling using the STELLA program (Richmond, Peterson & Vescuso 1987) on the Apple Macintosh computer. The boxes represent, respectively, the ambient reservoir (Box 1 = atmosphere), the mixed layer reservoir (Box 2 = biosphere, humus, surface water, and mixed layer of the oceans), and the deep-sea reservoir (Box 3 = deep sea and saprosphere). Sediments are transported from deep sea to sedimentary sink (Box s), but are not returned. The frequency response of this model is similar to that of other suitably parameterized models, including the box-diffusion model, for the longer periods associated with geomagnetic modulation (Damon, Sternberg & Radnell 1983: Fig. 1). It is important to include the sedimentary sink, because it significantly decreases the DC gain. We have emphasized this by keeping many of our results in terms of ^{14}C activity rather than converting them to $\Delta^{14}C$. This conversion is commonly done by calculating the $\Delta^{14}C$ relative to a reference activity determined by the model for a given year, *e.g.*, AD 1890. This makes the modeler's work too easy, by effectively adding one degree of freedom, and can lead to error if the DC gain is not balanced (Lazear, Damon & Sternberg 1980).

To initially parameterize the model, we took reservoir contents (n1, n2, n3, and ns) from Damon (1988). Two exchange rates remained fixed in the analysis: k_{12}, from the ambient reservoir to mixed layer, and k_{23}, from the mixed layer to deep sea. Values were $k_{12} = 1/10\ a^{-1}$ and $k_{23} = 1/30\ a^{-1}$, consistent with values used by previous investigators. We calculated exchange rates, k_{21}, k_{32} and k_{3s} from steady-state equations.

Earlier models (*e.g.*, Sternberg & Damon 1979) assumed continuously oscillating DMs, but in all our DM models (other than Laschamp models), we assume a constant DM prior to 20 ka BP. To renormalize the model to initial conditions for the Pleistocene, we made runs with constant production corresponding to the pre-20 ka BP value. From the resulting steady-state equilibrium values, we generated new initial values for n1, n2, n3 and ns, which we used with the fixed values for k12 and k23 to calculate values for the other exchange rates. Although n1, n2, n3, and ns change during the course of a run, the exchange rates were held constant.

Results

Figure 3 shows the results of several model calculations. For comparison, we show the tree-ring record back to 9.6 ka BP (Stuiver & Kra 1986), and the earlier Barbados coral data (Bard *et al.*

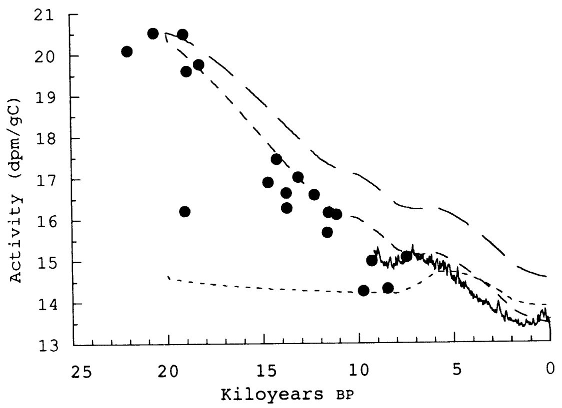

Fig. 3. The atmospheric ^{14}C activity record from tree rings (continuous curve) and Barbados corals (•), and modeled results for: the standard DM and box models (— —); the standard models with lowered DC gain (DC100)(- - -); and the DM model with a late Pleistocene value corresponding to the average field strength for the past 5 Ma (- - - -).

1990a). The revised coral AMS ^{14}C dates lower the activities at 20 ka BP by about 10% (Bard *et al.* 1990b), but do not substantively affect the implications herein. We converted the $\Delta^{14}C$ data for these records to activities by using a reference activity of 13.56 dpm/gC (Karlén *et al.* 1964). The results of the standard run give a model fluctuation curve that has the general shape of the data, but is, overall, too high. One can adjust for this by lowering the DC gain. Thus, we increased the initial ^{14}C content of the sedimentary sink from 34 to 50 dpm/cm$_e^2$, thereby reducing the DC gain from 108 to 100. This lowered the model curve (Fig. 3) to agree very well with the data. The model result still lags behind the data, a problem first noted by Damon (1970). This can be ameliorated by using a longer atmospheric residence time or a relatively smaller atmospheric reservoir (Sternberg & Damon 1979: Fig. 6). Of course, the problem could be due also to changes in heliomagnetic modulation or reservoir parameters.

According to the adjusted standard model, final reservoir decay rates for the present are n1 = 1.55, n2 = 8.72, n3 = 86.7 and ns = 37.8 dpm/cm$_e^2$. These compare favorably to reservoir estimates of n1 = 1.64, n2 = 9.19, n3 = 91.2, n4 = 41.2 (Damon 1988).

As an alternative model, the fast decrease to a lower DM before 12 ka BP generates an activity too high and too close to the present. If, instead of decreasing to a DM of 4.0 × 10^{22} A m^2, the field switches to its 5 Ma average of 8.67 × 10^{22} A m^2, the calculated activities are much lower than the coral activities in the Late Pleistocene (Fig. 3).

Thus, the fluctuation calculations show that the high activities suggested by the Barbados coral data can be explained by a low DM in the Late Pleistocene, using a reasonable ^{14}C reservoir model that includes a sizeable sedimentary sink. The long-term trend of the Holocene record can also be explained by geomagnetic modulation. Mazaud *et al.* (1991a) draw the same conclusion.[1] A lower production function, such as that of O'Brien (1979), would require a higher DC gain to generate the required activities, yet this would be inconsistent with the tendency of the sedimentary sink to lower DC gain.

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[1] *Note added in proof*: The paper by Mazaud *et al.* (1991b) was published after original submission of this manuscript. Utilizing relative paleointensity data from Tric *et al.* (in press), they reach virtually identical conclusions that the ^{14}C fluctuations shown in the coral record can be explained by a generally low DM in the Late Pleistocene.

LASCHAMP FLUCTUATIONS

A Laschamp-type event would have a negligible effect on the present inventory, because the best estimate for its timing is about seven ^{14}C half-lives ago. This would not be true necessarily for ^{14}C activity measured soon after the time of Laschamp itself. Grey (1971) first examined this problem, but, at that time, Laschamp was believed to have occurred about 20 ka BP. Grey (1971) also assumed that the DM had been oscillating sinusoidally for several cycles to determine initial conditions. To simplify modeling, Grey (1971) used steady-state equations for the mixed-layer and deep-sea reservoirs.

We have run a number of Laschamp models to examine the effect on the atmospheric activity record. The Laschamp event was superimposed upon a steady-state DM of 4.0 × 10^{22} A m^2; the initial conditions were also generated from this steady-state DM. Our standard Laschamp event is centered at 45 ka BP, lasting for 10 ka, decreasing to a minimum DM with a triangular shape (Fig. 4). Other cases changed the timing, duration or minimum DM. We used a different DM shape only for the 20 ka duration event – the DM decreased linearly for 5 ka to the minimum, remained constant for 10 ka, then increased linearly for 5 ka to the baseline value.

Figure 4 shows the results of the standard Laschamp event on atmospheric $\Delta^{14}C$. Table 2, which summarizes results for other models of the Laschamp event, shows the peak value of $\Delta^{14}C$ generated, as well as the values at 20 and 10 ka BP. None of these models is absolutely precluded by

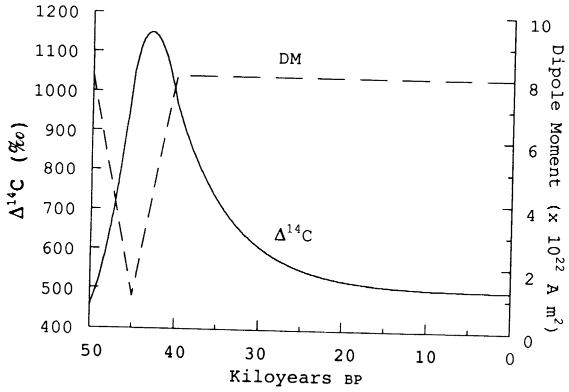

Fig. 4. The standard DM model for the Laschamp event and the corresponding atmospheric ^{14}C activity

TABLE 2. Effects of Laschamp-Type Events on ^{14}C Activity

Case	Age* (ka)	Length* (ka)	DM* (10^{22} A m^2)	Peak** (‰)	Time** (ka)	20 ka† (‰)	10 ka† (‰)
1	45	10	1.0	666	43.1	24	6
2	45	10	0.5	1219	43.1	46	10
3	45	10	2.0	275	43.1	10	2
4	45	5	1.0	444	44.1	12	3
5	45	20	1.0	1289	40.0	89	20
6	50	10	1.0	666	48.1	12	1
7	30	10	1.0	666	28.1	231	52

*Age, length and DM specify the midpoint in years BP, duration and minimum DM for Laschamp events.
**Peak indicates the resulting maximum in atmospheric ^{14}C above the steady-state value at the adjacent time in years BP.
†Resulting increases of ^{14}C above the steady-state value for 20 and 10 ka BP.

the ^{14}C calibration data. Higher amounts of Laschamp-generated ^{14}C at 20 and 10 ka BP, such as for Cases 5 and 7 in Table 2, are permitted, if other causes generate a ^{14}C deficiency, such as for some DM/initial conditions (*e.g.*, Beer *et al.* 1988: Fig. 3; Stuiver *et al.* 1991: Figs. 6, 8). However, as Figure 3 shows, this extra ^{14}C from a deep event is not required.

If the ^{14}C time scale could be calibrated back to 30 ka BP, the effects of a Laschamp pulse would become evident for most of these cases. The large pulse generated by longer or "deeper" events might also generate dating anomalies or inversions.

We wish to note, without undue speculation, the existence of a spike in the ^{10}Be record from two Antarctic ice cores at about 35 ka BP, lasting 1–2 ka (Raisbeck *et al.* 1987).

CONCLUSIONS

Our three major conclusions are:

1. The ^{14}C inventory, including sedimentary sink, implies both a low Late Pleistocene DM strength and a relatively high ^{14}C production function.
2. The ^{14}C activity record also requires a low DM, and is consistent with a low DC gain due to the sedimentary sink and a correspondingly high production function.
3. A global Laschamp event at 40–50 ka BP, with a significantly decreased DM, is not ruled out by the extant ^{14}C record; pushing this record back to 30 ka BP could constrain models for Laschamp.

Important research that would shed additional light on the problems discussed here include:

1. More research on tree rings, varves and corals to extend the calibration of the ^{14}C time scale for ambient reservoirs into the Pleistocene.
2. A search for the effects of a Laschamp event in older ^{14}C dates, *e.g.*, young dates and dating inversions.
3. More absolute and relative paleointensity data for the Late Pleistocene.
4. More research on the geographic extent, timing and magnetic recording of the Laschamp event.

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REFERENCES

Barbetti, M. 1980 Geomagnetic strength over the last 50,000 years and changes in atmospheric ^{14}C concentration: Emerging trends. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 10th International ^{14}C Conference. *Radiocarbon* 22(2): 192–199.

Barbetti, M. and Flude, K. 1979 Geomagnetic variation during the late Pleistocene period and changes in the radiocarbon time scale. *Nature* 279: 202–205.

Bard, E., Hamelin, B., Arnold, M. and Buigues, D. 1991 $^{230}Th/^{234}U$ and ^{14}C ages obtained by mass spectrometry on corals from Mururoa Atoll, French Polynesia. Abstract. *Radiocarbon* 33(2): 173.

Bard, E., Hamelin, B., Fairbanks, R. G. and Zindler, A. 1990a Calibration of the ^{14}C timescale over the past 30,000 years using mass spectrometric U-Th ages from Barbados corals. *Nature* 345: 405–410.

Bard, E., Hamelin, B., Fairbanks, R. G., Zindler, A., Mathieu, G. and Arnold, M. 1990b U/Th and ^{14}C ages of corals from Barbados and their use for calibrating the ^{14}C time scale beyond 9000 years B.P. *In* Yiou, F. and Raisbeck, G. M., eds., Proceedings of the 5th International Conference on Accelerator Mass Spectrometry. *Nuclear Instruments and Methods* B52: 461–468.

Beer, J., Siegenthaler, U., Bonani, G., Finkel, R. C., Oeschger, H., Suter, M. and Wölfli, W. 1988 Information on past solar activity and geomagnetism from ^{10}Be in the Camp Century ice core. *Nature* 331: 675–679.

Blinov, A. 1988 The dependence of cosmogenic isotope production rate on solar activity and geomagnetic field variations. *In* Stephenson, F. R. and Wolfendale, A. W., eds., *Secular Solar and Geomagnetic Variations in the Last 10,000 Years.* Dordrecht, The Netherlands, Kluwer Publishing Co.: 329–340.

Bonhommet, N. and Babkine, J. 1967 Sur la présence d'aimantations inversées dans la Chaîne de Puys. *Comptes Rendus de l'Academie des Sciences* B264: 92–94.

Castagnoli, G. and Lal, D. 1980 Solar modulation effects in terrestrial production of carbon-14. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 10th International ^{14}C Conference. *Radiocarbon* 22 (2): 133–158.

Champion, D. E. 1980 Holocene geomagnetic secular variation in the western United States: Implications for the global geomagnetic field. *US Geological Survey Open-File Report* 80-824. Denver, Colorado: 314 p.

Coe, R. S., Grommé, S. and Mankinen, E. A. 1978 Geomagnetic paleointensities from radiocarbon-dated lava flows on Hawaii and the question of the Pacific nondipole low. *Journal of Geophysical Research* 83: 1740–1756.

Damon, P. E. 1970 Climatic versus magnetic perturbation of the atmospheric C14 reservoir. *In* Olsson, I. U., ed., *Radiocarbon Variations and Absolute Chronology.* Proceedings of the 12th Nobel Symposium. Stockholm, Almqvist & Wiksell: 571–593.

_____1988 Production and decay of radiocarbon and its modulation by geomagnetic field-solar activity changes with possible implications for global environment. *In* Stephenson, F. R. and Wolfendale, A. W., eds., *Secular Solar and Geomagnetic Variations in the Last 10,000 Years.* Dordrecht, The Netherlands, Kluwer Publishing Co.: 267–283.

Damon, P. E., Cheng, S. and Linick, T. W. 1989 Fine and hyperfine structure in the spectrum of secular variations of atmospheric ^{14}C. *In* Long, A. and Kra, R. S., eds., Proceedings of the 13th International ^{14}C Conference. *Radiocarbon* 31(3): 704–718.

Damon, P. E., Lerman, J. C. and Long, A. 1978 Temporal fluctuations of atmospheric ^{14}C: Causal factors and implications. *Annual Reviews of Earth and Planetary Sciences* 6: 457–494.

Damon, P. E. and Sonett, C. P. 1991 Solar and terrestrial components of the atmospheric ^{14}C variation spectrum. *In* Sonett, C. P., Giampapa, M. S. and Mathews, M. S., eds., *The Sun in Time.* Tucson, The University of Arizona Press: 360–388.

Damon, P. E. and Sternberg, R. S. 1989 Global production and decay of radiocarbon. *In* Long, A. and Kra, R. S., eds., Proceedings of the 13th International ^{14}C Conference. *Radiocarbon* 31(3): 697–703.

Damon, P. E., Sternberg, R. S. and Radnell, C. J. 1983 Modeling of atmospheric radiocarbon fluctuations for the past three centuries. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 11th International ^{14}C Conference. *Radiocarbon* 25(2): 249–258.

Elsasser, W., Ney, E. P. and Winckler, J. R. 1956 Cosmic-ray intensity and geomagnetism. *Nature* 178: 1226–1227.

Grey, D. C. 1971 ^{14}C data and the Laschamp reversed event. *Journal of Geomagnetism and Geoelectricity* 23(1): 123–127.

Heller, F. and Petersen, N. 1982 The Laschamp excursion. *Philosophical Transactions of the Royal Society of London* A306(1492): 169–177.

Houtermans, J. 1966 On the quantitative relationships between geophysical parameters and the natural C^{14} inventory. *Zeitschrift für Physik* 193: 1–12.

Karlén, I., Olsson, I. U., Kållberg, P. and Kilicci, S. 1964 Absolute determination of the activity of two C^{14} dating standards. *Arkiv för Geofysik* 4(22): 465–471.

Lal, D. 1988 Theoretically expected variations in the terrestrial cosmic-ray production rates of isotopes. *In* Castagnoli, G. C., ed., *Solar-Terrestrial Relationships and the Earth Environment in the Last Millennia.* Amsterdam, Elsevier: 216–233.

Lazear, G., Damon, P. E. and Sternberg, R. 1980 The concept of DC gain in modeling secular variations in atmospheric ^{14}C. *In* Stuiver, M. and Kra, R. S., eds., Proceedings of the 10th International ^{14}C Conference. *Radiocarbon* 22(2): 318–327.

Levi, S., Audunnson, H., Duncan, R. A., Kristjánnson, L., Gillot, P.-Y. and Jakobsson, S. P. 1990 Late Pleistocene geomagnetic excursion in Icelandic lavas: Confirmation of the Laschamp excursion. *Earth and Planetary Science Letters* 96: 443–457.

Libby, W. F. 1967 Radiocarbon and paleomagnetism. *In* Hindmarsh, W. R., Lowes, F. J., Roberts, P. H. and Runcorn, S. K., eds., *Magnetism and the Cosmos.* New York, American Elsevier: 60–65.

Lingenfelter, R. E. and Ramaty, R. 1970 Astrophysical and geophysical variations in C14 production. *In* Olsson, I. U., ed., *Radiocarbon Variations and Absolute Chronology.* Proceedings of the 12th Nobel Symposium. Stockholm, Almqvist & Wiksell: 513–535.

Marshall, M., Chauvin, A. and Bonhommet, N. 1988 Preliminary paleointensity measurements and detailed magnetic analyses of basalts from the Skalamaelifell excursion, southwest Iceland. *Journal of Geophysical Research* 93(B10): 11,681–11,698.

Mazaud, A., Laj, C., Bard, E., Arnold, M. and Tric, E. 1991a Geomagnetic field control of ^{14}C production over the last 80 Ky: Implications for the radiocarbon time-scale. Abstract. *EOS, Transactions, American Geophysical Union* 72(44): 71–72.

_____1991b Geomagnetic field control of ^{14}C production over the last 80 Ky: Implications for the radiocarbon time-scale. *Geophysical Research Letters* 18(10): 1885–1888.

McElhinny, M. W. and Senanayake, W. E. 1982 Variations in the geomagnetic dipole 1: The past 50,000 years. *Journal of Geomagnetism and Geoelectricity* 34: 39–51.

McFadden, P. L. and McElhinny, M. W. 1982 Variations in the geomagnetic dipole, 2. Statistical analysis of VDMs for the past 5 million years. *Journal of Geomagnetism and Geoelectricity* 34: 163–189.

O'Brien, K. J. 1979 Secular variation in the production of cosmogenic isotopes. *Journal of Geophysical Research* 84(A2): 423–431.

Olsson, I. U., ed. 1970 *Radiocarbon Variations and Absolute Chronology.* Proceedings of the 12th Nobel Symposium. Stockholm, Almqvist & Wiksell: 652 p.

Phillips, F. W., Sharma, P. and Wigand, P. E. 1991 Deciphering variations in cosmic radiation using cosmogenic ^{36}Cl in ancient rat urine. Abstract. *EOS, Transactions, American Geophysical Union* 72(44): 72.

Raisbeck, G. M., Yiou, F., Bourles, D., Lorius, C., Jouzel, J. and Barkov, N. I. 1987 Evidence for two intervals of enhanced ^{10}Be deposition in Antarctic ice during the last glacial period. *Nature* 326: 273–277.

Ramaty, R. 1967 The influence of geomagnetic shielding on C14 production and content. *In* Hindmarsh, W. R., Lowes, F. J., Roberts, P. H. and Runcorn, S. K., eds., *Magnetism and the Cosmos.* New York, American Elsevier: 66–78.

Richmond, B., Peterson, S. and Vescuso P. 1987 *An Academic User's Guide to STELLA.* Lyme, New Hampshire, High Performance Systems: 392 p.

Roperch, P., Bonhommet, N. and Levi, S. 1988 Paleointensity of the earth's magnetic field during the Laschamp excursion and its geomagnetic implications. *Earth and Planetary Science Letters* 88: 209–219.

Salis, J.-S., Bonhommet, N. and Levi, S. 1989 Paleointensity of the geomagnetic field from dated lavas of the Chaîne des Puys, France. 1. 7–12 thousand years before present. *Journal of Geophysical Research* 94(B11): 15,771–15,784.

Schweitzer, C. and Soffel, H. C. 1980 Paleointensity measurements on postglacial lavas from Iceland. *Journal of Geophysics* 47: 57–60.

Sternberg, R. S. 1992 Radiocarbon fluctuations and the geomagnetic field. *In* Taylor, R. E., Long, A. and Kra, R. S., eds., *Radiocarbon After Four Decades: An Interdisciplinary Perspective.* New York, Springer-Verlag: 93–116.

Sternberg, R. S. and Damon, P. E. 1979 Sensitivity of radiocarbon fluctuations and inventory to geomagnetic and reservoir parameters. *In* Berger, R. and Suess, H. E., eds., *Radiocarbon Dating.* Proceedings of the 9th International ^{14}C Conference. Berkeley, University of California Press: 691–717.

Stuiver, M., Braziunas, T. F., Becker, B. and Kromer, B. 1991 Climatic, solar, oceanic, and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}C/^{12}C$ change. *Quaternary Research* 35: 1–24.

Stuiver, M. and Kra, R. S., eds. 1986 Calibration Issue. Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2B): 805–1030.

Tanaka, H. 1990 Paleointensity high at 9000 years from volcanic rocks in Japan. *Journal of Geophysical Research* 95(B11): 17,517–17,531.

Tauxe, L. and Valet, J.-P. 1989 Relative paleointensity of the earth's magnetic field from marine sedimentary rocks: A global perspective. *Physics of the Earth and Planetary Interiors* 13: 241–244.

Thouveny, N. and Creer, K. M. 1991 Laschamp: An ephemeral geomagnetic anomaly. Paper presented at XX General Assembly of IUGG, Vienna, August 11–24.

Thouveny, N., Creer, K. M. and Blunk, I. 1990 Extension of the Lac du Bouchet paleomagnetic record over the last 120,000 years. *Earth and Planetary Science Letters* 97: 140–161.

Tric, E., Valet, J.-P., Tucholka, P., Paterne, M., Labeyrie, L., Guichard, F., Tauxe, L. and Fontugne, M., in press, Paleointensity of the geomagnetic field during the last eighty thousand years. *Journal of Geophysical Research.*

Wada, M. and Inoue, A. 1966 Relation between the carbon 14 production rate and the geomagnetic moment. *Journal of Geomagnetism and Geoelectricity* 18(4): 485–488.