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GEOMAGNETIC FIELD CONTROL OF ^{14}C PRODUCTION OVER THE LAST 80 KY : IMPLICATIONS FOR THE RADIOCARBON TIME-SCALE

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Abstract. We have used a recent estimate of the geomagnetic dipole field strength over the last 80 ky to examine the extent to which changes in geomagnetic field intensity have affected the radiocarbon time scale. The magnetic record was converted into a ^{14}C production signal which was then used to produce a synthetic atmospheric $\Delta^{14}\text{C}$ record using a two box model for the carbon cycle. This calibration suggests that the geomagnetic field has been the main factor governing the production of cosmogenic ^{14}C atoms over the period of time considered, and that $\Delta^{14}\text{C}$ changes due to other causes, such as climatic changes, have been of lesser importance. The results indicate that the radiocarbon ages are 2 to 3 ky younger than true age in the interval 18-40 ky b.p., in good agreement with recent U-Th and ^{14}C age comparisons. Moreover the results predict that a negligible difference between true and ^{14}C ages should be observed around 45-50 ky.

Introduction.

The basic assumption of the radiocarbon dating method is that the atmospheric $^{14}\text{C}/^{12}\text{C}$ ratio (referred to as $\Delta^{14}\text{C}$) has remained constant through time. With this assumption, the pre-industrial epoch value can be used as a initial value for the ratios measured in fossil carbon samples [Libby, 1952]. However, evidence has accumulated that changes of $\Delta^{14}\text{C}$ have occurred in the past. For instance, significant discrepancies exist between ^{14}C dates and "direct dating" of tree rings or lake sediments dated by varves. A compilation of such data, given by Stuiver et al. [1986], has been used to correct ^{14}C dates. More recently, a comparison of U-Th and ^{14}C dating of coral reefs has unambiguously proven the existence of large $\Delta^{14}\text{C}$ changes for the past 20 Ky [Bard et al., 1990a].

Several distinct phenomena may produce changes in the atmospheric $\Delta^{14}\text{C}$. Since the ocean contains over 40 tons of radioactive ^{14}C , whilst less than one ton is present in the atmosphere, it has been suggested that substantial changes in atmospheric $\Delta^{14}\text{C}$ could arise from relatively small changes in oceanic ventilation, associated with climatic changes [Siegenthaler et al., 1980; Keir, 1983; Prentice et al., 1990; Adams et al., 1990]. Changes of $\Delta^{14}\text{C}$ and also of the abundance of other cosmogenic isotopes such as ^{10}Be , may result from changes in their rate of production in the upper atmosphere. These can in turn arise either from changes in the flux of cosmic rays, changes in solar activity, or from

variations in shielding by the Earth's magnetosphere. Since galactic and solar rays are mainly composed of charged particles, a large fraction of them are deflected by the Earth's magnetic field. Changes in the field strength will thus efficiently control the fraction of cosmic rays which impinge on the Earth's atmosphere and consequently, the rate of production of cosmogenic nucleides [Lal, 1988]. Because this deflection occurs at the edges of the magnetosphere, several Earth radii away from the Earth's surface, only changes of the dipole field strength will be effective.

Very little is known about the variations of the flux of the cosmic rays on a time scale of a few tens of thousand years. Changes in solar modulation are also poorly known, except those related to the 11 year cycle. Thus, the extent to which these affect ^{14}C production is difficult to evaluate. Several authors have considered the influence of variations of geomagnetic field strength on the abundance of cosmogenic isotopes in the atmosphere. However, so far only qualitative results have been obtained over a time period covering the last 50 ky, because of the lack of precise knowledge of the field intensity over this interval of time [Barbetti and Flude, 1979; Barbetti, 1980; Bard et al., 1990]. Such a record of field intensity is difficult to obtain because continuous records are potentially only obtainable from sediments, which even ideally can only provide a record of relative paleointensity. Absolute values can be retrieved from lavas, but these give only spot readings in time of the field strength.

We report here an evaluation of the influence of geomagnetic field intensity changes on atmospheric $\Delta^{14}\text{C}$ based on a new and continuous estimate of the dipole field strength over the last 80 Ky [Tric et al., in press].

A record of dipole field strength for the last 80 ky.

A detailed description of the record we have used is given elsewhere [Tric et al., 1991, in press]. It was established from four marine cores from the Tyrrhenian Sea and the Eastern Mediterranean. All cores meet criteria for relative paleointensity determinations given by King et al [1982, 1983], and precise age control was obtained from oxygen isotope and tephrochronological studies [Tric et al., in press]. The relative field intensity variations were calibrated using published absolute intensity, determined from volcanic rocks. The final record (Fig. 1) shows that over the last 80 ky, the intensity of the geomagnetic field was, on the average, lower than its present day value, with three minima at 21, 39 and 60 ky b.p.

There is a remarkable agreement between this record and different published Virtual Axial Dipole Moments (VADM)s determined from volcanic formations from widely separated geographical regions [Tric et al., in press]. This record also agrees with records obtained in the Pacific [Constable and

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Fig. 1. a) The field intensity record obtained by Tric et al. (in press). Shaded area corresponds to uncertainties in Virtual Axial Dipole Moments (VADM) determinations given by the authors. Full line before 10 ky represents data of McElhinny and Senanayake (1982).

Tauxe, 1987; Tauxe and Wu, in press] and in the northern Atlantic [Tauxe and Valet, 1987]. All these results suggest that the record of Tric et al [in press] is one of global dipole field variation. This record of the geomagnetic dipole intensity is more accurate and extends farther back in time than one given by McElhinny and Senanayake [1982]. It allows the first precise evaluation of the influence of the magnetic field on cosmonuclide production.

Implications for the radiocarbon time-scale.

We have examined the extent to which these changes in geomagnetic field intensity would have affected the radiocarbon time scale. First, we converted the magnetic record of Tric et al (in press) into a ^{14}C production rate, using the results of Lal [1988]. At high field values, the relative variations of the production of ^{14}C atoms can be approximated by $\sqrt{M_0/M}$, M being the dipole moment at the time considered, and M_0 its present day value [Elsasser et al., 1976]. At lower dipole intensities, the apparent saturation indicates removal of geomagnetic screening [Lal, 1988]. The curve of the variations of cosmogenic ^{14}C atom production deduced from geomagnetic dipole intensity changes is presented in Fig. 2. It was obtained from the paleointensity record of Fig. 1 by considering only geomagnetic intensity changes. High production peaks correspond to minima in dipole intensity, and in particular the high production observed on average between 18 and 45 ky is a direct consequence of a period of weaker geomagnetic dipole field intensity values at those times.

Because of the natural disintegration of ^{14}C atoms and other phenomena affecting the isotopic balance of carbon in the atmosphere, the signal of instantaneous ^{14}C production does not represent the atmospheric $\Delta^{14}\text{C}$ record. The ocean absorbs a large fraction of the ^{14}C produced in the atmosphere and conversely re-introduces previously created ^{14}C atoms in the atmosphere with some delay. We have converted the instantaneous production record of Fig. 2 into an atmospheric $\Delta^{14}\text{C}$ signal using a two box model for the carbon cycle [Houterman et al., 1973], already used by Bard

Fig. 2. a) Production of ^{14}C atom record deduced from the geomagnetic dipole intensity record of Tric et al. (in press), by using Lal's results (1988) for the dependence of the ^{14}C atom production upon geomagnetic dipole intensity variations.

et al. [1990]. In this model, the first box represents the atmosphere and a fraction of the oceanic mixed layer, while the second box represents the deeper parts of the ocean. The response to a pulse input is composed of two exponentials [Houterman et al., 1973]. The first, characterized by a relaxation time of about 50 years, corresponds to the absorption of the ^{14}C atoms from the first box to the deeper ocean, whilst the second corresponds to the radioactive decay and has a relaxation time of 8267 years. This model acts as a low pass filter which smooths out short term production variations, such as those related to the 11 year solar cycle. The curve of the synthetic atmospheric $\Delta^{14}\text{C}$ record obtained from filtering the production signal of Fig. 2 is shown in Fig. 3. Low values of the geomagnetic dipole moment, which was on average equal to $\sim 50\%$ of its present day value in the interval 18-40 ky b.p., gives rise to a positive $\Delta^{14}\text{C}$ of about 350‰.

To test whether this magnetic record of past atmospheric $\Delta^{14}\text{C}$ is realistic or not, we have expressed it in terms of shift of radiocarbon ages, and compared the results with spot comparisons of ^{14}C and U-Th ages from corals in Barbados [Bard et al, 1990 a,b]. The $\Delta^{14}\text{C}$ signal, and the

Fig. 3. Atmospheric $\Delta^{14}\text{C}$ signal obtained by filtering the production record shown Fig. 2b. The filter is the two-box model of Houterman et al (1973), already used by Bard et al (1990a). Short timed variations of the production record shown in Fig. 2b are smoothed out by the mixing of carbon in atmosphere and ocean.

corresponding shift of radiocarbon ages, are shown Fig. 4, together with the differences between U-Th and ^{14}C ages of Barbados corals found by Bard et al. [1990 a, b]. The shaded zone corresponds to the uncertainties in the dipole strength of the Tric et al.'s record. ^{14}C ages of corals were obtained using both the β -counting method [Bard et al., 1990a], (Fig. 4, open symbols) and the accelerator mass spectrometry (AMS) method (Fig. 4, dark symbols) [Bard et al., 1990b]. U-Th ages of corals were obtained using the U-Th Thermal Ionisation Mass Spectrometry (TIMS) technique [Bard et al., 1990 a, b]. Because this last method is more accurate than the counting technique, and not affected by climatic and/or oceanic circulation changes, it is assumed that the U/Th ages represent true ages, an assumption which is sustained by the complete agreement between U/Th and dendrochronological dating for ages younger than 9 ky [Bard et al., 1990a].

Fig. 4. Calibration of the radiocarbon time scale, together with spot calibrations of ^{14}C ages obtained from U-Th ages determinations. Open symbols show ^{14}C ages determined by β -counting ^{14}C disintegrations [Bard et al., 1990a]. Closed symbols show ^{14}C ages determined by accelerator mass spectrometry [Bard et al., 1990b]. The shaded area corresponds to the uncertainties of the magnetic intensities given by Tric et al (in press). Vertical axis on right gives atmospheric $\Delta^{14}\text{C}$.

A remarkable agreement is observed between our $\Delta^{14}\text{C}$ signal and the calibration ^{14}C ages of corals by U-Th dating, especially in the interval 7-15 ky. At about 20 ky, the ^{14}C ages of corals are more scattered. ^{14}C ages of corals obtained by AMS are older than ^{14}C ages obtained by β -counting, and according to Bard et al. [1990b], this discrepancy may reflect a minor contamination during sample preparation by modern carbon of coral samples measured by β -counting. Nevertheless, U-Th dating gives a correction slightly higher than the magnetic calibration. This difference possibly corresponds to changes in oceanic circulation [Shackleton et al., 1988], and in atmospheric CO_2 concentration between Holocene time and the end of the last glacial period [Siegenthaler et al., 1980; Prentice et al., 1990; Adams et al., 1990]. At 30 ky, there is a qualitative agreement between our

correction and the two U-Th calibrations (Fig. 4). Other comparisons between ^{14}C ages and those determined by other methods have revealed young ^{14}C ages. K-Ar dates obtained using the Cassinot technique [Cassinot and Gillot, 1982] are older than radiocarbon ages obtained on the same samples (difference between K-Ar and ^{14}C ages is 0.11 ± 1.4 ky at about 3.5 ky, 3.8 ± 1.4 ky at about 15.5 ky, and 3 ± 1.5 ky at about 20 ky) [Gillot, 1984]. ^{14}C ages are also younger than thermoluminescence dates (of 4.0 ± 4.3 ky at 33 ky) [Bell, 1991]. Although the uncertainties in these two cases are larger than those of TIMS U-Th dates, there is a qualitative agreement with the magnetic calibration of ^{14}C ages presented here.

Conclusion.

The importance of non magnetic contributions is still discussed, but it is generally considered that $\Delta^{14}\text{C}$ larger than 300‰ cannot be explained solely by climatic changes, or/and by changes in the distribution of the carbon in the different reservoirs [Siegenthaler et al., 1980; Shackleton et al., 1988; Bard et al., 1990a]. This hypothesis is also reinforced by a recent study of the distribution of radiocarbon in the glacial ocean, which concludes that the higher $^{14}\text{C}/\text{C}$ ratio in surface water during glacial time was primarily the result of a higher global inventory of radiocarbon [Broecker et al., 1990]. Thus, although other causes, such as solar modulation [Raisbeck et al., 1987], may have also perturbed the ^{14}C content in the atmosphere, the good agreement between the magnetic calibration of ^{14}C ages and that obtained from direct U-Th dating strongly enforces the hypothesis that geomagnetic variations are the major source of millennial variations of the abundance of atmospheric ^{14}C during the past 50 ky. This conclusion agrees with a recent detailed study of the past 10 ky [Stuiver et al., 1991]. In terms of ^{14}C ages, the low values of the geomagnetic dipole moment in the interval 18-40 ky, introduces a shift of the ^{14}C age of about 2 to 3 ky toward younger ages. Conversely a negligible difference between true and ^{14}C ages is predicted in the interval 45-50 ky.

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References

- Adams, J.M., Faure, H., Faure-Denard, L., McGlade, J.M., and Woodward, F.I., Increases in terrestrial carbon storage from the Last Glacial Maximum to the present, *Nature*, 348, 711-714, 1990.
- Bell, W. T., Thermoluminescence dates for the Lake Mungo aboriginal fireplaces and the implication for radiocarbon time dating, *Archaeometry*, 33, 43-50, 1991.
- Barbetti, M., and Flude, K. Geomagnetic variation during the late Pleistocene period and changes in the radiocarbon time scale, *Nature*, 279, 202-205, 1979.
- Barbetti, M., Geomagnetic strength over the last 50,000 years and changes in atmospheric ^{14}C concentration: emerging trends, *Radiocarbon*, 22, 192-199, 1980.
- Bard, E., Hamelin, B., Fairbanks, R. G., and Zinder, A.,

- 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, 1990a.
- Bard, E., Hamelin, B., Fairbanks, R. G., Zinder, A., Mathieu, G., and Arnold, M., U-Th and ^{14}C ages of corals from Barbados and their use for calibrating the ^{14}C timescale beyond 9000 years B.P., *Nuclear Instruments and Methods in Physics Research B52*, 461-468, 1990b.
- Broecker, W. S., Peng, T. H., Trumbore, S., Bonani, G., and Wolfli, W., The distribution of radiocarbon in the glacial ocean, *Global Biogeochemical Cycles*, 4, 103-117, 1990.
- Constable, C. G., and Tauxe, L., Paleointensity in the pelagic realm: marine sediment data compared with archeomagnetic and lake sediment records, *Geophys. J. R. Astr. Soc.*, 90, 43-59, 1987.
- Cassignol, C., and Gillot, P. Y., Range and effectiveness of unspiked potassium-argon dating: experimental groundwork and applications, in *Numerical dating in stratigraphy*, G. S., Odin Editor, Wiley, Chichester, 159-179, 1982.
- Elsasser, W. M., Ney, E. P., and Wenkler, J. R., Cosmic ray intensity and geomagnetism, *Nature*, 178, 1226, 1956.
- Gillot, P. Y., Datation par la méthode du potassium argon des roches volcanique récentes pléistocènes et holocènes. Contribution à l'étude chronostratigraphique et magmatique des provinces volcaniques de Campanie, des Iles Eoliennes, de Pantelleria Italie du Sud et de la Réunion Océan Indien, *Thèse de doctorat d'Etat*, Université Paris Sud, France, 1984.
- Houterman, J. C., Suess, H. E. and Oeschger, H. Reservoir models and production rate variations of natural radiocarbon, *J. Geophys. Res.*, 78, 1897-1907, 1973.
- Prentice, K. C., and Fung, I. Y., The sensitivity of terrestrial carbon storage to climate change, *Nature* 346, 48-51, 1990.
- Keir, R. S., Reduction of thermohaline circulation during the deglaciation: the effect on atmospheric radiocarbon and CO_2 , *Earth Planet. Sci. Lett.*, 64, 445-456, 1983.
- King, J. W., Banerjee, S. K., Marvin, J. J., and Özdemir, O., A comparison of different magnetic methods for determining the relative grain size of magnetite in natural minerals: some results from lake sediments, *Earth Planet. Sci. Lett.*, 59, 410-419, 1982.
- King, J. W., Banerjee, S. K., and Marvin, J., A new rock approach to selecting sediments for the geomagnetic paleointensity studies: application to paleointensity for the last 4,000 years, *J. Geophys. Res.*, 88, 5911-5921, 1983.
- Lal, D., Theoretically expected variations in the terrestrial cosmic-ray production rates of isotopes, *Soc. Italiana di Fisica-Bologna-Italy, XCV corso*, 1988.
- Libby, W. F., Radiocarbon dating, *Univ. Chicago Press* 124p, 1952.
- McElhinny, M. W., and Senanayake, W. E., Variations in the geomagnetic dipole I: the past 50,000 years, *J. Geomag. Geoelectr.*, 34, 39 1982.
- Raisbeck, G. M., Yiou, F., Bourles, D., Lorus, C., Jouzel, J. & Barkov, N. I., Evidence for two intervals of enhanced ^{10}Be deposition in Antarctic ice during the last glacial period, *Nature*, 326, 273-277, 1987.
- Shackleton, N. J., Duplessy, J. C., Arnold, M., Maurice, P., Hall, M. A., and Cartlidge J., Radiocarbon age of last glacial deep water, *Nature*, 335, 708-711, 1988.
- Siegenthaler, U., Heimann, M. and Oeschger, H., ^{14}C variations caused by changes in the global carbon cycle, *Radiocarbon*, 22, 177-191, 1980.
- Stuiver, M., Kromer, B., Becker, B., and Ferguson, C. W., Radiocarbon age calibration back to 13 300 years BP and the ^{14}C age matching of the German oak and U.S. bristlecone pine chronologies, *Radiocarbon*, 28, 969-979, 1986.
- Stuiver, M., Braziunas, T. F., Becker, B., and Kromer, B., Climatic, solar, oceanic, and geomagnetic influences on Late-Glacial and Holocene atmospheric $^{14}\text{C}/^{12}\text{C}$ change, *Quaternary Research*, 35, 1-24, 1991.
- Tauxe, L., and Wu, G. Normalized remanence in marine sediment data from the western equatorial Pacific: relative paleointensity of the geomagnetic field? *J. Geophys. Res.*, in press.
- Tauxe, L., and Valet, J. P., Relative paleointensity of the Earth's magnetic field from marine sedimentary records: a global perspective, *Phys. Earth Planet. Sci. Lett.*, 56, 59-68, 1989.
- Tric, E., Valet, J. P., Tucholka, P., Paterne, M., Labeyrie, L., Guichard, F., Tauxe, L., Fontugne, M., Paleointensity of the geomagnetic field during the last eighty thousand years, *J. Geophys. Res.*, in press, 1991.

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